「すばるHSCサーベイによるサイエンス」

@国立天文台、September 26-28, 2012

0.38 arcmin (23”)

@1100μm

7.5
arcmin

ALMA/ASTE

東京大学
THE UNIVERSITY OF TOKYO

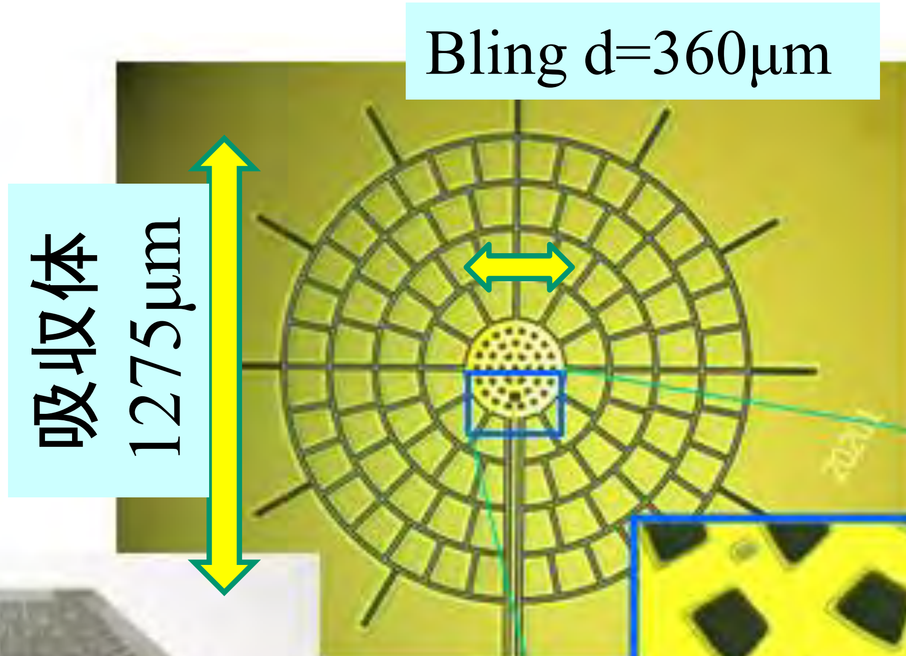
KOHNO Kotaro (IoA/RESCEU)

kkohno@ioa.s.u-tokyo.ac.jp

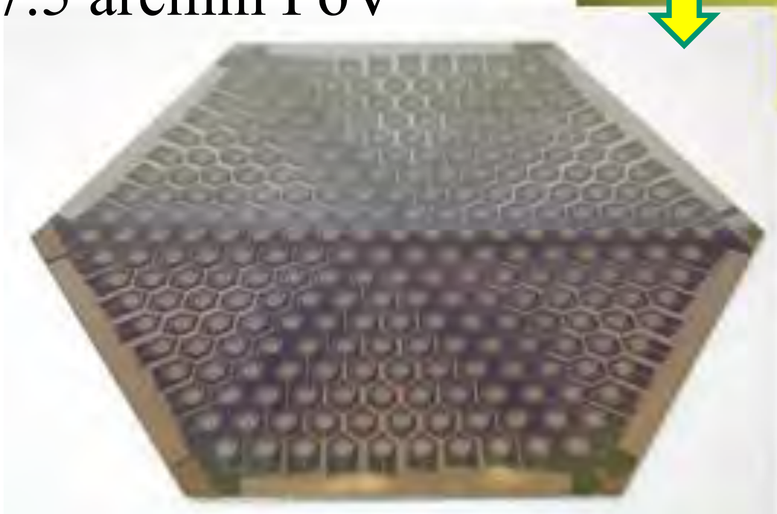
ASTE搭載用 TES 2 color camera

PI. 大島泰
（NRO）

350GHz(0.87mm)
270GHz(1.1mm)
400 pix in total.
7.5 arcmin FoV



Au mesh line
width~2μm
thickness~10nm



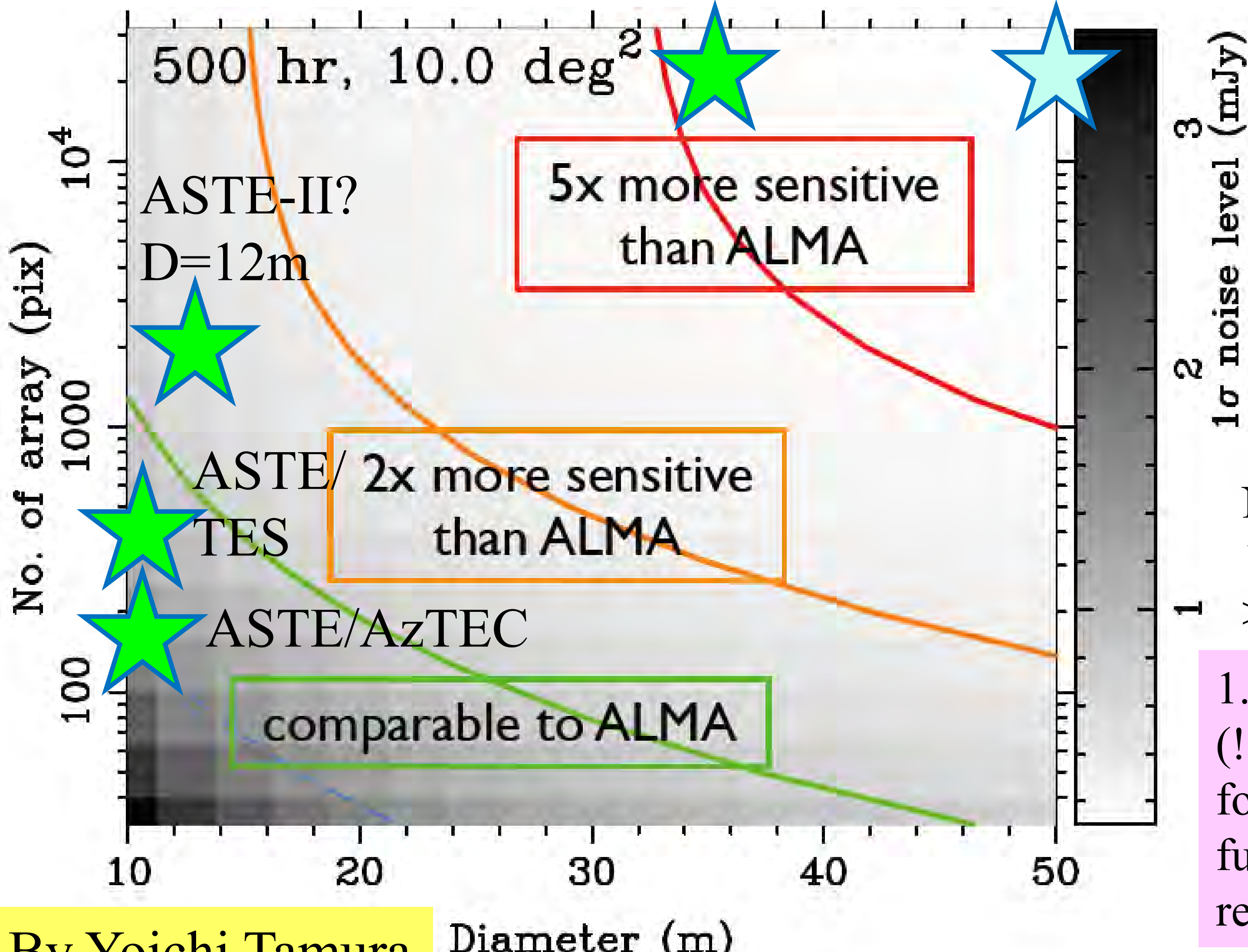
NAOJ, UC Berkeley, Cardiff, McGill, 東大、北大、KEKほか

Survey efficiency: Single dish vs ALMA

1.1mm (270 GHz)

D=35m

D=50m (option)



A deep survey of 10deg^2 area using 500 hours.

Bandwidth:
8 GHz for ALMA
50 GHz for SD

Num. of pixels
1 for ALMA
> 10^3-10^4 for SD !

1.2 million pointings (!!) will be needed for ALMA/Band 6 to fully cover a 10-deg^2 region.

By Yoichi Tamura

ALMAなう

- Cycle 0の科学運用（倍率9倍！）＋建設が進行中
- Cycle 1の公募 2012/7/12締切
- それに先立ち、Notices of intentの募集
  - 772件: cycle 0と比較して3割増し（601件）

  ➔予想応募件数は 1200件!?

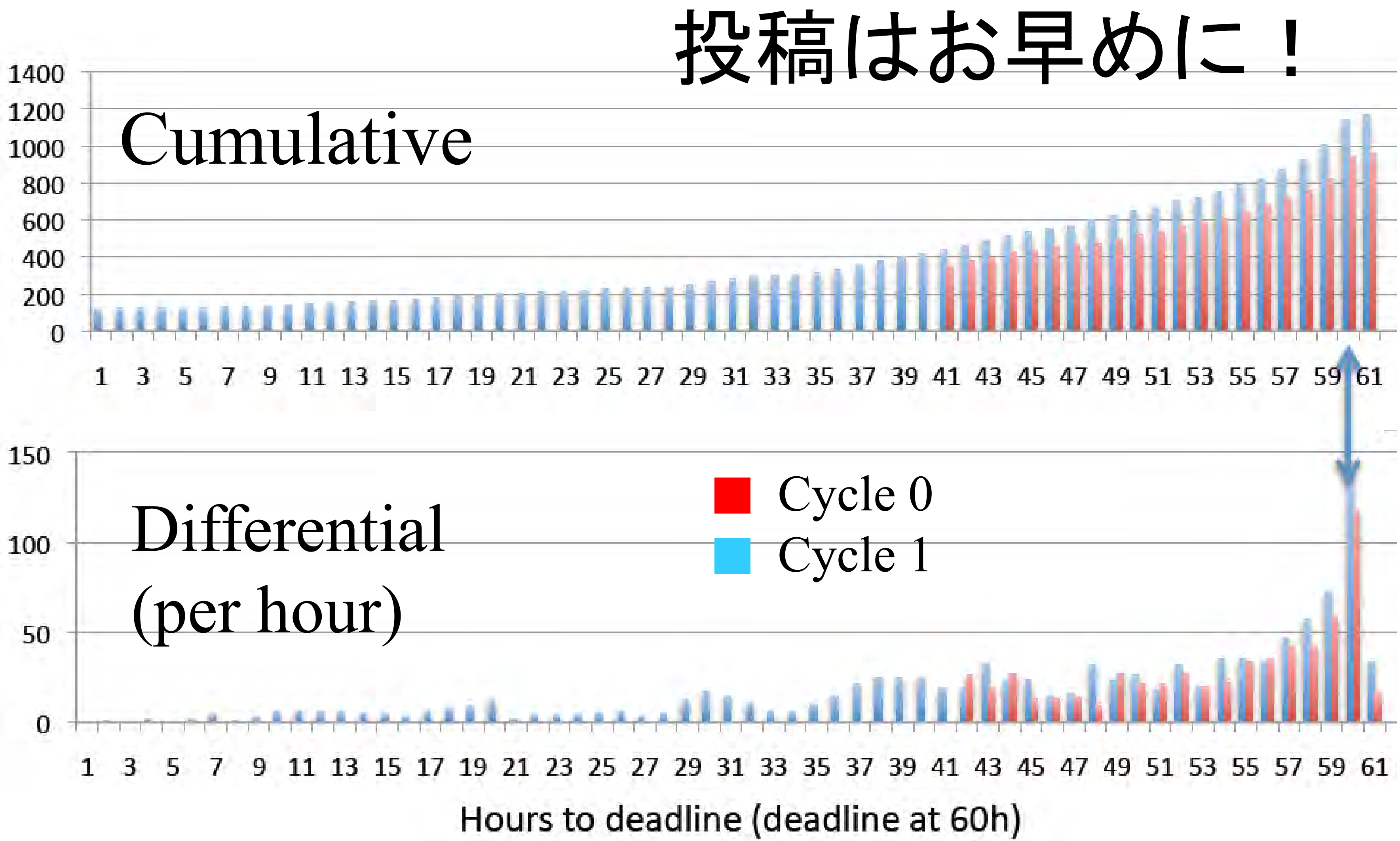
審査への御協力に感謝致します！

実際の応募数は

1161➔ **1133**

現在審査中

ALMA proposal submission



Outline

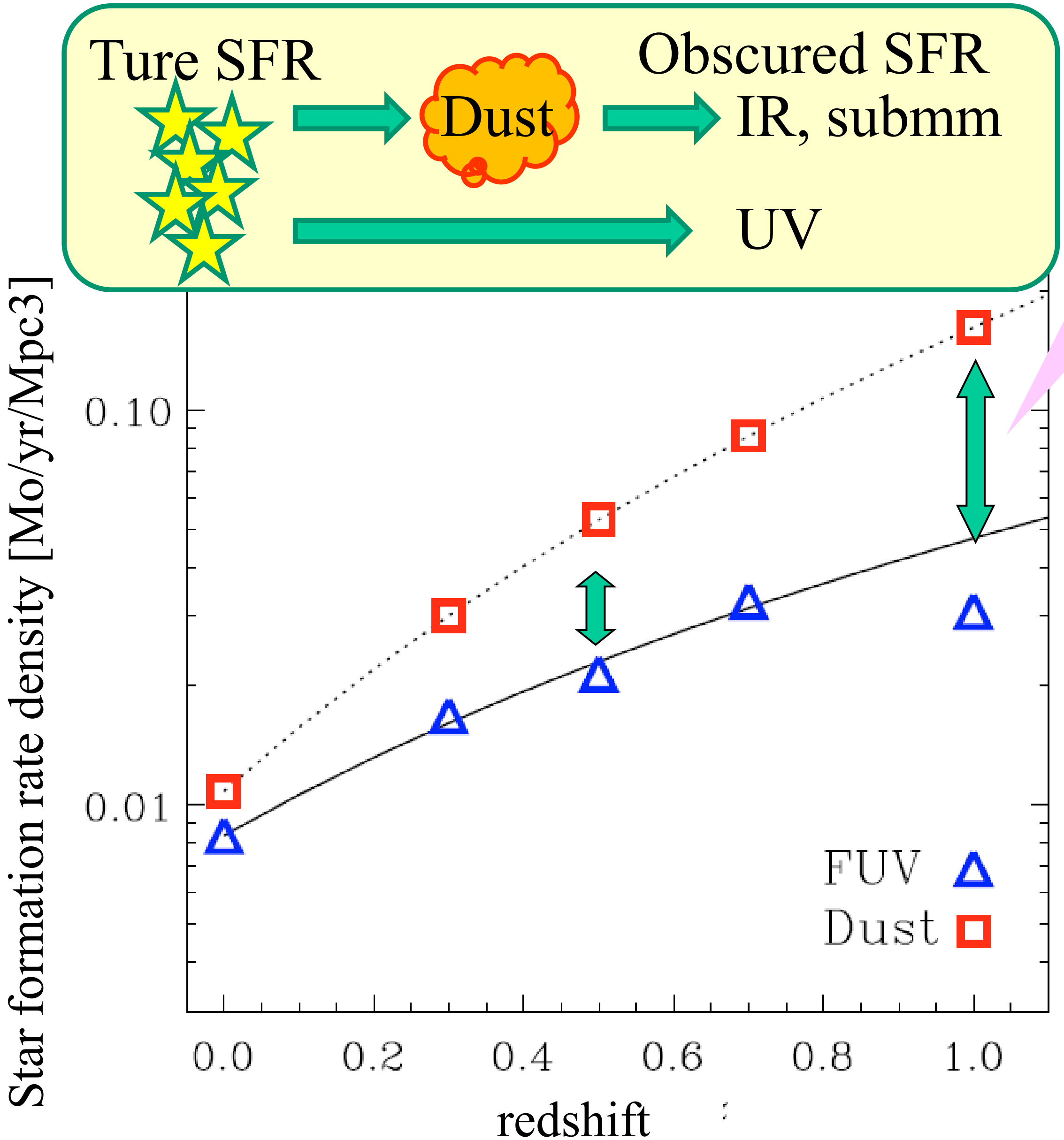
- Deep surveys in mm/submm wavelengths
  - Role of single dish telescopes equipped with large format mm/submm arrays
  - Superb capability of ALMA for spectroscopic follow up (even in the early phase!)
- HSC surveys and ALMA
  - Cross correlation between submm-selected galaxies and galaxies with photo-z from HSC surveys
  - Rare objects uncovered by HSC surveys: very suited targets for ALMA follow up!

Deep surveys

in mm/submm wavelengths:

Why mm/submm?

Because a large portion of the cosmic star formation is obscured by dust

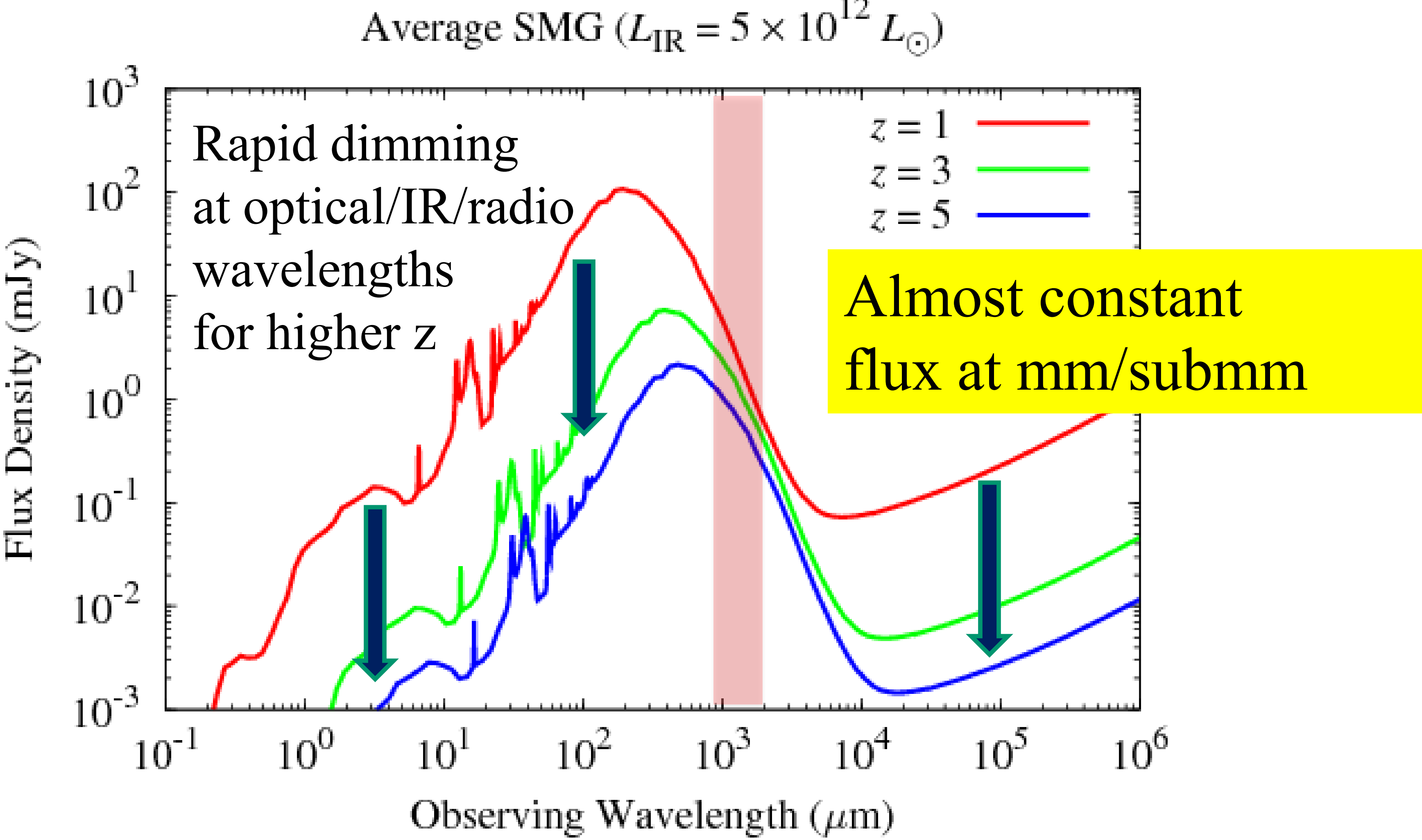


More hidden star formation @higher redshift (>70% at z~1)

Based on the comparison of Lum. Functions at FUV with GALEX & IR with IRAS/Spitzer

Takeuchi, Buat, & Durgarella 2005, A&A, 440, L17

And because mm/submm is the best to unveil the dust obscured star formation in the early universe



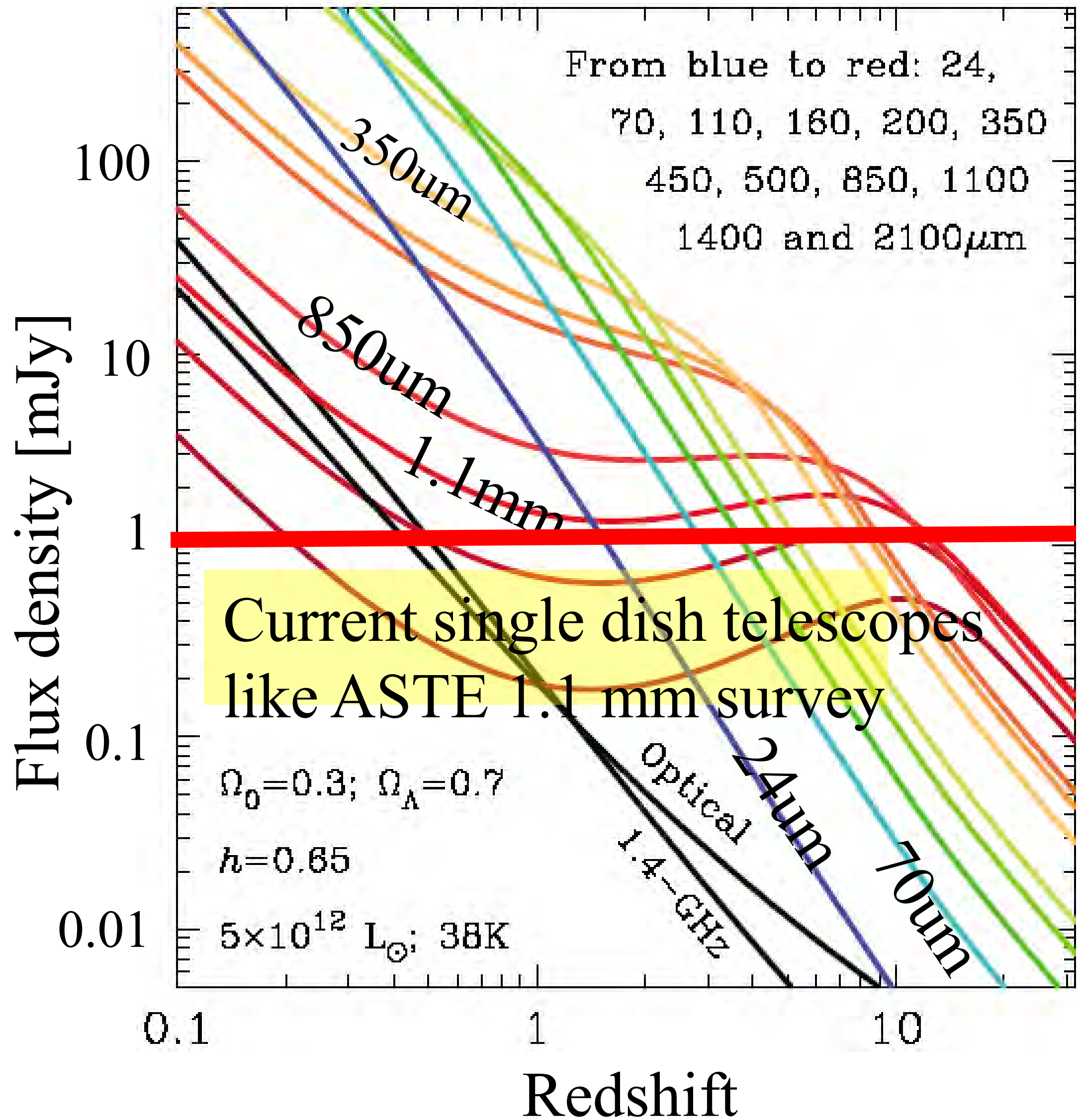
Mm/submm is a uniqe probe of dusty galaxies in the early universe

- Almost constant flux for 1 < z < 10 !!!

  at 850um ~ 1.1mm

  due to strong negative K correction
- Current survey is already sensitive to ULIRGs at z~10 (though limited by confusion)

Blain et al., 2002, Physics Reports, 369, 111-176



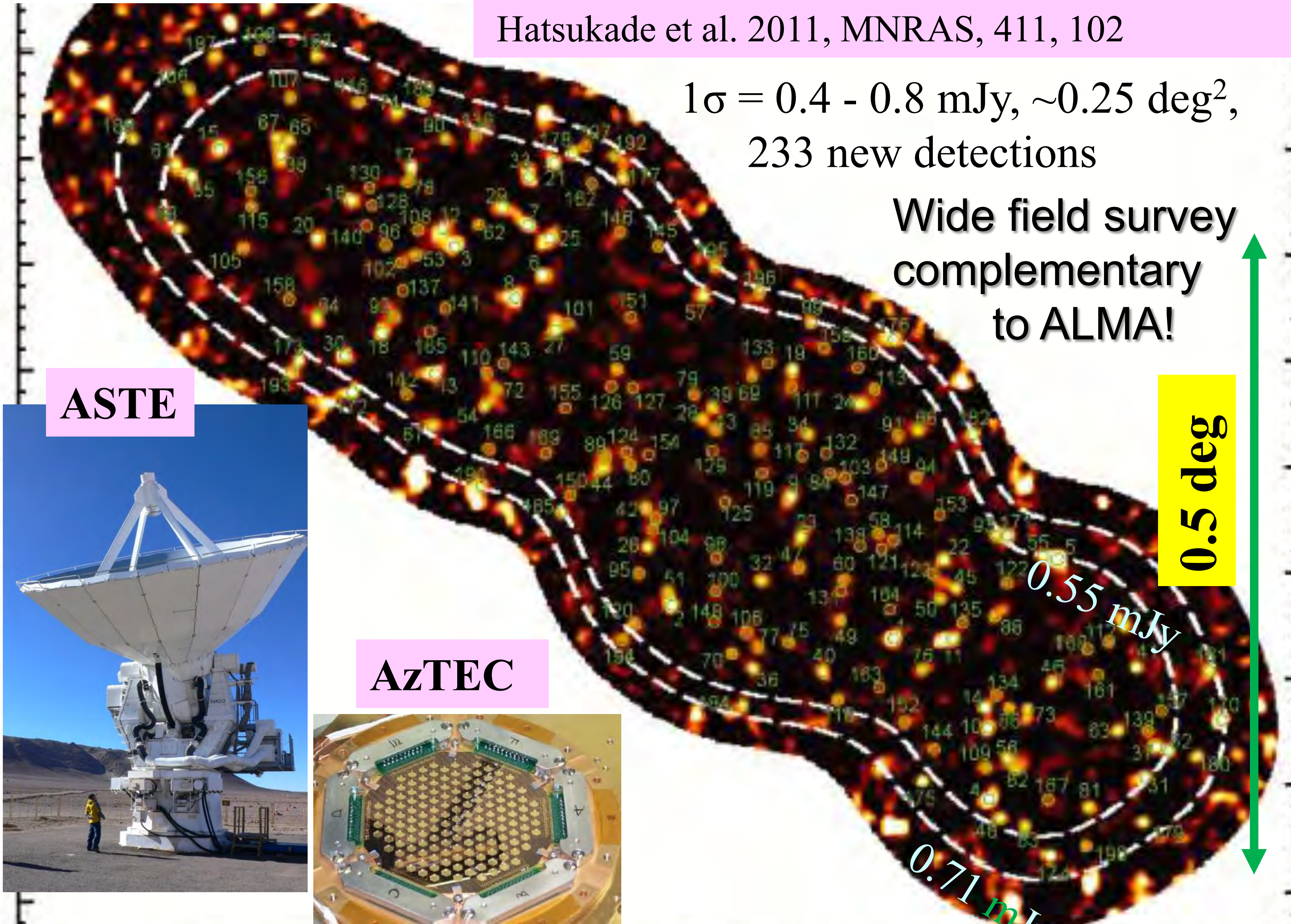
Deep mm/submm surveys

AzTEC/ASTE 1.1mm map of ADF-S

Hatsukade et al. 2011, MNRAS, 411, 102

1σ = 0.4 - 0.8 mJy, ~0.25 deg^2,
233 new detections

Wide field survey complementary to ALMA!



ASTE

AzTEC

Constraints on redshifts of AzTEC sources in ADF-S

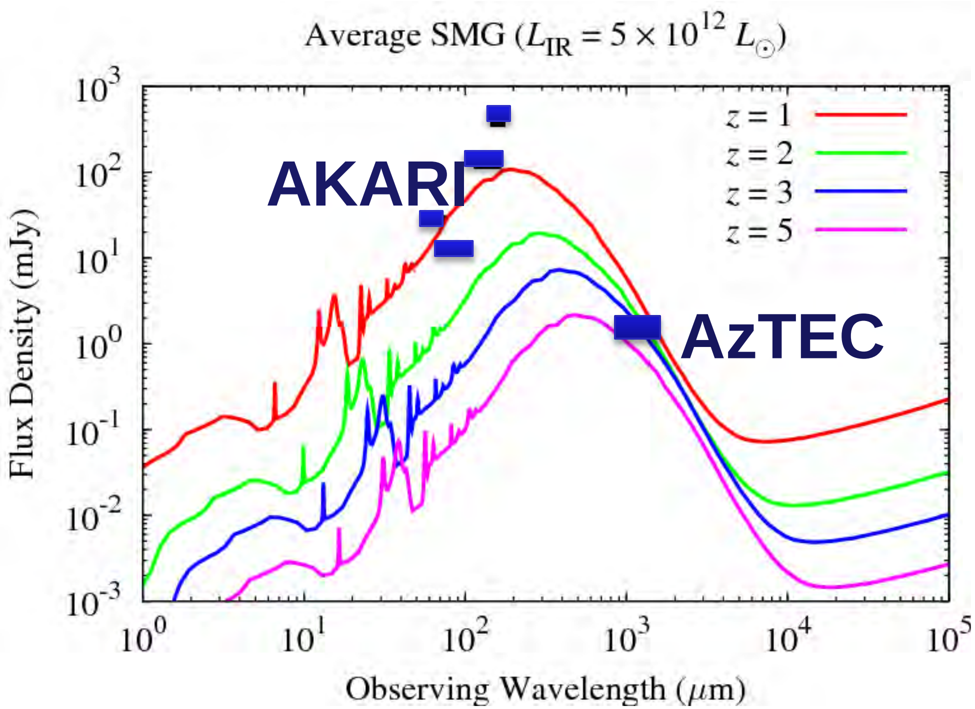
Hatsukade et al. 2011, MNRAS, 411, 102

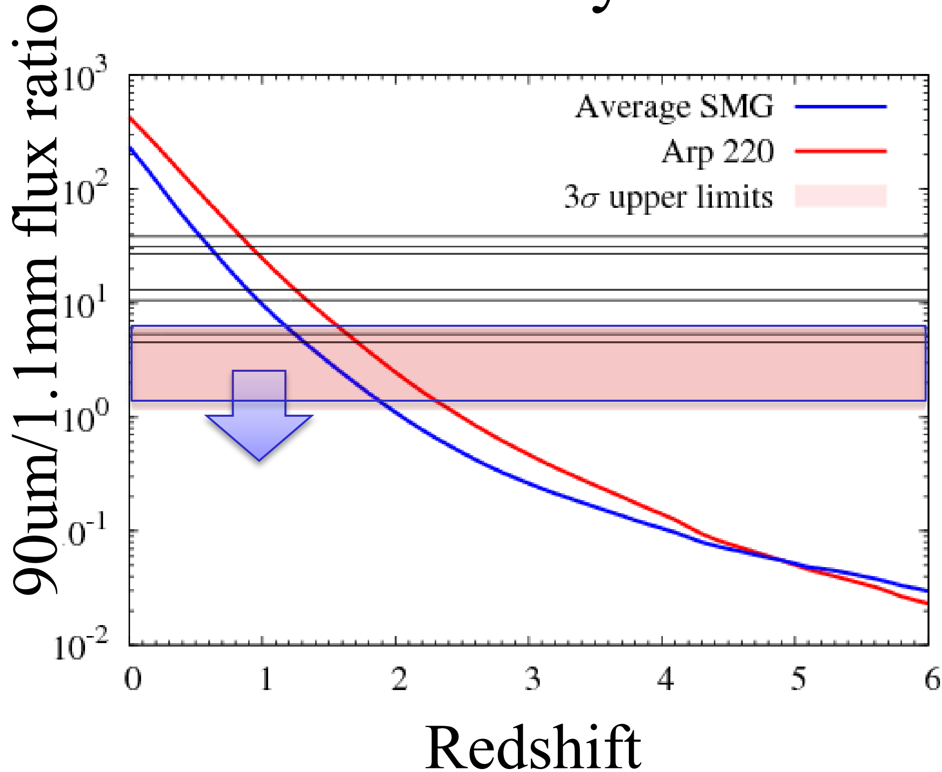
- 90um/1.1mm flux ratio

➔ most of the AzTEC sources (<u>196 of 198</u>) : z > 1

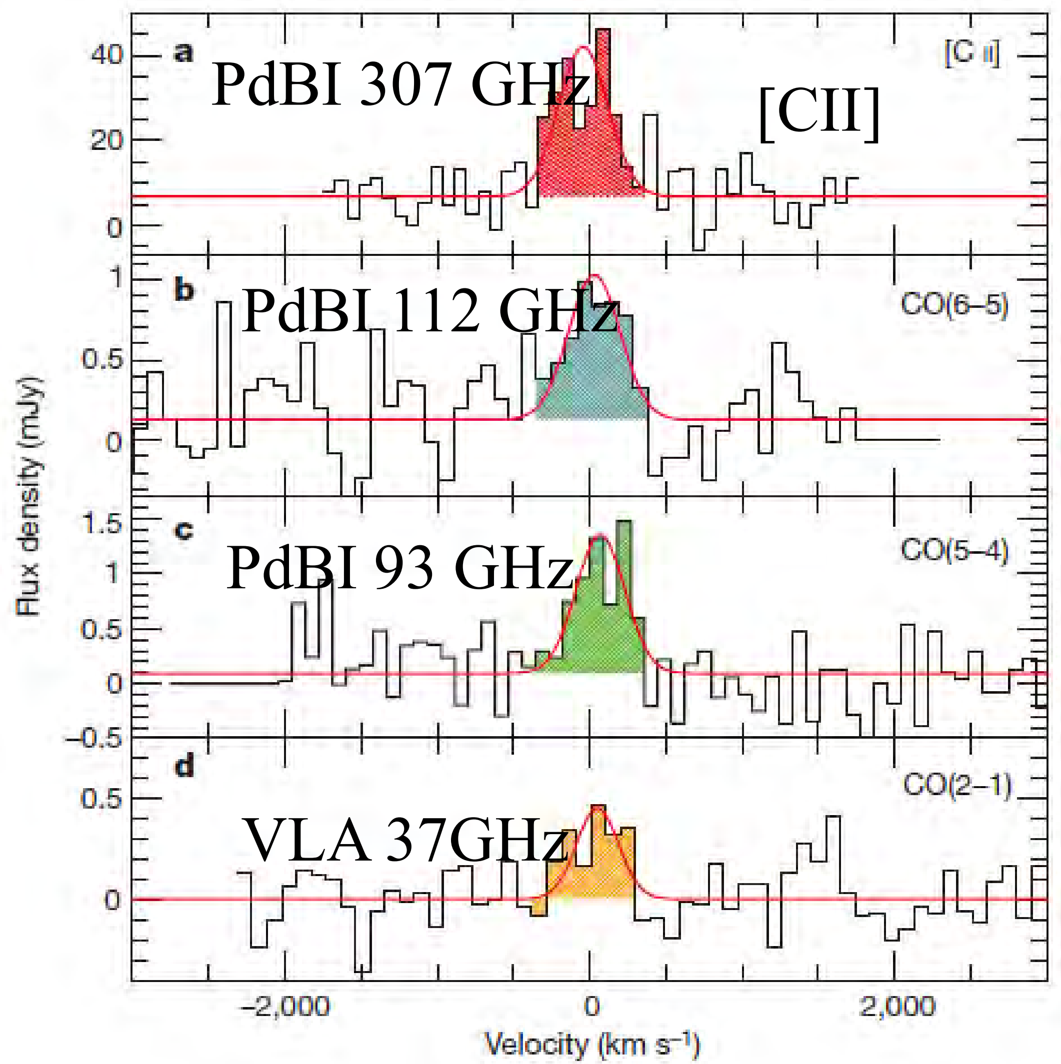
  – AKARI 90um sources : low-z, AzTEC 1.1mm sources: high-z

- L(FIR) ~ (3-14) x 10^{12} Lo, SFR ~ 500-2400 Mo/yr





[CII] at HDF850.1 ("classical" and typical unlensed submillimeter galaxy)



Redshift z=5.1 !!!

PdBI & VLA observations

L[CII] = 1.1x10^10 Lo
L(FIR) = (6.5 ± 1) x 10^12 Lo
➔L[CII]/L(FIR) ~ 2 x 10^-3

M(dust) = (2.8 ± 0.5) x 10^8 Mo
i.e., huge amount of dust exists already at z=5.1

Walter et al. 2012, Nature, 486, 233

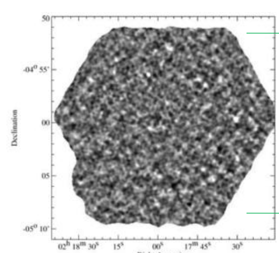
Mm/Submm deep surveys of SXDF

Camera/Telescope	Area	Noise level (1 σ, mJy)	Num. of Sources
SCUBA/JCMT	406 arcmin^2	~2 mJy @850um	60 (S/N > 3.4)
AzTEC/JCMT	1330 arcmin^2	1.0 – 1.7 mJy@1100um	28 (S/N > 3.7)
AzTEC/ASTE	1300 arcmin^2	0.4 – 0.9 mJy @1100um	252 (S/N > 3.5)

Improvement of sensitivity by factor of 2-3 is the issue because of the steep number counts !

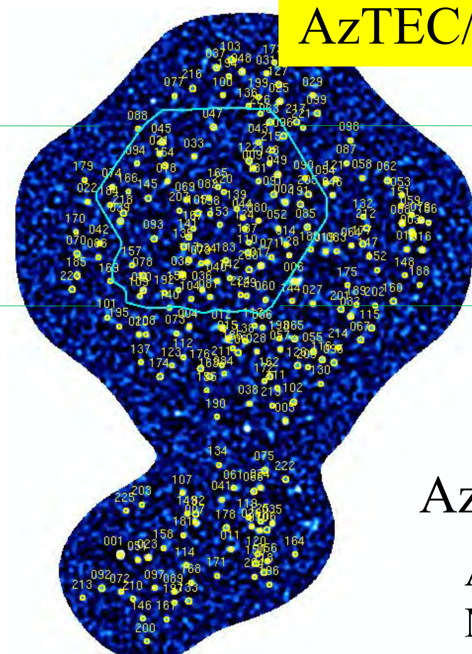
Ikarashi et al., 2012 in prep.

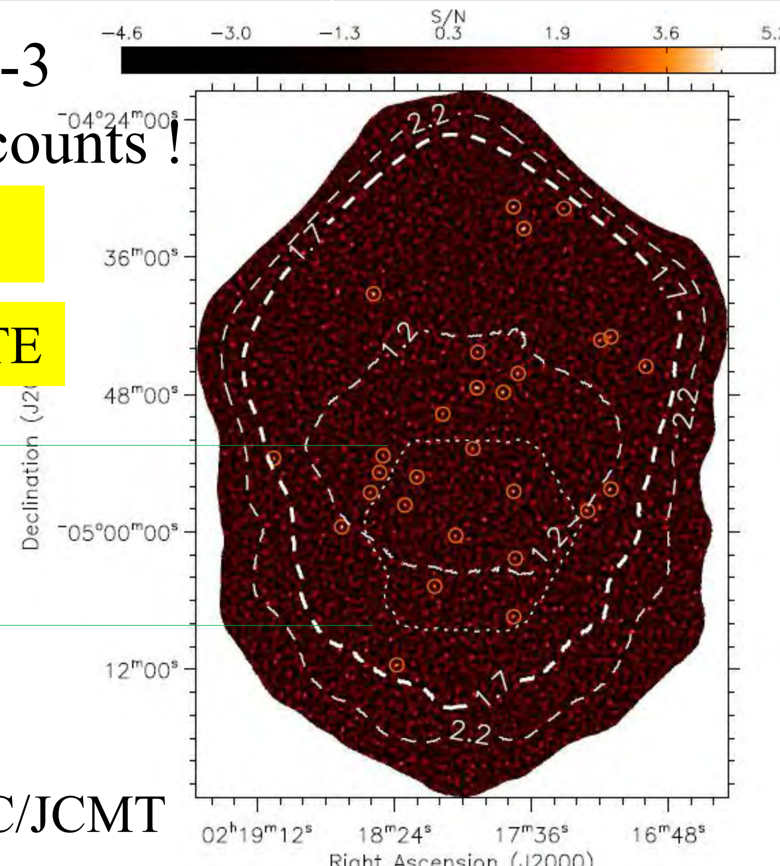
SCUBA/JCMT



Coppin et al. 2006 MNRAS, 372, 1621

AzTEC/ASTE



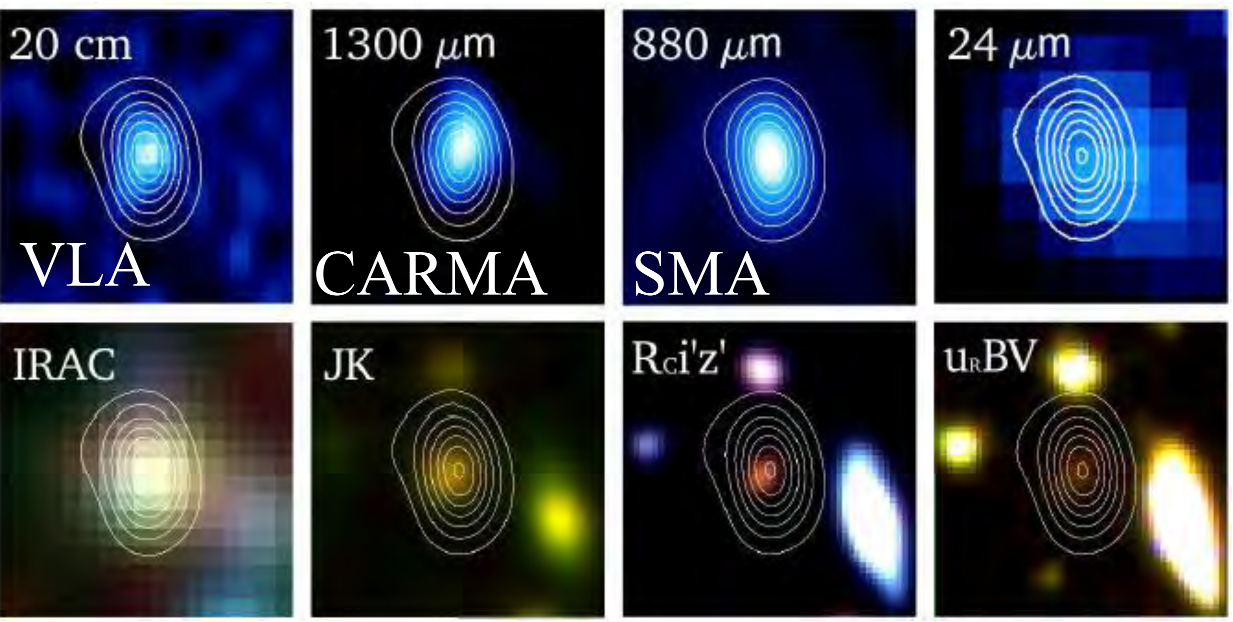


AzTEC/JCMT

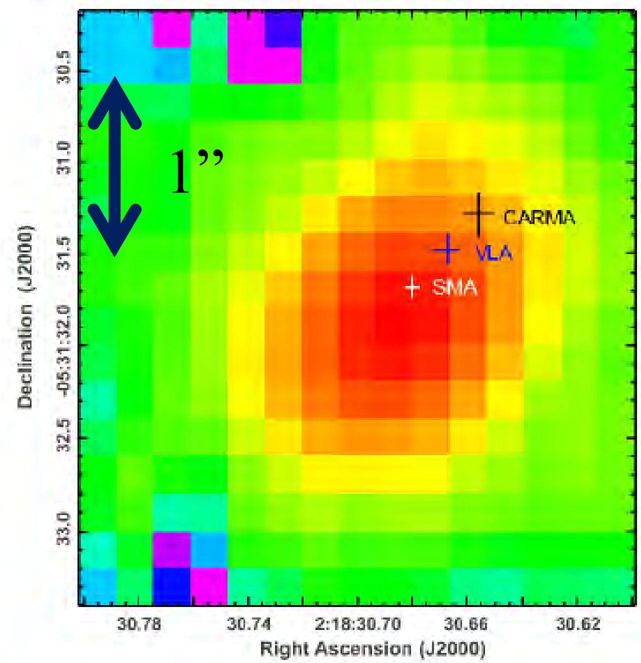
Austermann et al. 2009 MNRAS, 393, 1573

SXDF1100.1/Orochi: a ultra-bright SMG at z~3.4?

- Inconsistency between photo-zs with UV to NIR SED and FIR/submm to radio SEDs



Contour: SMA 880 um images



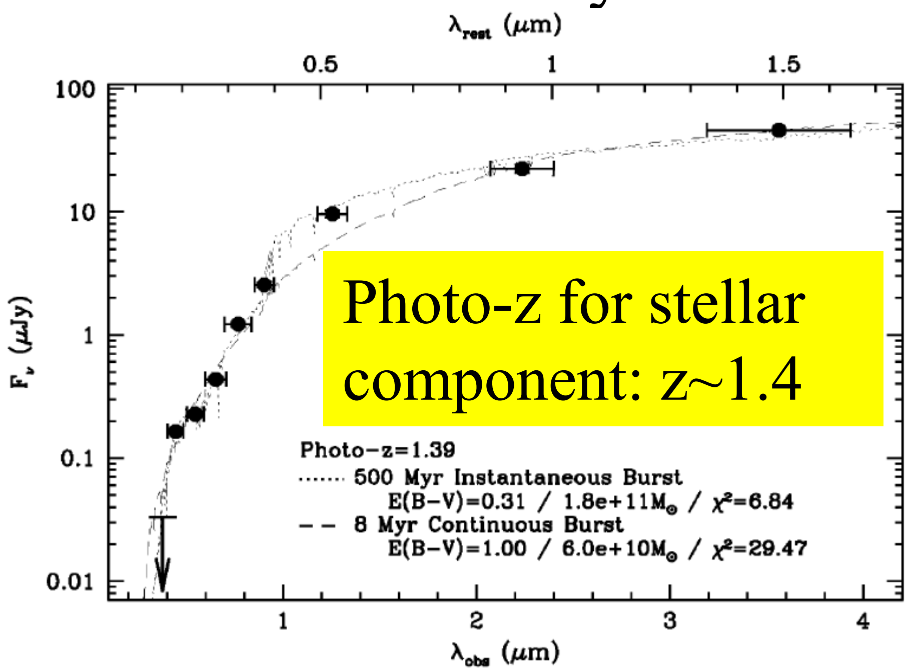
Ikarashi et al. 2011, MNRAS, 415, 3081

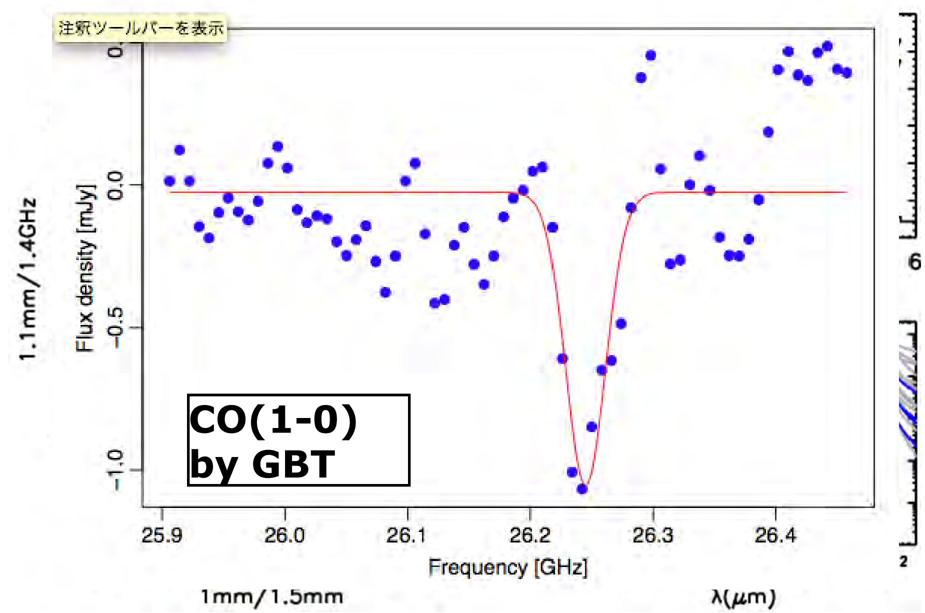
SXDF1100.1/Orochi: a ultra-bright SMG at z~3.4?

Ikarashi et al. 2011 MNRAS, 415, 3081

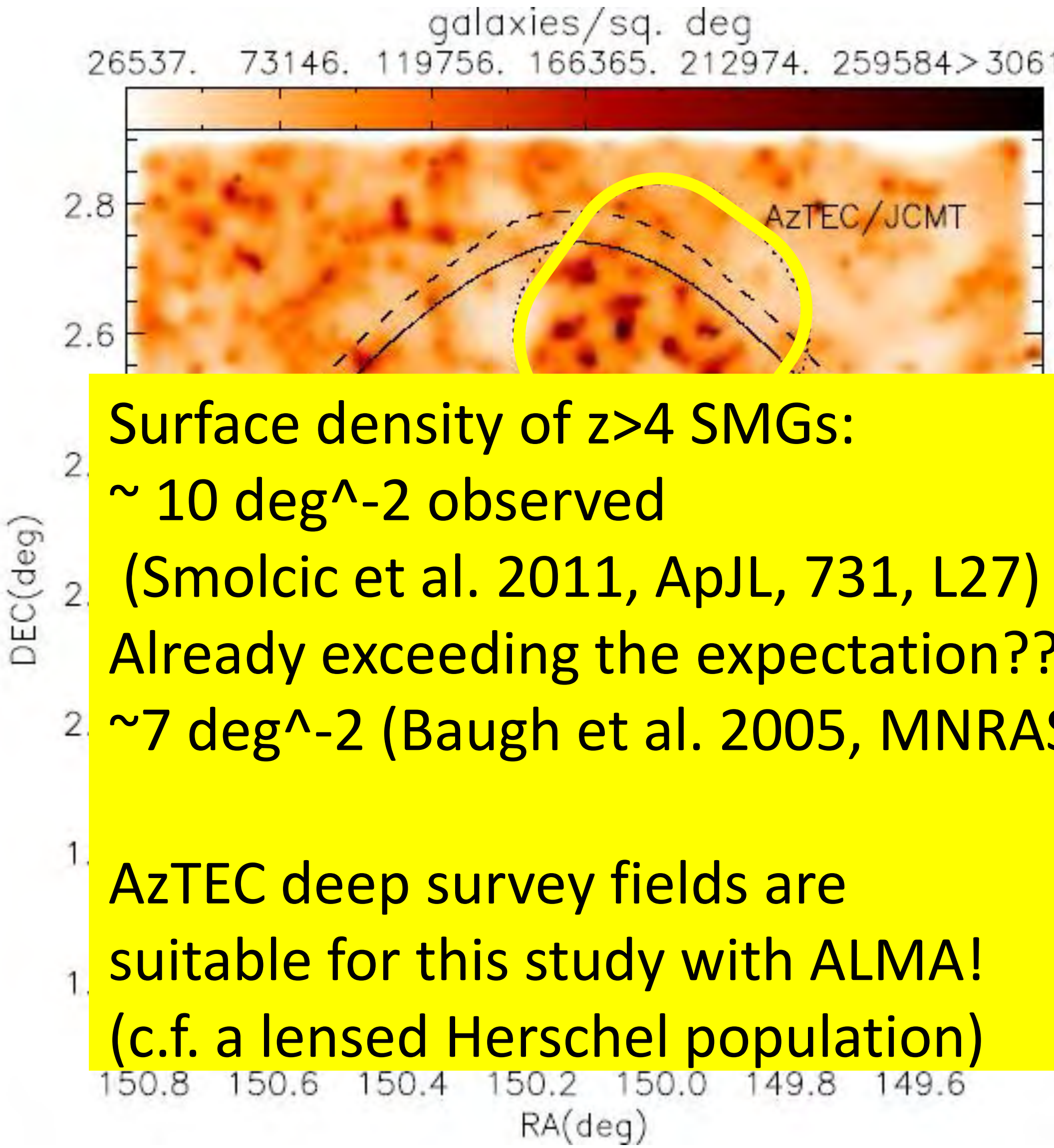
- Inconsistency between photo-zs with UV to NIR SED and FIR/submm to radio SEDs
- ➔ overlapping of z~3.5 SMG and foreground lensing object (cluster or a galaxy)?
- ➔ confirmed by GBT CO(1-0) spectroscopy

Photo-z for dust: z~3.4





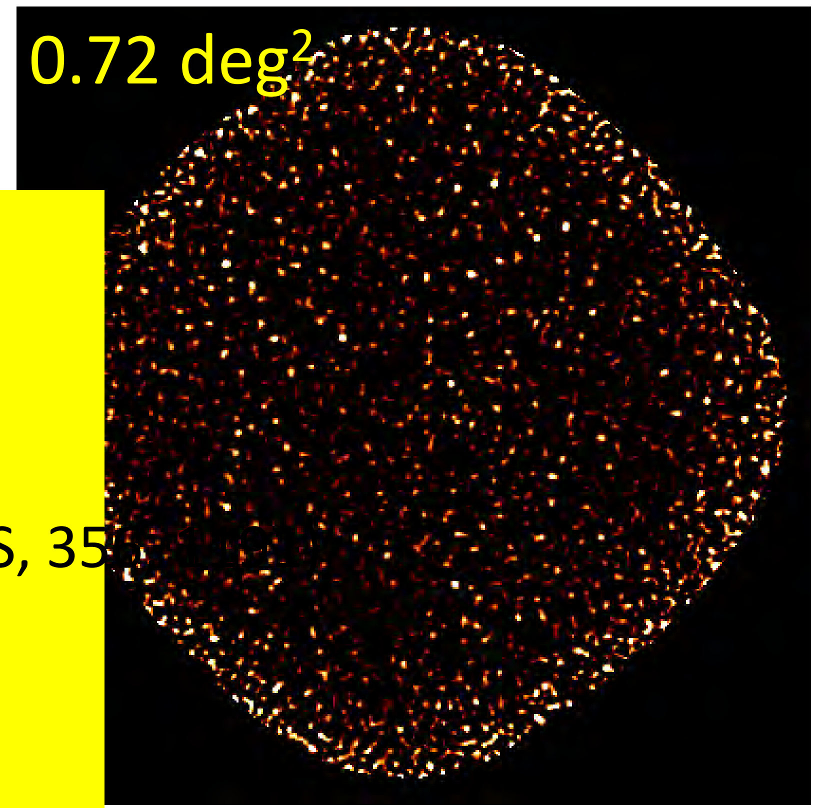
Num. of high-z SMGs from AzTEC in COSMOS



Surface density of z>4 SMGs:
~ 10 deg^-2 observed
(Smolcic et al. 2011, ApJL, 731, L27)
Already exceeding the expectation??
~7 deg^-2 (Baugh et al. 2005, MNRAS, 35

AzTEC deep survey fields are
suitable for this study with ALMA!
(c.f. a lensed Herschel population)

AzTEC/ASTE 1.1mm map
1σ~1.3 mJy, 189 sources

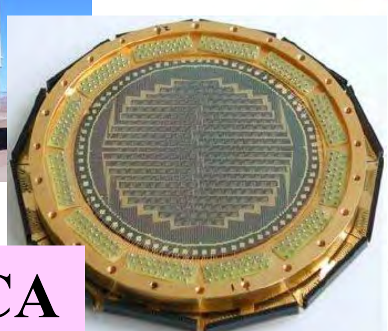


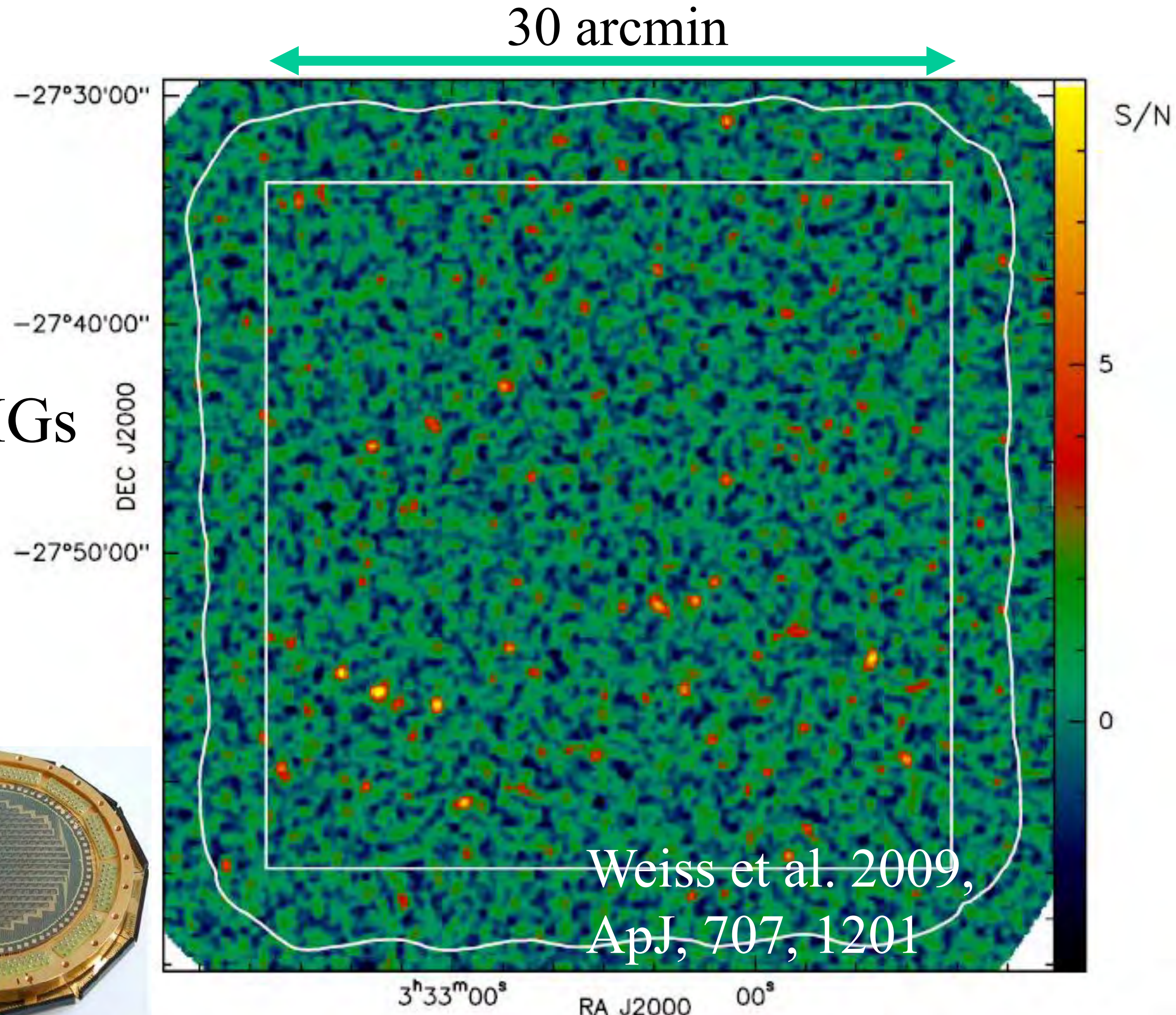
xaga et al. 2012,
MNRAS, 419, 1824

From ALMA cycle 0 results: ALMA as a redshift survey machine

LABOCA/APEX Extended Chandra Deep Field South Survey (LESS) at 870 µm

- 900 arcmin^2,
- 1.2 mJy (1σ),
- 310 hours
- 126 detections (>3.7 σ) of SMGs





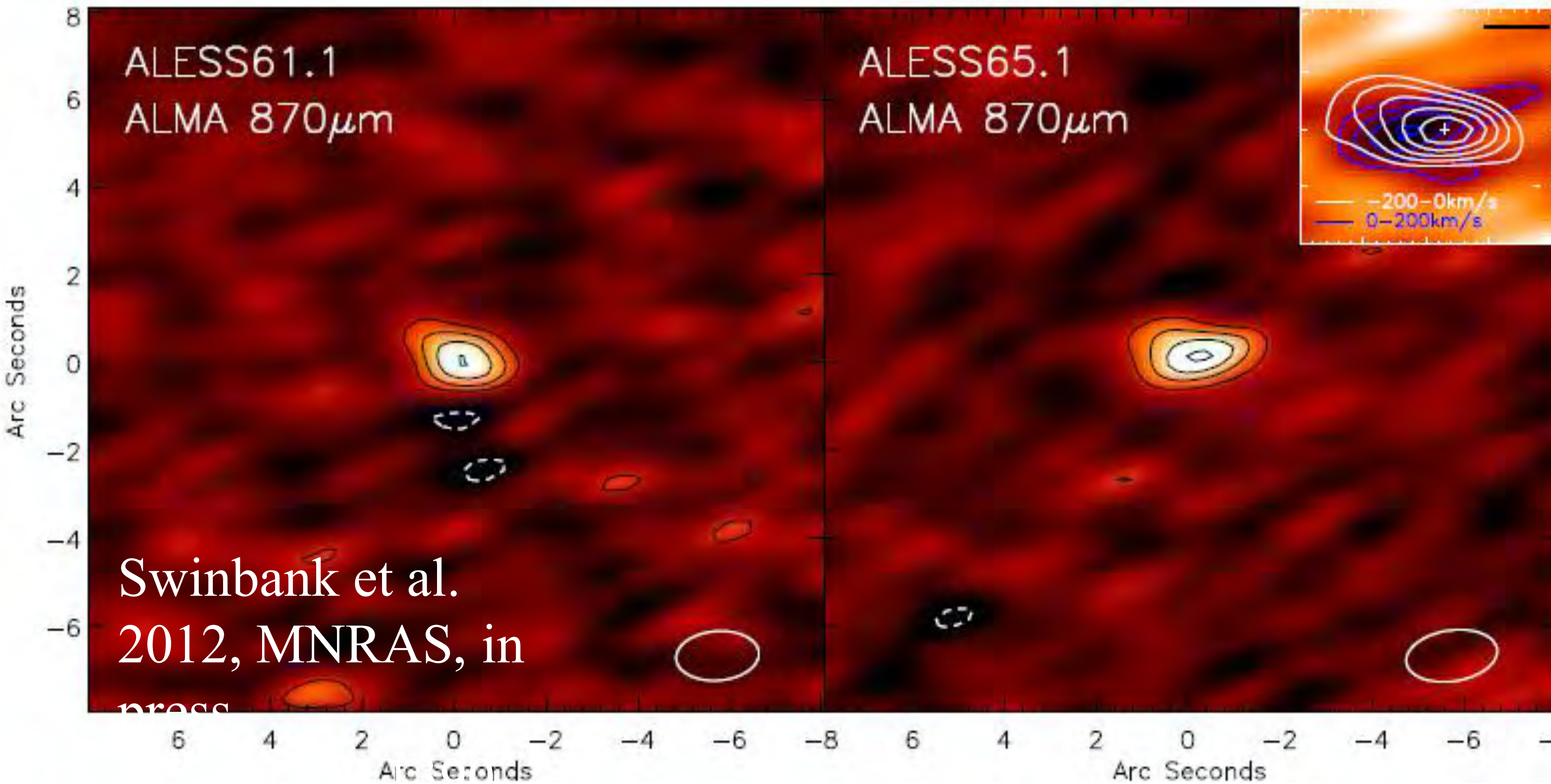
Weiss et al. 2009, ApJ, 707, 1201

ALMA observations of 2 LABOCA selected submillimeter galaxies LESS 61 & LESS 65

- A part of an approved cycle 0 program to observe all 126 LESS sources; 2011 October - November
- 345 GHz (Band 7), dual polarization
- 7.5 GHz total band width (LSB + USB)
- Covering 336.1-339.8 GHz & 348.1-351.9 GHz
- under good weather (PWV<0.5mm)
- 15 antennae, Compact configuration ➔ 1".8x1".2 beam
- On-source: 120 seconds each ➔ 0.44 & 0.42 mJy for continuum, 3.8 mJy/beam for dv=54.5 km/s (df=62.5 MHz) spectroscopy

Swinbank et al. 2012, MNRAS, in press arXiv:1209.1390

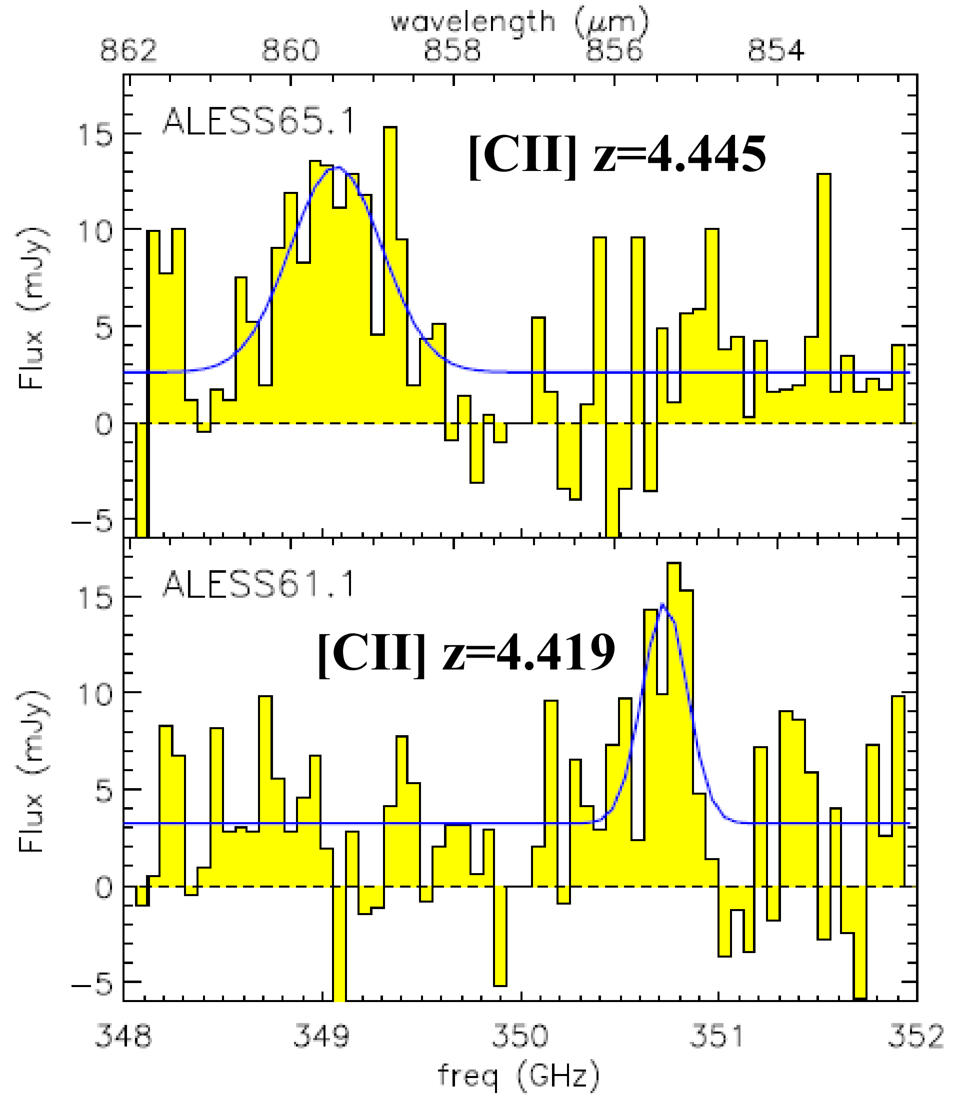
ALMA band 7 continuum images of two LABOCA selected SMGs



x3 deeper, x150 sharper (in beam area) than LABOCA with just 120 seconds on-source each !

Serendipitous [CII] detection

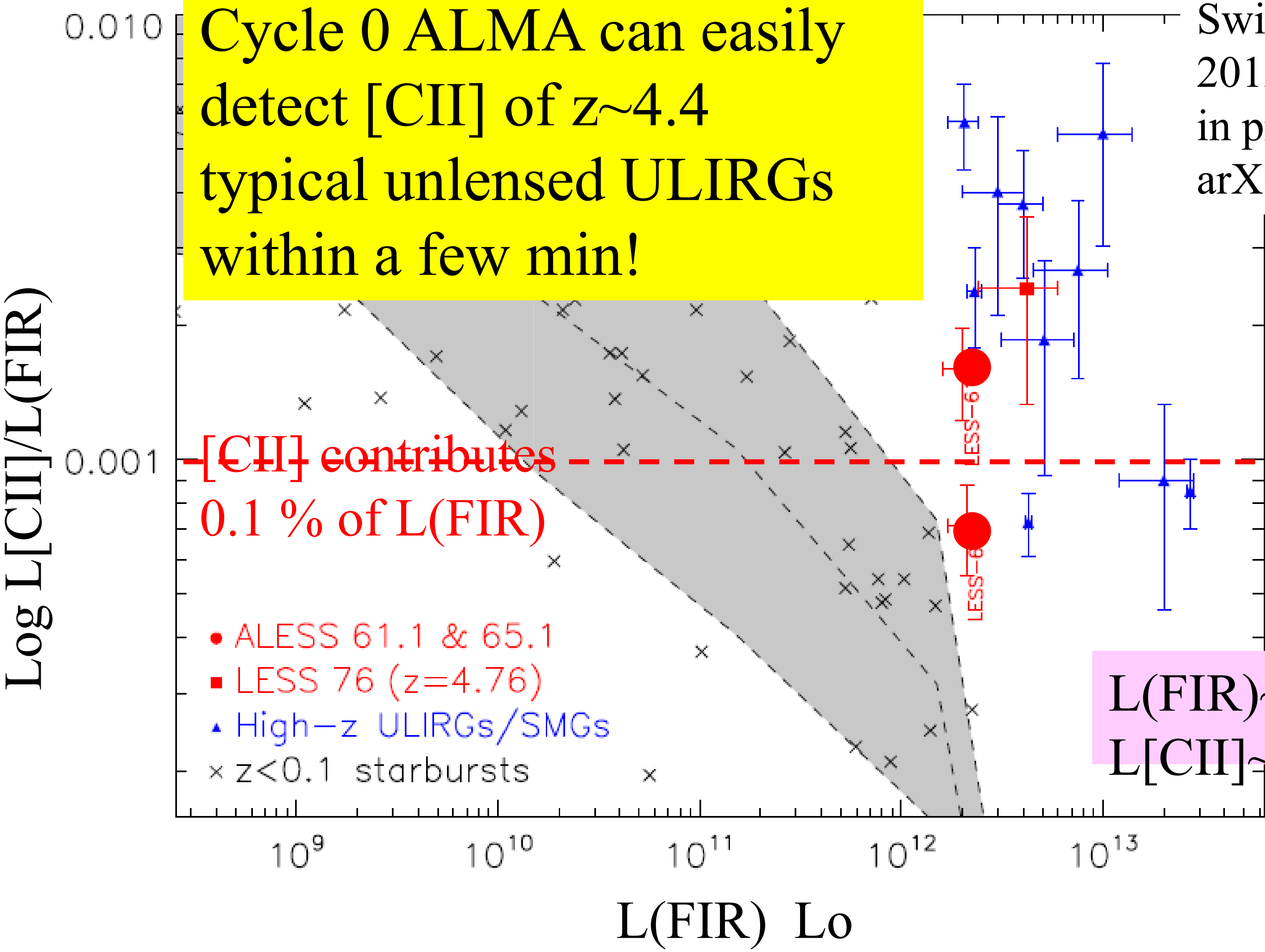
- ALMA band 7 frequency coverage 336.1-339.8 GHz & 348.1-351.9 GHz ➔ redshift coverage z=4.399-4.461 (USB) & z=4.590-4.656 (LSB) for [CII]158μm
- Line equivalent width: 0.44±0.06μm, 1.12±0.15μm ➔ similar to [CII] in local (U)LIRGs 0.76±0.06μm (Brauher et al. 2008)



L(FIR) vs L[CII]/L(FIR) in galaxies

Cycle 0 ALMA can easily detect [CII] of z~4.4 typical unlensed ULIRGs within a few min!

Swinbank et al. 2012, MNRAS, in press arXiv:1209.1390



[CII] contributes 0.1 % of L(FIR)

L(FIR)~2x10^12 Lo
L[CII]~2-5 x 10^9 L

Are they really [CII] at z~4.4 ?

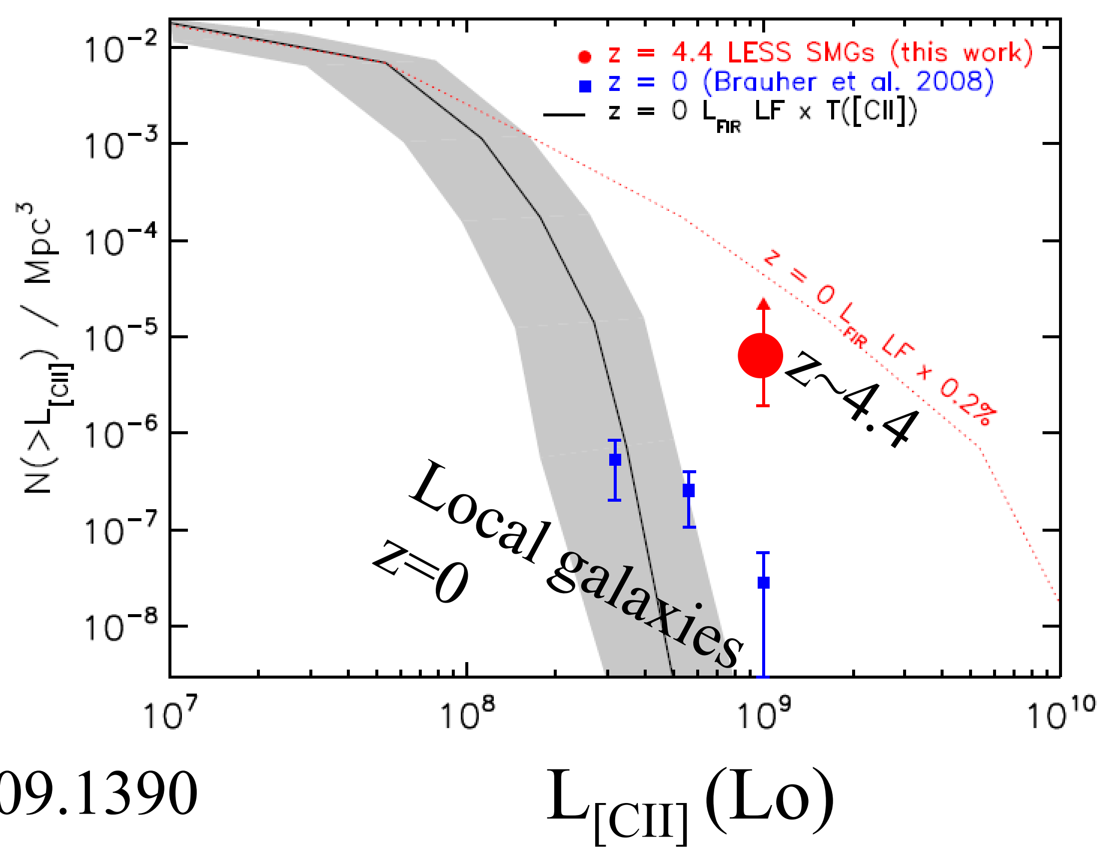
- They can be [OI]145μm@z=4.9, [NII]122μm@z=6.0, [NII]205μm@z=3.1, or [OIII]88μm@z=8.1, but the luminosities of these atomic lines are x10 fainter than [CII]
- They can be high-J CO (J=7-6@z=1.3, J=8-7@z=1.6, J=9-8@z=2.0, J=10-9@z=2.3), but again these lines are much fainter (x10) than [CII]
- Observed line/FIR continuum luminosity ratio is consistent to previous [CII] detections at high-z galaxies

Constraint on [CII] luminosity function by ALMA observations

- LABOCA selected SMGs: 0.5 x 0.5 deg^2, dz=0.12 at z~4.4 ➔ comoving volume of 2.9x10^5 Mpc^3

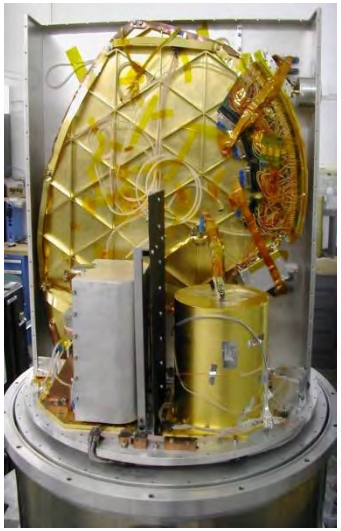
- Two [CII] emitters with L[CII]>1x10^9 Lo within this volume

➔ x1000 increase in the number density of luminous [CII] emitters from z=0 to z=4.4 !

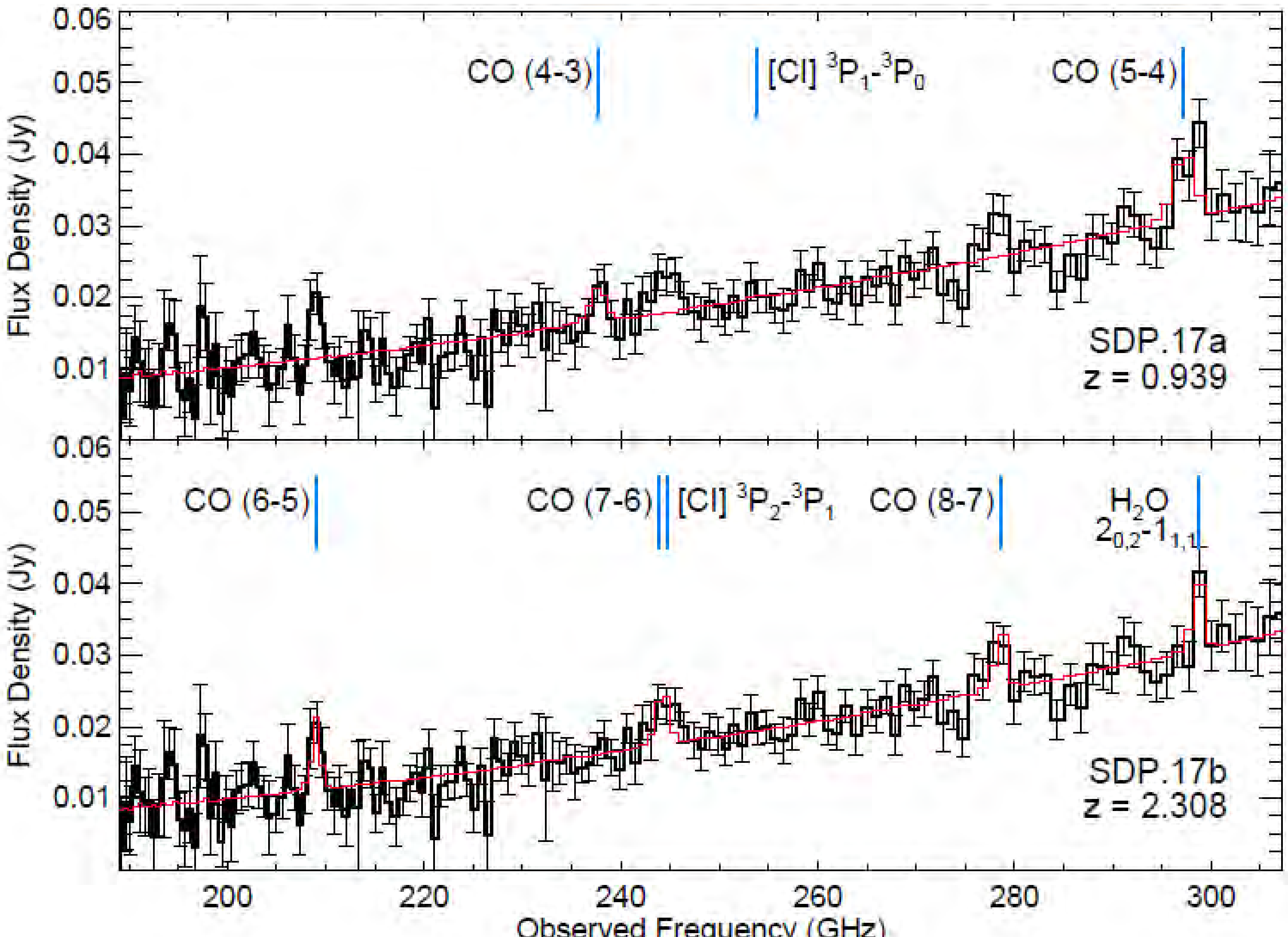


Swinbank et al. 2012, MNRAS, in press arXiv:1209.1390

Redshift survey w/ grating spectrometer Z-Spec



Z-Spec/CSO/APEX



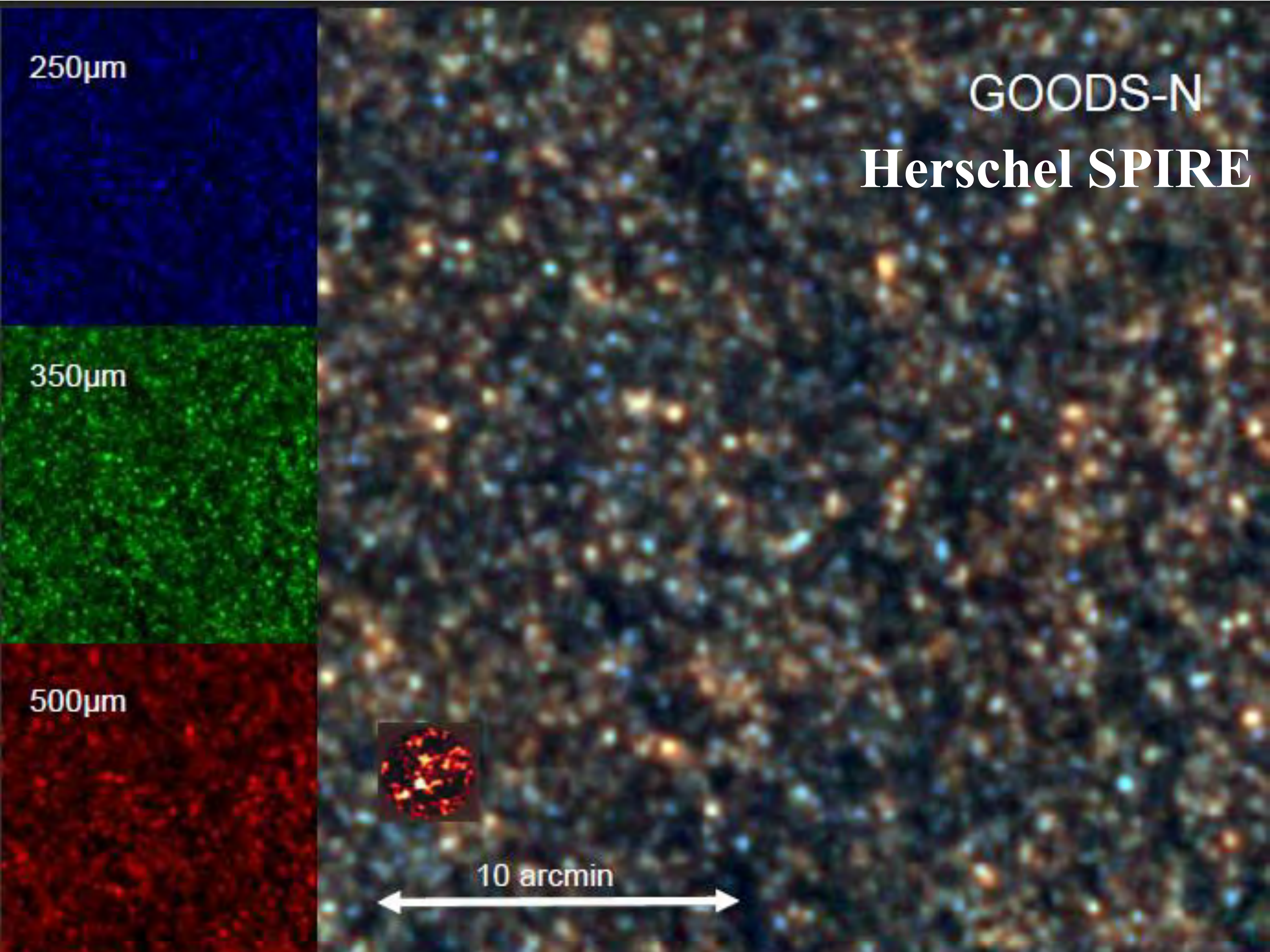
Lupu et al. 2012
ApJ, 757, 135

ALMA vs single dish telescopes: spectroscopy of single object

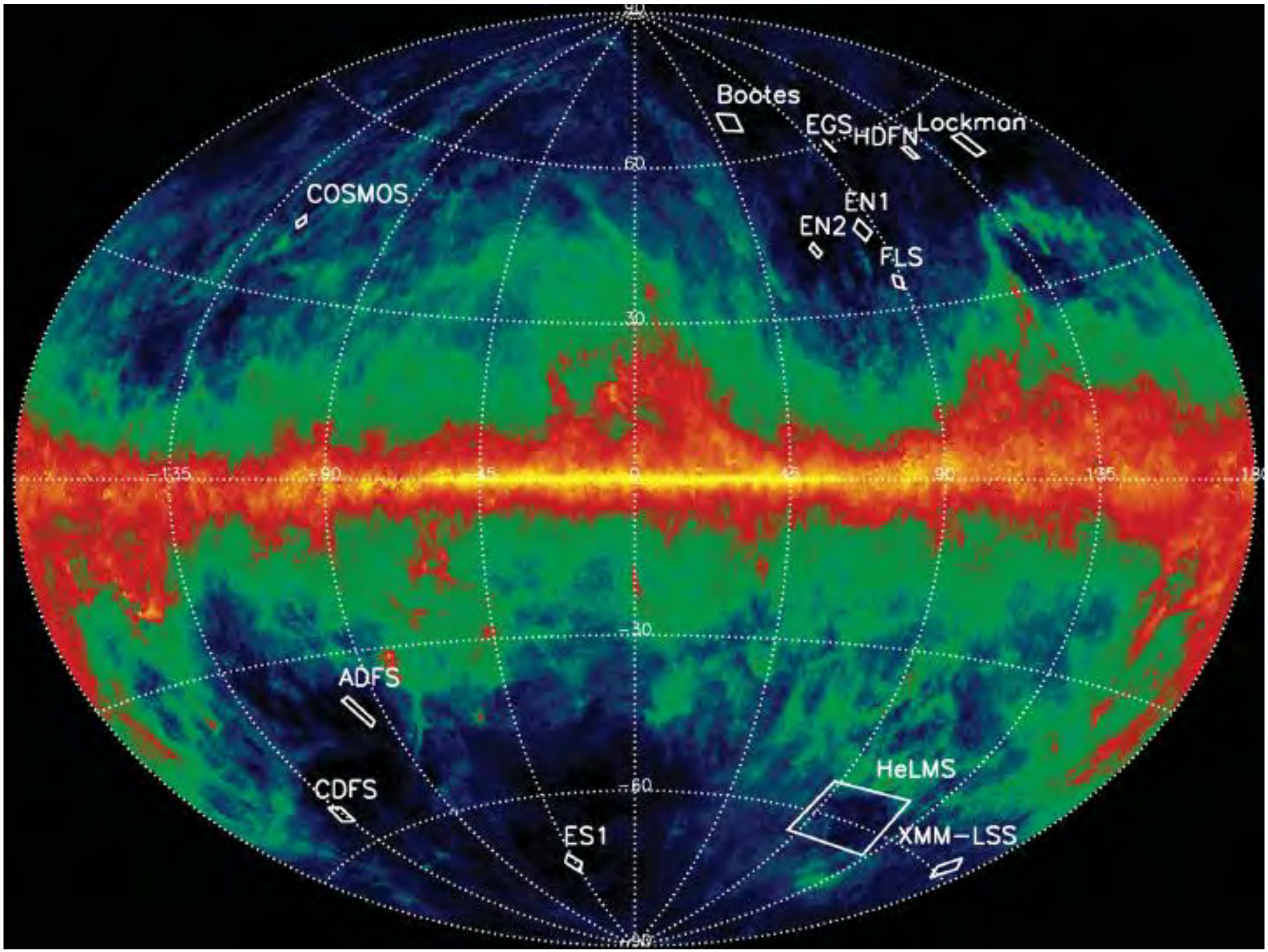
telescope	D [m]	Main beam eff.	Tsys [K]	Integration time
ASTE	10	0.6	125	65 hrs
CCAT	25	0.7	125	100 min
IRAM	30	0.54	350	~12 hrs
New 30m	30	0.7	125	48 min
New 50m	50	0.7	125	6.24 min or 374 sec

- ALMA instantaneous bandwidth: 8 GHz (4 GHz per sideband) for line survey, 24 sec per set, to detect [CII] at z=6.4 quasar J1148+5251 (L[CII]=4x10^9 Lo)
- ➔ A new **50 m telescope** should have the same line survey speed if it is equipped with 8 × (374sec/24sec) = **124 GHz bandwidth** (!) single beam receiver

Wide area mm/submm surveys


250μm
350μm
500μm
GOODS-N
Herschel SPIRE
10 arcmin

HerMES sky coverage



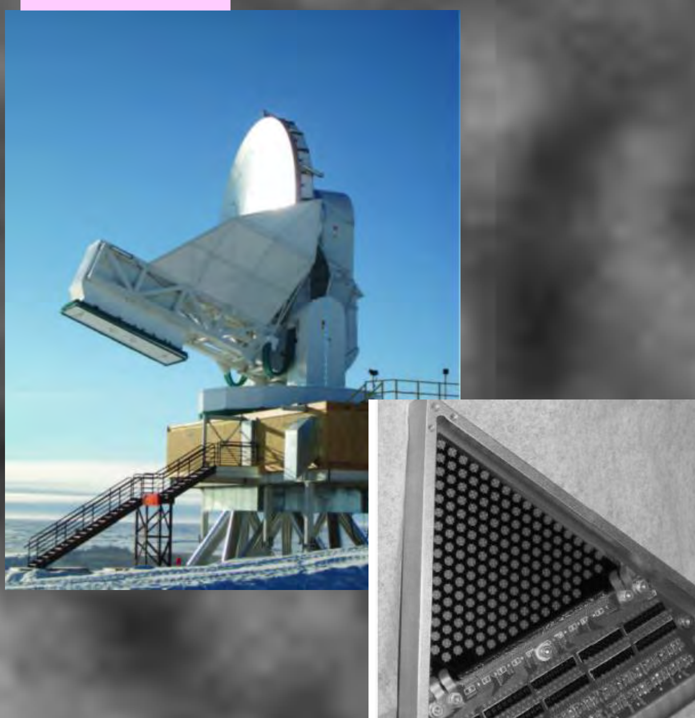
Oliver et al.2012, MNRAS424, 1614

Ultra-wide area mm survey (λ=2mm)

~ a few - a few 10 arcmin scale fluctuations ➔ primary CMB

~15-sigma SZ cluster detection

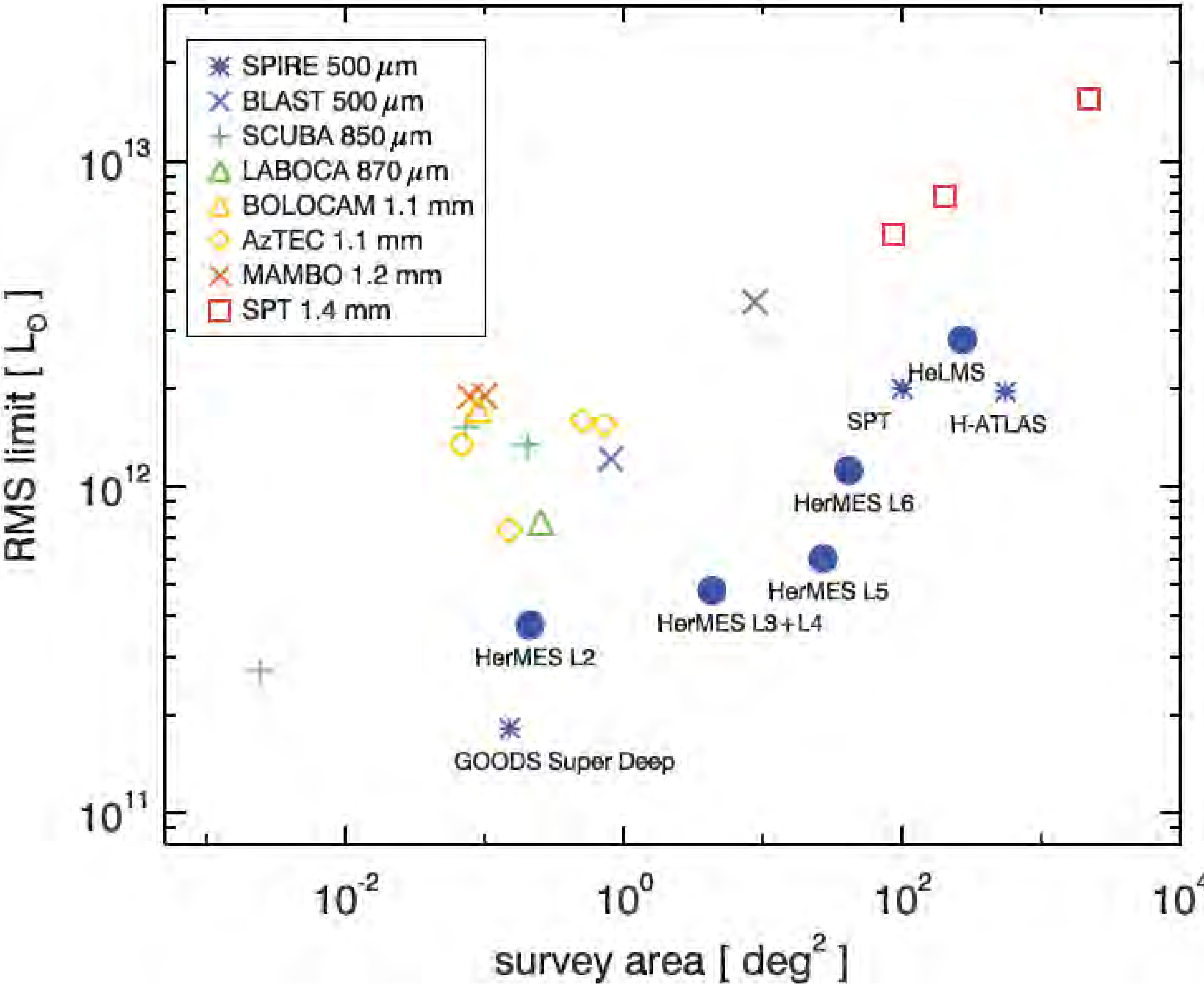
SPT



Bright emissive sources: radio loud local AGN & high-z dusty star-forming galaxies.

http://max.ifca.unican.es/sz2011/sz2011_talks/Monday/Rashid_Sunyaev/Santander1.ppt

Mm/submm surveys: area vs depth

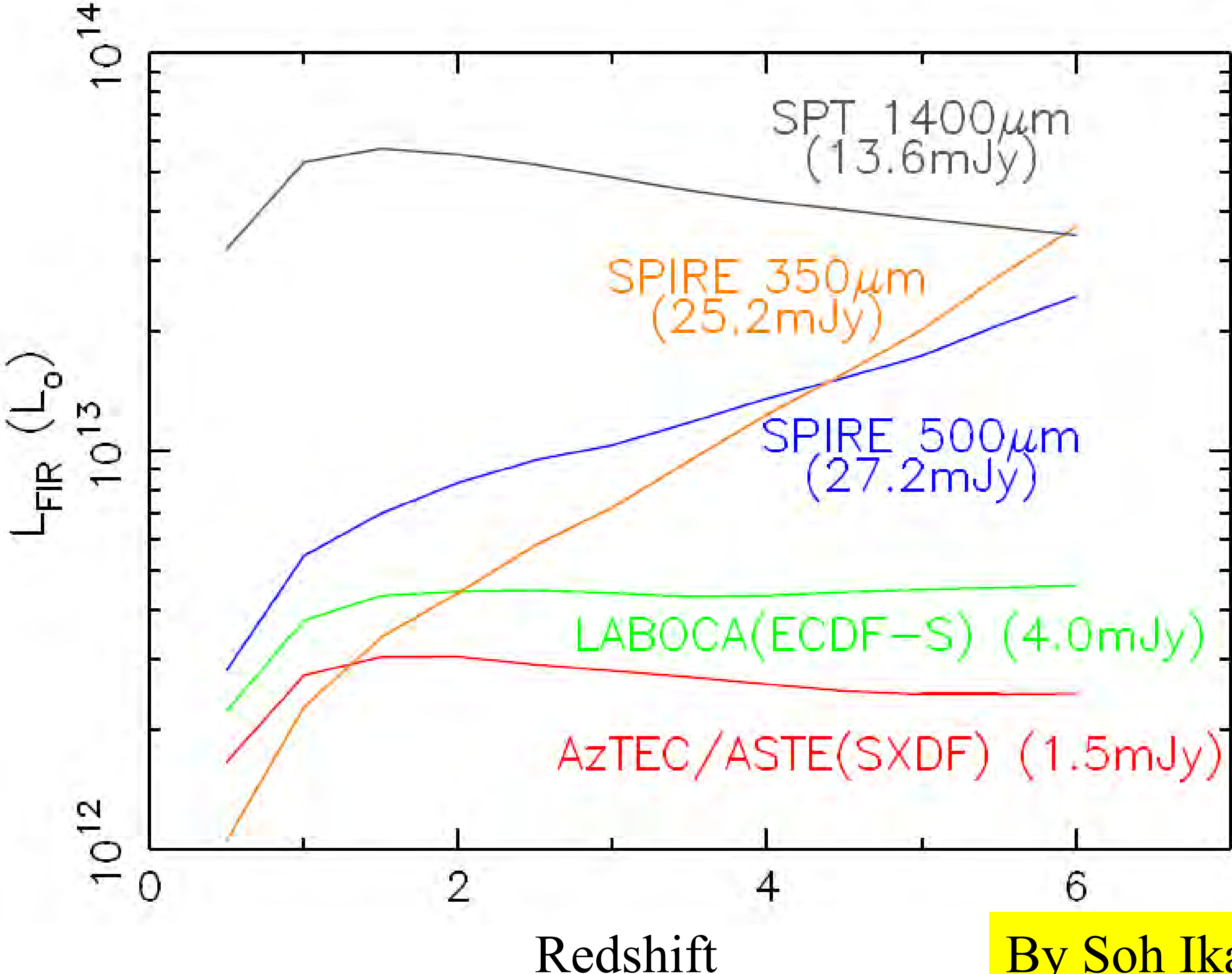


!caution!
This is a plot for z=2.
Confusion?

Different view at z>3 !!!

Oliver et al. 2012, MNRAS 424, 1614

FIR luminosity sensitivity vs redshift

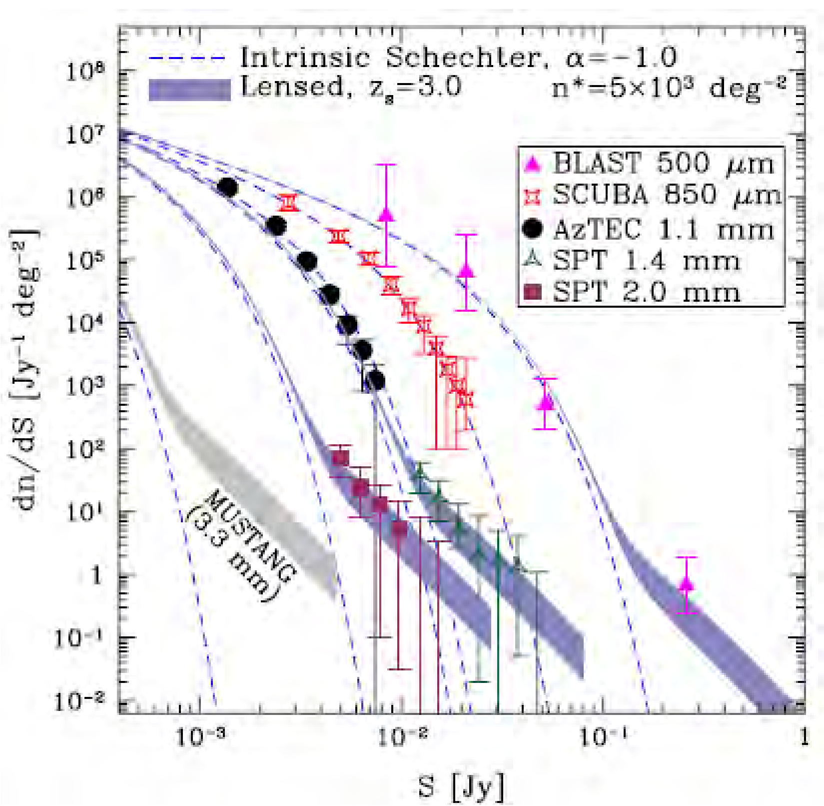


By Soh Ikarashi

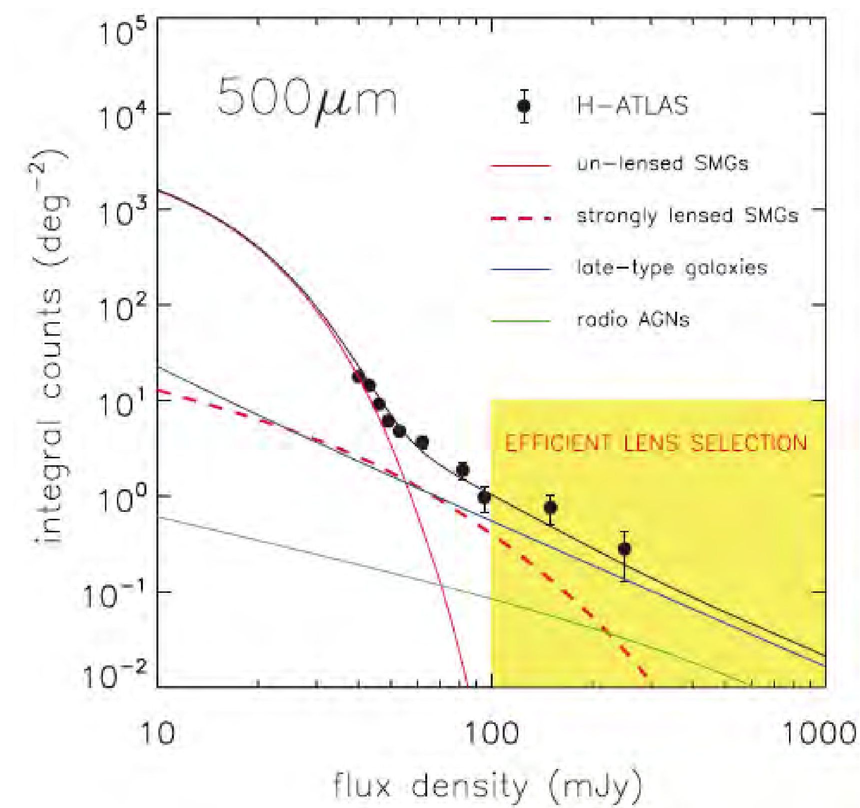
Discovery of rare population of mm/submm galaxies by wide surveys

Discovery of ultra-bright SMGs: gravitationally lensed populations?

- The brightest-end number counts of SMGs significantly deviate from the normal SMGs

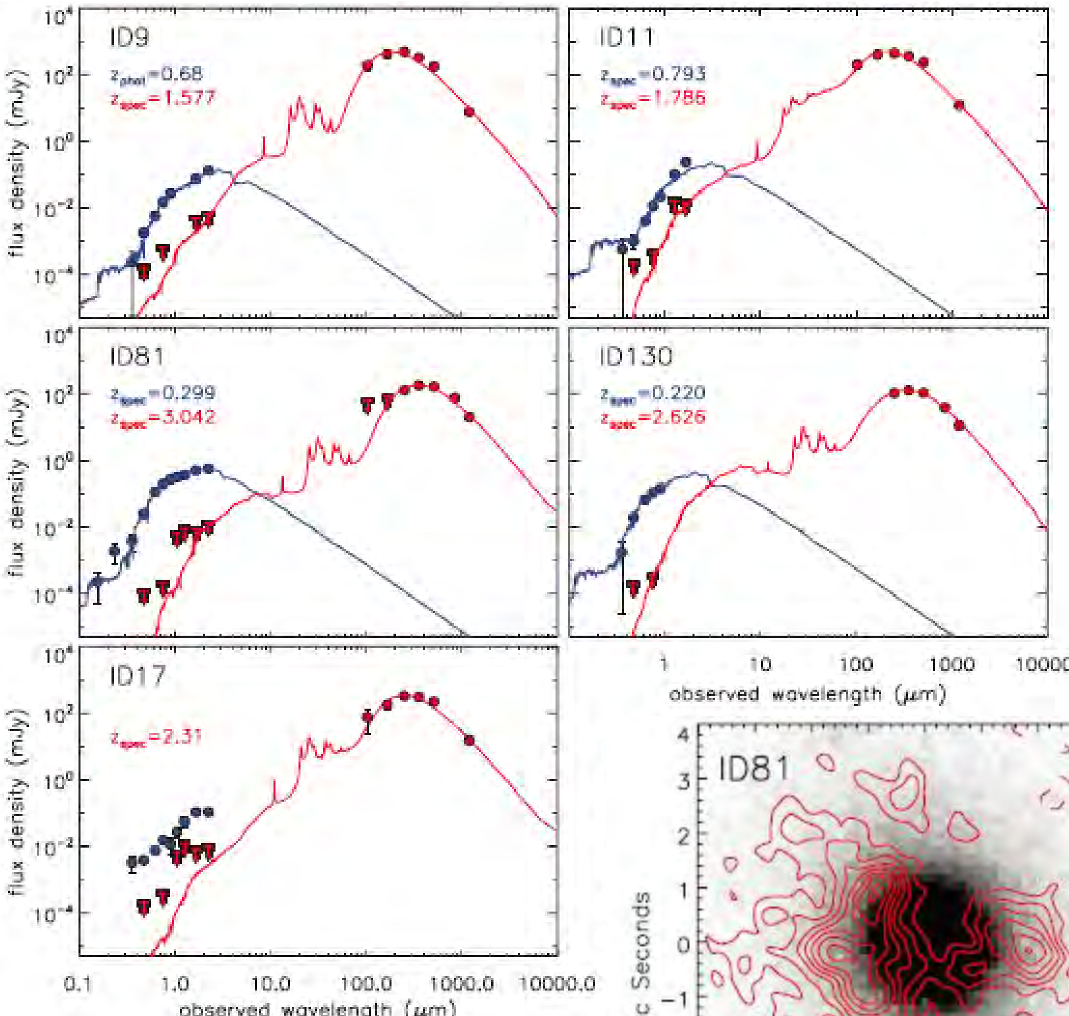


Lima et al. 2010, ApJ, 717, L31

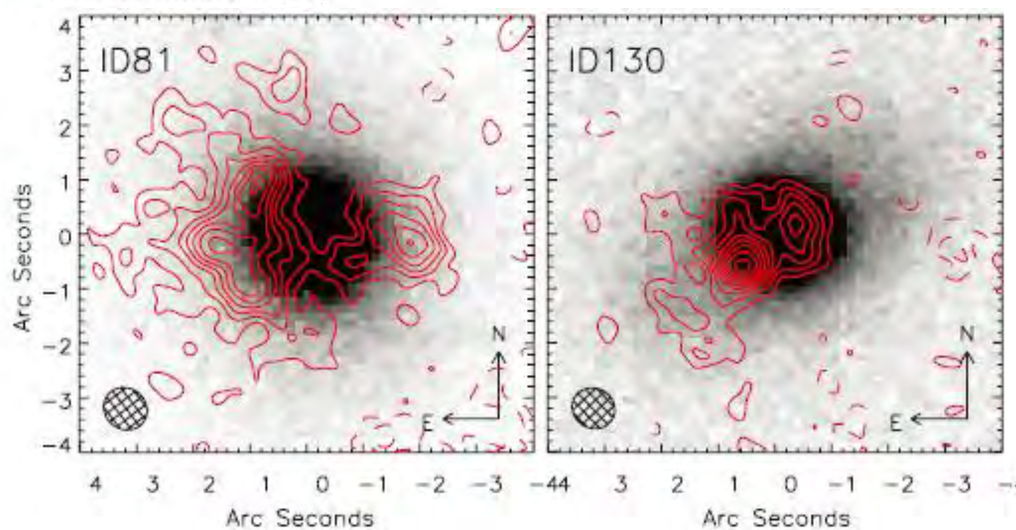


Negrello et al. 2010, Science, 330, 800

Ultra-bright FIR sources uncovered by Herschel



- Discrepancy between photometric redshifts from optically IDed objects and FIR-submm SEDs ➔ evidence for gravitational lens system
- It is confirmed by arcsec resolution SMA imaging !

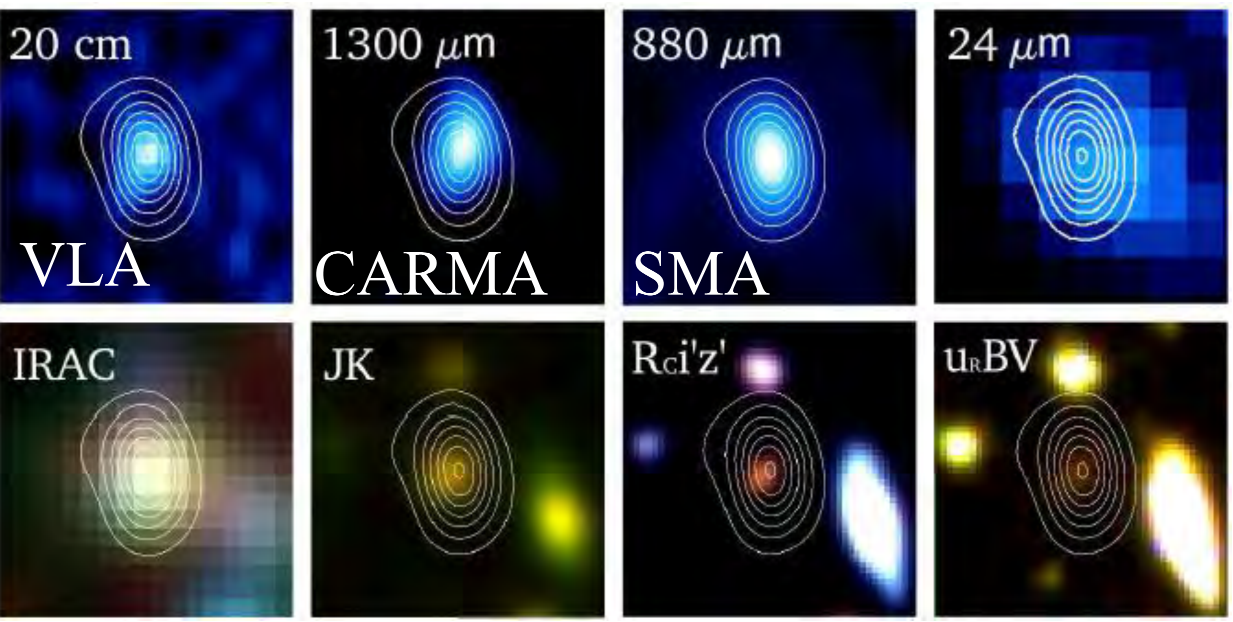


Contour: SMA
Image: Keck I band

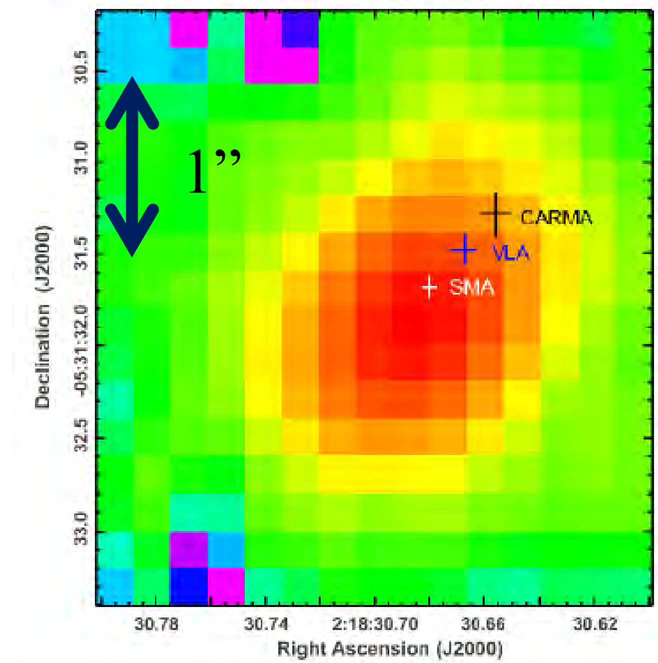
Negrello et al. 2010, Science, 330, 800

SXDF1100.1/Orochi: a ultra-bright SMG at z~3.4?

- Inconsistency between photo-zs with UV to NIR SED and FIR/submm to radio SEDs

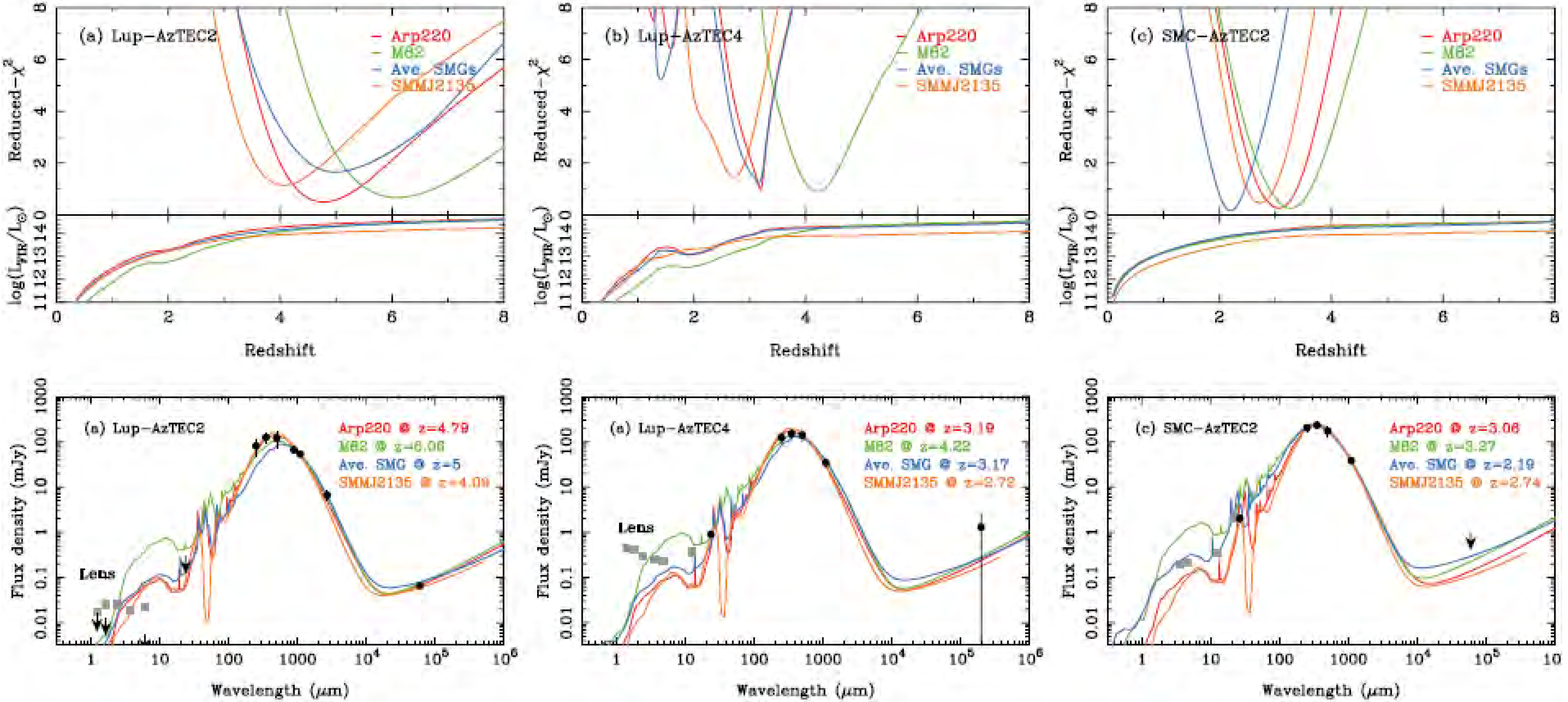


Contour: SMA 880 um images



Ikarashi et al. 2011, MNRAS, 415, 3081

More ultra-bright AzTEC sources:
➔ photo-z ~ 2 – 6 ?



Takekoshi et al., in prep.
Tamura et al., in prep.

So what?

- 「重力レンズは手段。目的ではない。」
  （by大栗さん）
- Internal structure of high-z dusty starbursts at ~100 pc scale !?
- ALMA study of surface brightness anomalies caused by dark matter substructure in the halo

  (Vegetti et al. 2012, Nature, 481, 341)
  - z=2.059 background galaxy + z=0.881 lensing galaxy

  ➔ Not only in continuum, but also in [CII] spectroscopy with ALMA ??

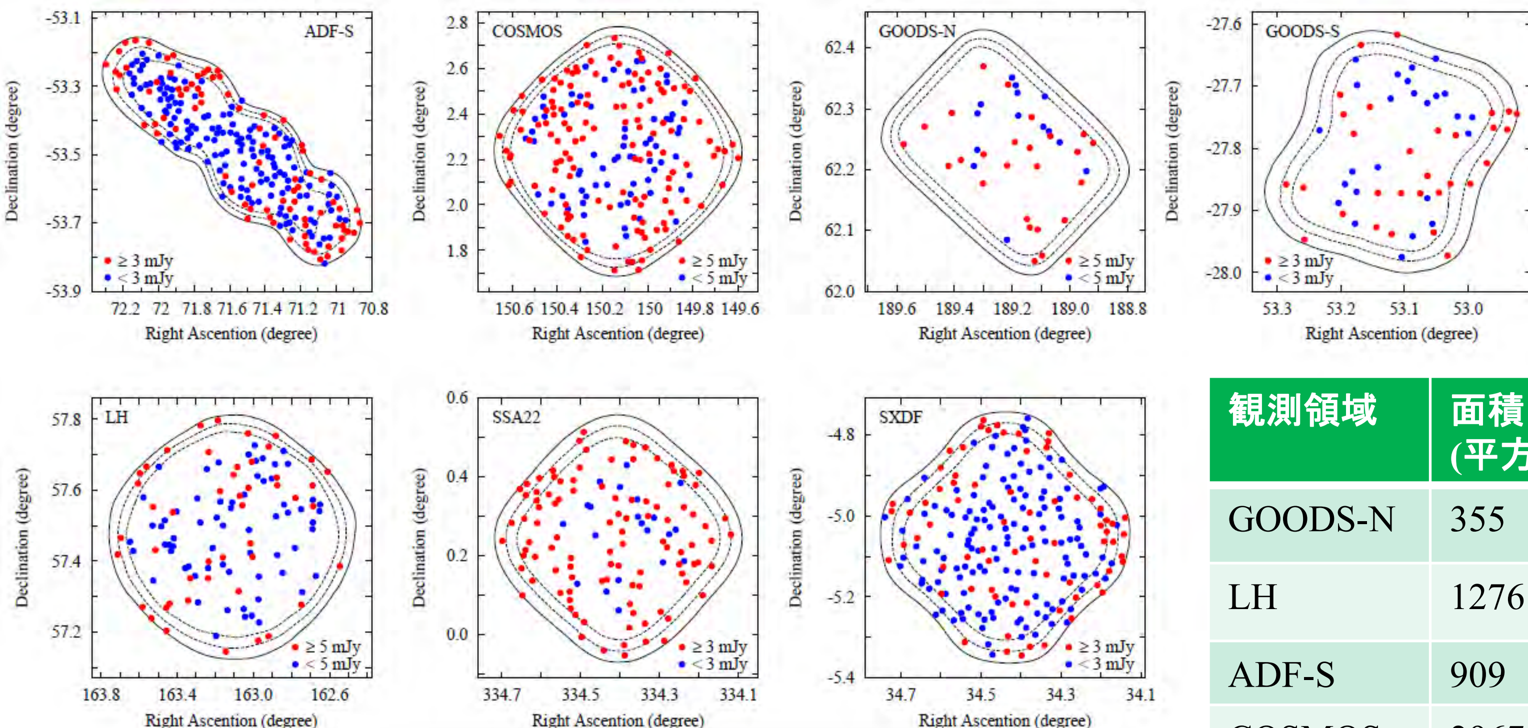
HSC surveys
and
ALMA/ASTE

HSC survey will provide interesting targets for ALMA follow up

- Clusters uncovered by HSC survey (Takada-san)
- Emission line galaxies such as [OII] emitters at $z=1.47$, 1.70, Hα emitters at $z=0.40$, 0.45 (Tanaka-san)
- > 30,000 LAEs, >3,000,000 LBGs! (Shimasaku-san)
- Very rare objects
  - $z>6$ quasars (Nagao-san)
  - gravitationally lensed galaxies (Oguri-san)

Dark halo mass of SMGs from auto-correlation function analysis

- Unprecedentedly large sample, but still poor statistics…



Hatsukade et al. in prep.

~1000 SMGs

観測領域	面積 (平方分)	検出した銀河の個数
GOODS-N	355	39
LH	1276	113
ADF-S	909	233
COSMOS	2967	205
GOODS-S	350	55
SSA22	973	125
SXDF	954	215

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

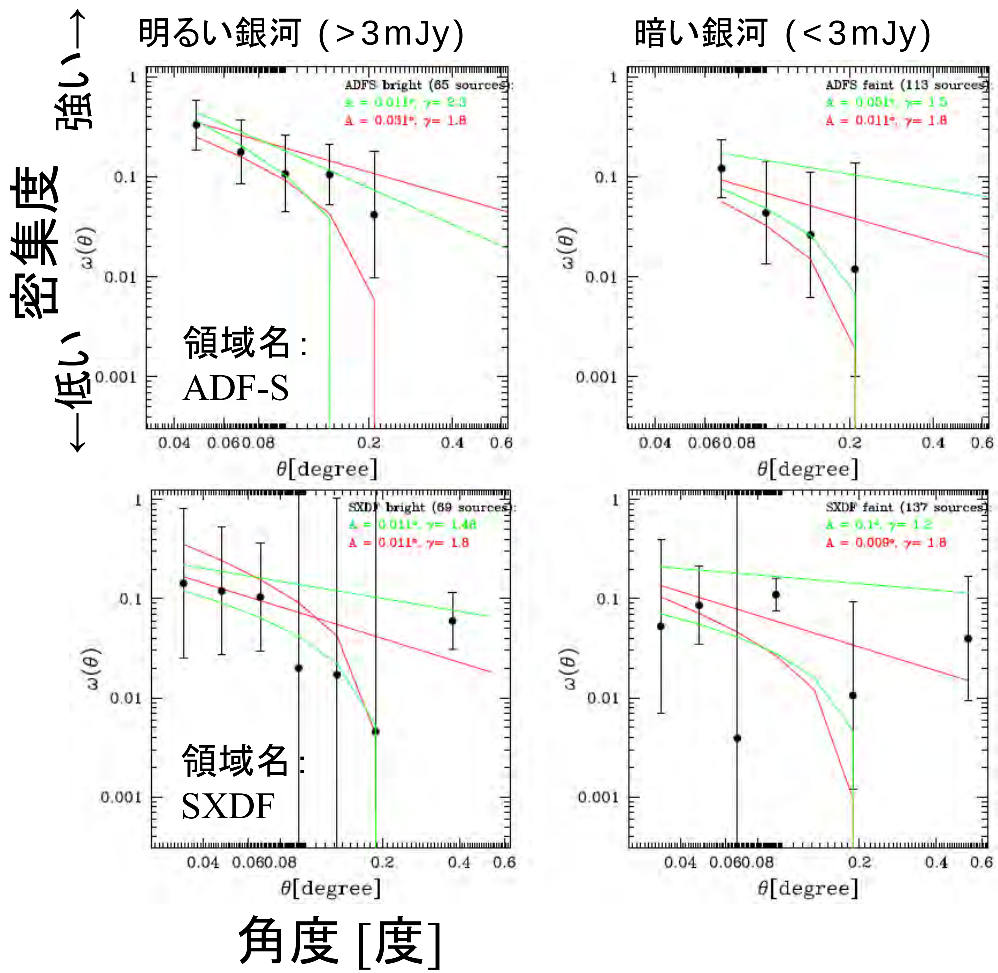
二体角度相関関数

$$\omega(\theta) = \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)},$$

Dark halo mass of SMGs from auto-correlation function analysis

Hatsukade et al. 2012, in prep.

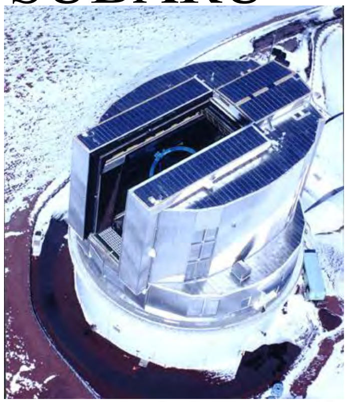
- 2体角度相関解析
  - 銀河の空間分布から､｢密集度｣を定量化 ➔ これらの銀河を含む暗黒物質分布情報を反映
- 結果
  - 明るい銀河で､より強い密集度
  - ある領域で､特に強い密集度
  - ➔ 明るい銀河は､より質量の大きい暗黒ハローに付随？or 狭い赤方偏移に集中？特に強い密集度は､未知の大規模構造を反映？
- 暗黒ハロー質量 **~10$^{12\text{-}13}$ M_{sun}**
  - 大質量の暗黒ハローに存在することを示唆
  - 近傍宇宙における､銀河団スケールに相当。これらの大質量星形成銀河は､現在の宇宙における銀河団へと進化していくことを示唆。



領域ごと･1.1mmフラックスごとの2点角度相関関数 ω(θ)

大規模構造の「底」で進む大質量星形成銀河の成長（redshift～3.1）

SUBARU



LAEs Lyα emitters

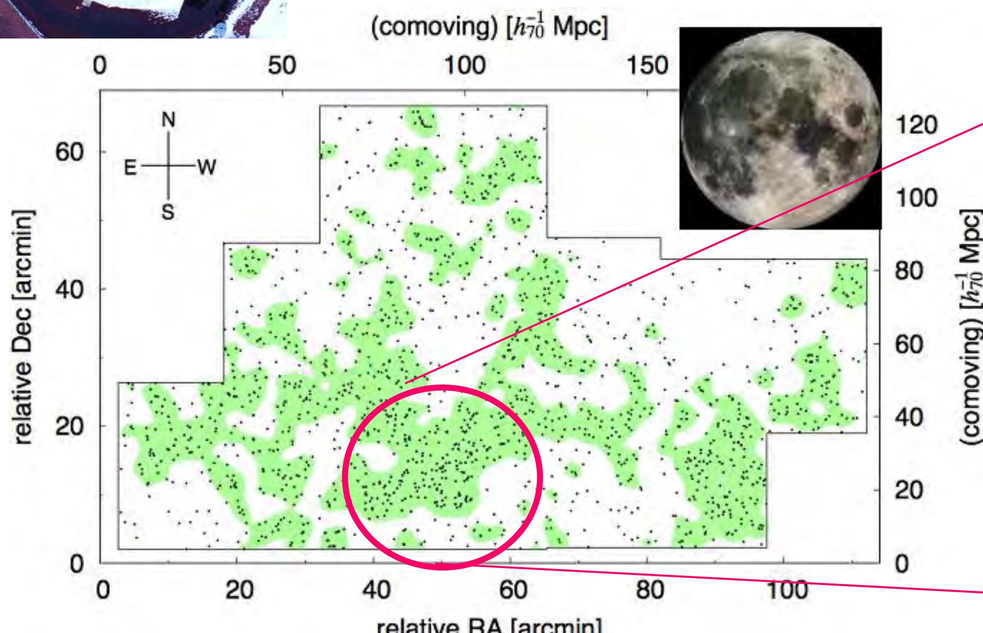
SFR ~ a few Mo/yr

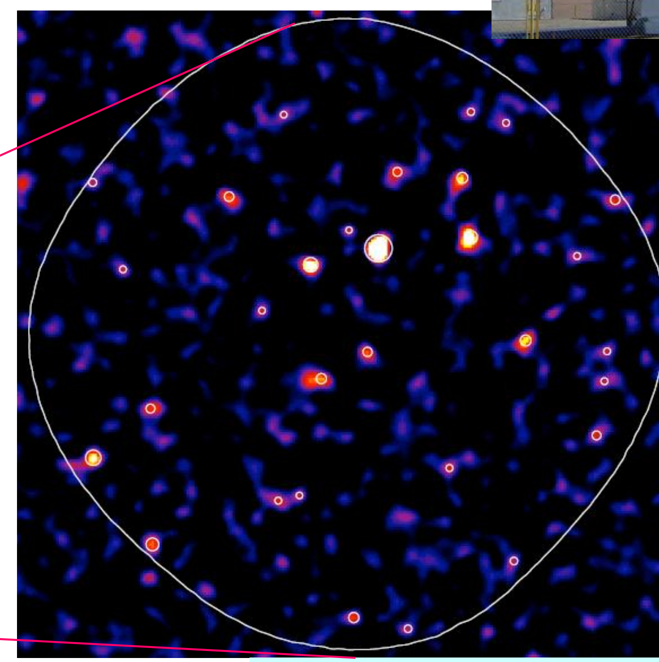
Distribution of LAEs
Around z~3.1
Nakamura et al.

SMGs

SFR ~ a few 100
– a few 1000 Mo/yr

ASTE

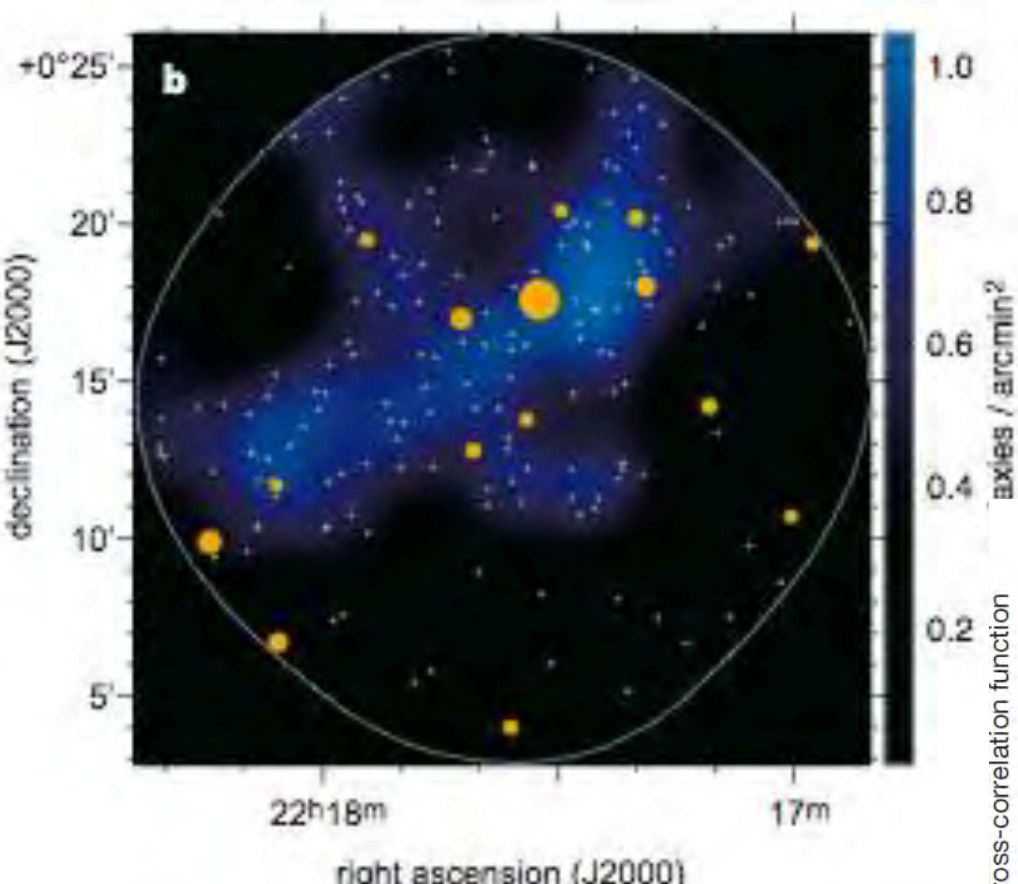




No one-by-one correspondence
to LAEs, but clustered at the LAE density peak

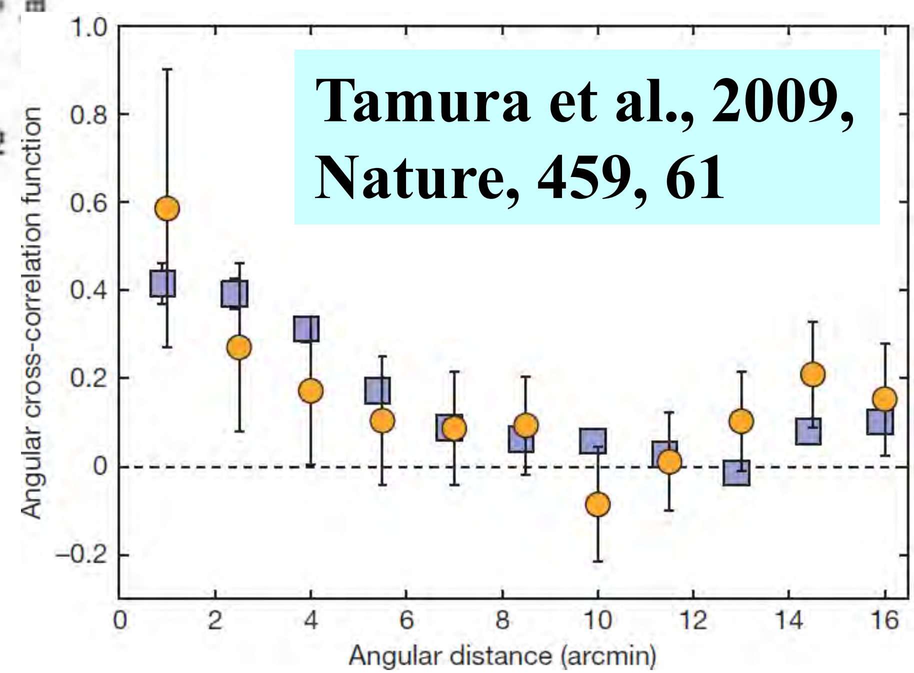
Tamura et al., 2009, Nature, 459, 61

Concentration of bright SMGs at the center of SSA22

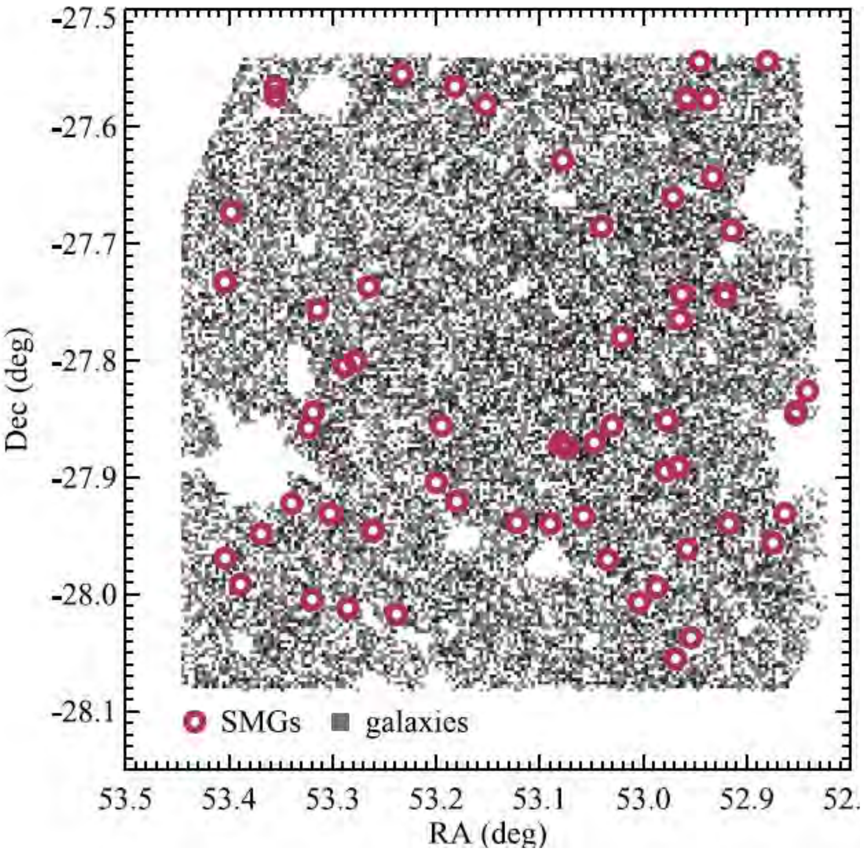


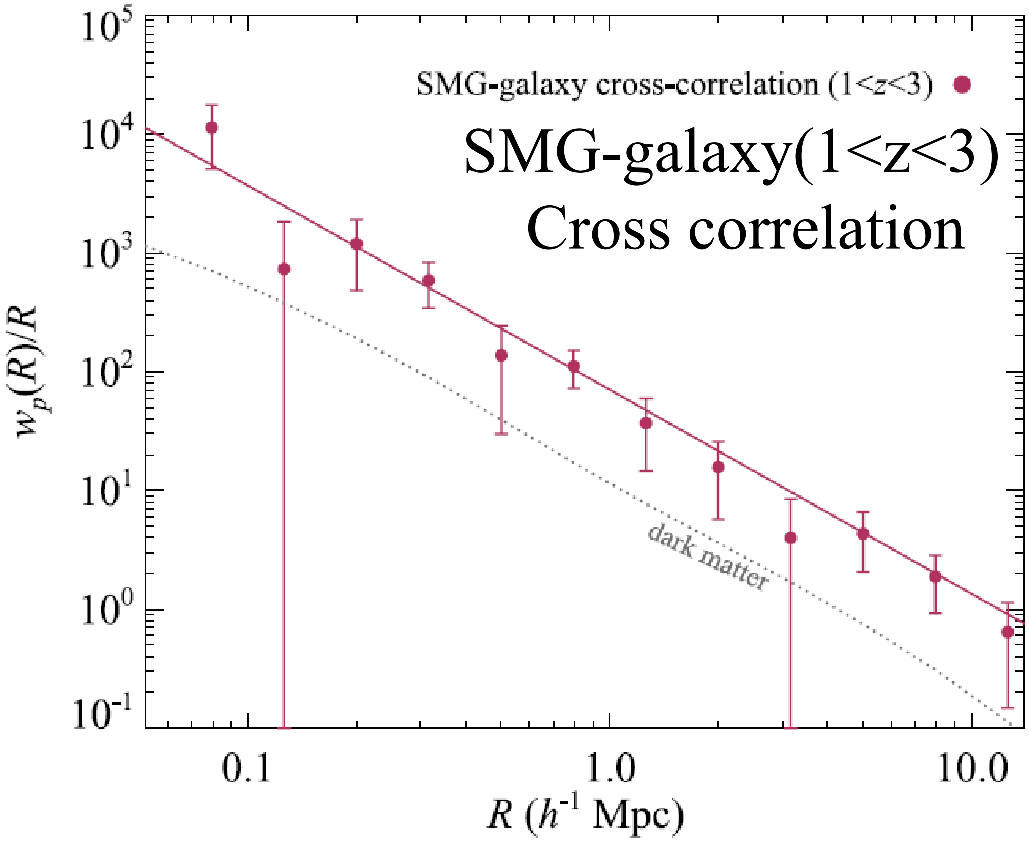
ライマンα輝線銀河（z=3.1）と暗黒銀河の空間分布の比較

ライマンα輝線銀河（z=3.1）と暗黒銀河の間の、２体相互相関関数。小角度スケール（２分角以下）で有意なシグナル
➔Overdensity of SMGs at z~3 !?



Cross-correlation analysis between SMG and IRAC selected galaxies



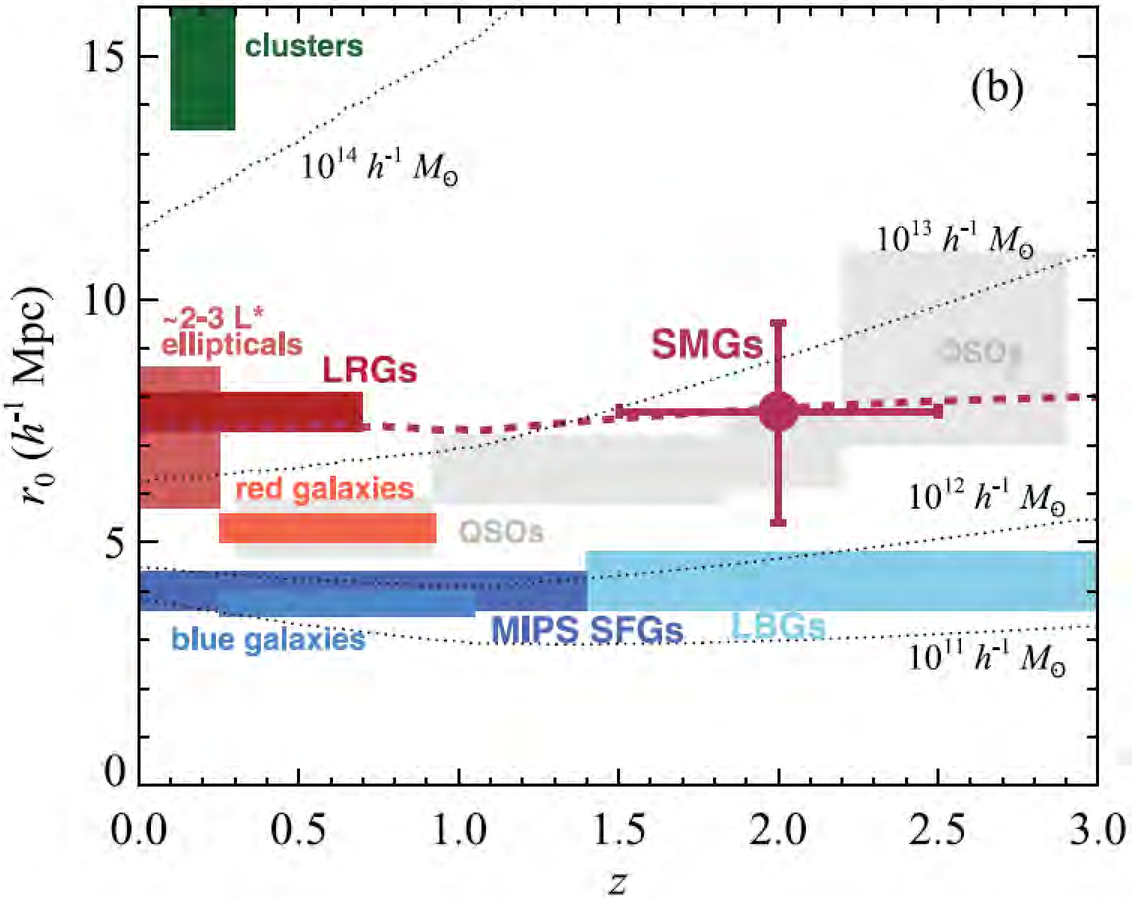


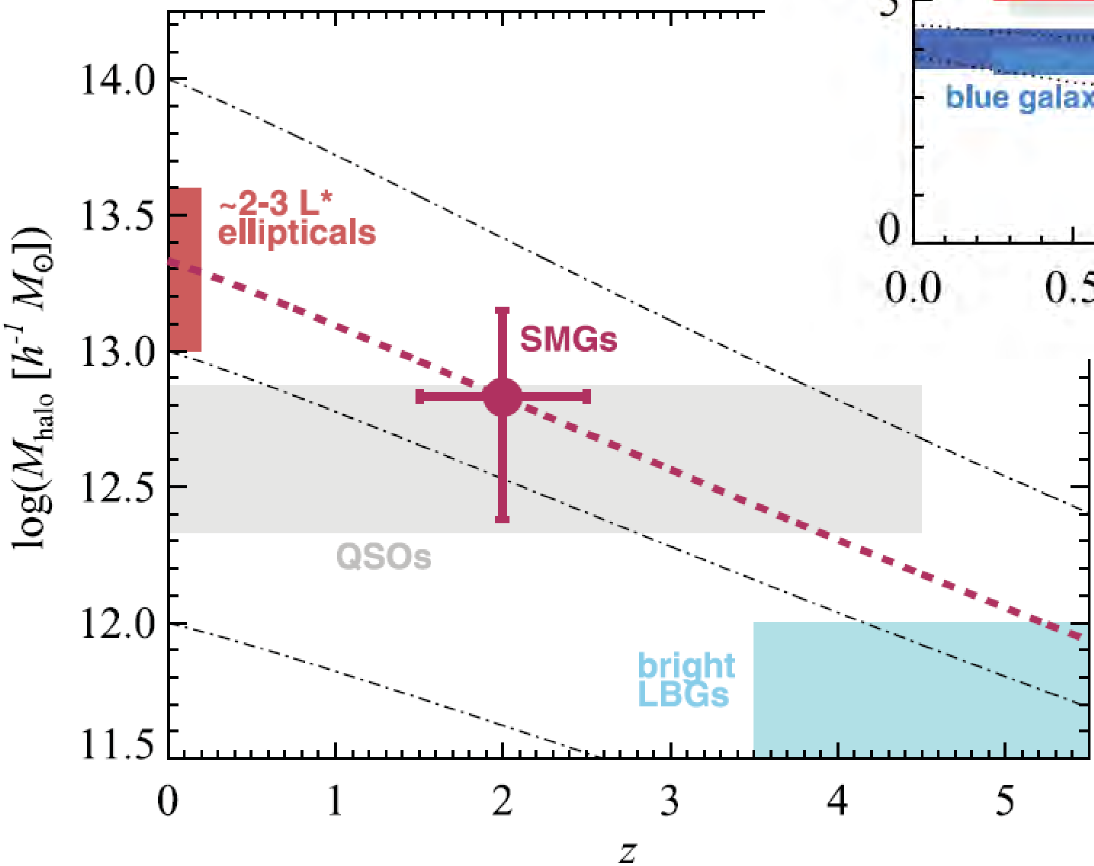
50 SMGs and ~50,000 IRAC galaxies

with photometric redshifts

Hickox et al. 2012, MNRAS, 421, 284

Dark halo properties of SMGs



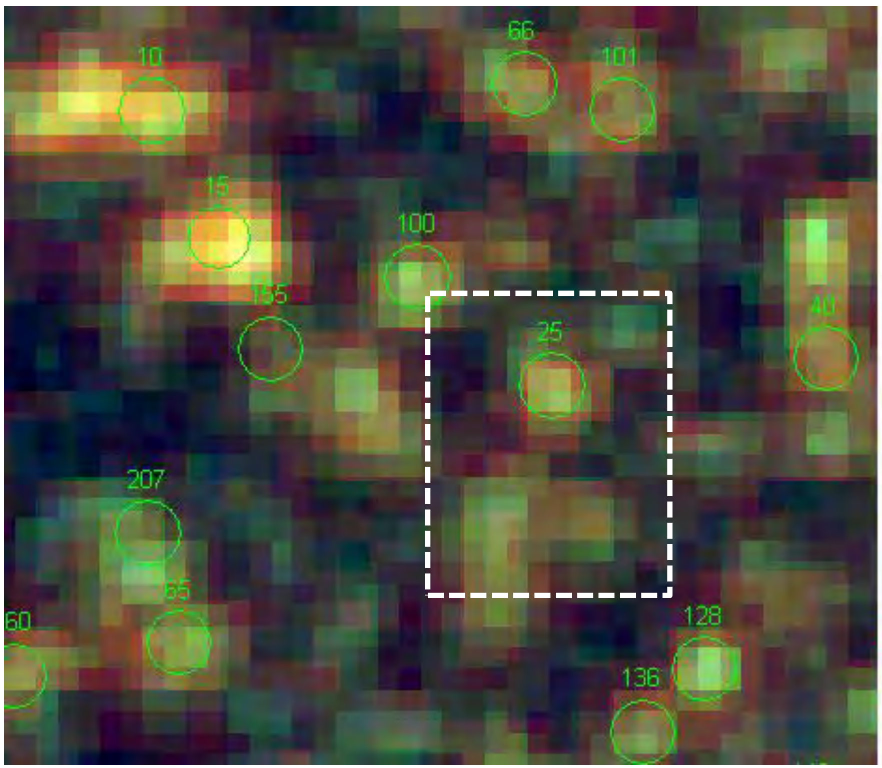


Dark halo mass vs galaxy properties: A key HSC science!

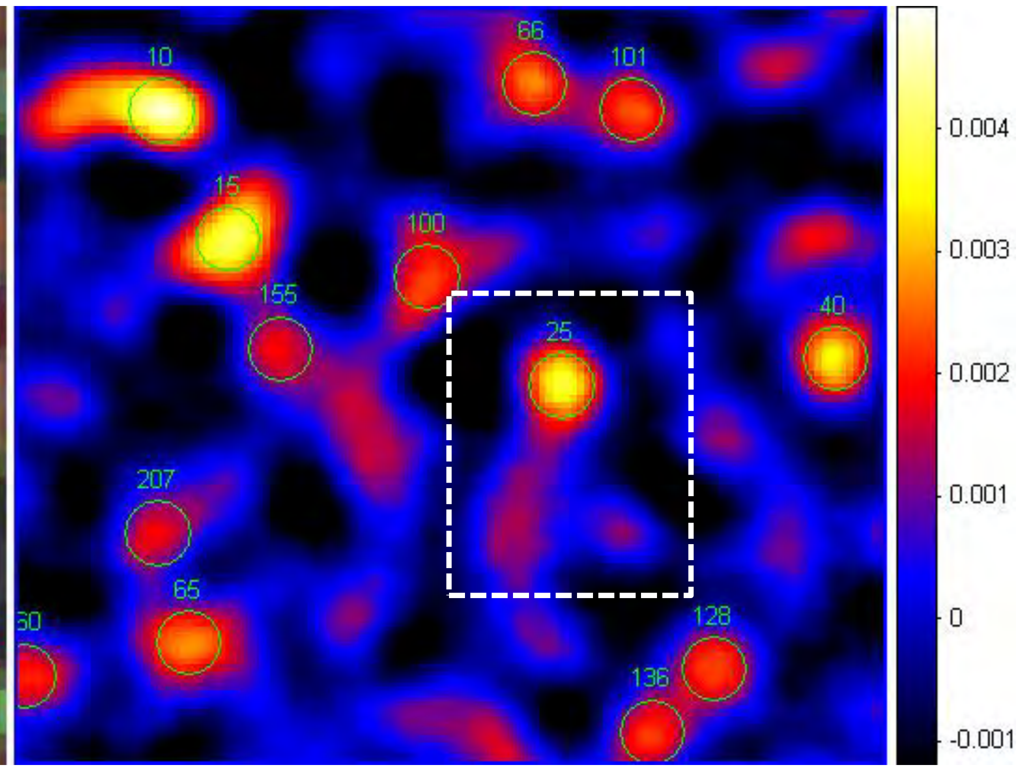
Hickox et al. 2012, MNRAS, 421, 284

Herschel vs AzTEC/ASTE images

Red Green Blue
SPIRE 500μm/350μm/250μm



AzTEC/ASTE 1100μm

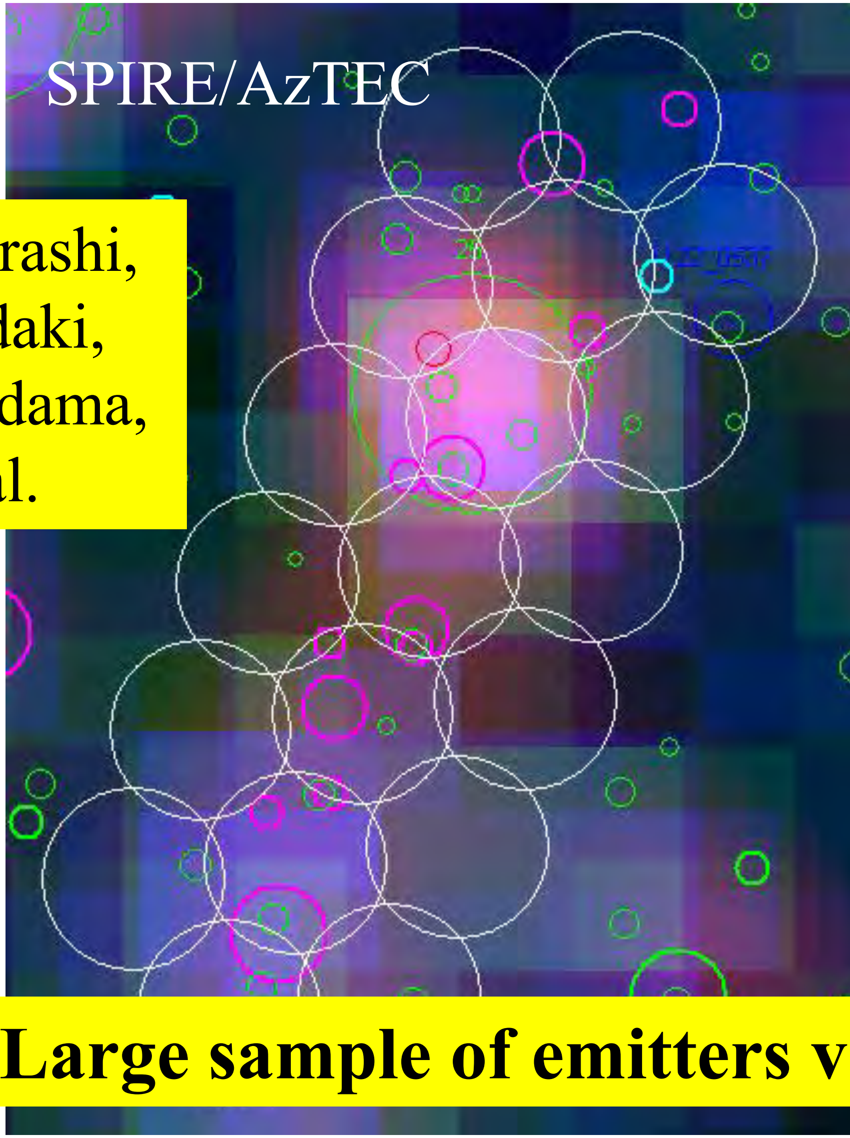


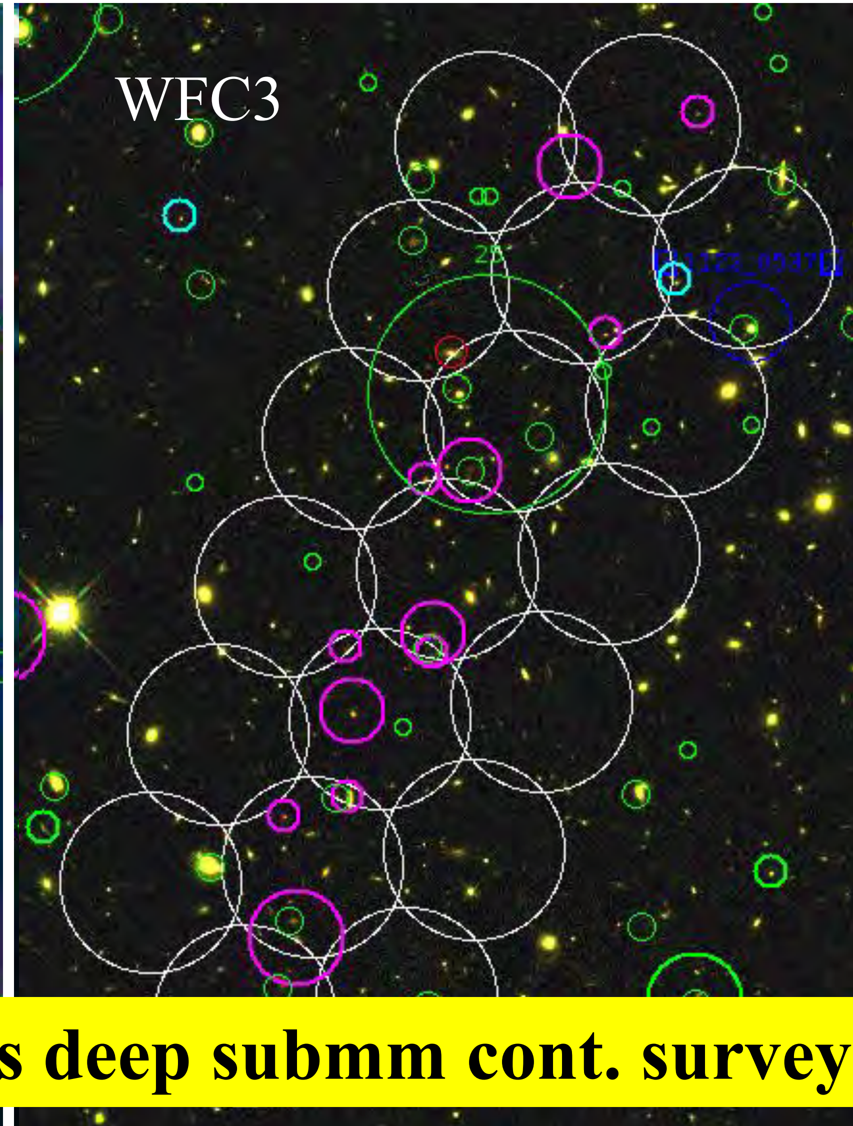
Subaru-XMM/Newton Deep Field (SXDF), 6'x7' area
Ikarashi et al., in prep.

Association of submm/mm fillament and z~2 Hα emitters !?

ALMA map
105”x50” ?

Ikarashi,
Tadaki,
Kodama,
et al.





Large sample of emitters vs deep submm cont. surveys

Rare objects from HSC

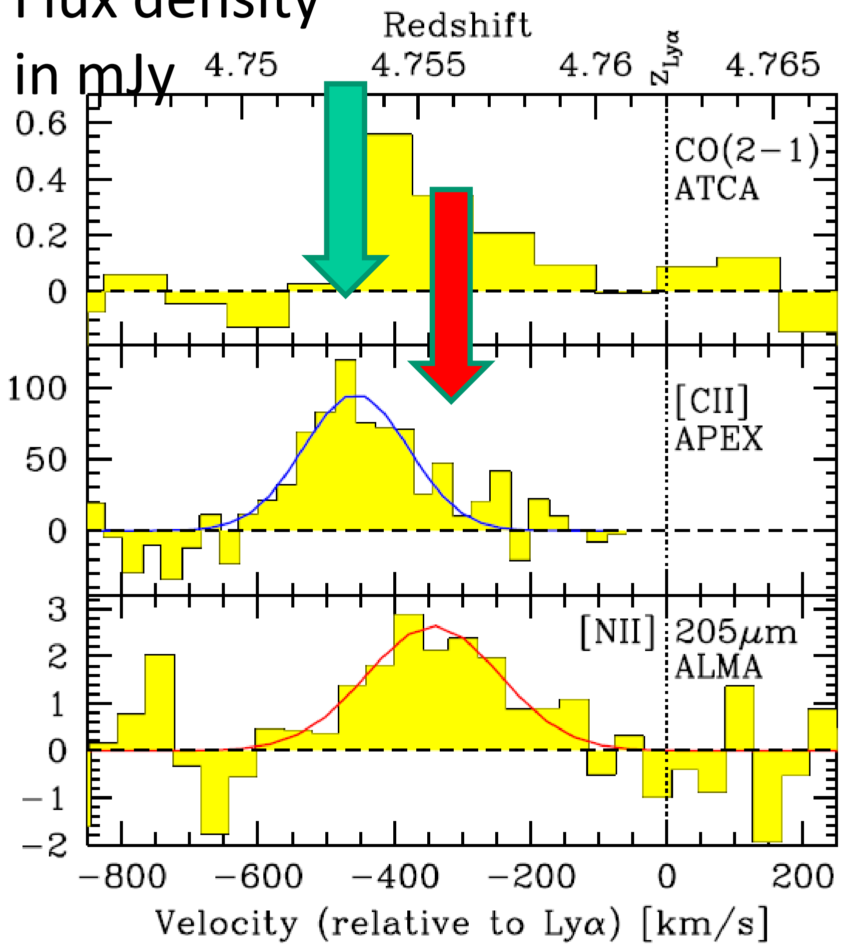
➔ follow up by ALMA

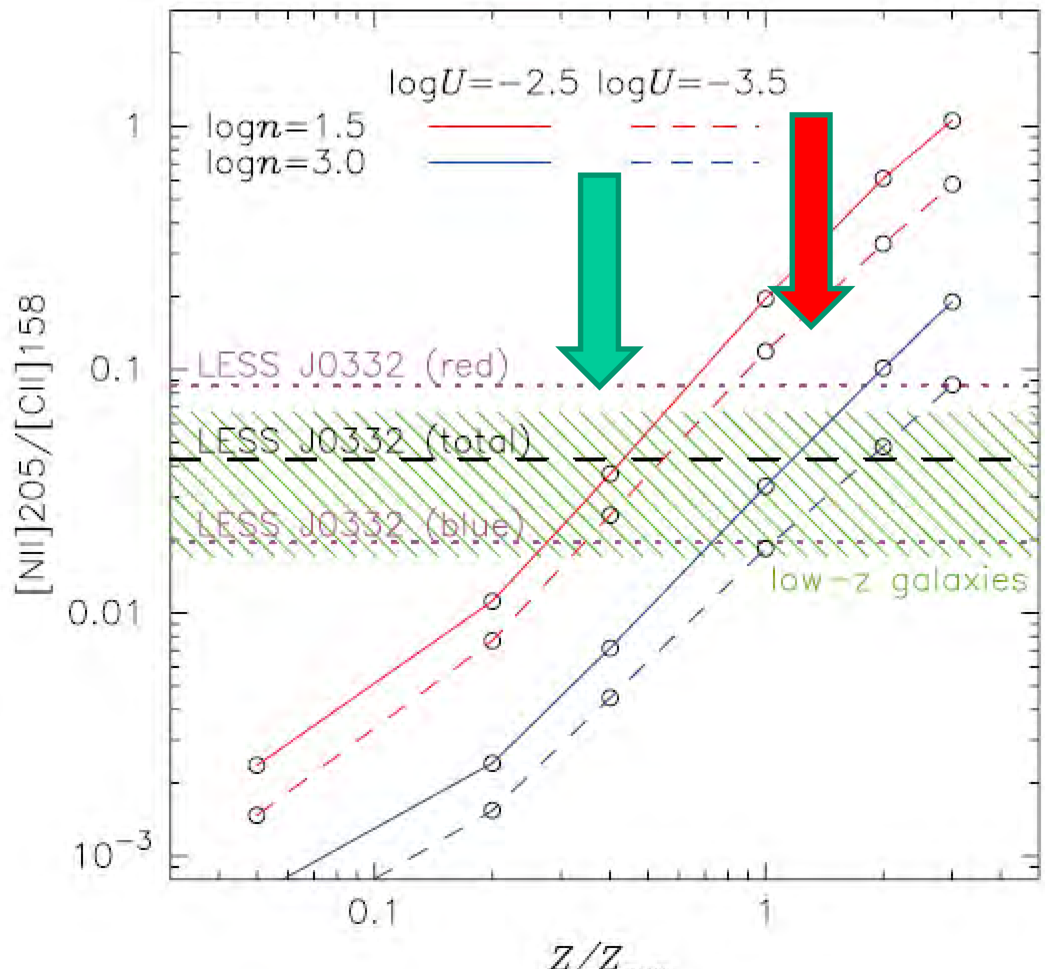
ALMA cycle 0 observations of the LABOCA source LESS 76

- Target: a luminous SMG LSS J033229.4–275619 at z=4.76
- ALMA band 6, 18 antennas, compact config., total observing time = 3.6 hours (3 separated runs, 1.2 hours each)
- F_obs = 253.96GHz ([NII]205 in USB)
- Bandwidth 1875 MHz
- PWV = 3-5mm for 1st run, 1-2mm for 2 runs
- 1σ~0.3 mJy (?) for dv=41 km/s

ALMA detection of [NII] 205μm toward an unlensed SMG at z=4.76

Flux density in mJy



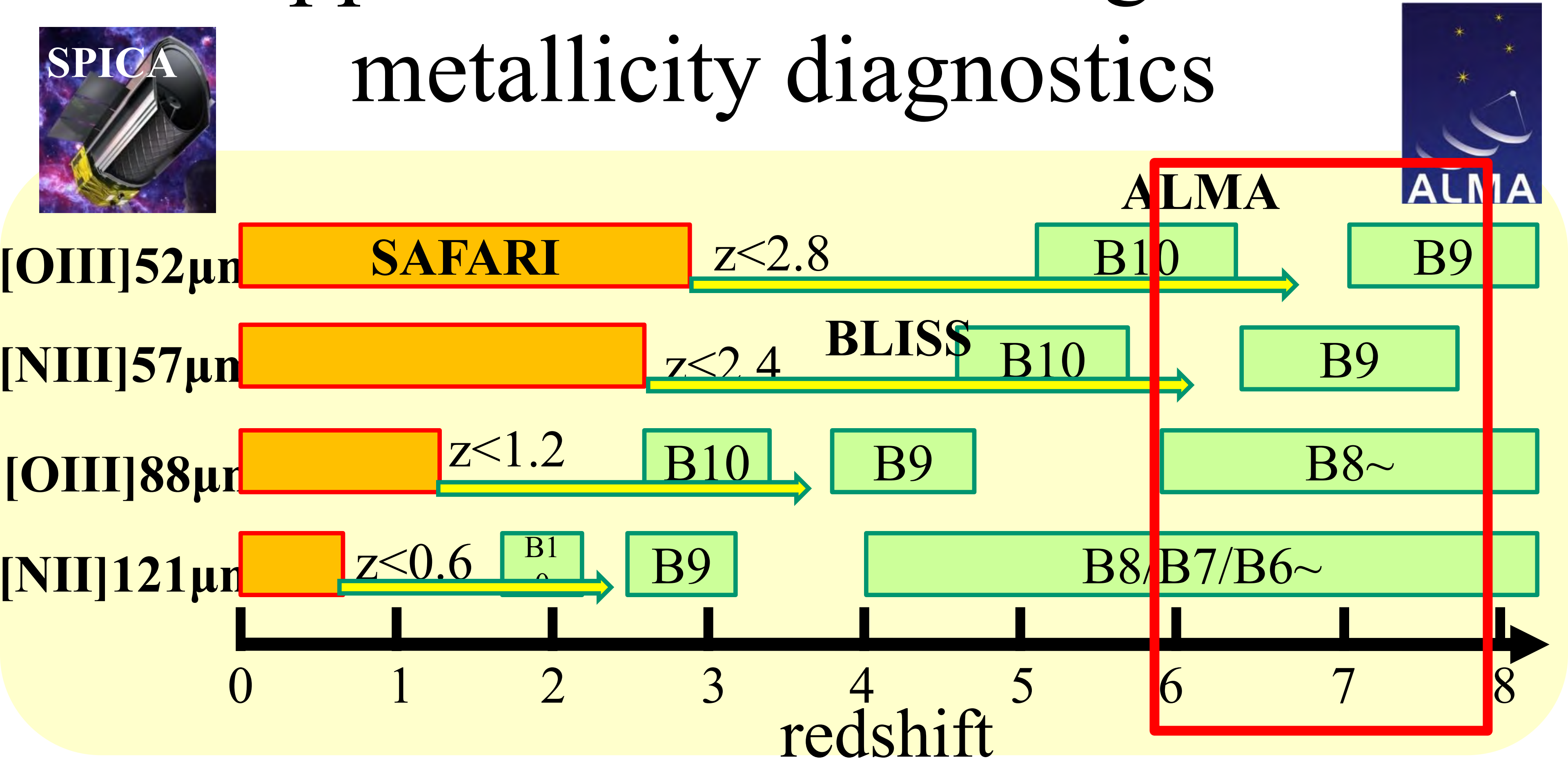


Nagao et al. 2012, A&A, in press (arXiv:1205.4834)

Continuum
= 3.5±0.1 mJy
@1.2mm

This is already chemically evolved.
Inhomogeneous?
Effect of outflow? can also seen.

The applicable redshift range for this metallicity diagnostics



- Expected sample of z>6 quasars are good targets for FIR line based metallicity diagnostics proposed by Nagao et al. !!

Summary

- Deep surveys in mm/submm wavelengths
  - Role of single dish telescopes equipped with large format mm/submm arrays ➔ synergies with HSC!!
  - Superb capability of ALMA for spectroscopic follow up (even in the early phase!)
- HSC surveys and ALMA
  - Cross correlation between submm-selected galaxies and galaxies with photo-z from HSC surveys
  - Rare objects uncovered by HSC surveys: very suited targets for ALMA follow up!