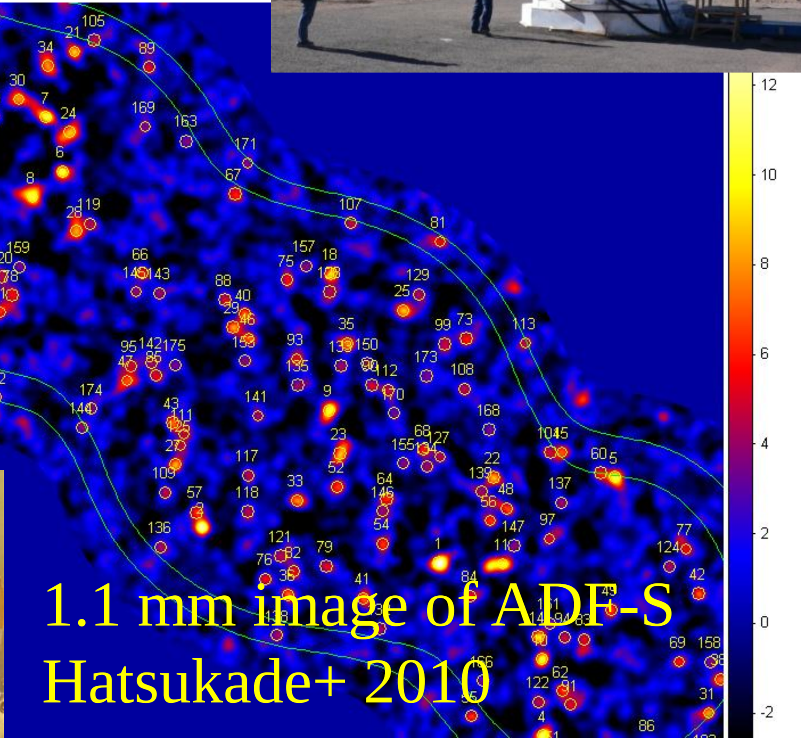
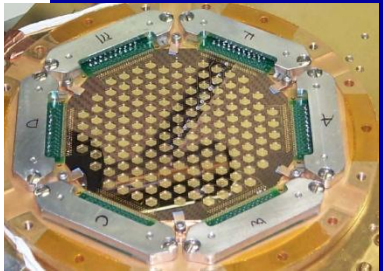
「プロジェクト4」成果報告：
サブミリ波による銀河探査
（サブミリ波・サブプロジェクト2）

RESCEU成果報告会
2010年8月28日 @高知

河野孝太郎
天文学教育研究センター
ビッグバン宇宙国際研究センター
（研究協力者）
kohno@ioa.s.u-tokyo.ac.jp

東京大学
THE UNIVERSITY OF TOKYO





サブ･プロジェクト2：概要

- （ミリ波･）サブミリ波での観測に基づく、
  - （主に）高赤方偏移銀河の形成進化過程の研究

    ➔ ダスト減光の影響のない「宇宙の星形成史」の探求

    ➔ それらをプローブとした、暗黒物質分布の探求
  - （そこに宿される）巨大ブラックホール形成進化過程の研究
- 手法としては
  - （ミリ波）サブミリ波帯の連続波カメラによる撮像サーベイ ➔ 形成途上の大質量銀河（サブミリ波銀河）の発見

    ⇔ 多波長同定でプロジェクト3（銀河プロジェクト）との連携
  - （ミリ波）サブミリ波帯の（超）広帯域分光 ➔

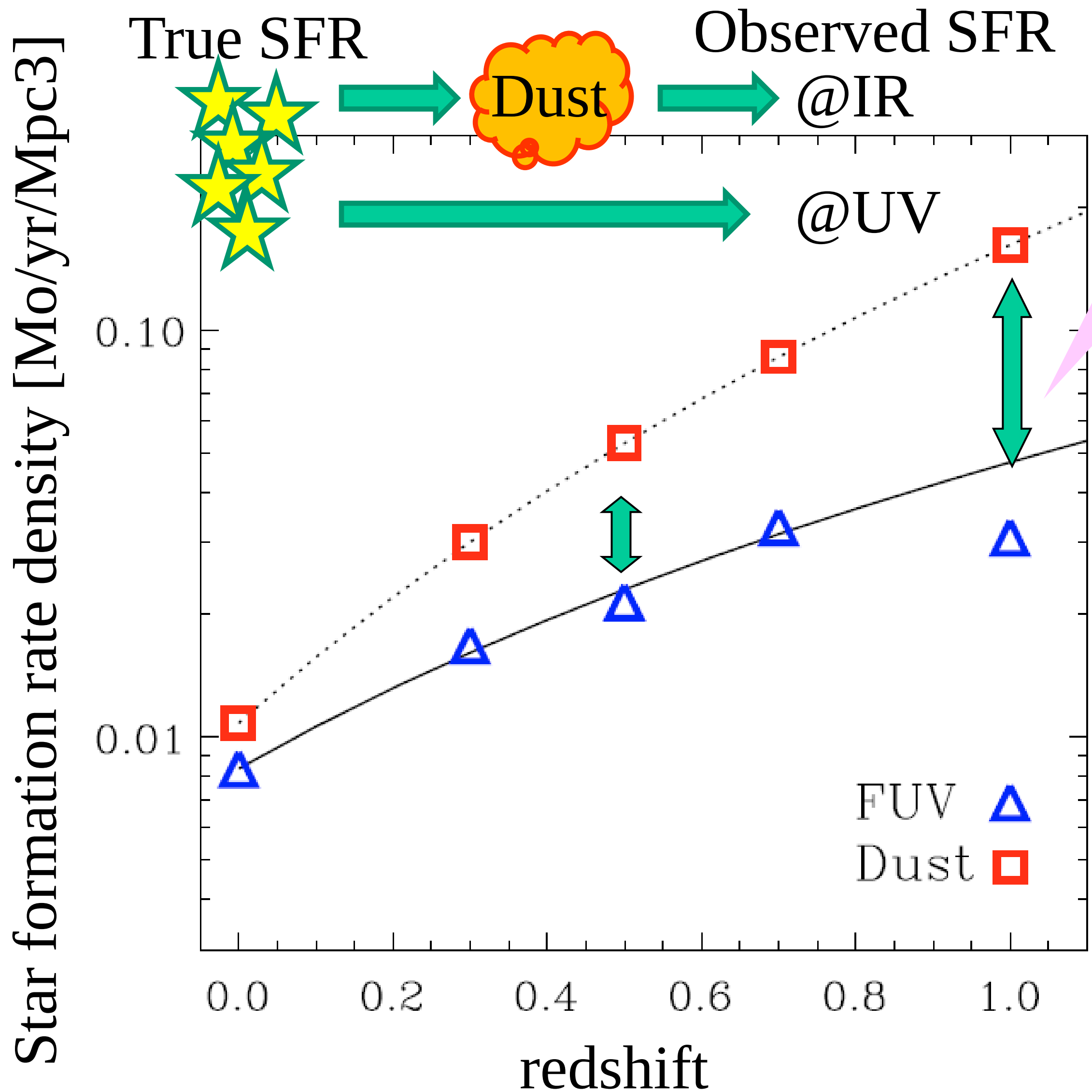
    (1) サブミリ波銀河の赤方偏移分布の測定

    (2) エネルギー源の診断（埋もれたAGNの発見）

    ⇔ サブプロジェクト1との連携（X線の星間物質の影響）

Why we observe high-z galaxies at millimeter/submillimeter wavelengths?

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

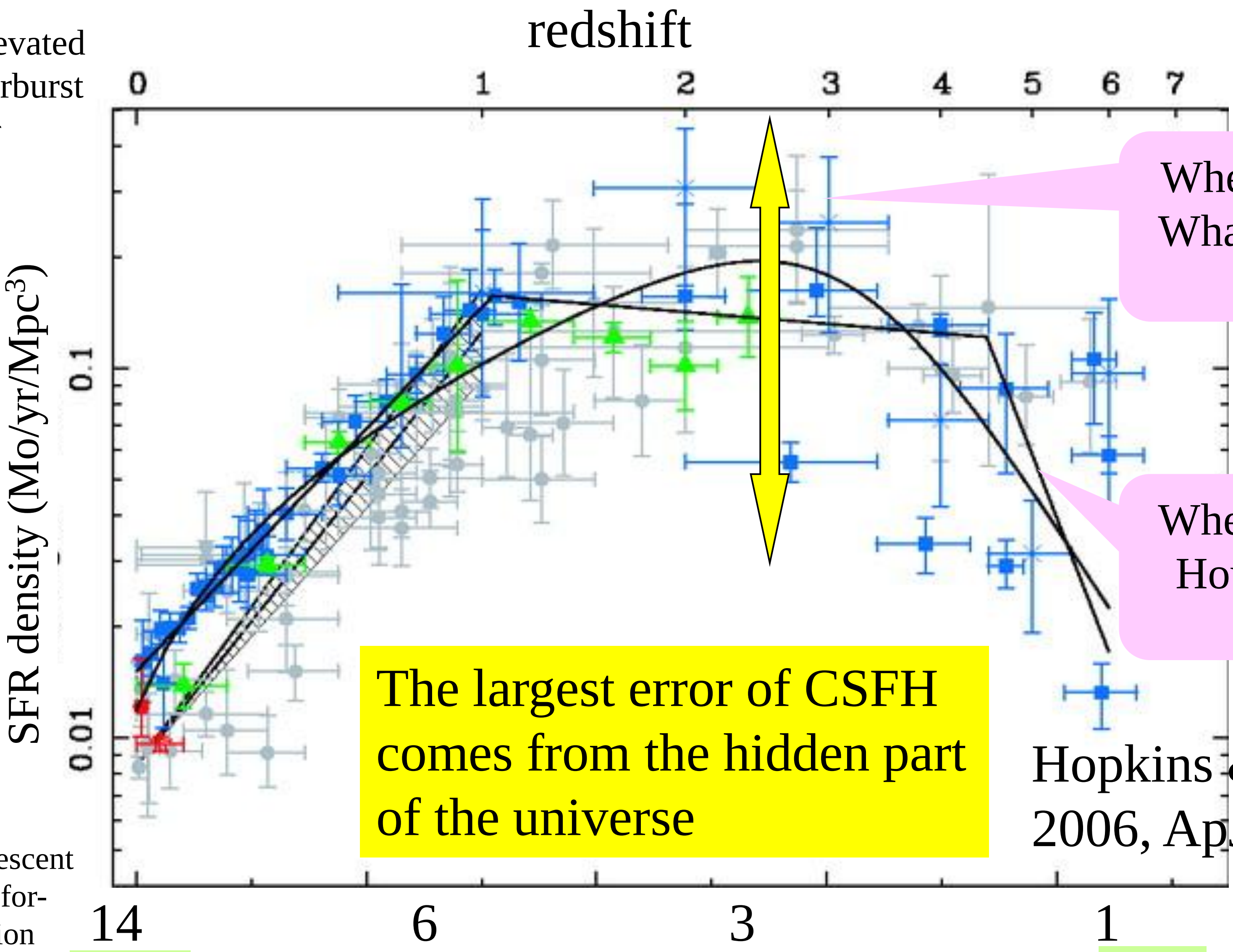


More hidden star formation @higher redshift (>70% at z~1)

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

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

Cosmic star formation history



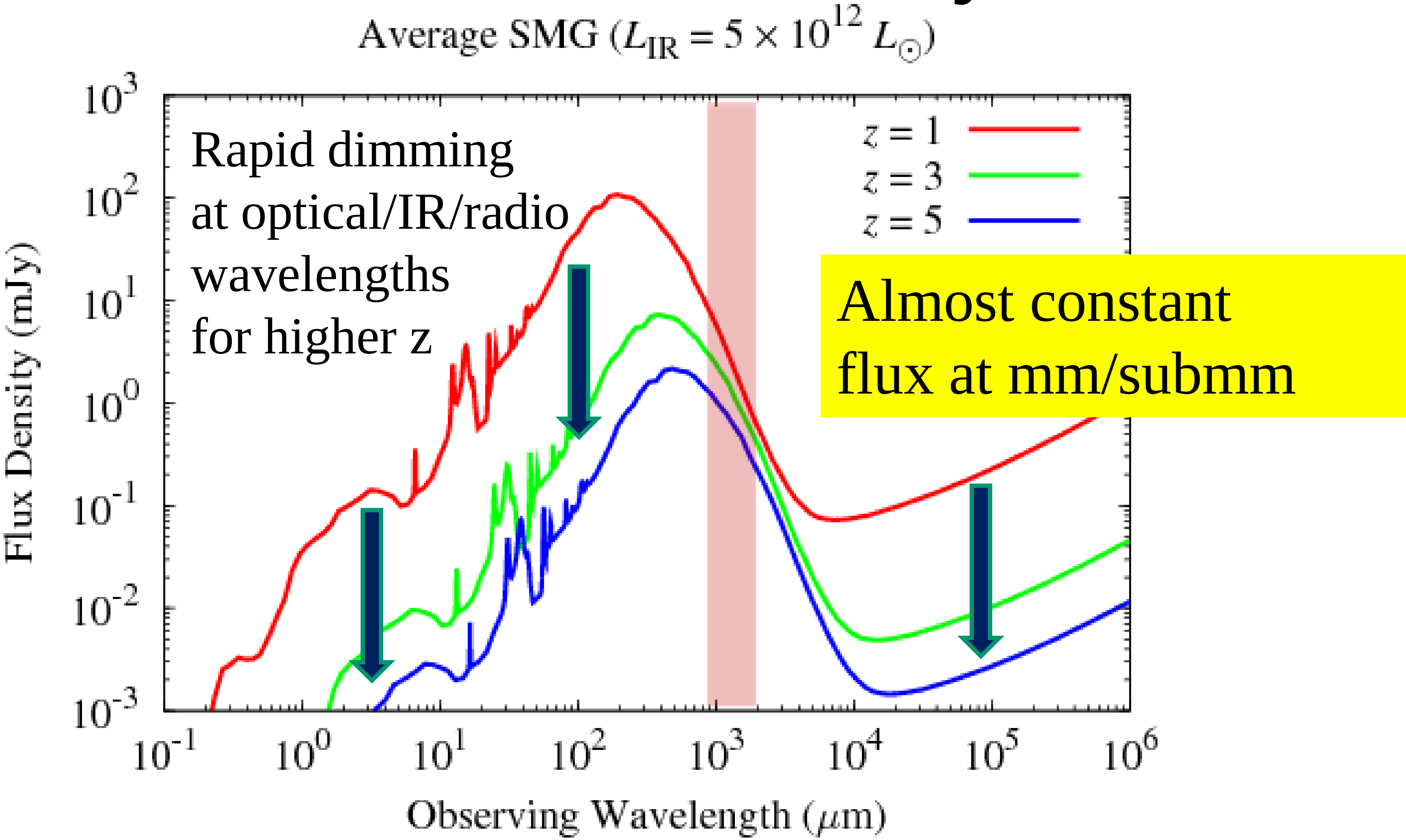
Where is the peak? What is the height?

When is the start? How steep it is?

The largest error of CSFH comes from the hidden part of the universe

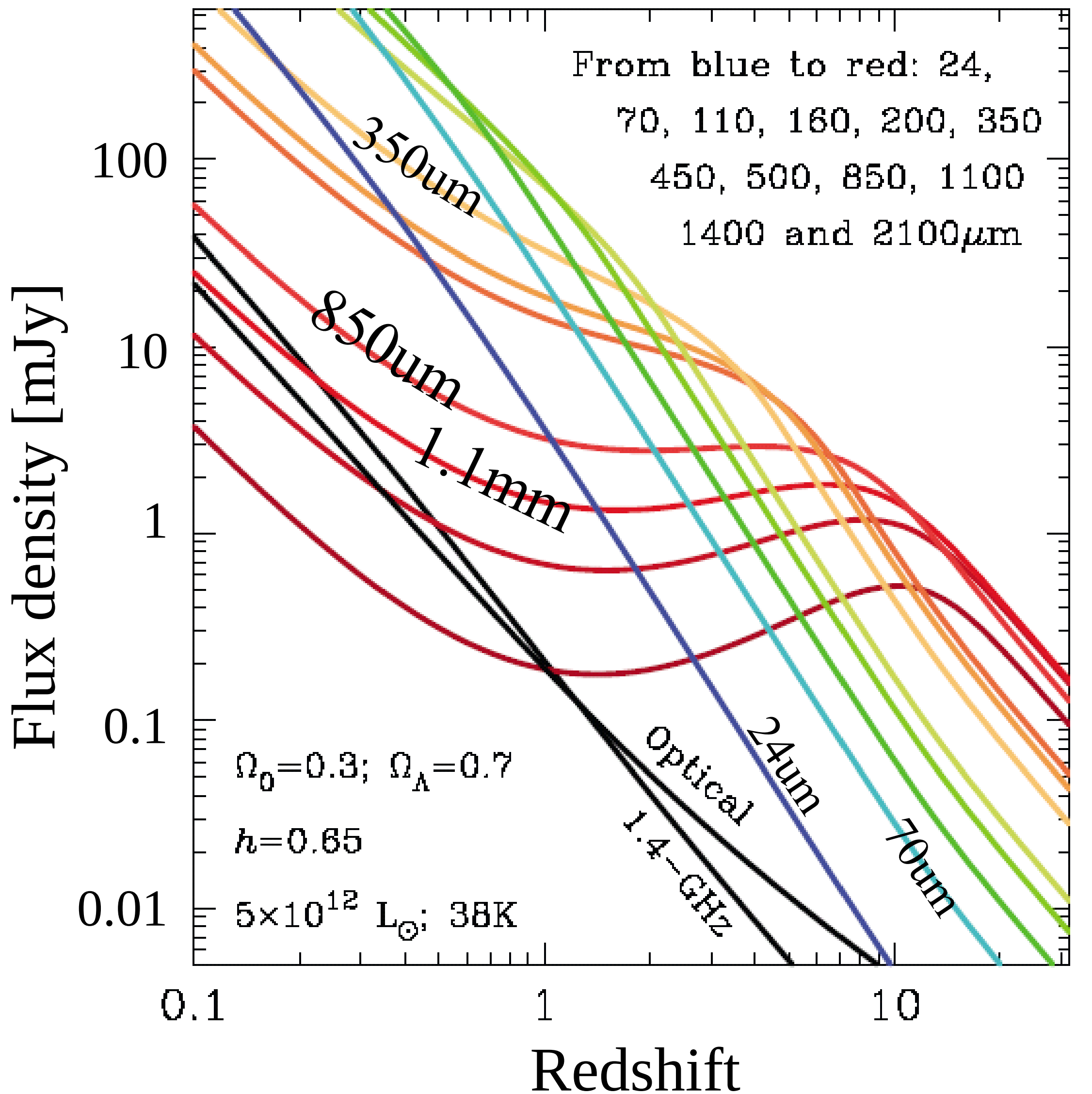
Hopkins & Beacom 2006, ApJ, 651, 142

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



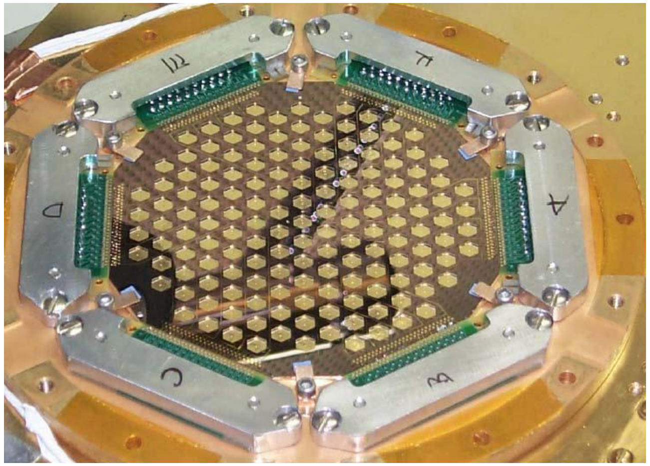
K correction as a function of λ

- Almost constant flux for ~1 < z < ~10 at 850um/1.1mm due to strong negative K correction
- 1.4 GHz intensity drops very rapidly: $S(z) \sim (1+z)^{-(4+\alpha)}$
  - α ~ 0.8 (Condon 1992 ARAA, 30, 575)



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

ASTE10m
(Ezawa et al. 2008)



AzTEC Camera, 144 pix, 1.1mm, FOV=8’, θ=28”
(Wilson et al. 2008)

AzTEC-on-ASTE surveys of Submillimeter galaxies (SMGs)

Collaborators

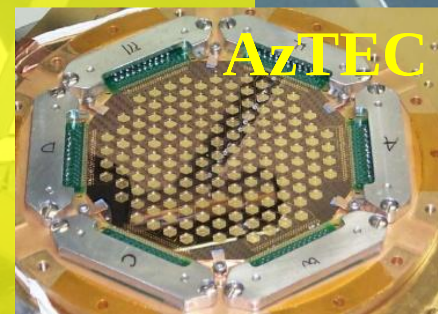
- Kohno, K., **<u>Ikarashi, S.,</u>** Tsukagoshi, T., Inoue, H. (Univ. of Tokyo), Kawabe, R., **<u>Tamura, Y., Hatsukade, B</u>**., Oshima, T, Nakanishi, K., Iono, D., Ezawa, H., (NAOJ), Komugi, S. (ISAS/JAXA), Tanaka, K. (Keio Univ.), Tosaki, T., (Joetsu U. of Edu.) & ASTE team
- Cortes, J., (JAO), Bronfman, L. (Univ. of Chile)
- Wilson, G.W., (PI. of AzTEC; UMASS), Aretxaga, I., Hughes, D.H., (INAOE), Yun, M.S., Austermann, J., Scott, K.S. (UMASS), Perera, T. (Univ. of Chicago), & AzTEC team
- ADF-S/SXDS/SDF/SSA22 collaborations

ASTE

- 10 m dish@4860 m
- Science op. Oct. 2004~
- Joint operation with NAOJ and universities including Univ. of Tokyo (Kohno labo. & Yamamoto labo.) etc.
- Remote observations from Mitaka etc.

Atacama Submillimeter Telescope Experiment

- **Main reflector: D=10m, 20 um (rms)**
- **Heterodyne spectroscopy :**
  350 GHz (CATS345)、THz RX
  490 GHz (ALAM Band-8 QM)
  + 8 GHz (max) width spectrometer
- **Continuum imaging:**
  1100 um (AzTEC) ***2007-2008***
  1100/850/450 um ***under development***
- **Remote observations from Tokyo/Nobeyama**
- **Joint project among NAOJ and Universities**



http://www.nro.nao.ac.jp/~aste/

The ASTE site: cluster of telescopes!

- Located at alt. 4,860 m in the Atacama desert in Chile
- Many mm/submm/Infrared facilities are coming!

This is a very dry site but …

※ ~4800m !

AzTEC-ASTE 1.1 mm deep surveys

- wide (~1.6 deg^2) & deep (1σ ~ 0.4 – 1.2 mJy ⇔ ULIRGs @z>1) surveys of blank fields: yielding >750 robust detections

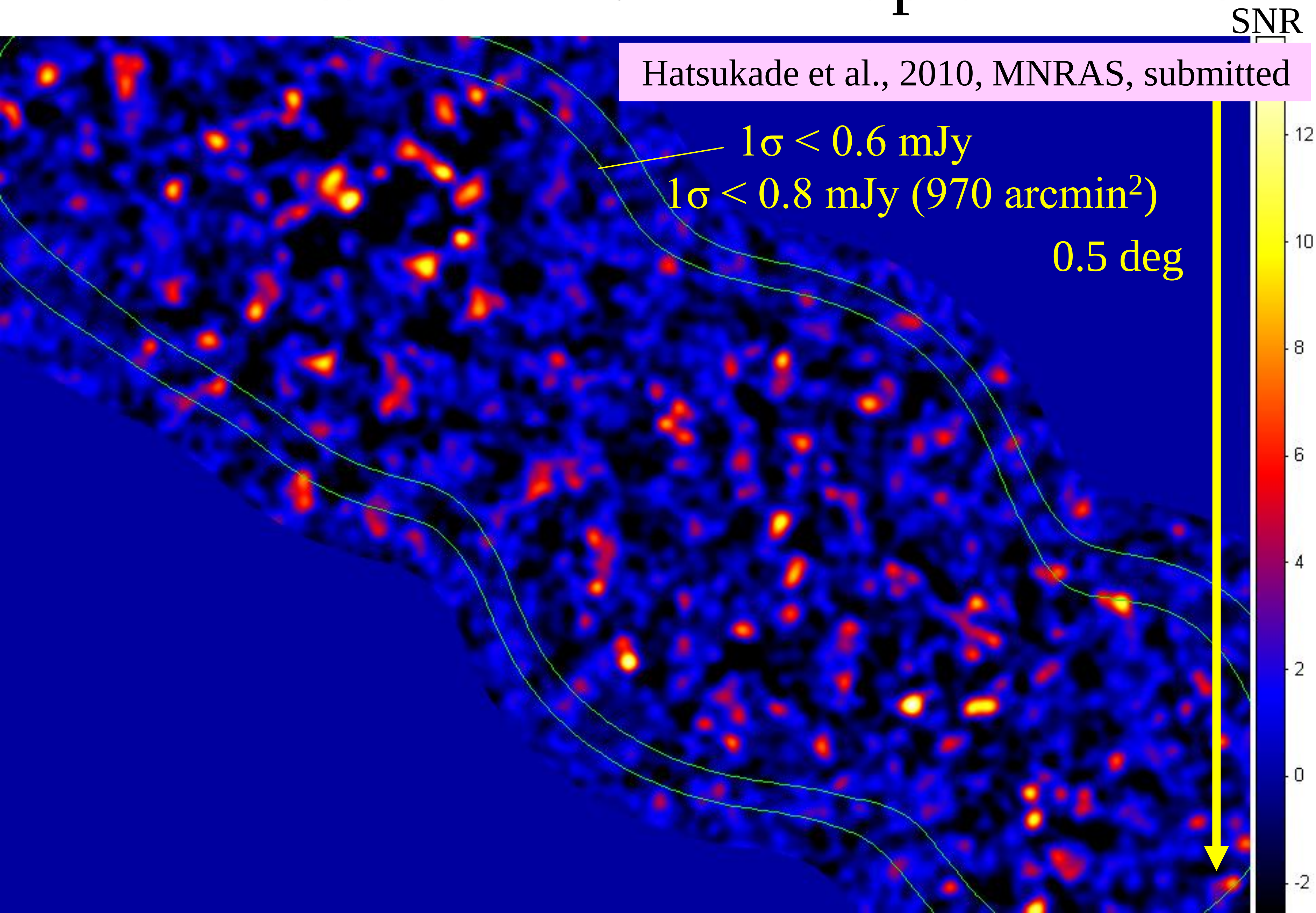
（+ HDF-S, ECDF-S）

Field name	Survey area (30-50% coverage)	Noise level (1 sigma)	Num. of sources (S/N > 3.5)
SXDF	960 arcmin^2	0.5 – 0.9 mJy	174
SSA22	810 arcmin^2	0.6 – 1.2 mJy	113
ADF-S	970 arcmin^2	0.4 – 0.8 mJy	191
SDF	210 arcmin^2	0.7 – 1.0 mJy	25
SXDF z=5.7 clump	300 arcmin^2	~ 0.8 mJy	30
COSMOS	2700 arcmin^2	~ 1.1 mJy	193
GOODS-S	270 arcmin^2	0.5 – 0.7 mJy	48

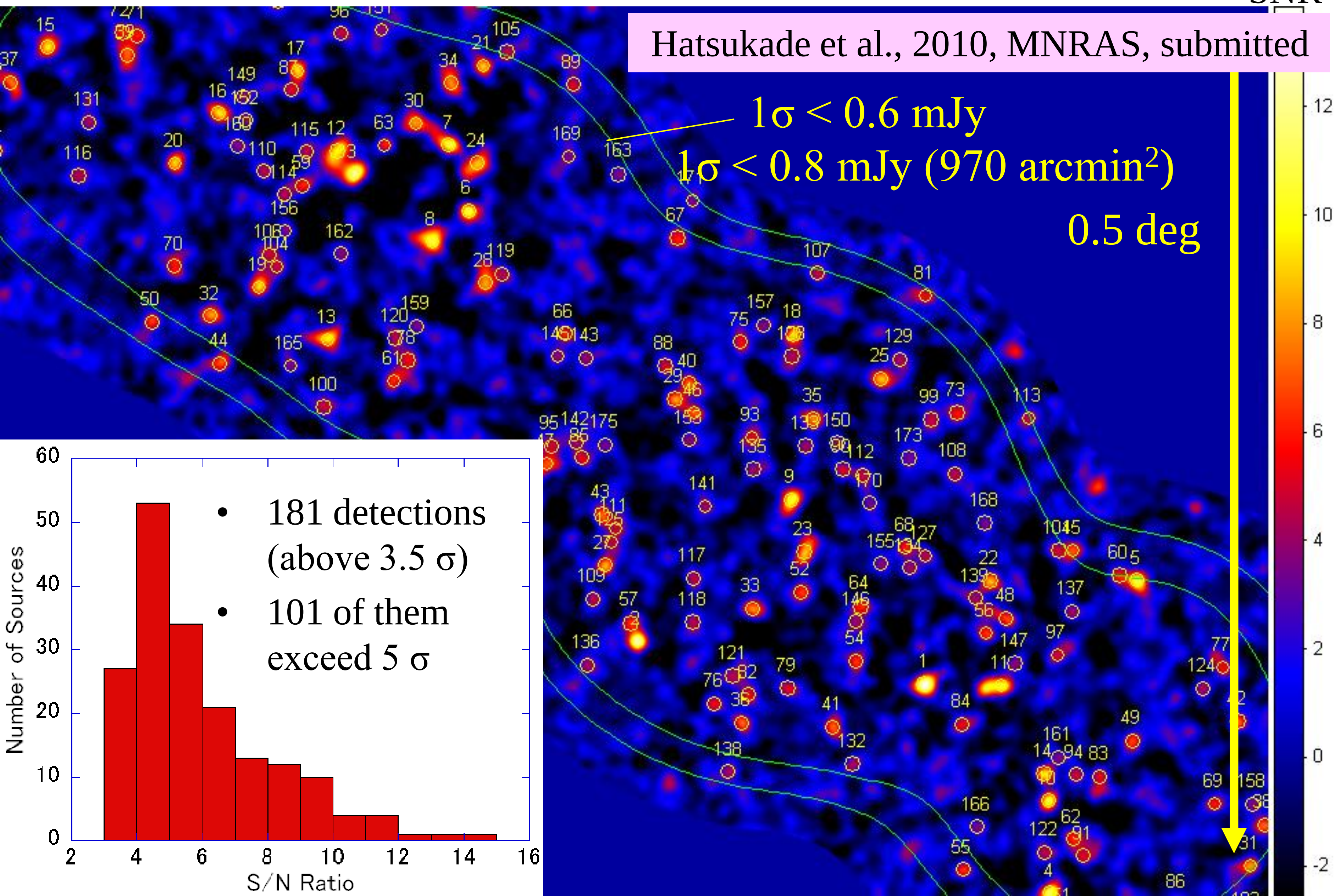
- Biased regions survey: ~1 deg^2, >680 detections
  - High-z radio galaxies, X-ray and optically selected proto-clusters; ~160 arcmin^2 x ~40 fields:

>1400 detections in total, ~x3 of the known (published) SMGs

AzTEC/ASTE 1.1mm map of ADF-S



AzTEC/ASTE 1.1mm map of ADF-S



Constraints on redshifts of AzTEC/ASTE sources in ADF-S

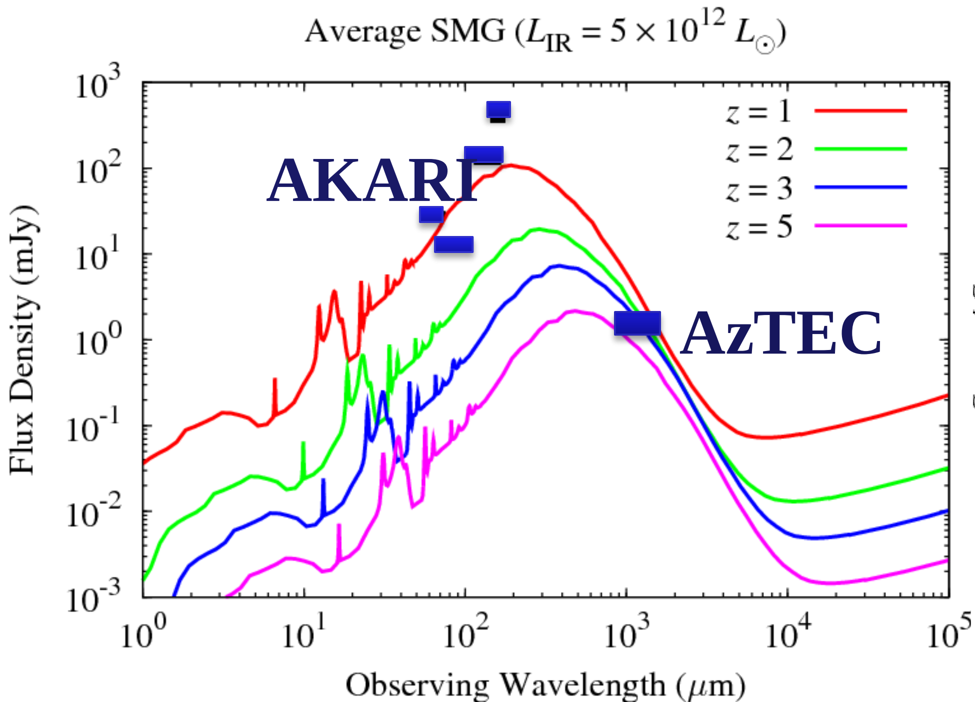
- 90um/1.1mm flux ratio

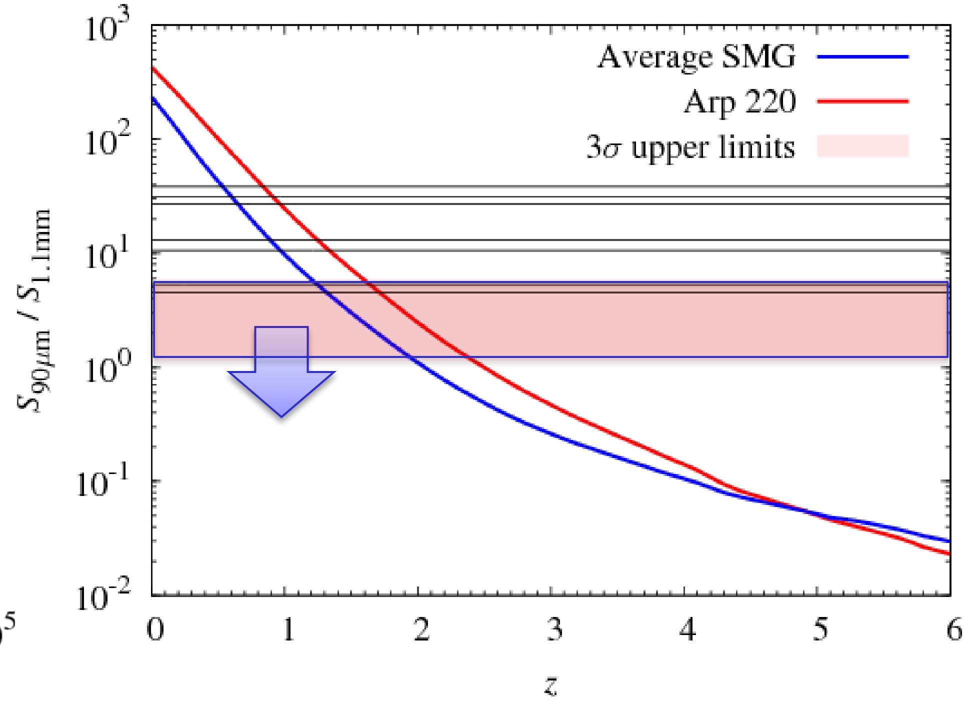
Hatsukade et al., 2010, MNRAS, submitted

➔ most of the AzTEC sources: z > 1

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

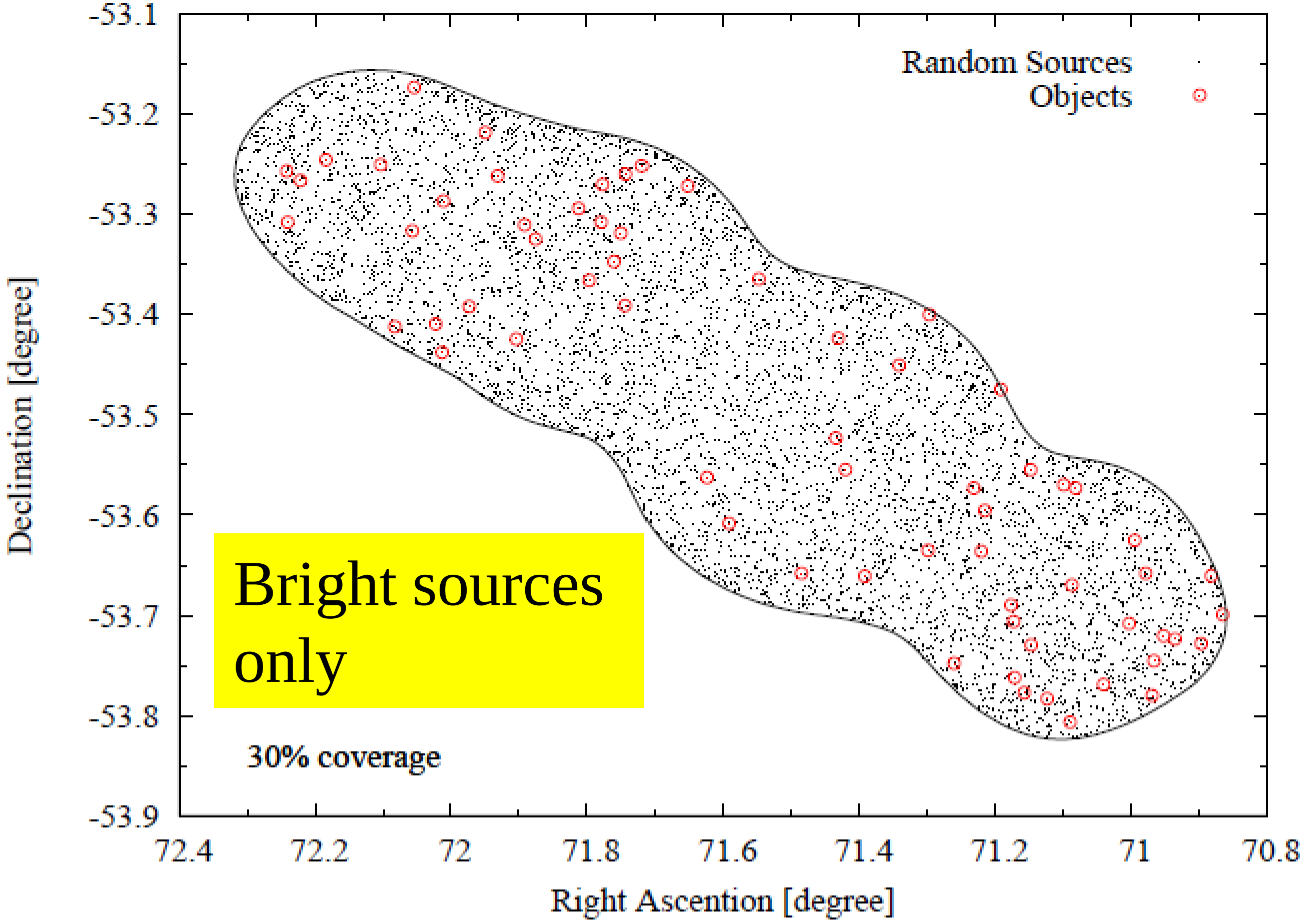
- L(FIR) ~ (3-14) x 10^{12} Lo, SFR ~ 500-2400 Mo/yr





Distribution of all/bright SMGs in ADF-S

- Distribution of bright SMGs deviates from random distribution!

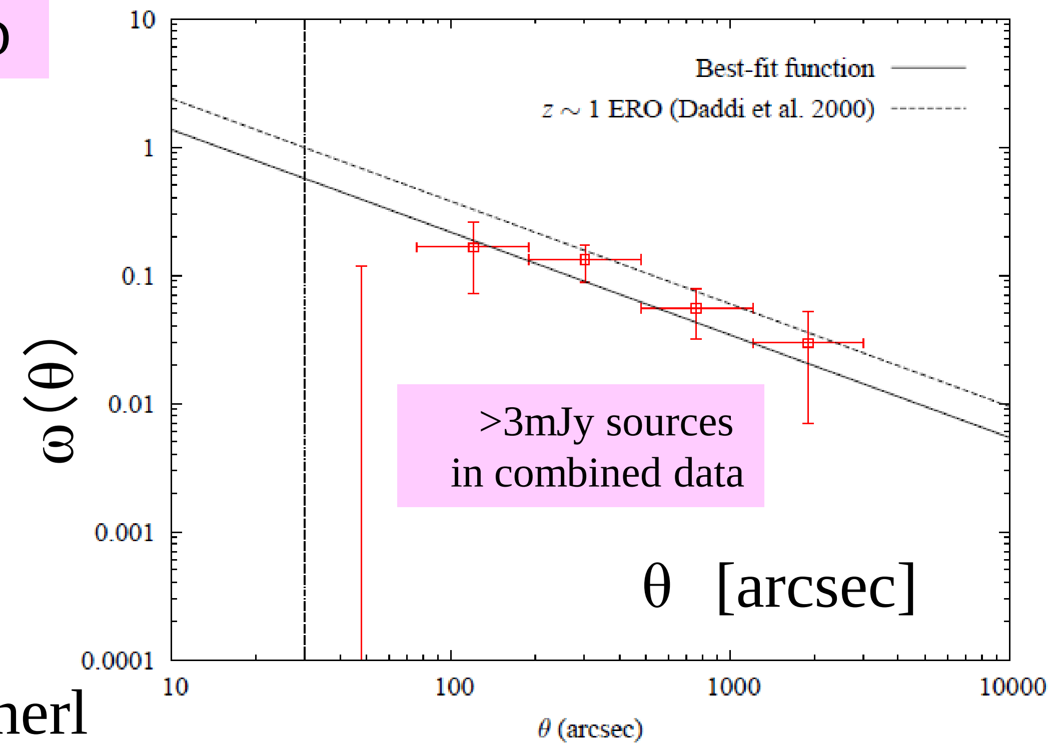


Clustering of AzTEC Sources

Field	Source	N source	Amplitude
ADF-S	all	174	0.82±3.0
	>3mJy	64	14±5.8
SXDF	all	191	0.50±2.0
	>3mJy	70	3.1±5.6
Combine	all	365	0.91±2.1
	>3mJy	134	9.0±4.0

Hatsukade 2010, PhD

- Evidence for clustering
  - Bright sources (L(FIR) ~ 10^{13}) are more strongly clustered
  - DH mass: $10^{13\text{-}14}$ Mo
- Field-to-field variance
  - ADF-S > SXDF

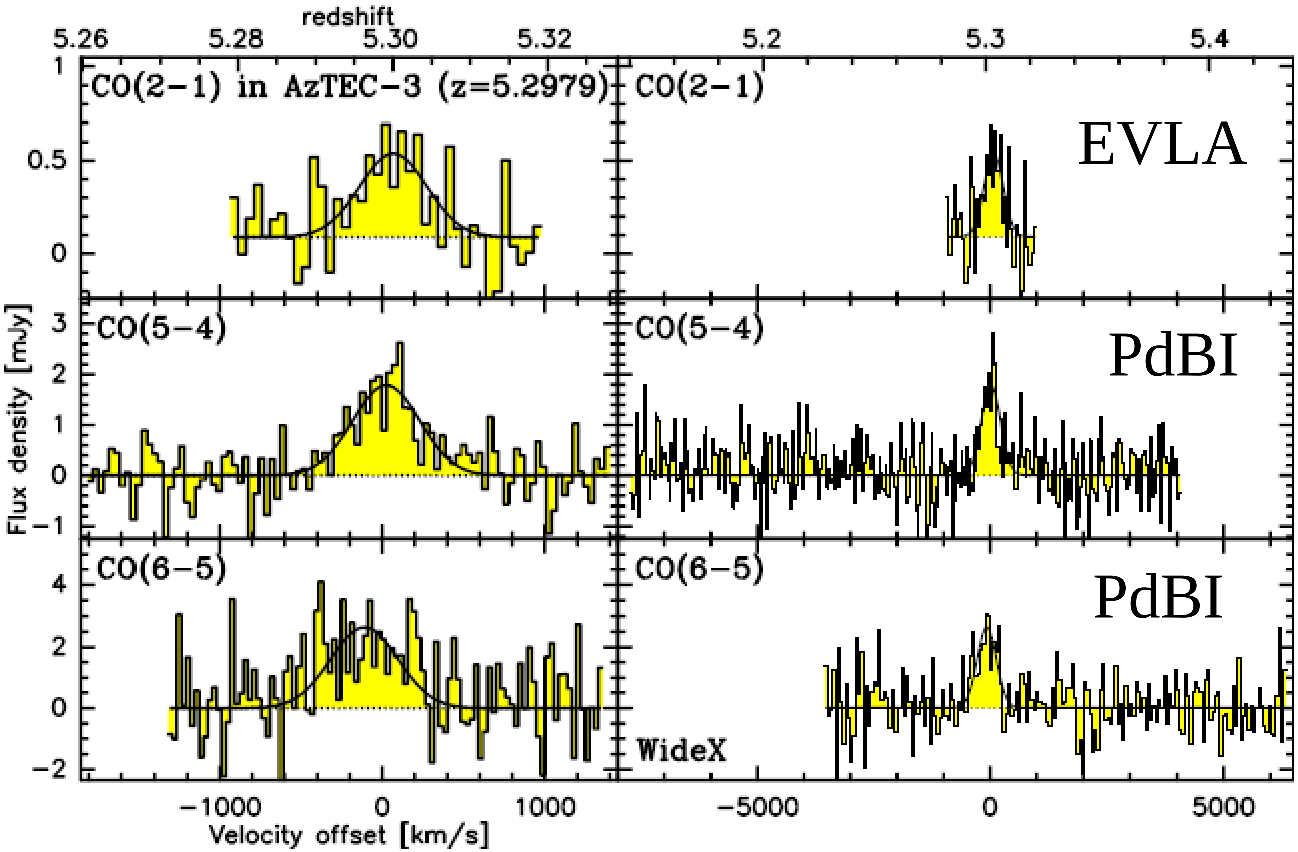


cf. Hersherl

One of the hot issues: Increasing the number of $z>4$ SMGs?

The highest redshift SMG to date (z=5.3)

- COSMOS-AzTEC3 ← uncovered by 1.1 mm !



4.4 hr, 0.52 mJy
→13 min for 50 ant.
→ 2.2 hr for 16 ant. of ALMA

Riechers et al. 2010, ApJ, 720, 131

FIG. 2.— *Left*: EVLA/PdBI CO(J=2→1) (*top*), CO(J=5→4) (*middle*) and CO(J=6→5) (*bottom*) spectra of AzTEC-3 at 6/10/10 MHz (49/33/27 km s^{-1}) resolution (histograms), along with Gaussian fits to the line emission (black curves). The velocity scale is relative to the source's redshift of z=5.2979±0.0004, as measured from the molecular line emission. *Right*: Same, but showing the PdBI data recorded with the WideX correlator (CO J=6→5 is re-binned to 20 MHz).

Properties of z=5.3 SMG

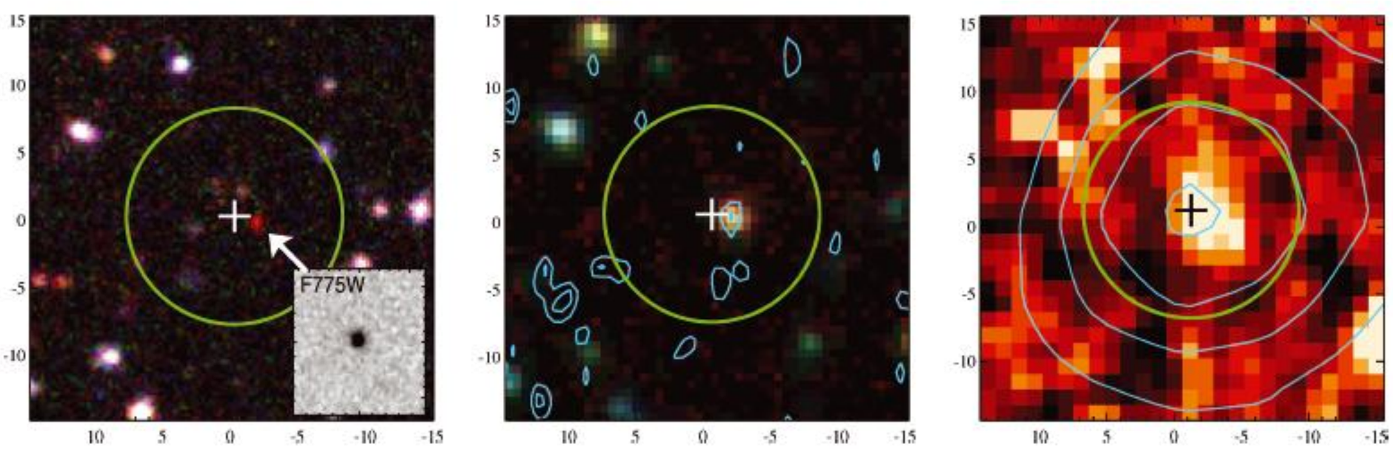
- L_{FIR} = (1.7±0.8) x 10^{13} Lo or SFR ~ 1800 Mo/yr
- Mstar = (1.0±0.2) x 10^{10} Mo
- CO source size: < 1” or <8 kpc
- L’co = 6.6 x 10^{10} K km/s pc^2

cf. Mstar ~ 10^{11} Mo
In SXDF860.6
Hatsukade 2010,
ApJ, 711, 974

➔ SFE = L_{FIR}/L’co = 260 Lo/(K km/s pc^2)
  - Comparable to typical z>2 SMGs (Greve et al. 2005) and quasar host galaxies (Riechers et al. 2006)
- Mgas = 5.3x10^{10} Mo ➔ Mgas/Mstar ~ 5 (!)
  - What is the origin of dust at z=5.3 !?
- t_SF (duration) ~30 Myr ➔ Mstar can be x6

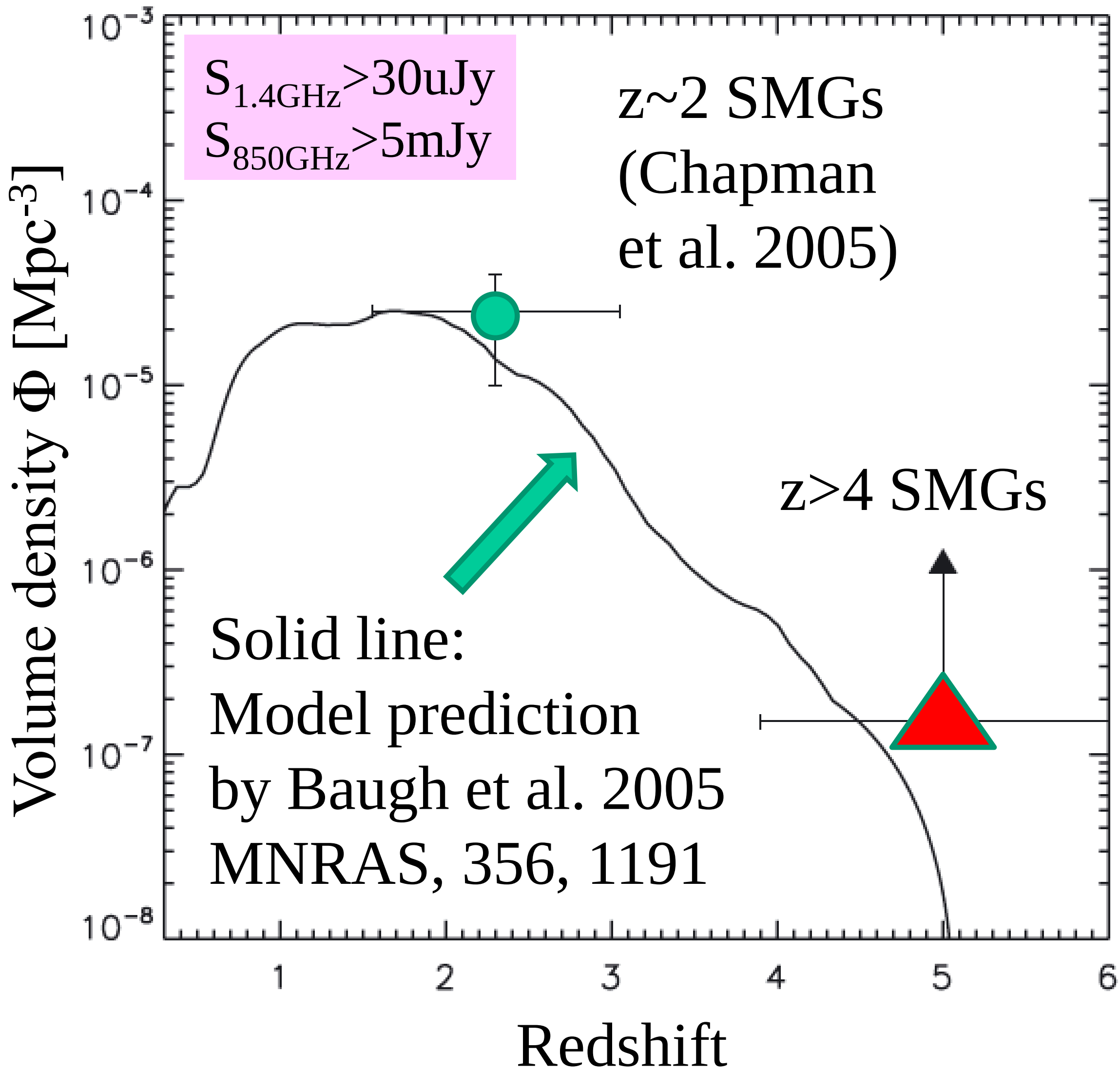
Further z>4 SMGs known

- z=4.76, LESS J0332-2756, by LABOCA/APEX
  - Coppin et al. 2009, MNRAS, 395, 1905
- z=4.54, COSMOSJ1000+0234 by AzTEC/JCMT
  - Capak et al. 2008, ApJ, 681, L53 for optical spec.
  - Schinnerer et al. 2008, ApJ, 689, L5 for CO spec.
- z=4.044, SMM J1635+6613@A2218 by SCUBA/JCMT
  - Knudsen et al. 2010, ApJ, 709, 210
- z=4.042, GOODS-N850.5, by SCUBA/JCMT



z=4.76 SMG: Optical (left) IRAC (middle) 24 um + 870um contour (right)

Too many high-z SMGs already !?



- Known number of the high-z (z>4) SMGs are already consistent to a L-CDM model prediction !?
- Number of high-z (z>4) SMGs can put tight constraint on models

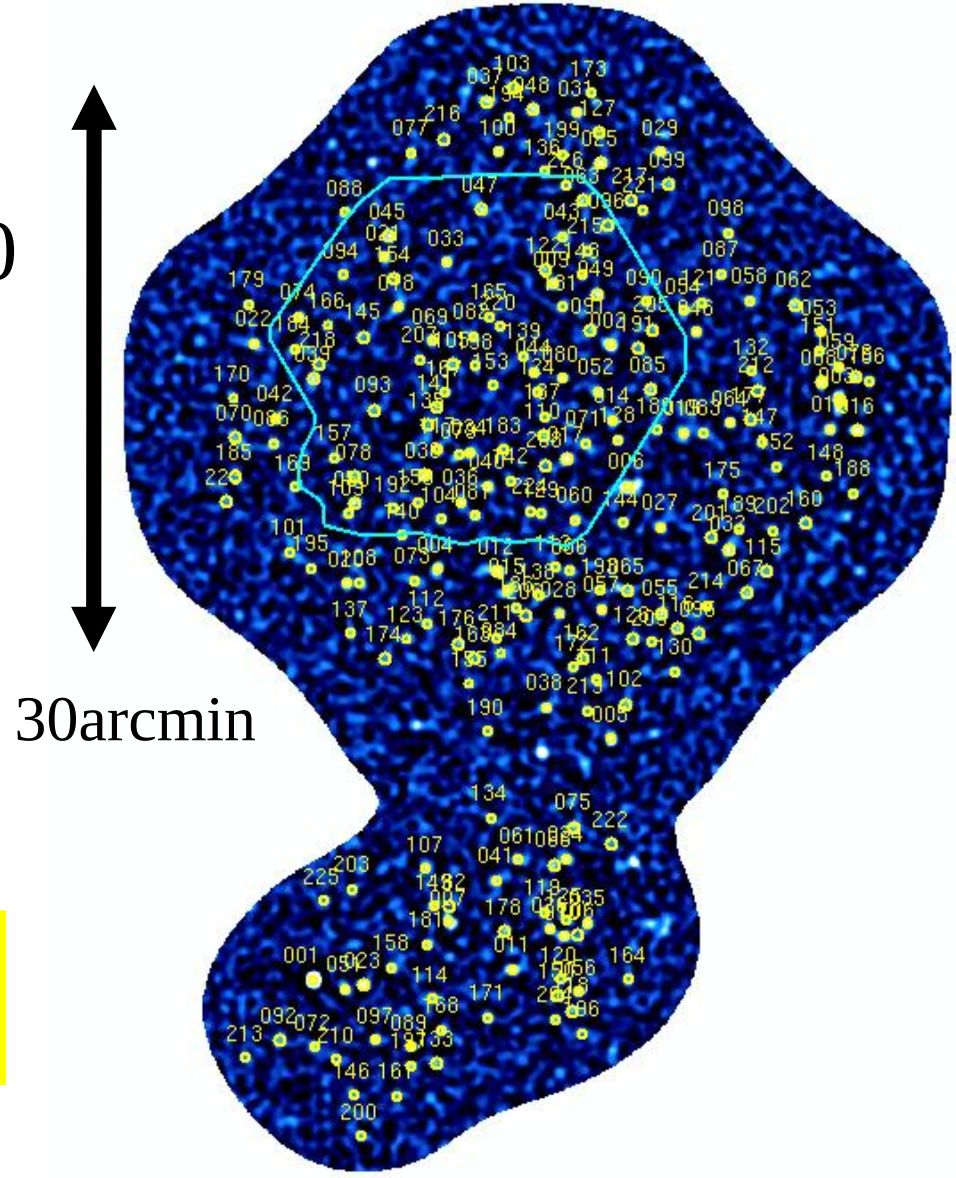
Coppin et al. 2009, MNRAS, 395, 1905

Further evidence for the presence of high-z SMGs

- Infrared faint SMGs
  - Reports on SMGs without K-band counterpart
  - ~1/4 of the AzTEC/ASTE SMGs in SXDF seems K-band faint, i.e., another high-z SMG candidates!
- Radio faint SMGs (see Younger et al. 2007)
  - 5 of 7 bright SMGs are radio faint (i.e., high z)
  - ~1/2 of the AzTEC/ASTE SMGs in SXDF have no radio counterpart (less than ~40 uJy)
- Flat 850/1100um spectrum SMGs
  - Higher-z ➔ flatter spectrum (small flux ratio)

AzTEC/ASTE 1.1 mm image of SXDF

- 0.4 ~ 1 mJy (1σ)
- Detected SMGs: ~230

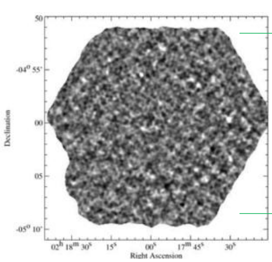


Ikarashi et al.
in prep.

Mm/Submm deep surveys of SXDF

Camera/Telescope	Area	Noise level (1 sigma, mJy)	Num. of Sources
SCUBA/JCMT	406 arcmin2	~2 mJy @850um	60 (S/N > 3.4)
AzTEC/JCMT	1330 arcmin2	1.0 – 1.7 mJy@1100um	28 (S/N > 3.7)
AzTEC/ASTE	~1000 arcmin2	0.5 – 1 mJy @1100um	226 (S/N > 3.5)

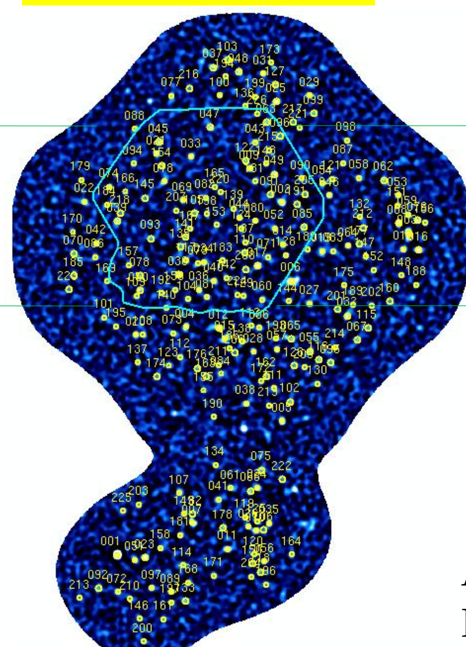
SCUBA/JCMT

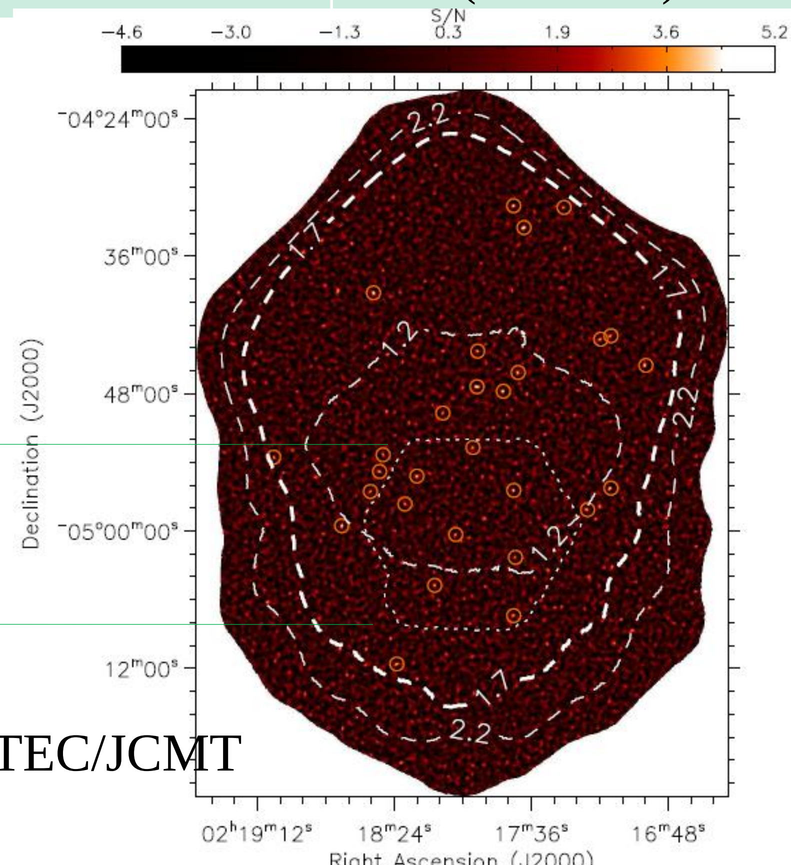


Coppin et al. 2006
MNRAS, 372, 1621

Ikarashi et al., 2010
in prep.

AzTEC/ASTE

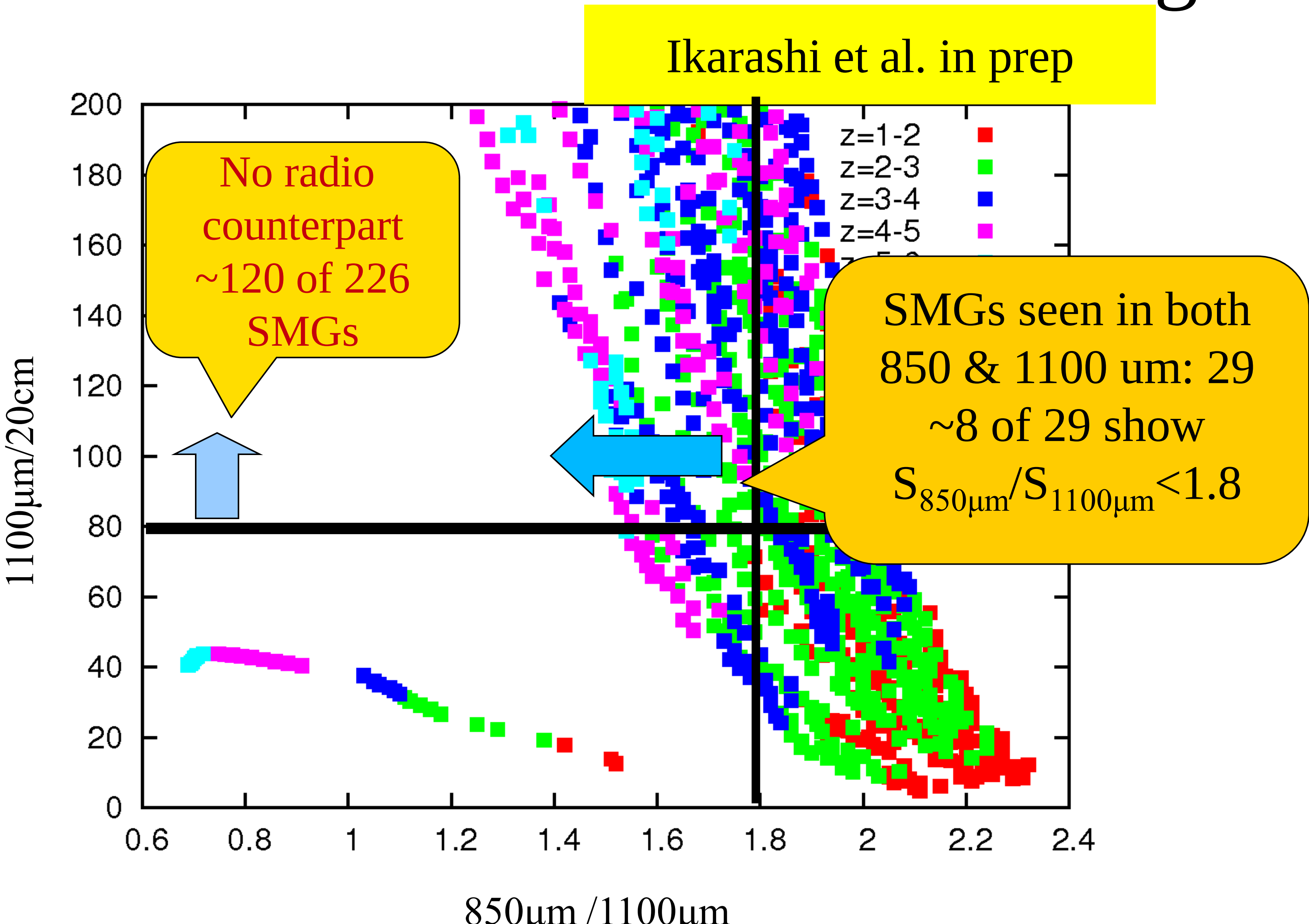




AzTEC/JCMT

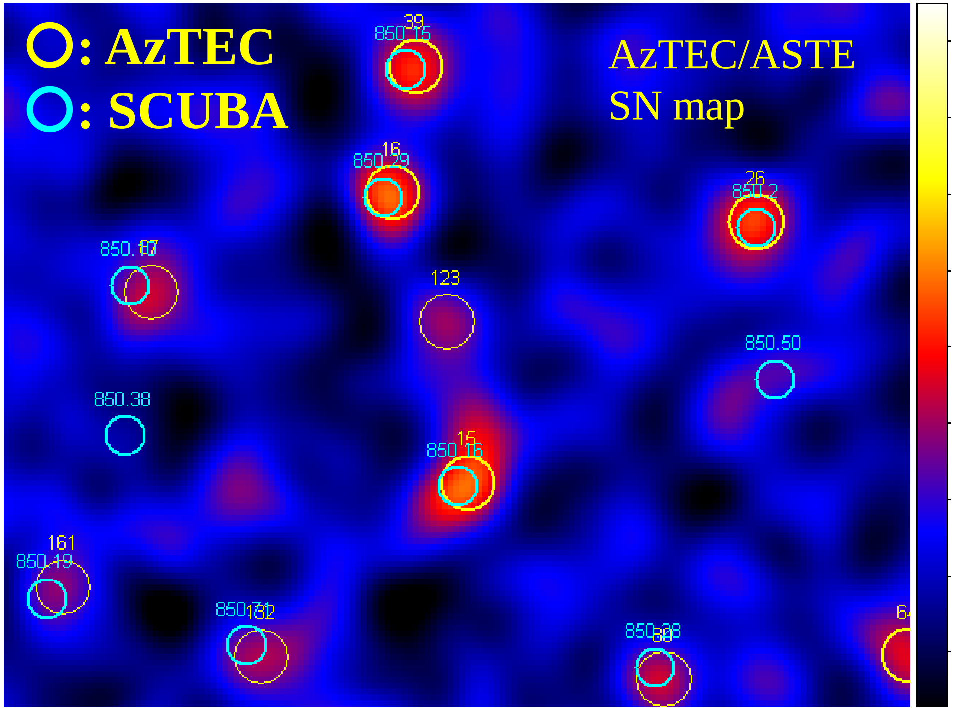
Austermann et al. 2009
MNRAS, 393, 1573

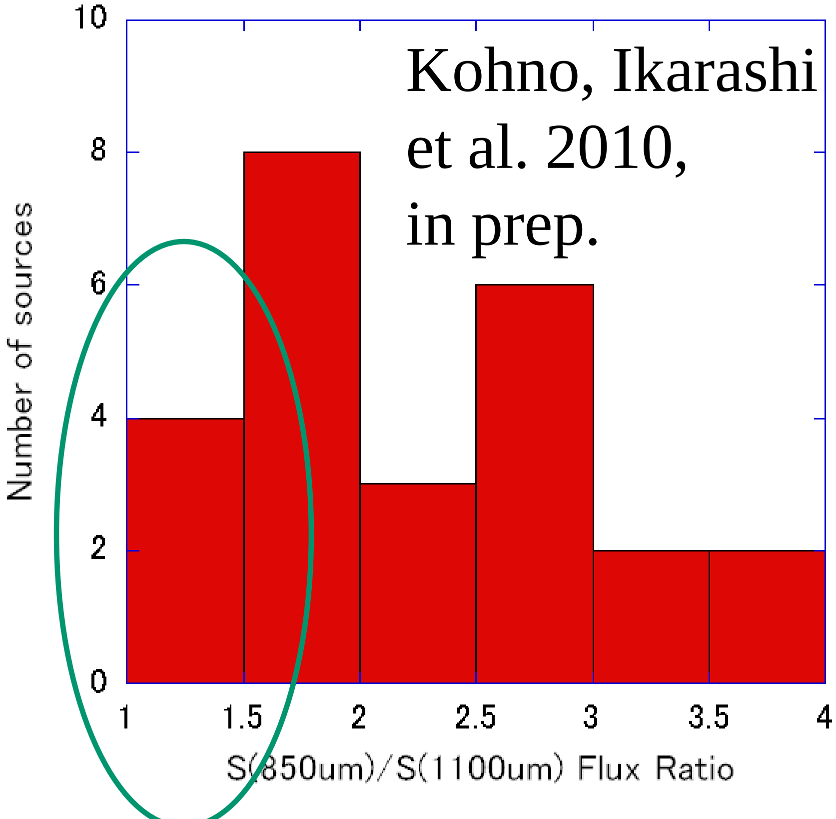
Radio/mm/submm color-color diag.



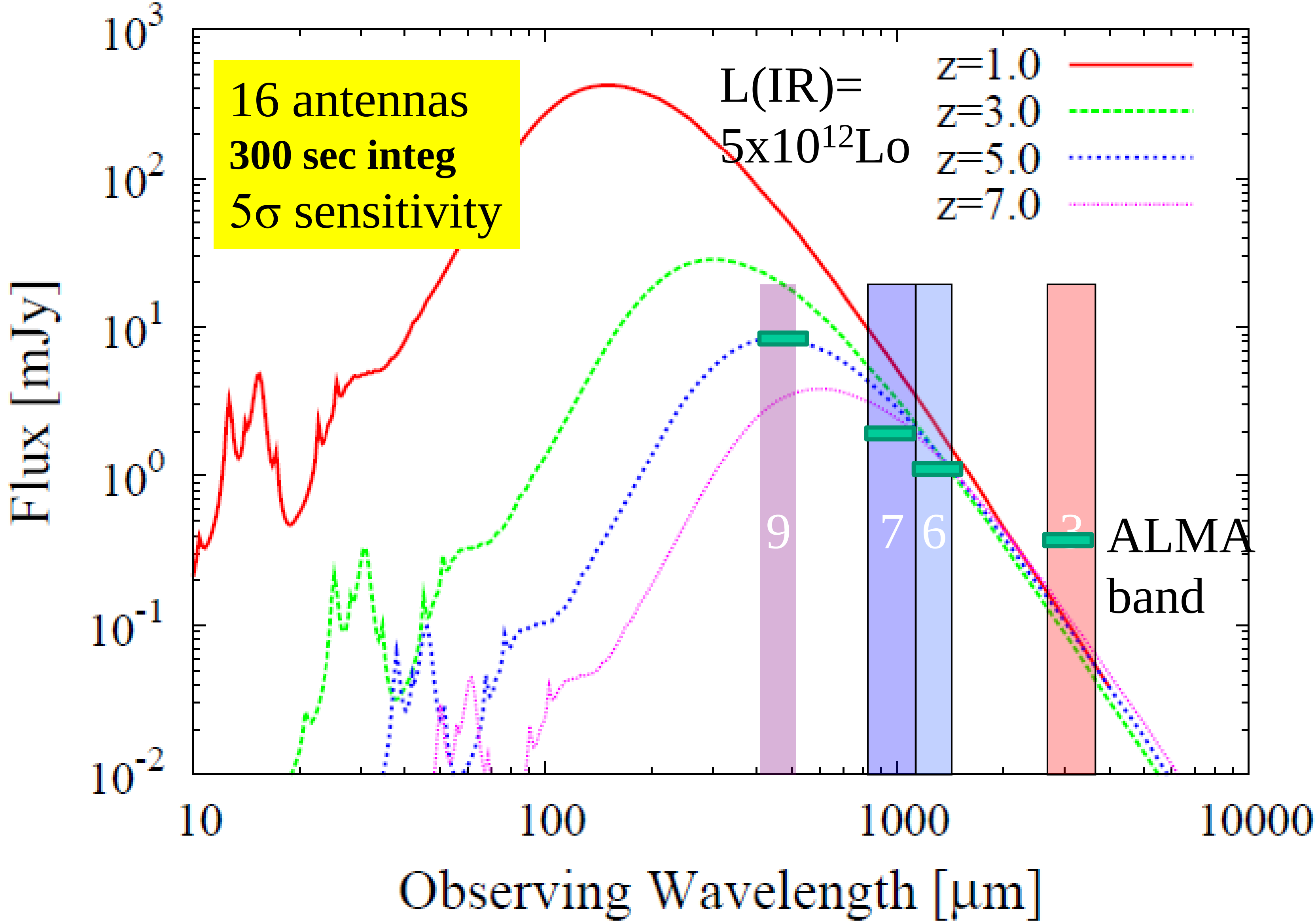
High-z SMG candidates in SXDF

- “Flat spectrum” SMGs: 850um/1100um flux ratio < 1.8 (i.e., flatter than a typical slope)
  - Combined analysis of SHADES and AzTEC-ASTE sources
  - ~20 % of the total SCUBA sources are “flat” (<1.8)
  - Many of them are 20cm faint





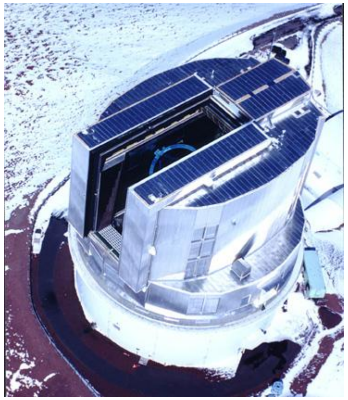
Submm photometry survey with Multi-color camera/ALMA-ES



Power source of SMGs: Mm/submm spectroscopy as a new power diagnostic for dusty IR galaxies

Bright SMGs in SSA22 by AzTEC/ASTE

SUBARU

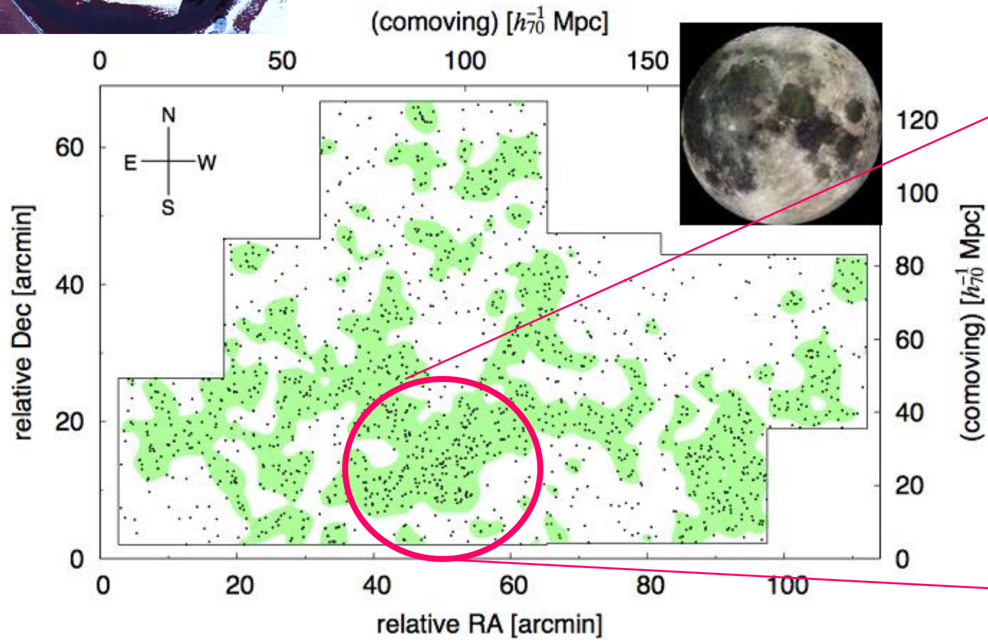


Lyman Alpha Emitters

LAEs

SFR ~ a few Mo/yr

Distribution of LAEs
Around z~3.1
Nakamura et al.

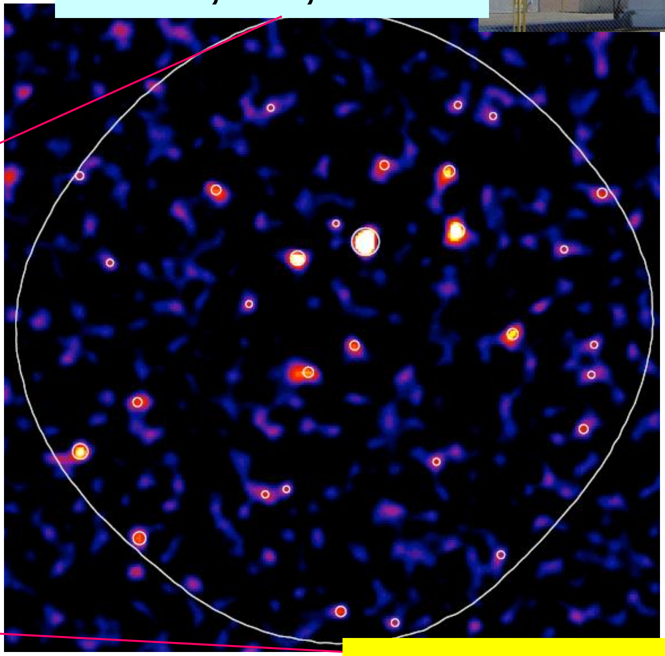


SMGs

SFR ~ a few 100
– a few 1000 Mo/yr

ASTE

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

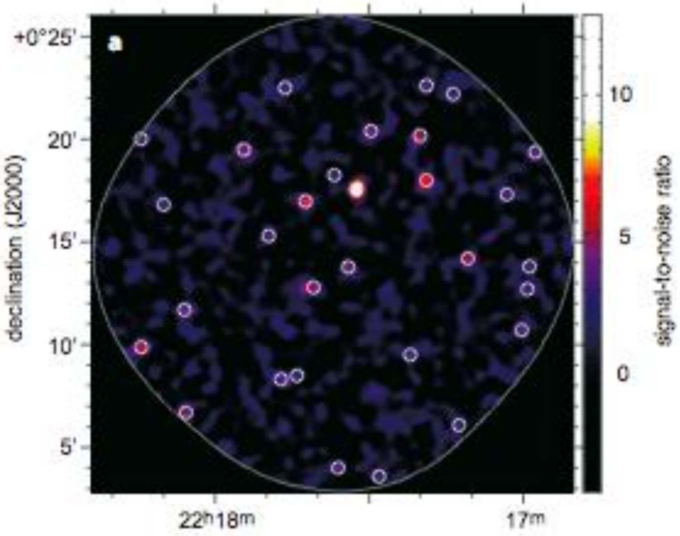


No one-by-one correspondence
to LAEs, but clustered at the LAE density peak

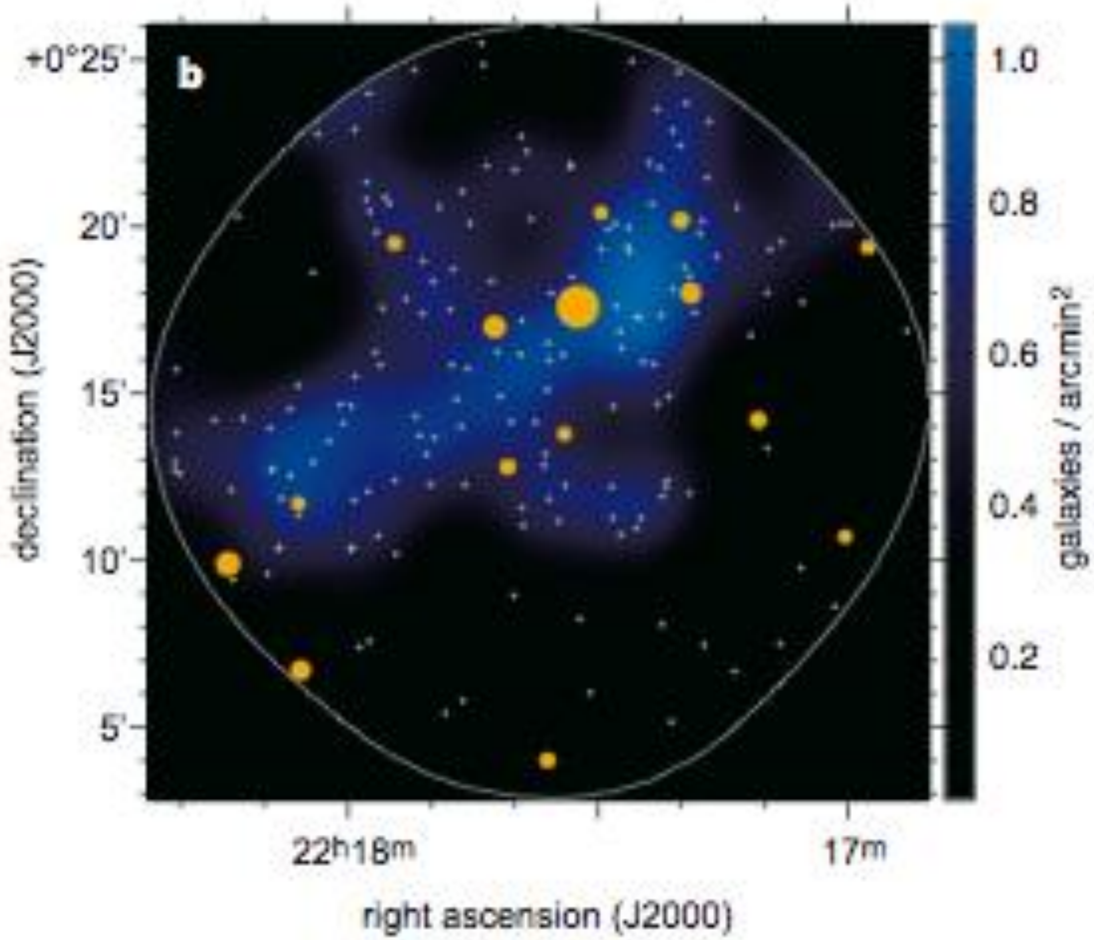
1.1 mm image
~390 $arcmin^2$

Clustering of SMGs toward the biased region traced by LAEs

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



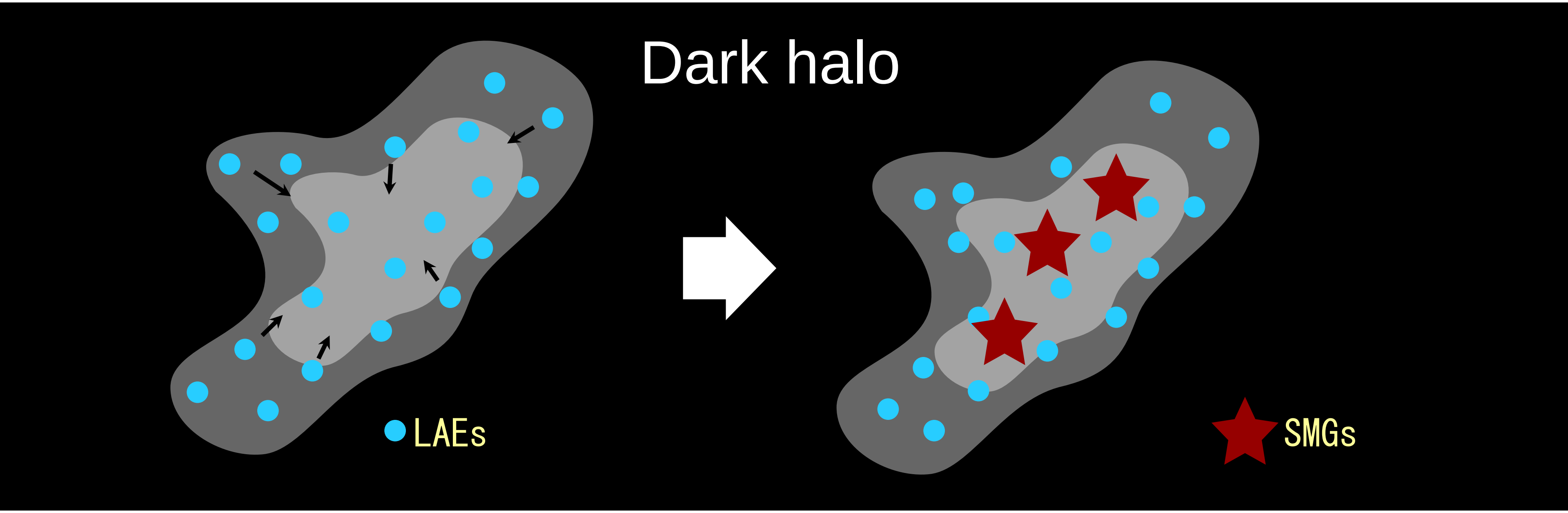
1.1mm image



Bright SMGs on Ly α emitters at z~3.1

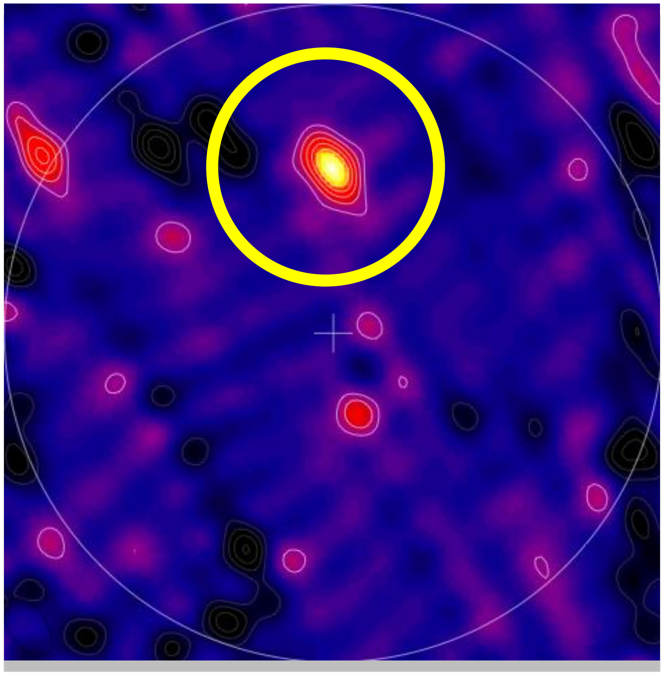
Tracing the heart of massive dark halo

- Structure formation w/ Λ cold dark matter model
  - young, less massive galaxies (LAEs) are falling into the heart of the massive dark halo
  - Massive starburst galaxies (SMGs) are grown there

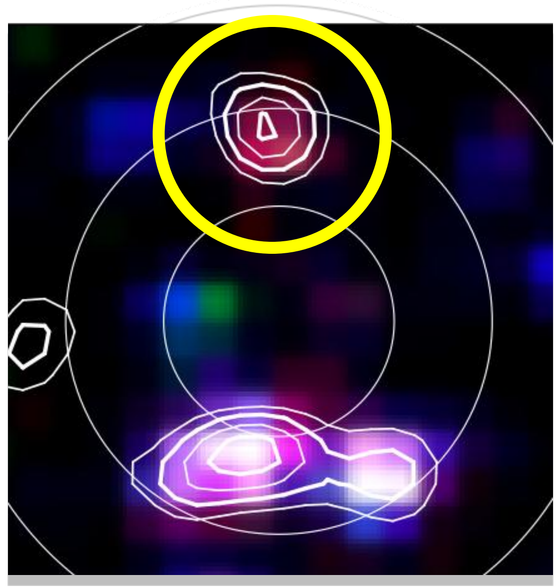


Multi-wavelengths ID of the brightest source in SSA 22

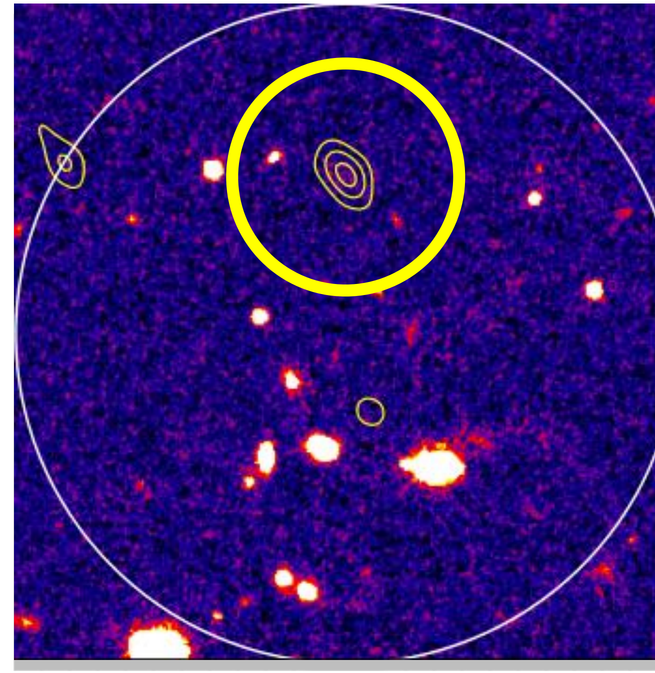
Ks > 24.9 mag(AB), 2σ upper limit



SMA 860 μm



Color :Spitzer/IRAC
Contour :VLA 20cm

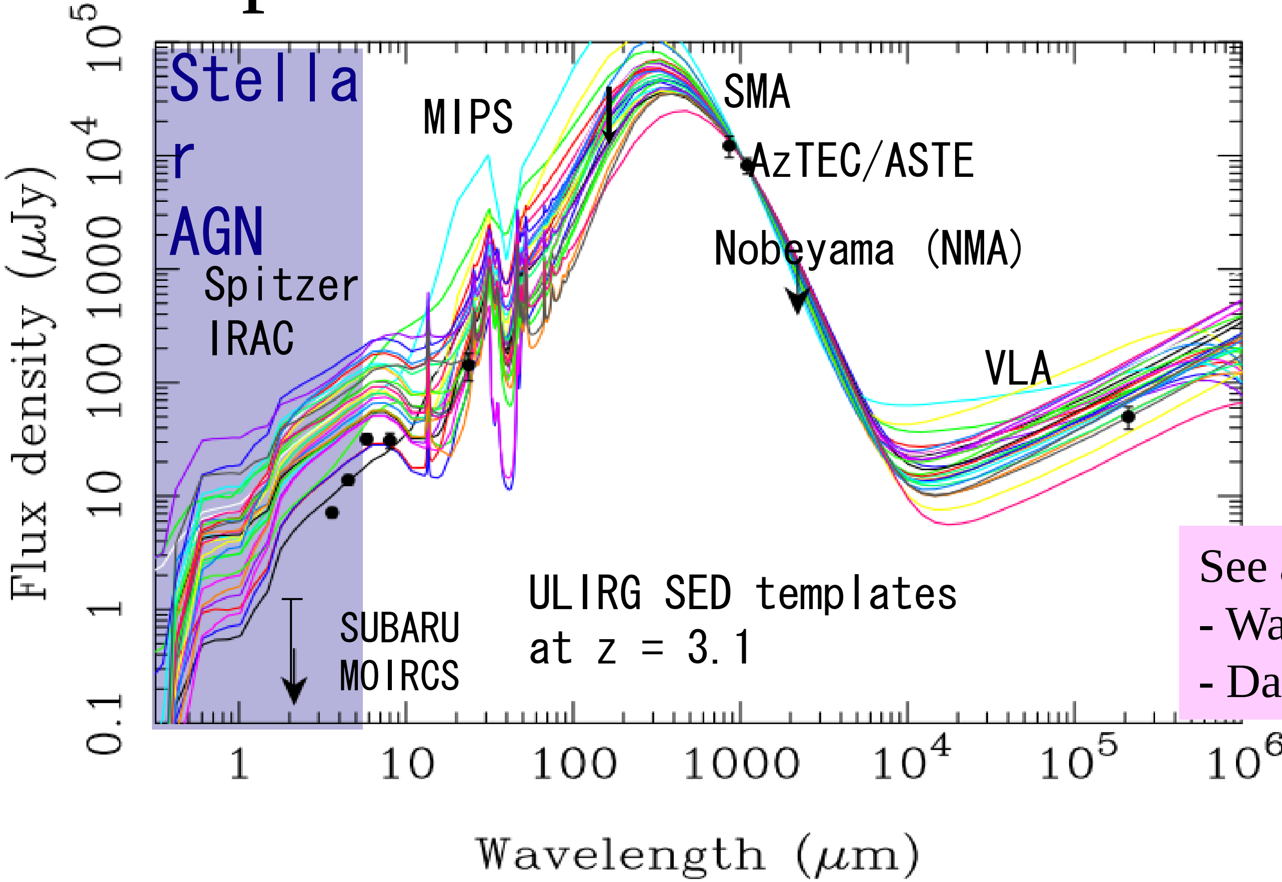


Color :Subaru/MOIRCS (Uchimoto et al., 2008)
Contour :SMA 860μm

- very “red” in MIR(IRAC) bands !
- K-drop out !?

Y. Tamura et al. 2010, submitted

K-drop SMG with elevated SFR >1000 Mo/yr



Y. Tamura et al. 2010 submitted to ApJ

See also: GOODS 850-5/GN10
- Wang+ 2009, ApJ, 690, 319
- Daddi+ 2009, ApJ, 695, L176

SFR~4000 Mo/yr

- SED at λ> 5μm is consistent with that at z=3.1
- Detection of a deeply obscured (N_H~10^{24}cm^{-2}) hard X-ray source ➔ proto-quasar phase? Growing SMBH?
- SED ➔ Mstar ~7x10^{10} Mo ➔ growing bulge?

Optical/infrared properties of SMGs

- Optically faint/often invisible
- Very red color in infrared (NIR/Spitzer MIR bands also)

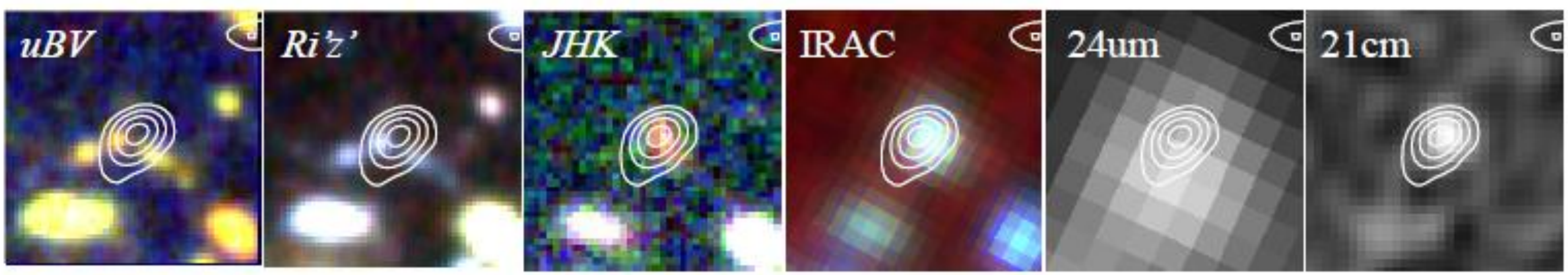
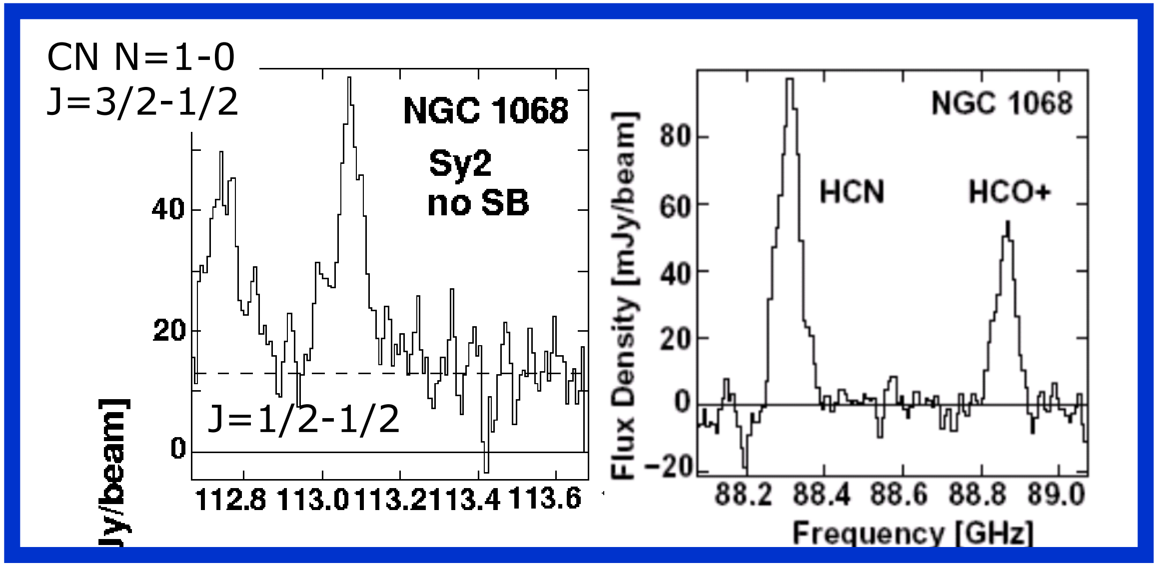
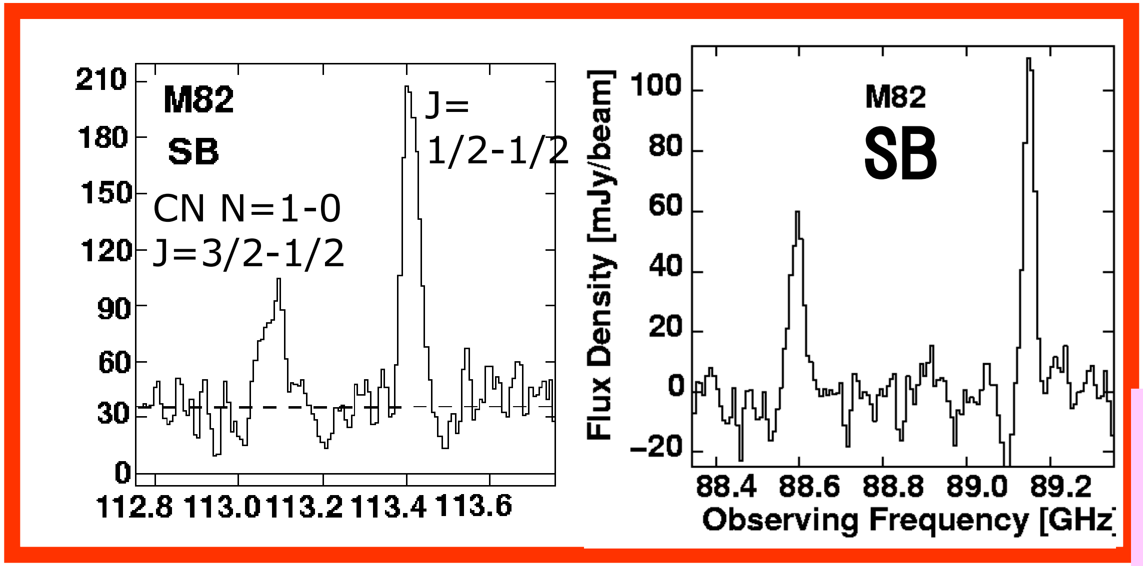


Fig. 2.— Multi-wavelength images of SXDF 850.6 with the SMA contours (2, 3, 4, and 5σ). The size of each image is $10'' \times 10''$ and north is up. From left to right: rgb image of MOSAIC II/u, SprimeCam/B, and V; rgb image of SprimeCam/R, i', and z'; rgb image of WFCAM/J, H, and K; rgb image of IRAC/ch1, 2, 3, and 4; MIPS 24 μm; VLA 21 cm.

SXDF 850.6, SMA contours on optical/infrared/radio images
Hatsukade et al. 2010, ApJ, 711, 974

Millimeter-wave molecular spectroscopy as a new diagnostic of nuclear energy source





AGN:

- **HCN/HCO^+ >2-3**
- $CN(J={}^3/_2-{}^1/_2)$ $/(J={}^1/_2-{}^1/_2)\sim1$？

➔XDR chemistry?

MIR pumping? Maser?

Starburst:

- **$HCN/HCO^+\sim1$**
- $CN(J={}^3/_2-{}^1/_2)$ $/(J={}^1/_2-{}^1/_2)\sim0.3$

➔PDR chemistry?

Nobeyama Millimeter Array

Kohno et al. 2001, 2005,

Kohno et al. 2008, ApSS, 313, 279

Summary (1)

- Project4, subproject 2: mm/submm studies of formation and evolution processes of massive galaxies ➔ cosmic star formation history, underlying DM, proto-quasar/super massive BH
  - Wide field mm/submm deep surveys ➔ uncovering new SMGs ⇔ multiwavelengths follow up [project 3]
  - Wide band mm/submm spectroscopy ➔ redshift, power source diagnostic ⇔ physical/chemical conditions of ISM [subproject1]

Summary (2): Recent results

- Unprecedentedly wide and deep 1.1 mm survey
  - Blnak fields including Subaru-XMM-Newton Deep Field, Subaru Deep Field, Akari Deep Field South, SSA 22, GOODS-S, COSMOS, etc.
  - Yielding ~1400 new detections of SMGs ➔ statistical studies are now feasible (e.g., clustering)
  - Long wavelengths survey ➔ likely to contain a lot of high-z (z>4) SMG candidates ! Efforts to make redshift search of them are on-going
  - Discovery of proto-quasar-like SMG at the bottom of the potential in SSA22
  - New diagnostic of power source in dusty galaxies