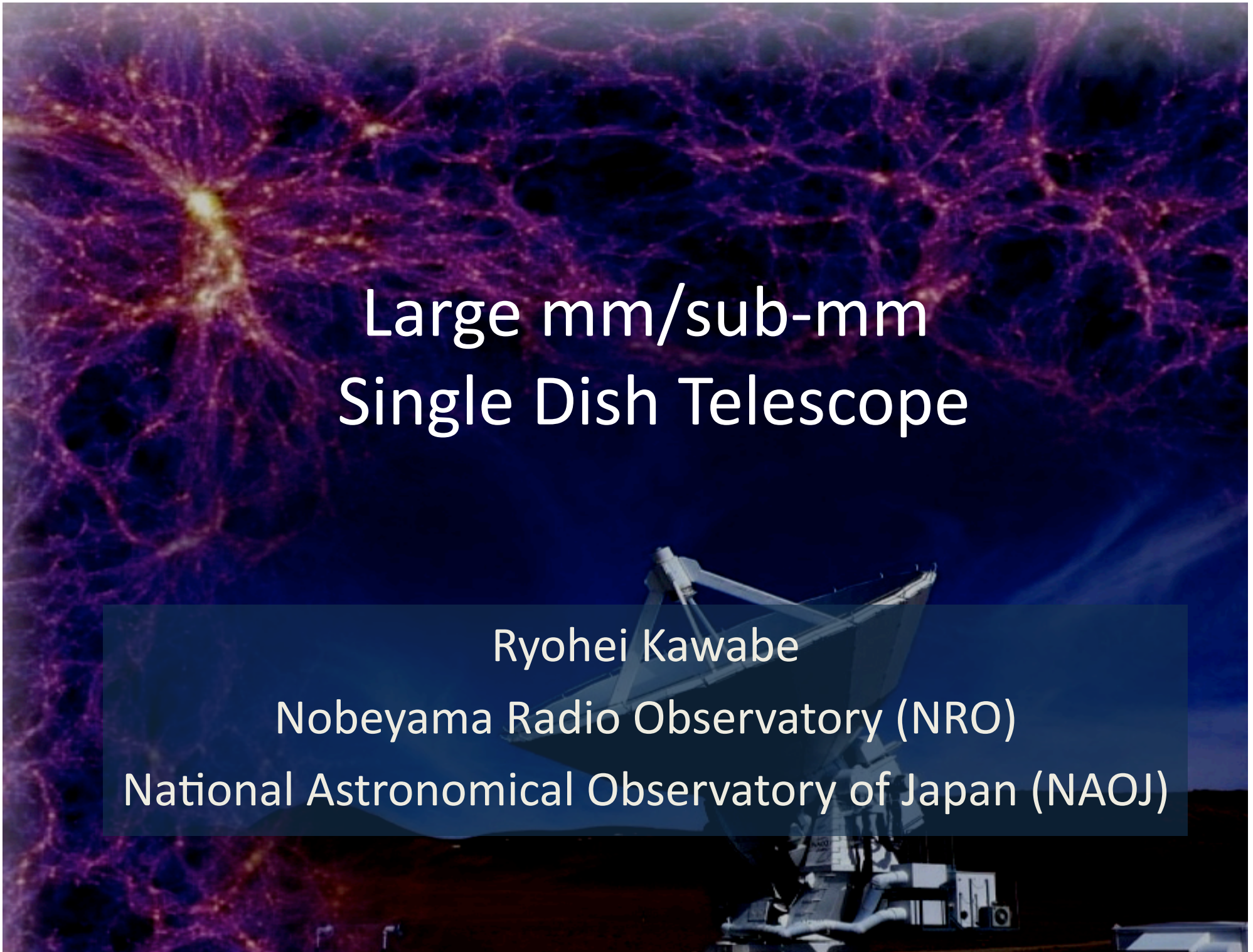


Large mm/sub-mm Single Dish Telescope

Ryohei Kawabe
Nobeyama Radio Observatory (NRO)
National Astronomical Observatory of Japan (NAOJ)

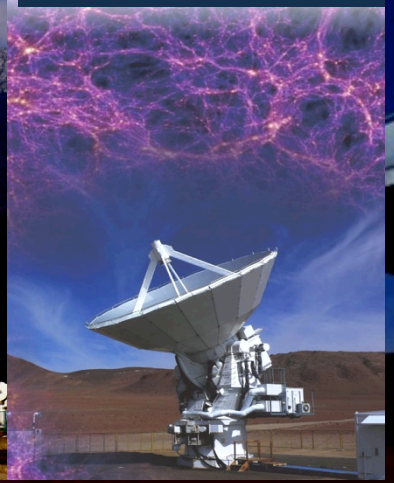
Roles of NRO in ALMA Era

- Enhancing Science with 45m/ASTE toward ALMA Era
- New Developments to create new seeds for the future
- Planning a Large mm/sub-mm Single dish for opening new discovery space in ALMA/SKA- era

NRO 45m Telescope

Natural Transition

ASTE 10 m
In Chie



D ~ 30-50 m
Freq. = 70 GHz – 1 THz?
Completion ~ 2018??

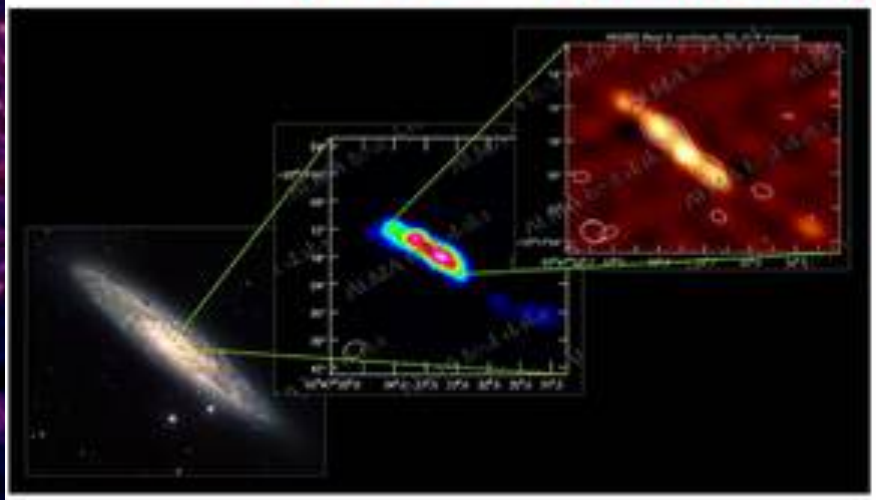
- Wide Field Imaging
- Census in the Universe
- Serendipity
- Incubate Original Ideas

K. Don and NOAO/AURA/NSF

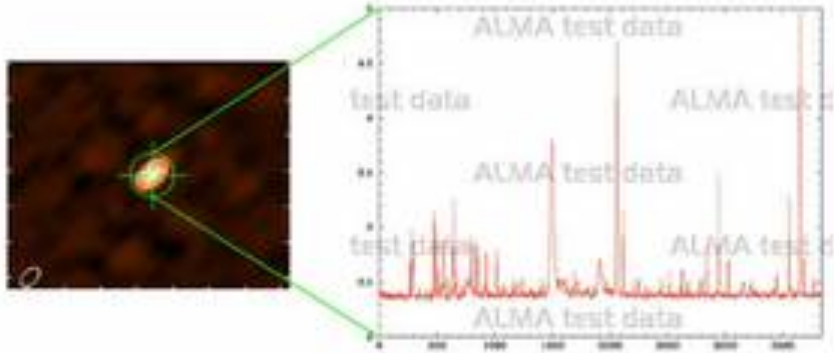
ALMA will come soon!

ALMA CSV Test Images

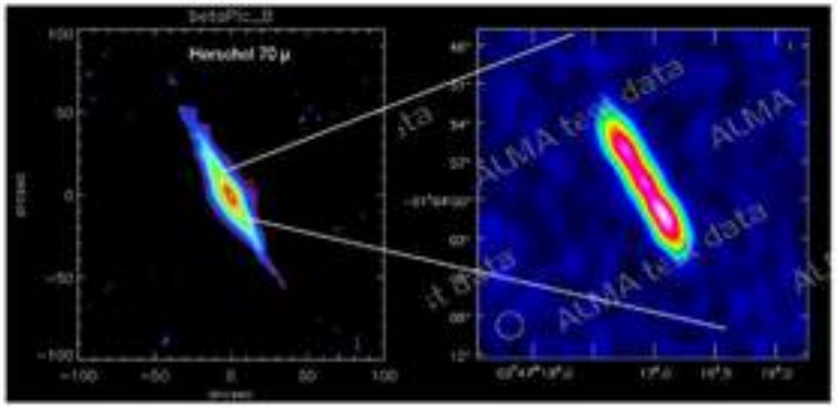
Credit: ALMA (E



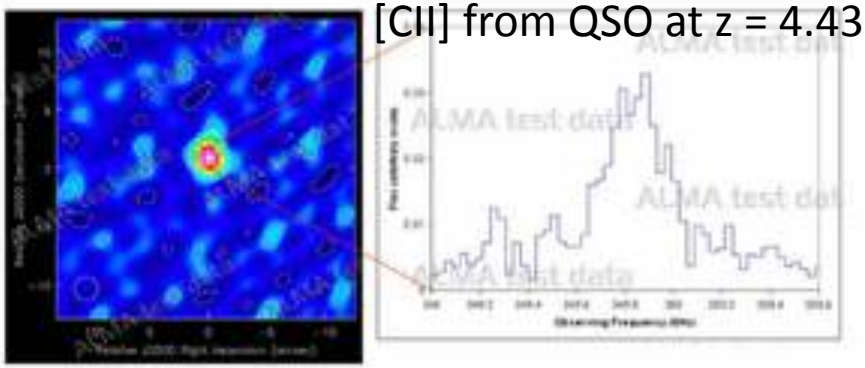
テスト画像１：渦巻銀河NGC253（左：可視光）（中央）230GHz のCO(2-1)輝線画像（右）690GHzの連続波画像とCO(6-5)輝線画像



テスト画像２：ホットコア分子雲G34.26+0.15の画像と周波数100GHz付近の分光スペクトル。多数の輝線が見える。



テスト画像３：がか座ベータ星の円盤。（左）天文衛星ハーシェルの70μm画像（Olofsson他）。（右）870μmのALMAテスト画像。



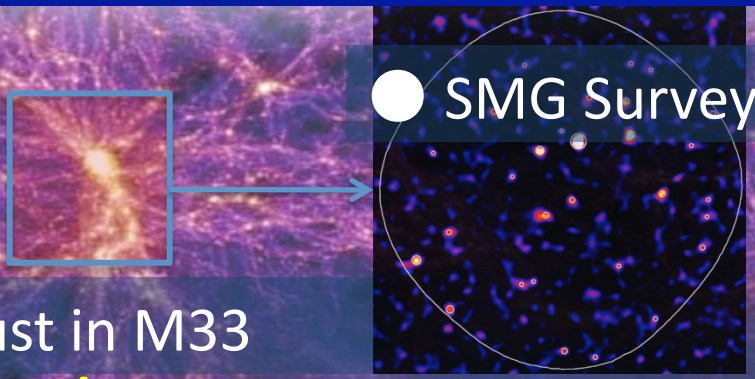
[CII] from QSO at z = 4.431

テスト画像４：赤方偏移z=4.431のクエーサーBRI 0952-0115の画像と158μm電離炭素輝線の分光スペクトル。

45m & ASTE Synergies create excellent SEEDs for ALMA Science

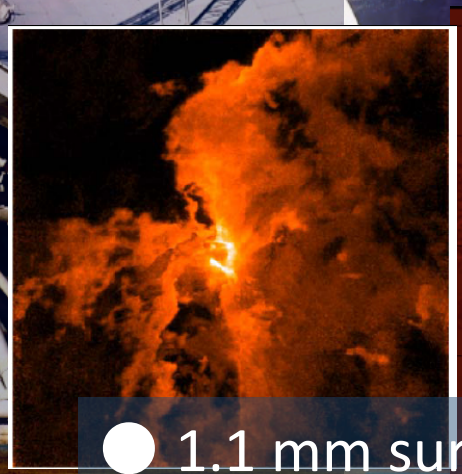
45m Legacy Programs

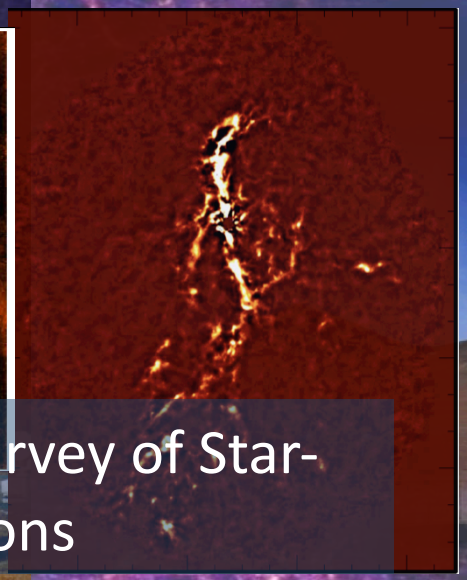
- Gas and Dust in M33



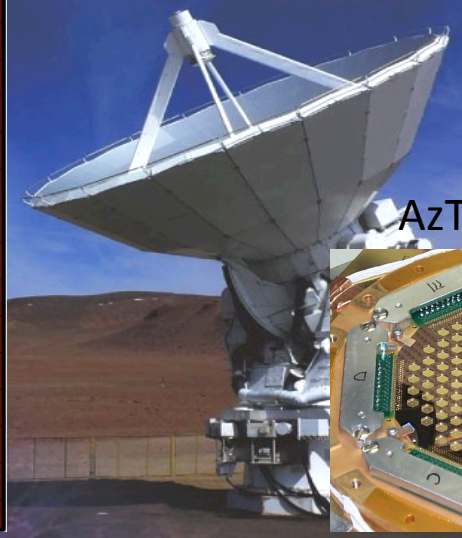
- SMG Survey

AzTEC/ASTE Key Science Programs

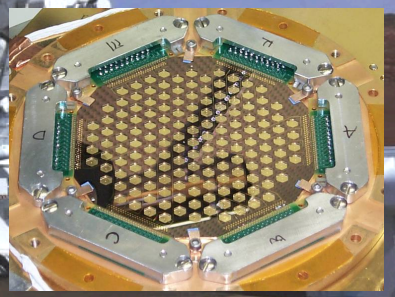




- 1.1 mm survey of Star-forming Regions



AzTEC 1.1m



45m & ASTE Synergies create excellent SEEDs for ALMA Science

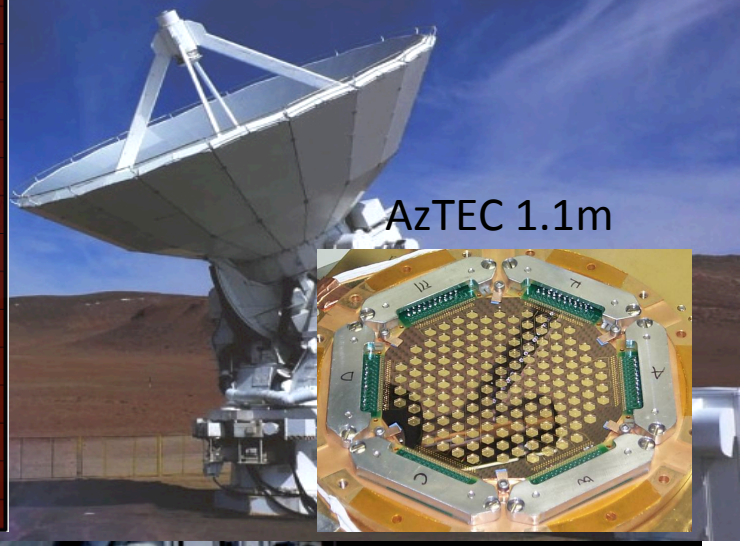
45m Legacy Programs

- SMG Survey
- Gas and Dust in M33

Wide Field Survey is a Key in the ALMA Era

AzTEC/ASTE Key Science Programs

- 1.1 mm survey of Star-forming Regions



AzTEC 1.1m

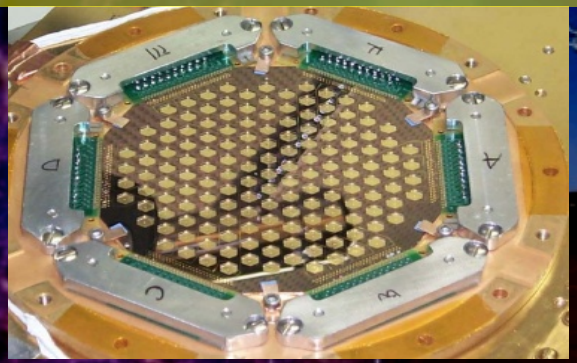
M51 CO(1-0)
NRO 45m (BEARS+OTF) + CARMA

Koda, Sawada + 2009

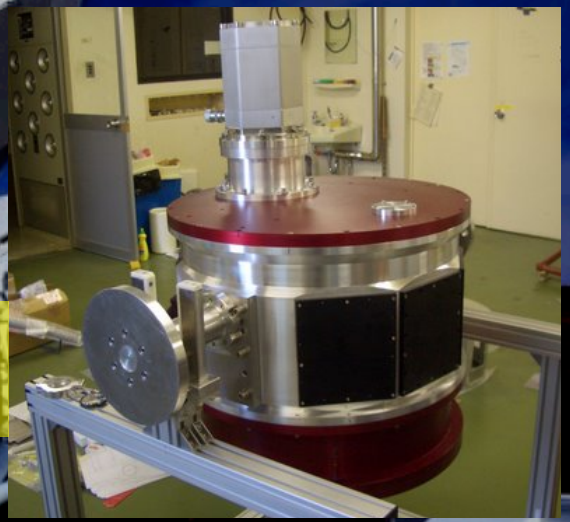
Outline

- Sub-millimeter Cosmology & “SMGs”
- SMG Survey with AzTEC/ASTE
- New Science with New Single Dish Telescope
- Synergies with other telescopes

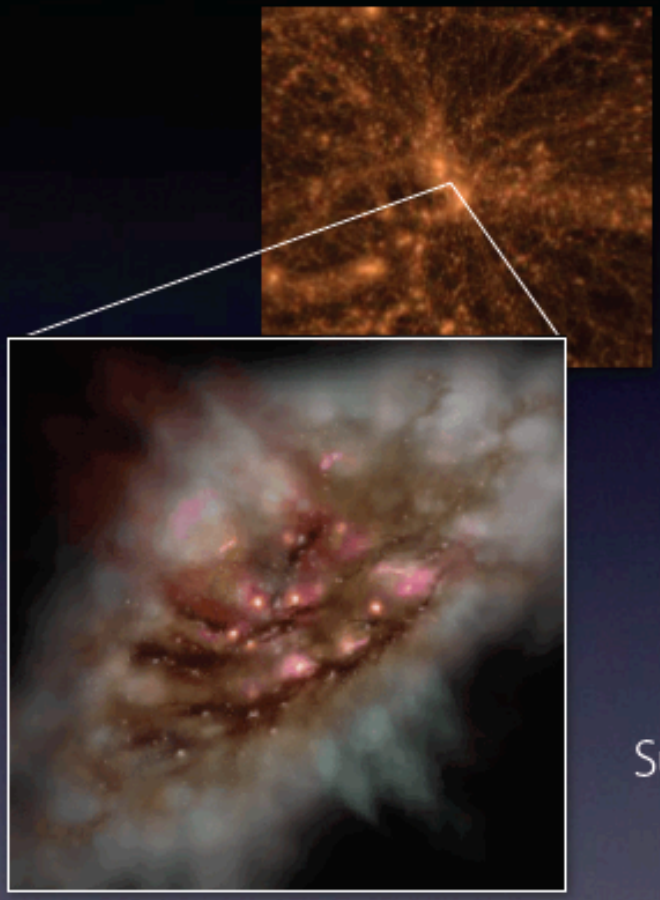
AzTEC 1.1 mm camera



New camera
TESCAM



Why are submm galaxies (SMGs) so important?



Cosmic Infrared Background

Cosmic star-formation history

Large-scale structure

Dark matter

Cosmology, Galaxy Formation

(large area of the sky)

Formation of

Giant ellipticals

"Galaxy Zoo"

Formation of

Super-massive black hole

Quasar

Galaxies and SMBHs

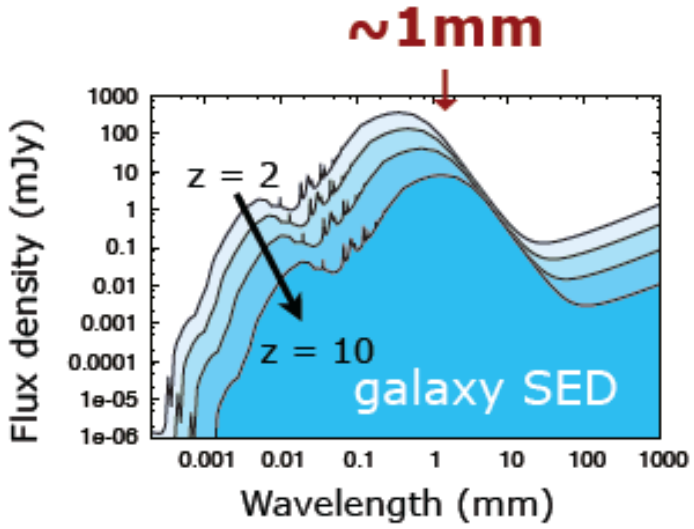
(large sample)

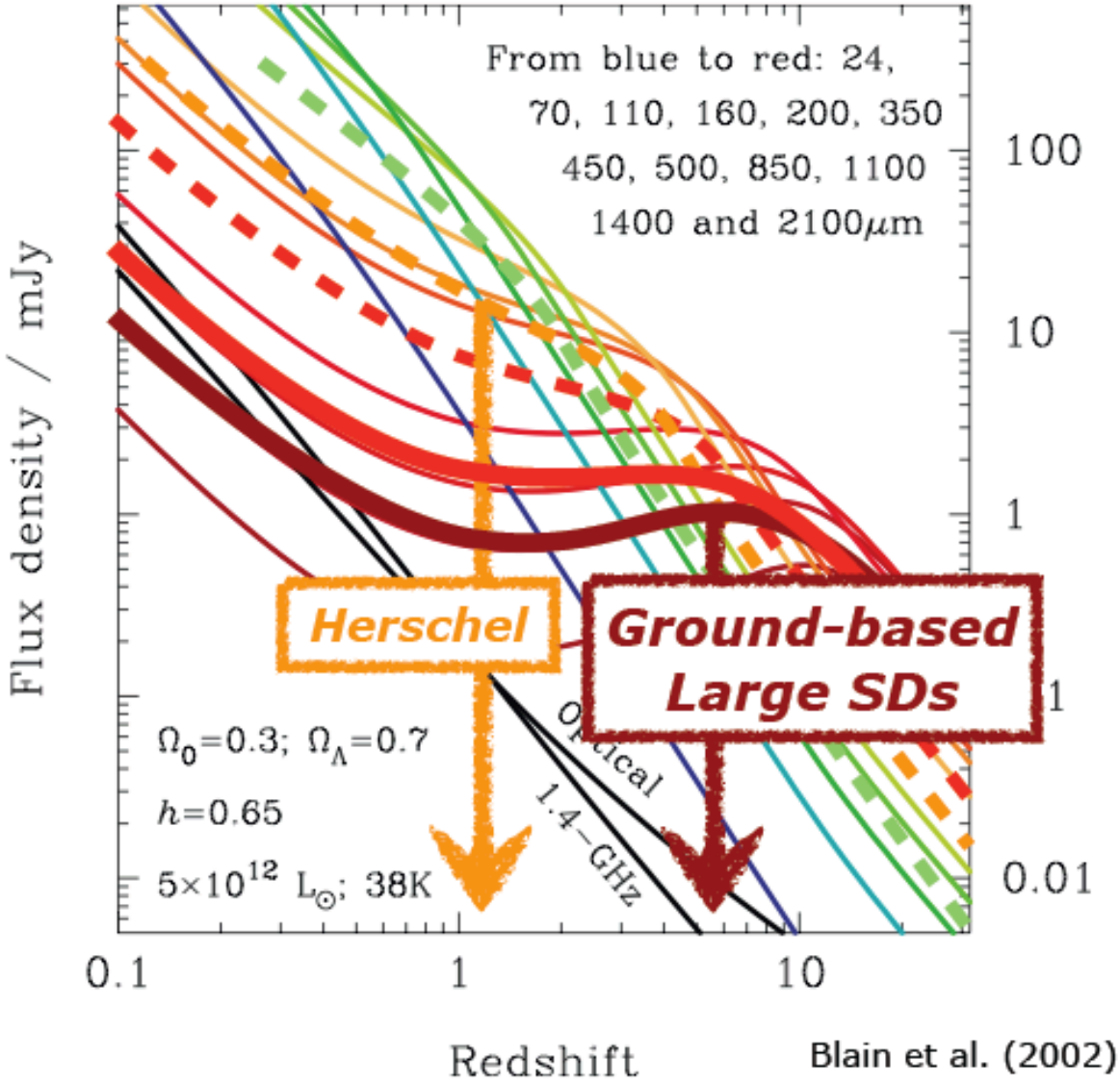
Submillimeter Cosmology

- ULIRGs found in local universe by IRAS
  - Starburst due to merging of disk gals; e.g., Arp220
  - 10^{12} L_{solar}; radiating its energy (>90%) at FIR (dust thermal emission), & SF Regions heavily obscured
- Submillimeter wavelength (~ 0.5 – 1 mm) has a very unique characteristic; negative-K correction allows us to reach such ULIRGs to z ≈ 10 ! (proposed by Blain & Longair, 1993)
- Submillimeter blank sky survey discovered high-z and very dark (in optical) massive starburst galaxies, i.e., Submillimeter Galaxies (SMGs) (e.g., Hughes et al., Nature, 1998)

Bright at (sub)millimeter
$L_{IR} \gtrsim 10^{12-13}\ L_{sun}$
SFR ≈ 100–1000 M_{sun}/yr
Massive
$M_{dyn} \approx 10^{11}\ M_{sun}$;
$M_{gas} \approx 10^{10-11}\ M_{sun}$

Ground-based large SD at 850- 1200 um



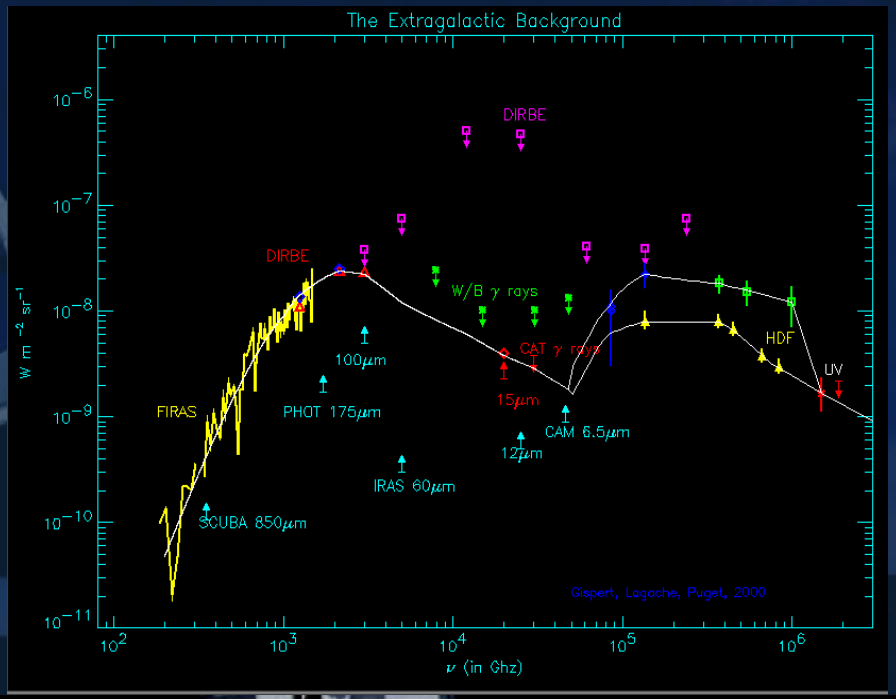


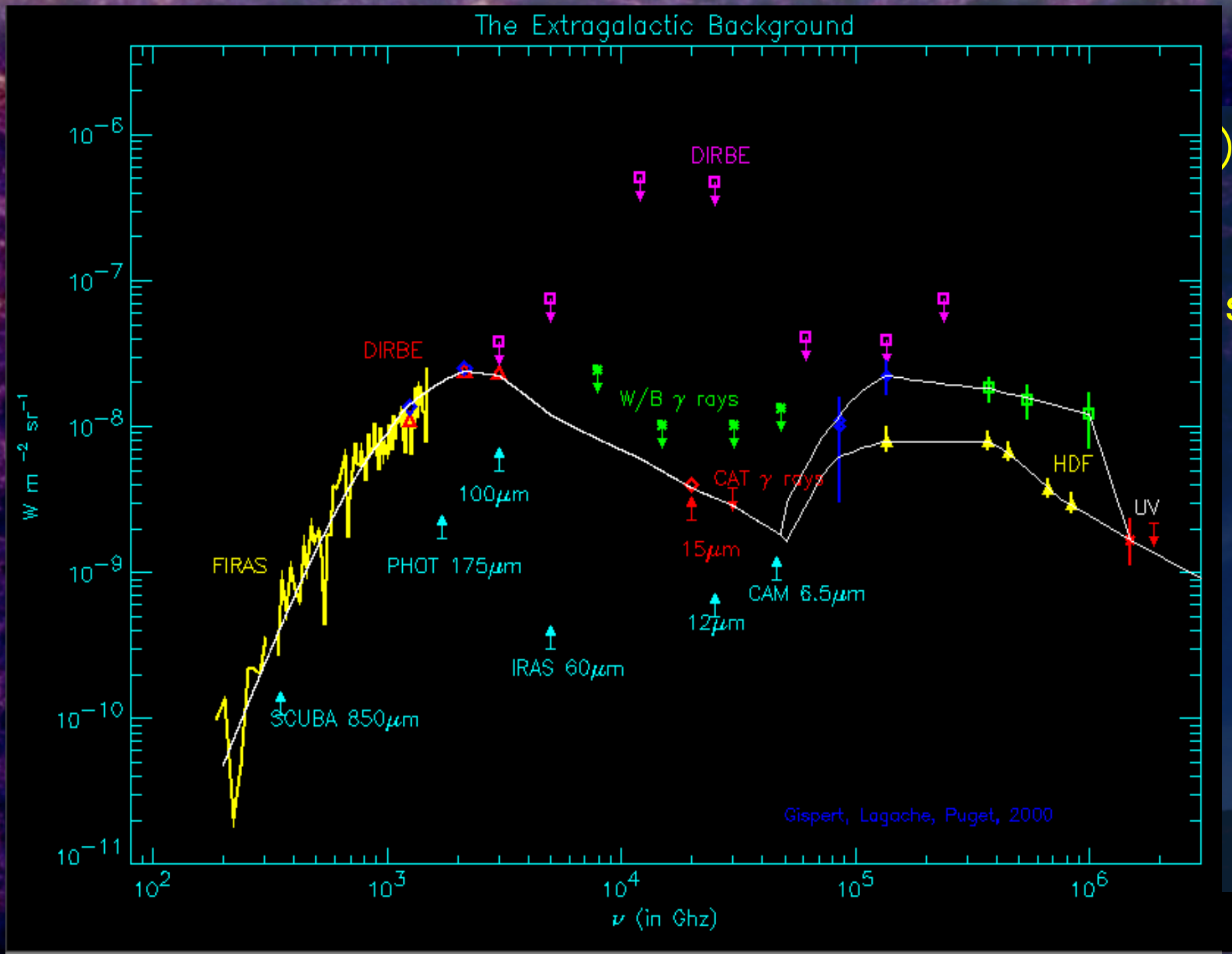
Blain et al. (2002)

SMG & Cosmic IR Background (CIRB)

- CIRB is extragalactic background (by dusty SF gals)
  - ＞90 % of Optical BG was resolved into gals
  - Only ~ 10 % of sub-mm BG was resolved to SMGs
- Key issues for the understanding of CIRB
  - What & where is the other 90 % of CIRB?
  - What is redshift distribution of CIRB sources?

  => related to cosmic SF

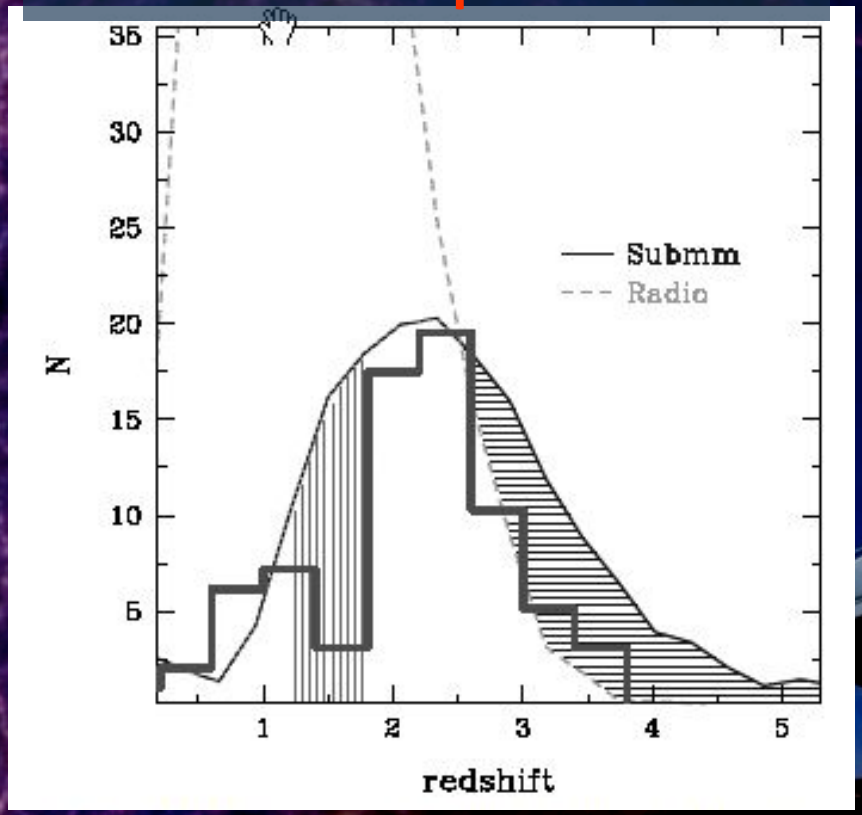



The Extragalactic Background
DIRBE
DIRBE
W/B γ rays
CAT γ rays
HDF
UV
100μm
15μm
12μm
CAM 6.5μm
PHOT 175μm
IRAS 60μm
SCUBA 850μm
FIRAS
W m⁻² sr⁻¹
ν (in Ghz)
Gispert, Lagache, Puget, 2000

SMG and Cosmic Star Formation History

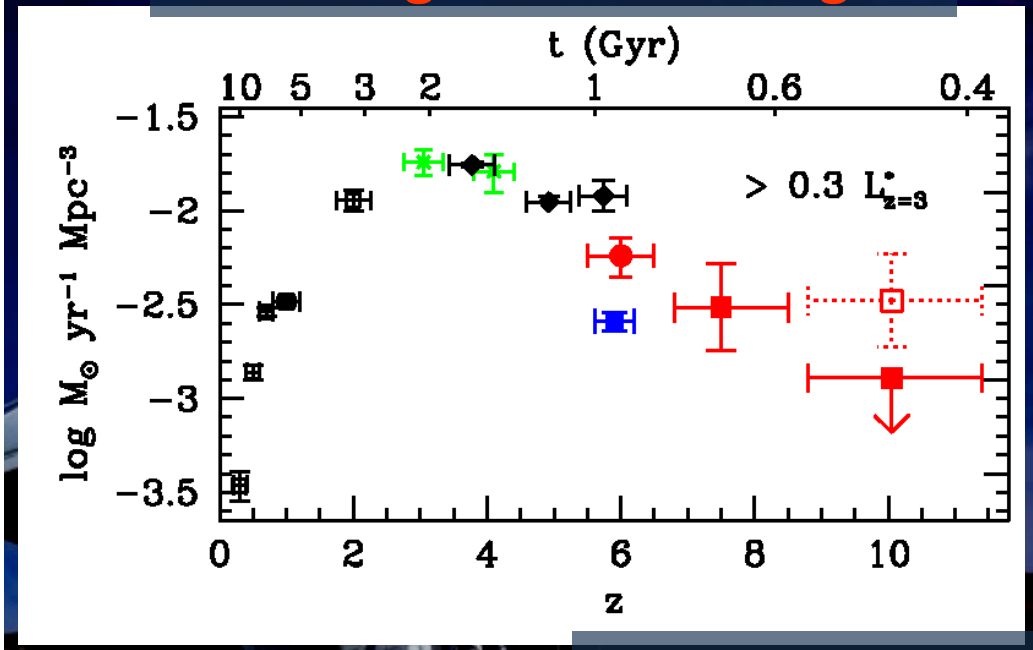
SMG is a Key to unveil hidden Star Formation (SF) & Cosmic SF History

SCUBA sources peak at z~2.4



Chapman et al. (2005)

Cosmic SFR peaks at z~3 ? ; hidden SF is expected to be large fraction at high-z



Bouwens et al. (2005)

(T_{univ} = 2~3 Gyr)

Large Scale Structure & SMG Clustering

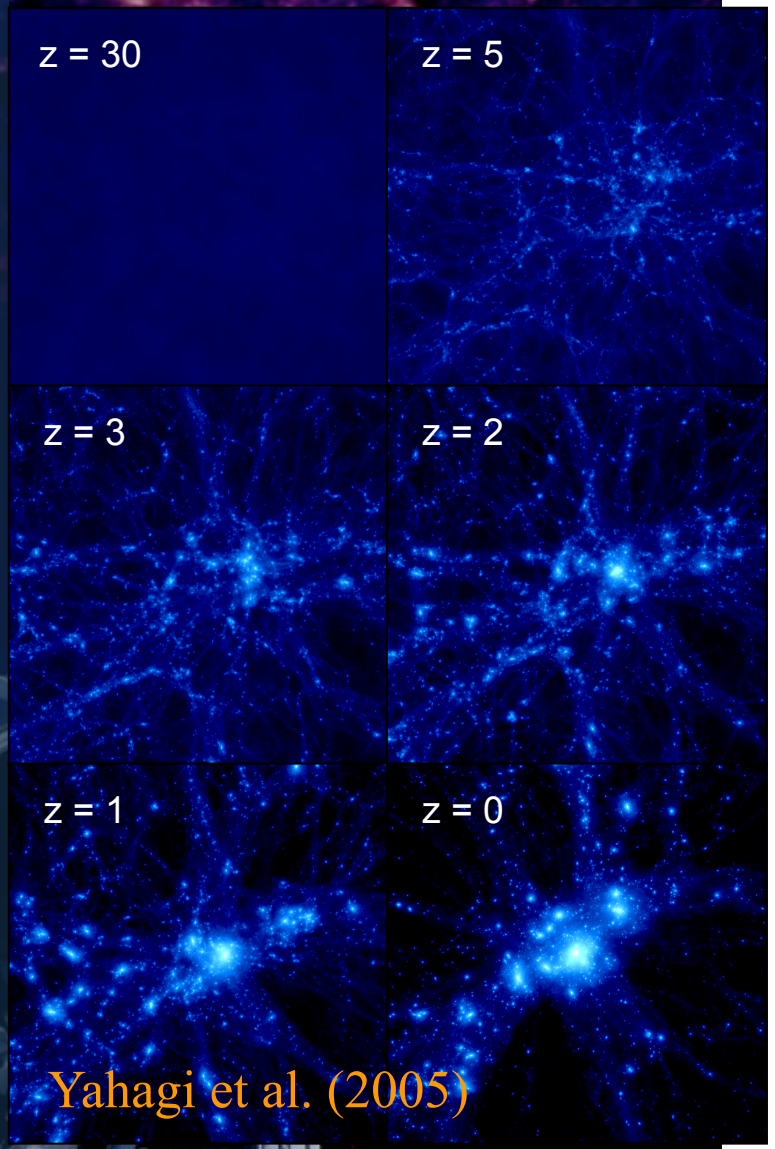
- SMG is a massive starburst galaxy at high-z & will be associated with massive Dark Matter halo

  => **Clustering of SMGs**

  => **tracing LSS invisible in opt/IR**

- Dark Matter Halo firstly formed
- DM Halos evolve to form **LSS** through "Hierarchical" Structure formation
- Baryonic matter collapses into DM Halo to form galaxies; evolving to massive by merging

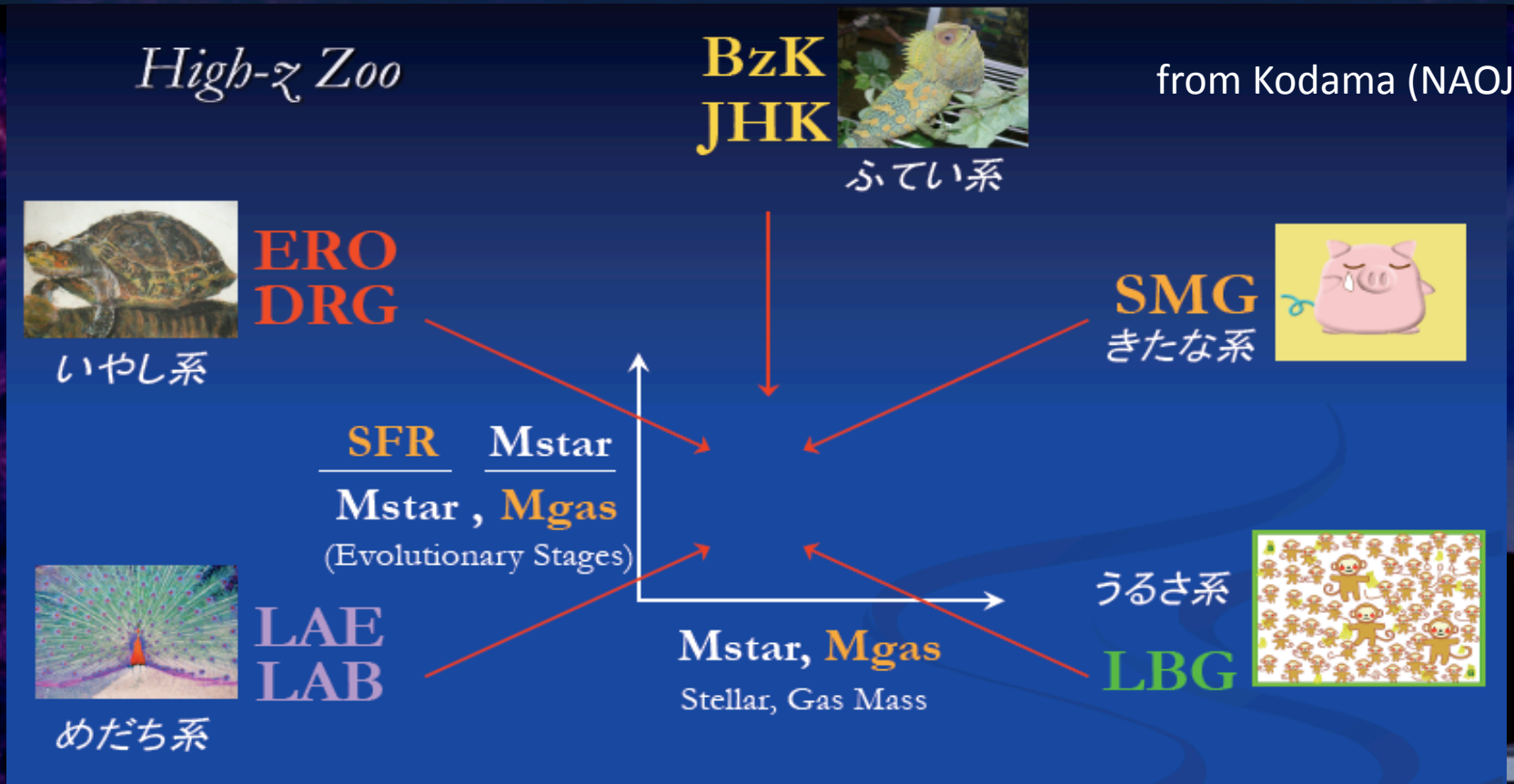
N-body simulation (Dark matter)



Yahagi et al. (2005)

Relations among high-z pops from "Zoo" Toward "Science Museum"

- Need to compare the high-z galaxies
  - through Spatial correlation
  - with the same measures; e.g., SSFR vs Mass



~ From "zoo" to "science museum" ~

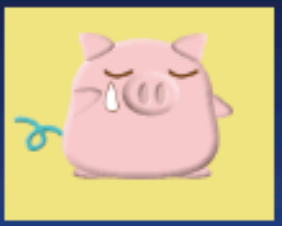
from Kodama (NAOJ)

Toward Unified View of
Galaxy Formation and Evolution

LAE
LAB

めだち系

SMG



きたな系

young

old

LAE

SMG

LBG

DRG

BzK

ERO

BLG (bulge)

Path ①
"bottom-up"

Path ②
"instantaneous"

small

Mstar

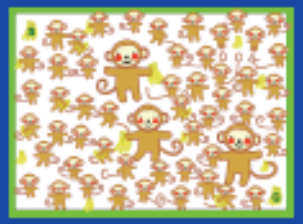
large

$$SSFR = \frac{SFR}{Mstar}$$

BzK
JHK

ふてい系

うるさ系



LBG

いやし系

ERO
DRG

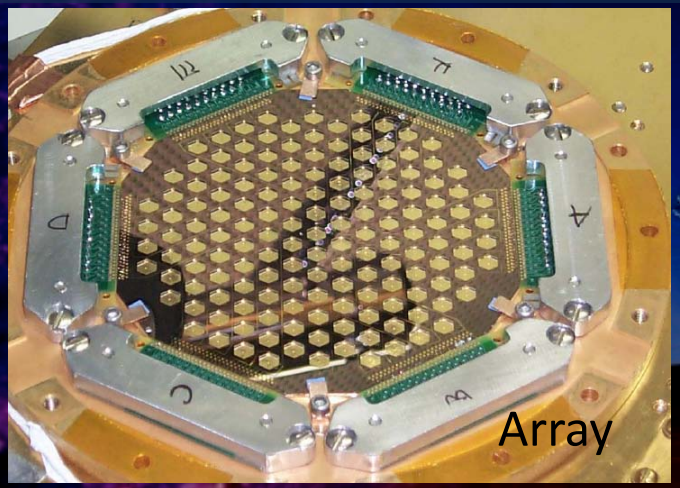
AzTEC on ASTE SMG Survey

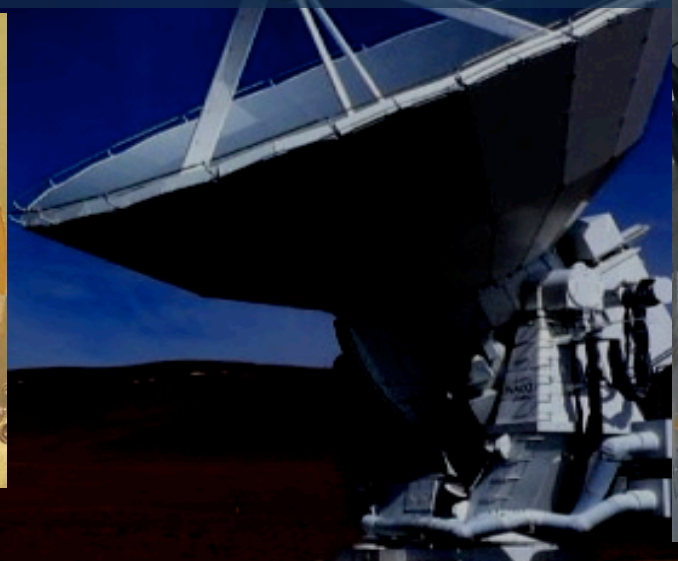
ASTE(Atacama Submm Telescope Experiment)

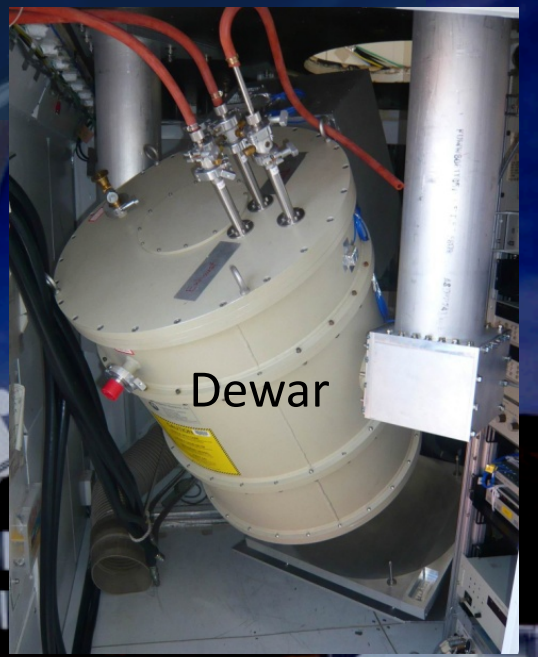
- 10 m submm telescope
- alt. 4860m, Atacama desert, Chile
- 350 GHz (0.87 mm) spectroscopy: CATS345+MAC/WHSF
  - beam = 22”, single pix
  - low Tsys & OTF
- 270 GHz (1.1 mm) continuum: AzTEC camera
  - 144 pix
  - FOV ~8 arcmin, beam = 28”

AzTEC on ASTE SMG Survey
AzTEC

- 144 pix Si_3N_4 micromesh "spider-web" bolometers
- PI: G. Wilson (UMASS); Developed for LMT 50m
- Wavelengths: 1.1 mm
- Spatial resolution: 28 arcsec @ ASTE
- Mapping speed: 10-30 $arcmin^2\ hr^{-1}\ Jy^{-2}$
- Successful operation on JCMT (late 2005)


Array




Dewar

AzTEC on ASTE SMG Survey Overview

- One of Key Science Projects with AzTEC
- Deep & Wide SMG Surveys in 2007 – 2008
  - spent > 80 % of AzTEC/ASTE time
  - reached to mostly confusion noise (0.5 mJy)
  - wide fields as much as possible to minimize cosmic variance
- 10-20 time higher mapping speed than SCUBA
  ; 10-30 arcmin^2 hr^{-1} Jy^{-2}
  - AzTEC has high sensitivity and stability + good pipeline
  - Excellent Atm. Condition; τ (220 GHz) down to 0.02
- Detected > several x 100 sources with surveys of > 1 deg2 in total

Blank Field Surveys

- Survey Area
  - 160 arcmin^2 to 1 deg^2
  - 2 deg^2 in total
  - wider than SHADES
- Depth
  - 0.5 to 1.0 mJy
  - corresponding to
    1-2 mJy at 0.85 mm
  - deeper than SHADES

AzTEC/ASTE

GOODS-S

SDF

SSA22
¼ deg^2
0.7- 1 mJy

SXDF
¼ deg^2
0.5-0.7 mJy

ADF-S
¼ deg^2
0.5-0.7 mJy

COSOS
1 deg^2
σ < 1 mJy

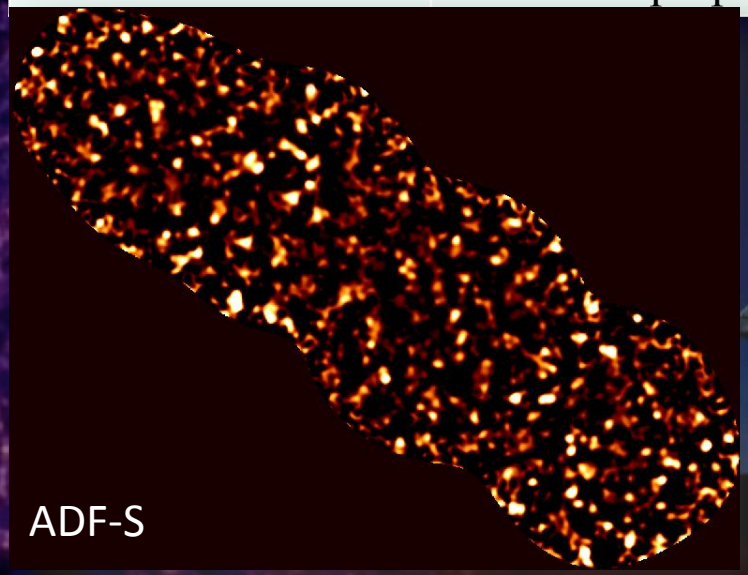
SXDF

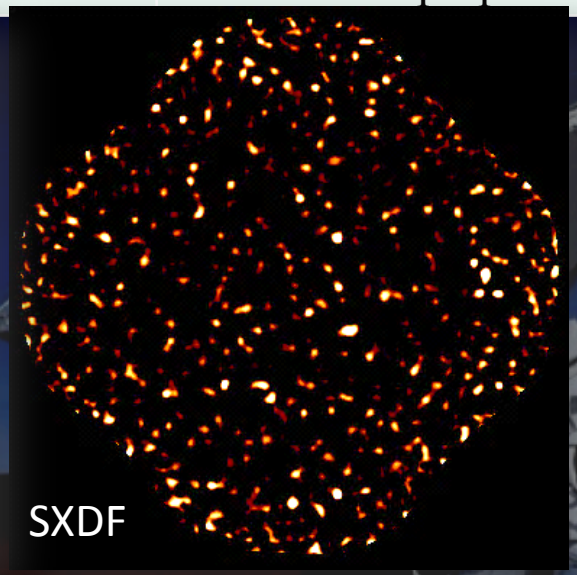
HDF

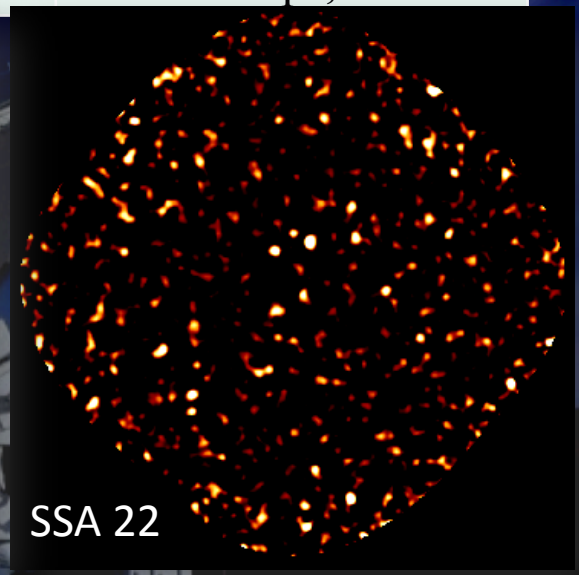
SCUBA/SHADES
σ(850) = 2 mJy

AzTEC/ASTE Deep Wide-field SMG Surveys

	AKARI Deep Field South (ADF-S)	Subaru/XMM-Newton Deep Field (SXDF)	SSA22
Coverage (arcmin^2)	**909**	**956**	**992**
Depth (1σ, mJy)	0.43-0.78	0.46-0.87	0.62-1.2
No sources (>3.5σ)	**198**	**206**	**127**
reference	Hatsukade+11a,11 b MNRAS In prep	Ikarashi+10 MNRAS, + 11 in prep.	Tamura+ 09, 10 Nature, 459, 61 ApJ,







AND More ….; ~ 40 Mass-Biased Fields

2.5<z HzRG proto-cluster

1.5<z<2.5 HzRG

0.5<z<1.5 HzRG

0.5<z<1.5 clusters

z<0.5 clusters

Wilson, Hughes, Yun et al.
Ezawa, Oshima et al.

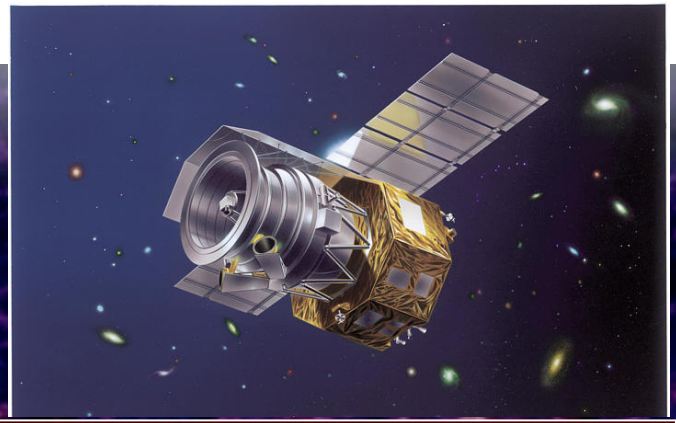
TNJ 1338-1942	TNJ 2007-1316	TNJ 2009-3040	SSA22
MRC 2104-242	MRC 0355-037	PKS 0529-549	
MRC 2201-555	MRC 2008-068	MRC 2322-052	
XMMJ 2215.9-1738	MACS-J 2129.4-0741	XLSSJ 0224-0325	SXDF UKIDSS cluster
RXCJ 0516.6-5430	Bullet Cluster	RXJ 1347-1145	Abell 2163	Abell 1835	RXCJ 2228-2037

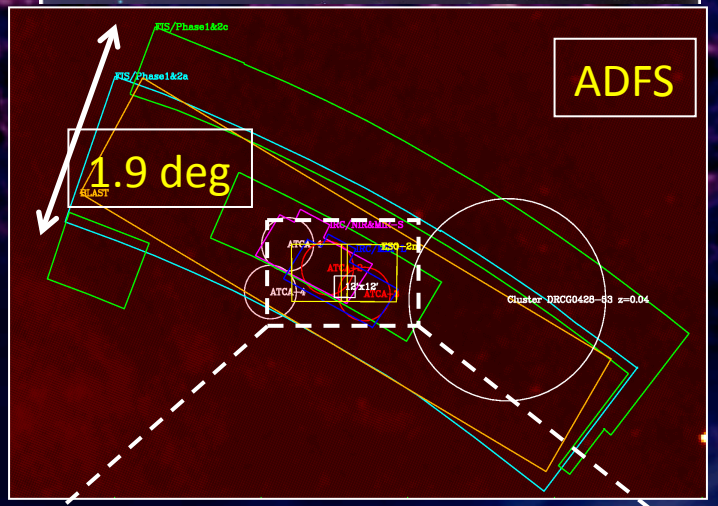
SMGs & SZE Survey

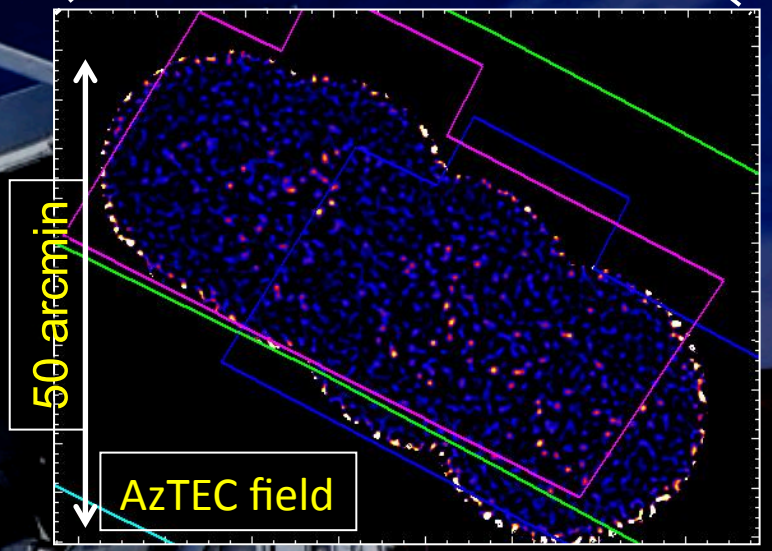
AKARI Deep Field South (ADF-S)

- Near South Ecliptic Pole
- Lowest-cirrus contamination
- Deep AKARI observations
  - IRC: 3.2, 4.6, 7, 11, 15, 24 um
  - FIS: 60, 90, 140, 160 um
- Multi-wavelength follow-up
  - GALEX (UV), CTIO (UBVRI Ks),
  - Spitzer
  - BLAST (250, 350, 500um),
  - LABOCA (870um), ATCA (20cm)

- AzTEC/ASTE Observations
  - 2007-2008
  - central ~1200 arcmin^2 area



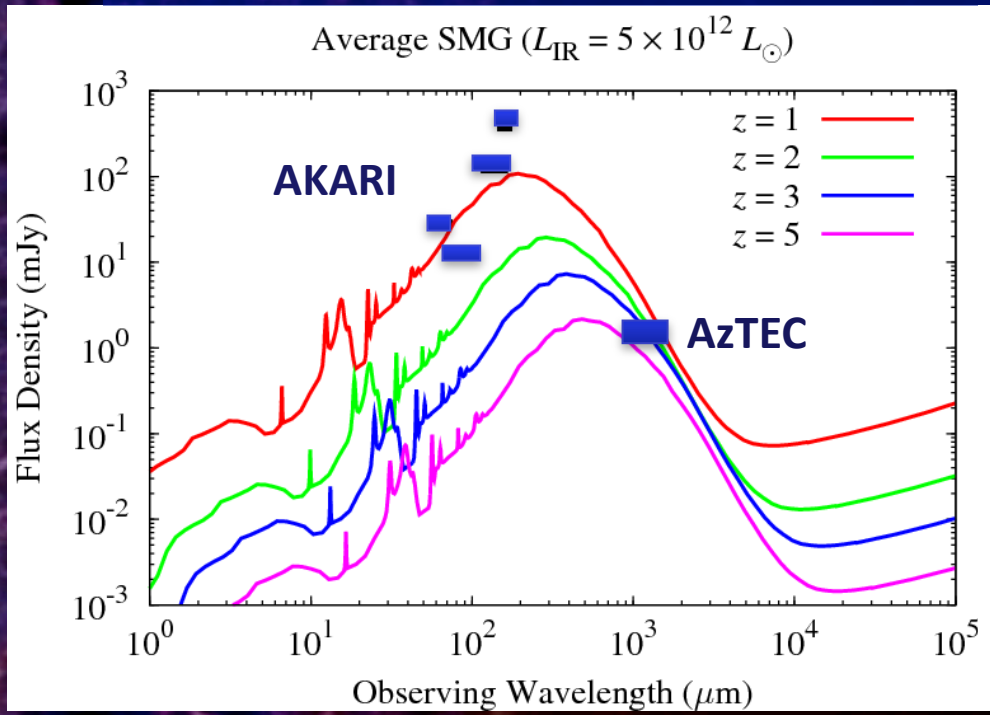


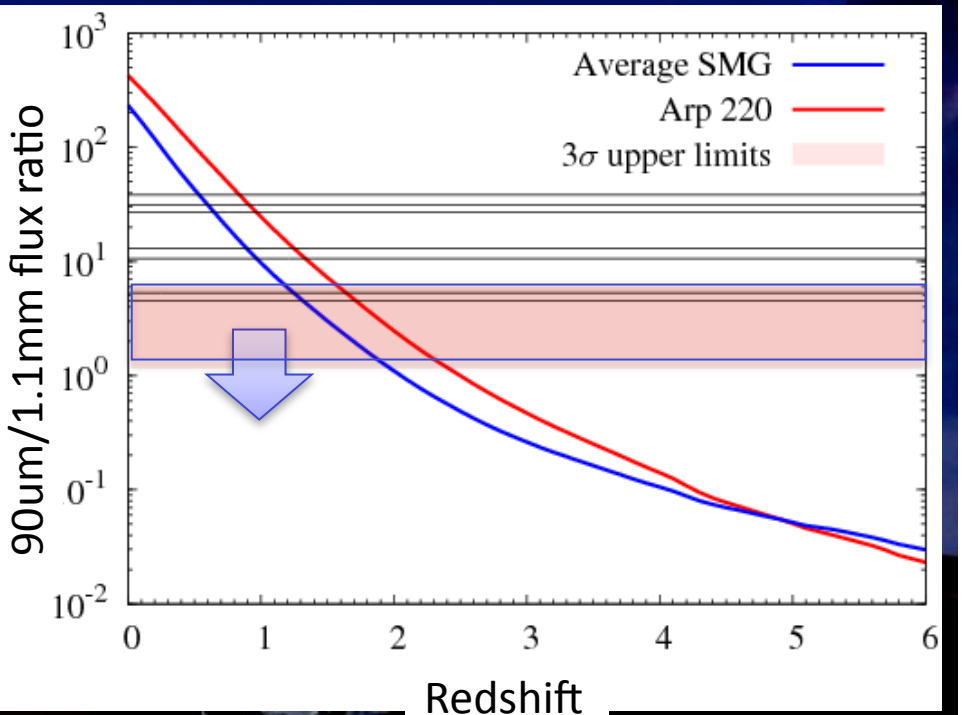


Constraints on *redshifts* of AzTEC/ASTE sources in *ADF-S*

Hatsukade + 2011, MNRAS

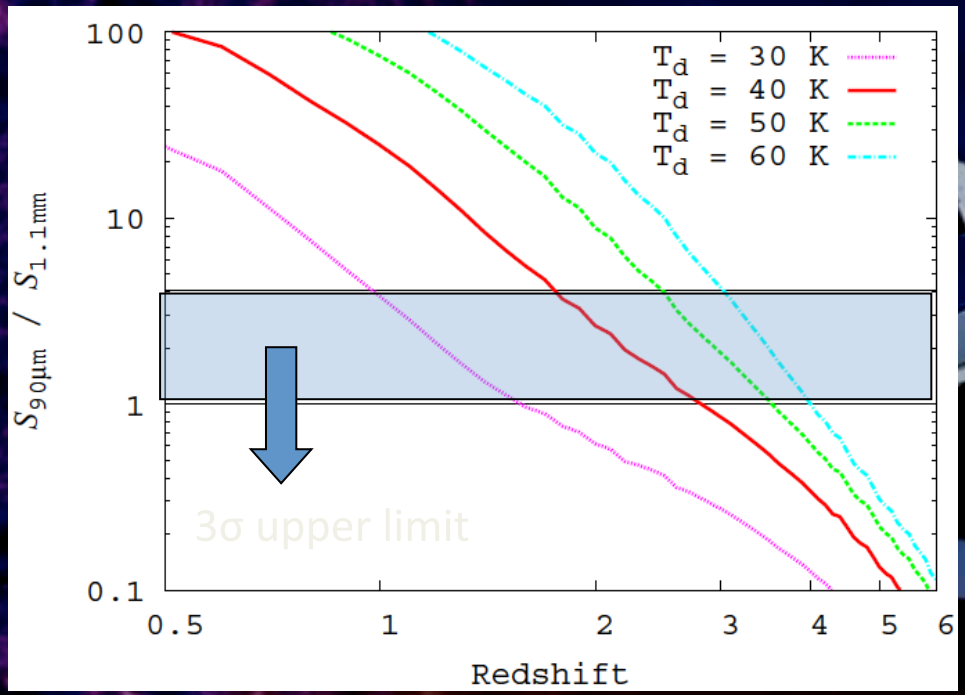
- 90um/1.1mm flux ratio
  - ➔ most of the AzTEC sources (196 out of 198) : z > 1
    - AKARI 90um sources : low-z, AzTEC 1.1mm sources: high-z
- L(FIR) ~ (3-14) x 10^{12} Lo, SFR ~ 500-2400 Mo/yr

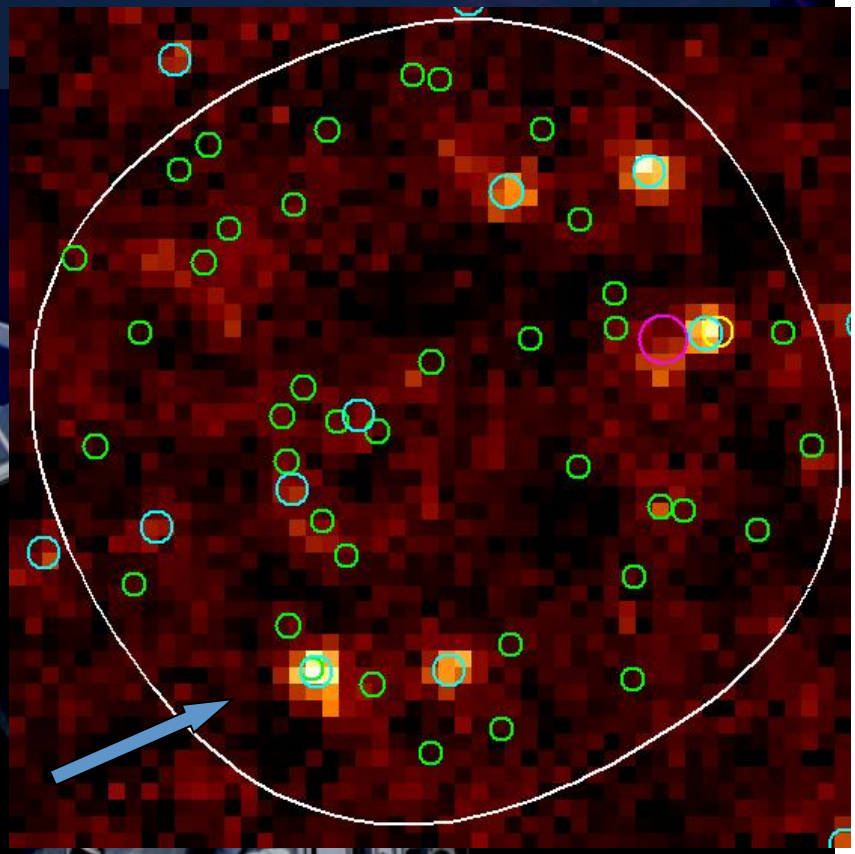




Comparison with AKARI 90um

- Only one AzTEC source (AzTEC12) is detected at 90um
- others: Upper limit to 90um/1.1mm flux ratio ➔ z ≳ 1
  - AzTEC source: higher L_{IR}, higher z
  - 90um source : lower L_{IR}, lower z

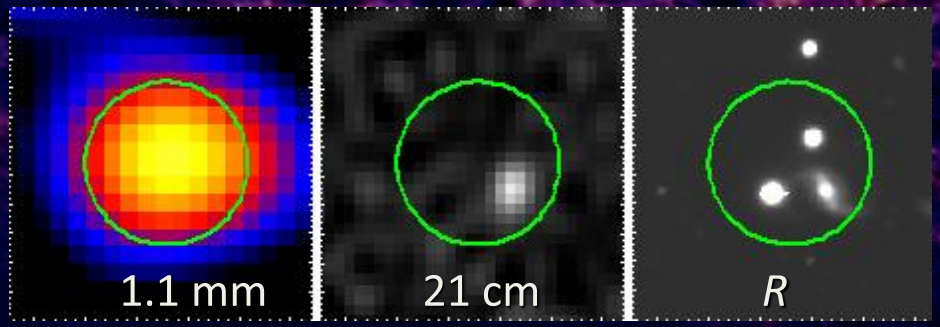


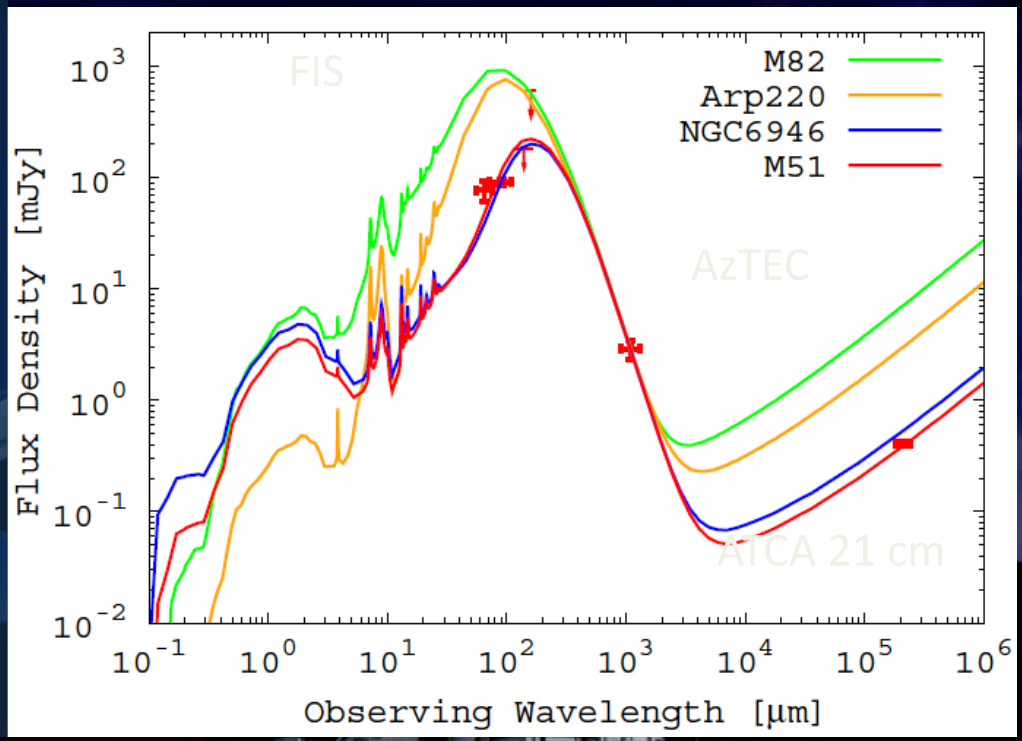


AzTEC12 – WIDE-S#178

- Detected with AKARI at
  - 90 um (WIDE-S)
  - 21 cm (ATCA)
- z_{spec} = 0.16
- Starburst;
  L ~ 3 x 10^{11} L_{solar}
- SFR(Hα) ~ 30 M_{sun}/yr

- Stacking Analysis toward
  45 90 um Sources in ADF-S
  - 7 σ 1.1 mm signal
  - <S1.1 mm> ~ 0.6 mJy
  - indication of fainter & Low-z (z <1) population
  - <L> ~ 10^{11} L_{solar}

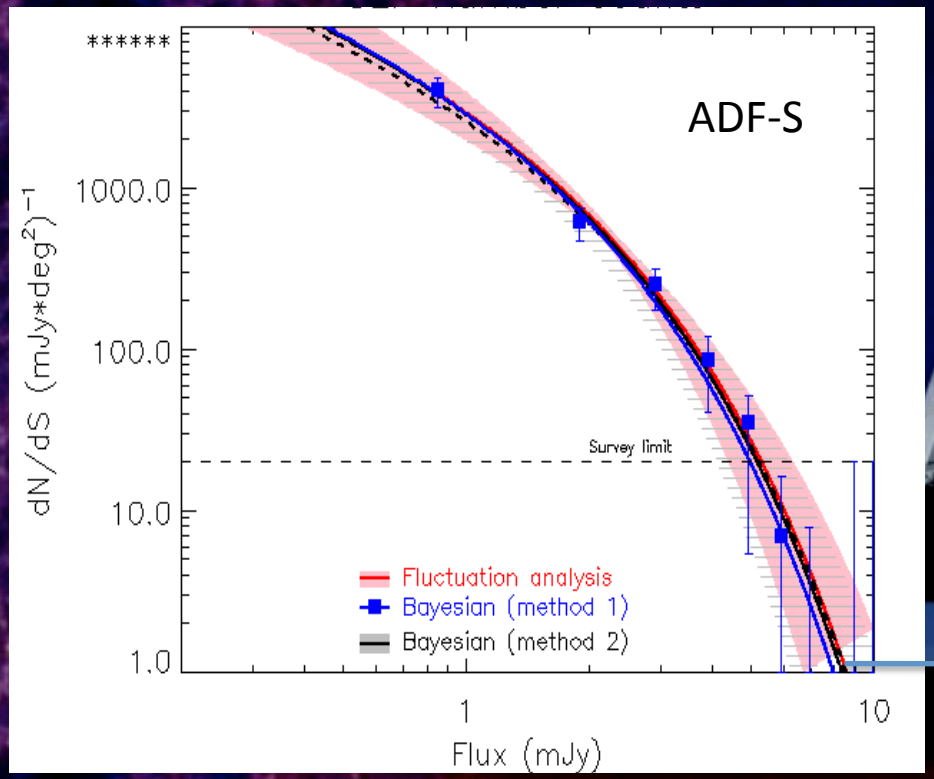


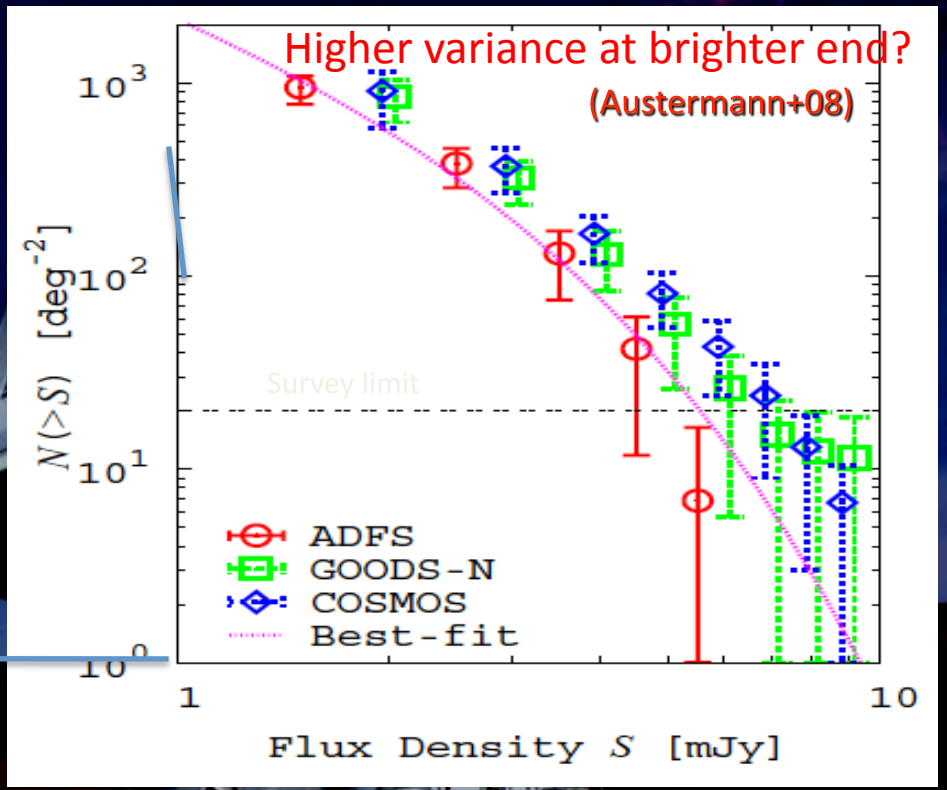


1.1 mm Number Count & CIRB

Hatsukade et al. 2010

- Number count of ADF-S toward much fainter fluxes
  - detected SMG ~ 10 % of CIRB
  - sum-up to 0.01 mJy with Number count ~ 100 %

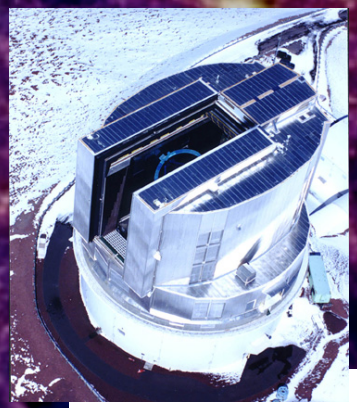




Bright SMGs in SSA22 by AzTEC/ASTE

Lyman Alpha Emitters

SUBARU



LAEs

SFR ~ a few Mo/yr

Distribution of LAEs

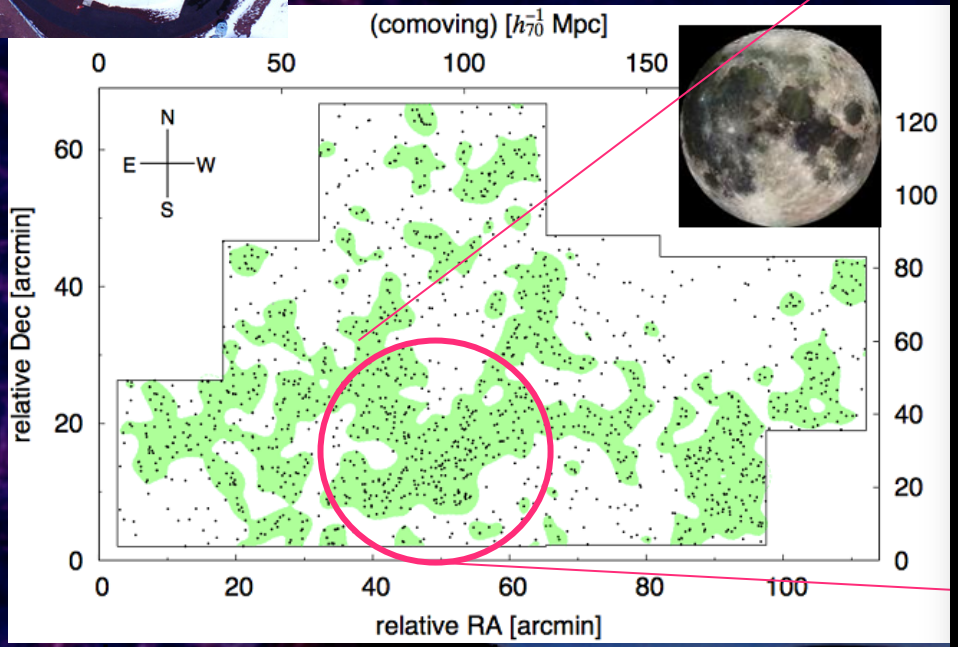
Around z~3.1

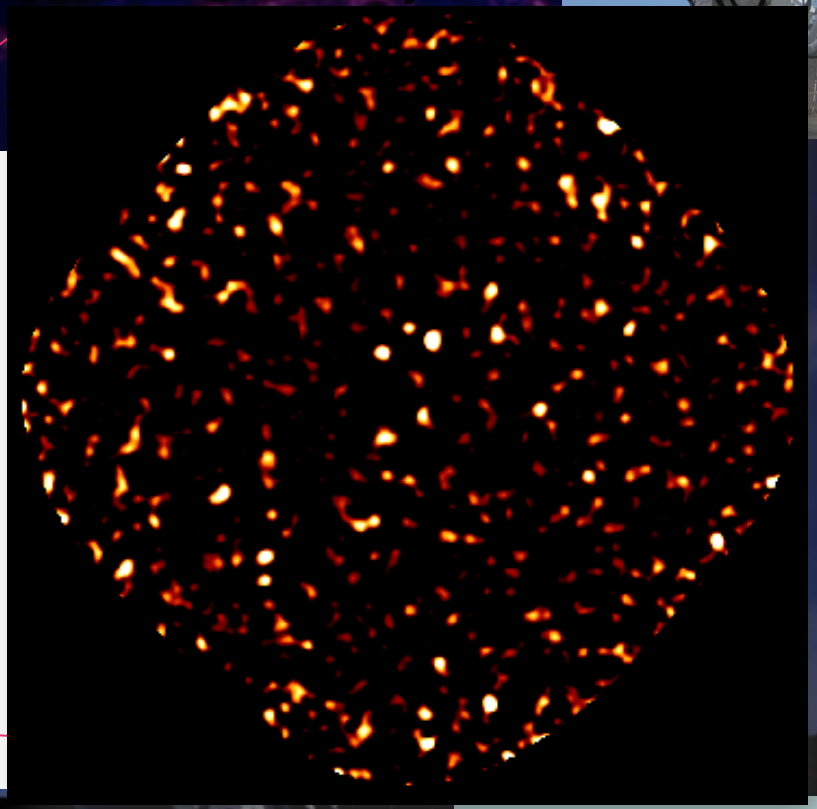
Nakamura et al.

SMGs

SFR ~ a few 100 – a few 1000 Mo/yr

ASTE





No one-by-one correspondence between SMGs LAEs, but SMGs cluster

nsity peak

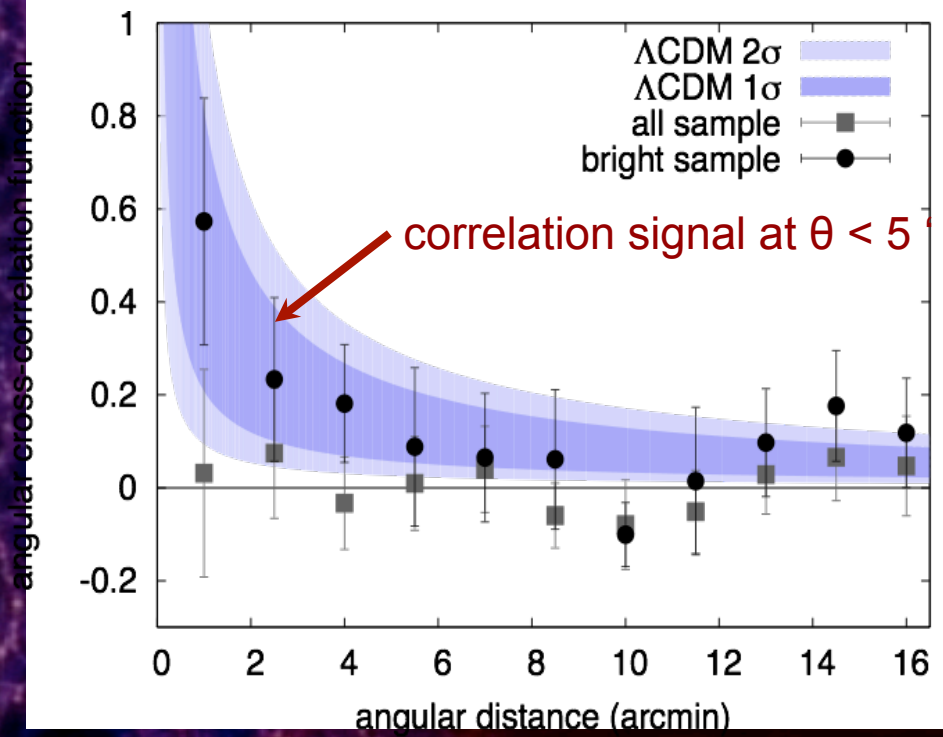
Tamura et al., 2009, Nature, 459, 61

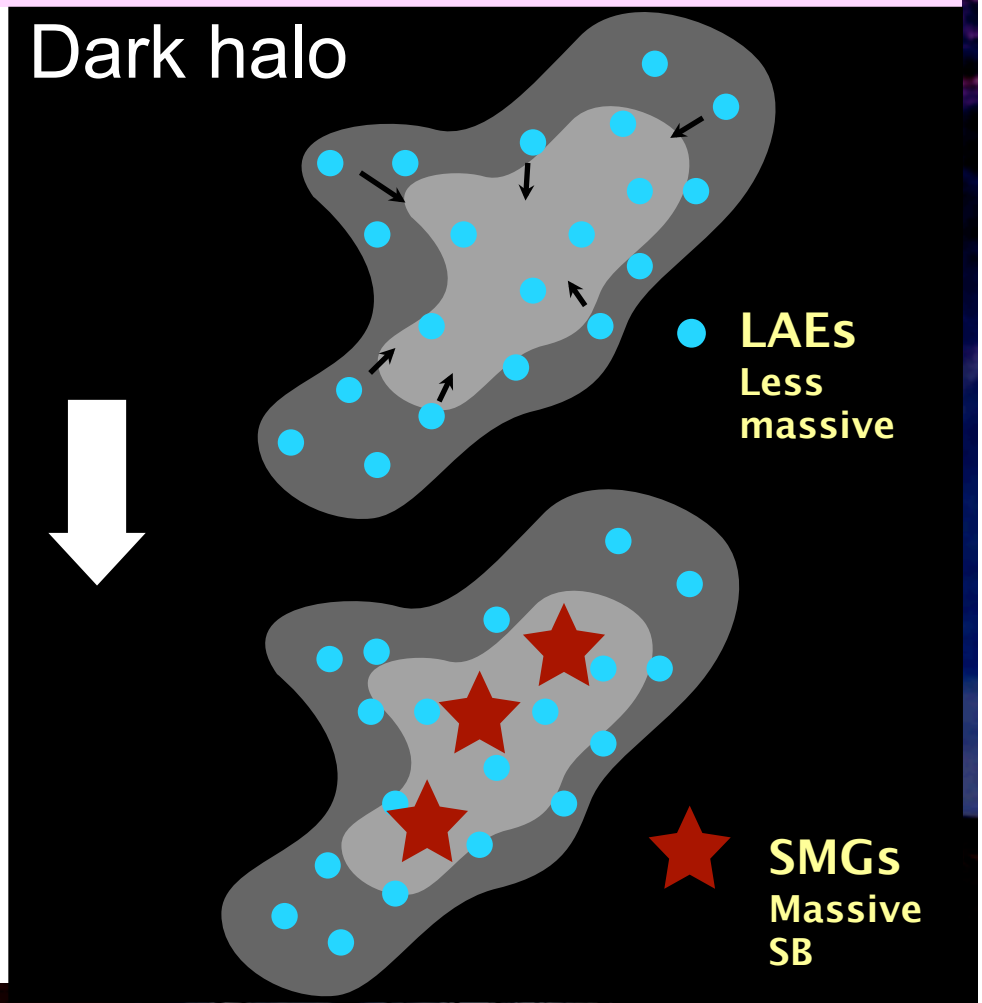
Angular cross correlation between SMGs & LAEs

A clear detection of cross correlation signal with z=3.1 LAEs

➔ detected bright SMGs in SSA 22 are also clustered around z~3 !

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



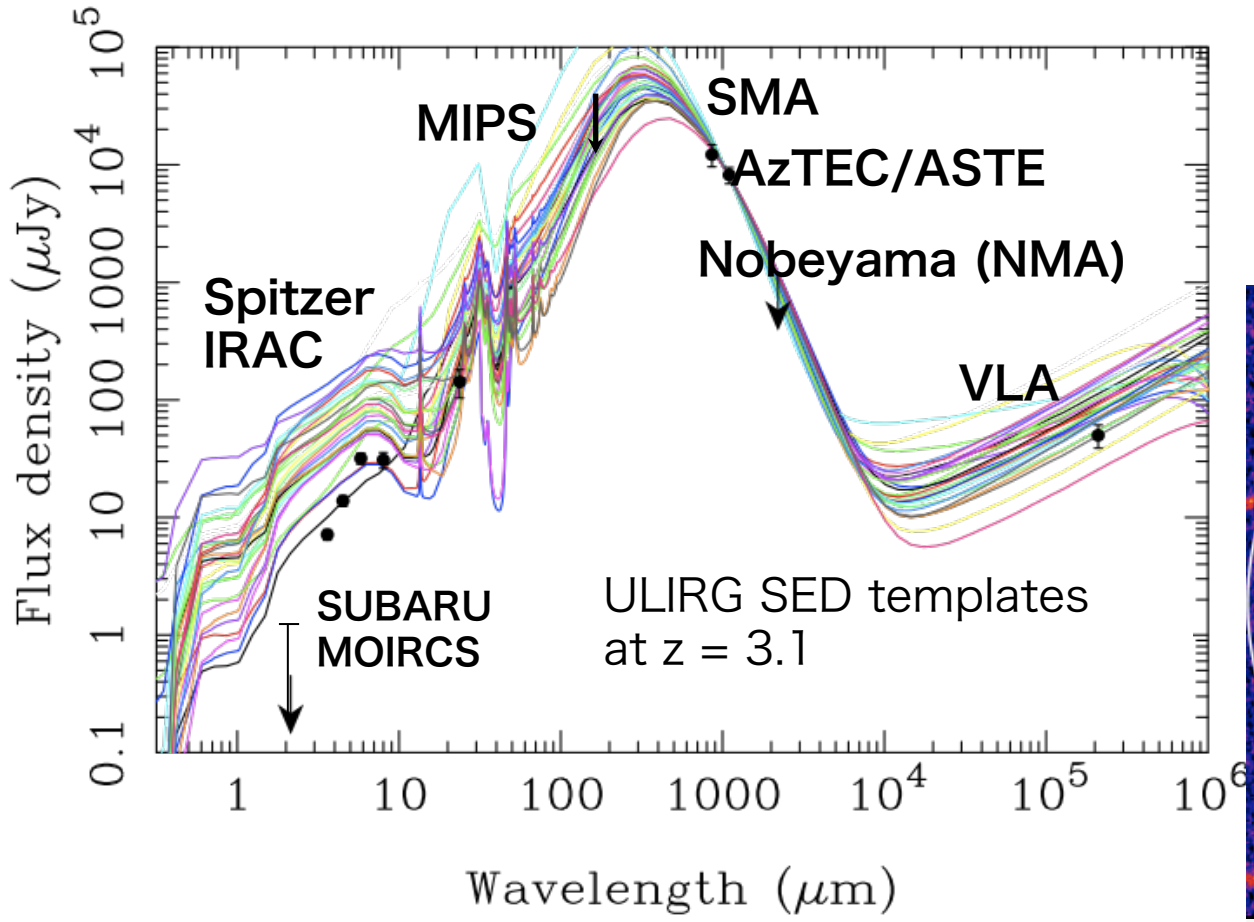


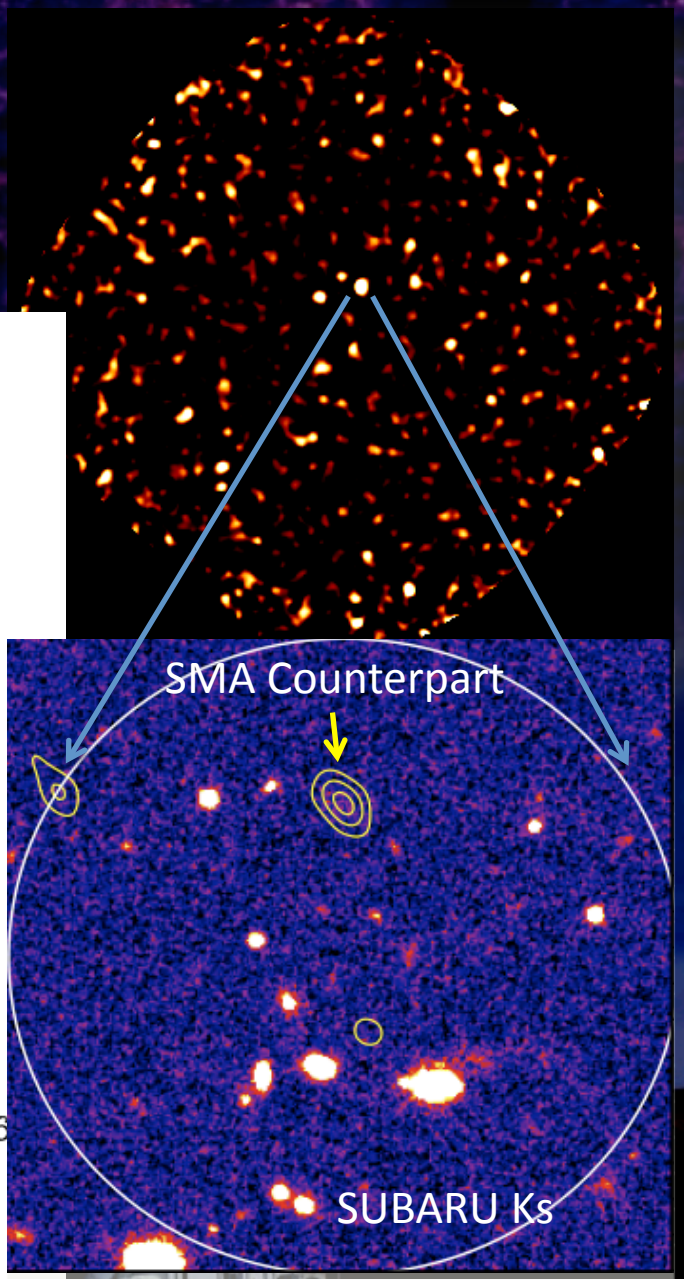
“K-drop SMG” with elevated SFR >1000 Mo/yr

Tamura + Spitzer in press

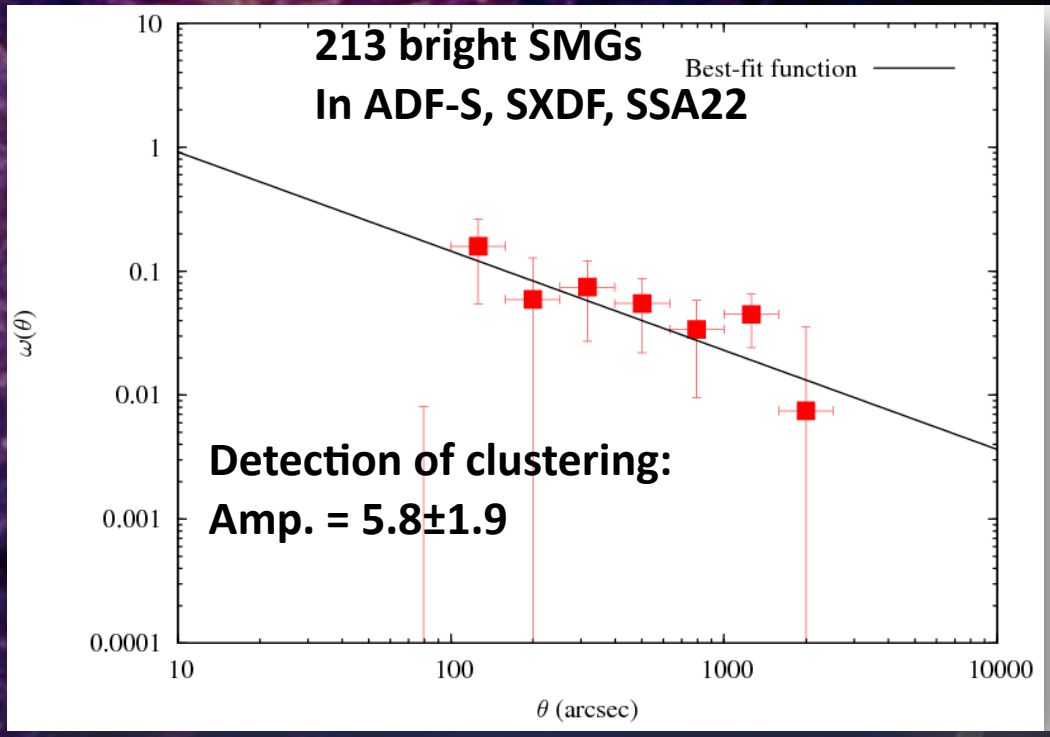
- Also Detected a deeply obscured (N_H~10^{24}cm^{-2}) hard X-ray source

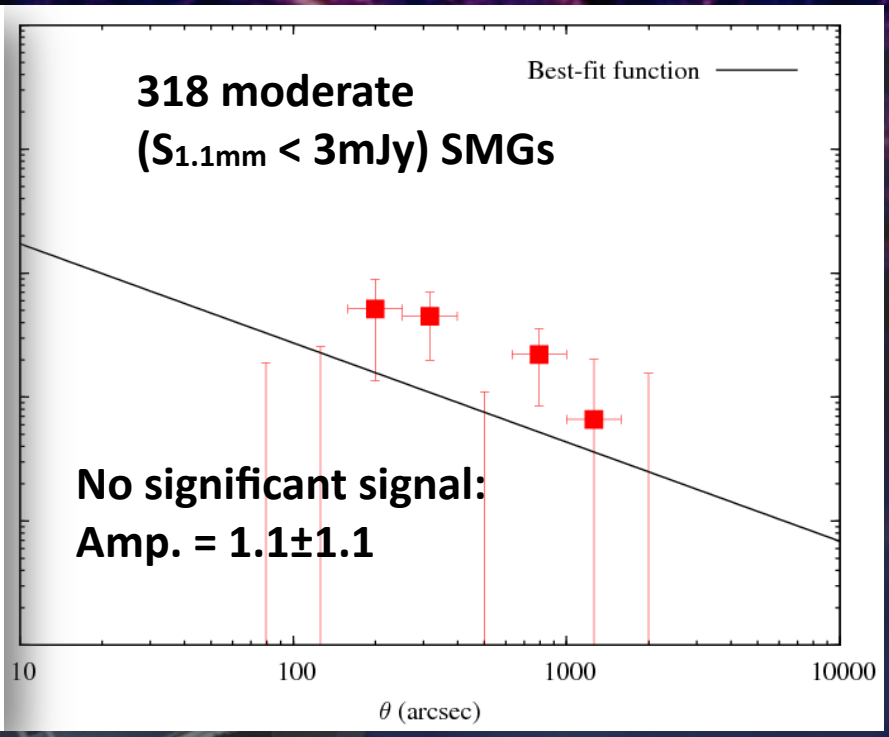
➔ witnessing formation of SMBH as well as massive galaxy formation





Bright ($S_{1.1mm}$>3mJy) SMGs are ***strongly clustered***





Field	Source	N source	Amplitude
ADF-S	>3mJy	65	14±6.7
	<3mJy	133	---
SXDF	>3mJy	69	6.1±5.6
	<3mJy	137	2.2±2.7

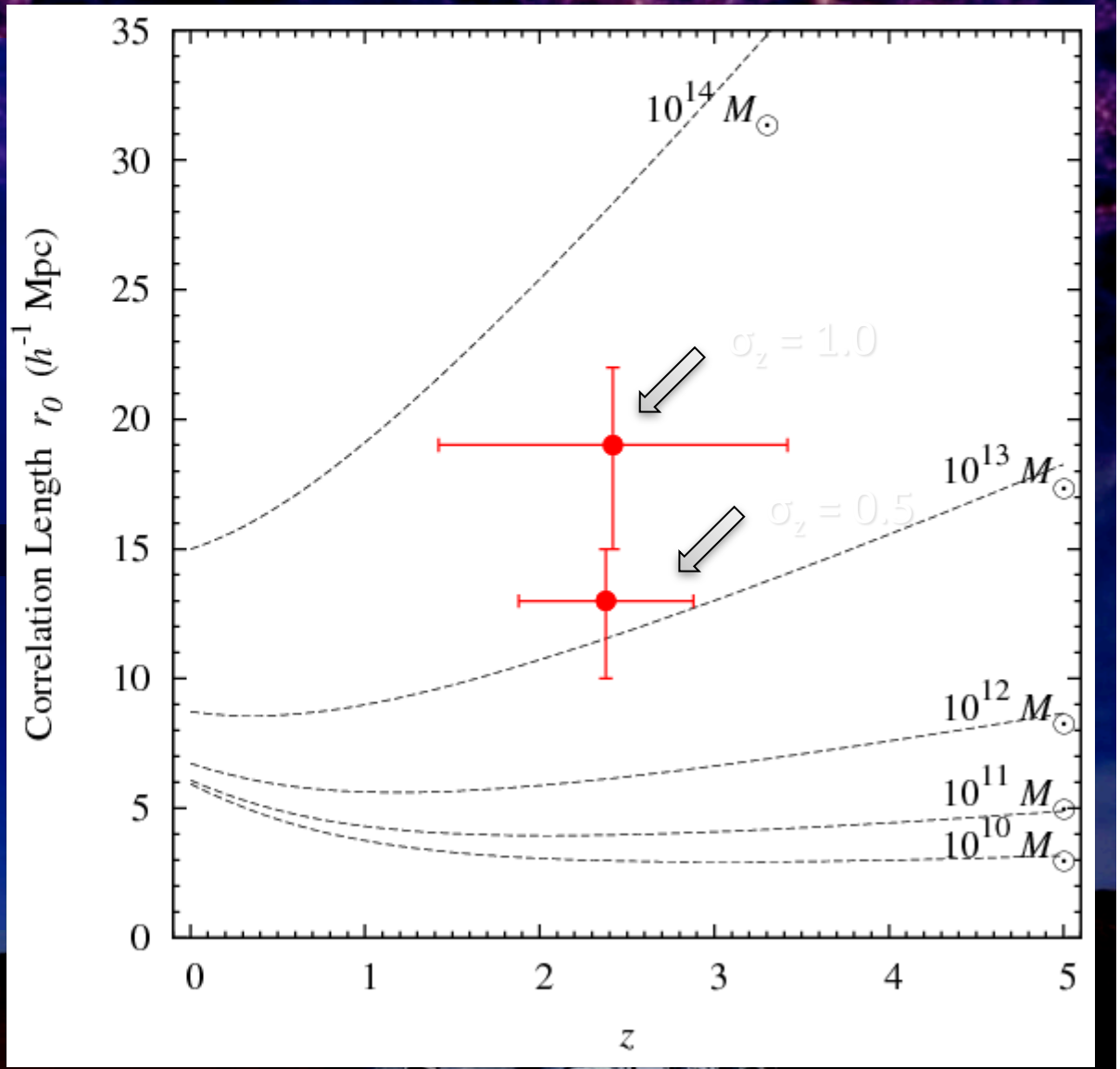
Field	Source	N source	Amplitude
SSA22	>3mJy	79	---
	<3mJy	48	---
Combine	>3mJy	213	5.8±1.9
	<3mJy	318	1.1±1.1

Correlation Length and Halo Mass

- Comparison of clustering properties between dark halo model and AzTEC sources

(Sheth & Tormen 99; Mo & White 02)

Mass of Dark Halo hosting bright AzTEC sources: ~ $10^{13\text{-}14}$ Msun



AzTEC/ASTE SMG Survey

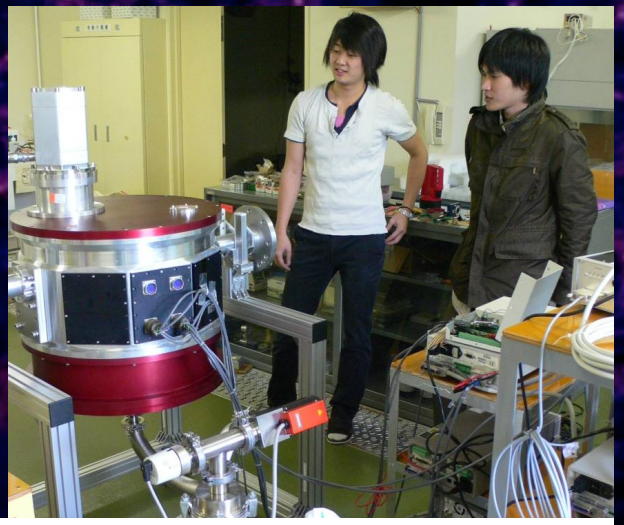
- Confusion Limited wide-area SMG survey
  - Reaches σ ~ 0.5 mJy & 2 deg2 in total
  - more than 1400 SMGs uncovered; z > 1 for most of them

  ~ 1 or 2 SMGs every hour observations
- Limitation of ASTE
  - Limitation of FOV (7.5 arcmin.); future 10 k-pix camera unavailable, & need larger FOV
  - Confusion Limited SMG survey

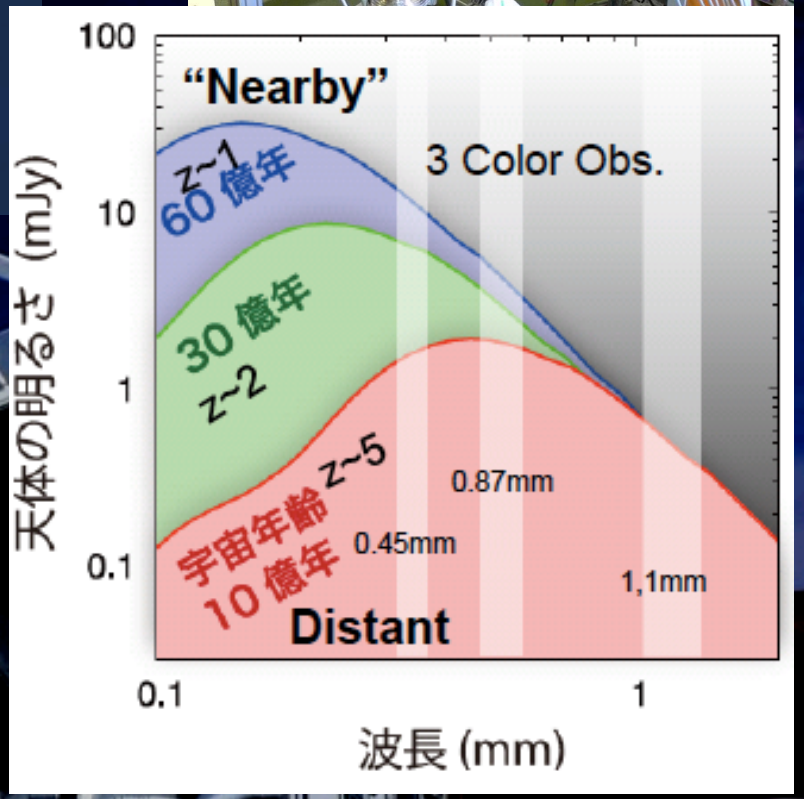
    ; need smaller beam, which also allows easy source ID
  - Small RX Cabin; can accommodate only one/two RXs
  - photo-z or spec-z is unavailable

Multi Color TES Camera for ASTE

- Main Purposes
  - Photo-z estimate for SMGs
  - New surveys of SMGs/SF regions
- Collaboration with UCBerkely (A. Lee), Cardiff, McGill, U. Tokyo, Hokkaido U.
- Installation will be in Oct 2011
- Science Oper. From Nov.



Wavelength	No. of pixs	Beam size	FOV (arcmin)
1.1 mm	169	28”	7.5
850 micron	271	22”	7.5
450 micron	881	11”	7.5



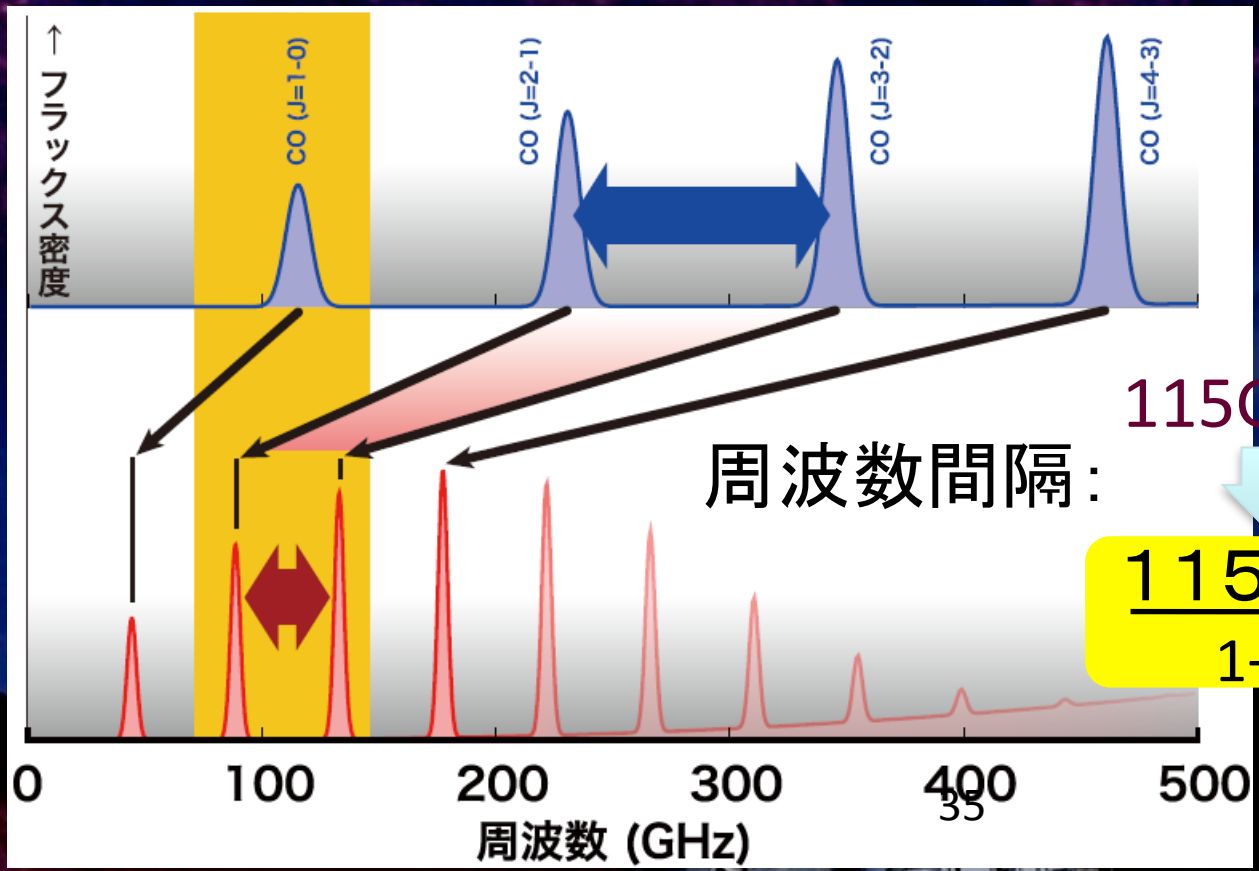
Redshift from CO ladder

- 超広帯域分光システムを導入
- 暗黒銀河が豊富に持つガス（CO、C、C^+等）のスペクトル線を利用

複数の輝線を検出➔周波数間隔から赤方偏移（距離）を決定

近い銀河
現在の宇宙
赤方偏移 0

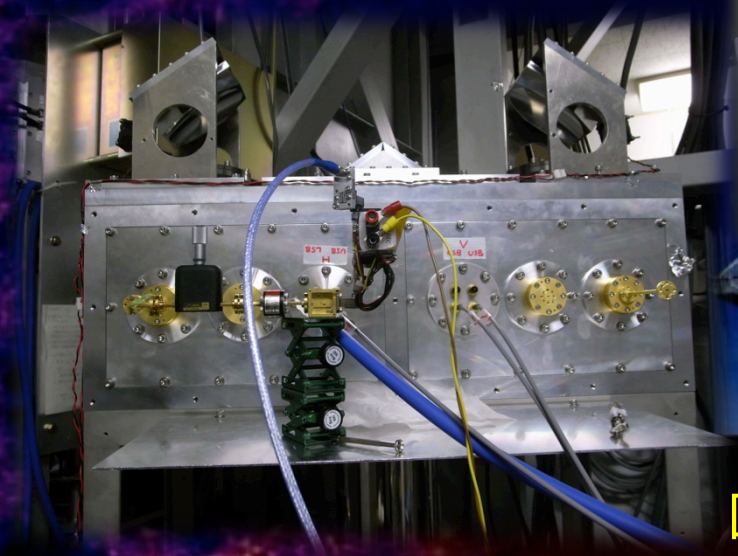
遠い銀河
初期の宇宙
赤方偏移 z



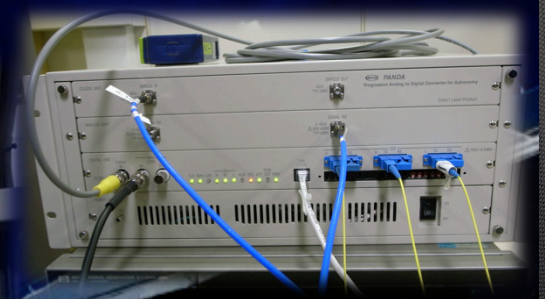
野辺山45m鏡搭載・超広帯域3mm帯分光システムの導入完了

- 2 beam 2SB 2polarization
- LO = 86 – 112 GHz
- IF = 4-8 GHz
- Beam separation = 45”

SIS Receiver “TZ100”

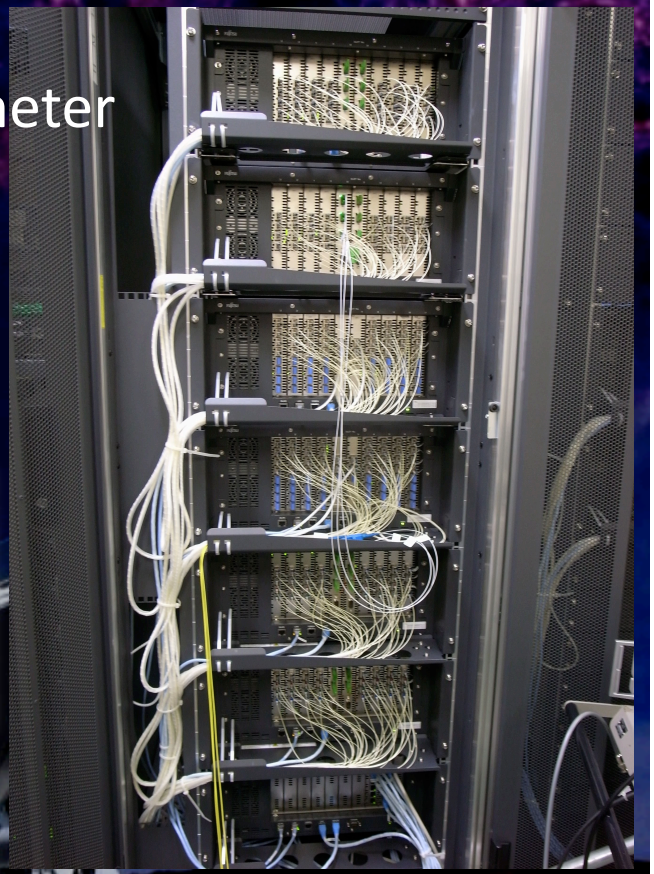


高速A/D
“PANDA”



- Max 16 IFs
- 4G Sample/sec

Spectrometer
“SAM45”



- BW = 16 MHz – 2 GHz
- Δv = 3.8kHz – 0.5 MHz

国立天文台、東大、他

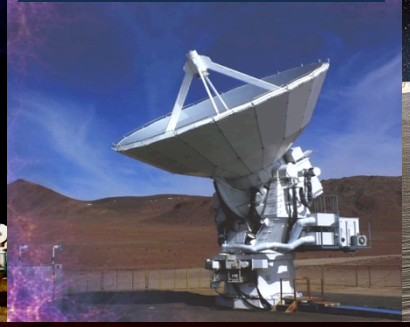
ALMA/SPICA Synergy TElescope (ASTE-II) (Tentative)

- A New Large mm/Sub-mm Single dish Telescope (in Chile)
  - complementary to ALMA, SPICA, SKA, ..
  - opening new discovery space in ALMA/SPICA/SKA- era
    Wide Field Imaging & Ultimate wide-band Spectroscopy

NRO 45m Tel

Natural Evolution

ASTE 10 m Telescope In Chie



D ~ 30 m or 50 m ?
Freq. = 70 GHz – 1 THz (or 400 GHz??)
Completion ~ 2018-20 ??

- "Wide Field" CO/[CII] Tomography
- Census in the Universe
- Serendipity
- Incubate Original Ideas

K. Don and NOAO/AURA/NSF

New Single Dish ("ASTE-II")

- D ~ 50m, Freq. = 70 – 400 GHz (4 mm – 750 um)
- FOV of telescope ~ 1 deg
- Mm/sub-mm Camera + MOS/Imaging Spectrometer

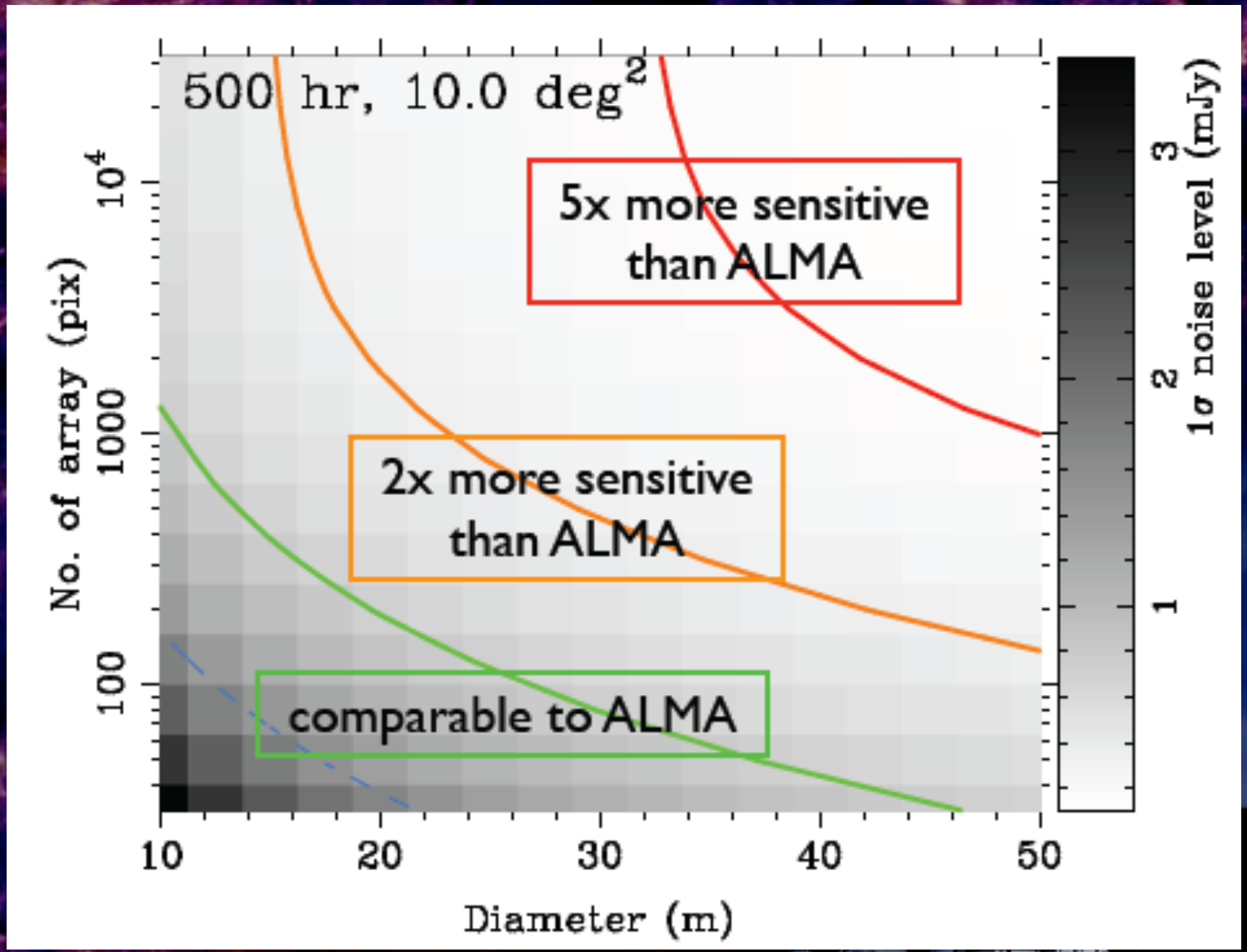
Beam size ~ 6" at λ 1mm; easy to ID IR/Radio count.

Source Confusion < 50 μJy; ~ ten times deeper

Redshift Survey by exploiting high-sensitivity & wide FOV; spec-z of SMG every 10-20 min. each pix

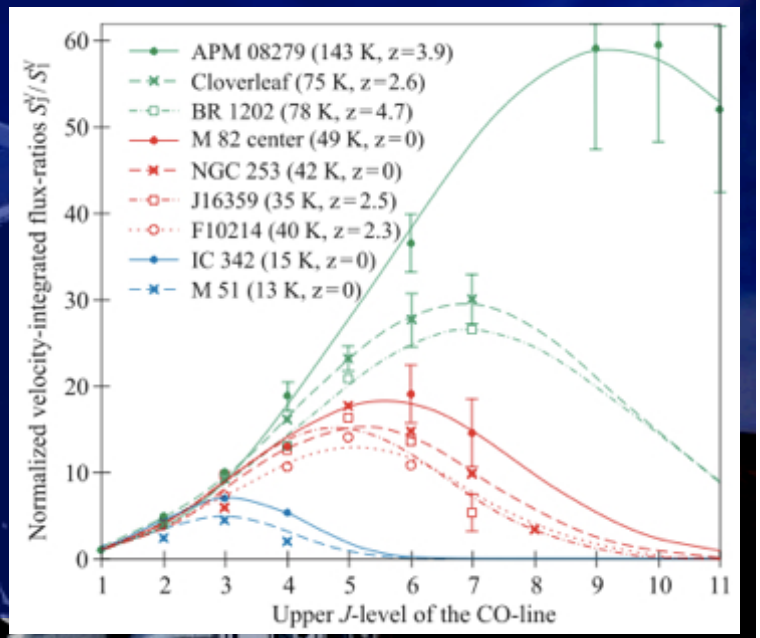
=> spec-z of several x 100 SMGs with 100 pix MOS/hour allows to unveil cosmic star formation history & LSS

Noise level achieved with SD



New Science with New Single Dish ("ASTE-II")

- SMG Redshift Survey
- Cosmic Star Formation History
- Understanding Galaxy Evolution
  Relation with high-z populations
- Starburst & QSO co-evolution
  with CO SEDs
- MW Galaxy Formation
- Census & Serendipity
- Survey of Galaxies in EoR?



New Single Dish ("ASTE-II")
MOS vs Imaging Spectrometer

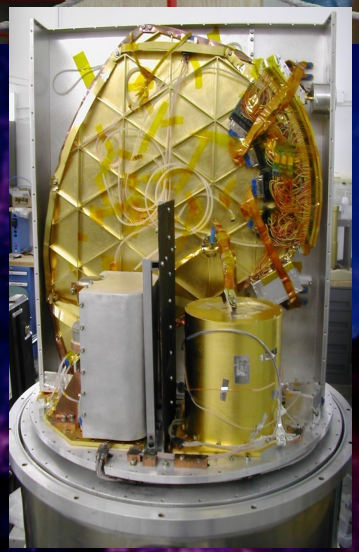
- **MOS; Multi Object Spectrometer**

  - Based on high-z SMGs uncovered with submm deep survey
    => vey efficient but some bias (samples galaxies@ z> 1)
  - Efficiency depends on multiplicity of technology available
    Grating spectrometer, Filter Bank IC, heterodyne array (SIS, HEMT)

- **Imaging Spectrometer**

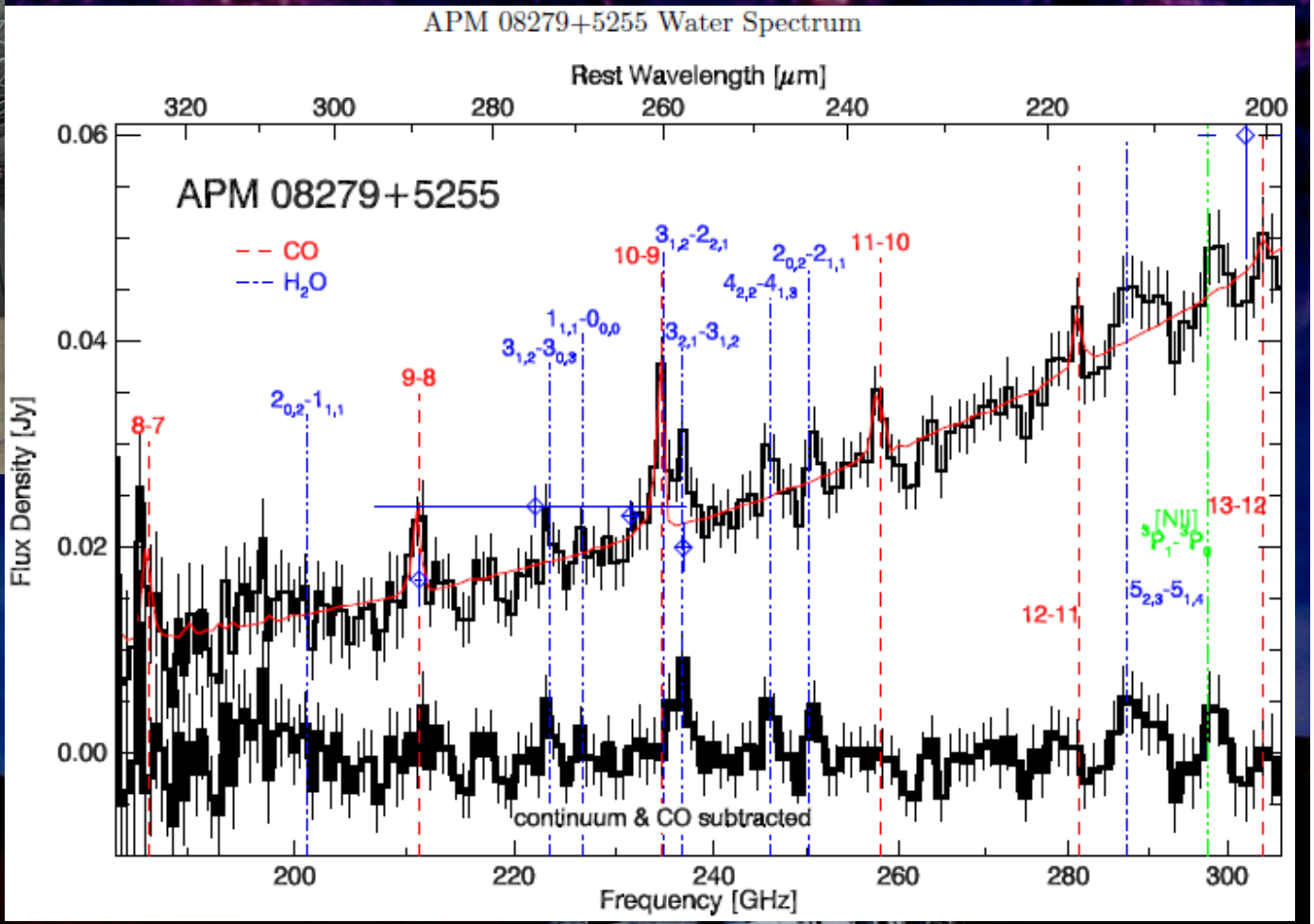
  - Blank Field Imaging & Spectroscopy; CO ladder and redshifted [CII]
  - CO is sensitive to "low-z" star-forming galaxies
  - redshifted [CII] + high-J CO are sensitive to the EoR era
  - Not efficient for high-z; Efficiency depends on multiplicity of technology available
    detector array + FTS, SIS/MEMT Array + Ultra-wide band Spectrometer (A/D + FFT analyzer)

暗黒銀河の赤方偏移決定



Z-Spec/ CSO,
ハワイ・マウナケア山

120億後年のかなたのクウェーサーの周囲のガスに、水蒸気がたくさん存在することを発見
Bradford et al. (2011)



Sensitivity-limited Survey with the New 50m Telescope ("ASTE-II")
"CO Tomography"

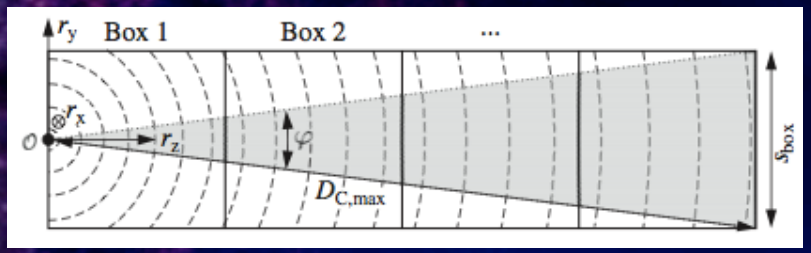
- 50 m Single Dish equipped with 1000 pix array detectors + spectrometers (covering ~ 70 GHz to ~ 345 GHz)
- 1000 hours observations in Chile ALMA site
- Area= 2 sq-deg, 10 sq deg, or …
- Extracting galaxies with at least one CO line detected at > 5σ from CO mock galaxies

  (from Tamura-san's work)

Cosmological CO Tomography
Mock CO-emitting Galaxies

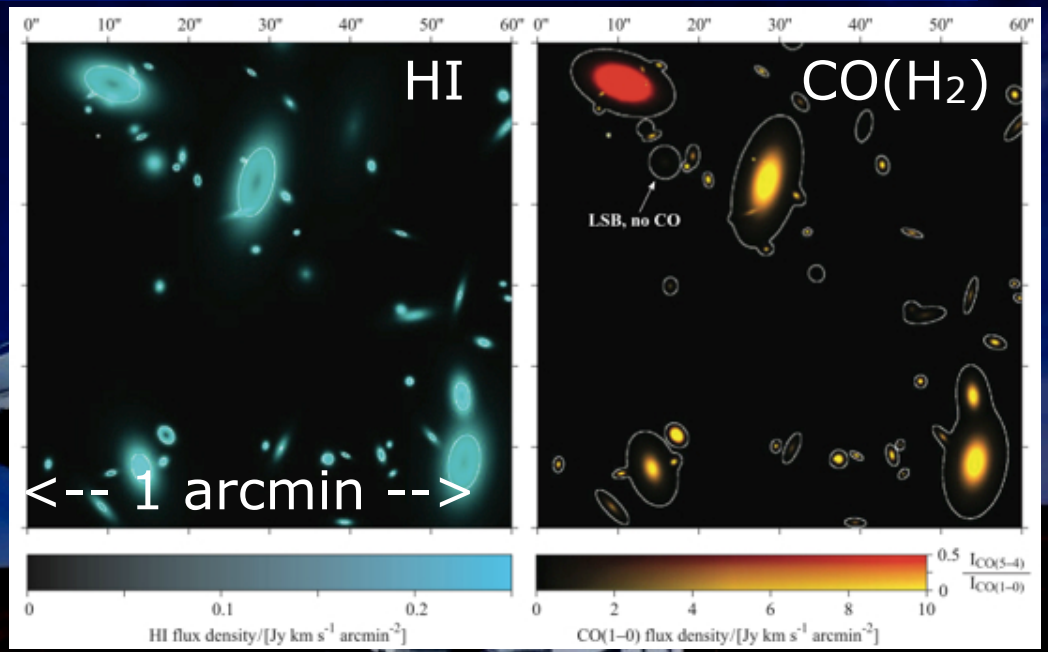
- S^3-SAX: A catalog of mock CO-emitting galaxies (Obreschkow et al.)
  - based on dark matter skeleton at redshift out to 10, which has been constructed in the Millennium simulation.
  - Semi-analytic modeling of galaxy mergers, stellar populations, MBH growth are treated in DeLucia07, Croton+06.
  - assign radial profiles of HI and H_2 density in each galaxy

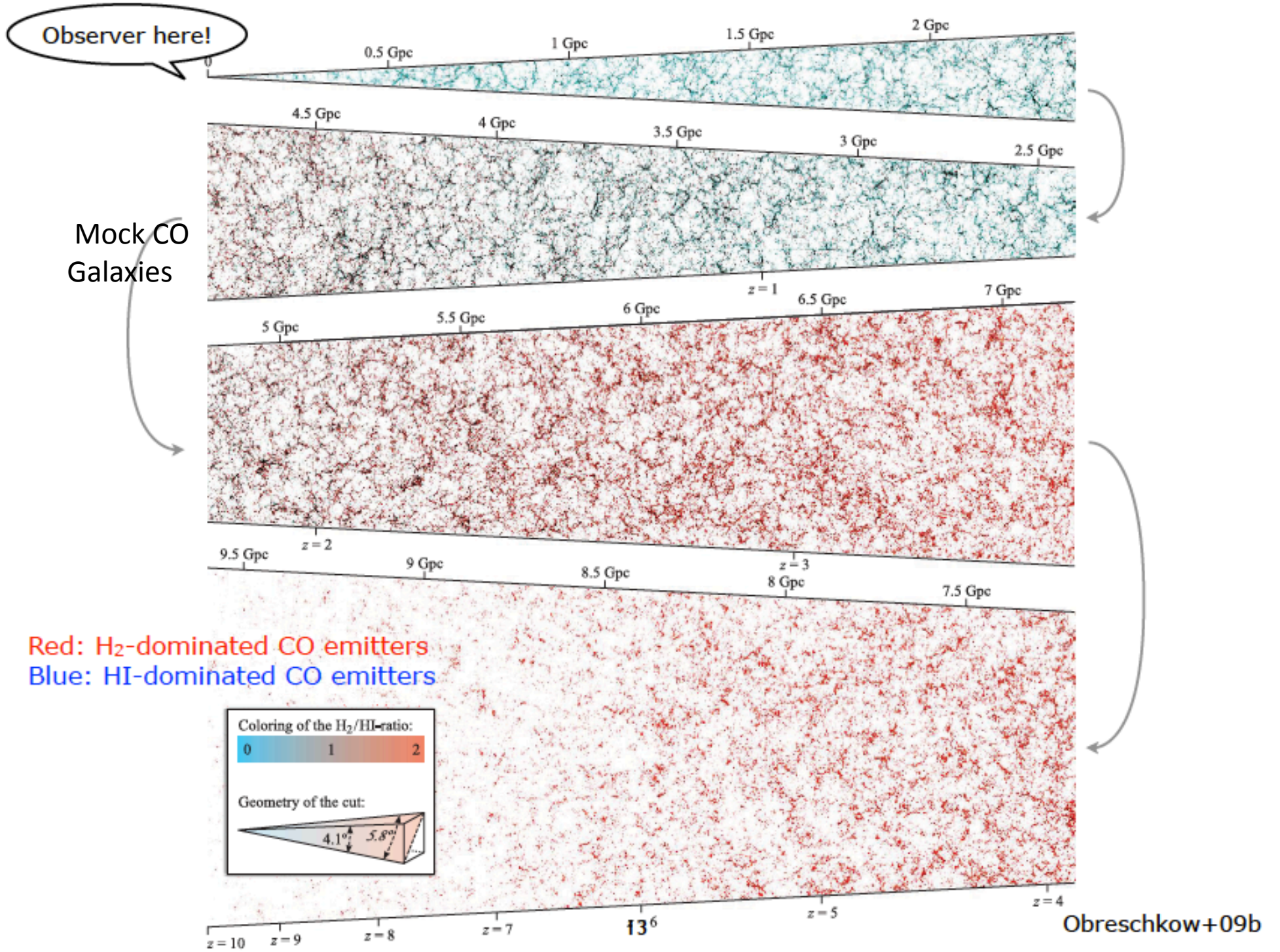
Obreschkow+09b



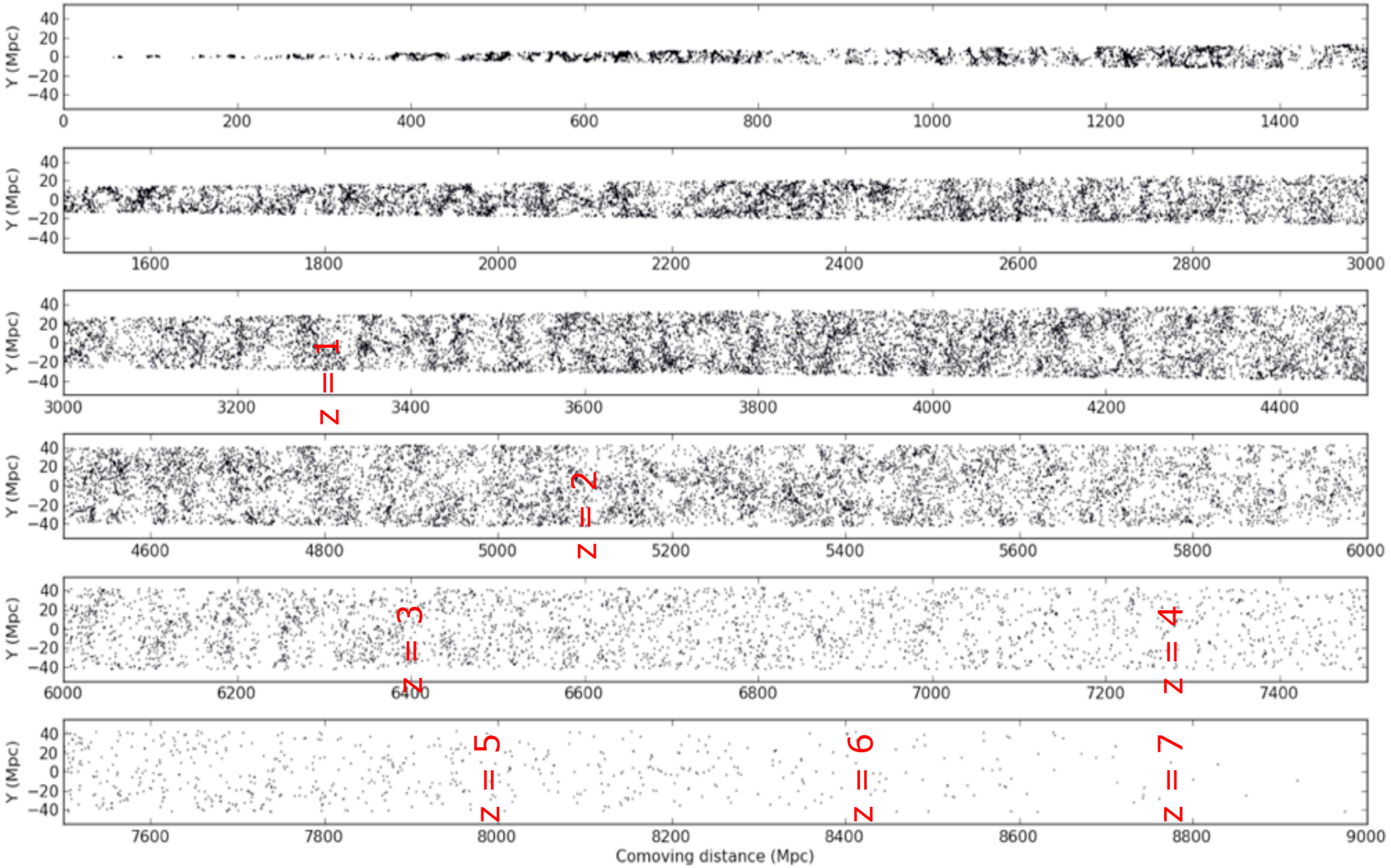
❖ Mock observing cone in the Millennium Simulation

❖ HI and CO sky realization (1 arcmin^2, z = 1.0-1.1)

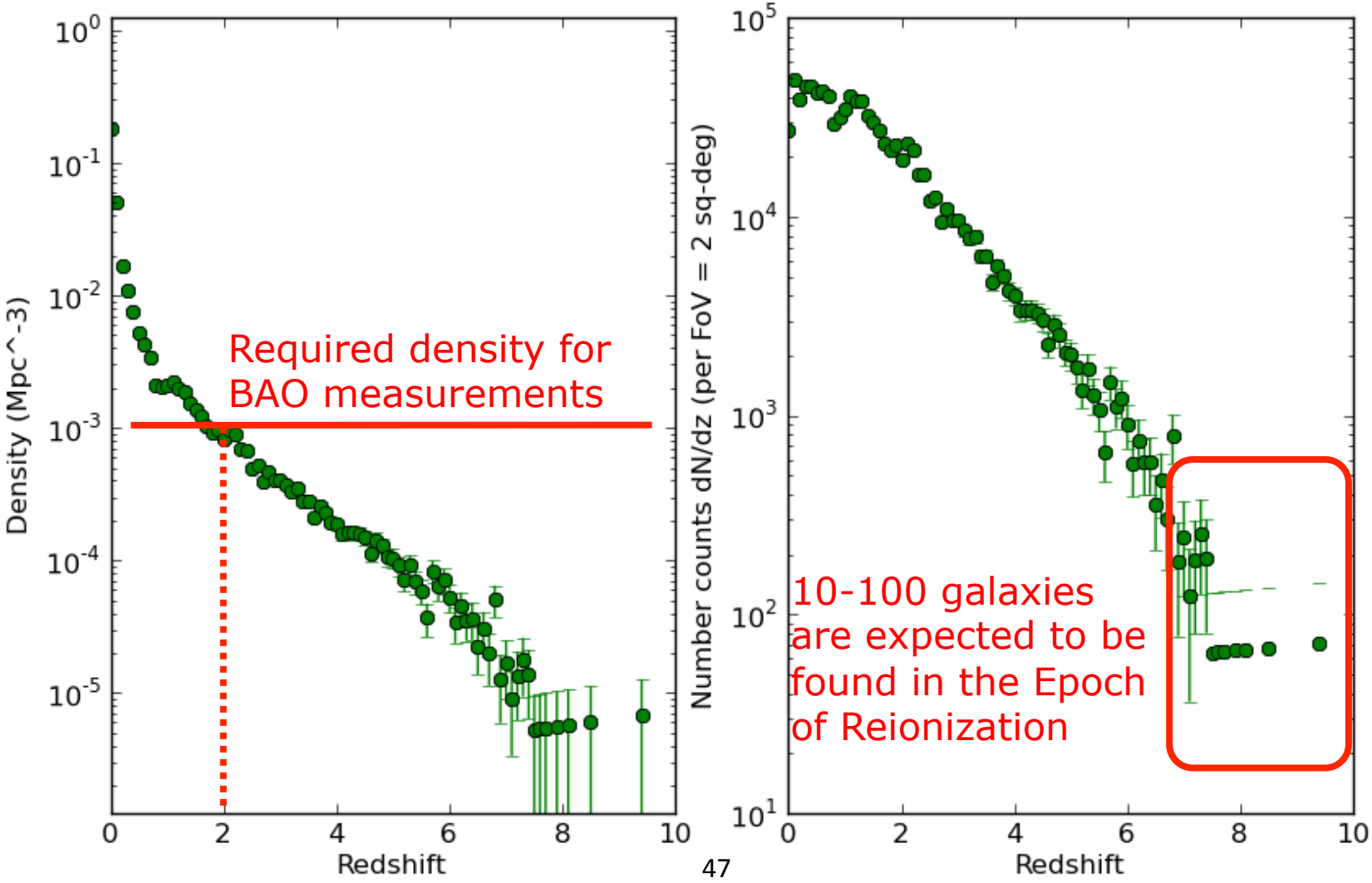



Observer here!
Mock CO Galaxies
0
0.5 Gpc
1 Gpc
1.5 Gpc
2 Gpc
4.5 Gpc
4 Gpc
3.5 Gpc
3 Gpc
2.5 Gpc
z = 1
5 Gpc
5.5 Gpc
6 Gpc
6.5 Gpc
7 Gpc
z = 2
z = 3
9.5 Gpc
9 Gpc
8.5 Gpc
8 Gpc
7.5 Gpc
z = 10
z = 9
z = 8
z = 7
z = 6
z = 5
z = 4
Red: H2-dominated CO emitters
Blue: HI-dominated CO emitters
Coloring of the H2/HI-ratio:
0
1
2
Geometry of the cut:
4.1°
5.8°
Obreschkow+09b

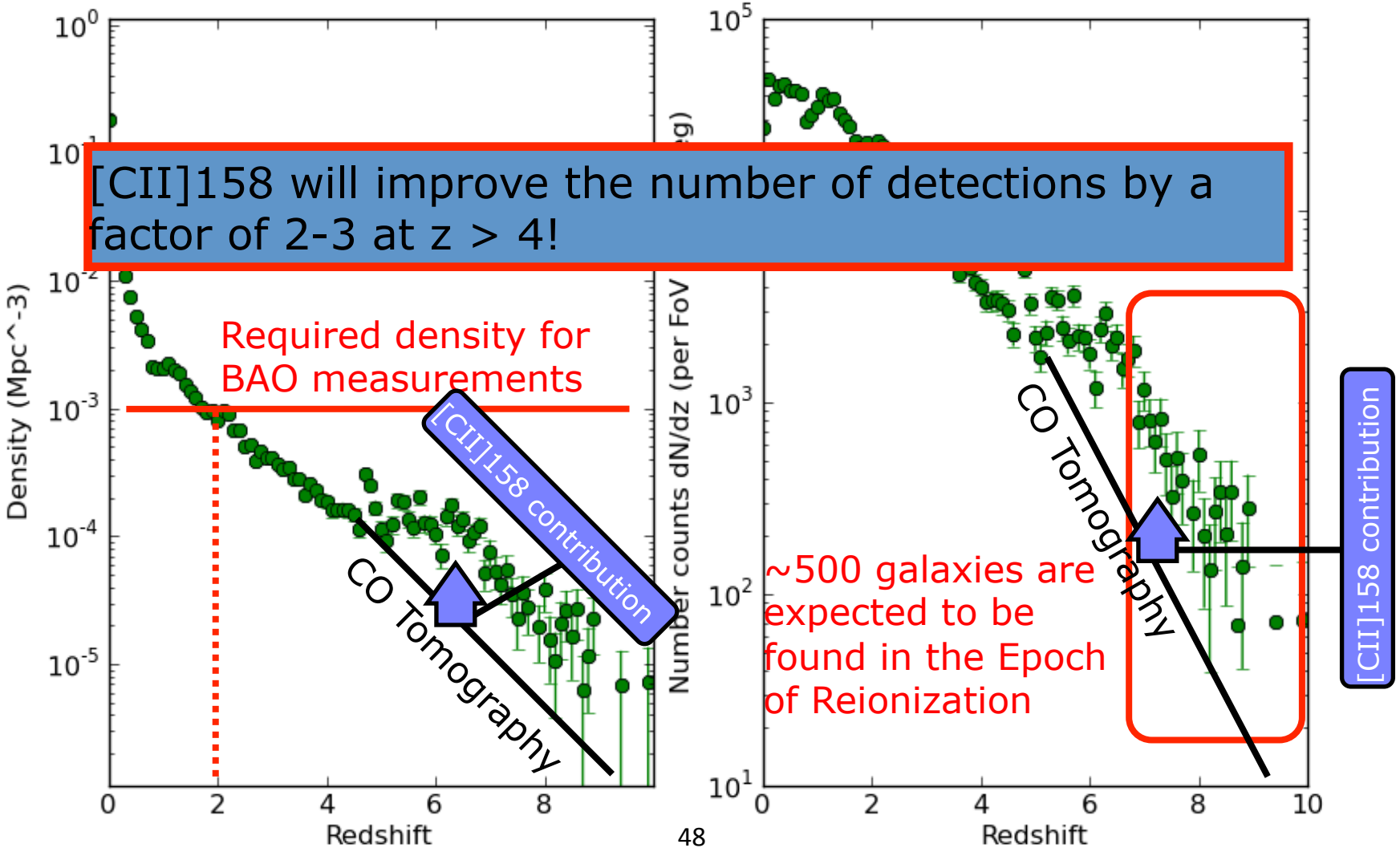
Galaxies with new 50m (ASTE-II)



Volume Density and Number Counts from the 2 deg^2 survey

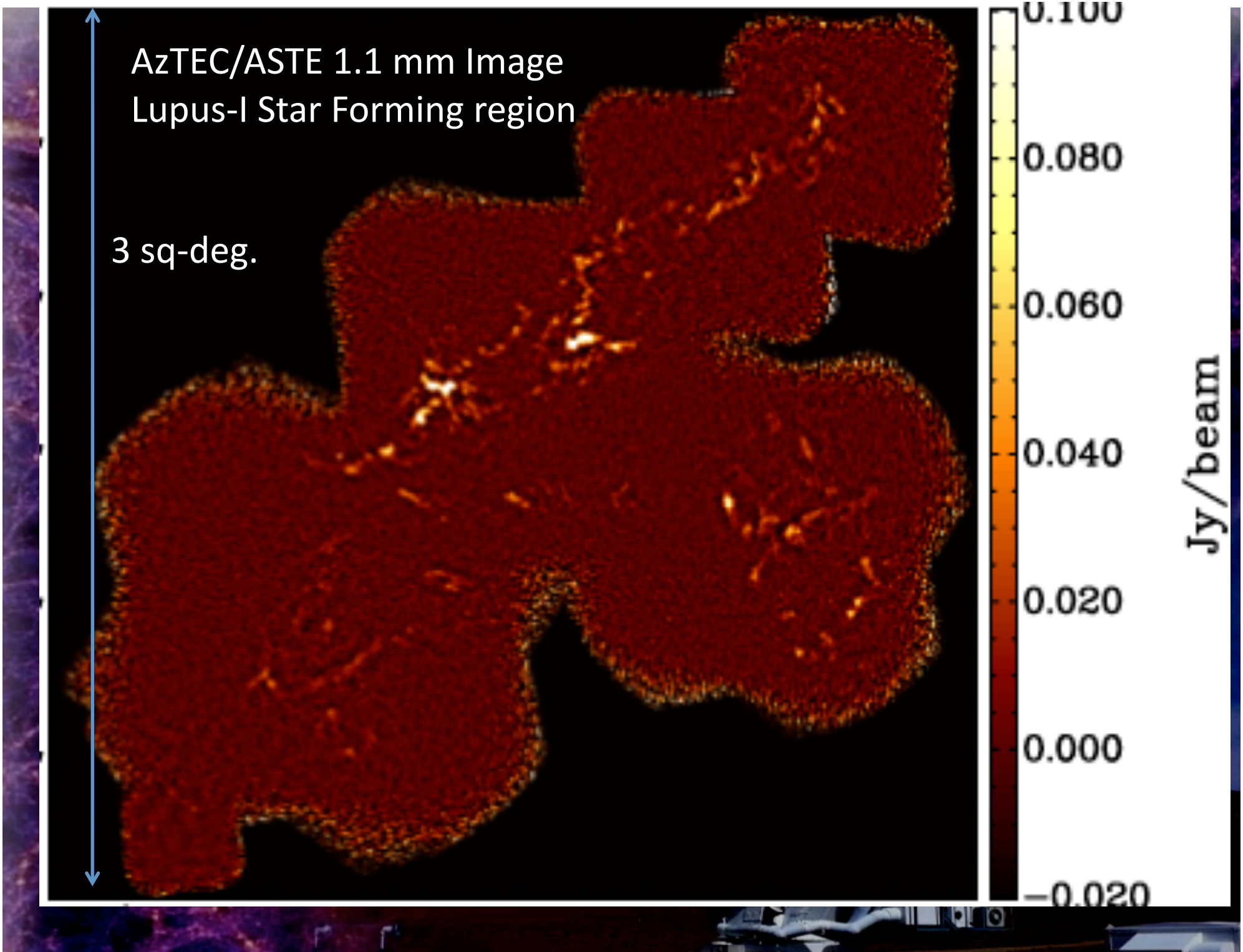


Volume Density and Number Counts from the 2 deg^2 survey



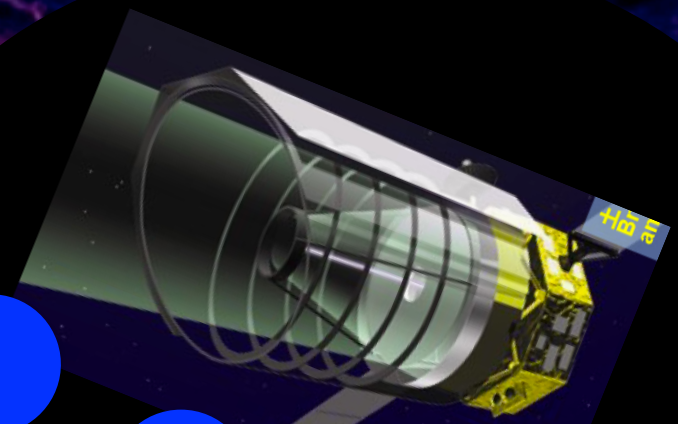
New Science with New Single Dish ("ASTE-II") ; GRB etc

- GRB Afterglow
  - multi-band photometry @70 – 650 GHz
  - Cold dust & gas in host galaxy
- Absorption line search toward GRB Afterglow
  - mostly continuous @ 100 – 400 GHz with R ~ 1000
  - Spectroscopy with R ~ 10^5
- AGN time variability
- MW galaxy mapping; 10 sq-deg. To > 1000 sq-deg.

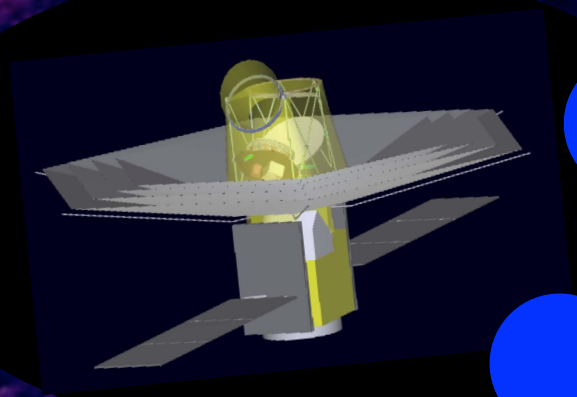

AzTEC/ASTE 1.1 mm Image
Lupus-I Star Forming region
3 sq-deg.
0.100
0.080
0.060
0.040
0.020
0.000
−0.020
Jy/beam

Synergies

SPICA/ISAS/JAXA



Litebird/KEK



Inflation to Dark Age

Satellite Technology

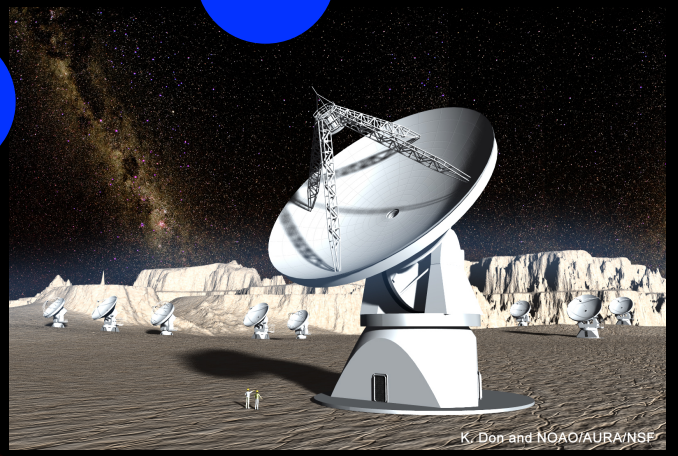
Origin of Life

Imaging Spectroscopy

Mm to FIR Camera

CMB Secondary

ALMA & “ASTE-II”
(JP Univ./NAOJ)



Summary

- A New Large mm/Sub-mm Single dish Telescope (in Chile)
- Baseline Plan; D ~ 50 m & Freq. = 70 – 400 GHz
- New Science with Wide FOV & Wideband Spectroscopy

Completion around 2020?
Synergies with
ALMA, SPICA, SUBARU
Litebird, SKA …CTA…