ASTE and TAO: results and future

The Submillimeter Universe:
The CCAT View
November 13, 2010
Cornell University

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東京大学
THE UNIVERSITY OF TOKYO

Synergy between CCAT & TAO/ASTE

(IoA, Univ. of Tokyo)

reciprocal relation

CCAT

existing, running telescopes

- Science preparation for CCAT with AzTEC/TESCAM surveys
- ASTE as a test bench of new instruments for CCAT

- On-site collaboration such as infrastructure (road to the summit, etc)
- Science: NIR/MIR and submm

ASTE

IoA/UT is one of the major driving institutions of ASTE project

miniTAO/TAO

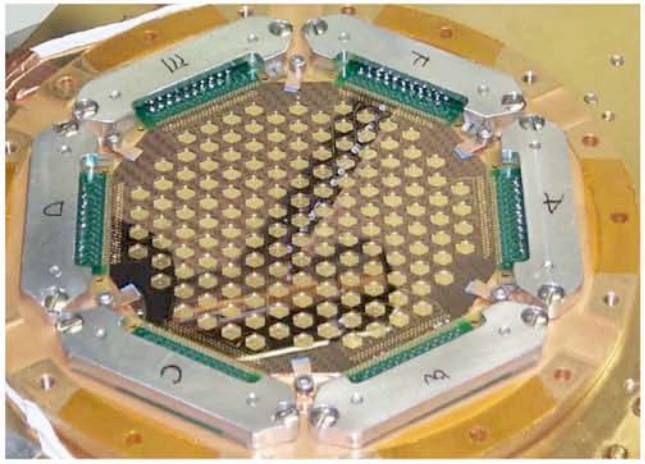
driven by IoA/UT

Access Road to the Chajnantor summit

- ~ 5.6 km to the summit
- Univ. of Tokyo constructed in 2006

TAO
THE UNIVERSITY OF TOKYO

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

PIs: K. Kohno (Univ. of Tokyo)
and G. Wilson (UMASS)

Collaborators

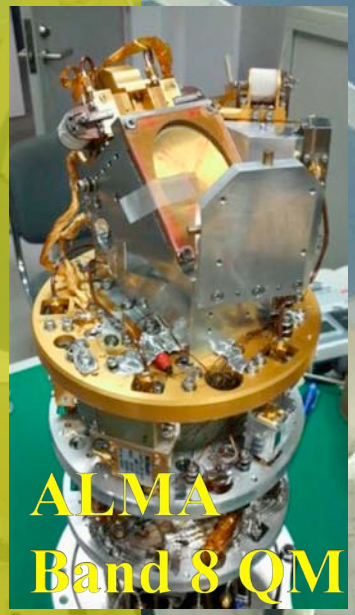
Bold font: ASTE executive committee members

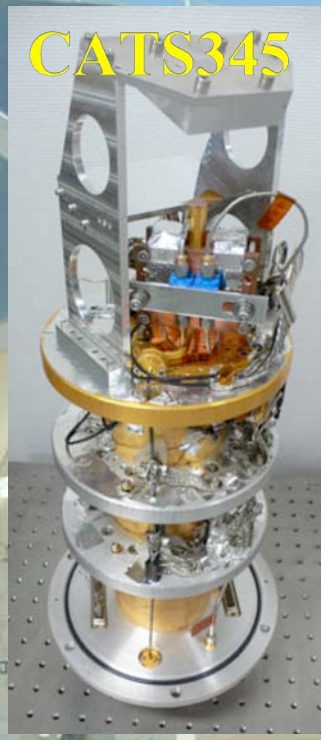
- **Kawabe, R., Oshima, T.,** Tamura, Y., Hatsukade, B., Matsuo, H., (NRO, NAOJ), **Ogasawara, R., Tatematsu, K.**, Nakanishi, K., Ezawa, H., (ALMA, NAOJ),
- **Kohno, K., Yamamoto, S., Sakai, T.**, Tsukagoshi, T., Inoue, H., Kenta, S., Ikarashi, S., Umehata, G. (Univ. of Tokyo),
- Minamidani, T., Takegoshi, T., (Hokkaido Univ.), Tanaka, K. (Keio Univ.), Tosaki, T. (Joetsu Univ. of Education), & ASTE team
- Cortes, J., (JAO), Bronfman, L. (Univ. of Chile), et al.
- Wilson, G.W., (PI. of AzTEC; UMASS), Aretxaga, I., Hughes, D.H., (INAOE), Yun, M.S., (UMASS), Austermann, J. (Colorado), Scott, K.S. (Univ. of Penn.), Perera, T. (Univ. of Chicago), & AzTEC team
- ADF-S/SXDS/SDF/SSA22 collaborations
- VLA: R. Ivison (Univ. of Edinburgh) et al.
- Z-Spec collaborations: M. Bradford (Caltech) et al.

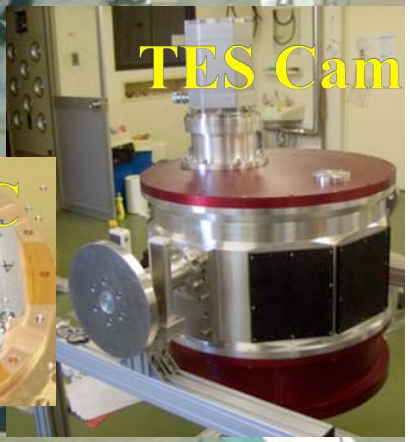
Atacama Submillimeter Telescope Experiment

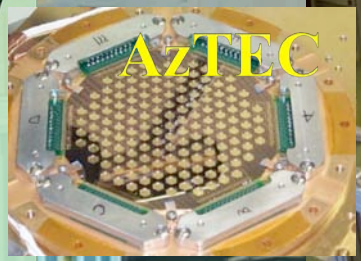
Atacama Submillimeter Telescope Experiment

- **Main reflector: D=10m, 20 um (rms)**
- **Heterodyne spectroscopy :**
  - **CATS345 (330-370 GHz)**
  - **ALAM Band-8 QM (400-500 GHz)**
  - **+ WHSF 8 GHz (max) 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/instruments/
http://www.nro.nao.ac.jp/~aste/cfp2010/
Next call for proposal will be issued by the end of 2010
(for the observing period from June to July, where
CATS345 or ALMA band 8 QM is available)

AzTEC/ASTE
1.1 mm deep surveys

Deep mm/submm surveys: Motivations

- Unveil hidden massive star-forming populations in the early universe ➔ determine "true" cosmic star formation history
- Clustering properties/LSS of SMGs ➔ underlying dark matter distributions as a function of redshift
- Understanding the formation and evolution of massive population of galaxies
  - Comparison with other high-z ; LBGs, LAEs, LABs, DRGs, BzKs, ...
  - Co-evolution of galaxies and super-massive BHs
- Understand the FIR cosmic backgrounds
  - Only ~10% of CFIRB (@lambda~1mm) is resolved into point sources so far. ➔ constraint on galaxy formation in the early epoch

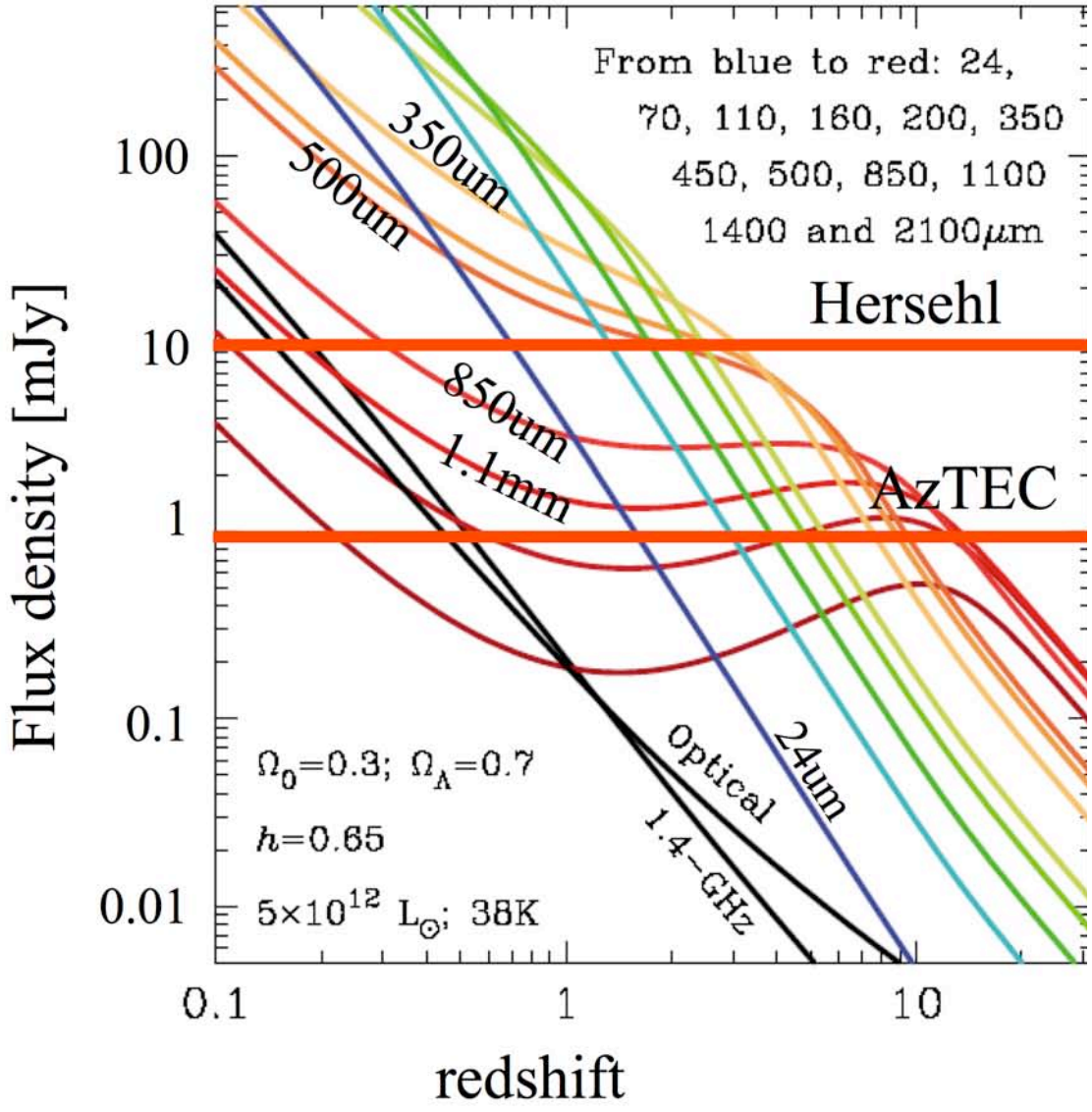
A large portion of cosmic SF is hidden by dust!
Mm/submm wide & deep surveys can probe them by negative K corr.

λ~1mm and SPIRE (λ250-500um) surveys: complementary to each other

- Almost constant flux for ~1 < z < ~10, at 850um ~ 1 mm, due to strong negative K correction
- It works at 350-500 um bands but less significant compared with 850um ~ 1 mm

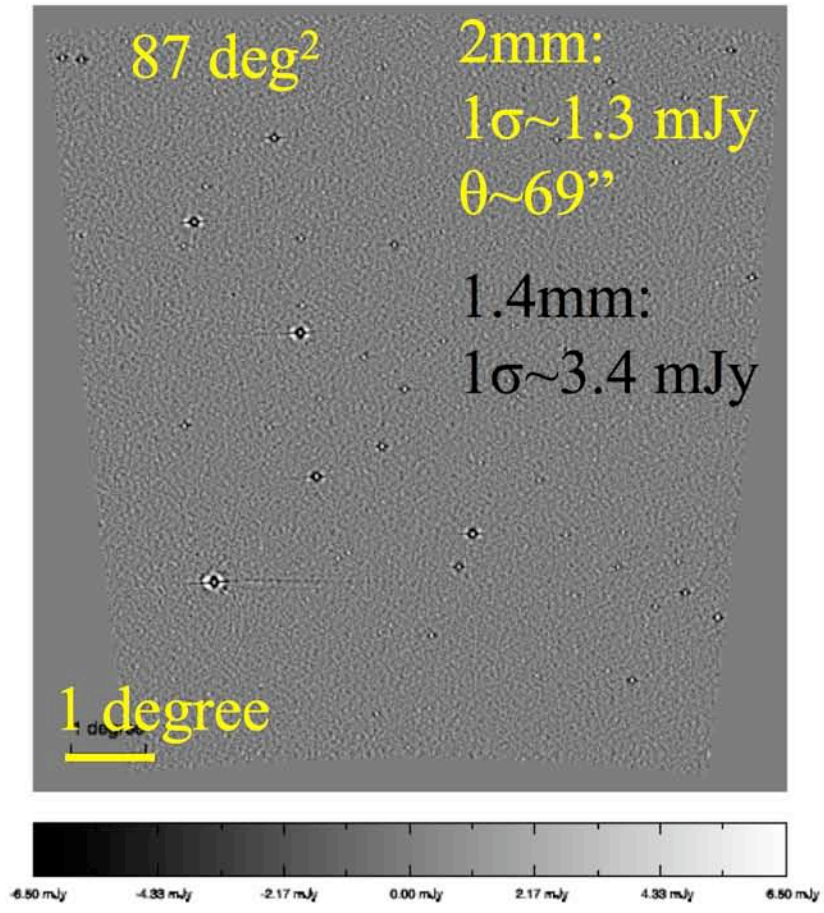
➔ Combination of these surveys offers efficient measures of redshifts

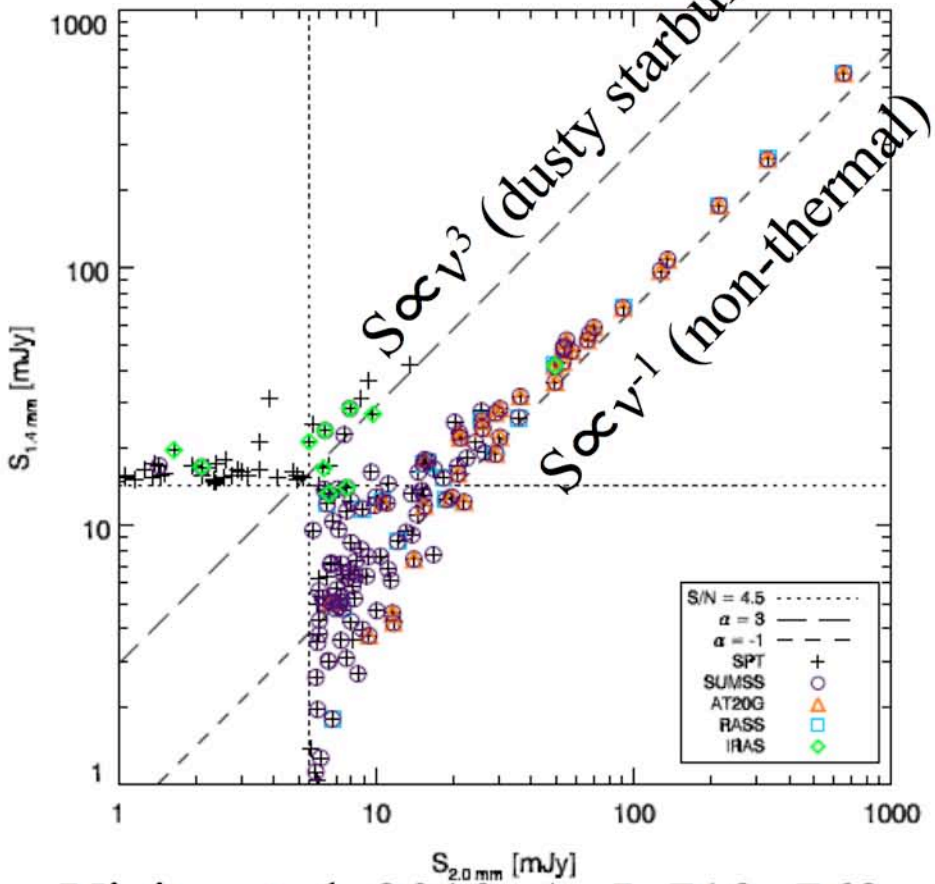
Blain et al., 2002, Physics Reports, 369, 111-176



SPT 1.4 mm & 2.0 mm surveys

- Longer wavelengths ➔ dominated by local non-thermal (radio-loud) objects (see also Voss et al. 2006, A&A, 448, 823 by MAMBO surveys)





Vieira et al. 2010, ApJ, 719, 763

AzTEC-ASTE 1.1 mm deep surveys

- wide (~1.6 deg^2) & deep ($1\sigma \sim 0.4 - 1.5$ mJy ⇔ ULIRGs @z>1) surveys of blank fields: yielding >820 robust detections

Field name	Survey area (30-50% cov.)	Noise level (1σ)	N. of sources (S/N > 3.5)	Reference
SXDF	956 arcmin^2	0.5 – 0.9 mJy	206	Ikarashi+ in prep.
SSA22	992 arcmin^2	0.6 – 1.2 mJy	127	Tamura+2009, Nature, 459, 61 Tamura+ in prep.
ADF-S	909 arcmin^2	0.4 – 0.8 mJy	198	Hatsukade+2010, MN, in press
SDF	210 arcmin^2	0.7 – 1.1 mJy	25	Ikarashi+ in prep.
COSMOS	2590 arcmin^2	1.0 – 1.5 mJy	189	Wilson+ in prep.
GOODS-S	270 arcmin^2	0.5 – 0.7 mJy	48	Scott+2010, MN, 405, 2260

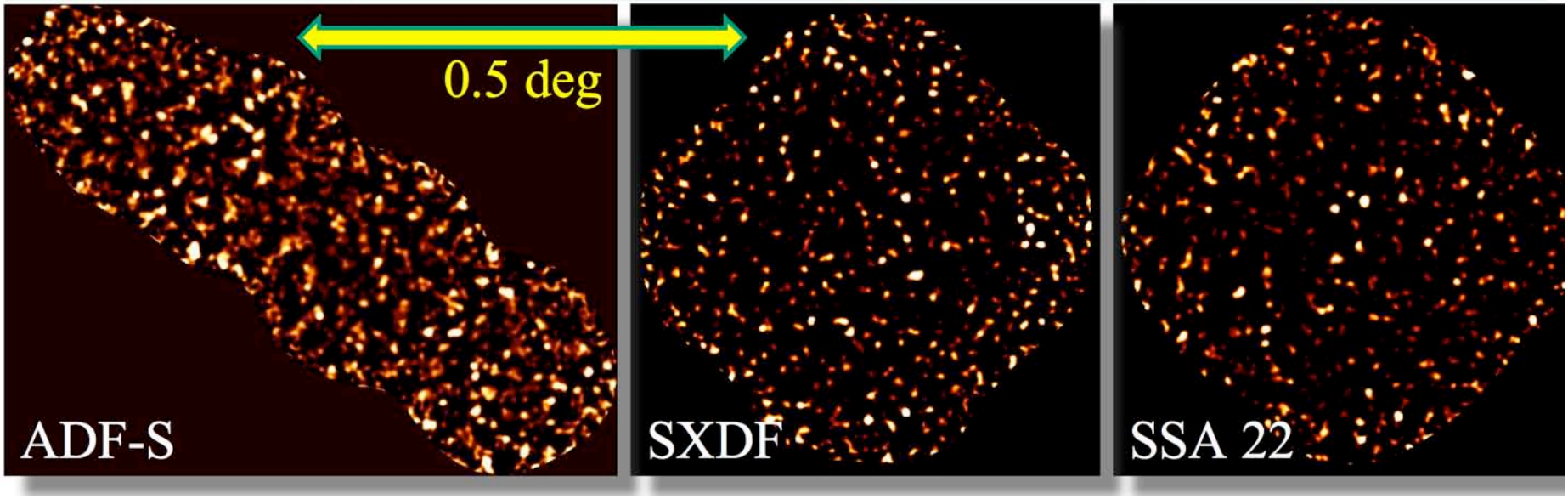
(+ SXDF clumps, HDF-S, ECDF-S)

- 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, the largest ~1mm selected SMG sample

AzTEC/ASTE 1.1 mm Deep 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
N sources (>3.5σ)	**198**	**206**	**127**
reference	Hatsukade+10 MNRAS in press	Ikarashi+10 arXiv1009.1455I	Tamura+09 Nature, 459, 61



Ultra-bright SMGs:

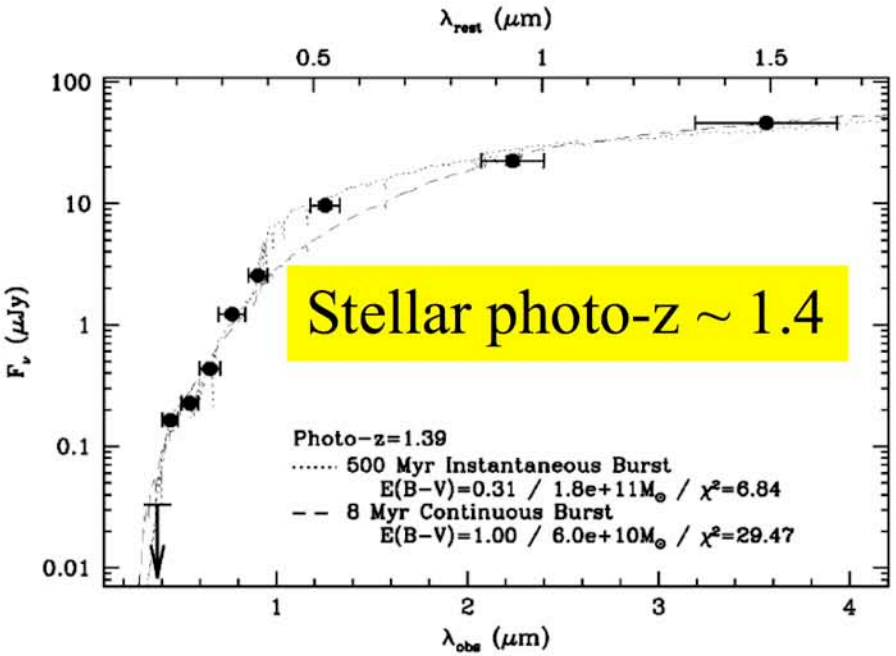
a lensed population
providing opportunities to make
detailed studies of high-z extreme
starbursts

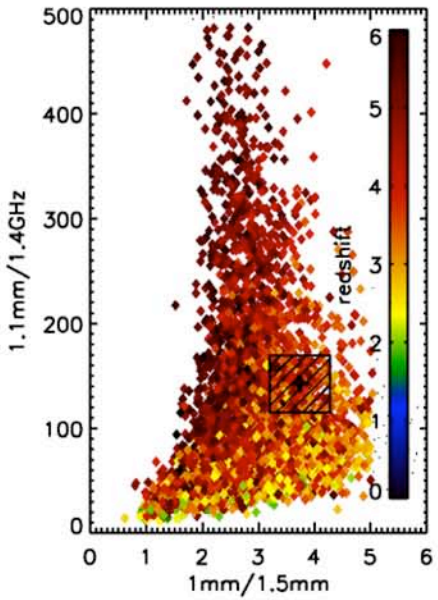
SXDF1100.1/Orochi: a z~3.4 SMG behind a cluster/gal at z~1.4?

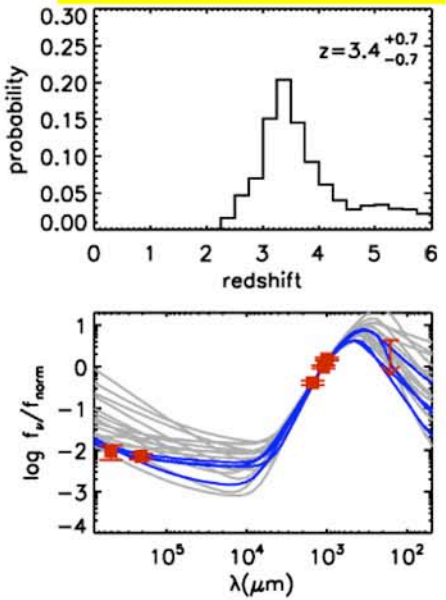
Ikarashi et al. 2010, submitted to MNRAS

- Inconsistency between photo-zs with UV to NIR SED and FIR/submm to radio SEDs
- ➔ overlapping of z~3.4 SMG and foreground lensing object (cluster or a galaxy): importance of interferometric IDs with high resolution !

Submm-radio photo-z ~ 3.4

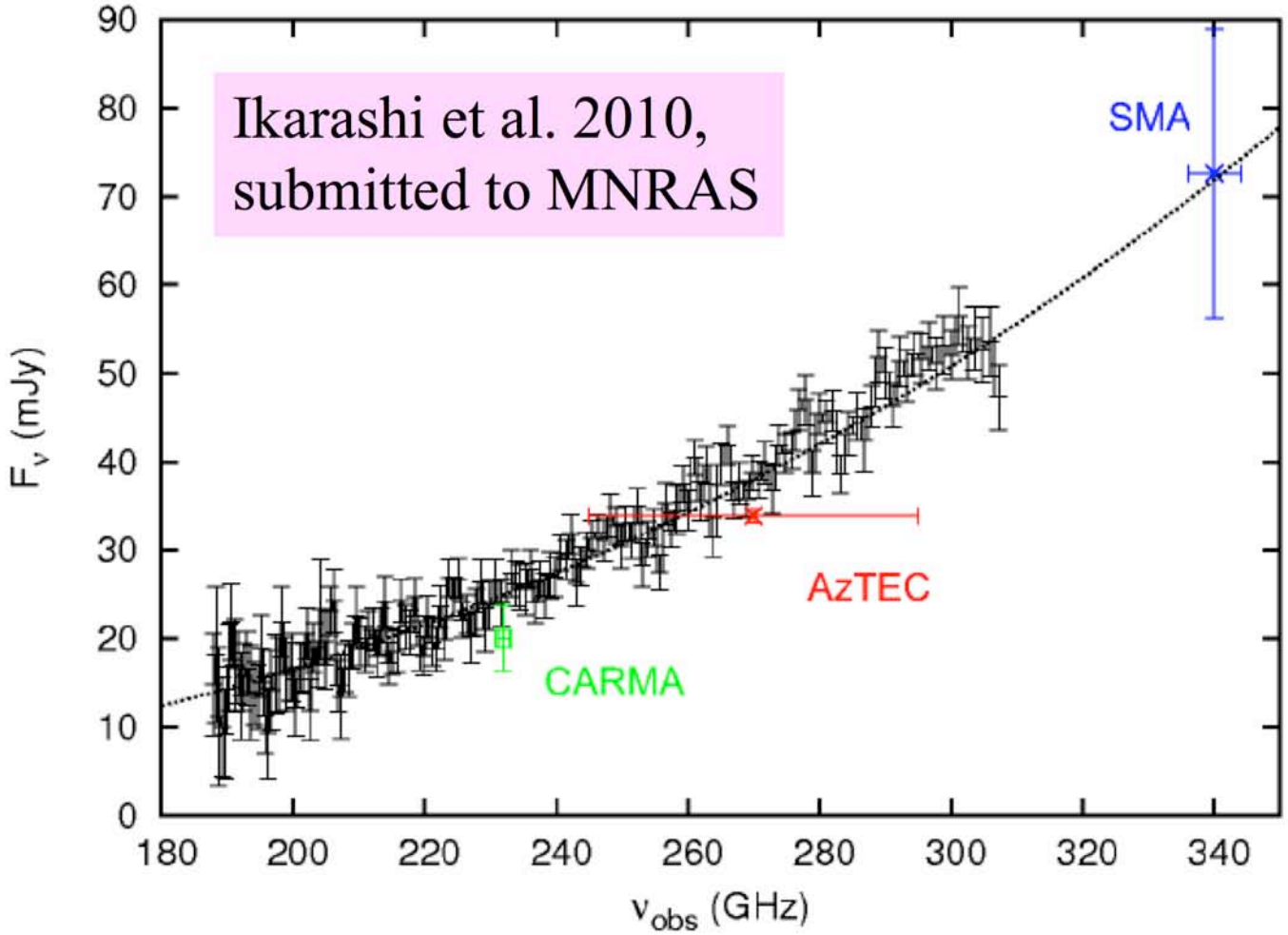






Z-Spec/CSO spectrum of Orochi

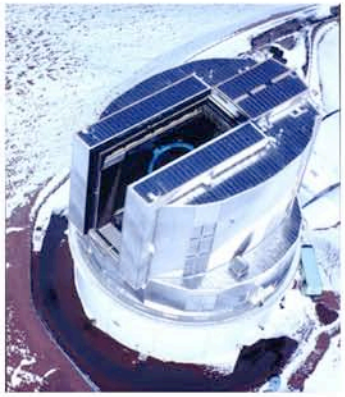
- No significant lines; the very low line-to-continuum ratios also indicate this is a high redshift source



Clustering properties: relation to large scale structures

Bright SMGs in SSA22 by AzTEC/ASTE

SUBARU

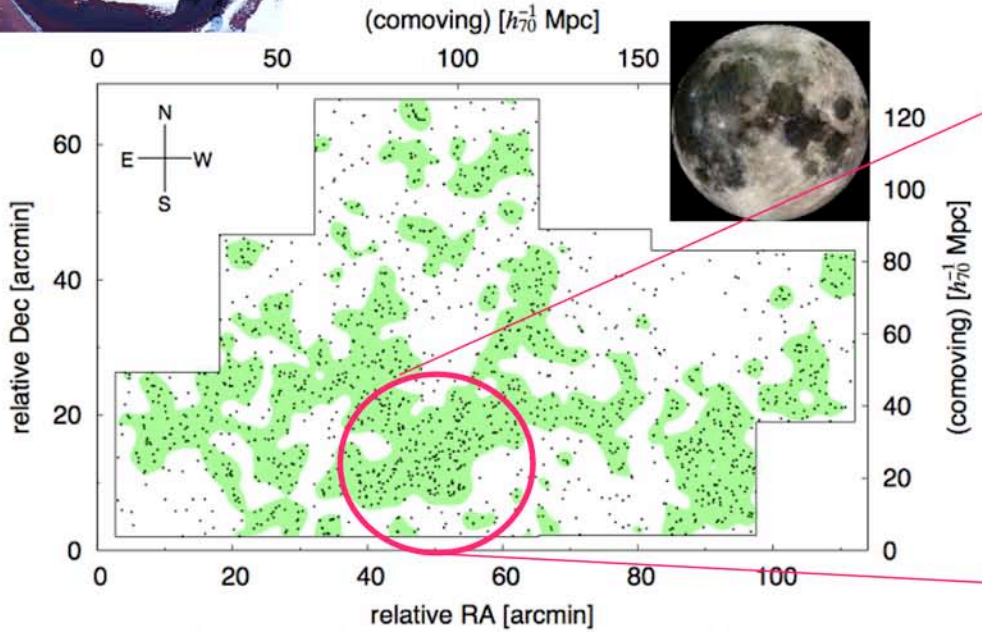


Lyman Alpha Emitters

LAEs

SFR ~ a few Mo/yr

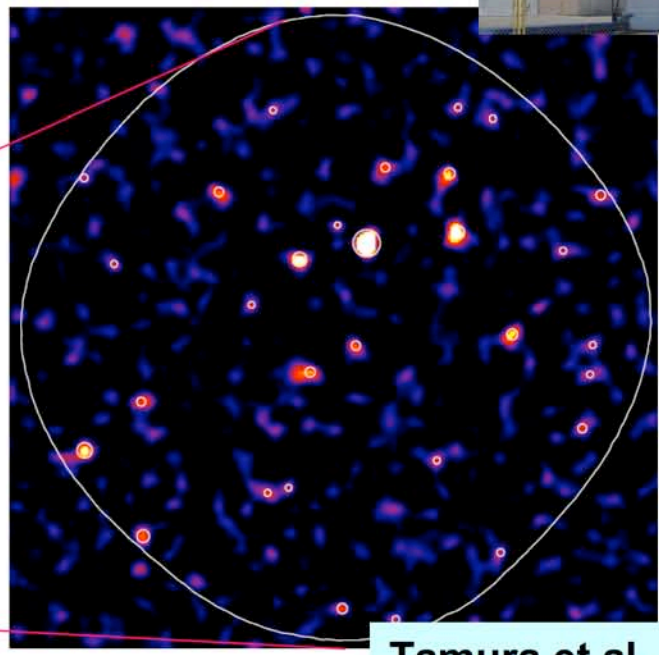
Distribution of LAEs
Around z~3.1
Nakamura et al.



SMGs

SFR ~ a few 100
– a few 1000 Mo/yr

ASTE

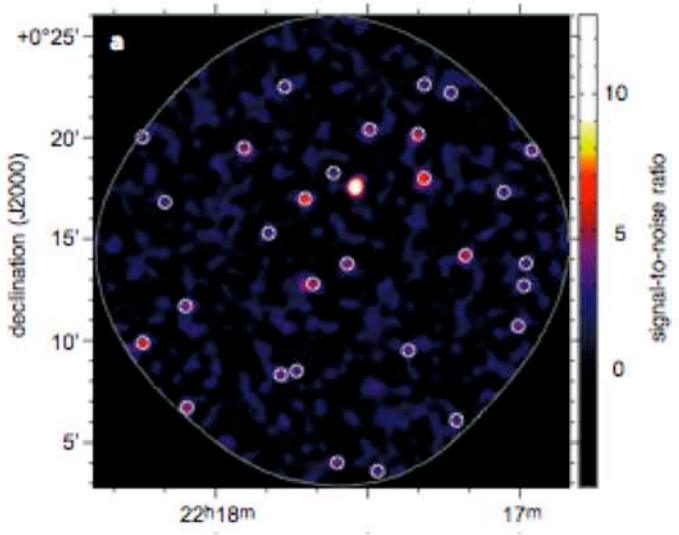


Tamura et al., 2009, Nature, 459, 61

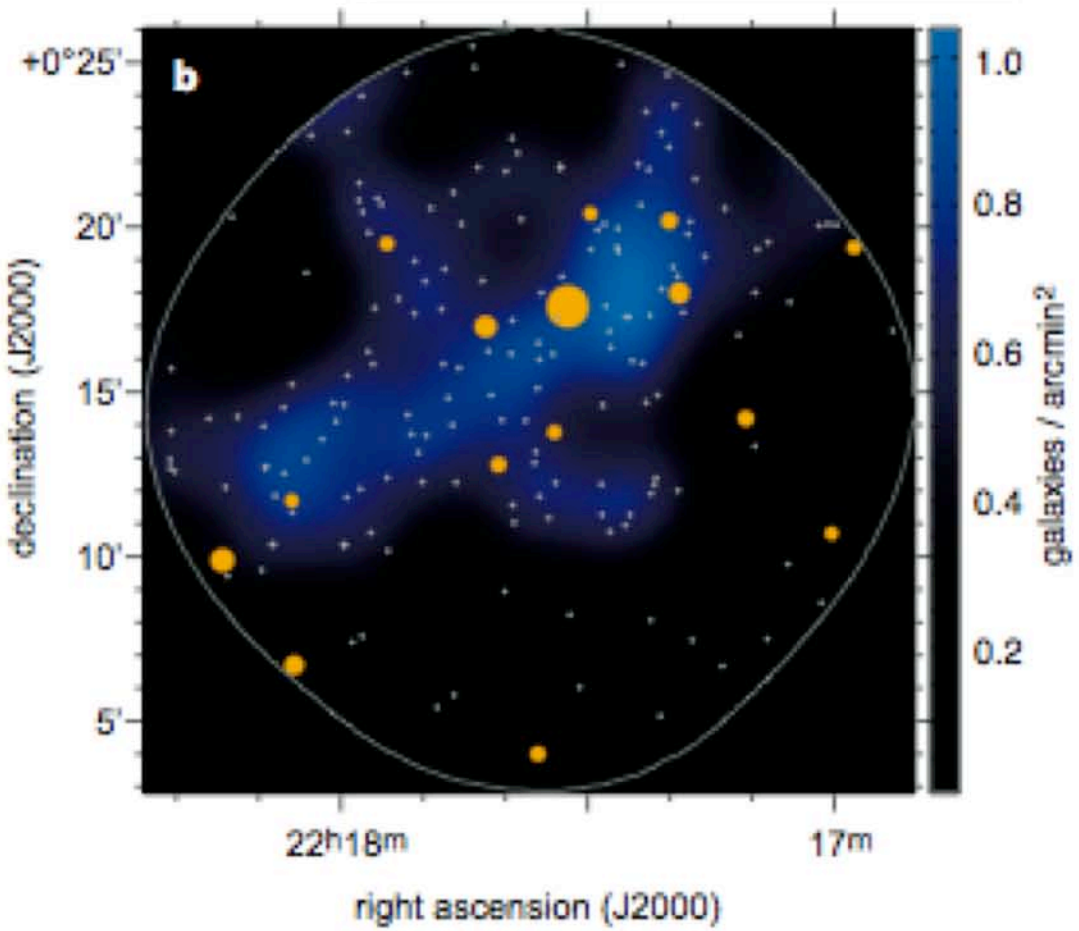
No one-by-one correspondence
to LAEs, but clustered at the LAE density peak

Clustering of SMGs toward the biased region traced by LAEs

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



1.1mm image

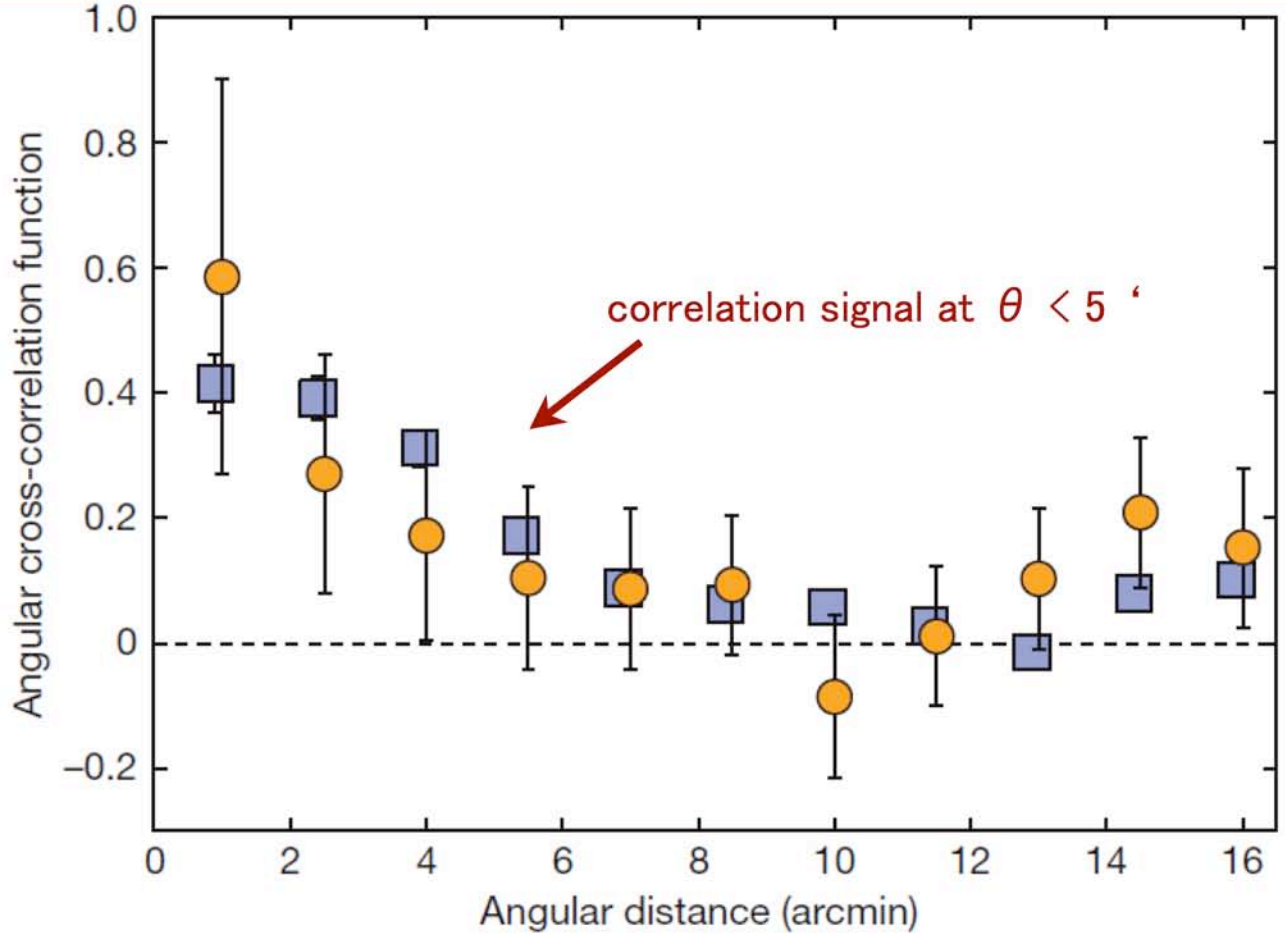


Bright SMGs
on Ly α emitters
at z~3.1

Angular cross correlation between SMGs & LAEs

- Landy & Szalay's estimator
- probability of finding a source of the other population at distance θ

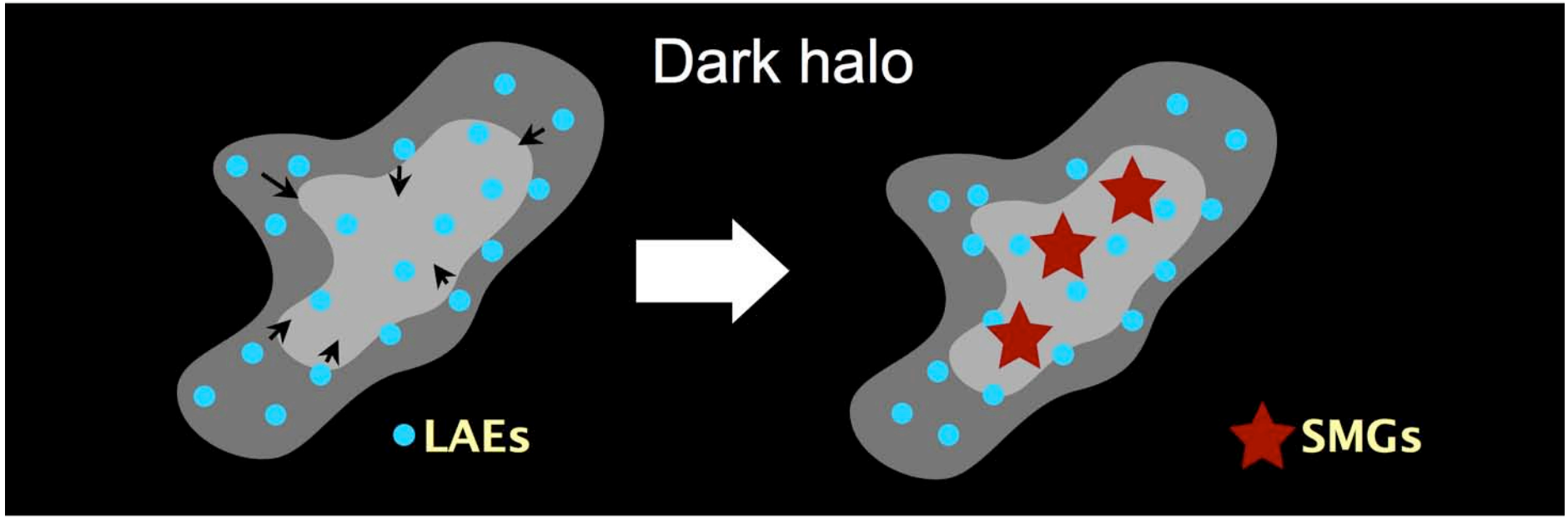
- A clear detection of cross correlation signal with z=3.1 LAEs
  ➔ detected bright SMGs in SSA 22 are also clustered around z~3 !



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

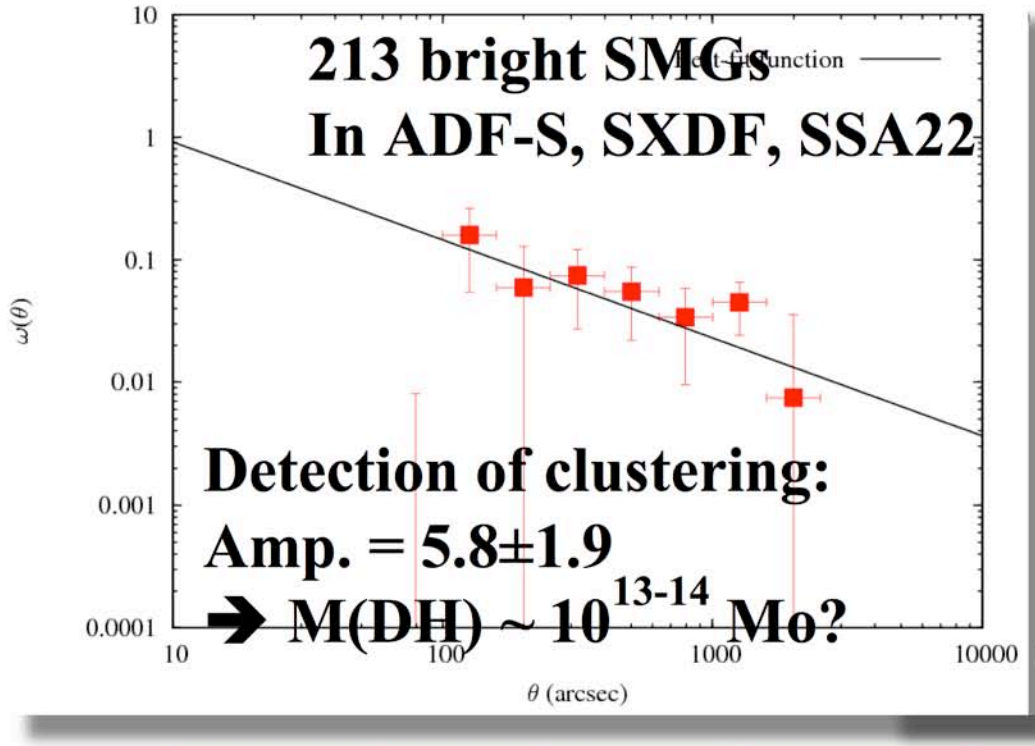
Tracing the heart of massive dark halo with SMGs

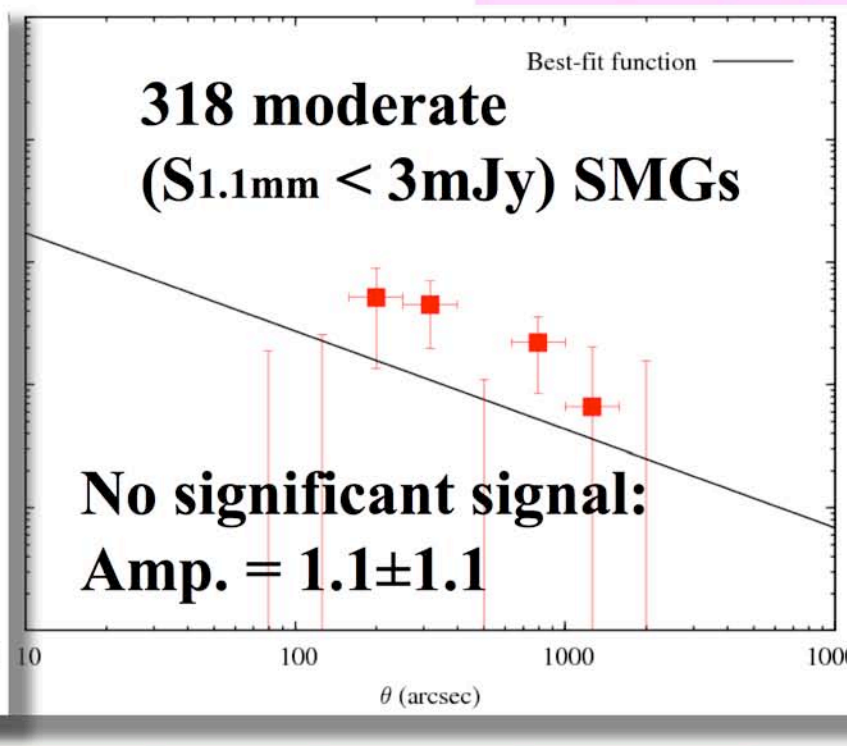
- Structure formation w/ Λ cold dark matter model
  - young, less massive galaxies (LAEs) are falling into the heart of the massive dark halo
  - Massive starburst galaxies (SMGs) are grown there



Bright ($S_{1.1mm}$>3mJy) SMGs tend to be strongly clustered

Hatsukade+ 2010, in prep.





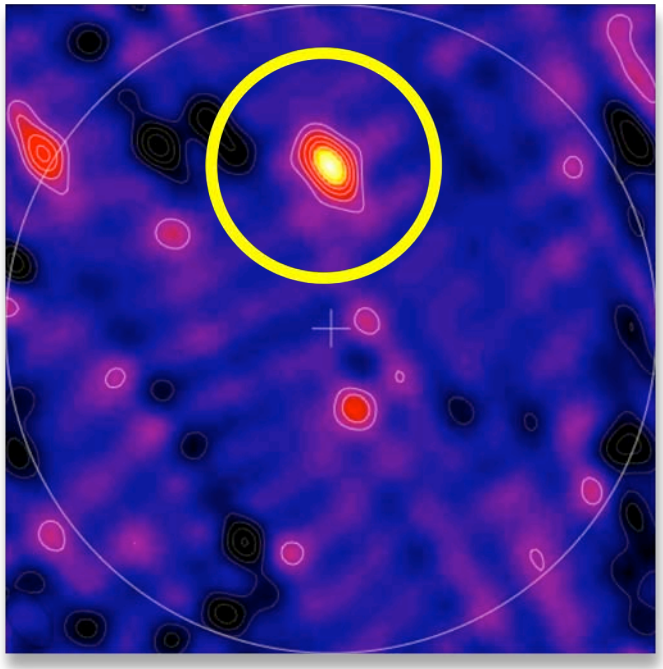
Field	Source	N source	Amplitude	Field	Source	N source	Amplitude
ADF-S	>3mJy	65	14±6.7	SSA22	>3mJy	79	---
	<3mJy	133	---		<3mJy	48	---
SXDF	>3mJy	69	6.1±5.6	Combine	>3mJy	213	5.8±1.9
	<3mJy	137	2.2±2.7		<3mJy	318	1.1±1.1

Very dark SMGs:

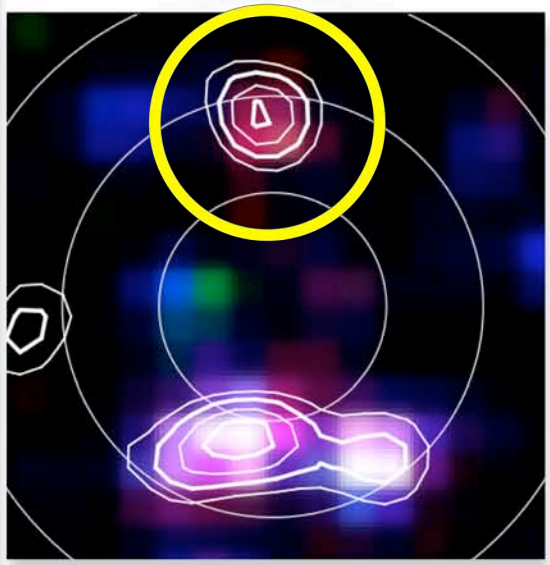
Extreme starburst population
Unexplored with NIR surveys
using existing 8m class
telescopes

Multi-wavelengths ID of the brightest SMG in SSA22

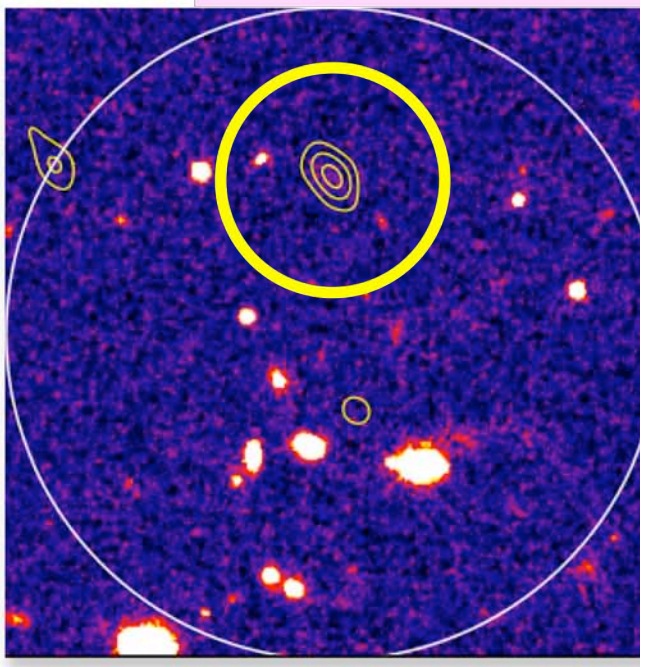
Ks > 24.9 mag(AB),
2σ upper limit



SMA 860μm



Color : Spitzer/IRAC
Contour : VLA 20cm



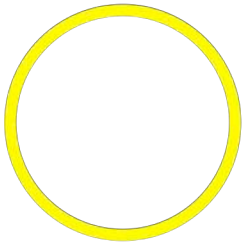
Color: 2um Subaru/MOIRCS
(Uchimoto et al., 2008)
Contour : SMA 860μm

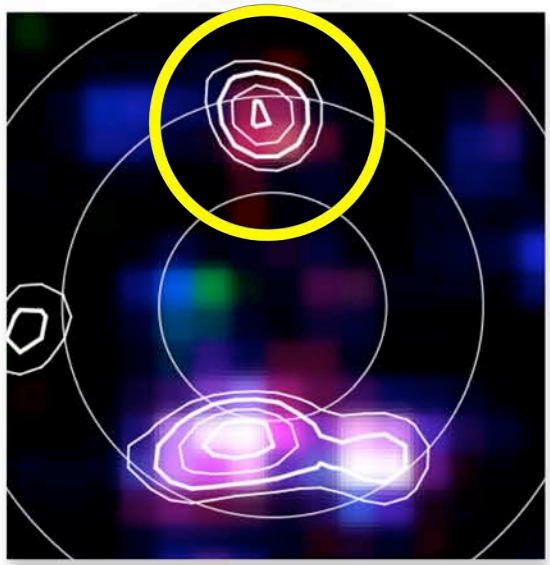
- very "red" in MIR(IRAC) bands !
- K-drop out !? even with SUBARU

Y. Tamura et al.
2010, in press

Multi-wavelengths ID of the brightest SMG in SSA22

Ks > 24.9 mag(AB), 2σ upper limit





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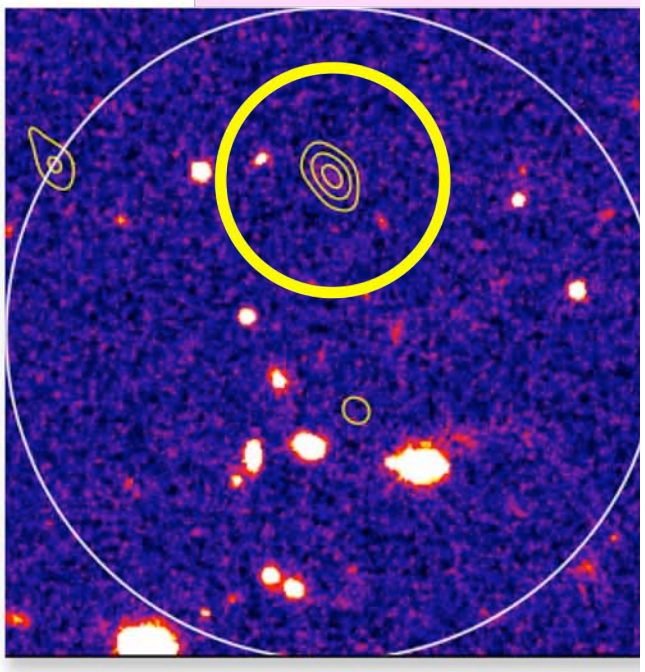

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- very "red" in MIR(IRAC) bands !
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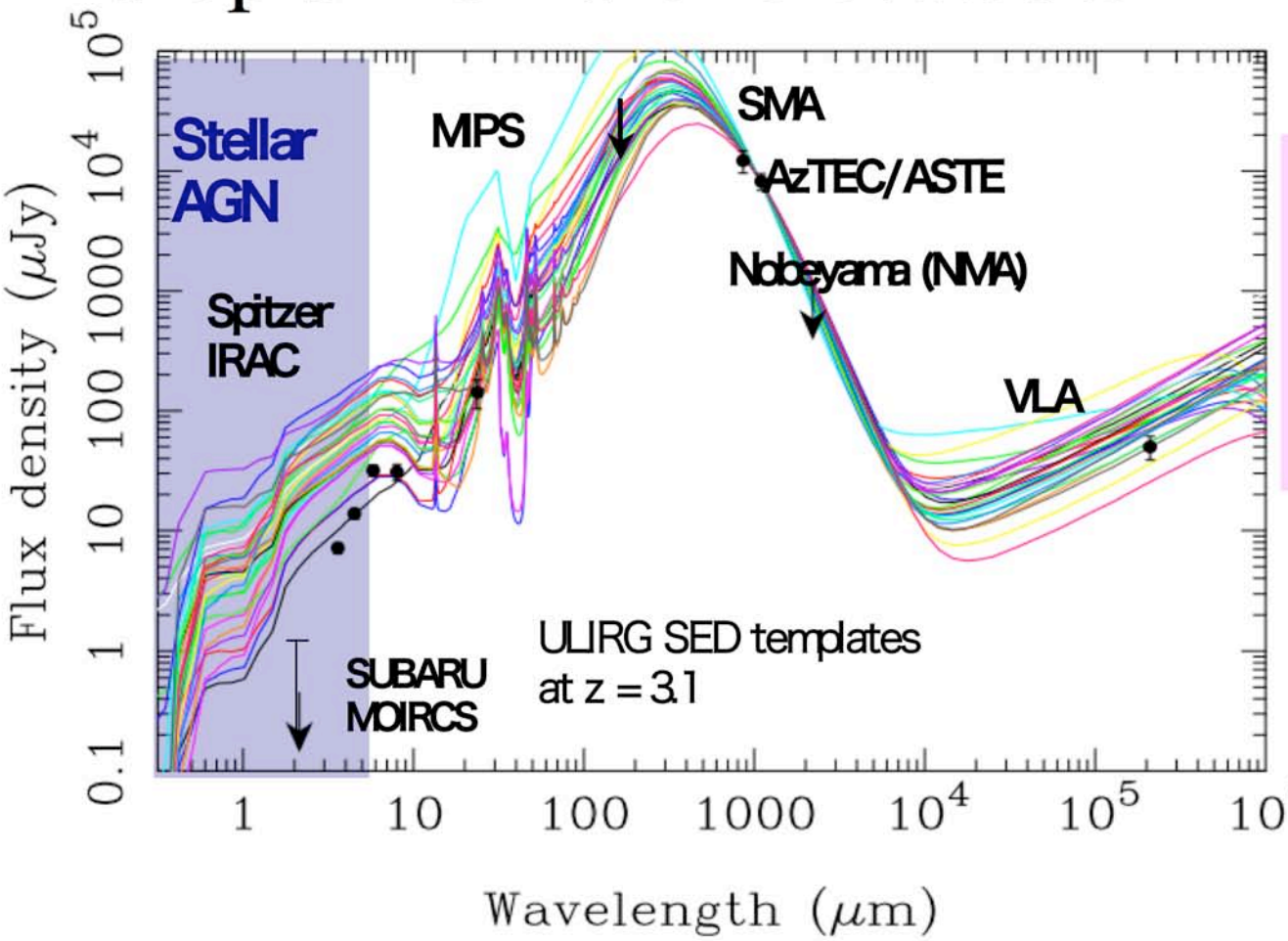
Y. Tamura et al. 2010, in press

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



Tamura et al. 2010 in press

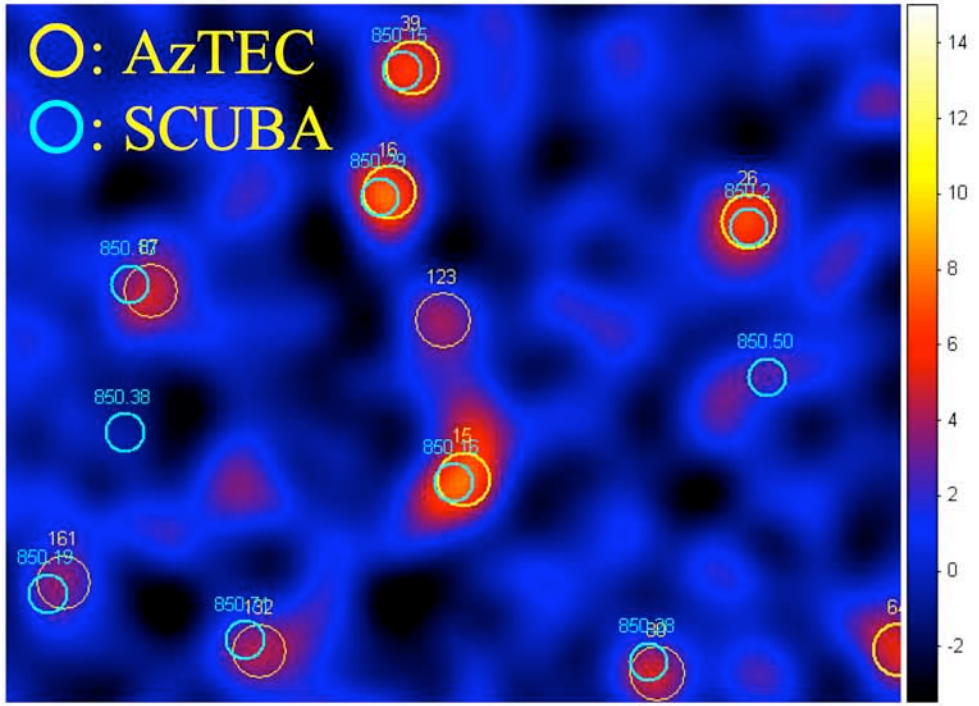
It is very surprising that this kind of monster can't be uncovered with existing NIR deep surveys!

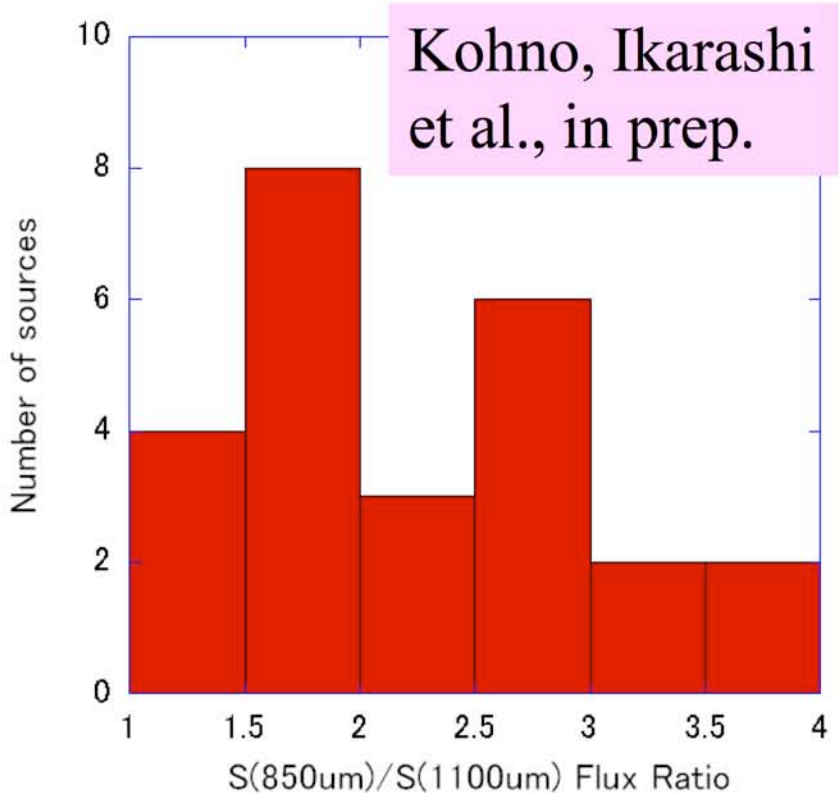
- Detection of a deeply obscured ($N_H \sim 10^{24} cm^{-2}$) hard X-ray source ➔ proto-quasar phase? Growing SMBH?
- SED ➔ Mstar ~7×10^{10} Mo ➔ growing bulge?

A quest for the highest-z Submm galaxies

A search for high-z SMGs 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)
  - Most of them are 20cm faint

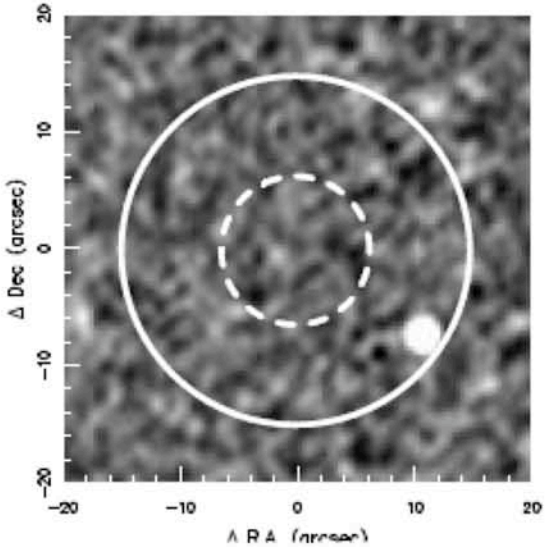




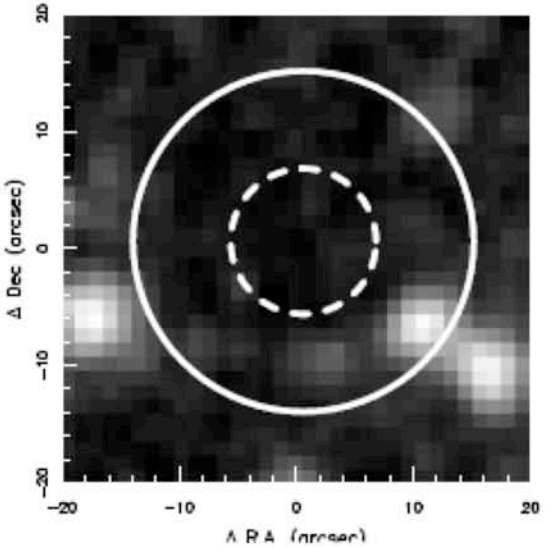
Very high-z SMG candidates from AzTEC/ASTE in SXDF

- Nothing can be seen @deep 20cm, 24um, 8um despite the high significance detection at 1.1mm

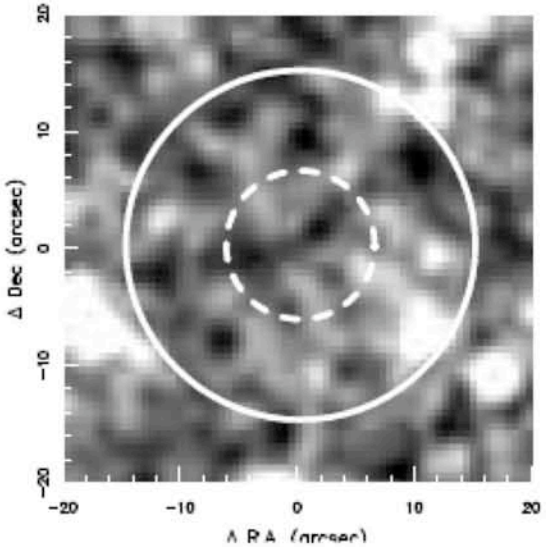
VLA 20cm



MIPS 24um



IRAC 8um



Ikarashi et al., in prep.

Future plans

Future plan with ASTE(+NRO 45m)

- Extended, multi-color surveys to constrain the redshift distribution of mm-selected SMGs ➔ can address evolutions of cosmic SF, LLS, massive galaxies, etc.
  - 1100/850/450um multi-color TES array ➔ dz~0.5
  - Moderate size (~1000 pix in total), but superb atmosphere in Atacama & fast scan capability of ASTE will help us
- Spectroscopic redshift with 32 GHz width z-machine on NRO 45 m telescope @3mm band
  - make best use of ALMA RX and ACA correlator technologies
- Explore the power source of SMGs
  - Establishing the proposed diagnostic method of nuclear power source in dusty galaxies using HCN/HCO^+ and other mm/submm lines

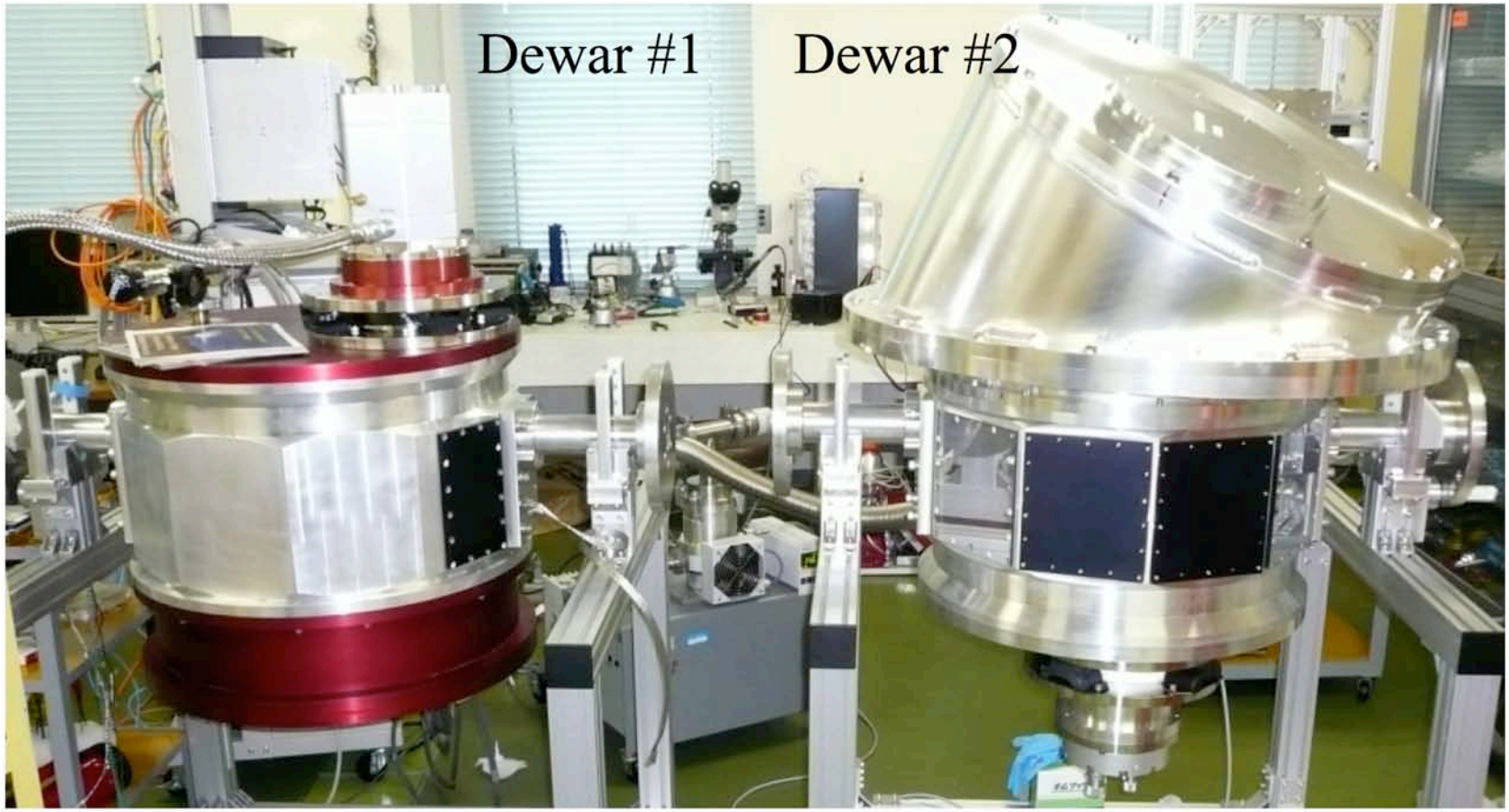
Expected mapping speeds with multi-color TES array on ASTE

	Num. of pix	Beam size	Mapping speed [arcmin^2 mJy^{-2} hr^{-1}]
AzTEC 1100 um	105	28”	20
New TES array 1100um	169	28”	30 (➔ improved by fast-scan technique?!)
850 um	271	22”	~5
450 um	881	11”	~0.3

cf. SPIRE@500um:
~ 15 arcmin^2 mJy^{-2} hr^{-1}

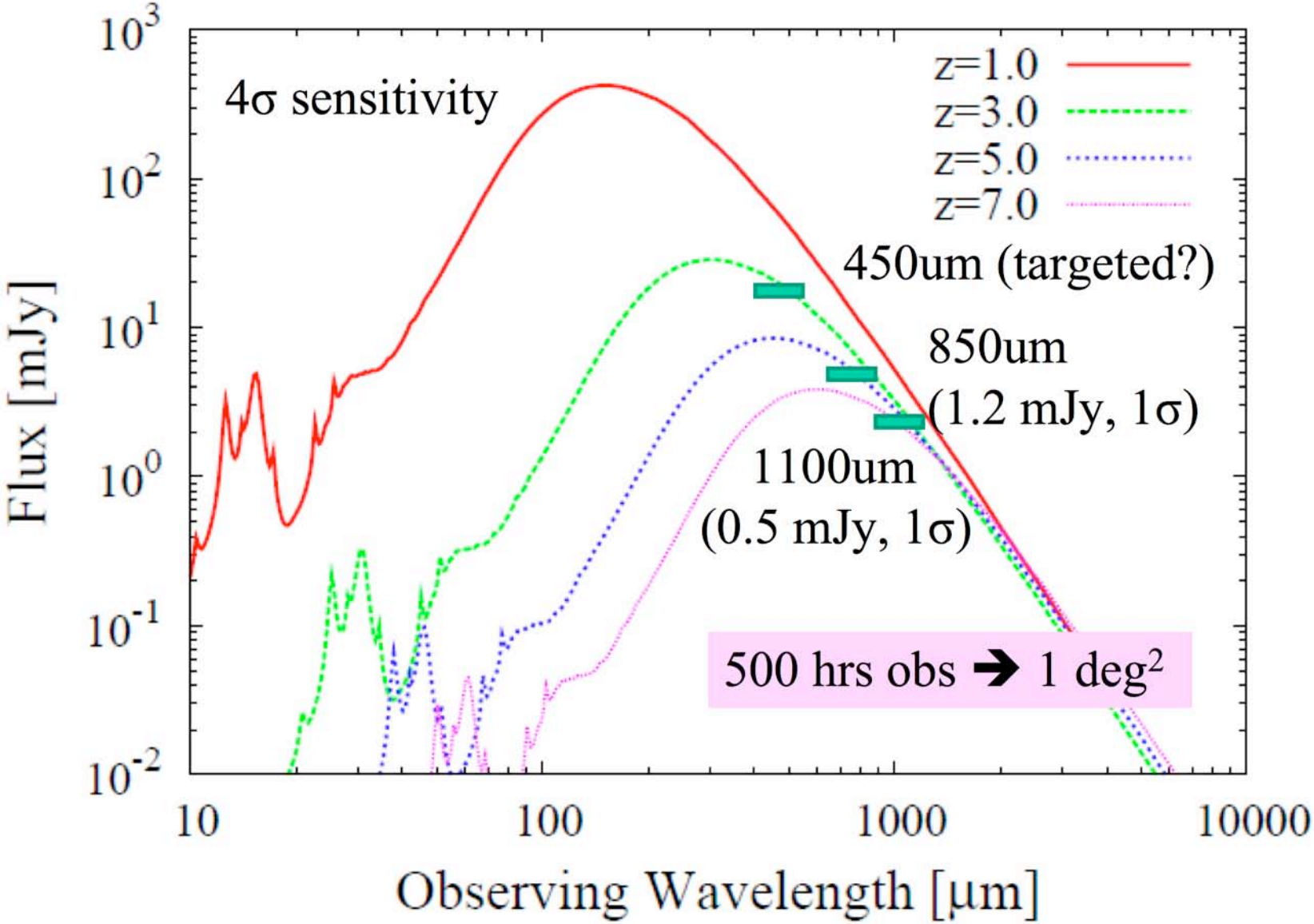
- Possible strategy
  - Unbiased survey at 1100/850 um bands ➔ uncover interesting sources (especially z>4 SMG candidates)
  - Targeted photometry/high-reso imaging at 450 um bands

Dewars in the lab. of NRO



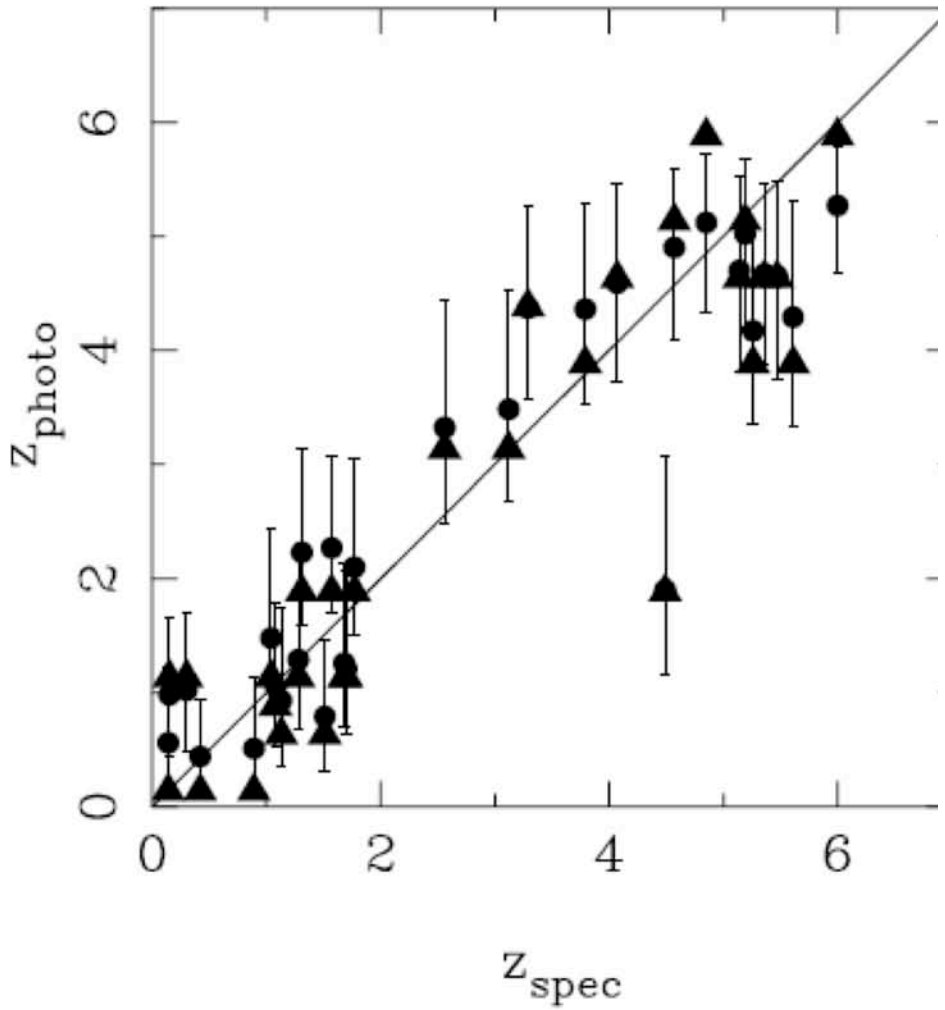
Development team:
NRO-NAOJ, Univ. of Tokyo, Hokkaido Univ., KEK in Japan +
UC Berkley (TES array), Cardiff (filters, etc.), McGill (readout)

Planned survey sensitivity with multi-color TES camera on ASTE



A simulation on "dust-z" accuracy

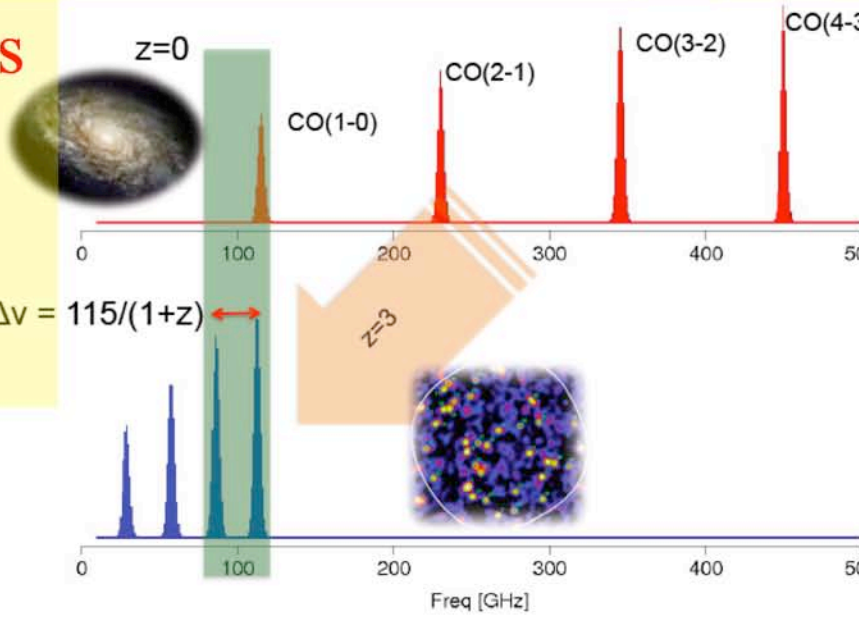
- 3 bands (1100um, 850um, & 450um)
- "Virtual observations" of modeled SMGs with various SEDs (with "appropriate" weighting)
- dz~0.5 can be achieved with 3 bands photometry of SMGs

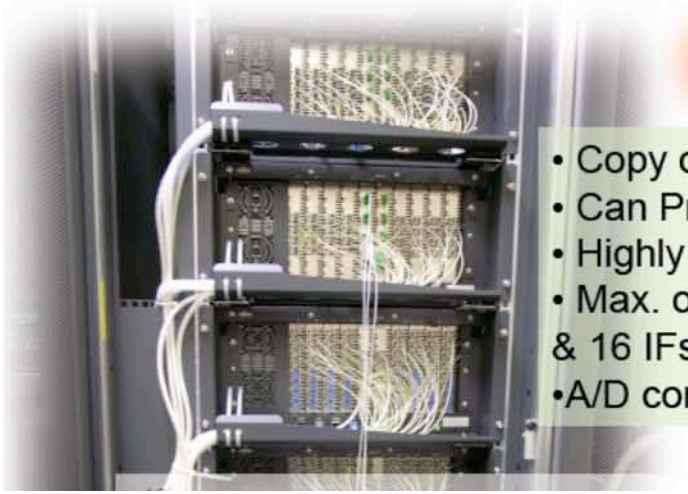


Yoichi Tamura, 2009

z-machine for NRO 45m Telescope

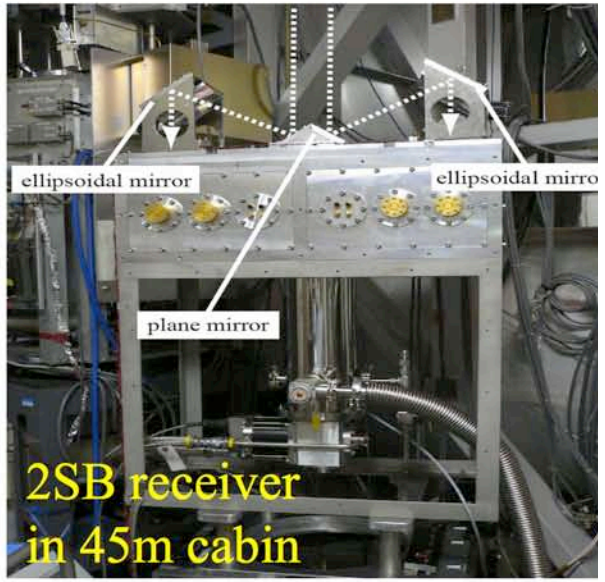
- Blind CO line Search for SMGs
- 2GHz x 16 units = 32 GHz
- Make the best use of ALMA-J technologies !
  - Receivers & ACA corr.
- Commissioning in progress
- Science verification: Dec. 2010-





SAM 45

- Copy of the ALMA/ACA correlator.
- Can Process 32 GHz in total
- Highly flexible
- Max. of 8192 channels/IF(2-4 GHz) & 16 IFs. = > ~ 130 k ch. In total
- A/D converter (4 Gsps & 3 bits).



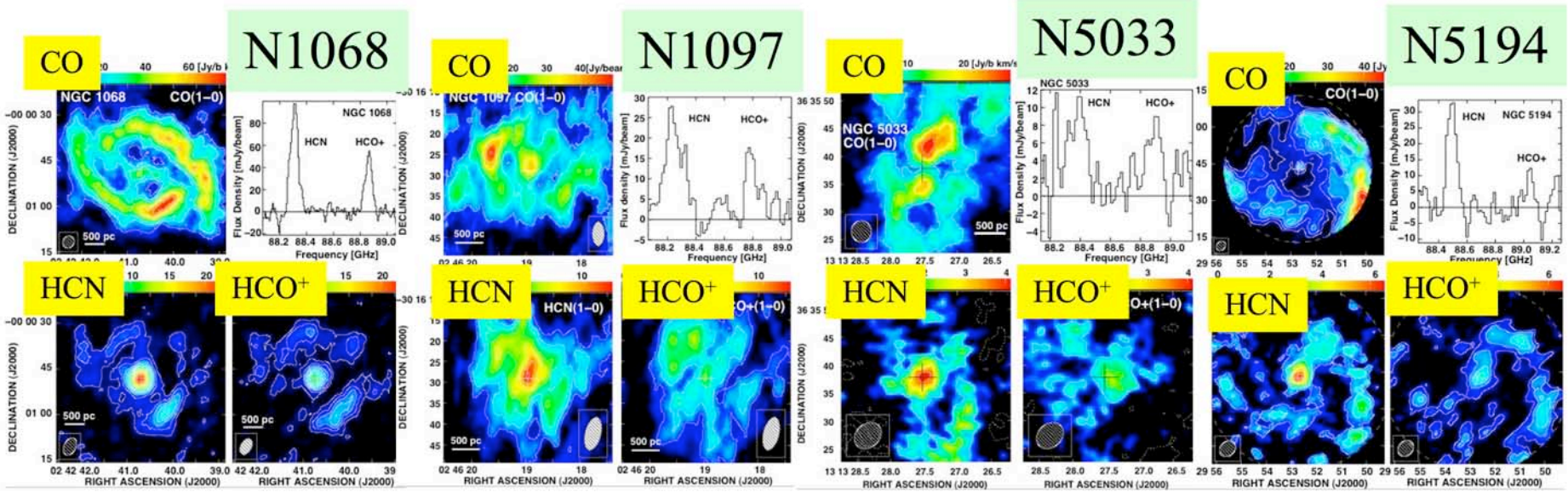
Exploring the growth of proto-quasars within extreme starbursts

- Infrared: often very dark
- X-ray: can be Compton thick, sensitivity issue
- Mm and submm spectroscopy may provide new diagnostics of the power source in extremely dusty nuclei
  - Need high angular resolution and sensitivity

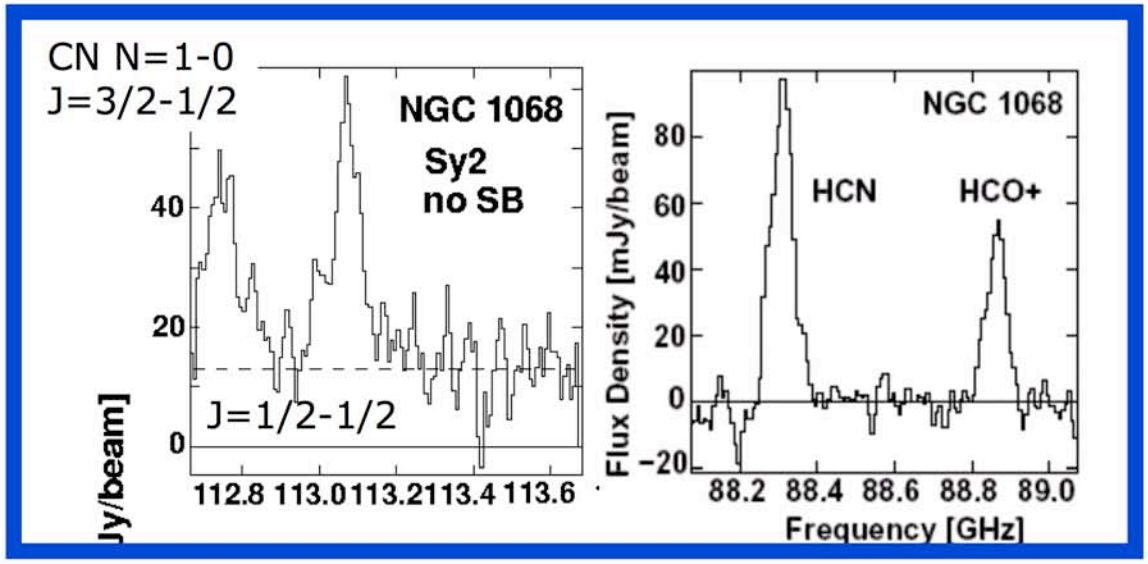
    ➔ need ALAM !
  - to establish the method using nearby galaxies is the way to go now (ASTE, NRO 45m + wide-band spectroscopy systems)

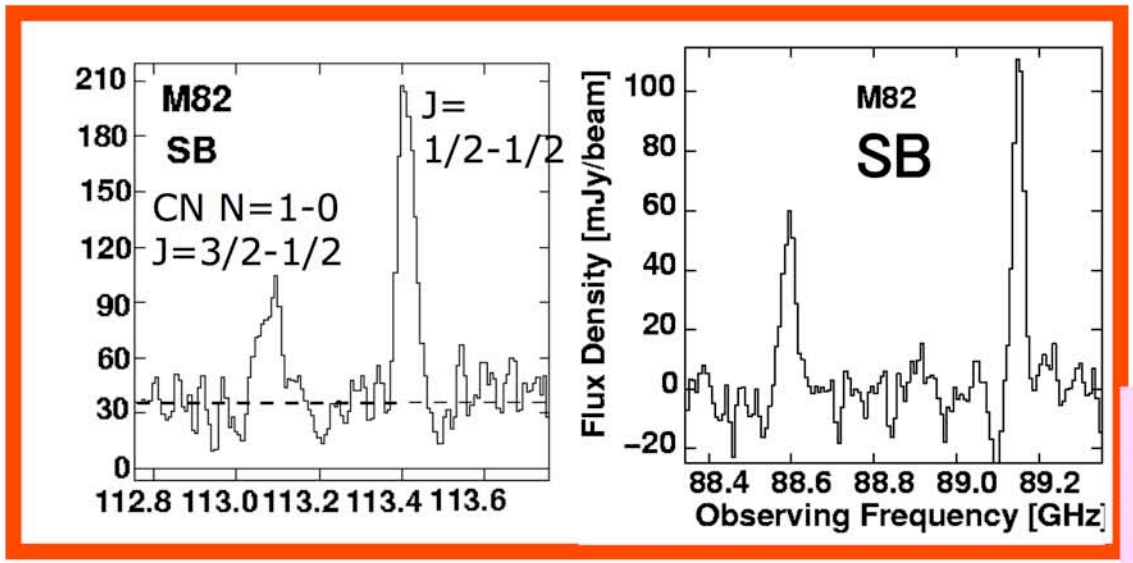
“HCN Enhanced Nuclei” (HENs)

- NGC 1068 (Sy 1.8) : Jackson et al. 1993 (NMA), Tacconi et al. 1994 (PdBI), Helfer & Blitz 1995 (BIMA), Kohno et al. 2008, ApSS, 313, 279
- NGC 5194 (Sy 2) : Kohno et al. 1996, ApJ, 461, L29 (NMA)
- NGC 1097 (Sy 1) : Kohno et al. 2003, PASJ, 55, L1 (NMA)
- NGC 5033 (Sy 1.5) : Kohno et al. 2005, astro-ph/0508420 (NMA)
- NGC 4501 (Sy2), NGC 4388 (Sy2) : Kohno et al. (in prep.; NMA)



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





AGN:

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

➔XDR chemistry?

MIR pumping? Maser?

Starburst:

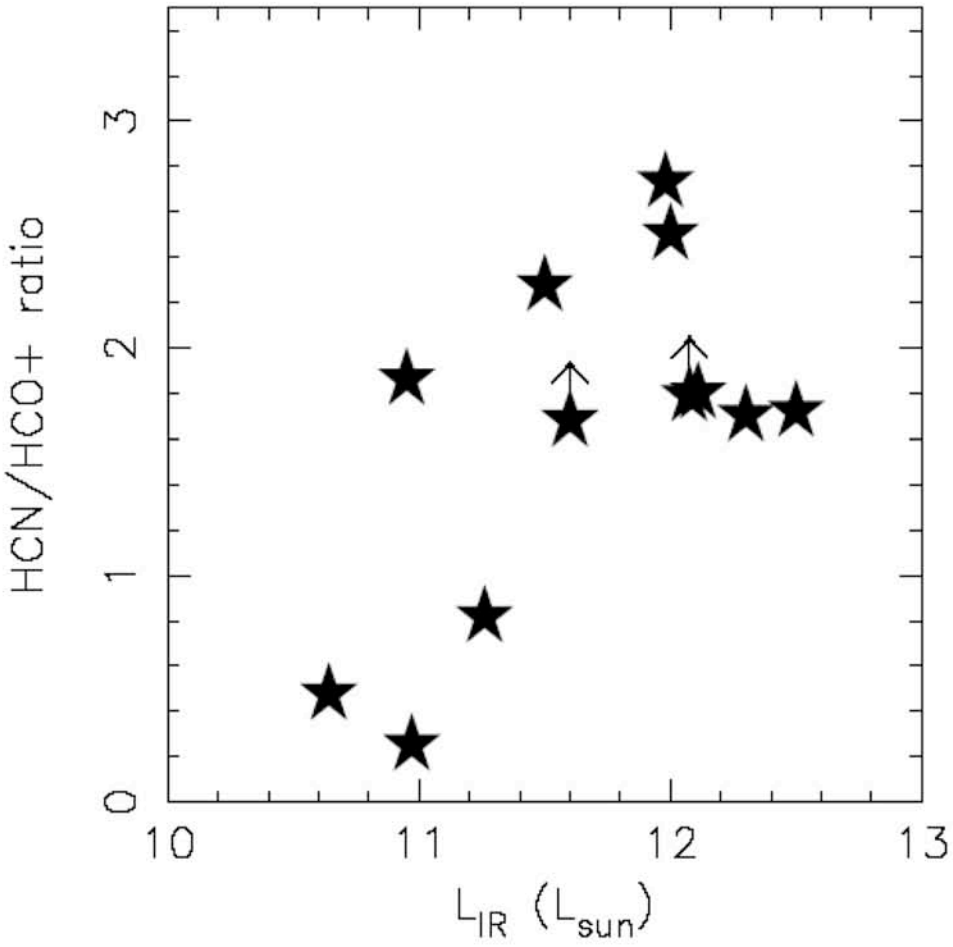
- **HCN/HCO$^+$ $\sim$1**
- CN($J=^3/_2$-$^1/_2$) /($J=^1/_2$-$^1/_2$)$\sim$0.3

➔PDR chemistry?

Nobeyama Millimeter Array
Kohno et al. 2001, 2005,
Kohno et al. 2008, ApSS, 313, 279

Larger AGN contribution to more luminous IR galaxies ?

- Local LIRGs/ULIRGs
- HCN/HCO^+ ratios vs L(FIR) ➔ trend?➔ larger contribution of AGN in more luminous IR galaxies?
- What is going on @HyLIRGs～SMGs?



Imanishi, et al.
2007, AJ, 124, 2366

ALMA spectroscopy of dusty starbursts can probe heavily obscured, growing AGN?

Larger AGN contribution to more luminous IR galaxies ?

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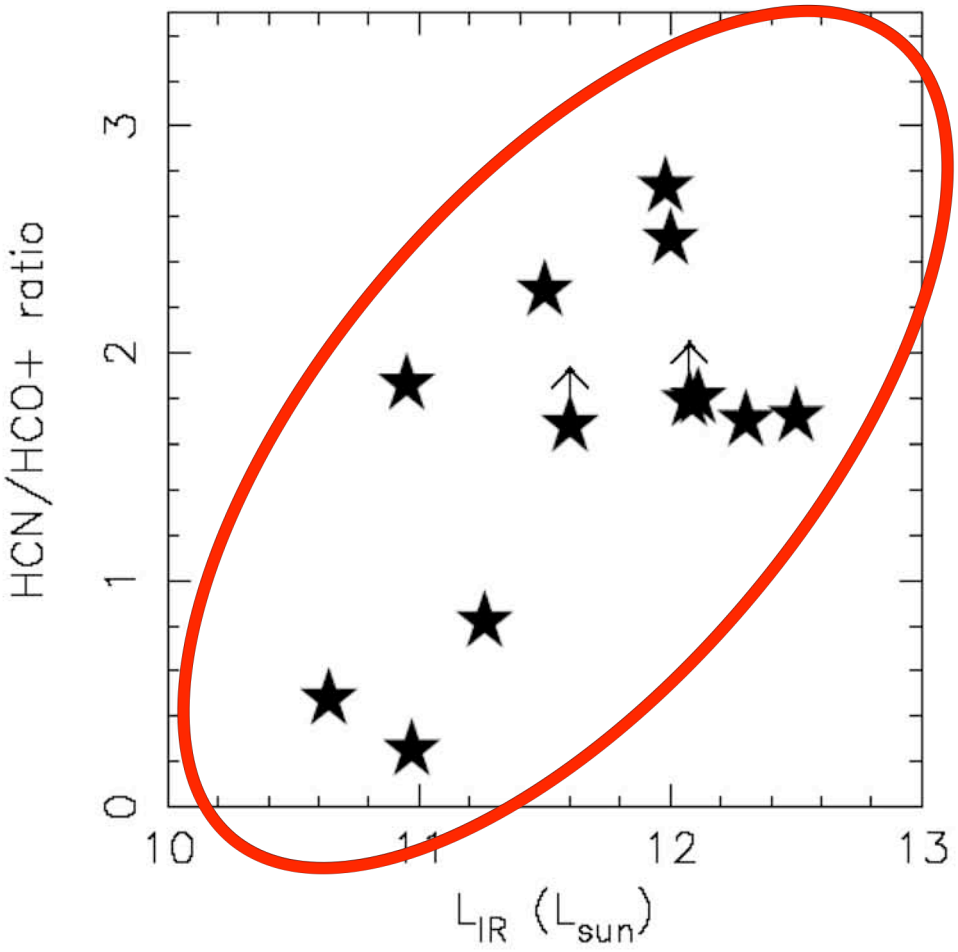
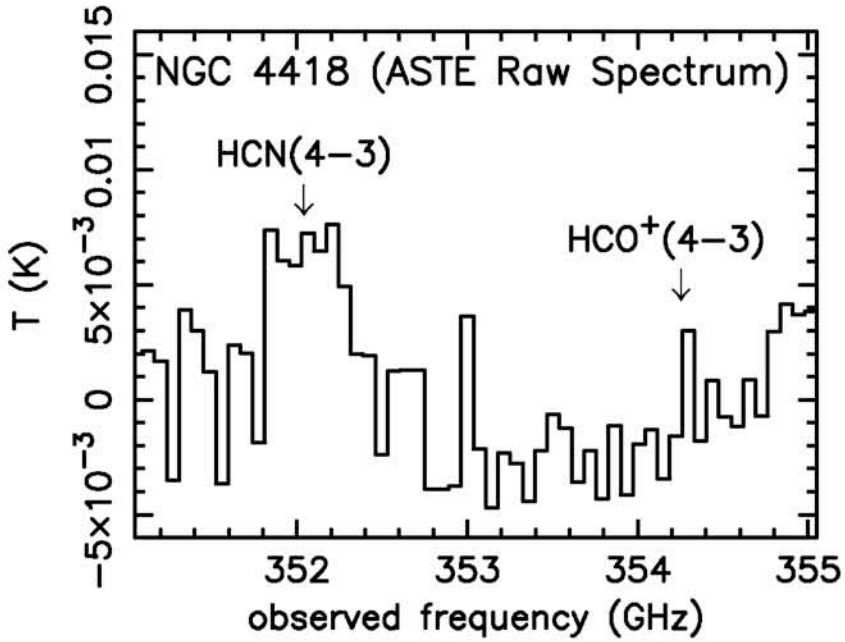


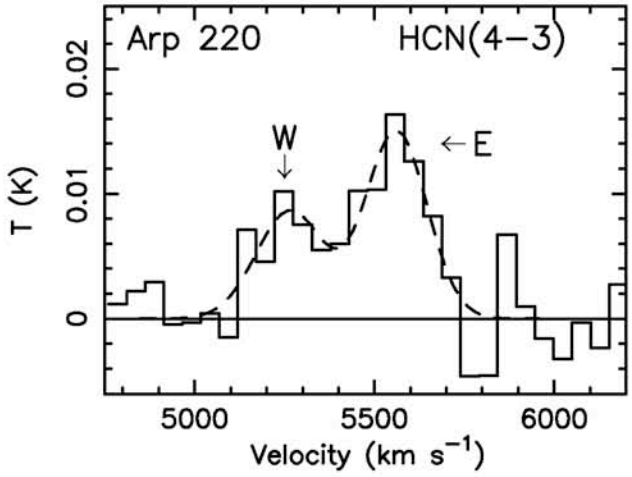
Imanishi, et al.
2007, AJ, 124, 2366

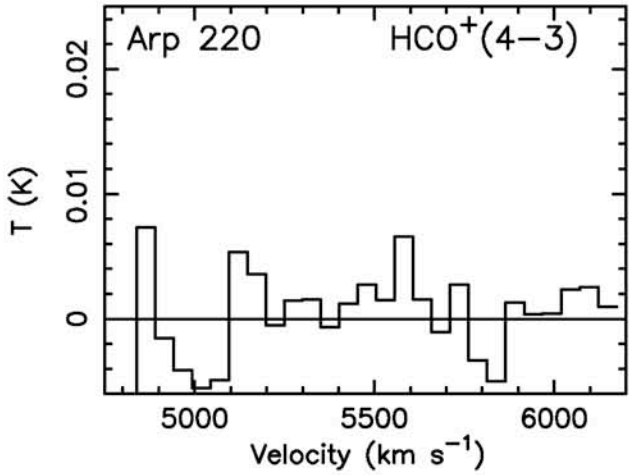
ALMA spectroscopy of dusty starbursts can probe heavily obscured, growing AGN?

Simultaneous HCN(4-3) & HCO^+(4-3) measurements in LIRGs/ULIRGs

- CATS345+WHSF on ASTE
- 2~3 hours integ. each
- Tsys ~ 180 – 300 K (SSB)
- High HCN/HCO^+ ratios even for high-J, consistent to J=1 ratios







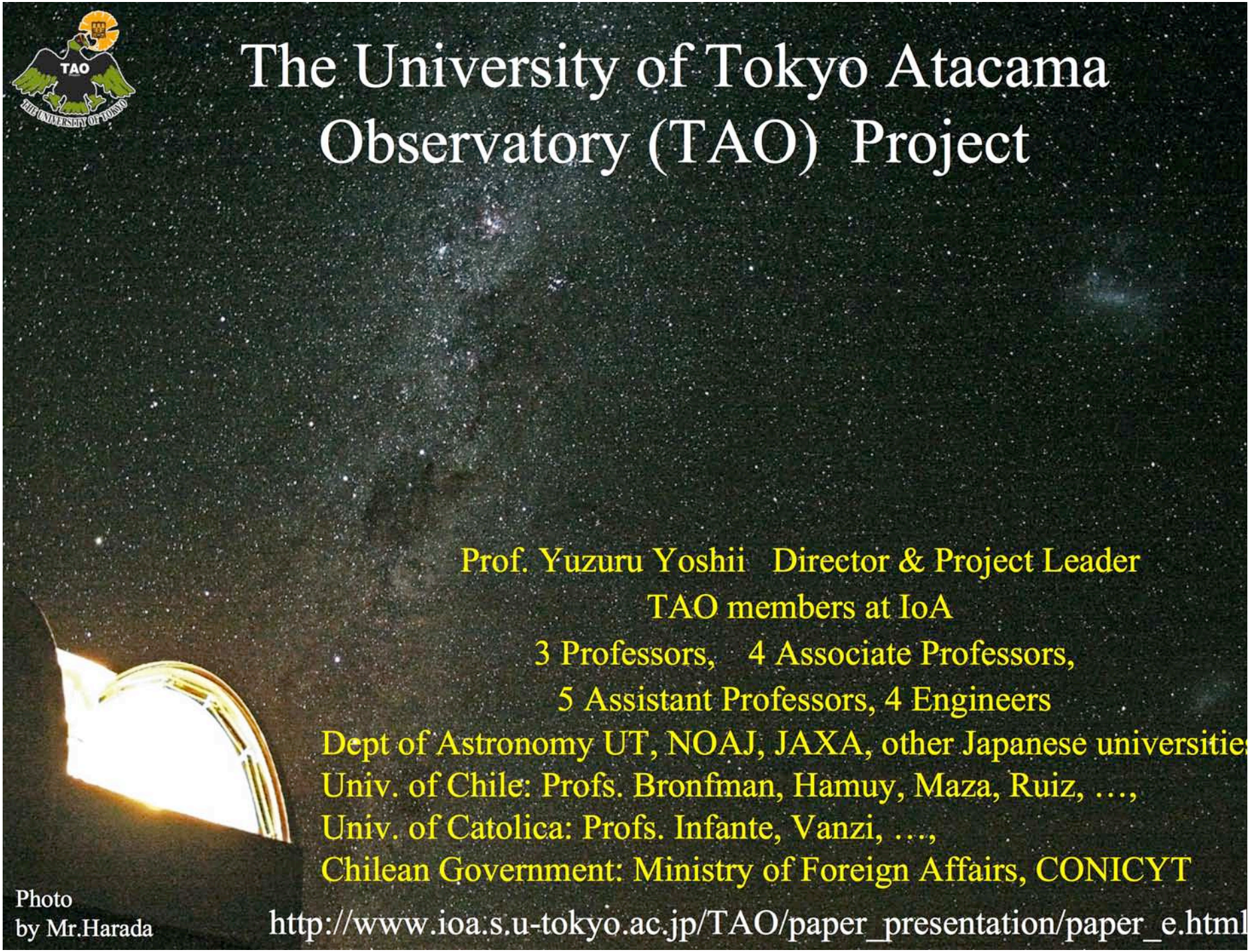
Imanishi et al. 2010, PASJ, 62, 201

ASTE 2013-2015? Open for new instruments

- Multi-chroic TES bolometer (with UC Berkeley)
- 200 um or 350 um imaging array (with MKIDs) for x3 higher spatial resolution follow up of Hershel sources; and/or Z-Spec like spectrometer with MKIDs + grating (with Cardiff Univ.)
- 64 pix heterodyne 350 GHz imaging array (SuperCam) for southern extension of Galactic plane surveys (with Univ. of Arizona)
- Various possibilities are now discussed

➔ ASTE can be a good workbench for the planned CCAT instruments producing preparatory science

The University of Tokyo Atacama Observatory (TAO) Project



Prof. Yuzuru Yoshii Director & Project Leader

TAO members at IoA

3 Professors, 4 Associate Professors,

5 Assistant Professors, 4 Engineers

Dept of Astronomy UT, NOAJ, JAXA, other Japanese universities

Univ. of Chile: Profs. Bronfman, Hamuy, Maza, Ruiz, …,

Univ. of Catolica: Profs. Infante, Vanzi, …,

Chilean Government: Ministry of Foreign Affairs, CONICYT

Photo by Mr.Harada

http://www.ioa.s.u-tokyo.ac.jp/TAO/paper_presentation/paper_e.html

Site Study Instruments @ Summit

Started site testing at the summit in 2006

- Weather monitor (continuous)
- Cloud monitor (continuous)
- Seeing monitor

- Container
- Solar Power Generator

Site Studies Summary

Good weather

usable 82%

photometric 63%

(Miyata et al. 2008)

Low water vapor

PWV 0.38mm(10%)

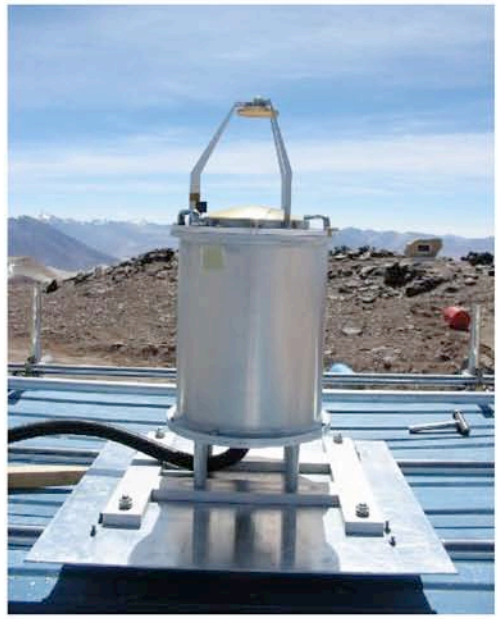
0.85mm(median)

(Miyata et al. 2008)

Seeing

Median 0.69”

(Motohara et al. 2008)



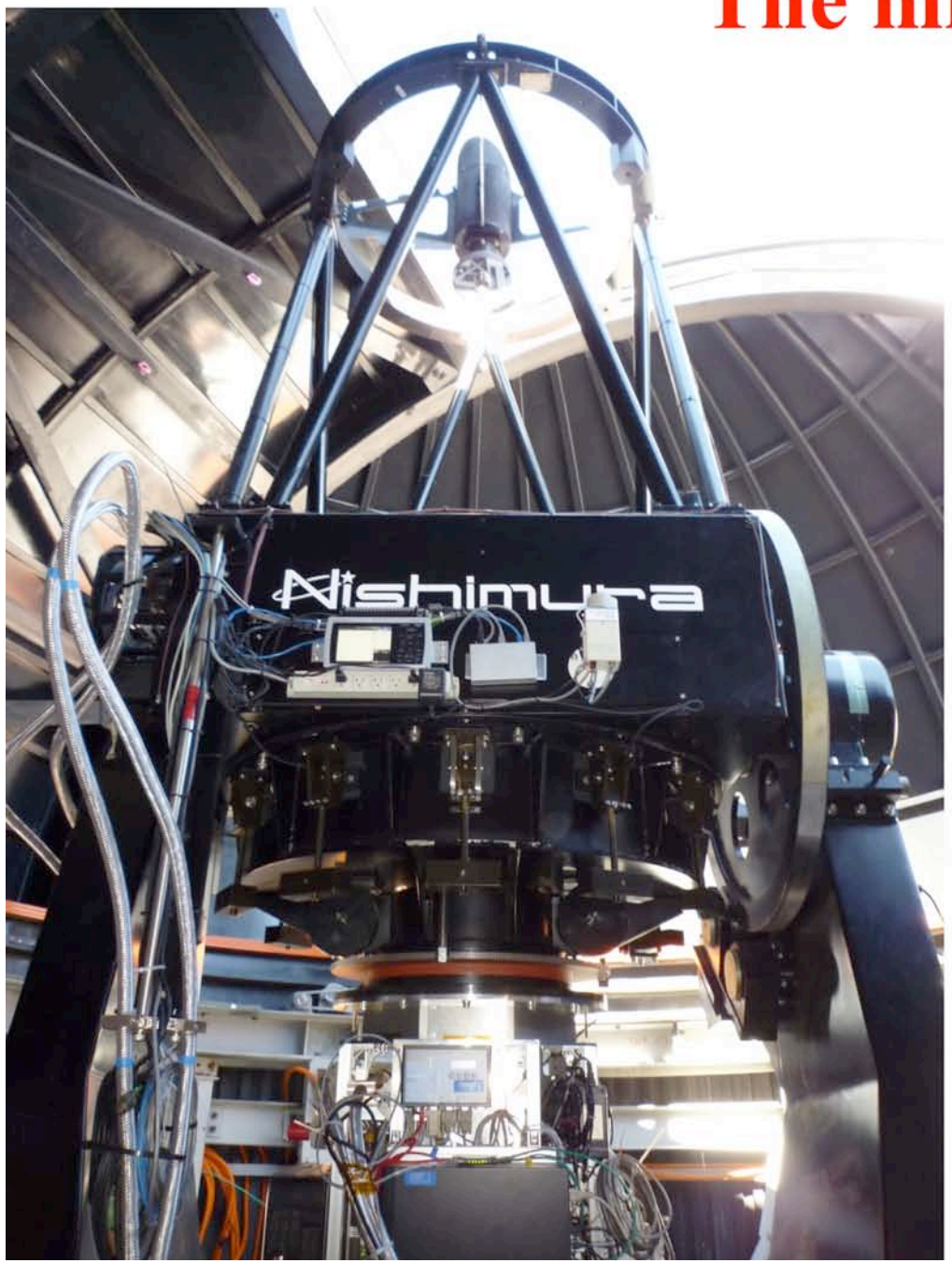
The miniTAO telescope
a Pathfinder 1-m Telescope

Great Local workers

construction
Started in Dec.2008

Completed in March 2009

The miniTAO telescope



Primary mirror

Φ1.0m

Cassegrain focus

focal ratio F/12

field of view Φ10'

plate scale 16.6"/mm

Vendor

Nishimura Co.

First Light March 2009

Pointing accuracy σ=1.8 arcsec

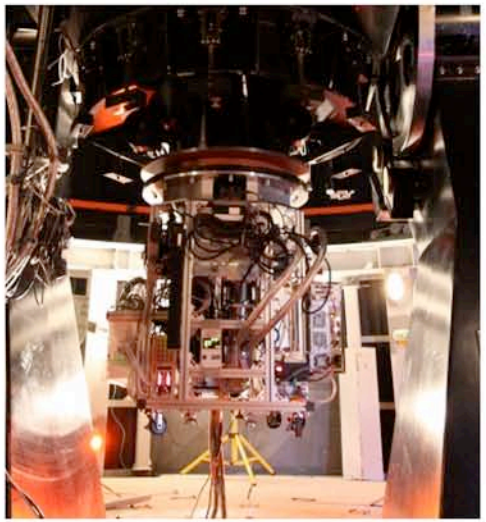
Hartmann constant σ=0.19 arcsec

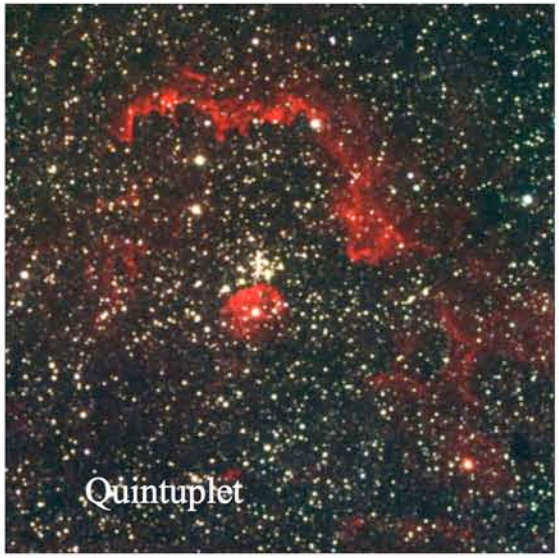
Seeing FWHM=0.5-1.0 arcsec

TAO
THE UNIVERSITY OF TOKYO

ANIR: Atacama Near Infrared Camera

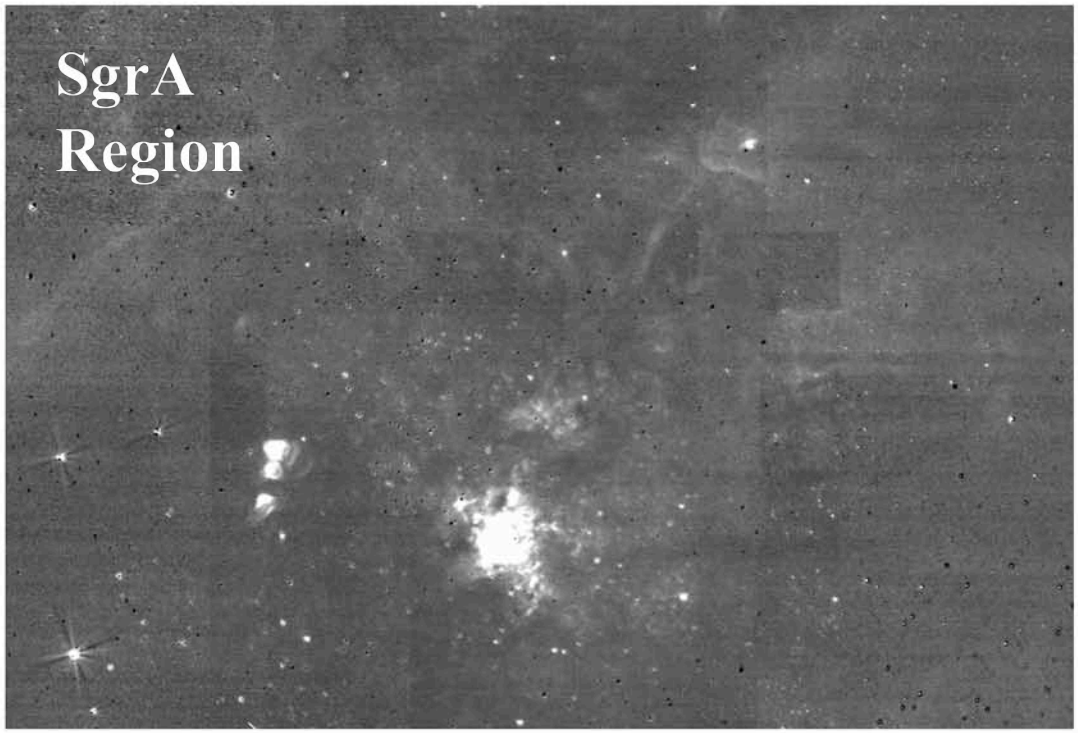
- NIR/Optical (0.4-2.5μm) imager with FoV of 5.2'
- First light on June 8, 2009
- Successfully obtained Paα images @ 1.8751μm !!



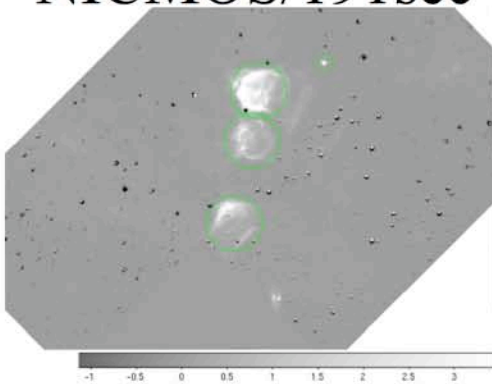


Comparison with HST for Pa alpha

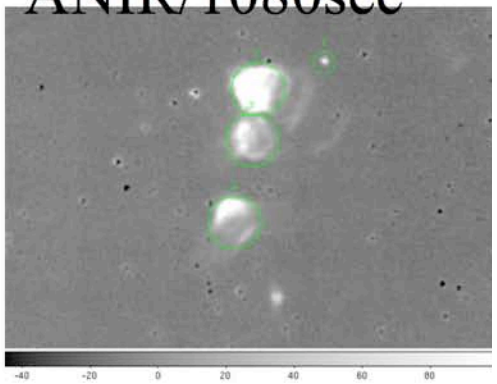
- Pa alpha
  - Sensitivity of ANIR: relatively good
  - transmittance is 50% max
    - but invisible velocity range exists.



NICMOS/191sec



ANIR/1080sec



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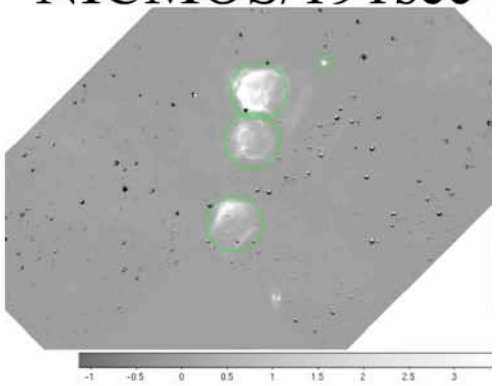
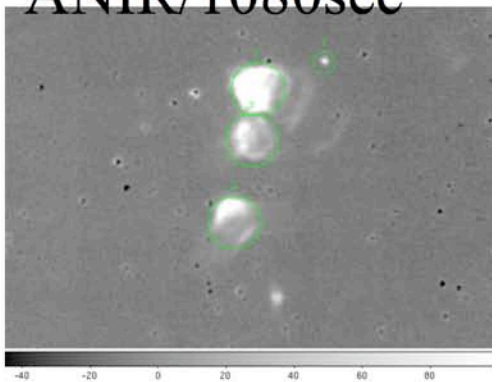
NICMOS/191sec



ANIR/1080sec



MAX38

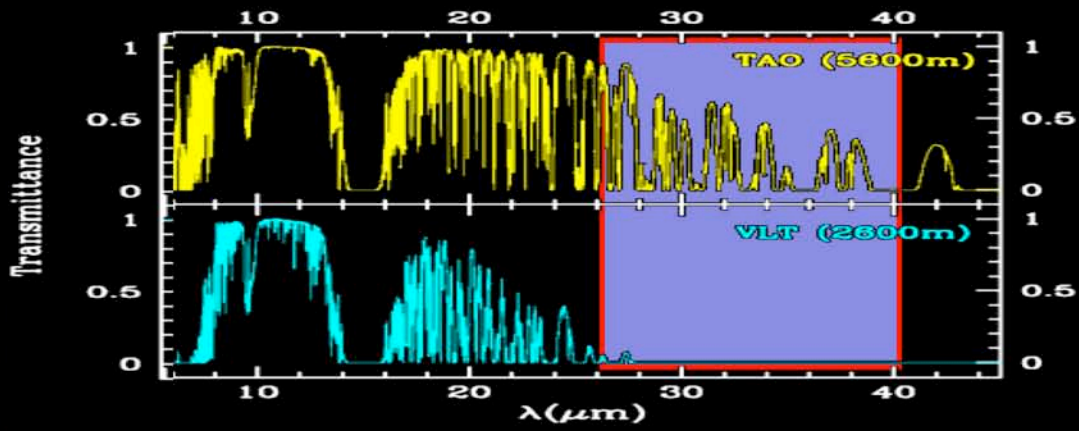
Mid-infrared Astronomical eXplorer

-- explores 30 micron astronomical windo

-- first light : 2009/11/08 CST

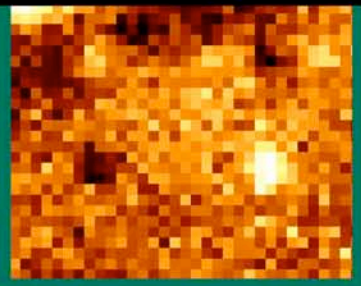
→ successfully obtained 31/38 micron images for the first time from ground-based telescopes!

Exp time ~50sec Size 40"x80"



Filter 31μm
the Galactic center

IK Tau (Mira)



Filter 37μm
Exp time ~50sec
3 Hz chopping

The 6.5-m TAO telescope

- Best Infrared Telescope on the earth

  Galaxies, Extra-solar Planets, Dark Energy, …

  from New Windows
- Construction: ~6 years
- Already two instruments funded

  by Japanese government

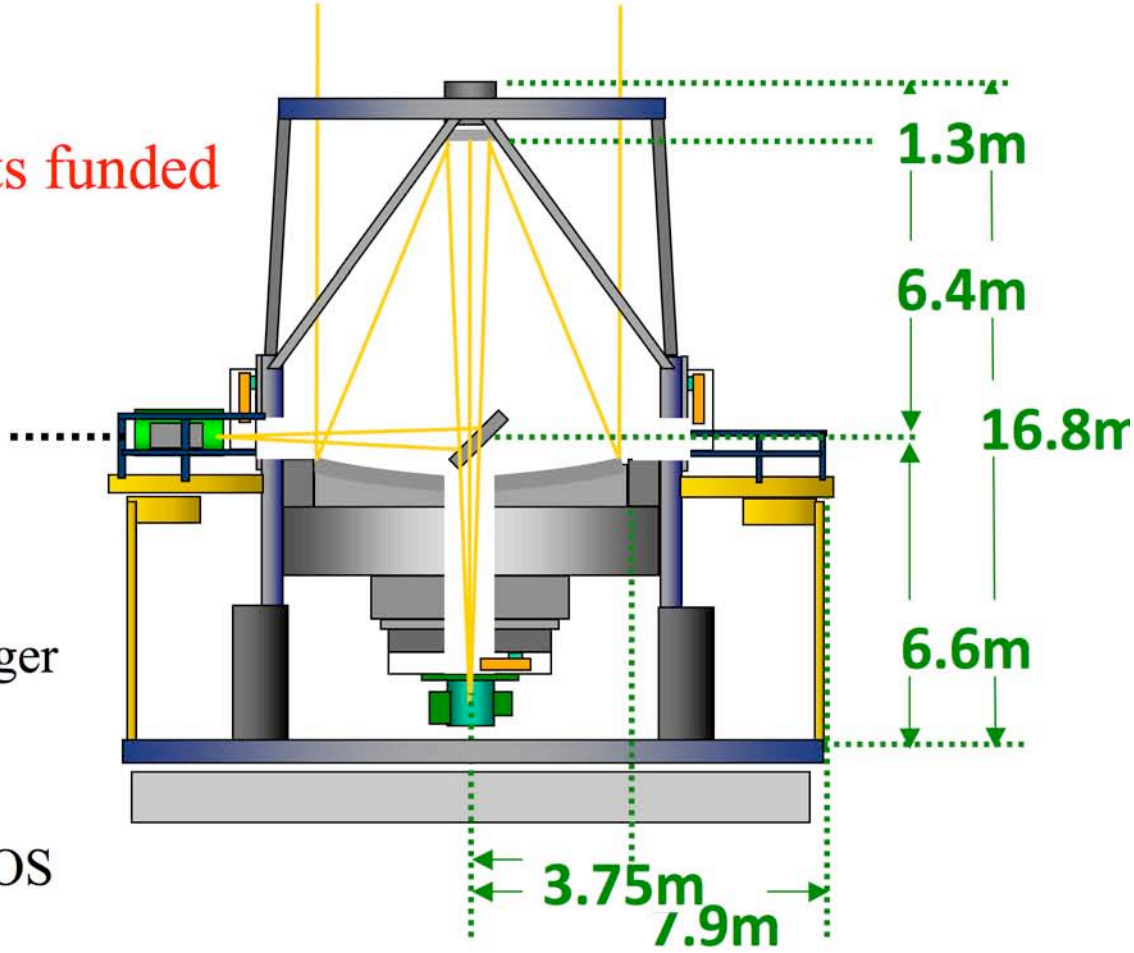
  in June 2009

  – **MIMIZUKU**

  for MIR multi-field imager

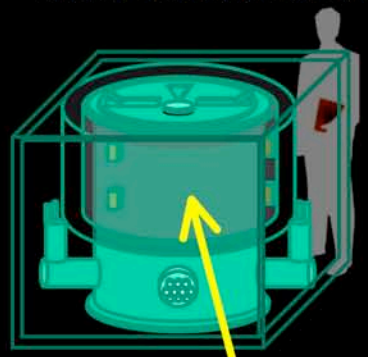
  – **SWIMS**

  for NIR imaging and MOS



TAOMIR instrument - MIMIZUKU

Mid-Infrared Multi-field Imager for gaZing at the UnKnown Universe



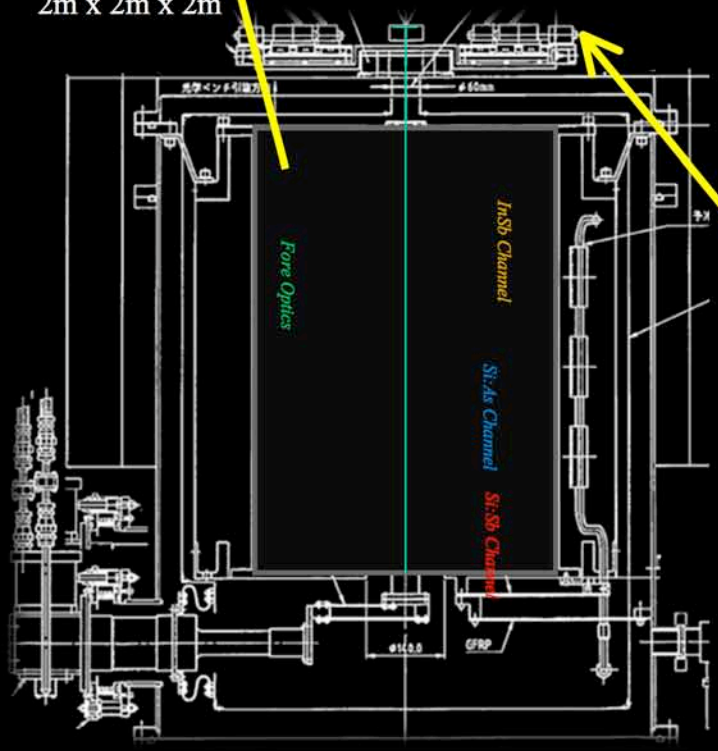
2m x 2m x 2m

✓ Highest spatial resolution in 30um

~ 1" @ 30um @ TAO 6.5m

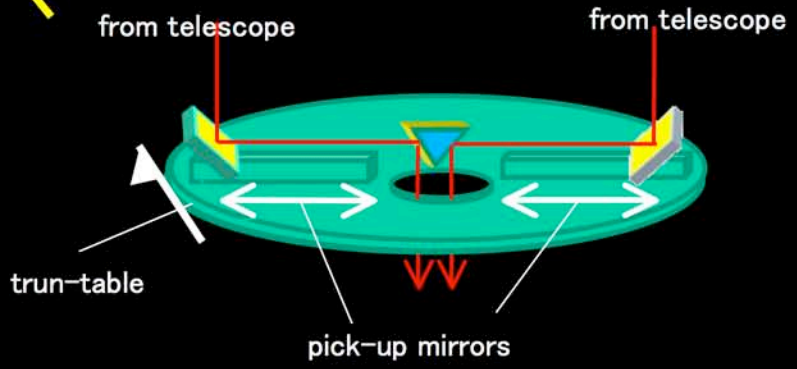
✓ Wide wavelength coverage with three channels

* InSb channel for 1-5um (AlladinnII 1k)
* Si:As channel for 6-25um (Aquarious 1k)
* Si:Sb channel for 25-38um (DRS HF 128x128)



✓ Field Stacker Unit

-- picks up two discrete fields from the telescope FOV
-- achieves simultaneous observations of two objects
→ dramatically improves accuracy of the photometry
→ enables us <u>monitoring observations in MIR</u>

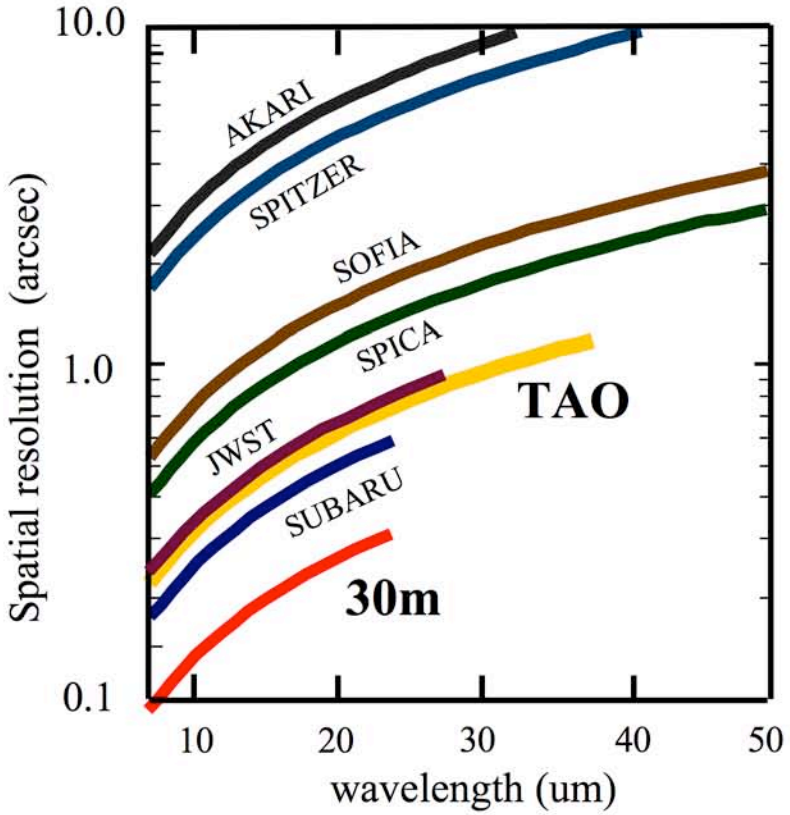


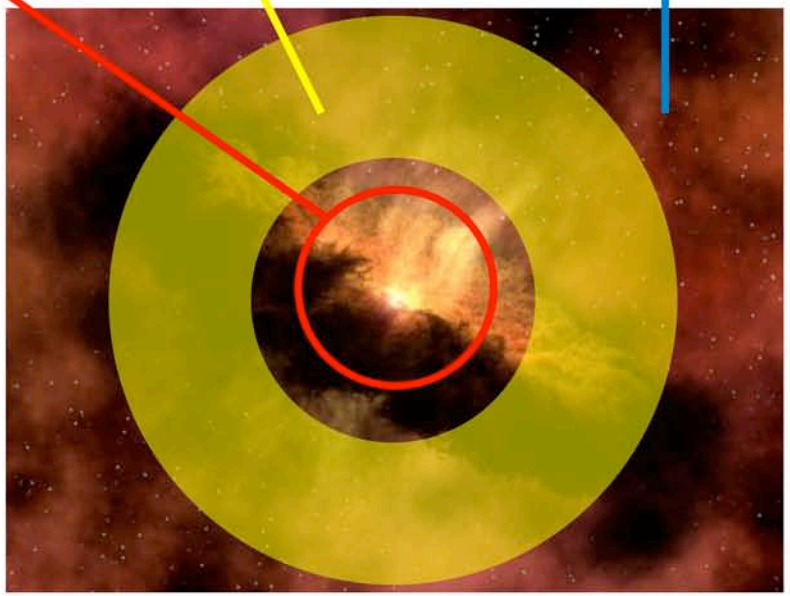
TAO-MIMIZUKU

30m-MIR 7um – 20um
500K-150K region

λ = 20um – 40um
~100K region

CCAT/ALMA
λ > 200um
~a few 10 K region





High spatial resolution observations of dust disks

Monitoring observations in MIR is also very unique -> Trigger TMT/JWST ToO

TAO-NIR Instrument - SWIMS

Simultaneous-color **W**ide-field **I**nfrared **M**ulti-object **S**pectrograph

Key Feature

Near-IR "Two-band Simultaneous" Obs.

with
- •Wide F.o.V. (ϕ 9'.6)
- •High Spatial Resolution (0".12 /pix)
- •R~1000 Grism MOS

Science Case

✓Cont. atmos. Window at NIR @ 5,640m

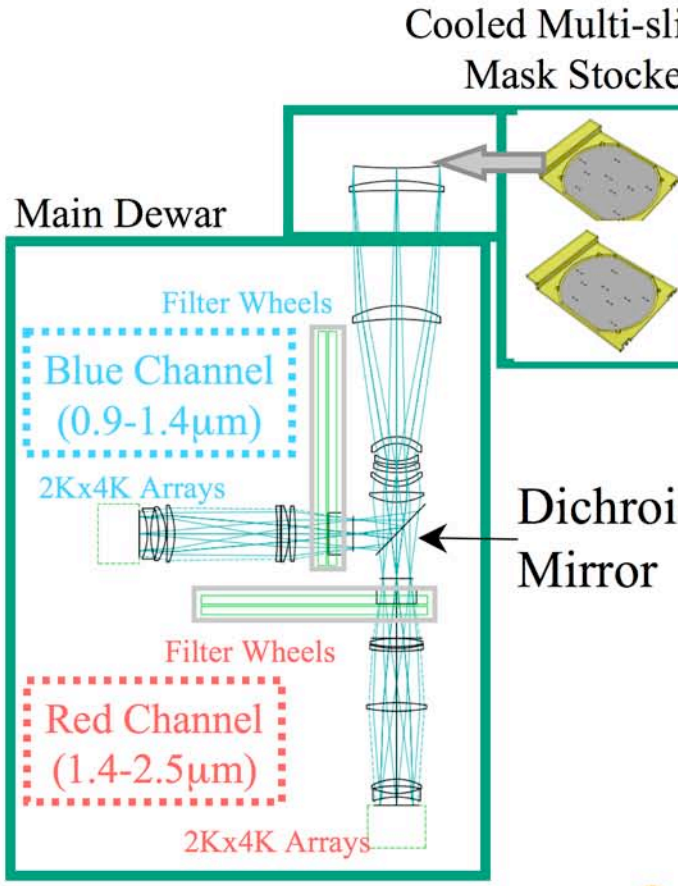
✓Wide spectral coverage by two-band MOS

→ **Comprehensive Redshift Surveys (z~1-3)**

Plan

Performance Verification on Subaru@Hawaii

→ Scientific Obs. will start on TAO@Chajnantor.



Summary

- Both TAO and ASTE can make a significant contribution to CCAT
  - TAO & CCAT: on-site collaboration (e.g., infrastructure) + science synergies
  - ASTE & CCAT: science + workbench for prototypes of CCAT instruments
- AzTEC/ASTE deep 1.1 mm surveys: ~2.6 deg^2, 0.4-1.5 mJy depth (1σ), yielding >1400 SMGs
  - Science lighlights including clustering, proto-quasar in SMG, very high-z SMG candidates, etc.
- Future plan of ASTE: unveiling the redshift distribution and power sources in dusty extreme starbursts in the early universe
  - Multi-color (1100/850/450um) TES array (~1000 pix), ~2013
  - 32 GHz bandwidth redshift machine on NRO 45 m telescope
  - establish new power diagnostic based on HCN/HCO$^+$ and other molecules
  - New instruments are welcome (middle 2013 ~ !?)
- miniTAO 1m pathfinder is operating up to 37 um !
- TAO 6.5m is also in progress (2 instruments already funded)