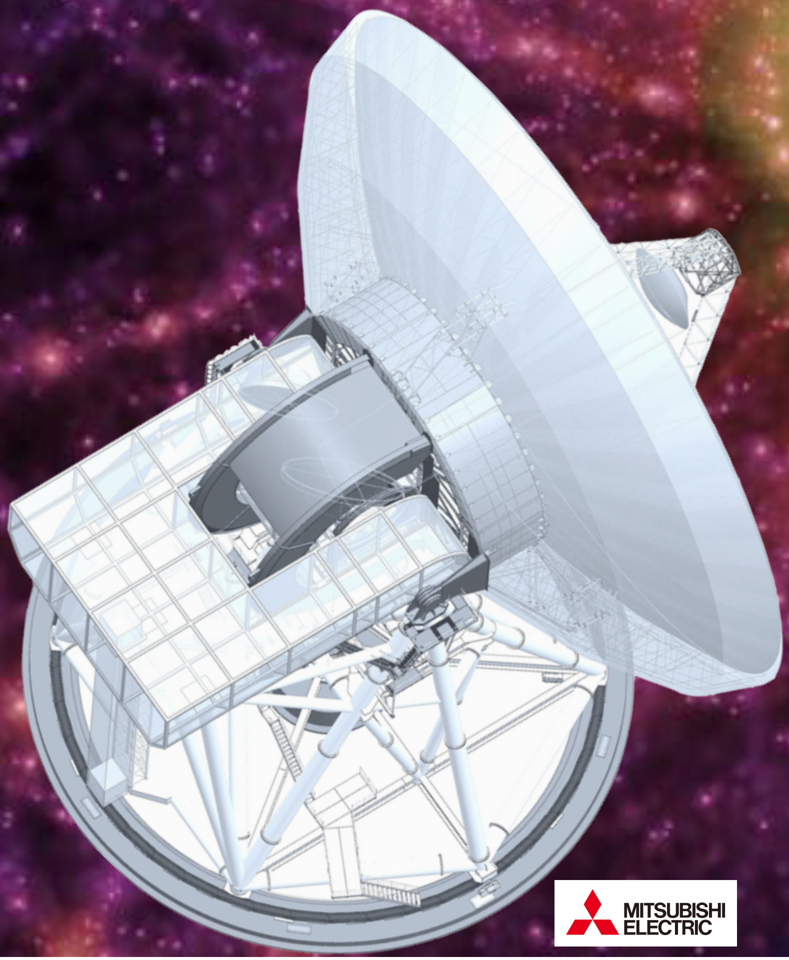
LST

LARGE SUBMILLIMETER TELESCOPE

New 50-m class single dish telescope

15.6 Mpc/h

Large Submillimeter Telescope (LST)



MITSUBISHI ELECTRIC

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Shun Ishii (NAOJ)
Kotaro Kohno, Tatsuya Takekoshi
(U. Tokyo),
Yoichi Tamura (Nagoya U.) and
LST Working Group

Overview

✦ The LST is a new telescope optimized for

- wide-area imaging and spectroscopic surveys in the freq. range of 70-420 GHz allowing exploration of universe in 2D and 3D
- also achieving high-cadence performance for transients

✦ LST targets observations at higher freq. up to 1THz, using an inner high-precision surface (under-illumination) to enhance science

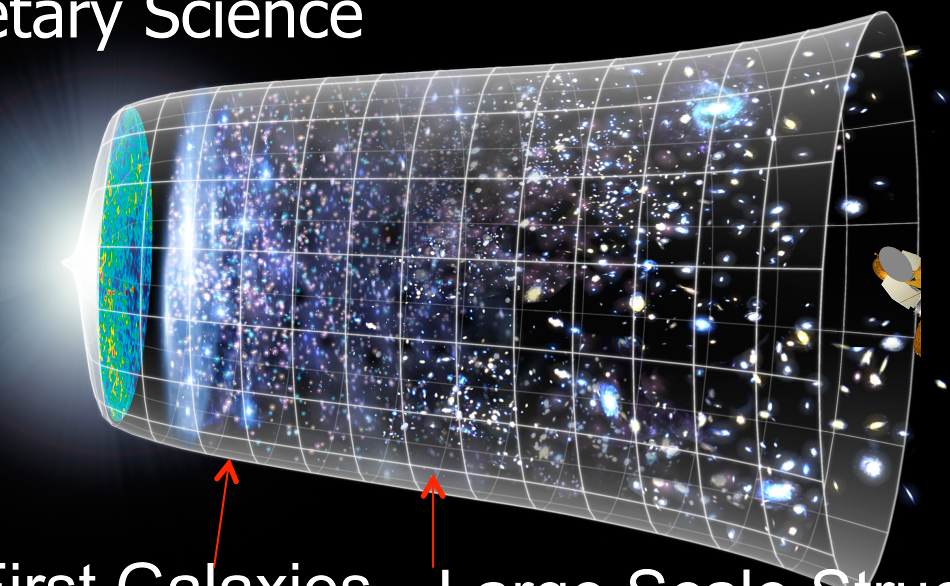
✦ Through exploitation of its synergy with ALMA, the LST will contribute research on a wide range of topics in astronomy and astrophysics, e.g., chemistry, SZ, VLBI,..

✦ Basic Concept, Specs., Key Sci & Instrument etc. introduced

Science Goals in Mm & Submm Astronomy

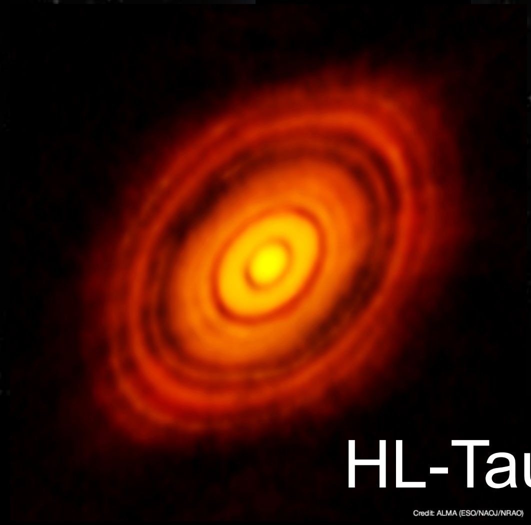
- ✦ Challenge and resolve basic problems in the expanding, accelerating, and diverse universe

  - e.g., Cosmology, Formation and Evolution of Galaxies/ SMBH, Star Formation, Interstellar Chemistry, Solar system and Planetary Science



ALMA opens new era

High Angular resolution



"This is a just "Dream comes True" image!"

For high-z study

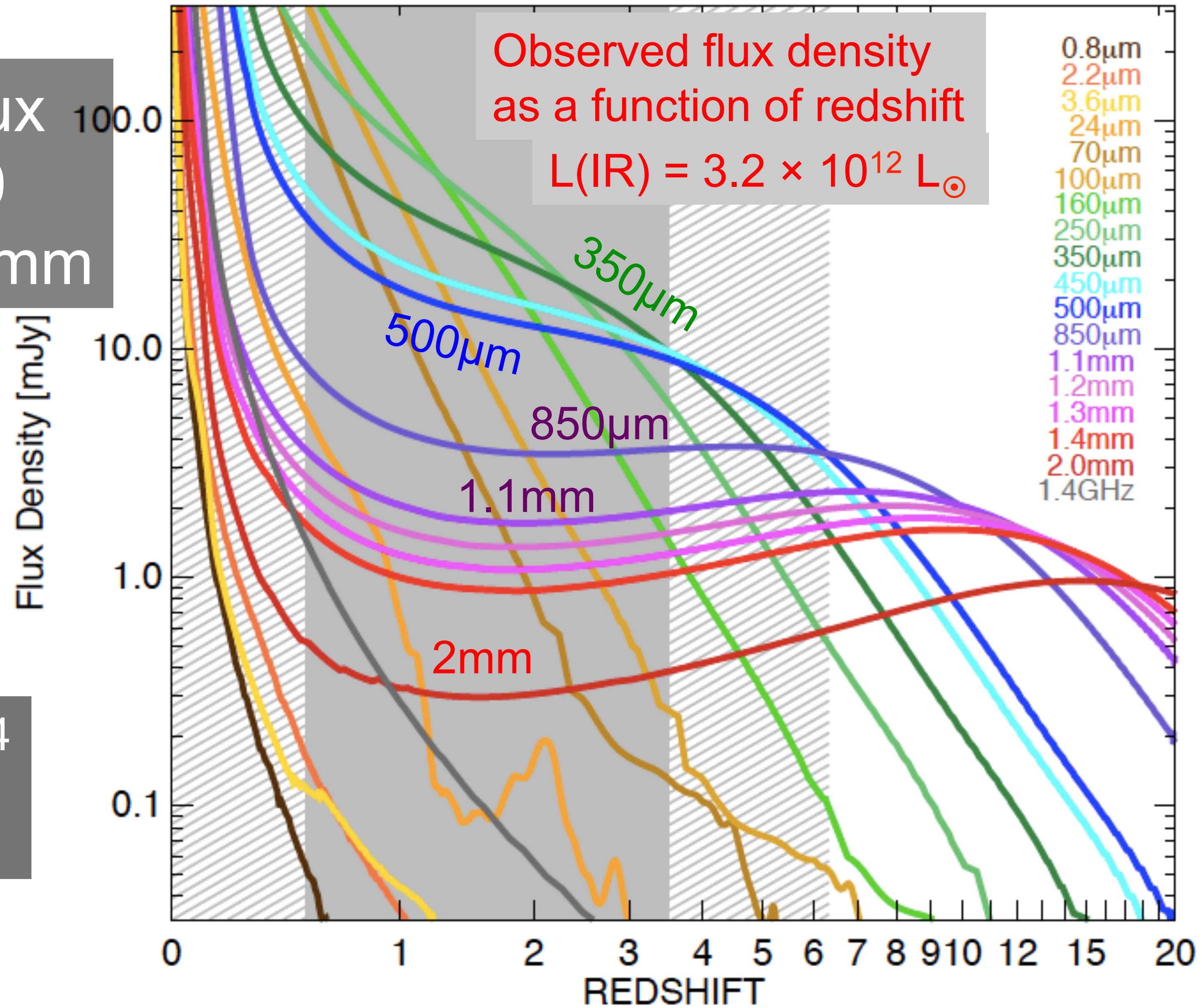
- Negative K-correction as a Unique characteristic of mm/submm can be exploited
- Spectral lines such as fine structure lines [CII], [OIII] are also very useful as well as molecular lines CO, H2O

Strong negative K-correction @mm/submm gives uniform selection function for high-z dusty galaxies

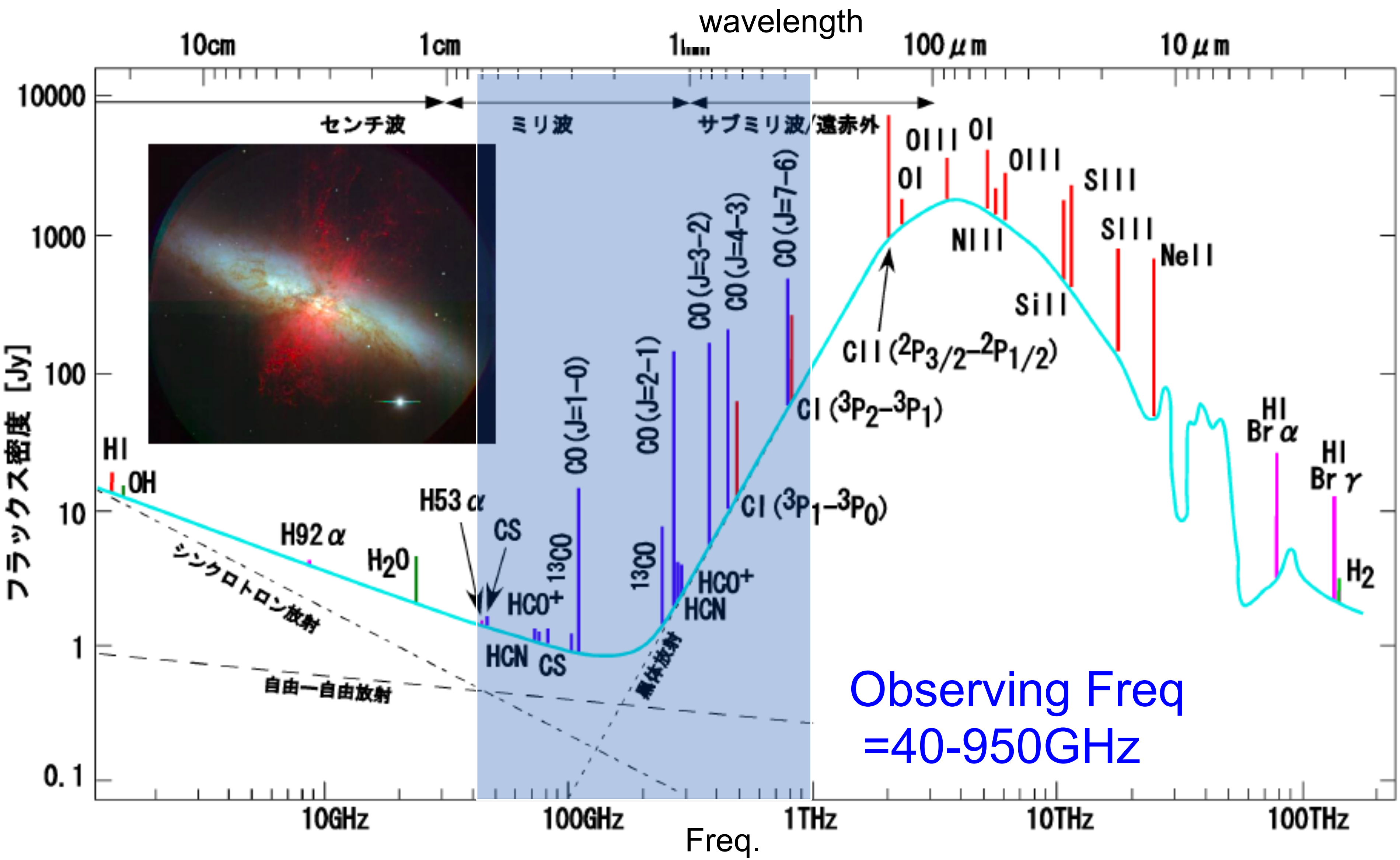
Almost flat flux for 1 < z < 10 around λ ~ 1mm

λ = 850 μm
1.1 mm
1.3mm
(also 750μm)

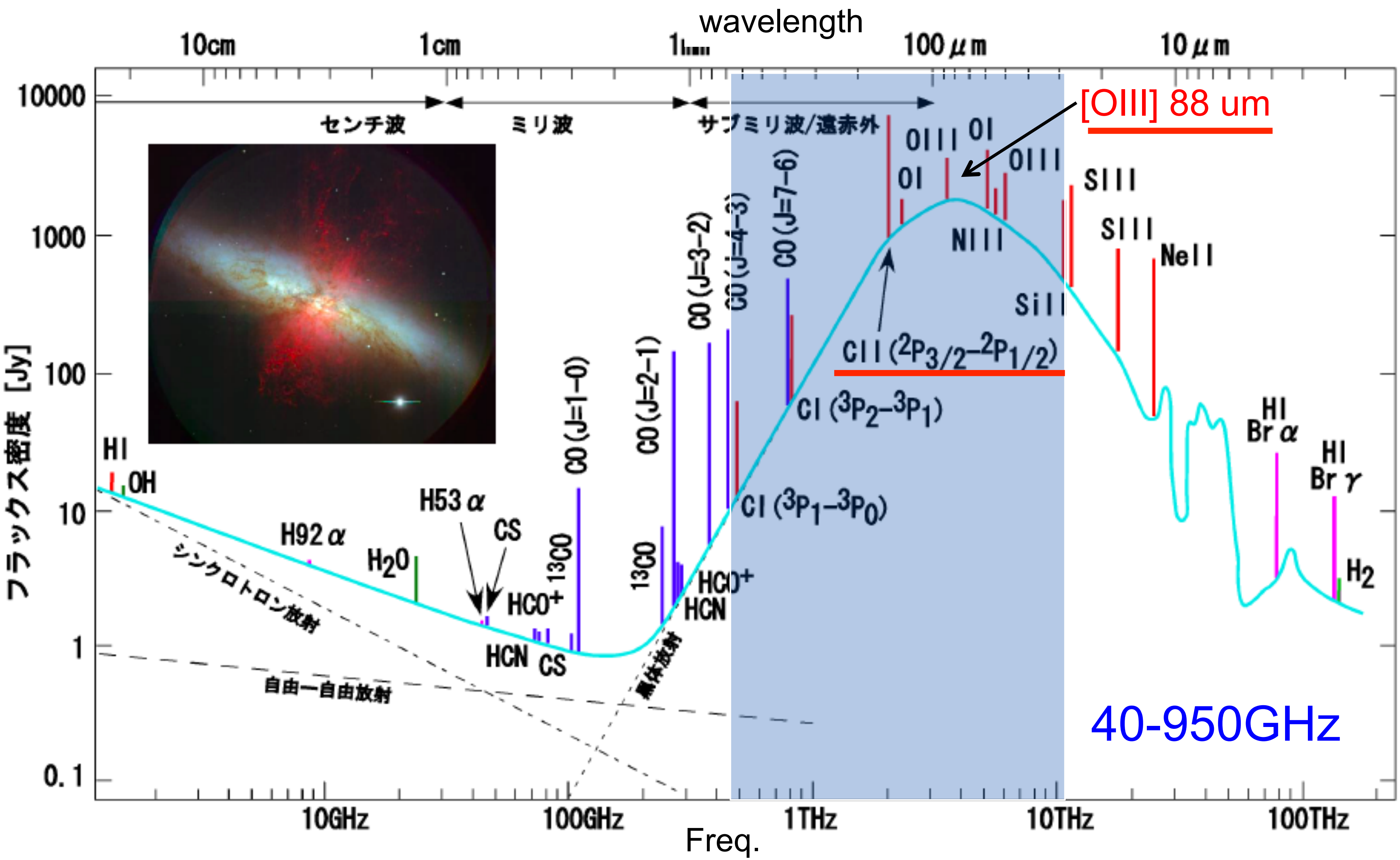
Casey et al. 2014
Physics Reports
541, 45



Starburst Galaxy M82



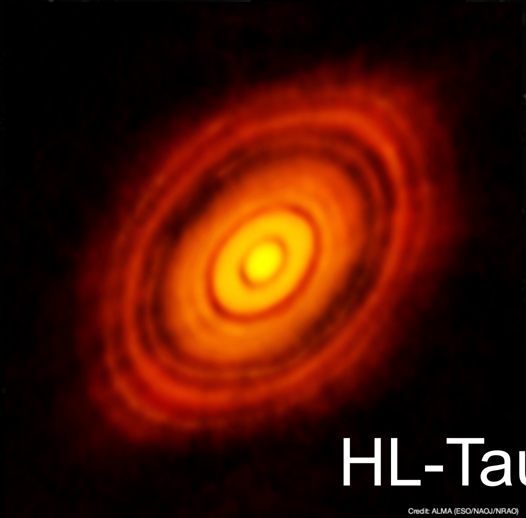
Star-forming Galaxy at z=10



ALMA opens new era

High Angular resolution

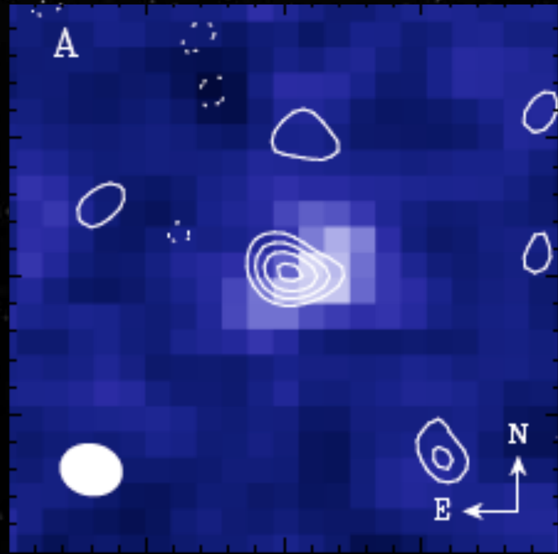
High sensitivity



HL-Tau

Credit: ALMA (ESO/NAOJ/NRAO)

[OIII] at z= 7.2



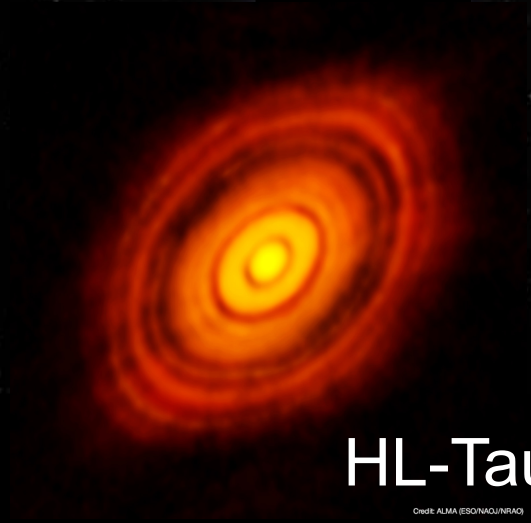
The universe unveiled by ALMA is very limited in terms of sky and spectroscopic coverage, in other words, in 2D and 3 dimensional volume of the universe.

ALMA opens new era

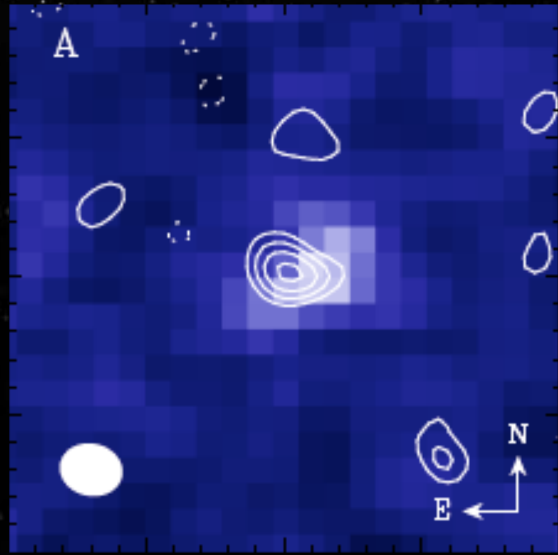
LST will facilitate new discovery space complementary to ALMA

High Angular resolution

High sensitivity



HL-Tau



[OIII] at
z= 7.2

Time domain Science

Ultimate
Wide Field Imaging

Instantaneous
Wide Frequency Coverage

Pursue new “Dreams”

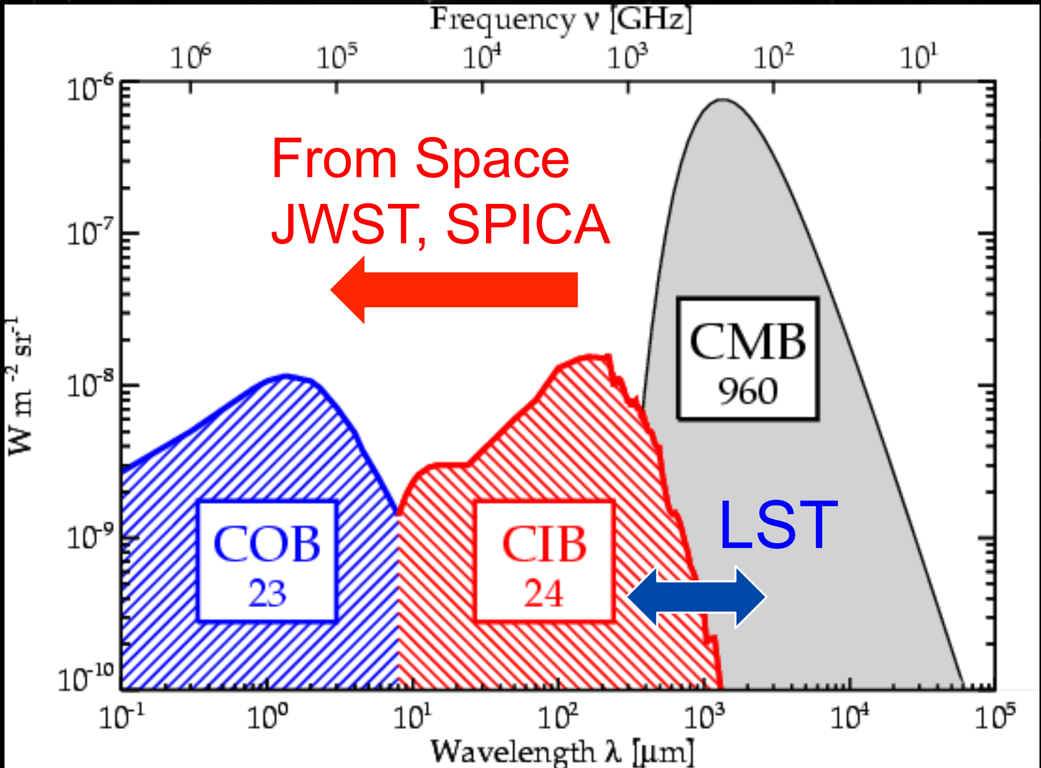
Incubate Future Science

> Spectroscopic Imaging in 3D of Early Universe
> Spectroscopic & Polarimetric Imaging: Dust Properties & B-field

Resolve CIB in 2D & 3D

LST
LARGE SUBMILLIMETER TELESCOPE

Cosmic IR Background (CIB) as 2[nd] Major component

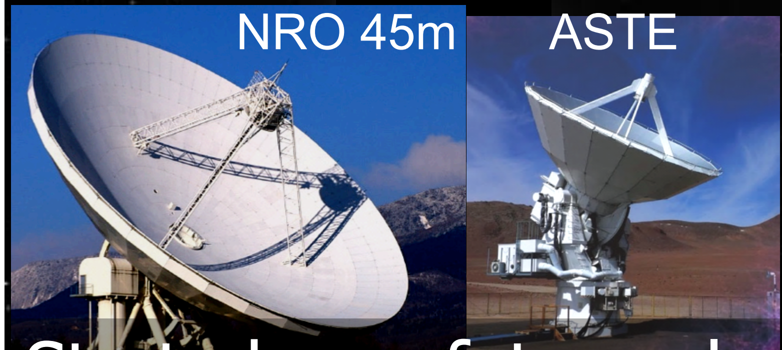


CMB or CMB-pol correlates with CIB discrete sources via ISW or gravitational lensing?

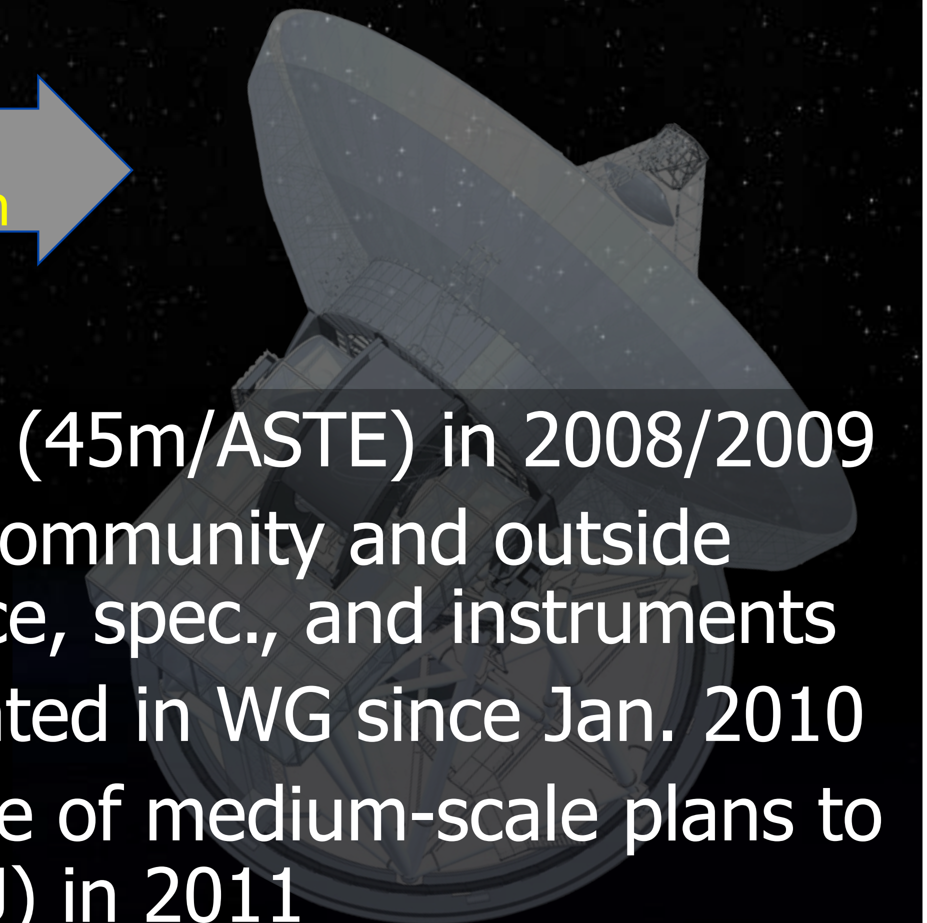
- Spatially Resolving CIB to DSFGs down to LIRGs
- Redshift Search of DSFGs and LSS study via CO/[CII] Tomography; can we find galaxies in EoR?
- Search for Dusty Sources (Proto-QSOs) powered by AGNs via CO-SLED
- Cosmic SF history together with History of SMHB formation/evolution can be investigated
- Dust/Metal Production

Chronology of LST

LARGE SUBMILLIMETER TELESCOPE



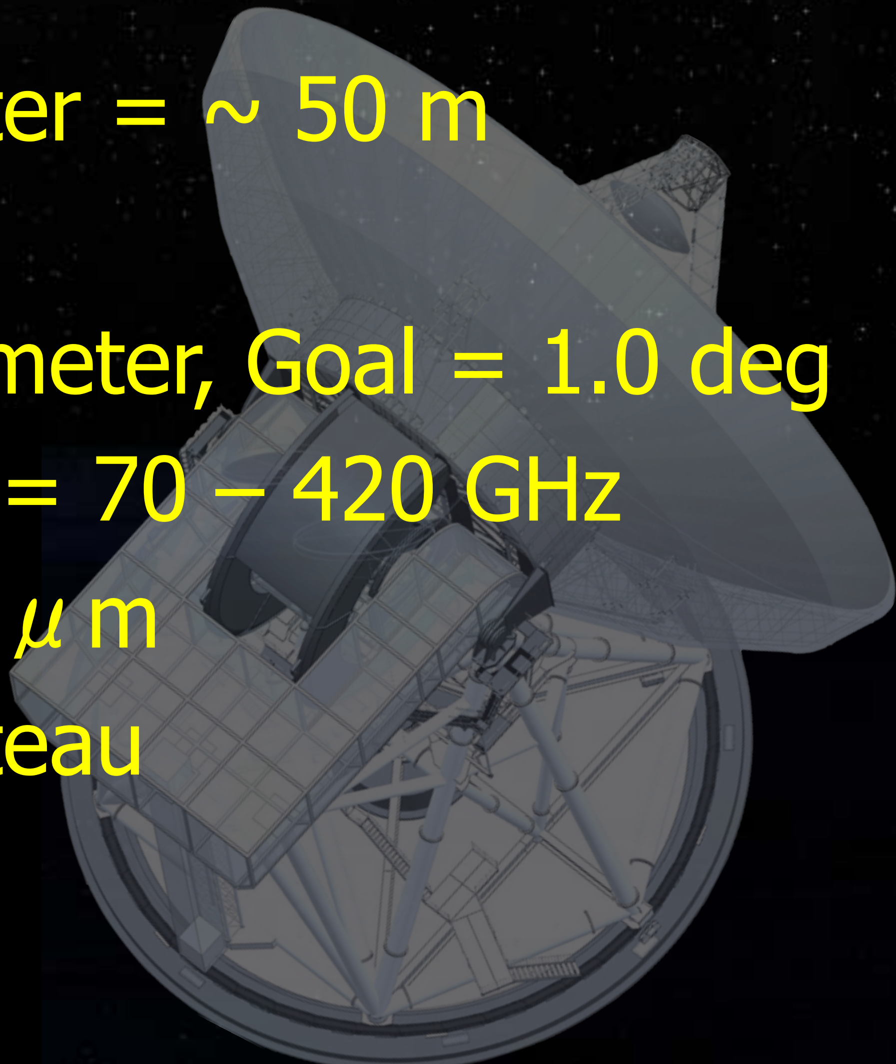
Natural Evolution



- Started as a future plan of NRO (45m/ASTE) in 2008/2009
- Exchanged basic idea with JP community and outside potential collaborators; science, spec., and instruments
- Science case has been investigated in WG since Jan. 2010
- Proposed a tentative plan as one of medium-scale plans to Science Council of Japan (SCJ) in 2011
- Concept and Science case updated in 2014/2015 based on Feedback from SCJ and further discussions
- (will be proposed to SCJ for Master Plan 2020)

LARGE SUBMILLIMETER TELESCOPE

Basic Concept
:Tentative Specifications



- ✦ Large Aperture: Diameter = ~ 50 m
- ✦ Large FOV
  : F.O.V = 30 arcmin. diameter, Goal = 1.0 deg
- ✦ Main Frequency Range = 70 – 420 GHz
- ✦ Total surface rms $\leq 45\ \mu m$
- ✦ Possible site; ALMA plateau

Why 50 m diameter?

✦Larger dish, less confusion noise

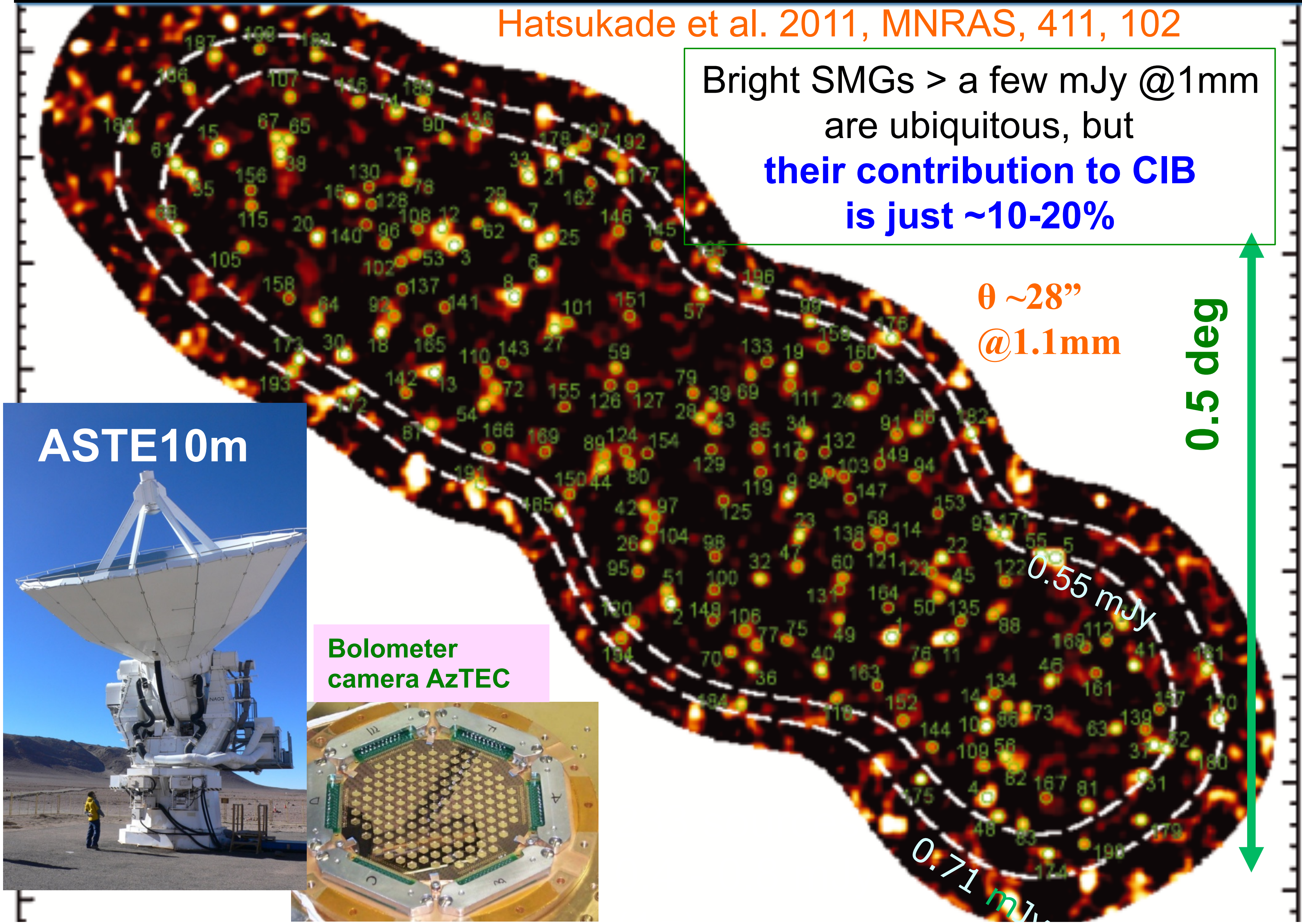
✦Less confusion noise allows us to resolve majority (> 50 %) of CIB contributors at mm to submillimeter wavelength with uniform selection function

✦Make it easy to identify confident counterparts in Opt/IR images with ~ 4" beam (850μm/350 GHz)

✦Better sensitivity for point-sources and transients

"Submm galaxies" are bright, but..

Hatsukade et al. 2011, MNRAS, 411, 102

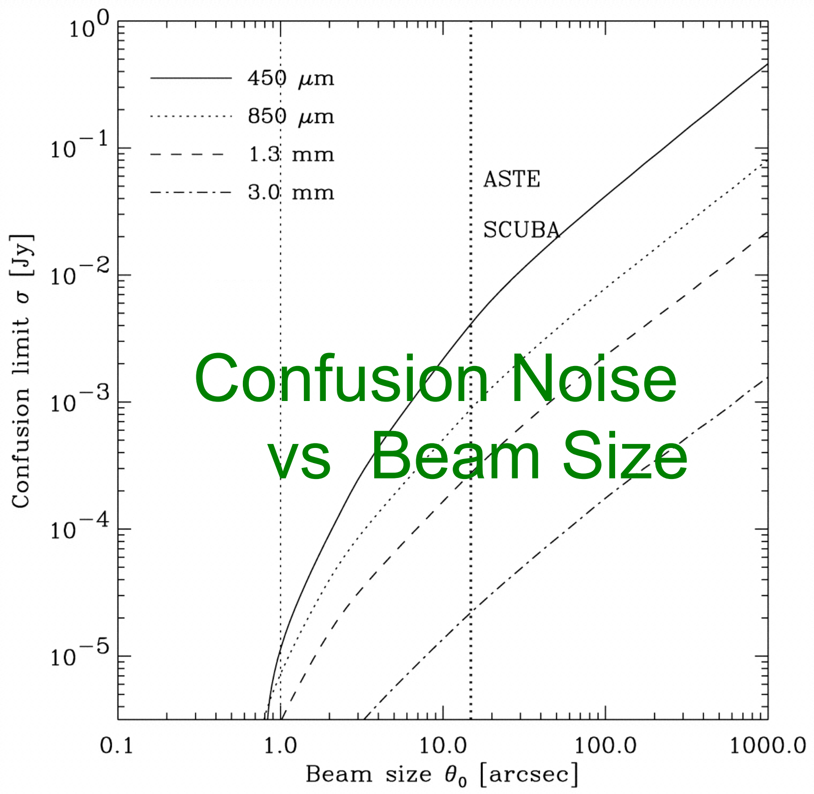


Bright SMGs > a few mJy @1mm are ubiquitous, but **their contribution to CIB is just ~10-20%**

Merit of Large Dishes

		ASTE	CCAT	50m	50m/CCAT
Source Confusion[a]	$\propto D^{-1.4}$	1	1/3.6	1/10	(1/2.6)
Spatial Resolution	$\propto D^{-1.0}$	1	1/2.5	1/5	(1/2)
Survey Speed[b]	$\propto D^2$	1	6	25	(4)
Speed of pointed obs. (for point-like sources)	$\propto D^4$	1	36	600	(16)

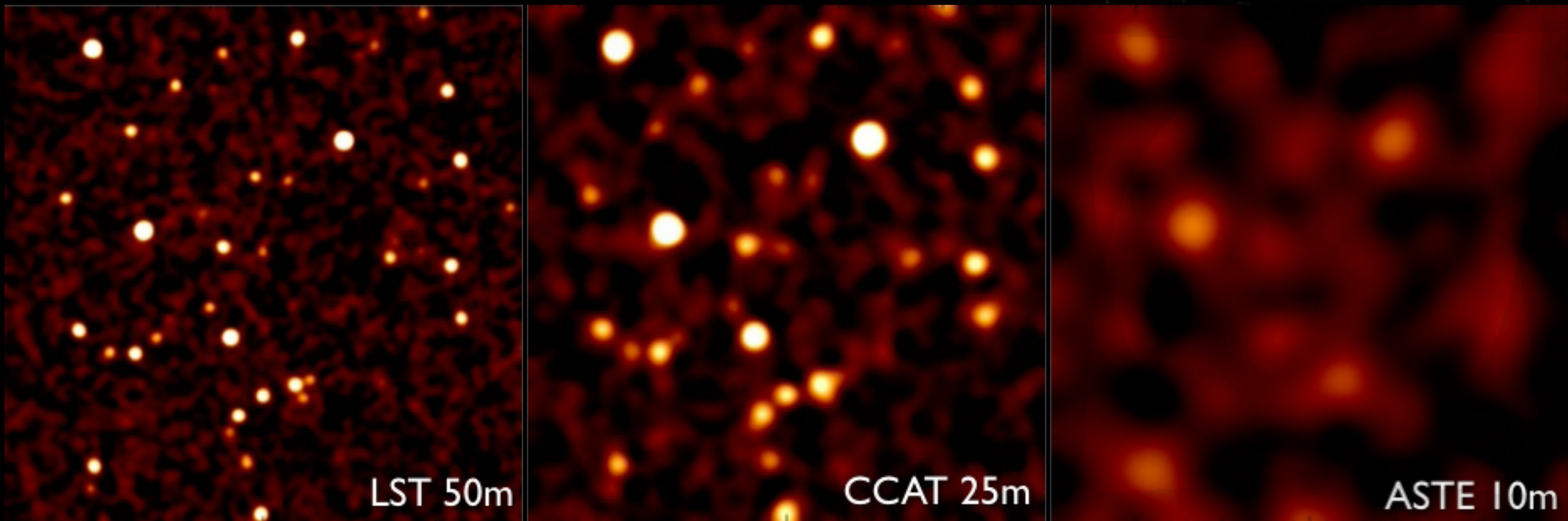
LMT in Mexico can also improve source confusion by 10x!



a. Takeuchi, RK, Kohno+ 2001
b. Evaluated as survey area covered with fixed observing time and depth, e.g., in unit of deg^2/hours

Confusion Noise: rough estimate

- Confusion Noise $\propto D_{tel}^{-1.4}$
- 50m/LST: x 10 deeper than 10m/ASTE etc
- x 3 deeper than 25m/CCAT
- CIB resolved more with less confusion



LMT

confusion limits (5σ) of mm/submm telescopes

Unit: mJy

	LMT, LST, AtLAST	IRAM ,SST	CCAT	JCMT	APEX , GLT	CSO, ASTE, Tsukuba	SPT 1.2′@2mm 1.0′@1.4mm	Herschel
Dish D	50m	30m	25m	15m	12m	10m	10m※	3.5m
3.3mm	0.052	0.084	0.098	0.15	0.17	0.20		0.40
2.0mm	0.13	0.23	0.28	0.44	0.53	0.61	1.4?	1.22
1.3mm	0.29	0.58	0.72	1.2	1.5	1.7	2 – 4?	3.50
1.1mm	0.36	0.78	0.97	1.7	2.0	**2.0,** 2.4		4.94
860μm	0.42	1.02	1.3	2.3	2.9	3.4		7.36
750μm	0.53	1.37	1.8	3.2	4.0	4.8		10.28
500μm								**30.5**#
450μm	0.26	1.5	2.2	4.8	6.3	7.6		18.0
350μm	0.058	1.0	1.8	4.7	6.4	8.0		**27.5**# , 20.7
200μm	0.0008	0.04	0.17	1.7	2.9	4.2		17

Bold font: based on the measured number counts

#: Oliver et al. 2012, MNRAS, 424, 1614

Adopted number counts: Bethermin et al. (2012); definition of confusion: 30 beams per source

confusion limits (5σ) ➔ fraction of CIB resolved

Note: CIB measured has an uncertainty of 10%

	LMT, LST AtLAST	IRAM, SST	CCAT	JCMT	APEX, GLT	CSO, ASTE	SPT 1.2′@2mm, 1.0′@1.4mm	Herschel
Dish D	50m	30m	25m	15m	12m	10m	10m※	3.5m
3.3mm	19.3%	10.5%	8.4%	4.4%	3.3%	2.6%		0.7%
2.0mm	34.3%	19.6%	15.8%	8.4%	6.3%	4.9%	1.4%?	1.2%
1.3mm	51.1%	30.7%	25.1%	13.7%	10.3%	8.2%	2 – 4%?	2.0%
1.1mm	58.3%	36.0%	29.6%	16.3%	12.3%	9.8%		2.4%
860μm	70.2%	45.3%	37.7%	21.2%	16.2%	12.9%		3.2%
750μm	75.5%	49.7%	41.5%	23.5%	17.9%	14.3%		3.5%
500μm								
450μm	95.4%	73.8%	64.1%	39.2%	30.6%	24.7%		6.4%
350μm	99.2%	86.3%	77.6%	50.9%	40.6%	33.3%		9.3%
200μm	99.9%	99.6%	98.2%	83.0%	72.6%	63.6%		24.1%

confusion limits (5σ) ➔ fraction of CIB resolved

Note: CIB measured has an uncertainty of 10%

	LMT, LST AtLAST	IRAM, SST	CCAT	JCMT	APEX, GLT	CSO, ASTE	SPT 1.2′@2mm, 1.0′@1.4mm	Herschel
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3.3mm	19.3%	10.5%	8.4%	4.4%	3.3%	2.6%		0.7%
2.0mm	34.3%	19.6%	15.8%	8.4%	6.3%	4.9%	1.4%?	1.2%
1.3mm	51.1%	30.7%	25.1%	13.7%	10.3%	8.2%	2 – 4%?	2.0%
1.1mm	58.3%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.4%
860µm	70.2%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.2%
750µm	75.5%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.5%
500µm		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
450µm	95.4%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.4%
350µm	99.2%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9.3%
200µm	99.9%	99.6%	98.2%	83.0%	72.6%	63.6%		24.1%

50m-class submm telescope(s)
captures majority of CIB contributors
, dusty star-forming galaxies, up to
epoch of reionization, EOR
freely from cosmic variance
also with multi-bands

Why Large FOV?

- ✦ Higher Mapping Speed for Confusion-noise limited Wide-field Surveys; 100-1000 deg^2.
  - => census of star-forming galaxies
  - => various unbiased/biased fields covered
- ✦ Sampling large scale structure of Warm Intergalactic medium (WIM) in cluster of galaxies via SZ; as large as 1 deg^2 (~ 1 Mpc)
- ✦ Quick counter-part identification of GRBs or Gravitational-wave sources after X/γ-ray alert, and also high cadence for variable source search

Mapping Speed at 1.1 mm

scaled to AzTEC/ASTE (conservative) value

- ✦MS ∝ D^2 x N_{pix}
- ✦$MS_{AzTEC, ASTE}$ ~ 15 amin^2/mJy^2/hr
  for N_{pix} ~ 100
  (atmospheric noise limited)

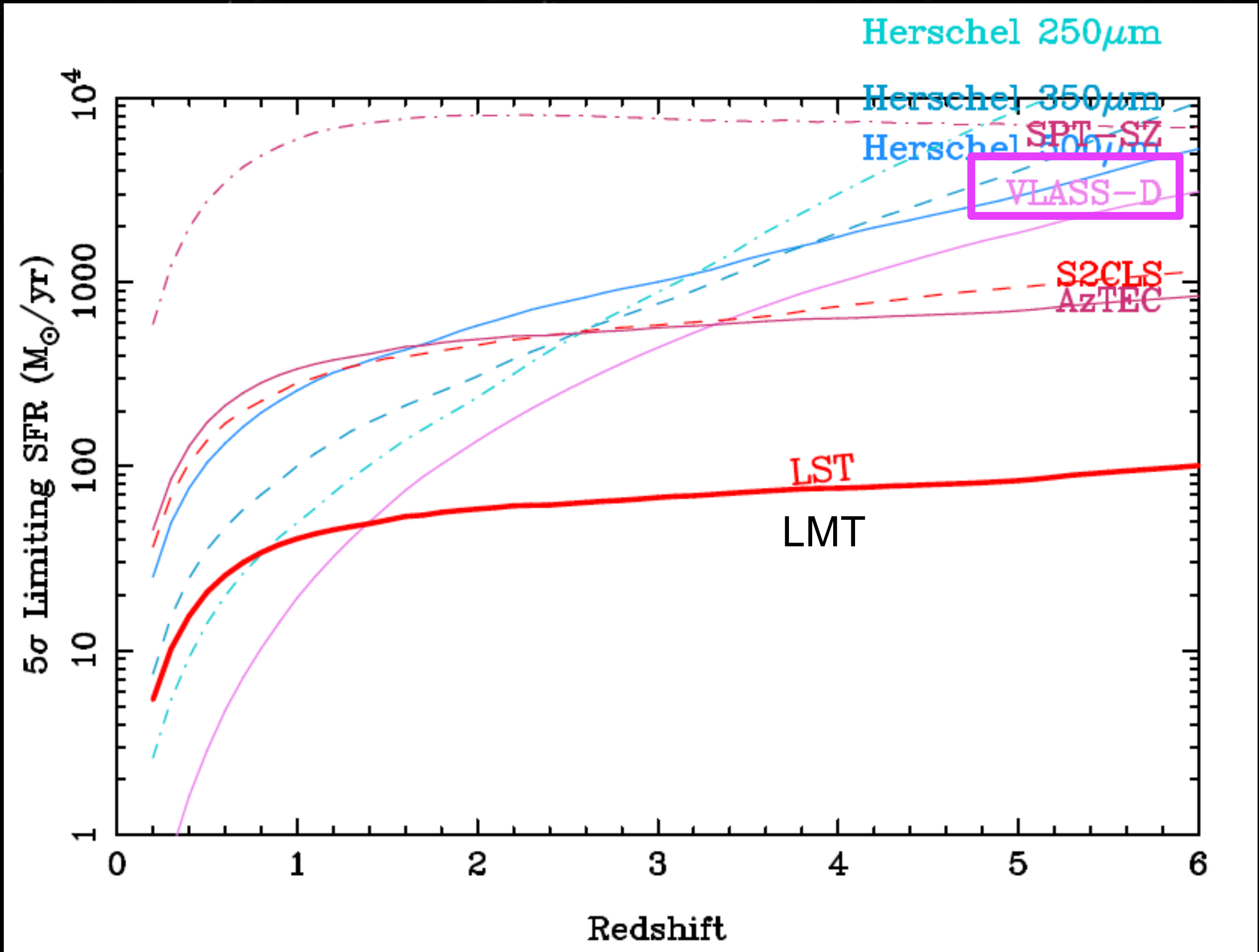
Xcam
:future camera
for LST

- ✦$MS_{Xcam,LST}$ ~ 10 deg^2/mJy^2/hr (10^4 pix)
  ~ 100 deg^2/mJy^2/hr (10^5 pix)
  10^5 pix => FOV~ 30 amin in diameter
- ✦$MS_{Xcam,LST}$ ~ 0.5 deg^2/$\sigma_{confusion}$^2/hr (10^5 pix)
  => 500 deg^2 with 1000 hrs (confusion-noise)

Confusion-limited "Blank Field" Survey

LST — LARGE SUBMILLIMETER TELESCOPE

LST-Deep : comparable to JVLA for z~ 1-2
> 10 times deeper for z > 3

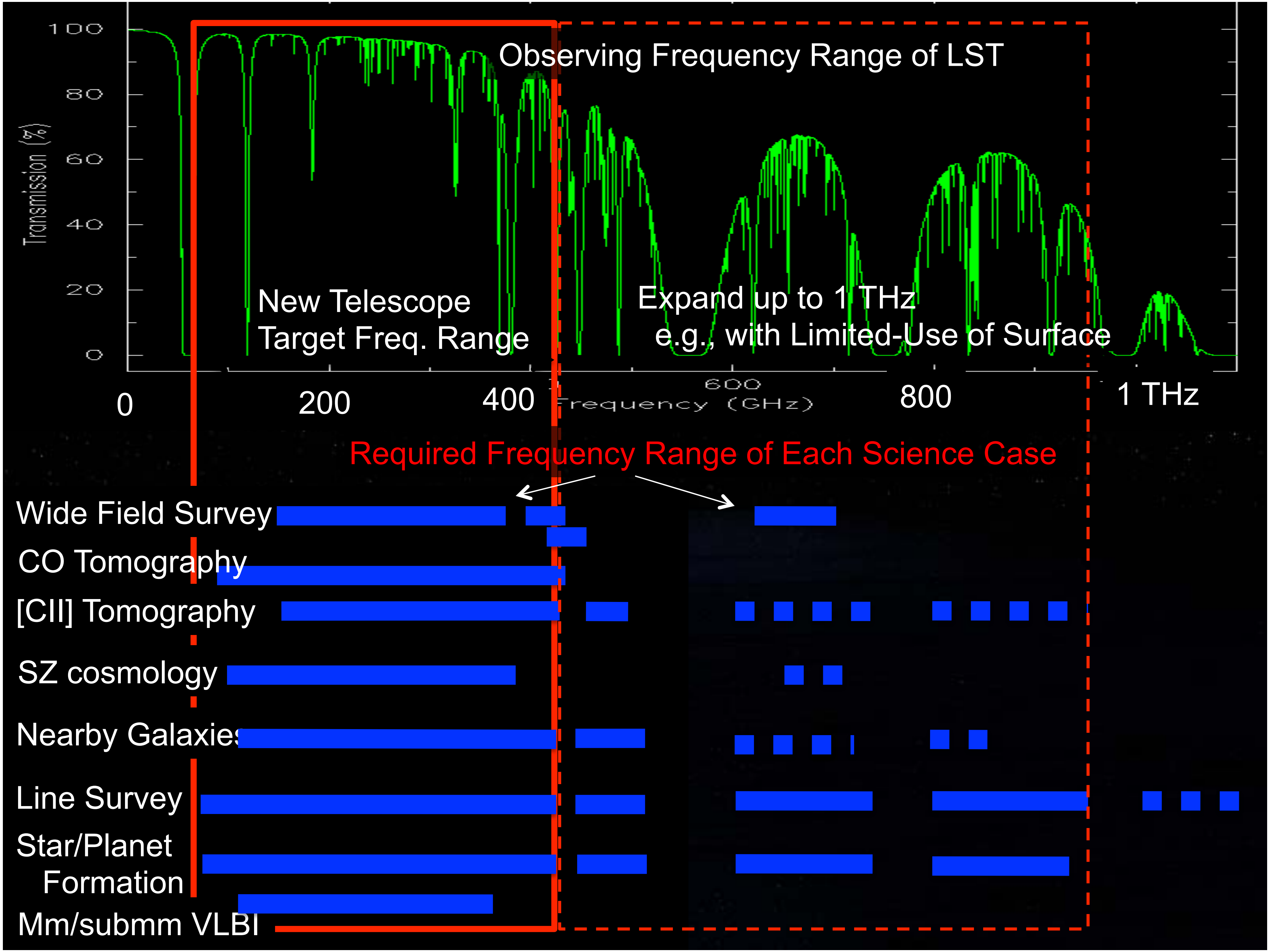


VLASS-Deep; 0.8"
- S-band(2-4 GHz)
- 1.5 μJy (1σ)
- 10 deg^2
- 3391 hours
- N/deg^2 = 9200

LST-Deep: 5" beam
- 1.1 mm
- 72 μJy (1σ)
- 500 deg^2
- 1000 hours (FOV=0.5 deg.)
- N/deg^2 ~ 20000

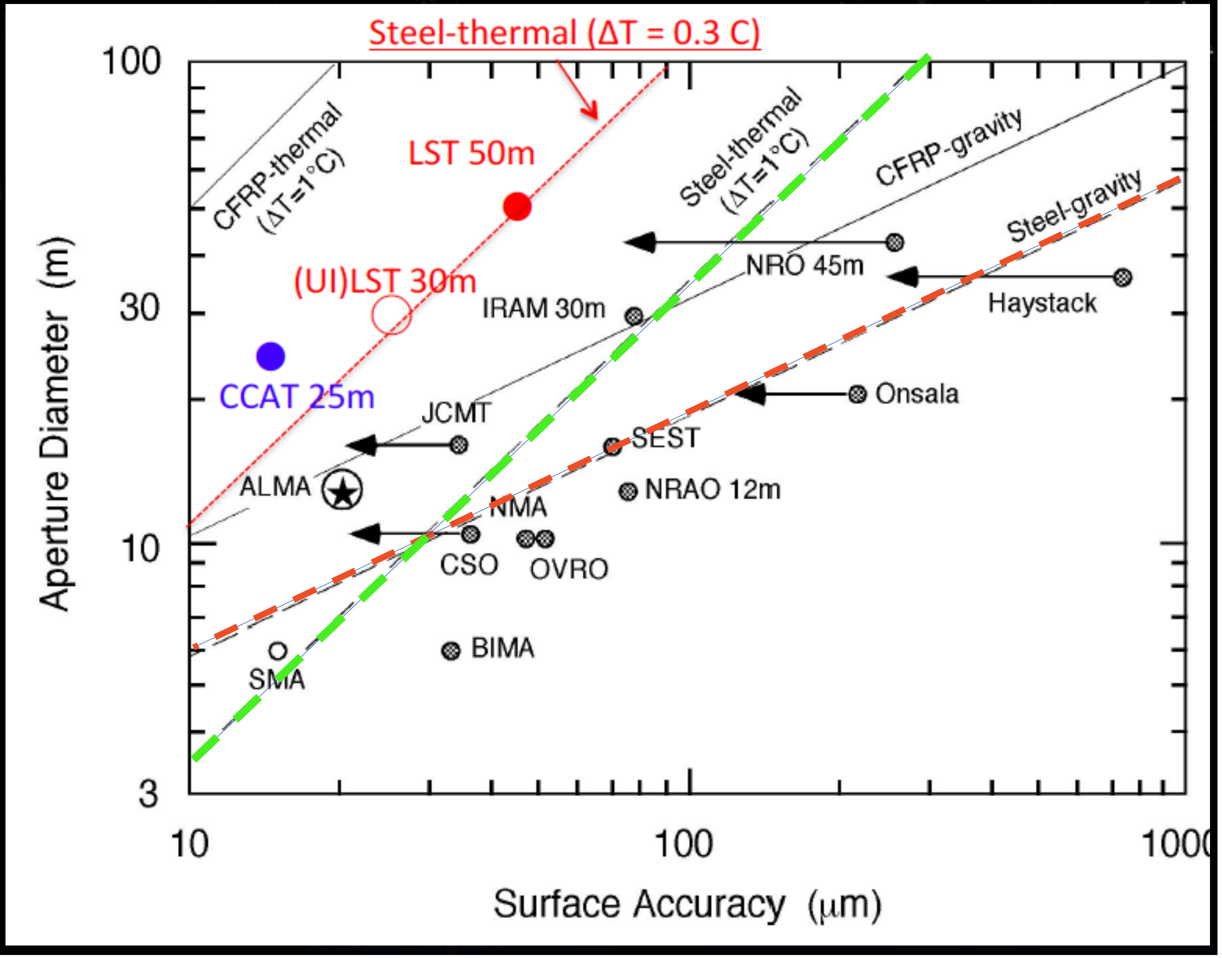
Why 70-420 GHz + up to 1THz?

- ✦70-420 GHz is the best for unveiling CIB and Cosmic Star-formation history up to z~ 10 (Era of Reionization) in cont. & lines
- ✦Well-matched with other science cases and atmospheric windows in high-sites
- ✦Up to 1THz（with limited use of main dish、under-illumination) for enhancing science and synergy with ALMA


Observing Frequency Range of LST
100
80
60
40
20
0
Transmission (%)
New Telescope
Target Freq. Range
Expand up to 1 THz
e.g., with Limited-Use of Surface
0
200
400
600
Frequency (GHz)
800
1 THz
Required Frequency Range of Each Science Case
Wide Field Survey
CO Tomography
[CII] Tomography
SZ cosmology
Nearby Galaxies
Line Survey
Star/Planet
Formation
Mm/submm VLBI

Why 45 μm rms?

- ✦ High aperture efficiency up to 420 GHz (λ=715 μm) => ε_{rms} = λ/16 = 45 μm
- ✦ Active surface control required for gravitational & thermal deform.
- ✦ Freq > 420 GHz needs ε_{rms} ~ 30 μm? for D~30m (under-illumination)



Transformational Science Case

- ✦ Exploration of Cosmic Star Formation History and Large Scale Structures via two kinds of surveys
  - Multi-band Deep Continuum Survey over ~10^3 deg^2 ("2.5D" survey with using color of sources)
  - Blind CO/CII line emitter search (Tomography) up to z~ 10, EoR, using imaging spectrograph ("3D") not severely affected by source confusion noise

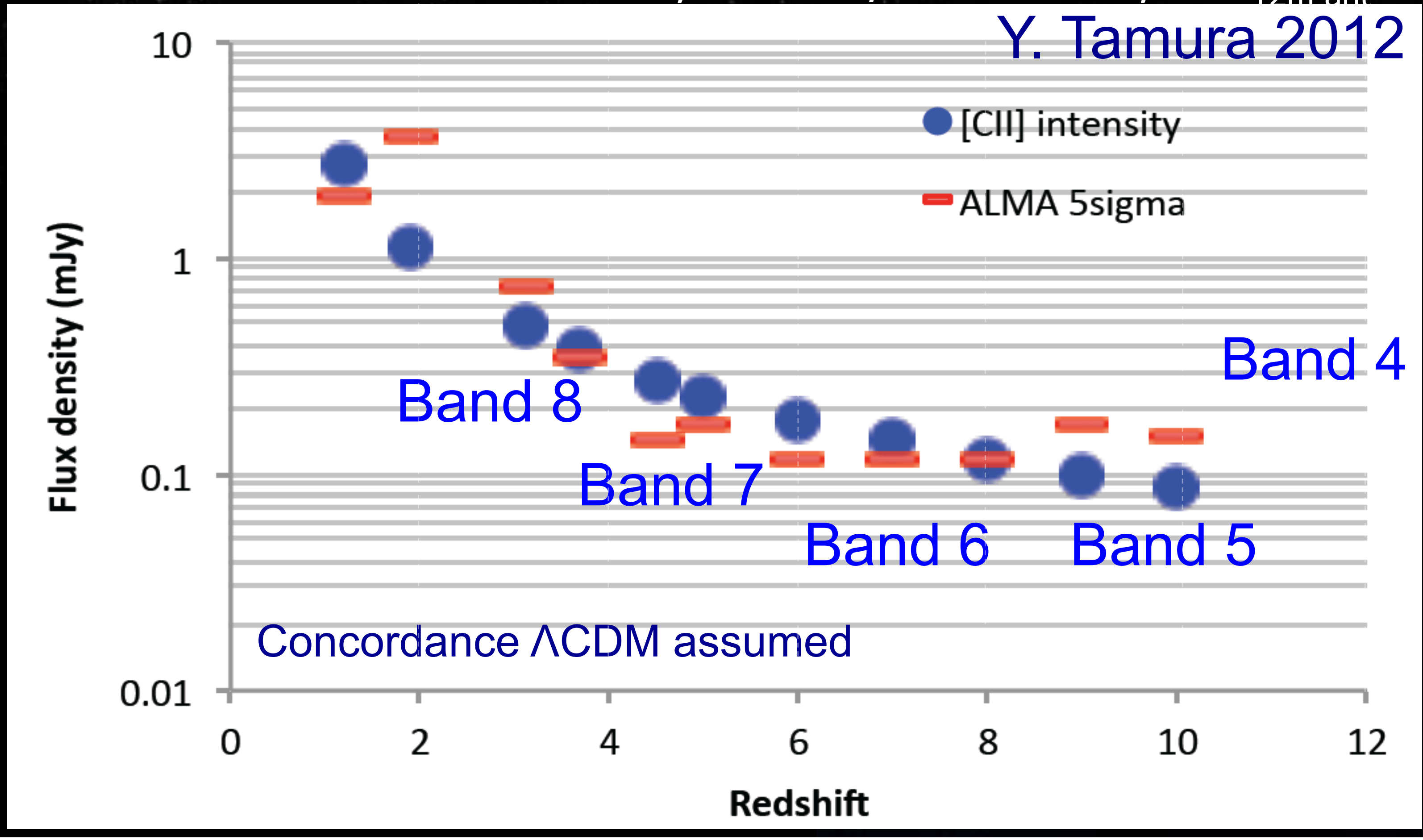
(Blind vs multi-object spectroscopy still needs to be investigated, but blind can provide us with census of "non-biased" line emitters, in which strong-line but continuum-weak emitters will be included)

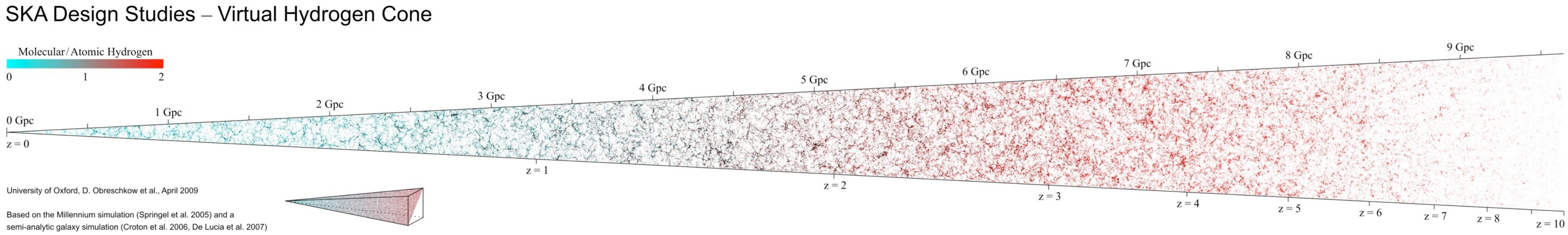
RK+ 2016 (SPIE proceedings paper)

Uniform "selection function" of [CII] expected in LST+ultra wide spectrometer

Blind [CII] emitter search can reach up to z ~ 10, and will be a powerful tool to uncover CSFH and EoR

- ✦ L[CII] ~ 10^7.7 Lsun (our galaxy; COBE) assumed
- ✦ On-source 24 hours with ALMA; 100 km/s resolution, & $N_{12m\ ant}$ =50





CO/[CII] Tomography

+ [OIII] emitter

RSD Redshift Space Distortion

Verify GR by estimating the growth rate of structure, dark energy problem

LSS Cosmic Large-Scale Structure

Investigate the correlation between dark and baryonic matters from clustering analysis, dark matter problem

CSFH Cosmic Star-formation History

Investigate mass/luminosity function of molecular gas as a function of redshift, "hidden" history of baryonic matter

EoR Epoch of Reionization

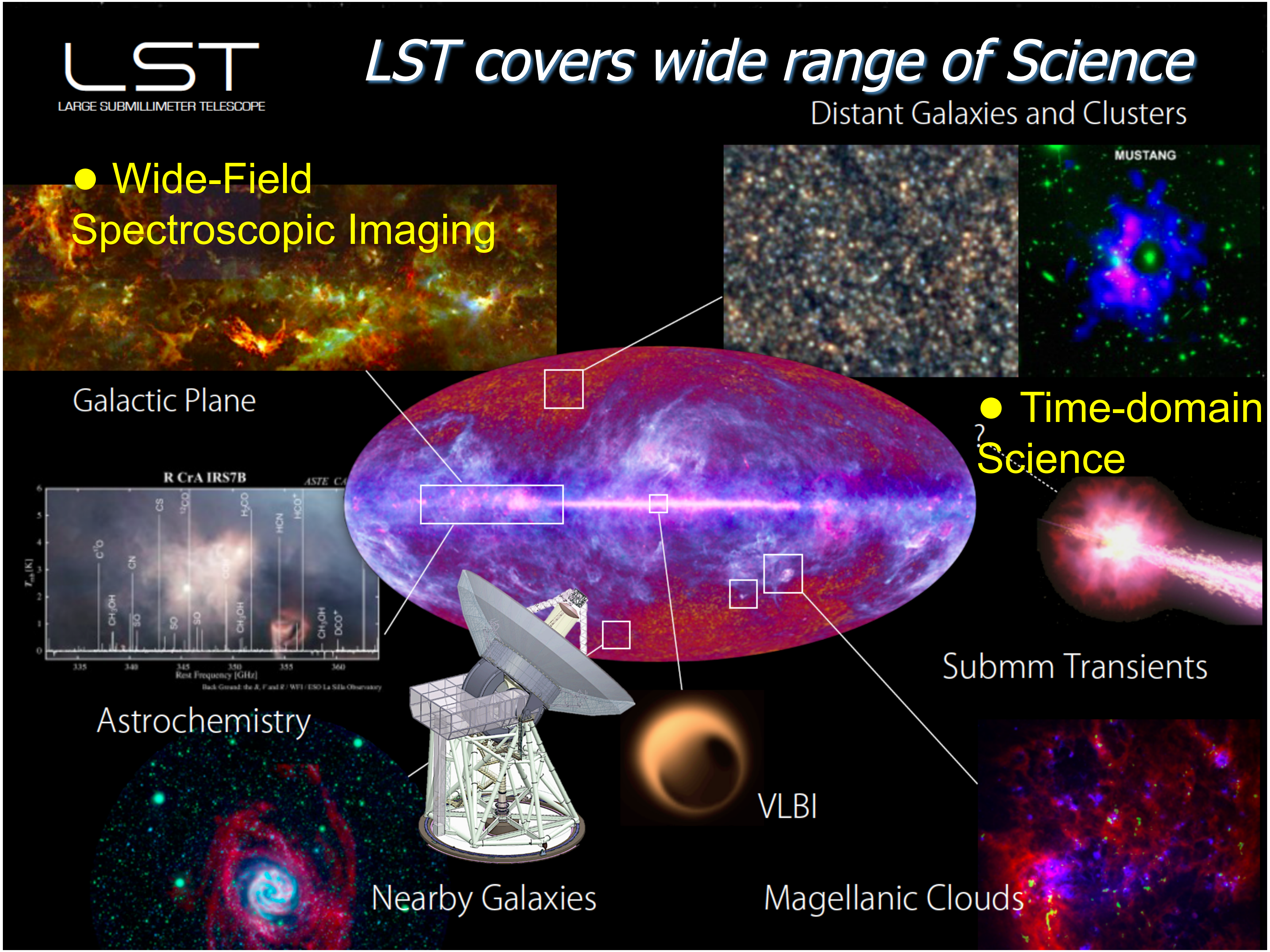
Search for earliest "hidden" galaxies, first generation galaxies

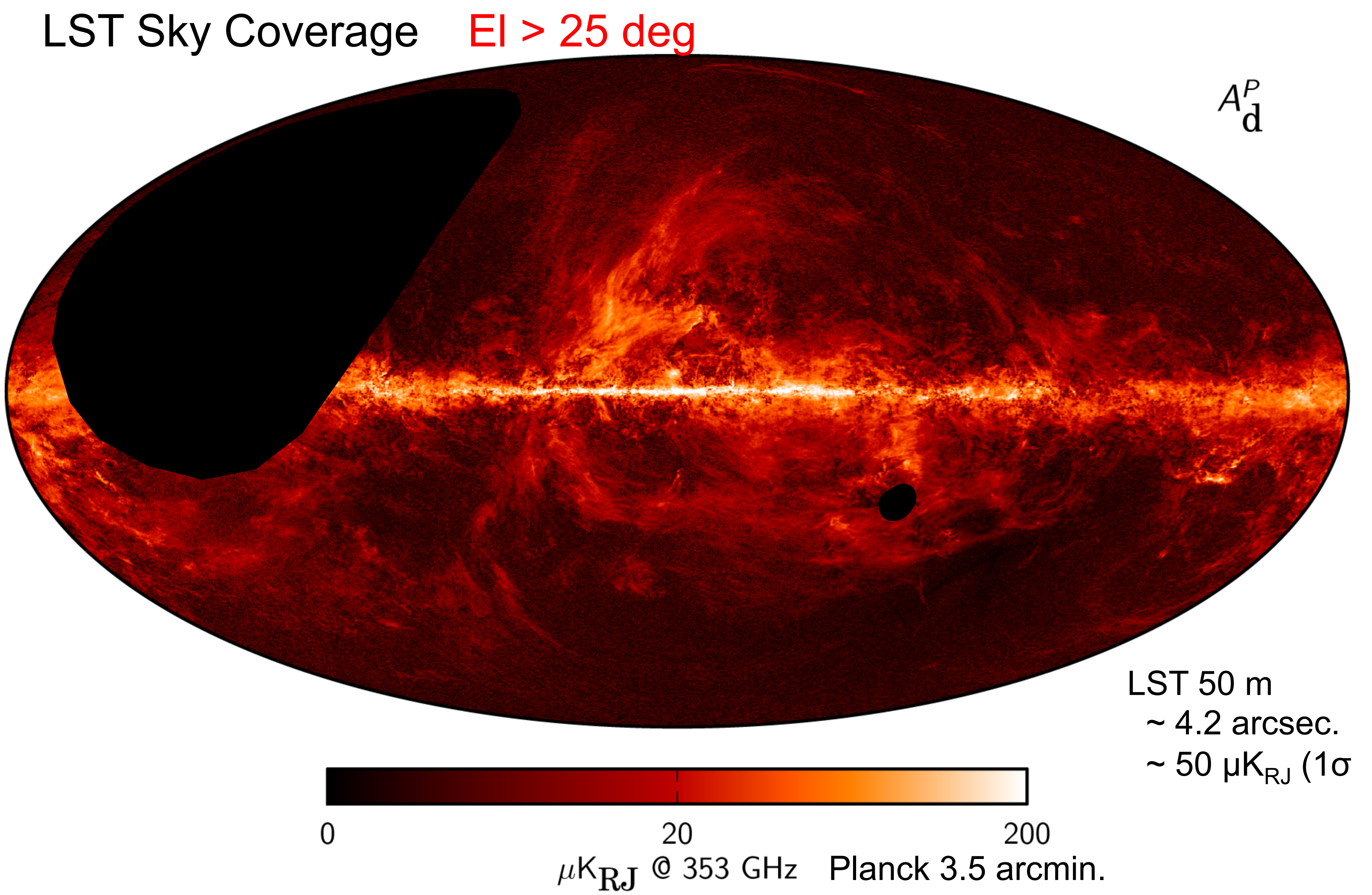
Evolution of Galaxies

Cosmic evolution of galaxies proved through properties of interstellar medium

... and serendipitous discoveries

Line emitters, transient and variables, ...

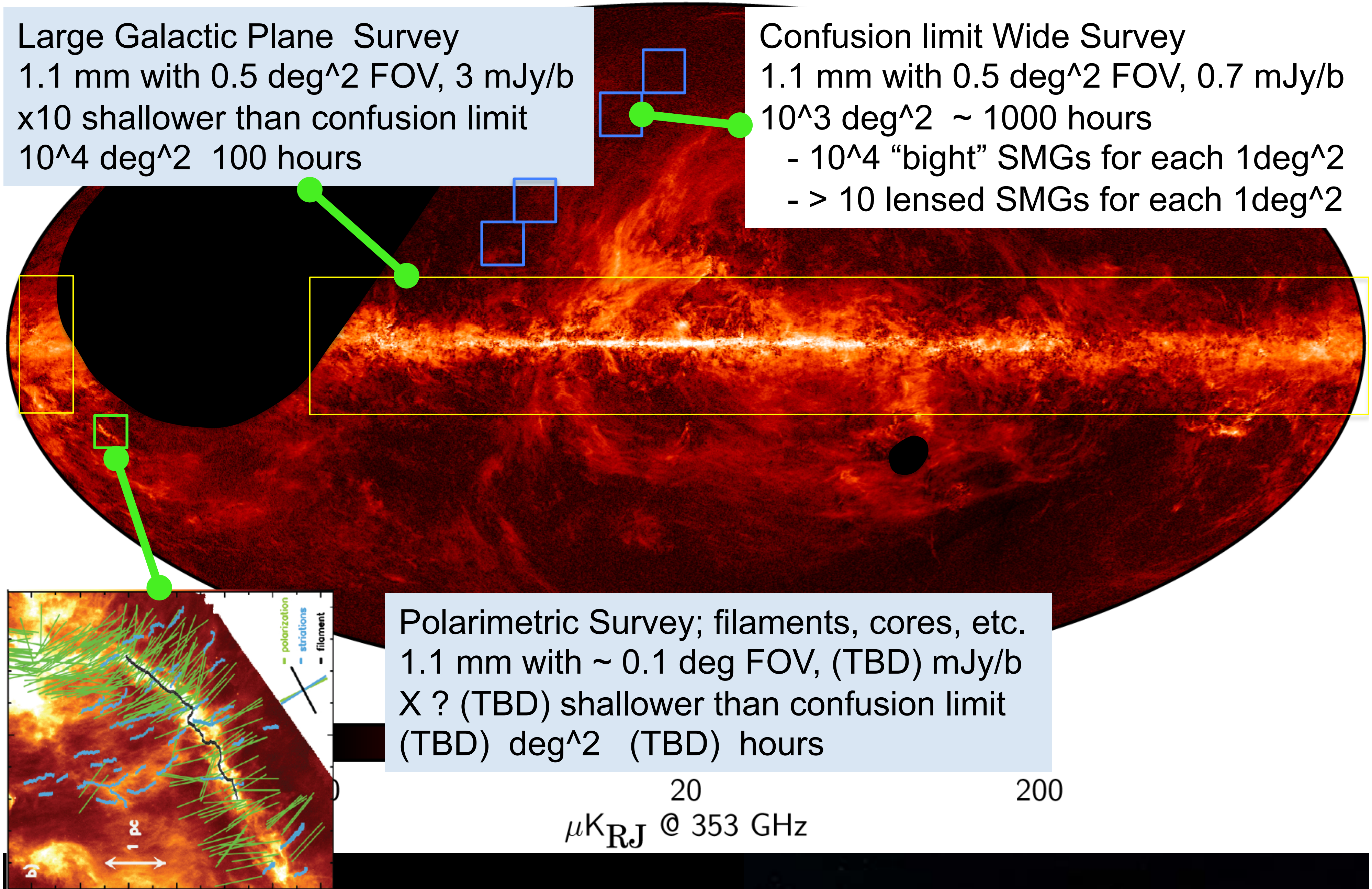

LST
LARGE SUBMILLIMETER TELESCOPE
LST covers wide range of Science
Distant Galaxies and Clusters
MUSTANG
● Wide-Field
Spectroscopic Imaging
Galactic Plane
● Time-domain
Science
?
R CrA IRS7B
Rest Frequency [GHz]
Submm Transients
Astrochemistry
VLBI
Nearby Galaxies
Magellanic Clouds


LST Sky Coverage
El > 25 deg
A_d^P
LST 50 m
~ 4.2 arcsec.
~ 50 μK$_{RJ}$ (1σ
0
20
200
μK_{RJ} @ 353 GHz
Planck 3.5 arcmin.

LST Our Galacy Survey Examples

Large Galactic Plane Survey
1.1 mm with 0.5 deg^2 FOV, 3 mJy/b
x10 shallower than confusion limit
10^4 deg^2 100 hours

Confusion limit Wide Survey
1.1 mm with 0.5 deg^2 FOV, 0.7 mJy/b
10^3 deg^2 ~ 1000 hours
- 10^4 “bight” SMGs for each 1deg^2
- > 10 lensed SMGs for each 1deg^2

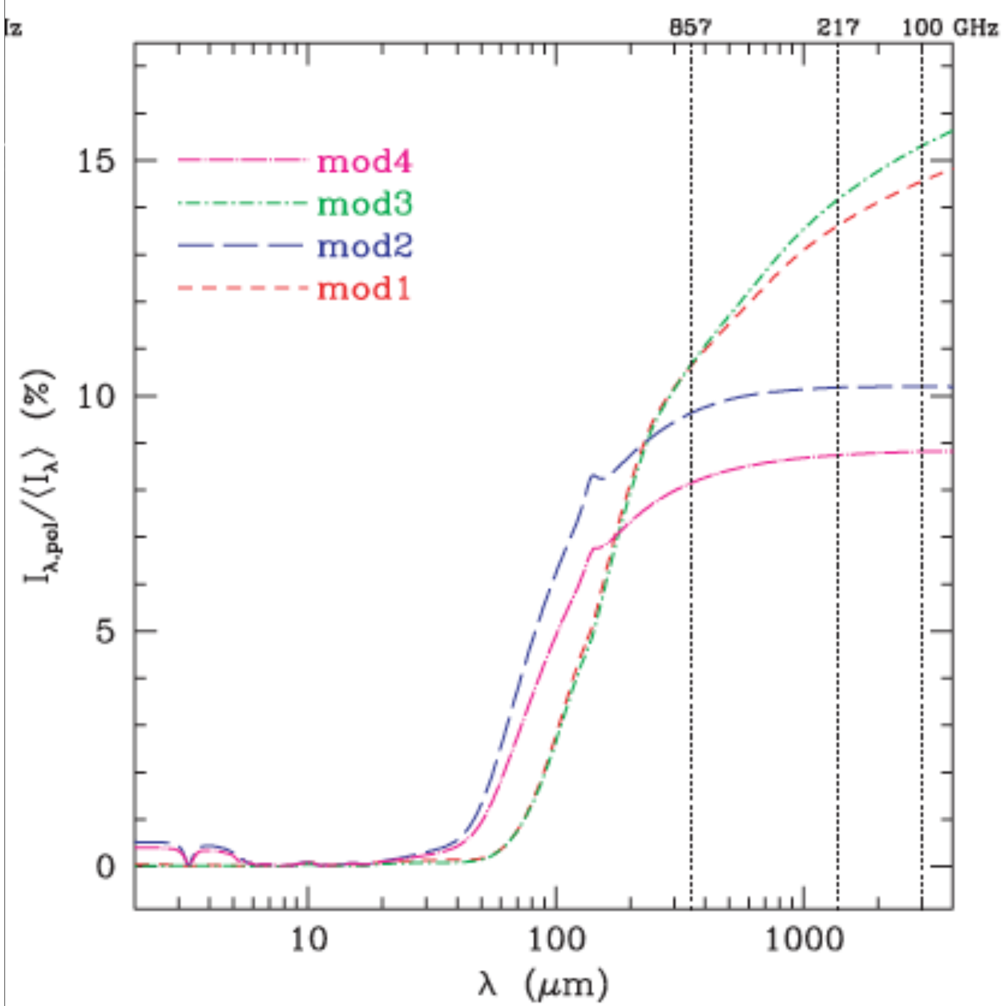


Polarimetric Survey; filaments, cores, etc.
1.1 mm with ~ 0.1 deg FOV, (TBD) mJy/b
X ? (TBD) shallower than confusion limit
(TBD) deg^2   (TBD) hours

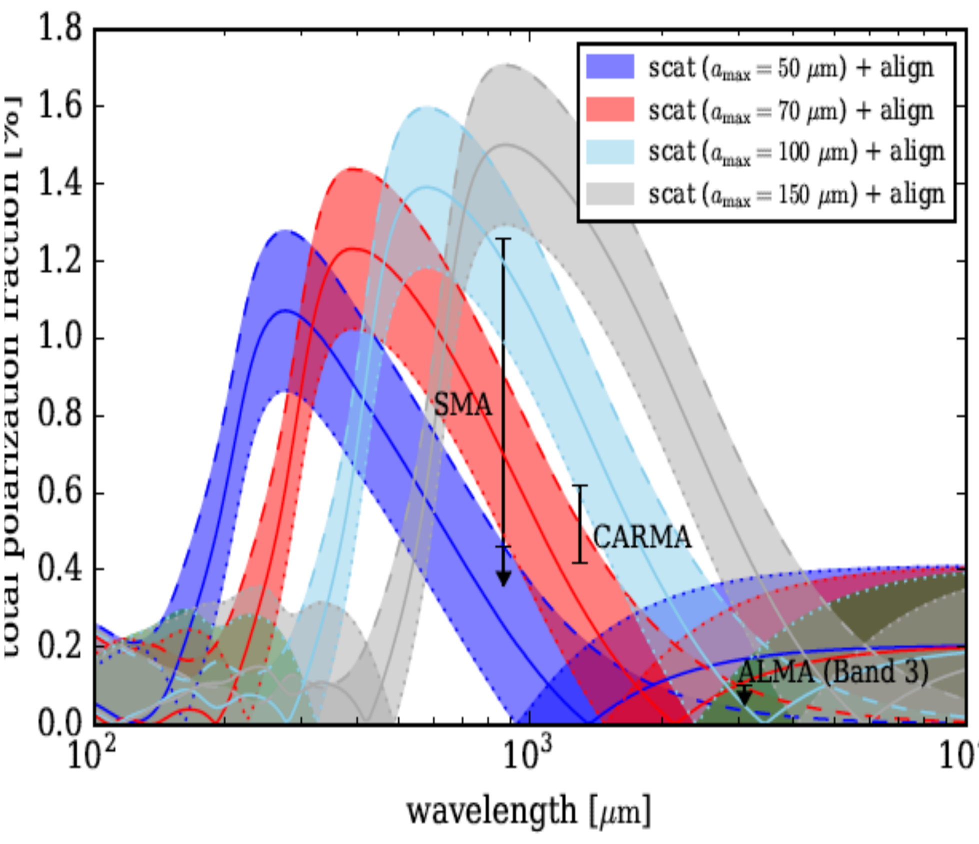
Spectroscopic Polarimetry

Polarization depends on dust composition and sizes

Draine & Fraisse +2009
Polarized Intensity for dust models



Kataoka+2017;
Self Scattering of dust in
proto-planetary disks;
grain-size dependence



Technical Feasibility Study

- ✦Science Requirement & Technical Specification
- ✦Operation condition & Operation Planning
- ✦Optics Design
- ✦Conceptual Design of Telescope Structure
- ✦Surface Accuracy Budget Analysis
- ✦Developments of Key Instruments
- ✦Millimetric Adaptive Optics (MAO) concept under development: started R&D and plan to demo

LST

LARGE SUBMILLIMETER TELESCOPE

Optics Design for wide FOV

very preliminary

Richey-Chretien Optics for D= 50 m main reflector

Lyot-Stop at Sub-refrector: $D_{effective}$ ~ 46.7 m

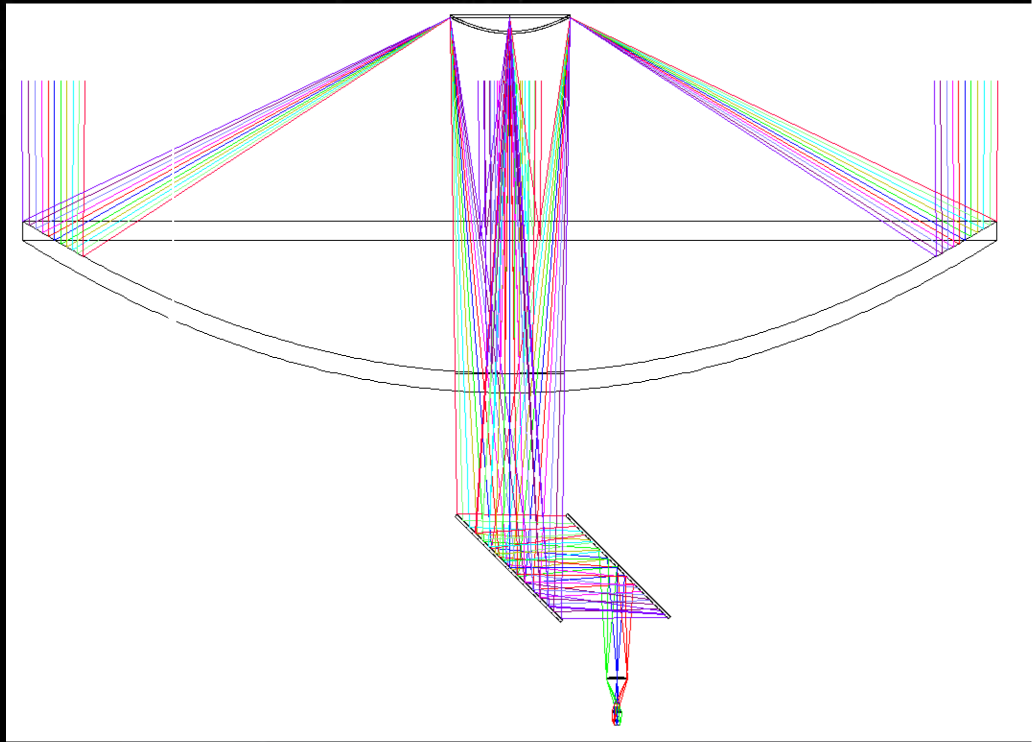
FOV ~ 0.66 deg. in diameter at 850 micron achievable

But...

- large mirrors

  $D_{sub\text{-}ref}$ ~ 6.2 m

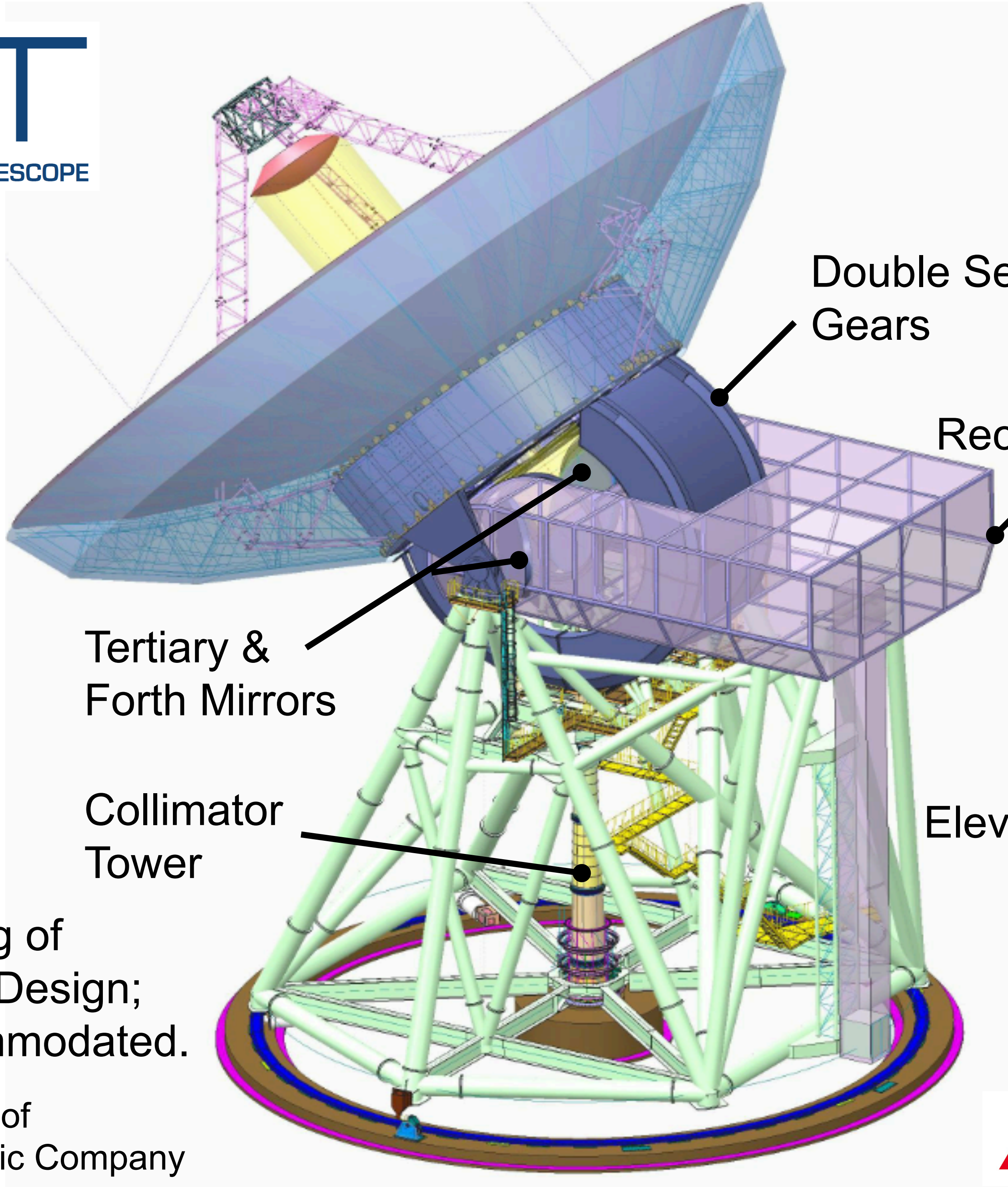
  #3 mirror ~ 7 m diameter
- huge RX cabin needed
- big impact on telescope mechanical structure?
- being investigating better optics design



Takekoshi, Oshima + in prep.

LST

LARGE SUBMILLIMETER TELESCOPE



The First Drawing of
LST Conceptual Design;
Major req. accommodated.

Image Courtesy of
Mitsubishi Electric Company

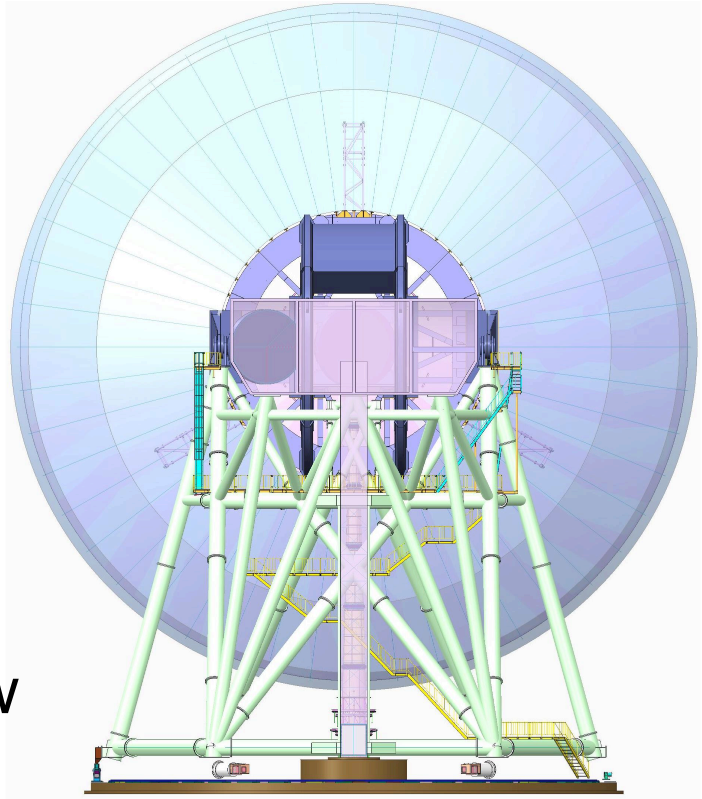
MITSUBISHI ELECTRIC

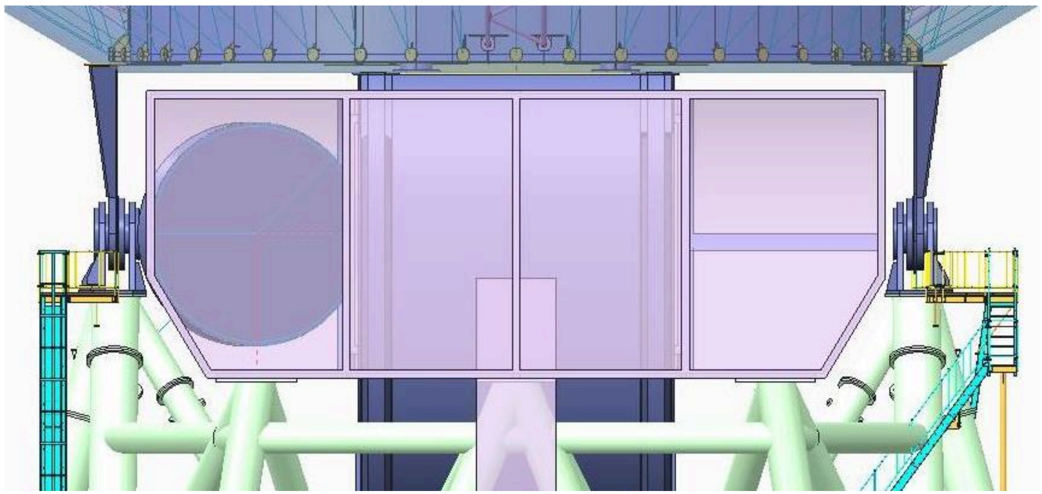
LST

LARGE SUBMILLIMETER TELESCOPE

#3, & #4 mirrors
limit the minimal size of
receiver cabin..

Back View





Top View

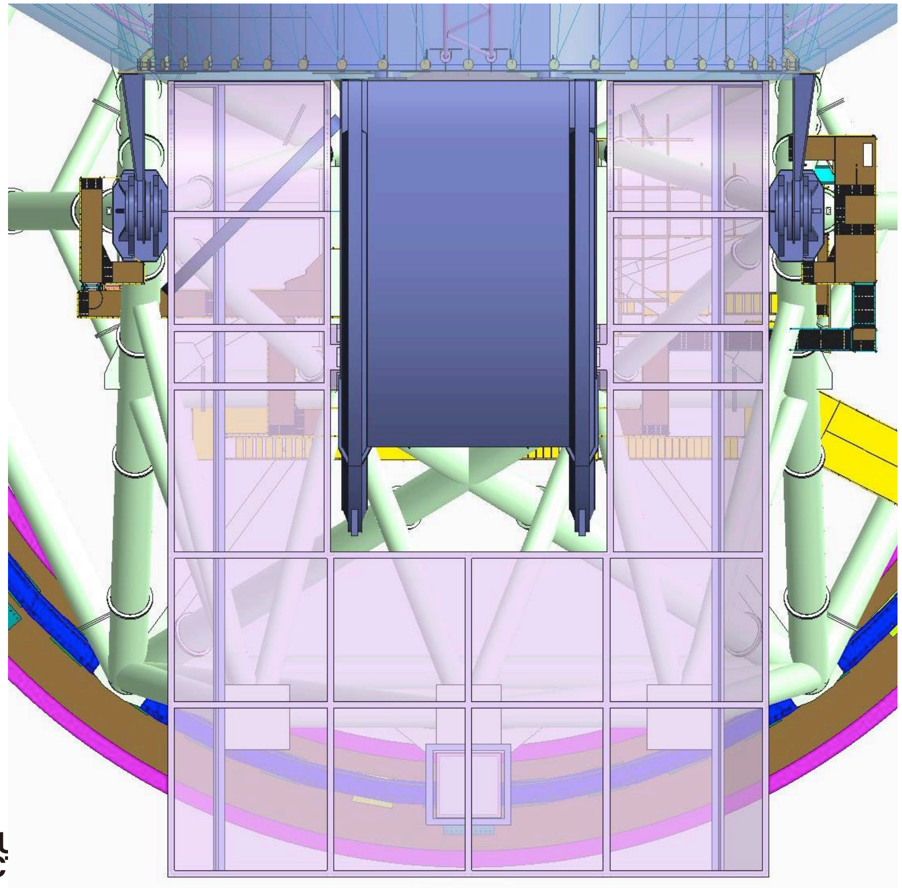
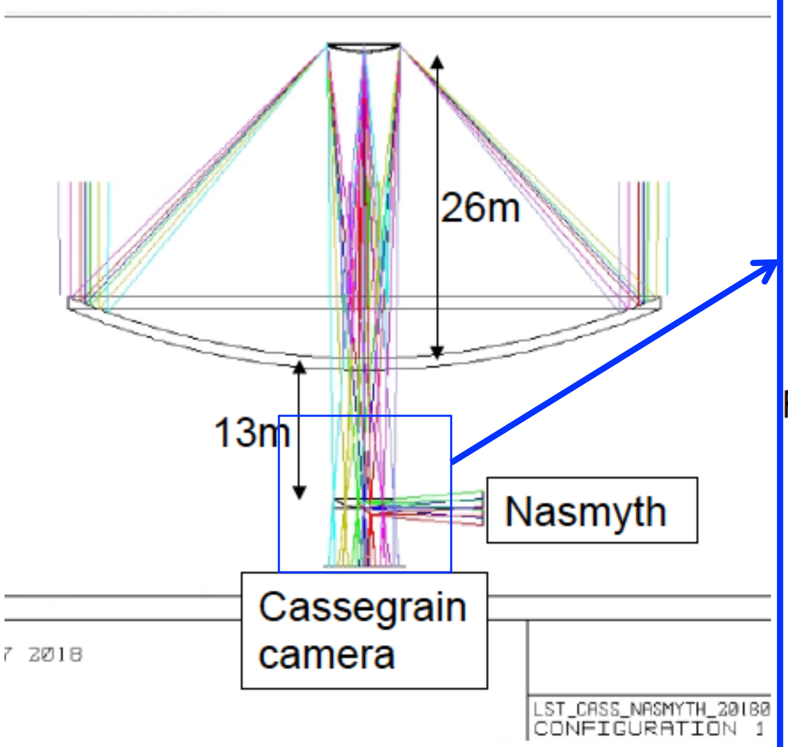
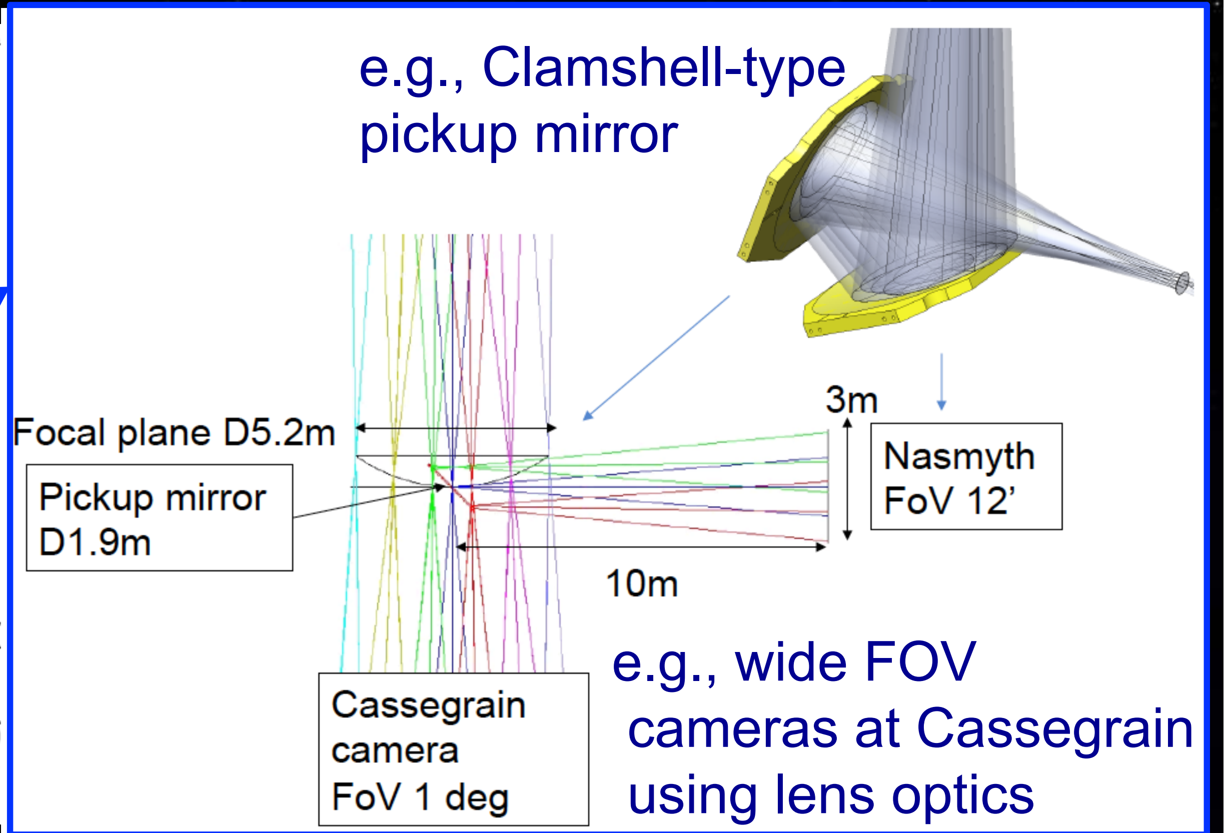


Image Courtesy of
Mitsubishi Electric Company

Hybrid of Nasmyth and Cassegrain

- D_1=50m, D_2=6.6m, F/6 keeed, but M=15→10
- FoV = 0.76 deg @850 micron; a little improved
- Primary focal ratio=0.6➔secondary is a bit far?

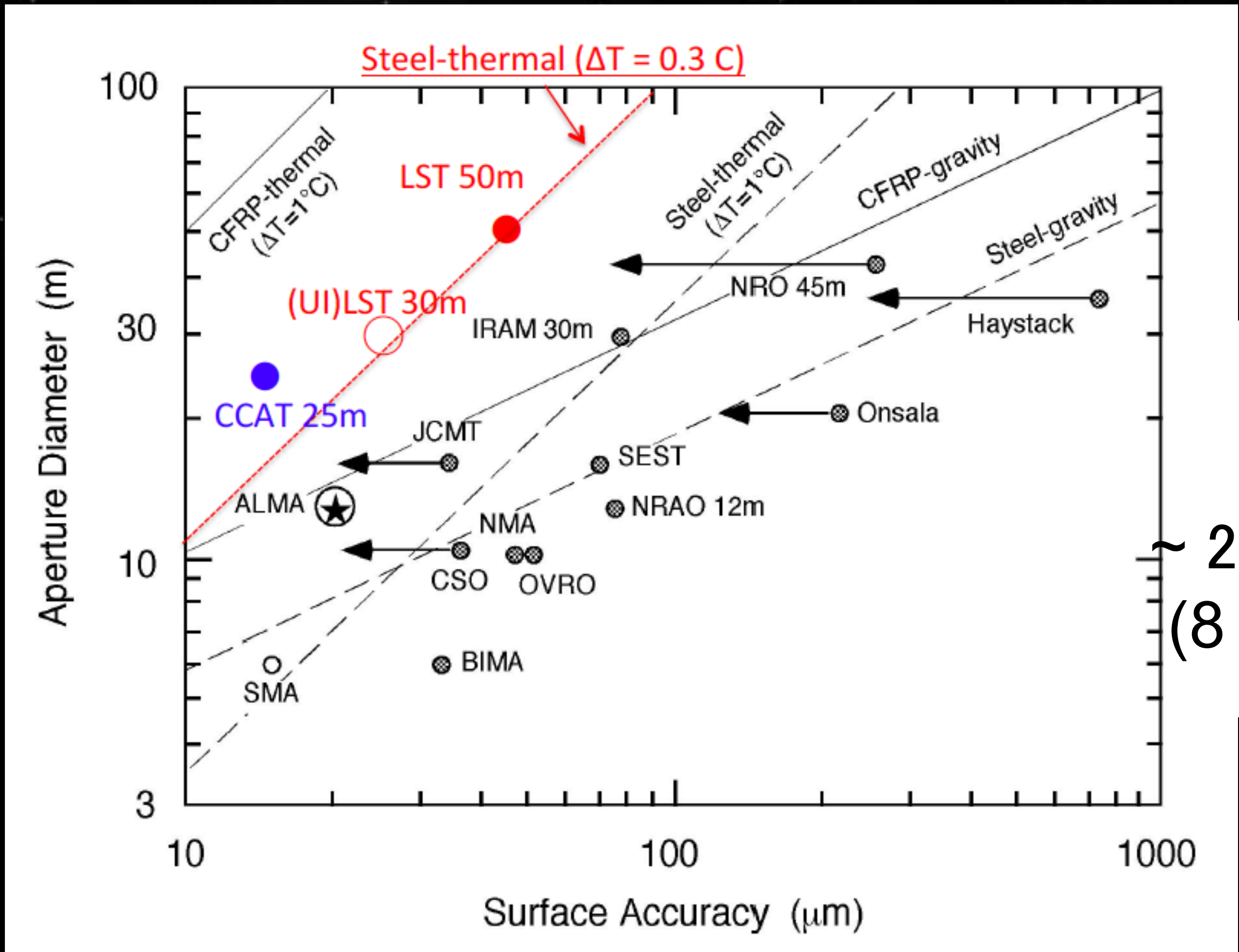


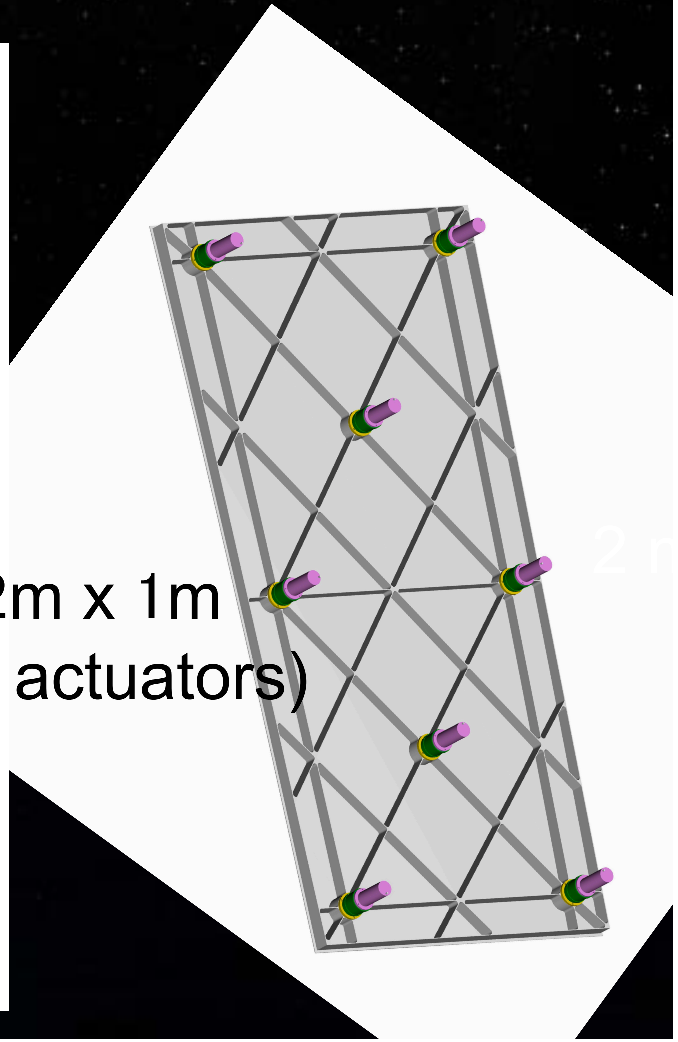


LARGE SUBMILLIMETER TELESCOPE

Active Surface Control Required

45 µm rms needs careful mech/thermal design as well



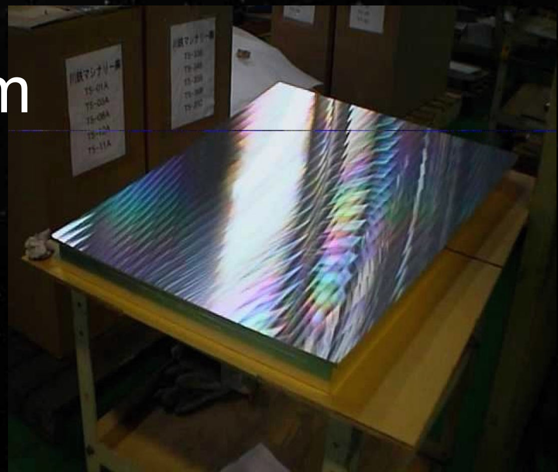


~ 2m x 1m
(8 actuators)

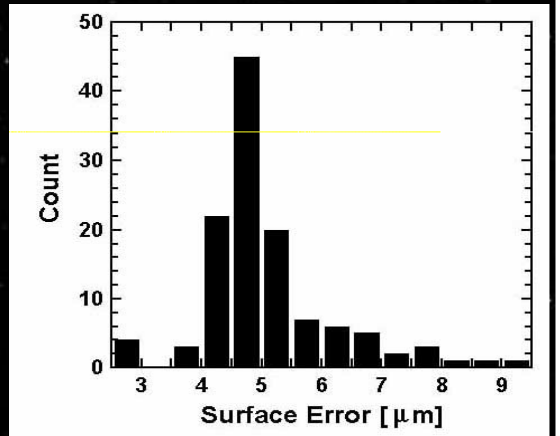
Machined Aluminum Panels for ASTE

204 surface panels
-Machined from Aluminum mono-block
- Size: ~ 80 cm x 80 cm (average)
- Weight : ~ 12-15 kg/m^2
- Accuracy : ~ 5 μm (rms)
- three motorized actuators at back side (612 actuators in total)

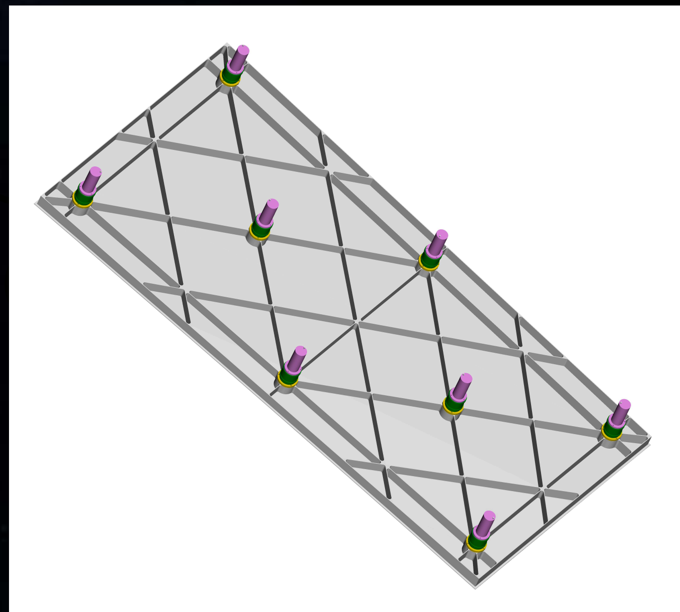
Machined Aluminum panel



Surface Errors



LST needs larger panels
- larger than 2 m x 1m
- 8 actuators for each
- ~ 2000 panels in total
- ~ 16 x 10^3 actuators



Tentative Surface Error Budget for LST

& comparison with IRAM 30m Telescope

Error budgets for Gravity and Thermal Deformation can be smaller
Wind-Load is current headache, some correction etc. needed

Table 3. Tentative surface error budget for LST and comparison with IRAM 30-m telescope (Baars et al. 1987[14]). All unit is μm in rms.

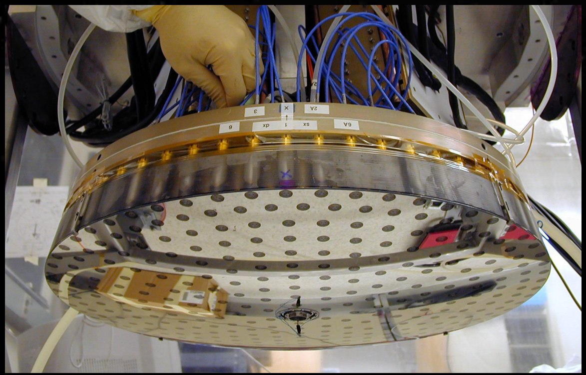
Telescope	IRAM 30-m	LST 50-m	Note
Gravity (residual)	40	15	FEM modelling + active surface control
Thermal (residual)	20	15	FEM modelling + active surface control
Wind (residual)	30	25	IRAM spec is for wind velocity $\leq$ 12 m/s Wind load correction using pressure sensors
Surface panel	26	20	
Subreflector (residual)	20	15	Correction with active surface control
#3, 4 mirrors (residual)	10	15	Correction with active surface control
Measurements and setting errors	35	15	Holography using astronomical sources
Total (RSS)	70	44.1	

RK+ in SPIE proceedings; White paper by RK, Kohno

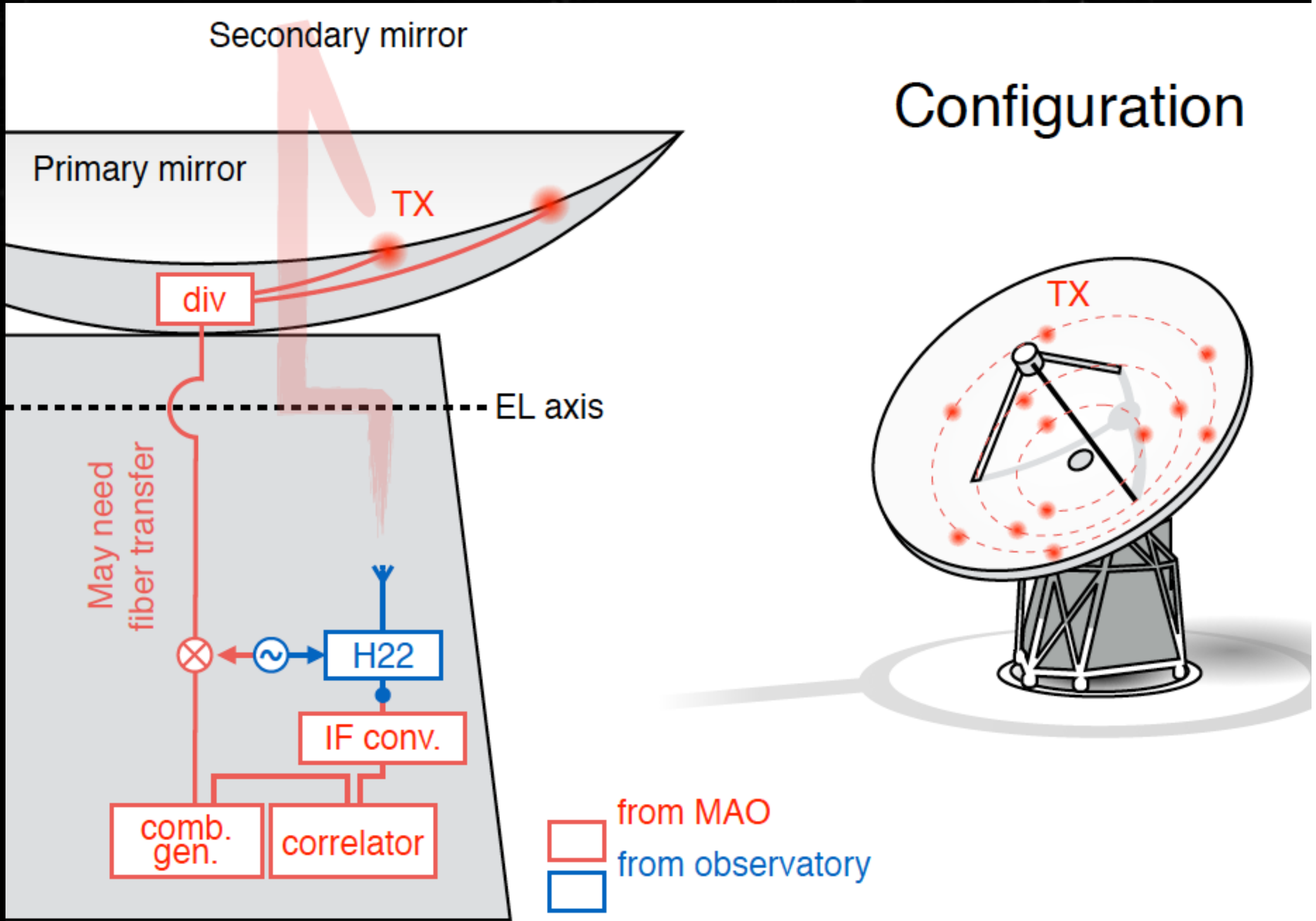
Millimetric Adaptive Optics (MAO)

Yoichi Tamura, RK et al.

Transmitters on Dish (ToD) to measure short-timescale deform.
Correction with adaptive secondary or other optics

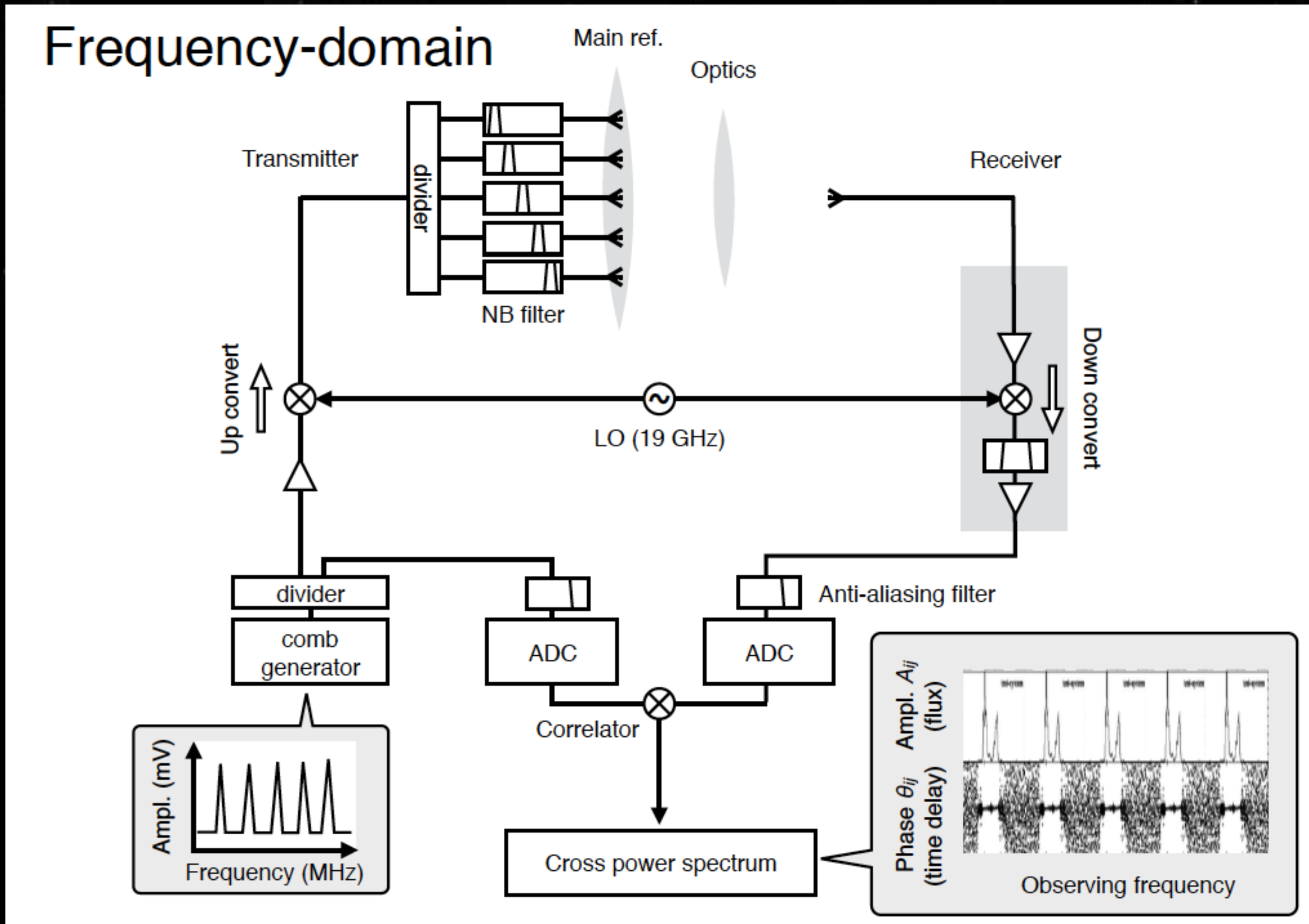


The MMT adaptive secondary built by the U. Arizona and Arcetri : 336 voice coils equipped at the back



Millimetric Adaptive Optics (MAO)

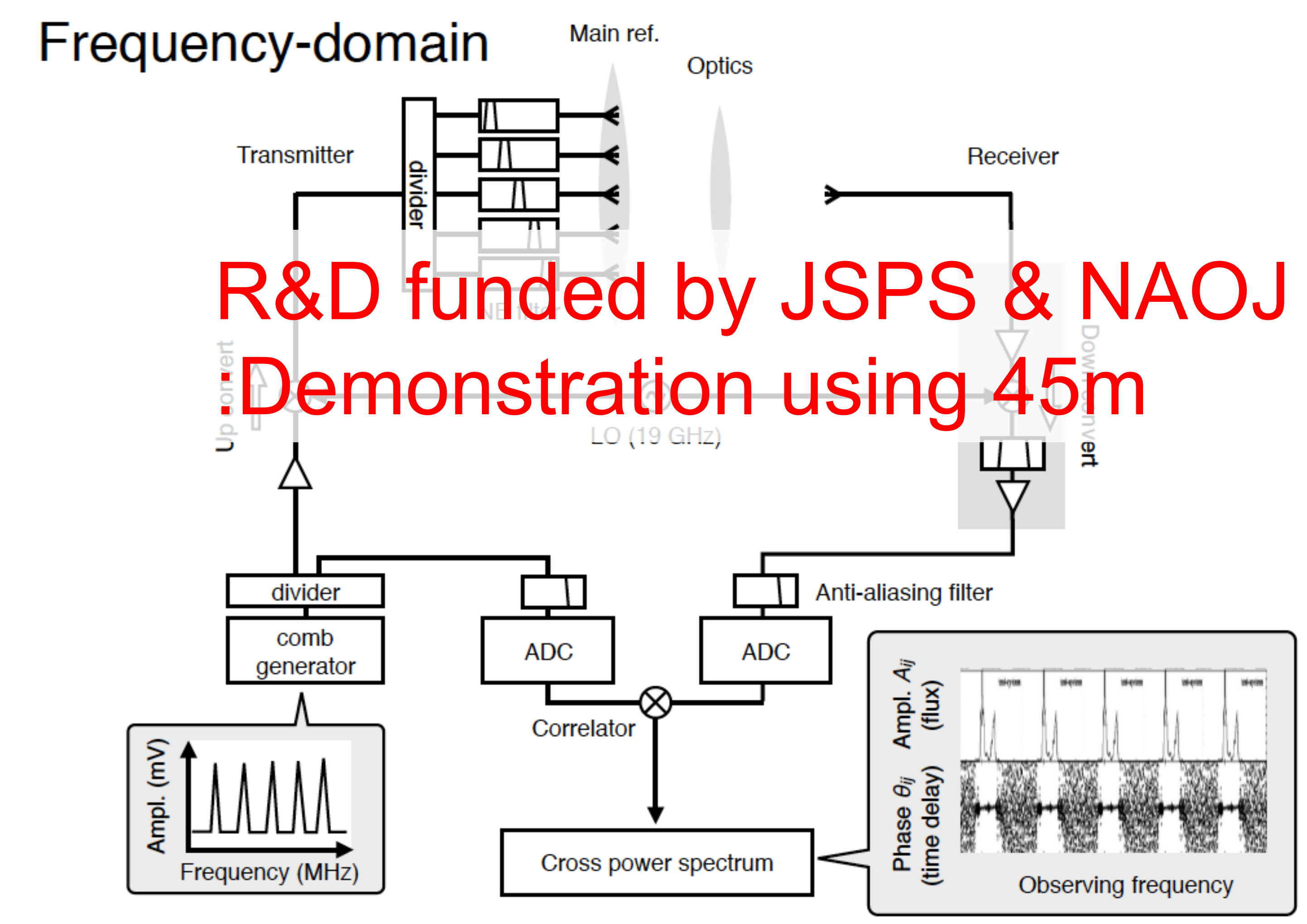
Frequency Domain Multiplication Scheme is baseline for transmitter signal distribution to telescope surface



Millimetric Adaptive Optics (MAO)

Yoichi Tamura, RK et al.

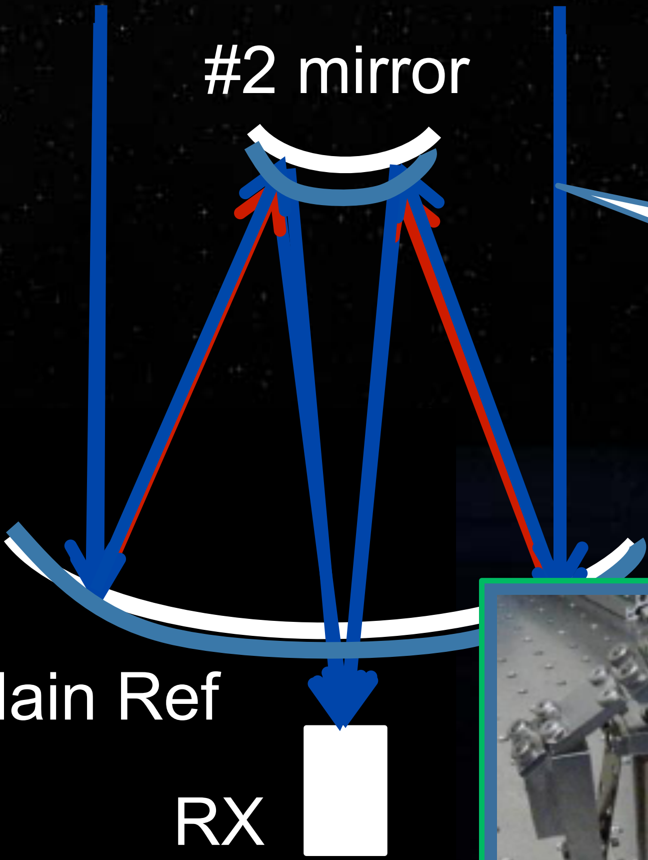
Transmitter signals discriminated in Frequency Domain are prepared on main reflector



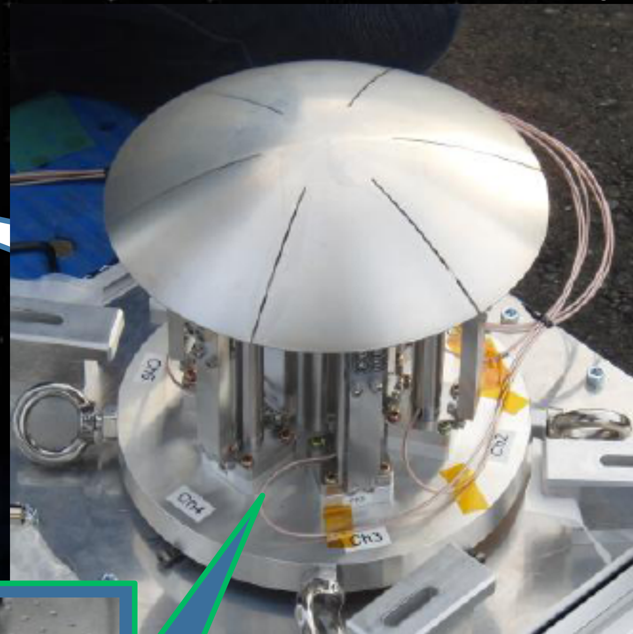
R&D funded by JSPS & NAOJ
:Demonstration using 45m

Deformable Mirror Development

Radio Telescope
Prototype
for baloon/space



Deformable Secondary



actuators
at back side

actuator unit

Seki, Kogiso+

Key Focal Plane Instruments

- ✦ Ultra-Wideband Medium-spectral Resolution Imaging Spectrometer Array: Blind <u>CO/[CII] Tomography</u>

  Freq= 150 GHz - 420 GHz & N_{pix} of > 300 (~ 1000)
- ✦ Multi-Chroic Wide–Field Camera

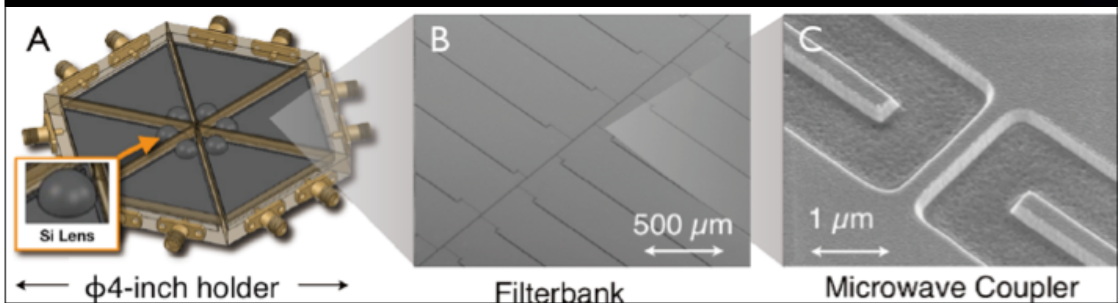
  covering 3, 2, 1.1, 0.85 mm, (+0.45, 0.35 mm)
- ✦ Multiple-band Heterodyne Array Receivers (~ 100 beams)

  \+ Ultra-wideband Spectrometers (for line survey)

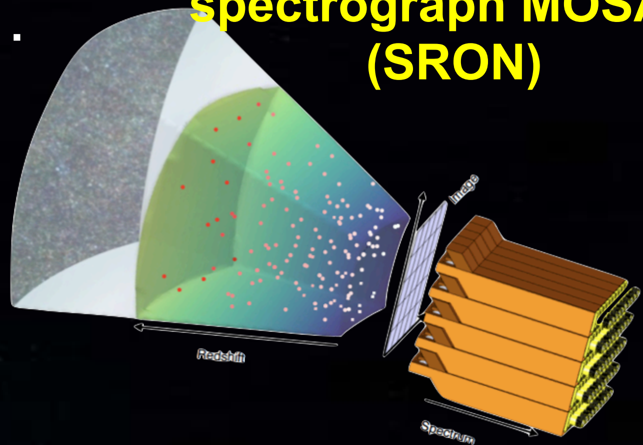
DESHIMA
Deep Spectroscopic High-z Mapper

=> “Super DESHIMA” <=
or “Super MOSAIC”…

Mm/submm multi-object spectrograph MOSAIC (SRON)

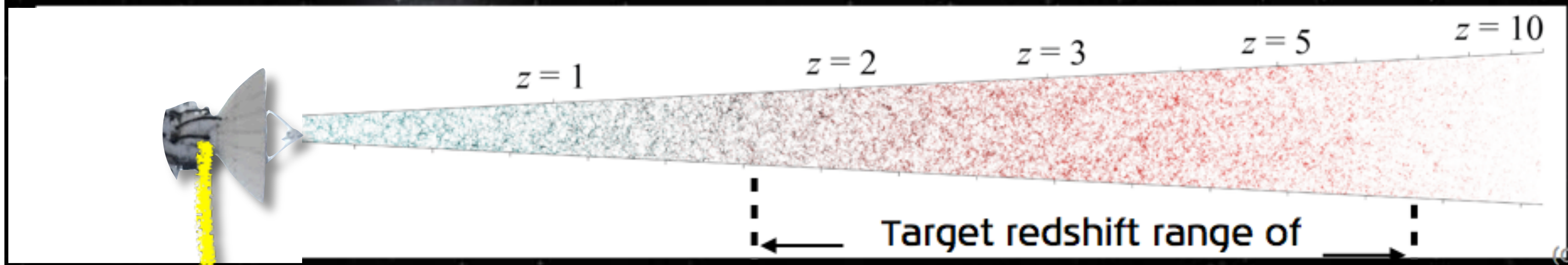


<u>Deep Spectroscopic</u> <u>High-Z</u> <u>Mapper</u>



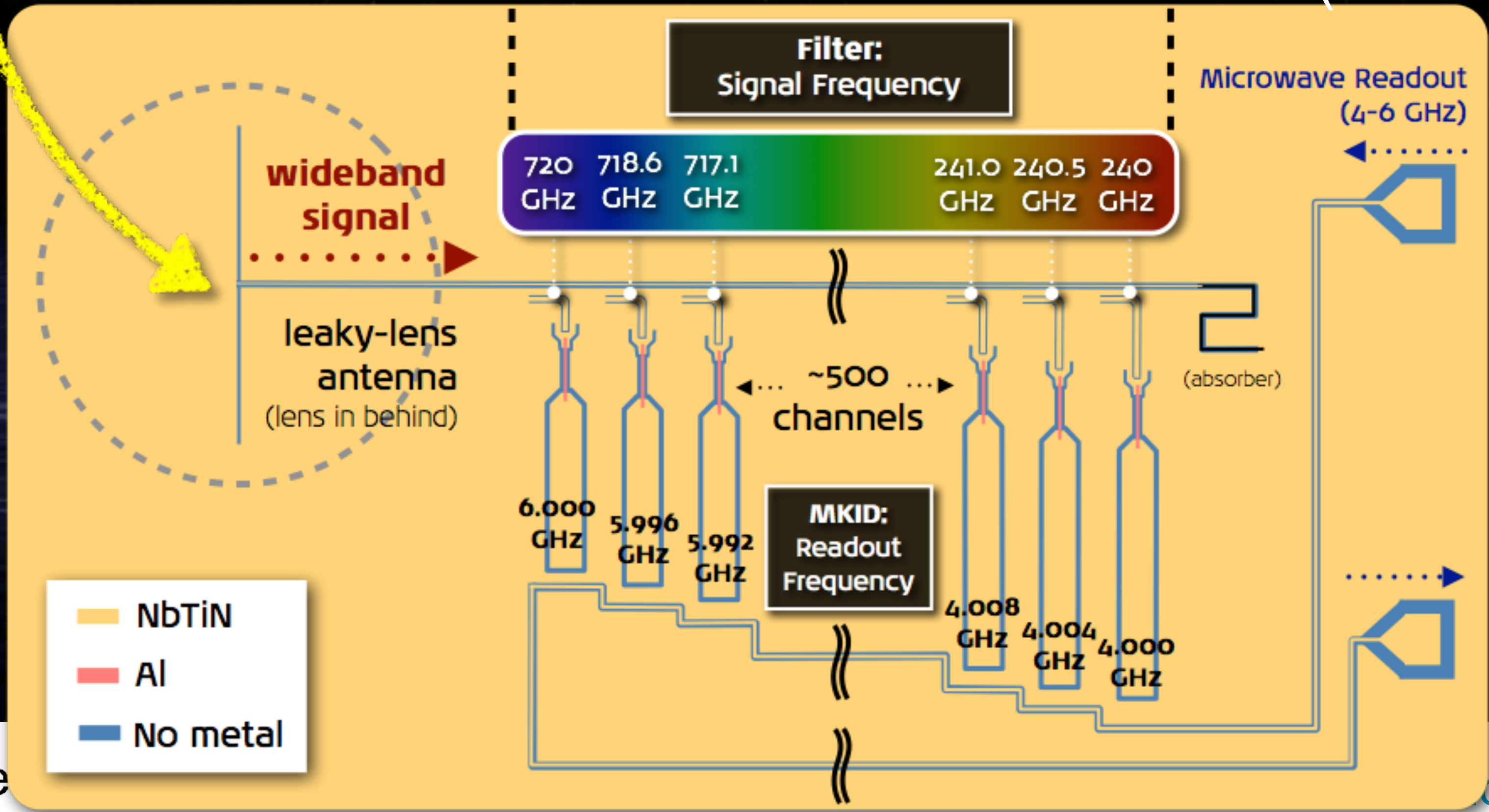
DESHIMA: Deep Spectroscopic High-Z Mapper

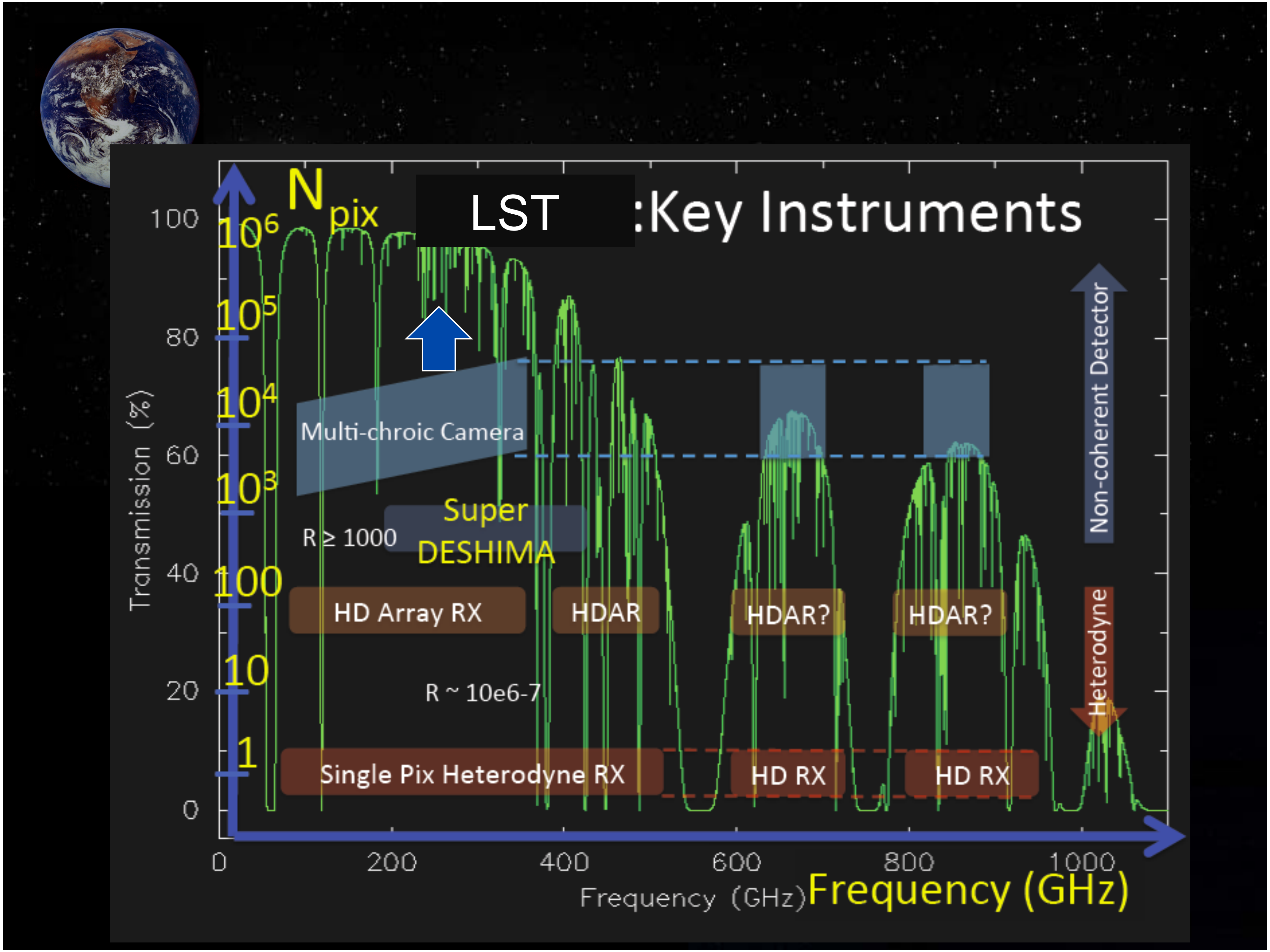
Superconducting On-chip filterbank Spectrometer



cf. SuperSpec

A. Endo (TU Delft) +





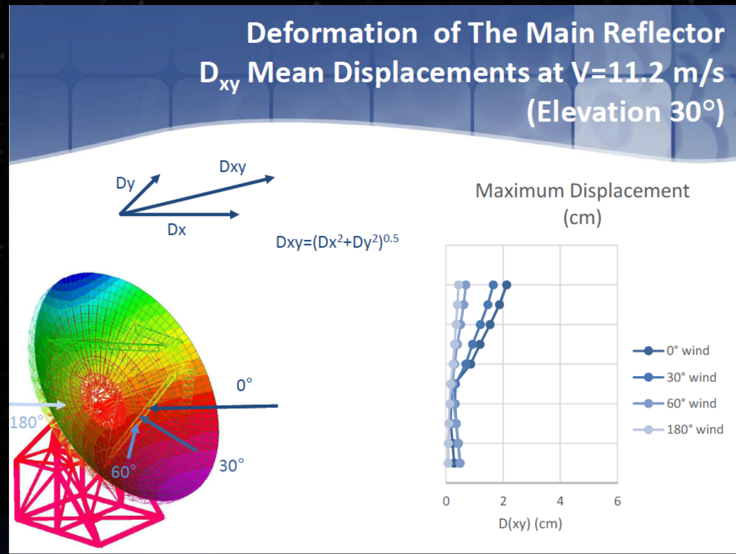
LST :Key Instruments
N pix
10^6
10^5
10^4
10^3
100
10
1
Transmission (%)
100
80
60
40
20
0
0
200
400
600
800
1000
Frequency (GHz)
Frequency (GHz)
Multi-chroic Camera
Super DESHIMA
R ≥ 1000
HD Array RX
HDAR
HDAR?
HDAR?
R ~ 10e6-7
Single Pix Heterodyne RX
HD RX
HD RX
Non-coherent Detector
Heterodyne

R&D plan in the next 3 yrs

- ✦ MAO concept demonstration on NRO45m or LMT; accelerometers also used to investigate wind effects
- ✦ Simulation of dynamical effects of 50m dish due to wind and comparison with measurements with accelerometers; needs FEM
- ✦ Wind measurement with LIDER from MELCO
- ✦ DESHIMA science run on ASTE, & development of its array/MOSAIC

  => A. Endo's TalkMELCO
- ✦ Multichroic KID or TES camera

; 2 mm, 1.3mm, 1.1mm, 850um,..



International Collaboration?

Yes, we are positive. Need close cooperation.

✦ Discussion via workshops

- e.g., LSTWS2015: "Large millimeter/submillimeter telescope in the ALMA era", Mitaka/Japan

- Status of Other Telescopes updated

e.g., Caltech ~ 30m survey telescope

✦ Recent Progress in Europe

- European perspective: ~ 40m class similar to LST

: A good-sign toward a future "40-50 m class" sub-mm single disk telescope in ALMA plateau as a single international project, although it will be hard to project and secure construction budget

Summary

- ✦50m class submillimeter single dish telescope
- ✦Covers 70 – 420 GHz (full aperture)
- ✦Targets up to ~ 1THz (central ~30 m)
- ✦Exploration of large 2.5D & 3D volume in universe and unveiling CIB & CSFH
- ✦Key Instruments
  - large format cameras (~ 10^5 pixels)
  - Imaging spectrograph (R~ 1000, 10^3 pix)
  - Heterodyn Array (> 100 beams)