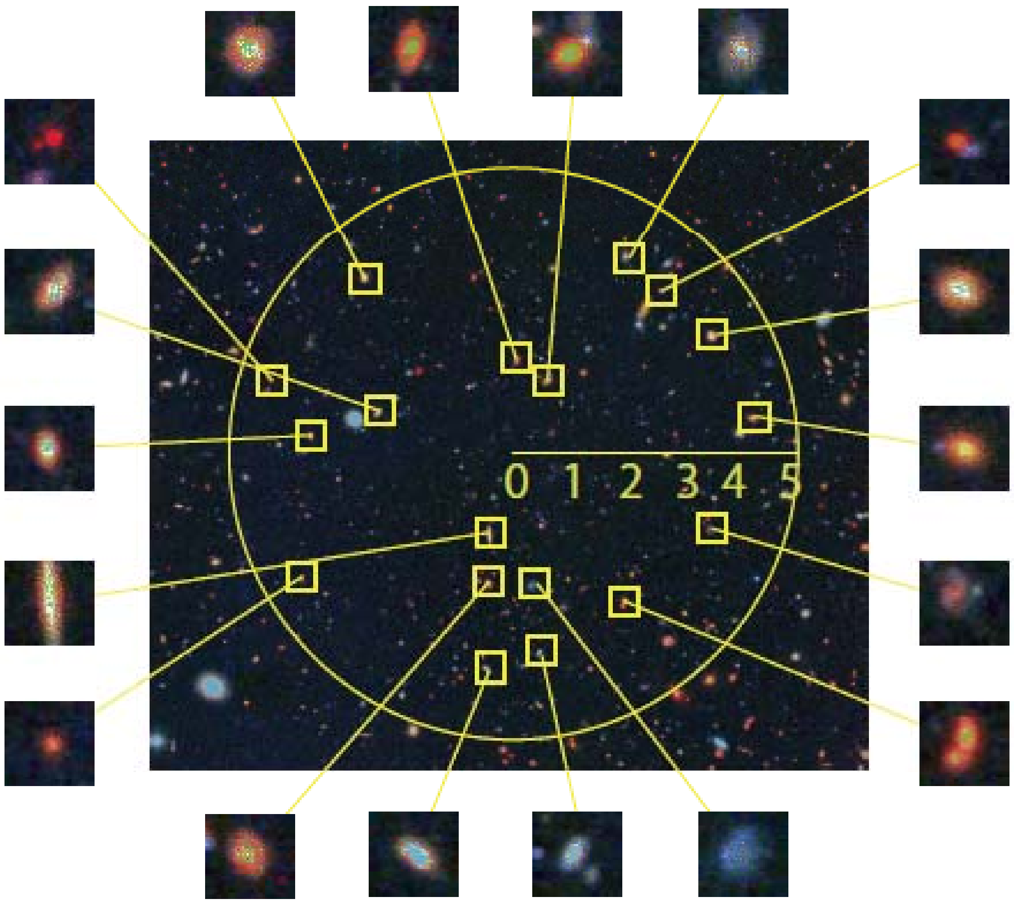
TMT-AGE: Wide field of regard multi-object adaptive optics for TMT

Masayuki Akiyama (Tohoku Univ.)

Shin Oya (Subaru), Yoshito Ono (Subaru/Tohoku U.),
Hideki Takami (NAOJ), Shinobu Ozaki (NAOJ),
Yutaka Hayano (Subaru), Ikuru Iwata (Subaru),
Kazuhiro Hane (Tohoku U.), Tong Wu (Tohoku U.),
Tomoyasu Yamamuro (Opt Craft),
Yuji Ikeda (Photocoding)

TMT-AGE:
TMT Analyzer for Galaxies in the Early universe

- Multi-IFU NIR spectroscopy of ~20 objects scattered in wide (d=10’) Field of Regard (FoR) assisted by MOAO correction



SCIENCE DRIVERS

TMT-AGE

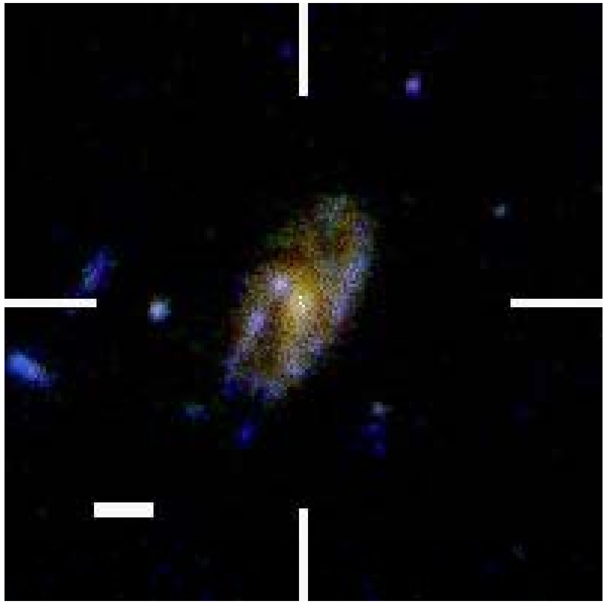
Three Science Drivers

1. Revealing the history of establishment of the internal structure of galaxies
   - By spatially-resolved spectroscopy of z=1-5 galaxies.

2. Revealing the violent star-formation process during the formation phase of galaxies
   - By integrated spectroscopy of z>5 galaxies.

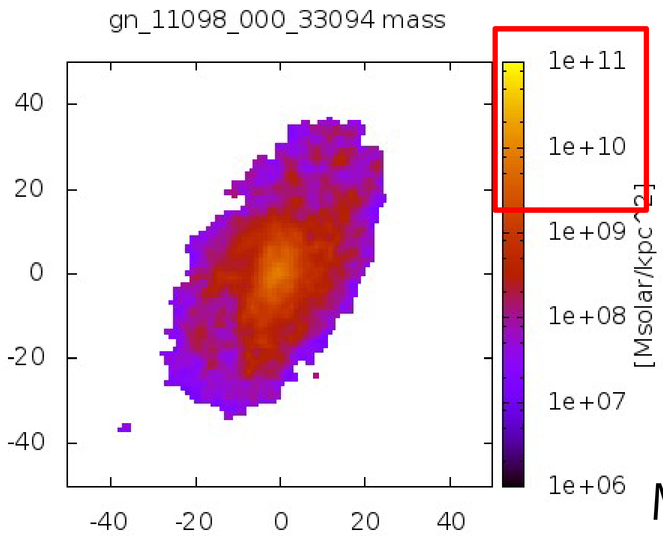
3. Identifying galaxies in the early universe (z>8)
   - By follow-up spectroscopy of candidates picked up by future wide-field IR surveys (Euclid, WFIRST, WISH,,,) from space.

1. Galaxy "establishment" history



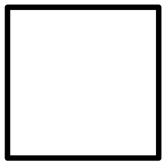
Example: a massive galaxy at z=1.3
0.06" pixel map with FWHM=0.18" (HST H-band FWHM) (FWHM=0.067" with JWST)
10h, SN=10, R=3,000 detection limit:
H-band continuum detection limit corresponds to 6×10^{9} Ms/kpc^2
H-band unresolved line limit corresponds to 0.06 Ms/yr/kpc^2

Stellar mass distribution



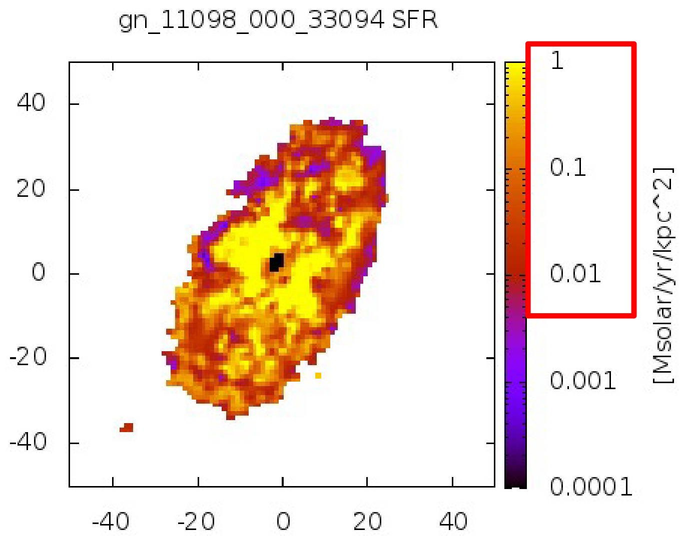
100x100 = 6"x6"

2" FoV



Masuda 2014 Master Thesis

Star-formation rate distribution



100x100 = 6"x6"

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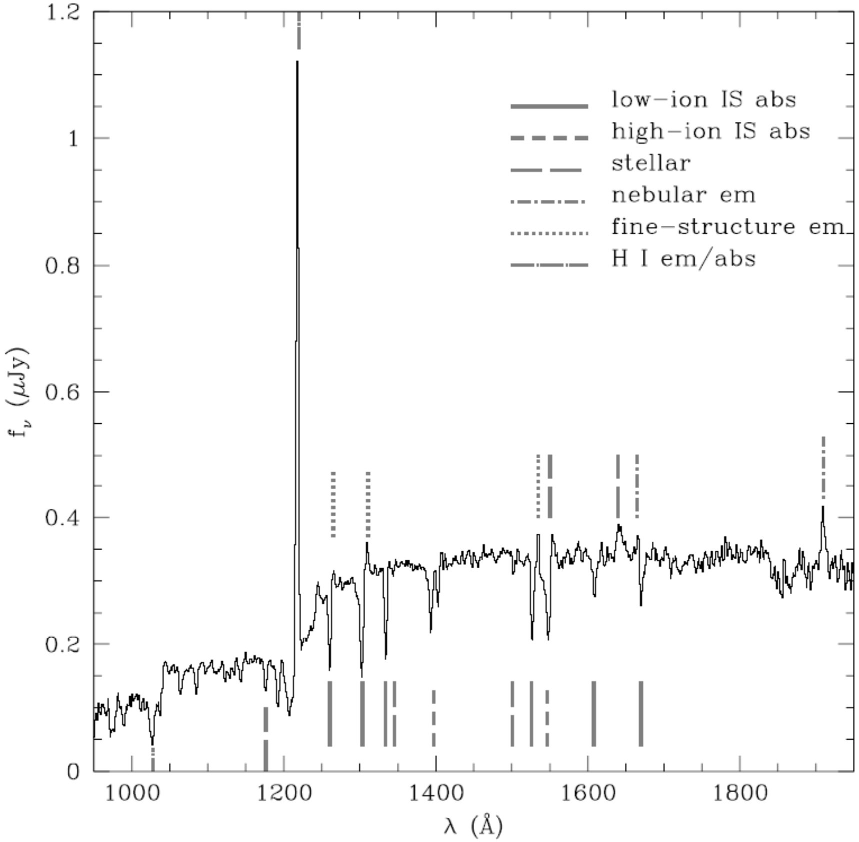
2. Understanding star-formation in young galaxies

Average of rest-UV spectra of Z~3 star-forming galaxies



Shapley et al. 2003

- Rest-frame UV features of star-forming galaxies
  - Low-ion IS abs line:
    - ➢ Distribution and dynamics of neutral gas
  - High-ion IS abs line:
    - ➢ Distribution and dynamics of ionized gas
  - Stellar emission:
    - ➢ High-mass star contents
  - Nebular emission:
    - ➢ Galaxy rest-frame

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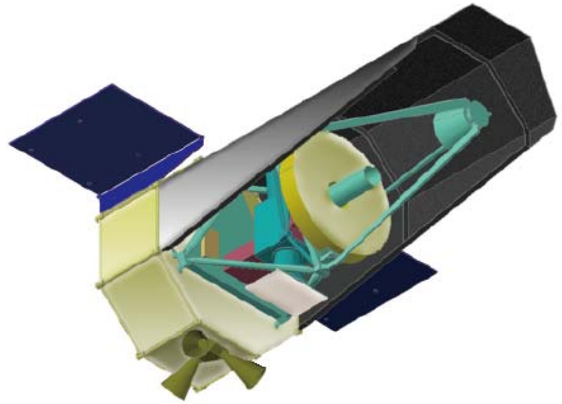
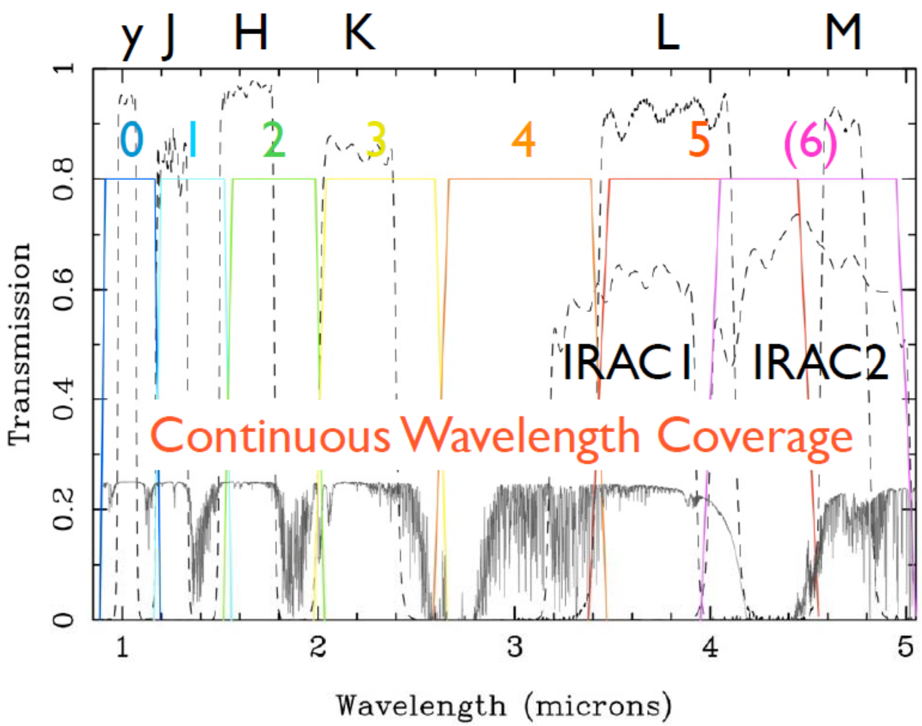
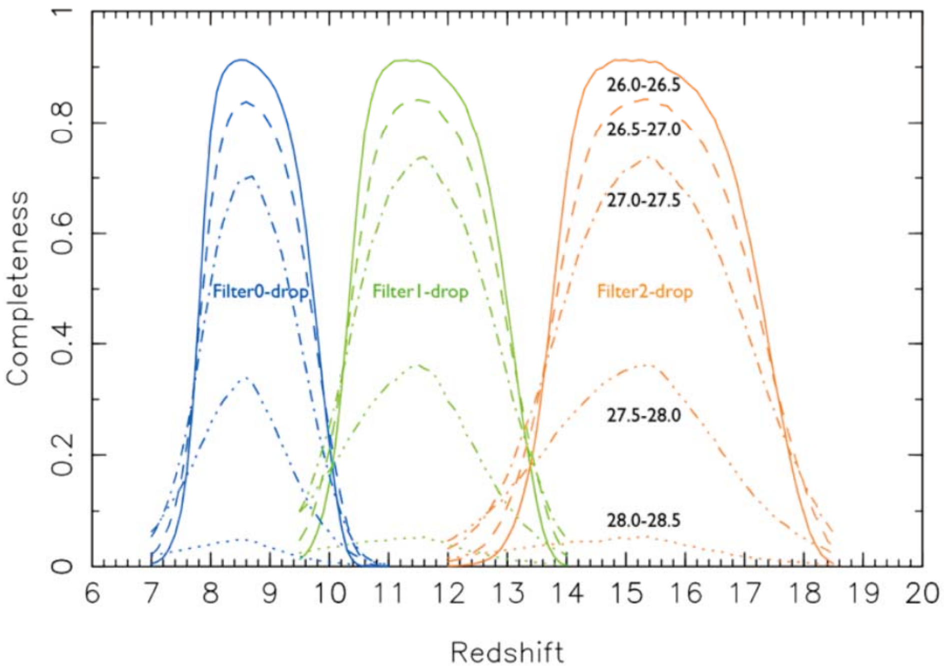
3. Identify galaxies at z>8

- Follow-up spectroscopy of candidates picked up by future wide-field (>10sq.deg) IR imaging surveys (Euclid, WFIRST, WISH,,,) from space.



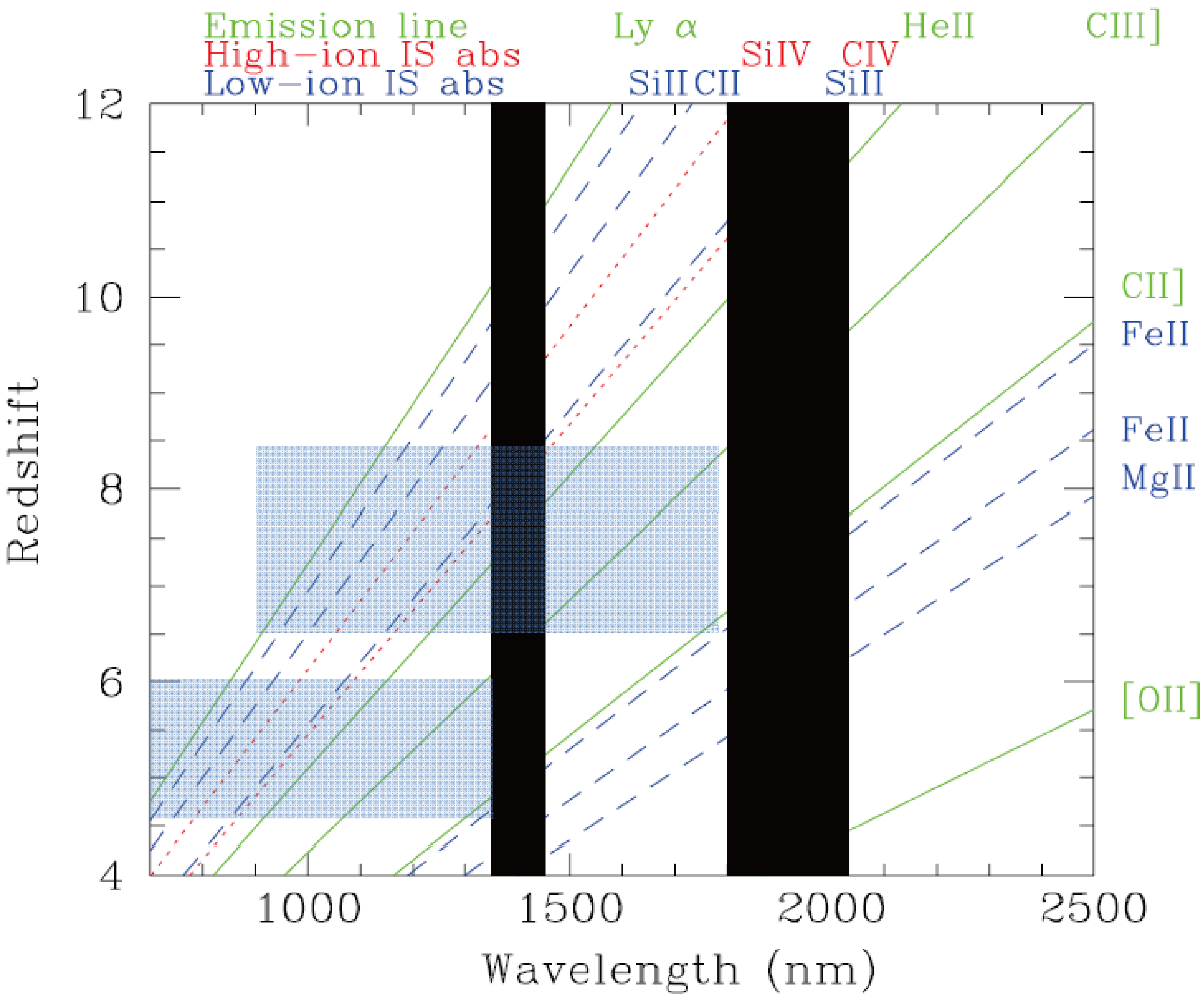
www.wishmission.org





Diagnostic lines for high-z galaxies

- Most of the redshifted diagnostic lines can be covered within 7000-18000A.



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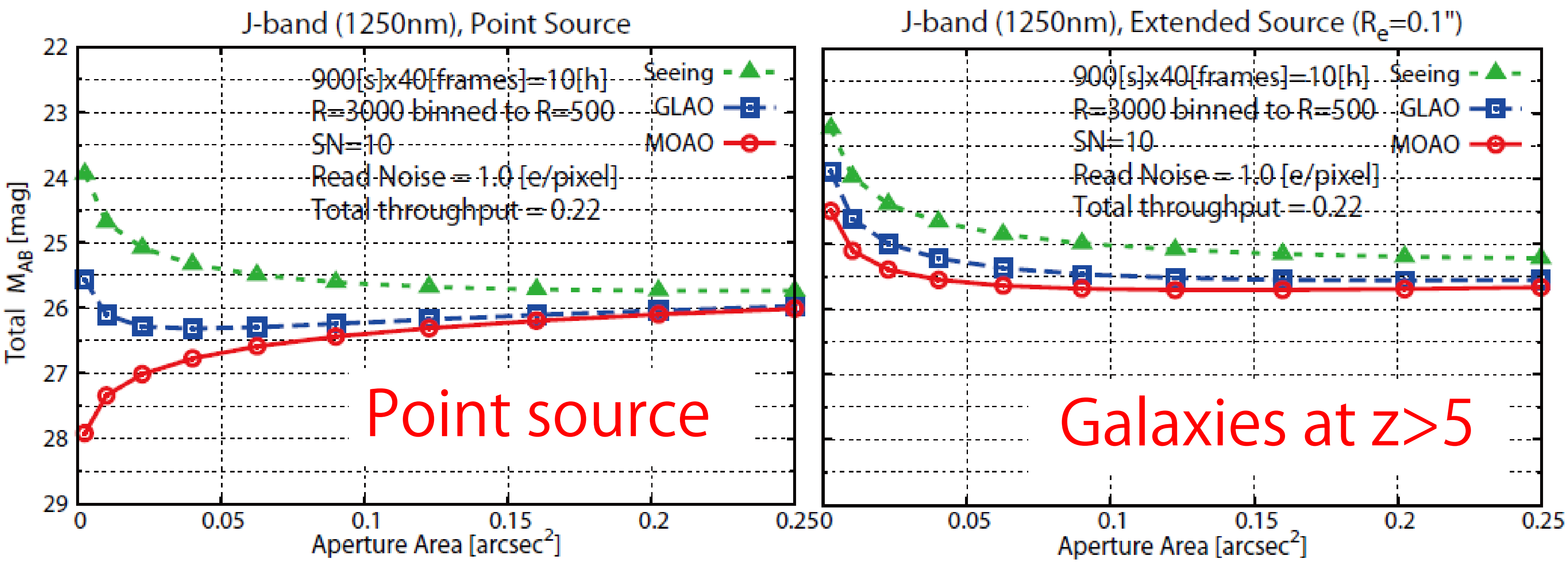
Baseline Detection limits – integrated J-band



- Red (MOAO), blue (GLAO), green (seeing-limit) lines show the detection limits for each system with different aperture size.
- SN=10 for continuum with 10h integration
- R=3,000 spectroscopy binned to R=500
- Typical size of z>5 galaxies: effective radius of 0.1"

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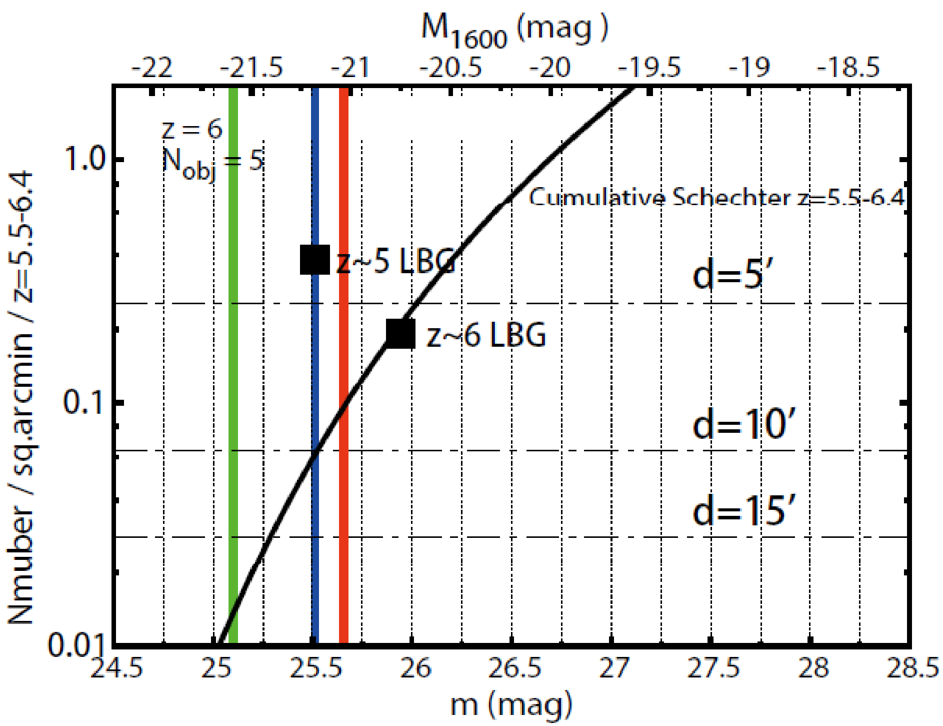
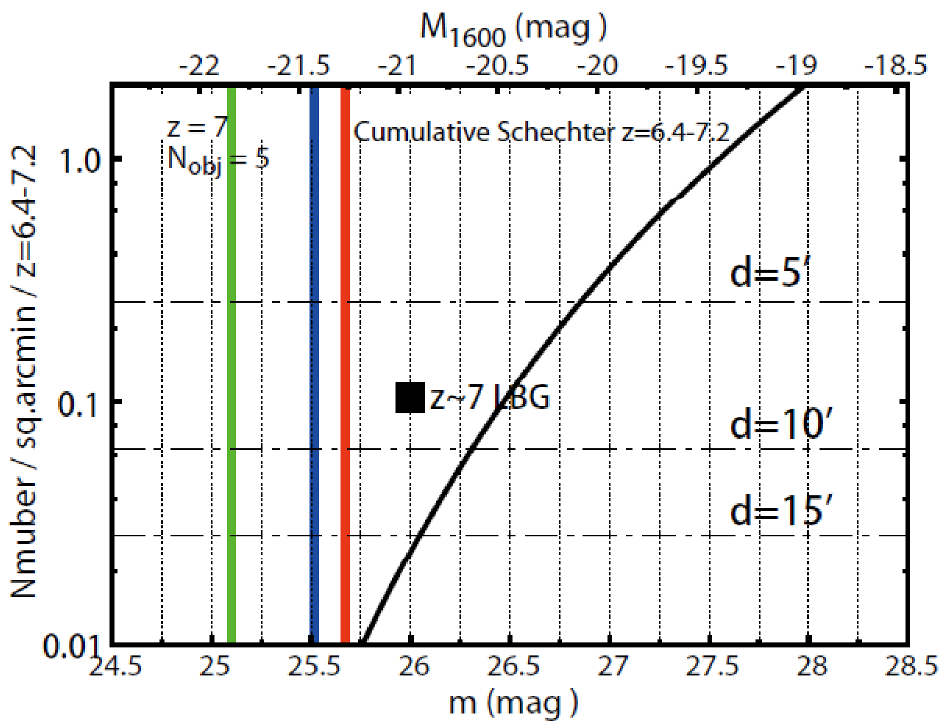
Number density

- Red (MOAO), blue (GLAO), green (seeing-limit) lines show the detection limits for each system.
- Number density of luminous z~6-7 LBGs is not so high.





Filled squares from Bouwens et al. 2014,
V-dropout for z~5, i-dropout for z~6, and Y-dropout for z~7

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Requirements

1. Spatially-resolved spectroscopy of z=1-5 galaxies.
   - High spatial and spectral resolution multi-IFU spectrograph within d=5′ FoR (IRMOS-like)
   - 0.05x0.05″ sampling IFUs with 2″ FoV
   - R=10,000 spectroscopy for v~30km/s

2. Integrated spectroscopy of z>5 galaxies.
3. Follow-up spectroscopy of candidates of z>8 galaxies
   - High-sensitivity with moderate AO correction in short NIR wavelength range within d=10′ FoR
   - 0.3x0.3″ – 0.5″x0.5″ aperture integrated spectroscopy
   - R=3,000 (5A resolution, 2A/pix) for absorption/emission lines with rest-frame EW of 1A.

MOAO PERFORMANCE FEASIBILITY WITHIN A WIDE FOR

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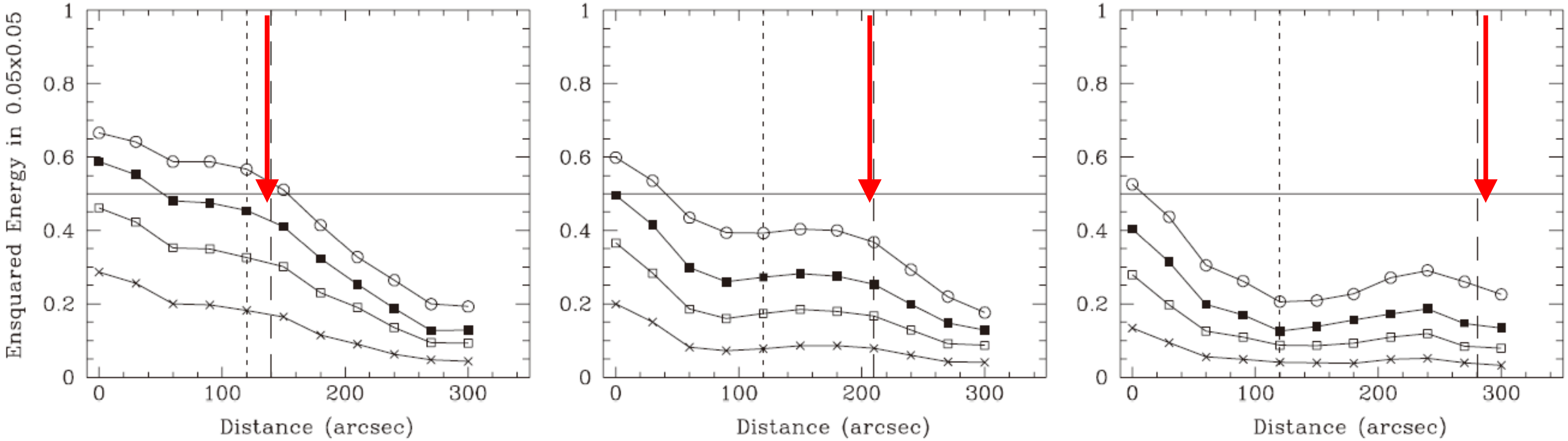
AO performance simulation

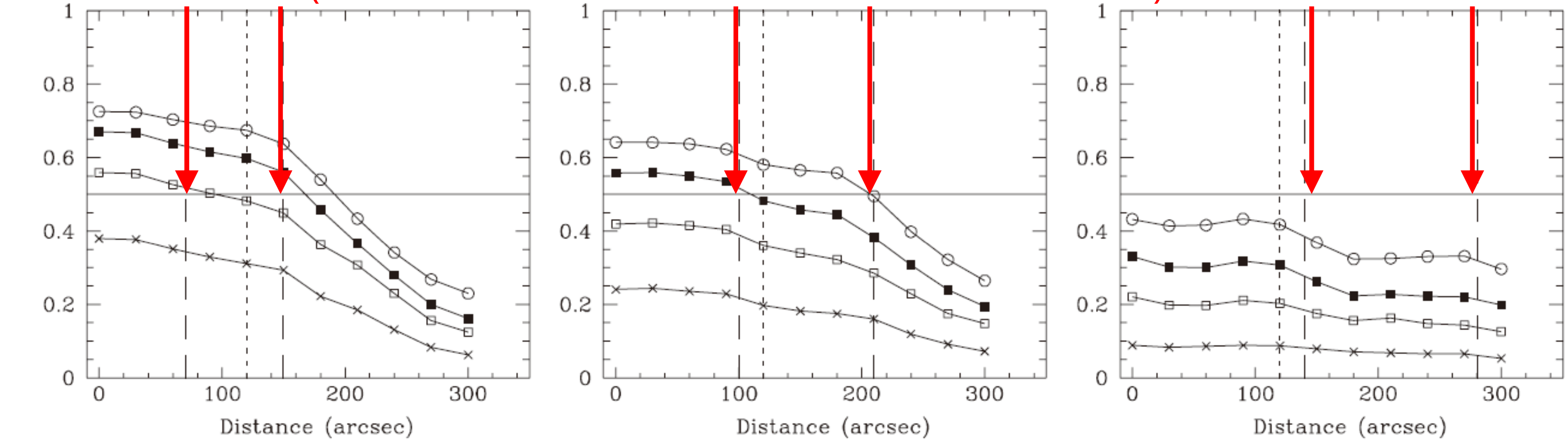
- We check AO performance feasibility within d=10′ FoR with end-to-end AO simulator MAOS (Wang & Ellerbroek 2012) .
- We consider 6 LGS case and 8 LGS case with changing the radius of the asterism (those are within the scope of the TMT-LGSF specification [Subsystem Requirements Document]).

Ensquared E. Within 0.05x0.05"

6 LGS case (red arrows indicate the radius of LGS asterism)



8 LGS case (red arrows indicate the radii of LGS asterism)

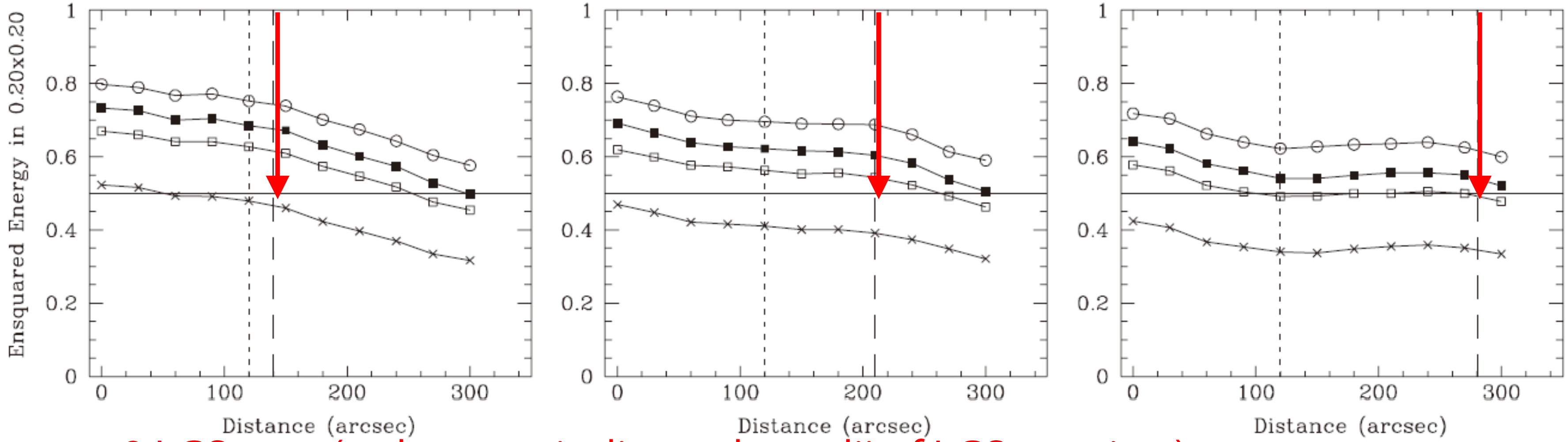


LGS asterism in IRMOS

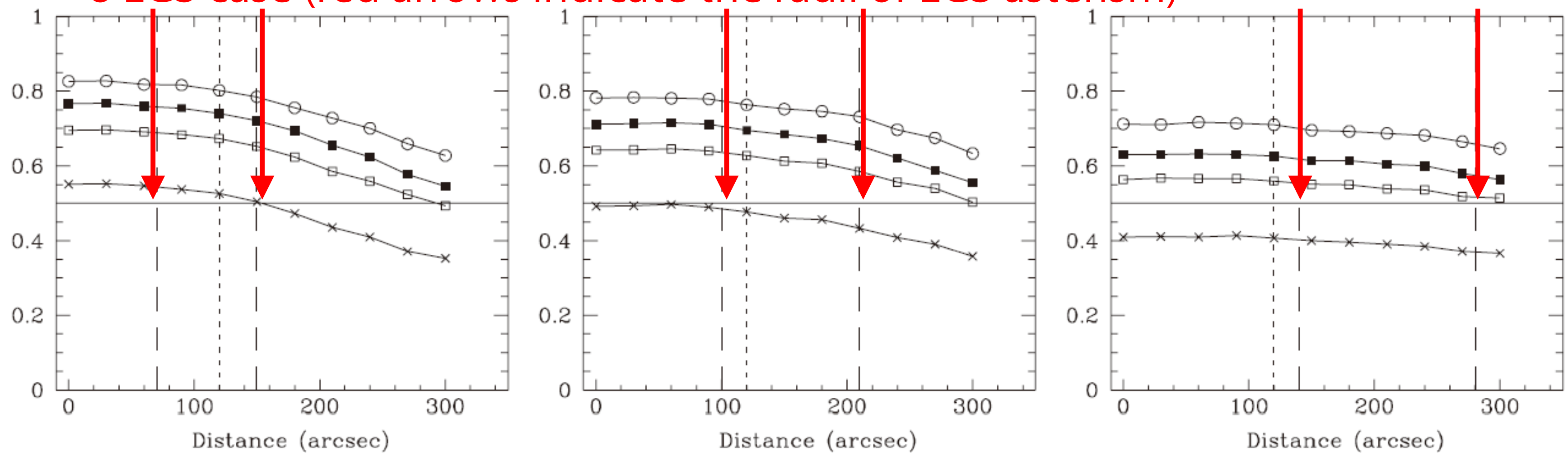
From top to bottom, K, H, J, 0.9um

Ensquared E. within 0.2"x0.2"

6 LGS case (red arrows indicate the radius of LGS asterism)



8 LGS case (red arrows indicate the radii of LGS asterism)



LGS asterism in IRMOS

From top to bottom, K, H, J, 0.9um

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Good AO correction wide FoR

- There is a possibility that good AO correction can be achieved even within d=8′-10′ FoR with a new tomography algorithm utilizing wind profile (direction and speed) information

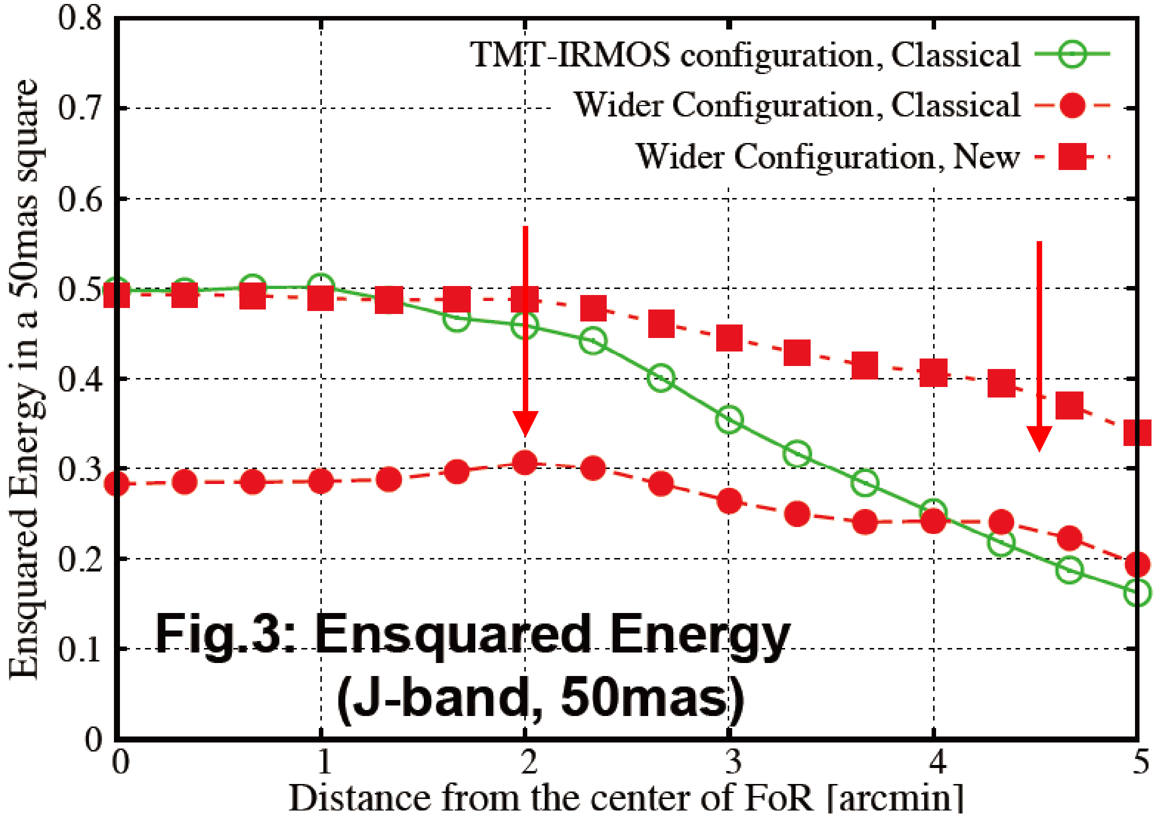

Fig.3: Ensquared Energy (J-band, 50mas)

See poster by Y.Ono et al. 9148-258 on Thursday

SYSTEM CONSIDERATION

MOAO SYSTEM DESIGN AND REQUIREMENTS FOR DMS
OPTICAL DESIGN FOR A COMMON DM SYSTEM

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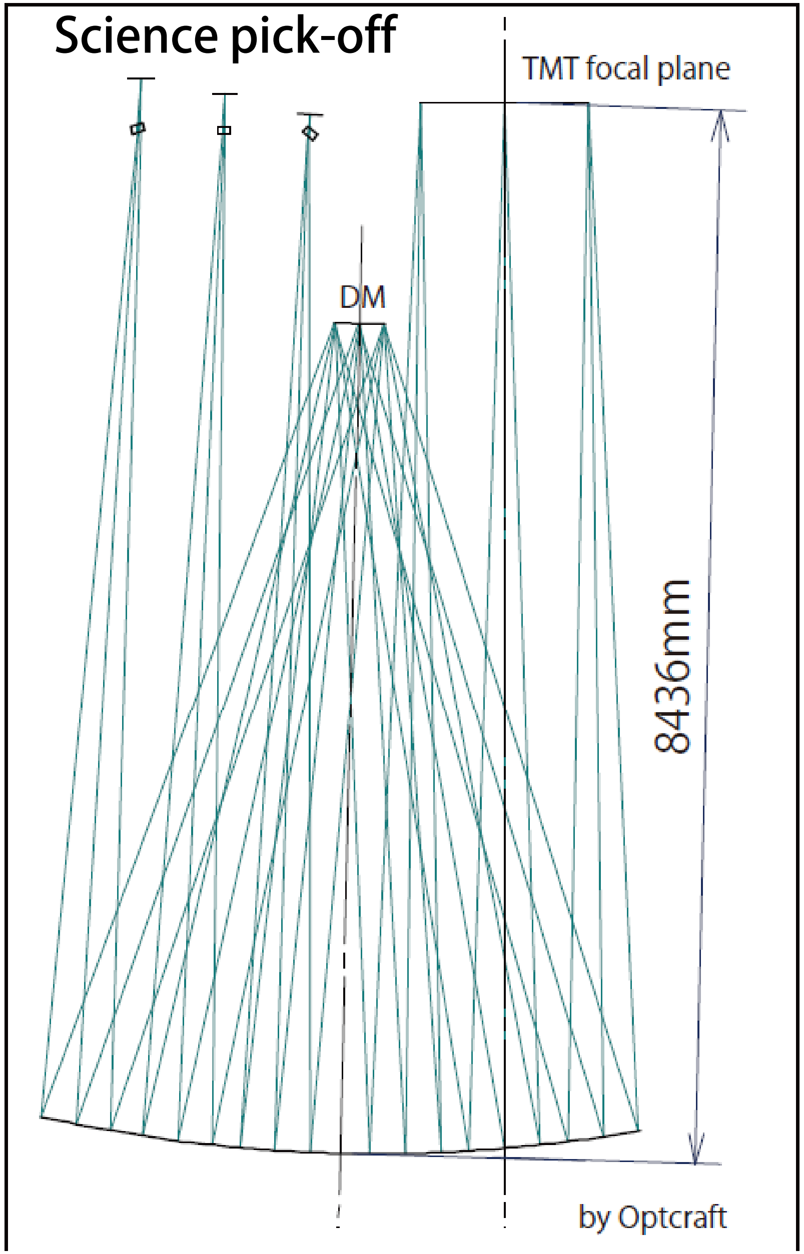
Stroke Requirements for DMs

- Three configurations are considered
  - A) One 60x60 DM for each science path
  - B) Small Woofer (30x30) and Tweeter (60x60) DMs for each science path
  - C) Large common (30x30) DM and 60x60 DM for each science path. Common DM corrects for common turbulence with in the wide FoR, like Ground-Layer AO.

	30x30 DM		60x60 DM	
	PV	IA	PV	IA
A			5.5 (10.0)	2.5 (4.0)
B	5.5 (10.0)	2.5 (4.5)	1.0 (2.0)	1.0 (1.5)
C	5.0 (8.0)	2.5 (3.5)	3.0 (5.5)	1.0 (2.0)

Zenith Distance with r0=0.156 (ZD=60 with r0=0.121)
Red: requirements larger than current MEMS DM

Optical designs for the common DM system

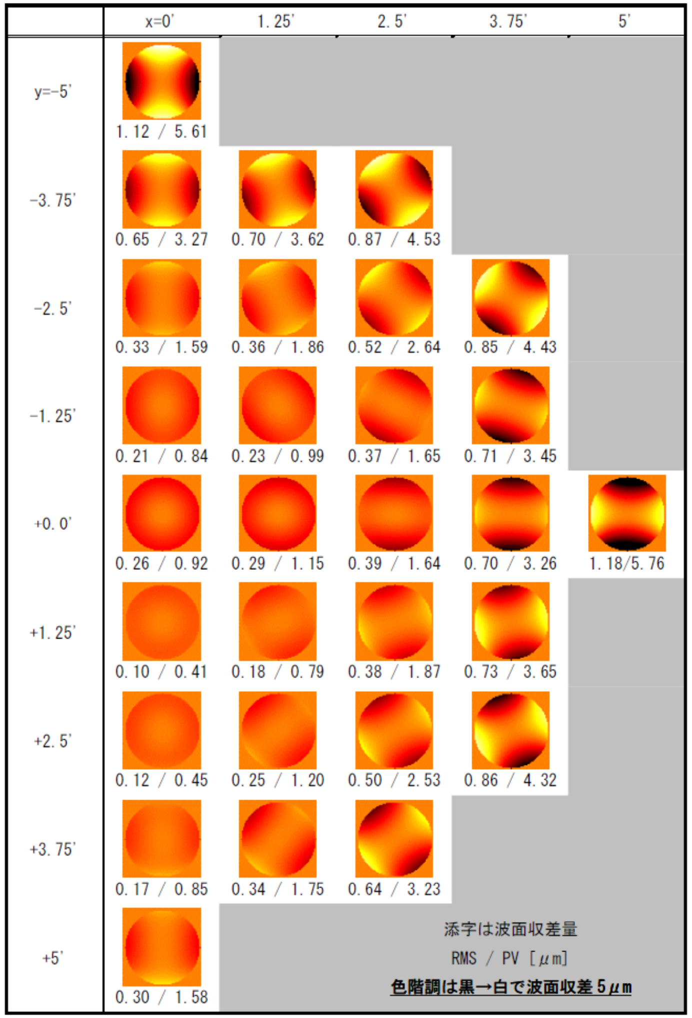


- At first, we consider modified Offner system, following IRMOS-Tipi design.
- Extendig FoR to d=10’.

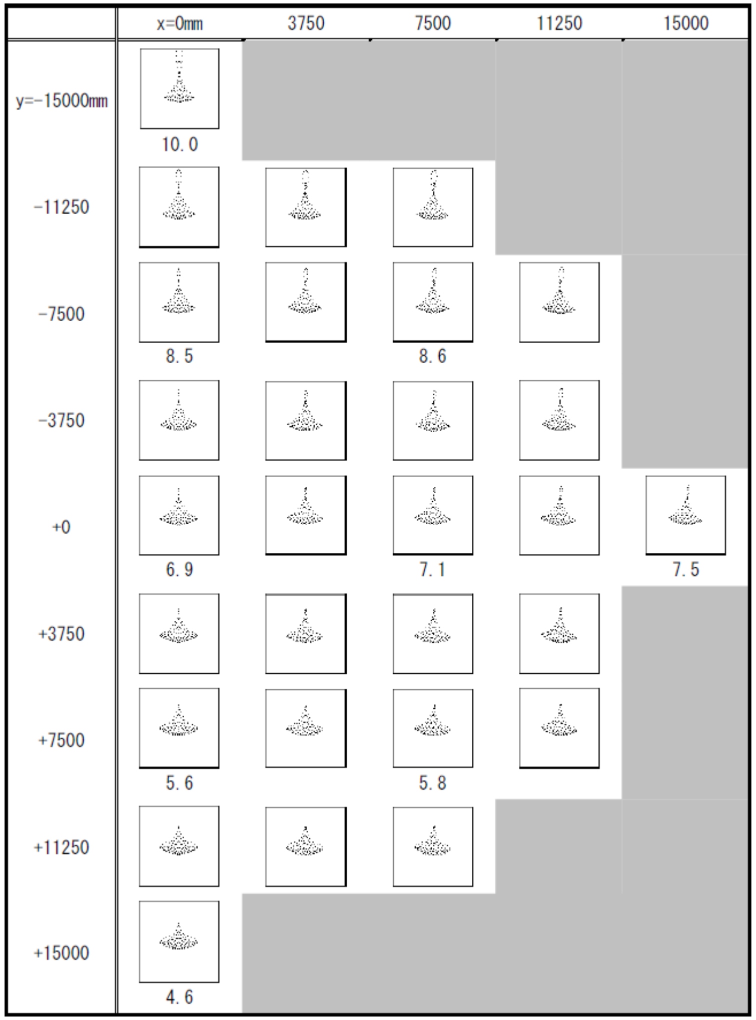
- Modified Offner system by Optcraft (T.Y.)

Performance

- Wavefront at pickoff focal plane
- For each FoR position



- Pupil image distortion at DM plane
- For each pupil position



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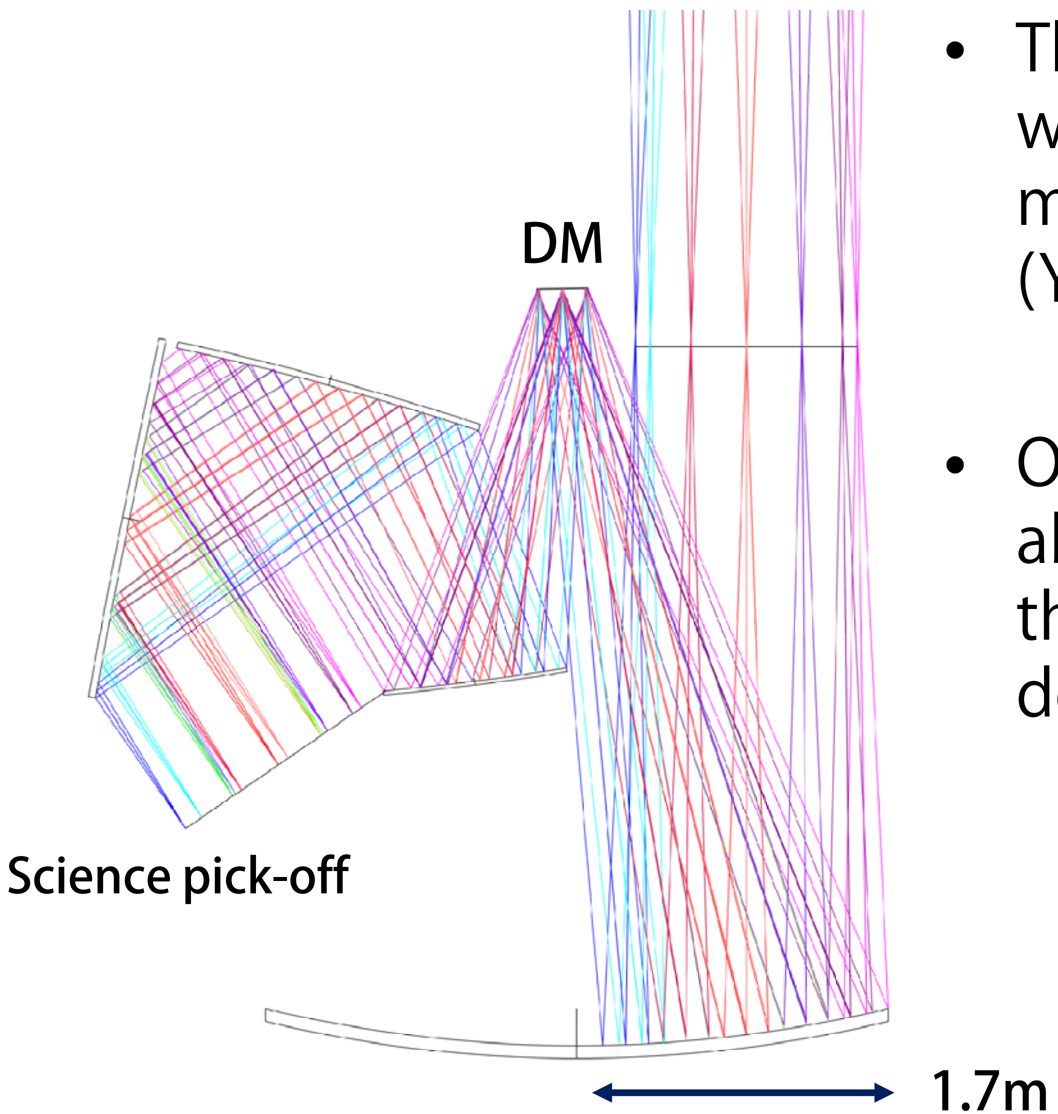
Optical designs for the common DM system



- Three Mirror Array design with free form curve mirrors by Photocoding (Y.I.)
- Overall system size is about half of the size of the modified Offner design.

STATUS OF RELATED DEVELOPMENTS

WFS FOR MOAO SYSTEM

MEMS DM

TOMOGRAPHY WITH GPU

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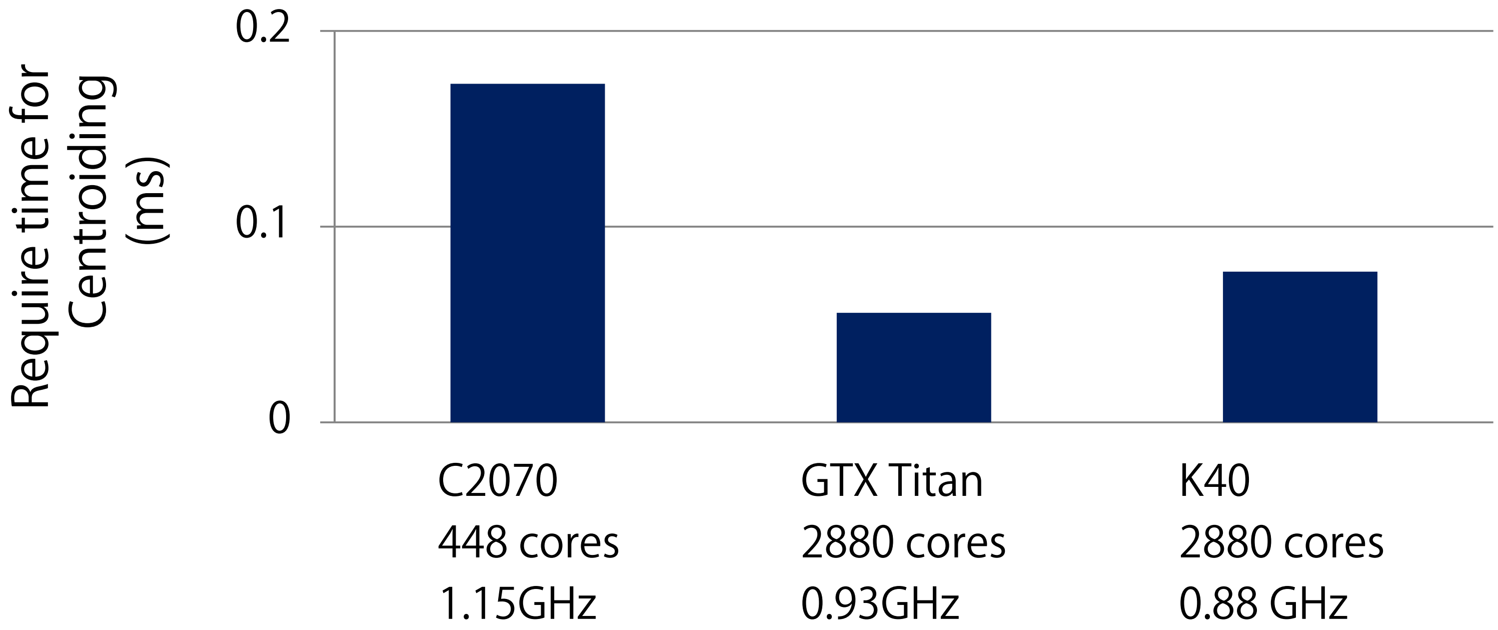
LGS-WFS for MOAO system

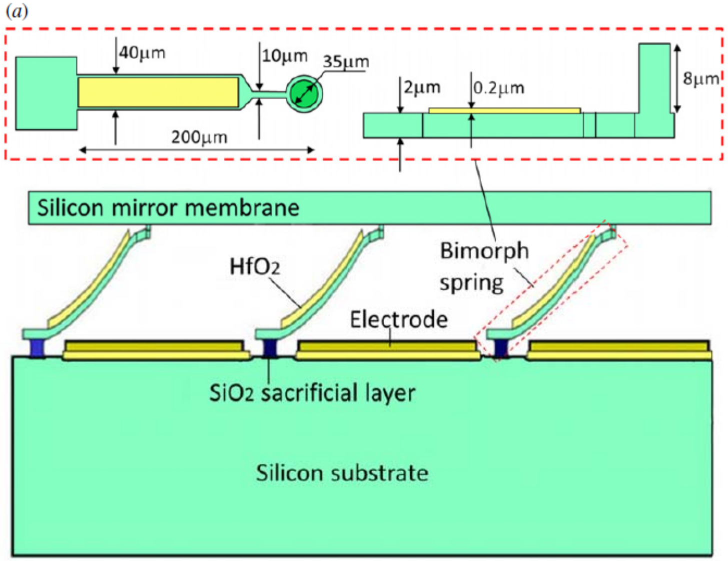
- Because of the elongation of the SH-WFS spots for LGS, 0.4" sampling 5" sub-sperture FoV is necessary. The FoV can cover the large spot wondering for the open-loop MOAO system.
- We test centroiding with parallel calculation with GPGPU. Sufficiently fast centroiding can be done for 60x60 WFS with 10x10 subaperture.

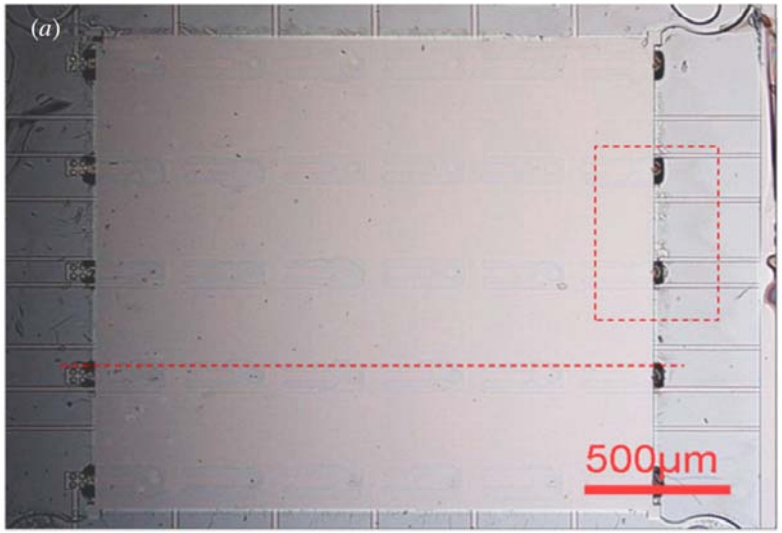


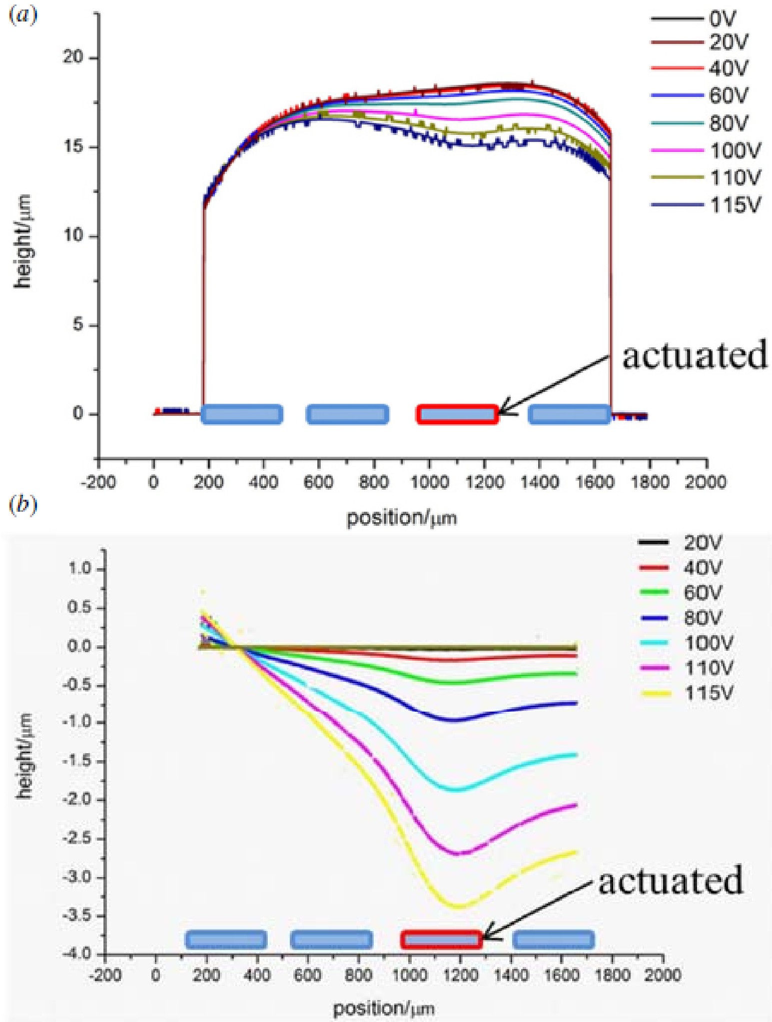
- We tested data transfer between EM-CCD CCD60 (E2V) readout with Nuvu camera CCCP electronics and GPGPU.

TMT-AGE MEMS DM with bimorph spring structure

- Prototype with 4x4 elements







Wu et al. 2013,

J.Micromech.Microeng, 23, 125003

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Tomographic estimation with GPGPU

Solving Minimum Variance Reconstructer for 7 layer atmosphere with 8 60x60 LGS WFS system by Conjugate Gradient method (see Ono et al. 9148-258 poster Thursday).

We try two setups with Nvidia C2070 and GTX Titan. 300 iterations are required to converge the solution from zero initial guess. The number can be reduced to ~5 with using the solution from previous time-step as the intial guess.

Currently both boards are installed with PCIe2.0 bus, and data transfer time can be reduced by 1.5 with using PCIe 3.0 setup.

	C2070	GTX Titan
Transfer data to GPU	0.2 ms	
One iteration of C.G.	5.57 ms	0.73 ms
Transfer data from GPU	0.4 ms	
Total with 300 iterations	~1700 ms	~200 ms

Summary

Moderate correction in wide FoR (d~10′) is important for high sensitivity spectroscopy of faint targets.

Such correction can be achieved with the current tomography algorithm. Better correction can be achieved with a new algorithm with wind profile information (see Y.Ono poster on Thu. 9148-258).

There are solutions for the common DM optical design FoR of d~10′.

We will complete the concept proposal by end of FY 2015.

Requirements for $1<z<5$ galaxies

<u>High spatial and spectral resolution wide-wavelength coverage</u>

- Velocity resolution of 30km/s R=10,000 (1A resolution, 0.5A/pix) stellar dynamics in bulge/disk region

- 9000-16000A coverage (14,000pix) for z=1.4
- 12000-22000A coverage (20,000pix) for z=2.4
- 16000-22000A coverage (12,000pix) for z=3.4

- 0.05"x0.05" aperture IFU spectroscopy
- Size of FoV for each IFU : ~2" for the continuum spectroscopy for the most massive galaxies.
- More extended region (~5") can be detected by emission line spectroscopy

Requirements for z>5 galaxies

<u>Moderate corrections in short NIR wavelength range.</u>

- 0.3x0.3" – 0.5"x0.5" aperture integrated spectroscopy
- Size : re=0.1" : 2re diameter=0.4"
- FoV 1" is sufficient

- 7000-13500A coverage (3300pix) for z=5.0-6.0
- 9000-18000A coverage (4500pix) for z=6.5-8.5

- R=3,000 (5A resolution, 2A/pix) for absorption/emission lines with rest-frame EW of 1A.

1. Galaxy "establishment" history

- Revealing gas and stellar dynamics, internal metallicity distribution by spatially-resolved spectroscopy of z=1-4 galaxies.

- Diagnostic lines = [NII]/Ha, [OIII]/Hb, 4000A break, Balmer break, [OII]

- All of the features are observable at
  - z~1.4 (9000-16000)
  - z~2.4 (12000-22000)
- Without [NII]/Ha
  - z~3.4 (16000-22000)
- Without [NII]/Ha, [OIII]
  - z~5.0 (22000)

Baseline Detection limits – spatially-resolved

	$J(1250\mathrm{nm})$	$H(1650\mathrm{nm})$	$K(2200\mathrm{nm})$
$R = 3,000$ flux density (erg s^{-1} cm^{-2} Hz^{-1})	3.2×10^{-31}	2.9×10^{-31}	7.7×10^{-31}
$R = 3,000$ line flux (erg s^{-1} cm^{-2})	2.5×10^{-20}	1.7×10^{-20}	3.6×10^{-20}
$R = 500$ flux density (erg s^{-1} cm^{-2} Hz^{-1})	1.2×10^{-31}	1.1×10^{-31}	2.7×10^{-31}
$R = 500$ line flux (erg s^{-1} cm^{-2})	5.8×10^{-20}	4.0×10^{-20}	7.0×10^{-20}

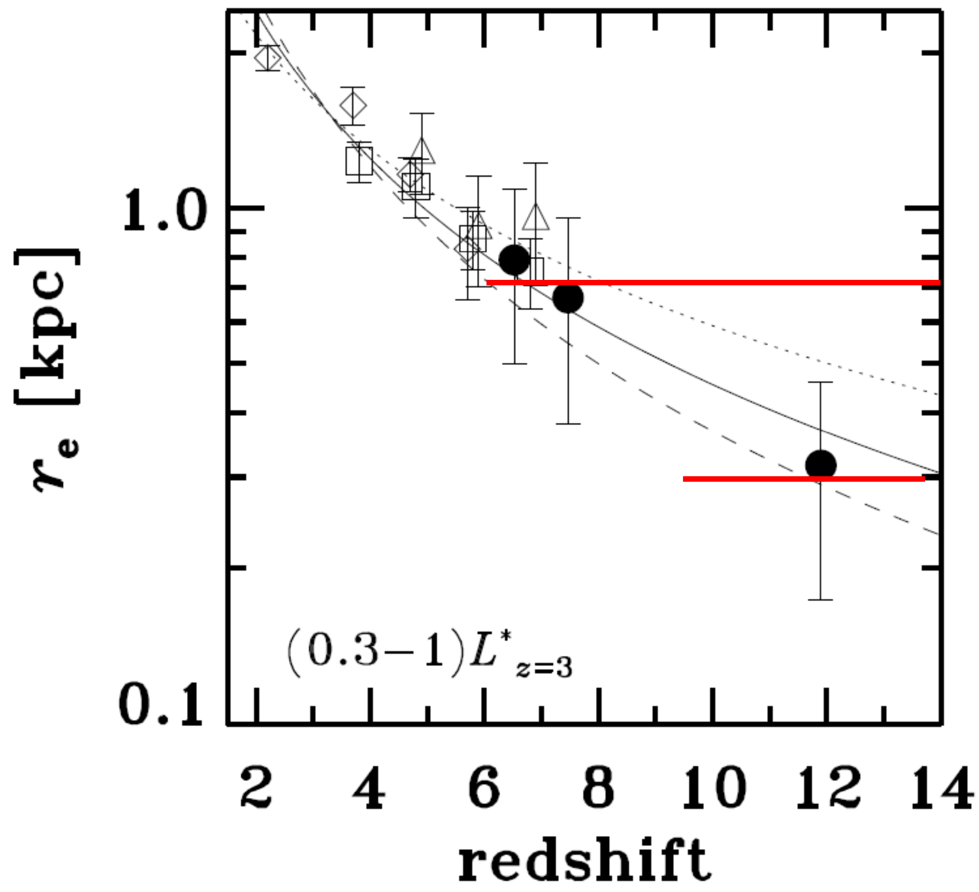
- Detection limits in 0.05”x0.05” aperture
- SN=10 in 10h integration with 22% throughput (atm-tel-inst-det) and 1e RoN

- R=3,000 flux density corresponds to
  - JAB= 27.64mag, HAB=27.74 mag, KAB= 26.68mag
  - H-band limit : stellar mass of ~1×10^{8} Ms/pix ~ 6×10^{8} Ms/kpc^{2} at z~1
  - H-band limit : stellar mass of ~1×10^{9} Ms/pix ~ 6×10^{9} Ms/kpc^{2} at z~1.3

- R=3,000 line flux corresponds to
  - SFR = 0.002 Ms/yr/pix = 0.012 Ms/yr/kpc^{2} for z=1.5 Ha emission line
  - SFR = 0.01 Ms/yr = 0.06 Ms/yr/kpc^{2} for z=2.5 Ha emission line

Sizes of high-z galaxies

- z>5 galaxies are compact, but still extended compared with the diffraction-limit of TMT.



0.7 kpc = 0.13″ @z=7-8

0.3 kpc = 0.07″ @z=10

Ono et al. 2009

Maximum (20 objects 4Kx4K each)

- 0.01"/pix with 0.02"/slice
  - 1x0.8" FoV = 100 pix/slice x 40 slices = 4000 pix
- 0.02"/pix with 0.05"/slice
  - 2x2" FoV = 100pix/slice x 40 slices = 4000 pix
- <u>0.05" / pix with 0.05"/slice</u>
  - <u>5x2" FoV = 100pix/slice x 40 slices = 4000 pix</u>
- 0.1"/pix with 0.2"/slice
  - 10x8" FoV = 100 pix/slice x 40 slices = 4000 pix

- R=3,000 (5A resolution) with 2A/pix 8000A coverage = (J+H), (H+K)
- R=5,000 (3A resolution) with 1A/pix 4000A coverage = (J), (H), (K)

IFU sampling (20 objects 1Kx1K each)

For spatially-resolved spectroscopy of 1<z<5 galaxies

- 0.05″ / pix with 0.05″/slice
  - 2.5x1″ FoV = 50pix/slice x 20 slices = 1000 pix

For integrated spectroscopy of z>5 galaxies

- 0.1″/pix with 0.2″/slice
  - 1x2″ FoV = 10 pix/slice x 10 slices = 100 pix
  - Dithering within the IFU FoV.

TMT-AGE:
TMT Analyzer for Galaxies in the Early universe

- Put more emphasis on science cases for very high-redshift galaxies ($z>5$)
  - The targets are faint
  - Low number density at the TMT detection limit
- In order to maximize the efficiency of observation for statistical number of targets, we consider FoR as wide as d=10′
  - Compared to previous MOAO concept studies for TMT (IRMOS-UF/HIA, IRMOS-Tipi) with d=5′