Input to future Subaru AO systems from tomography AO experiment RAVEN - what we have learned / achieved -

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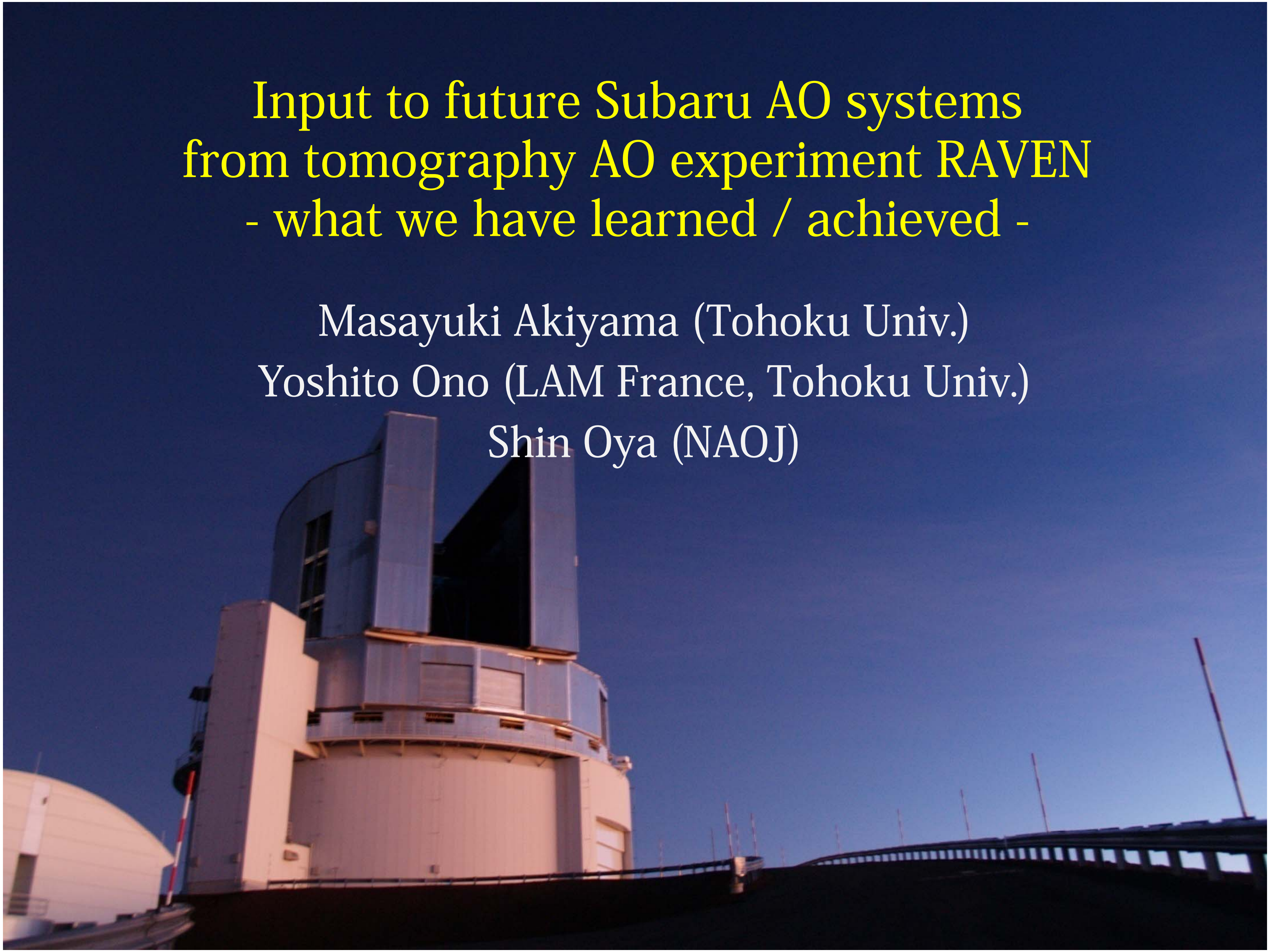


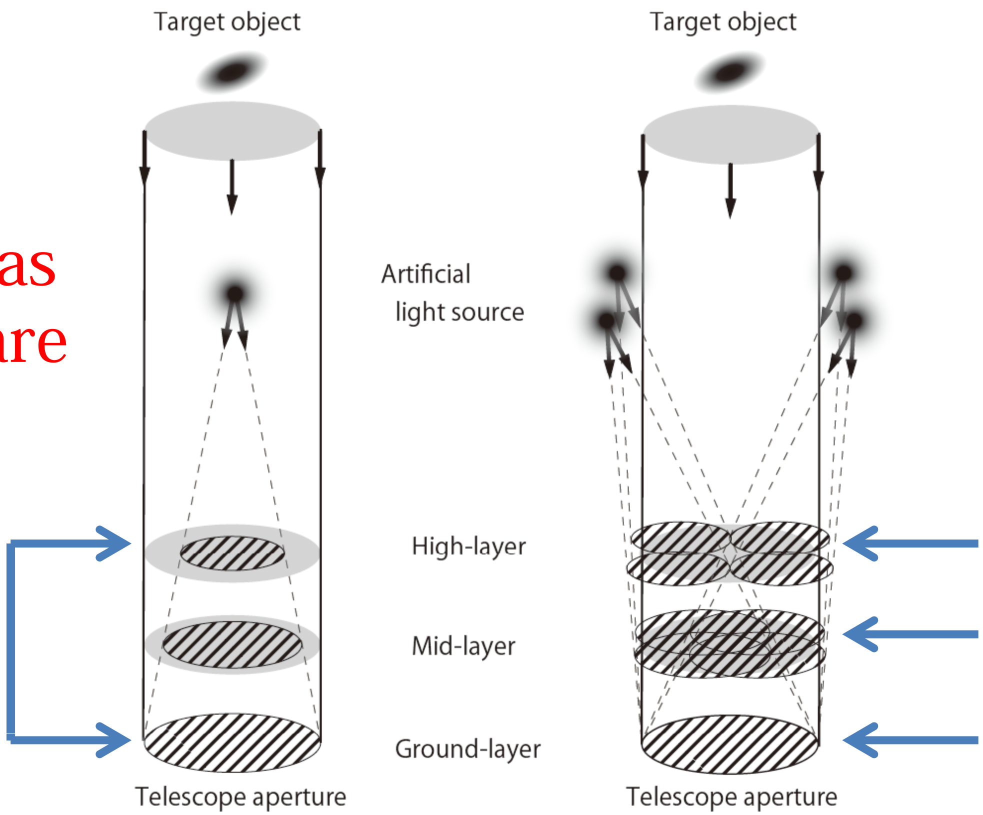
INTRODUCTION TO TOMOGRAPHIC AO

Classical vs. tomographic LGS AO system

- In the classical AO system, integrated wavefront distortion is measured with one light source, i.e. turbulence layers are degenerated.
- In the tomographic AO system, each wave-front sensor measures integrated wavefront distortion from one light source, but multiple light sources and sensors are used to estimate the turbulence layer at each altitude separately.

1. Outside areas of the “cone” are not covered

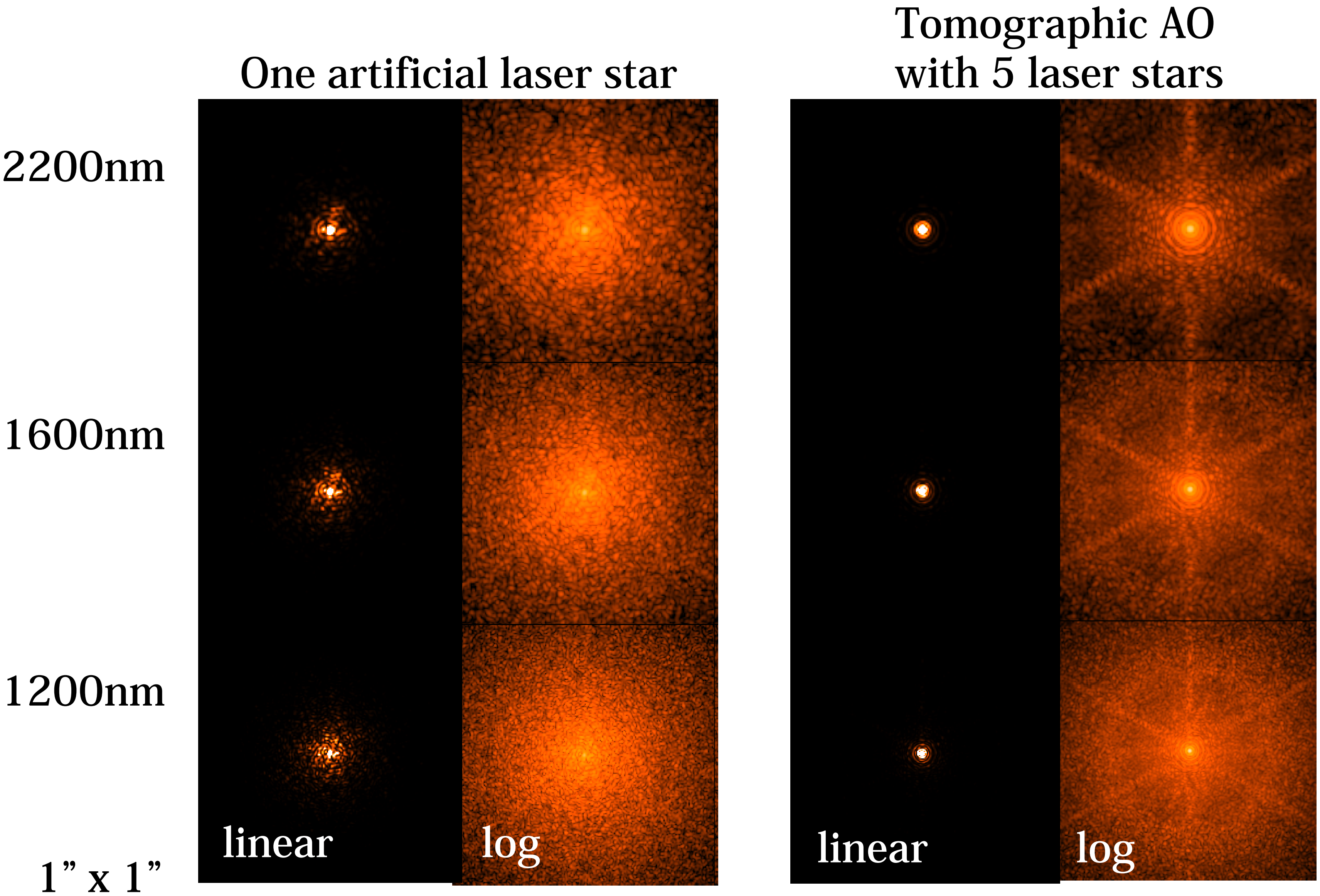
2. Integrated/ Degenerated



1. All areas are covered

2. Separated “3D” estimates

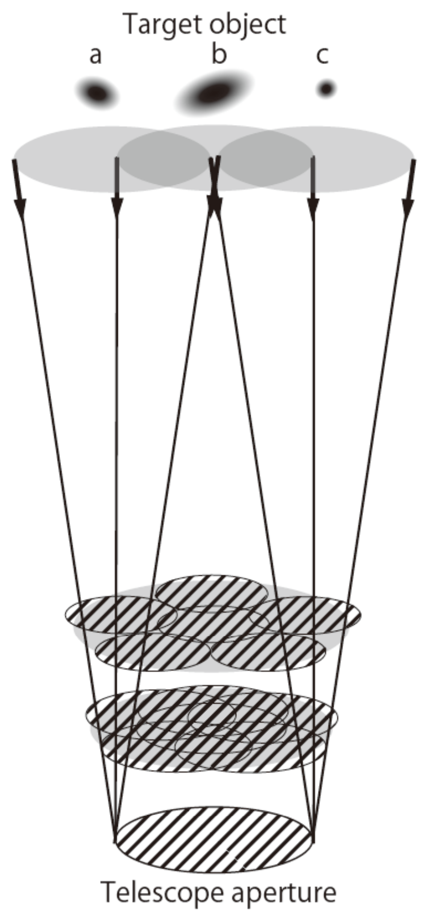
Point Spread Function with tomographic AO



Simulation with 30m aperture

Flexibility of tomographic AO systems

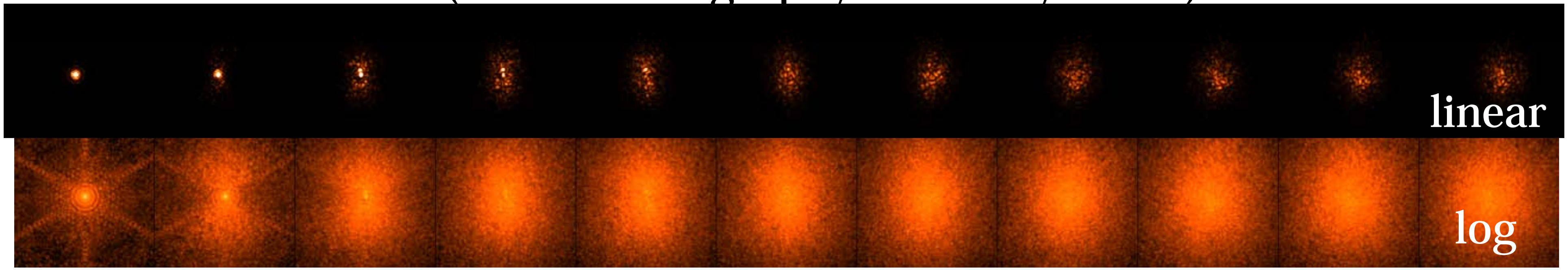
- In the tomographic AO system, AO correction performance can be optimized by scientific purpose



- Ground-layer AO : Wide-field coverage, seeing improvement
- Multi-Object AO : Moderately wide-field, good correction for multiple objects
- Laser-Tomography AO : Narrow-field, full correction for one

K-band PSFs with tomographic AO in the narrow vs. wide-field modes

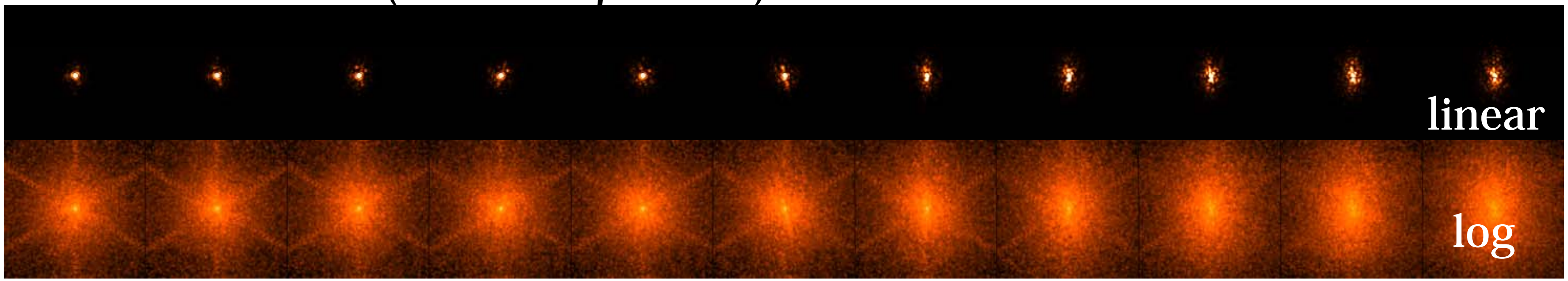
Narrow-field mode (“Laser Tomography Multi Layer AO”)



0” 60” 120” 180” 240” 300”

- Ensquared Energy within 0.05” ~50% up to 30”

Wide-field mode (“Multi-Object AO”)

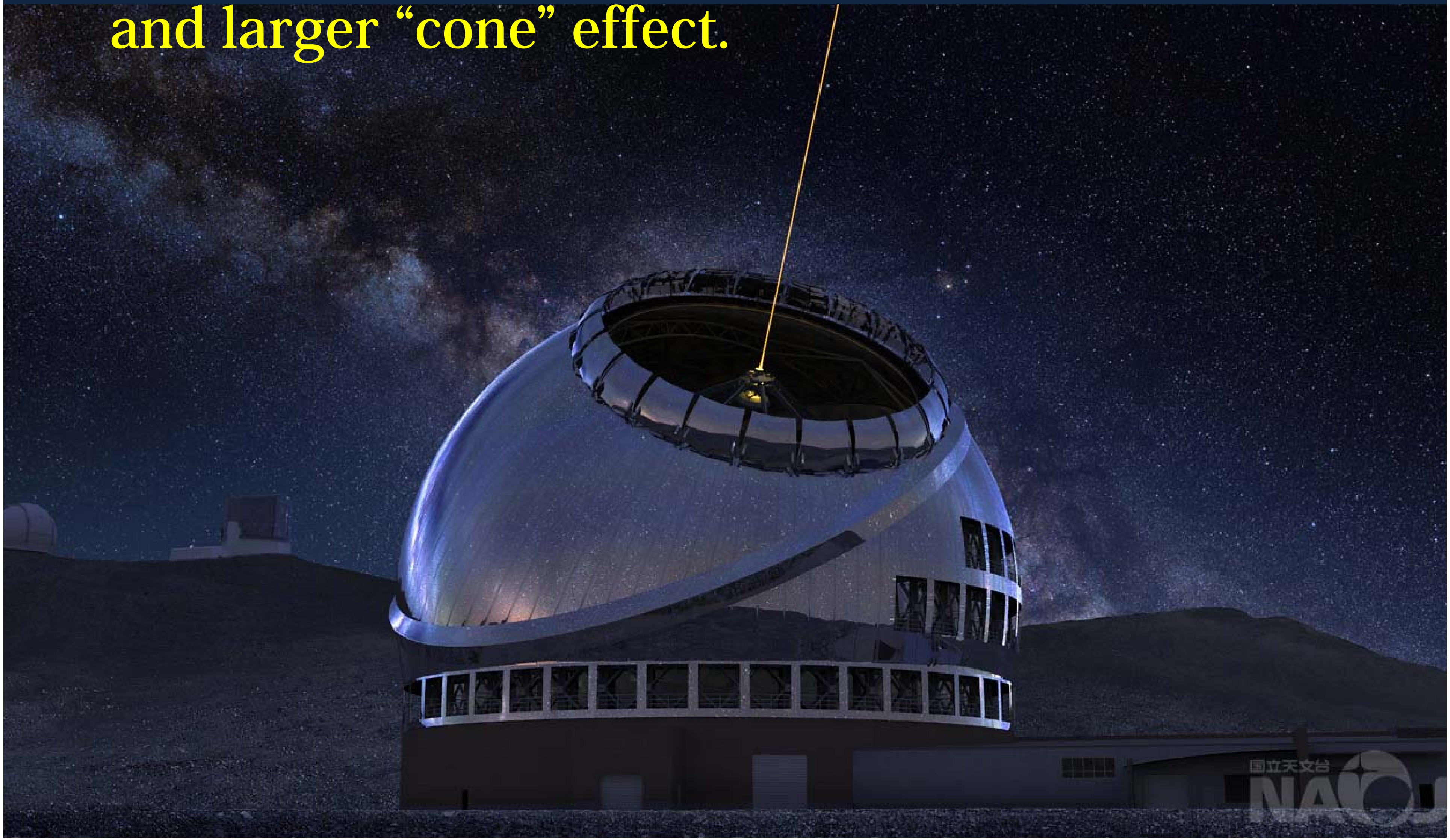


0” 60” 120” 180” 240” 300”

- Ensquared Energy within 0.05” ~50% up to 150” (<u>25 time larger area</u>)

Simulation with 30m aperture

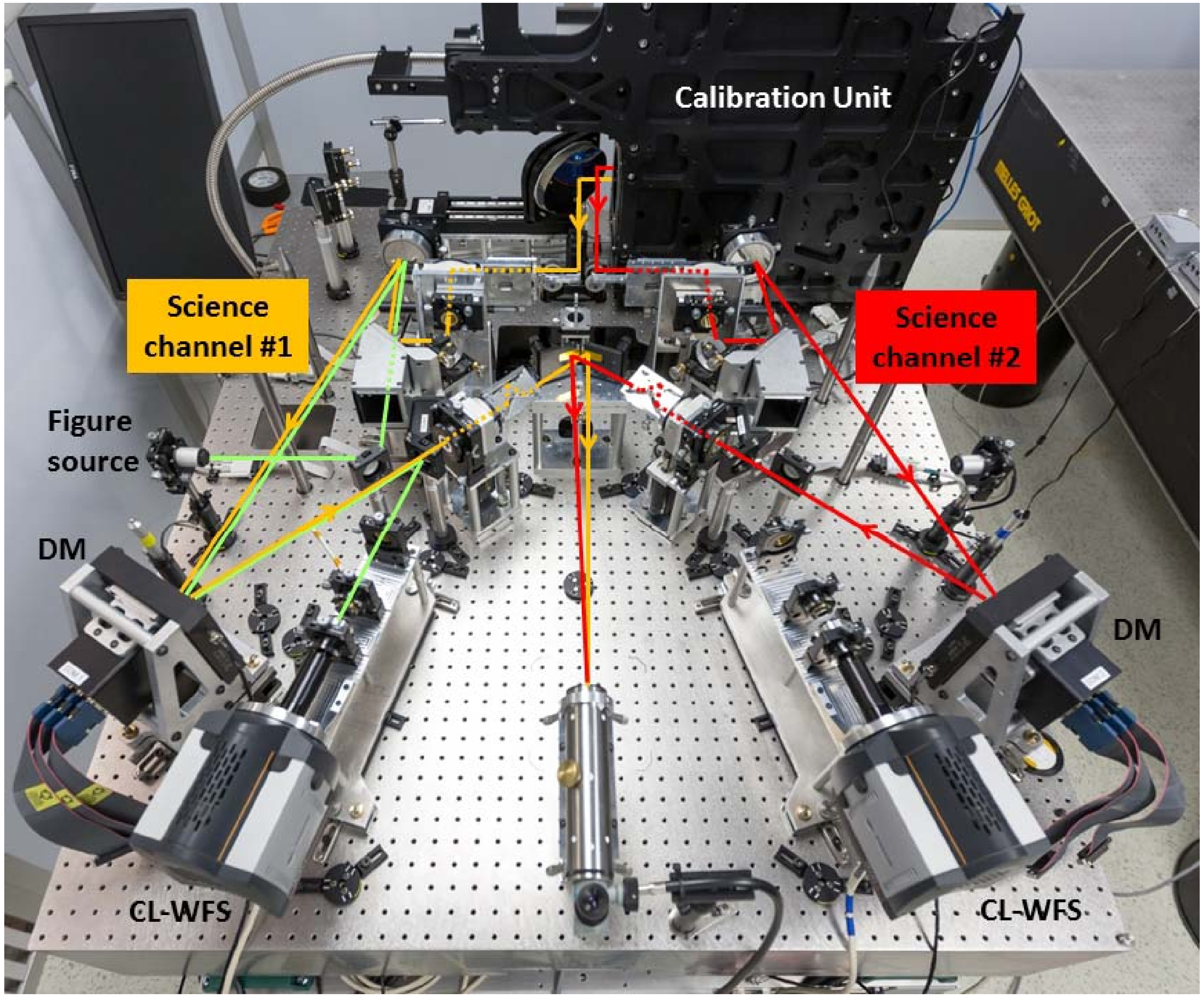
Next generation extremely large telescope, TMT (Thirty Meter Telescope) requires a tomographic AO system, because of the larger aperture size and larger “cone” effect.



TESTING THE TOMOGRAPHIC WAVEFRONT ESTIMATION ON-SKY WITH SUBARU/RAVEN

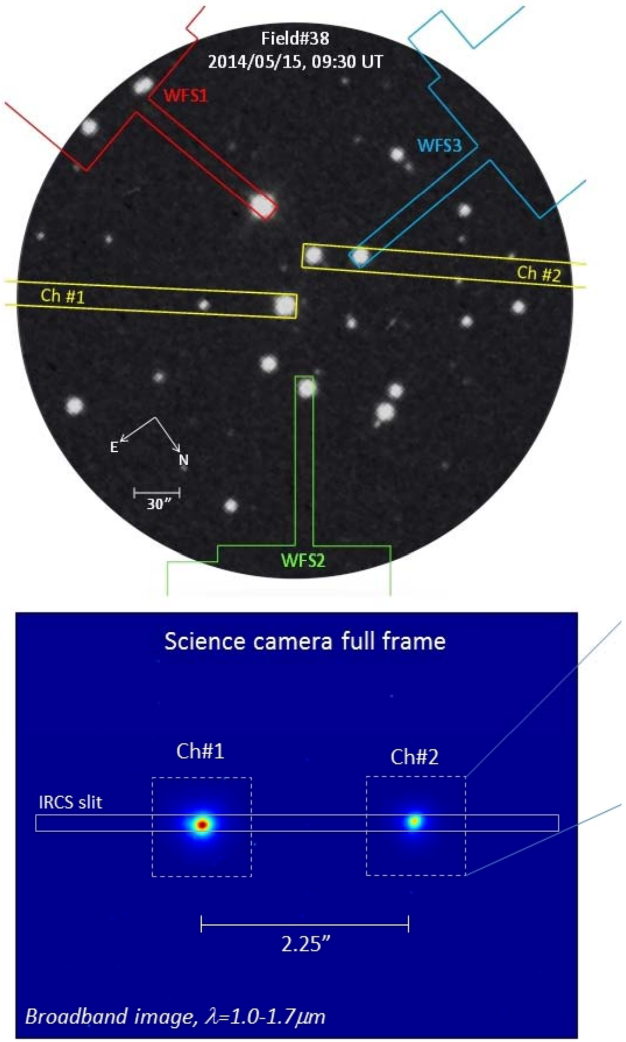
Tomography AO on-sky demonstration : RAVEN

- On-sky demonstrator of tomography AO system on the Subaru telescope
- PI: Colin Bradley (U.Vic, Canada) in collaboration with NRC, NAOJ, Tohoku U.

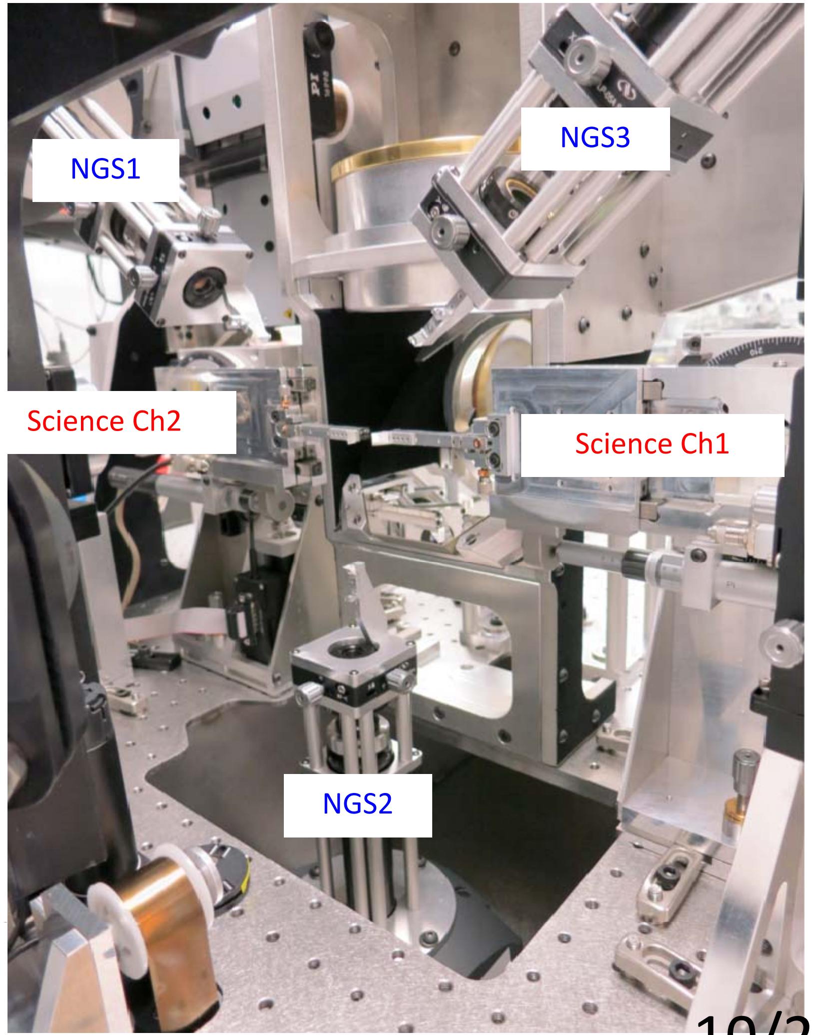


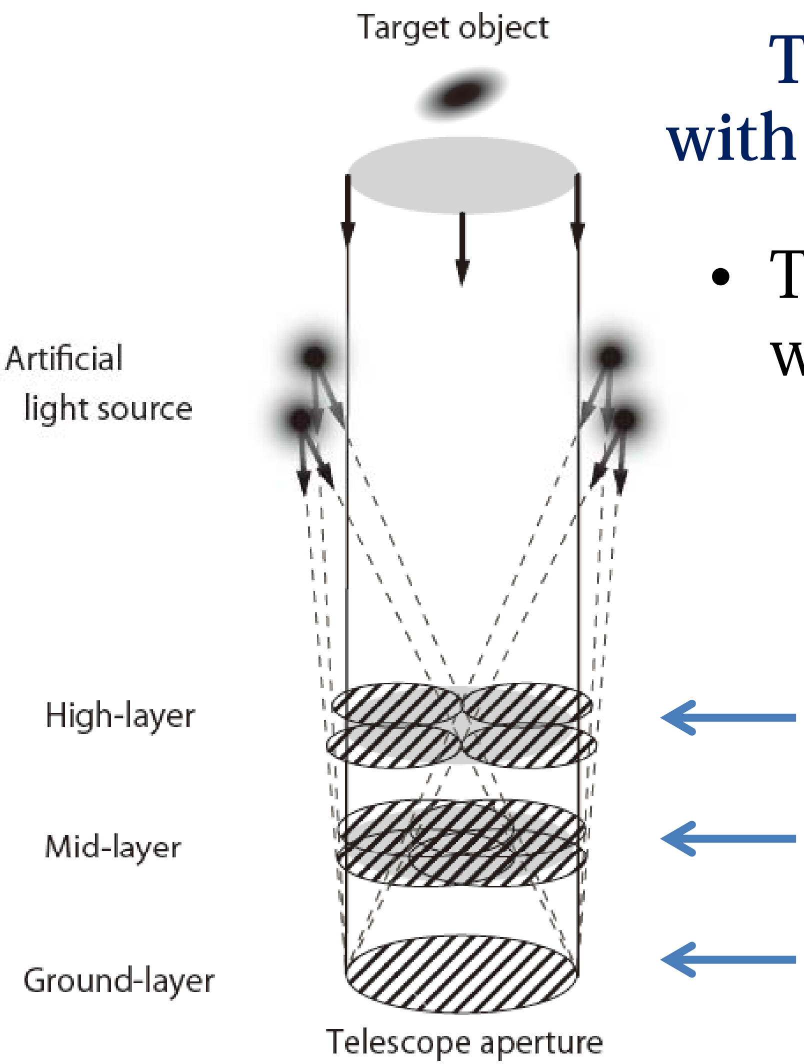
Tomography AO on-sky demonstration : RAVEN

- Correcting for 2 target directions based on WFS data of 3 natural guide stars.



Pick-off Arms





Tomography matrix construction with the real-time atmospheric profiling

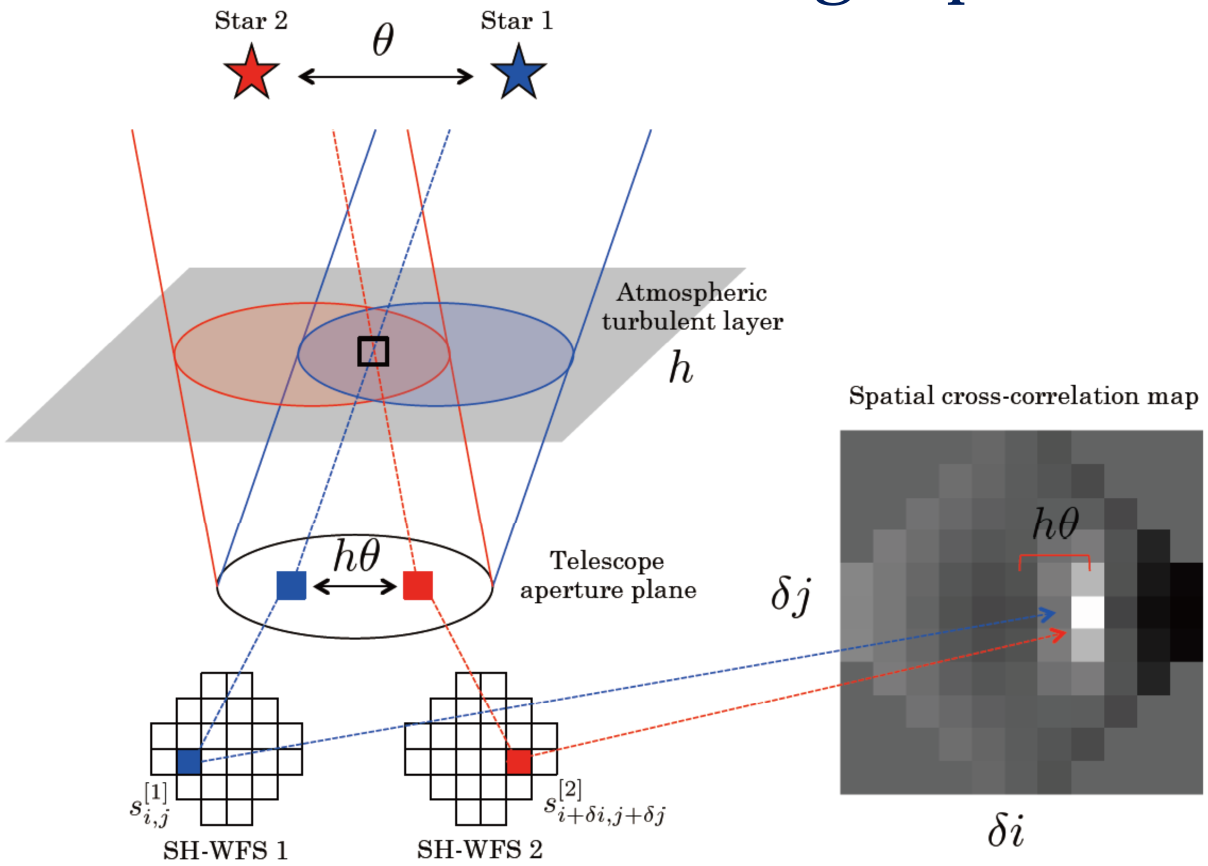
- Tomography matrix are constructed with
  1. Configurations of the reference light sources

  2. <u>Turbulence height profile</u>

     Cannot be fully separated with the limited measurements.
     Turbulence height profiles are used to set up the turbulence layer altitudes and strength of each layer

  3. <u>Wind height profile (for predictive estimation)</u>

Tomography AO ingredient I : Turbulence height profile

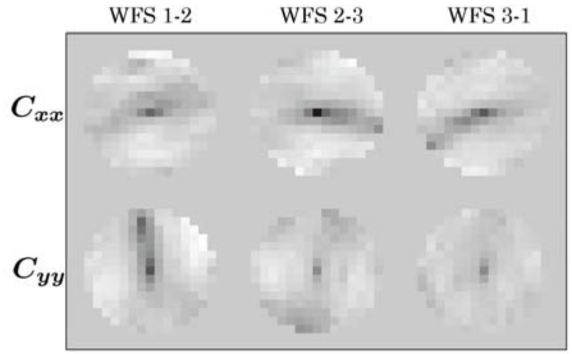


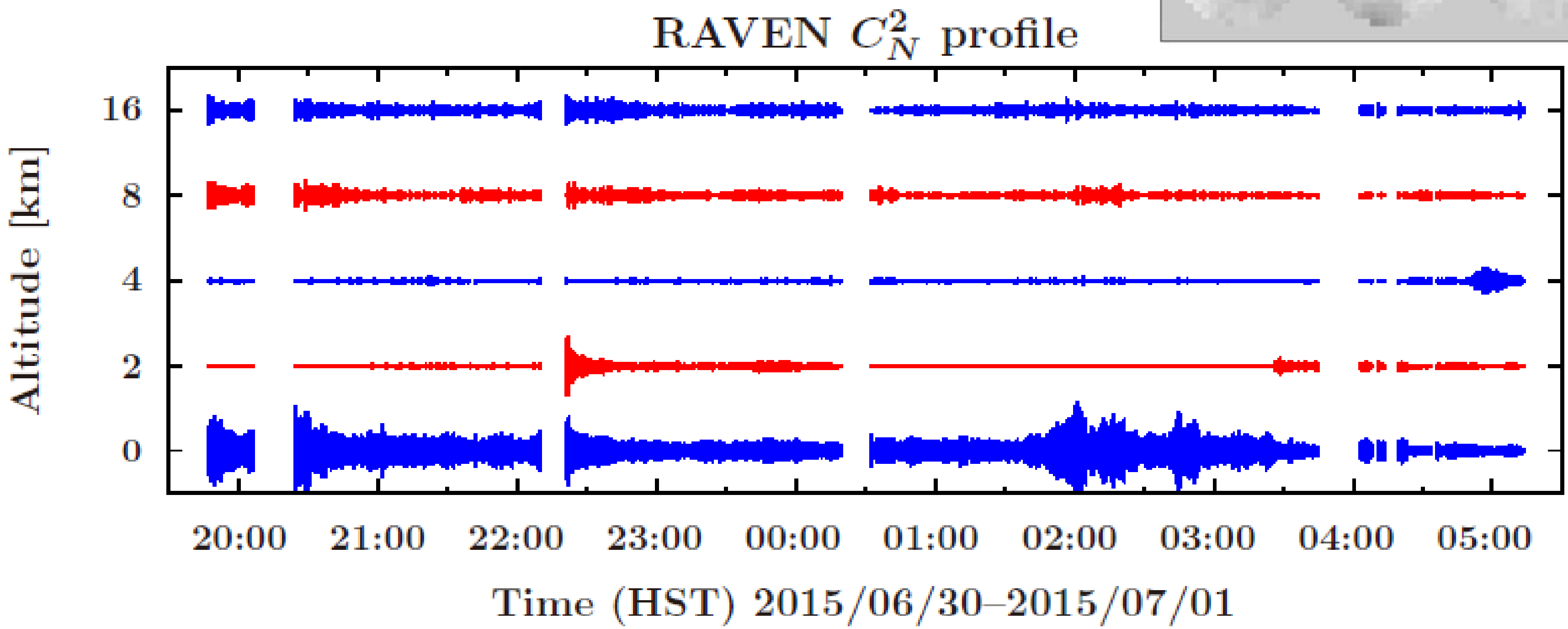
Ono et al. 2016 MNRAS in press

- Turbulence height profile can be estimated with taking cross-correlation between two WFSs monitoring two different reference stars.

Tomography AO ingredient I : Turbulence height profile

- Real-time turbulence height profiling with cross-correlation of multiple WFSs.

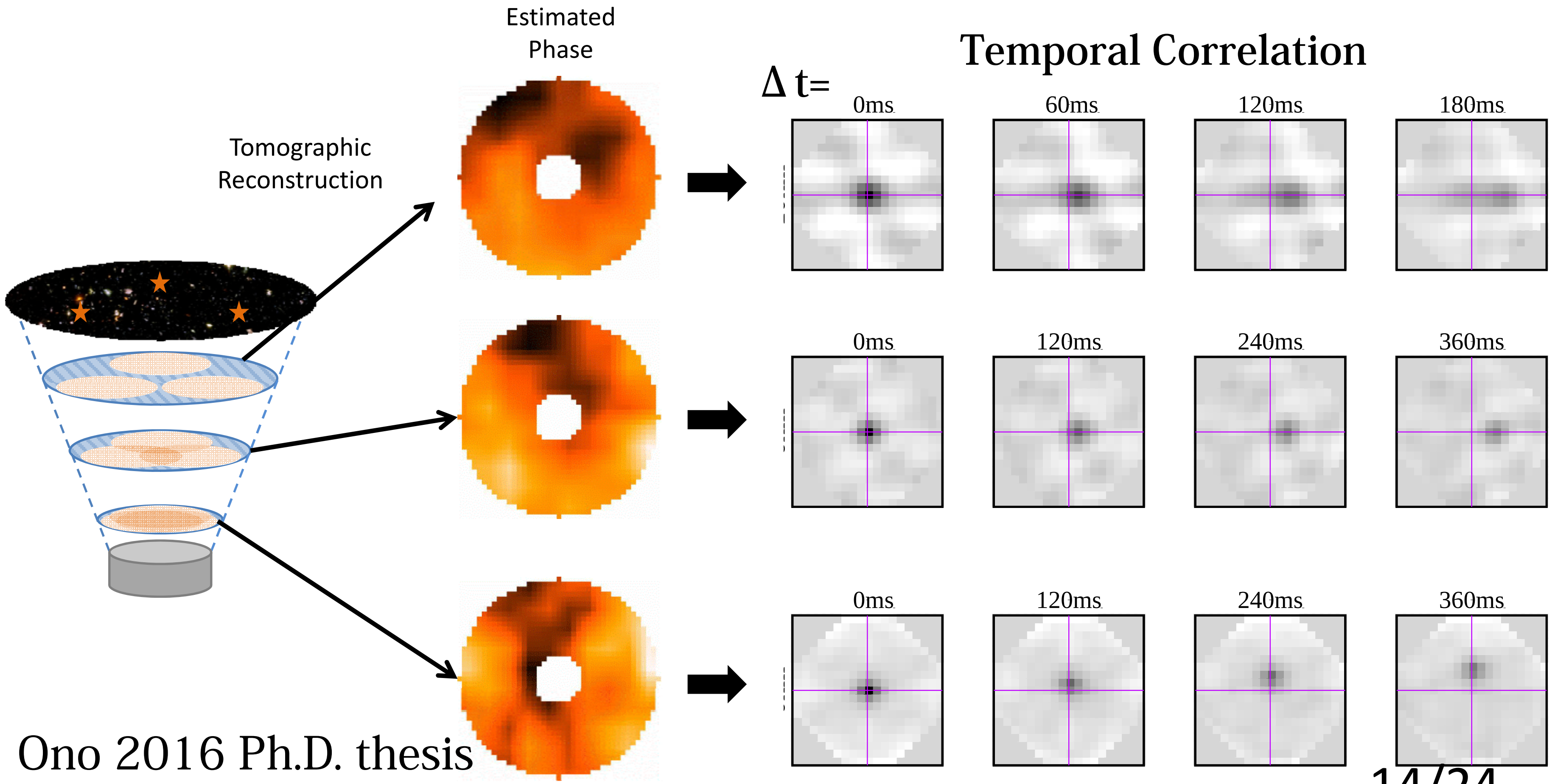




Ono et al. 2016 SPIE

Tomography AO ingredient II :
Wind profile

- Wind direction and velocity of each turbulence layer can be estimated with cross-correlation of wavefront sensor data at two different time steps.



Ono 2016 Ph.D. thesis

Tomography AO ingredient II : Wind profile

- Result of a real-time wind profiling above Subaru.

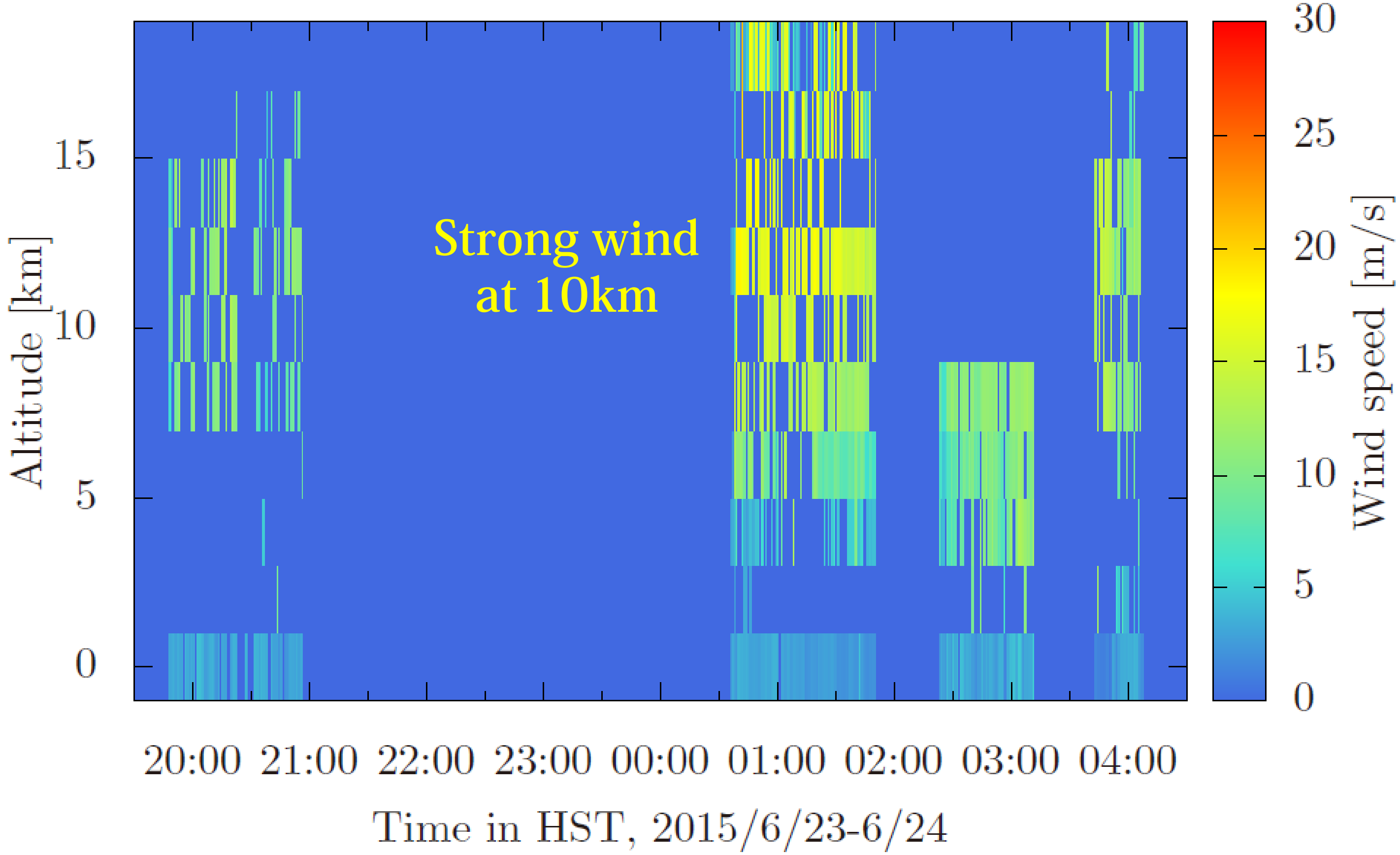


Figure. 6.12: Wind speed profile on June 23–24th, 2015.

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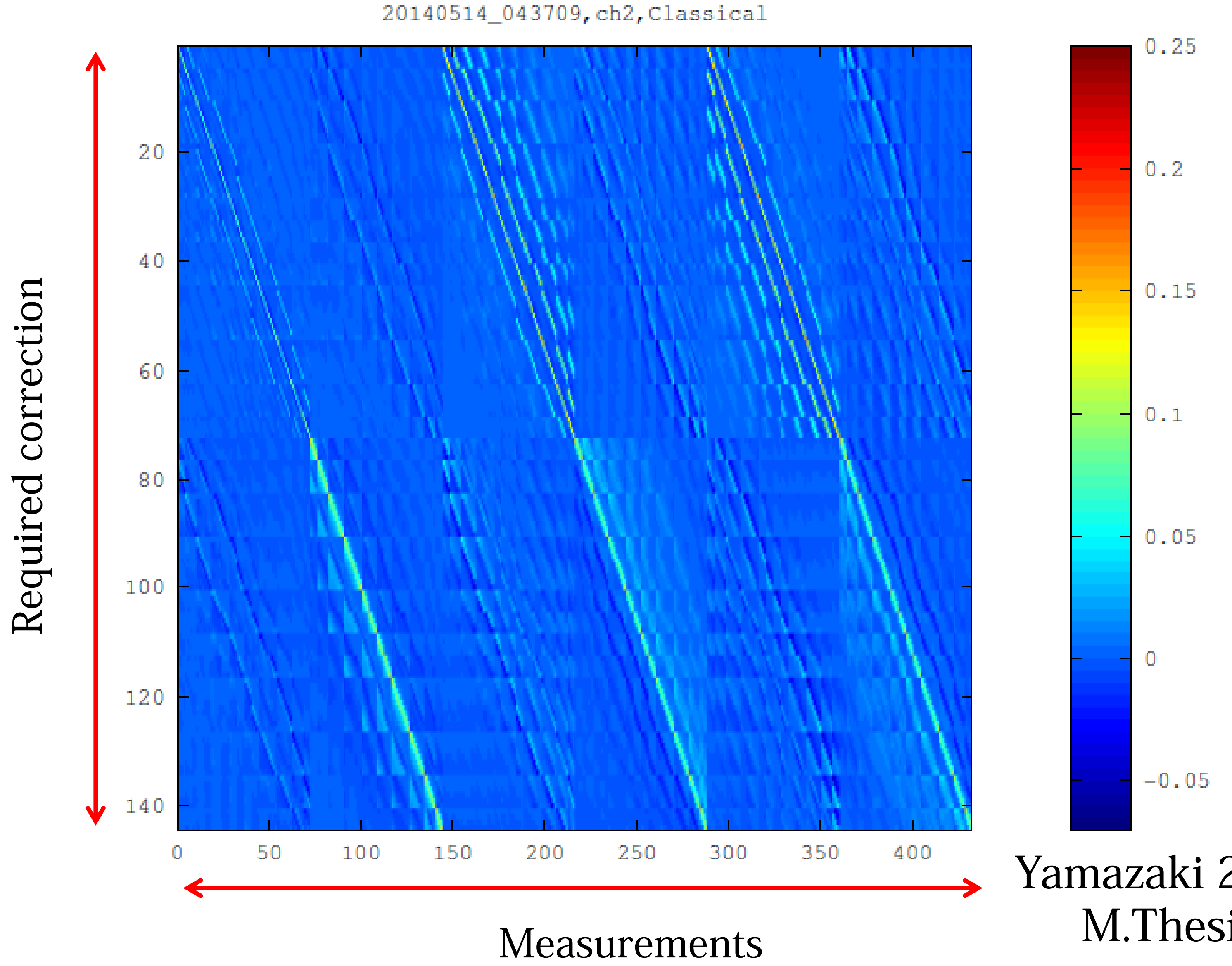
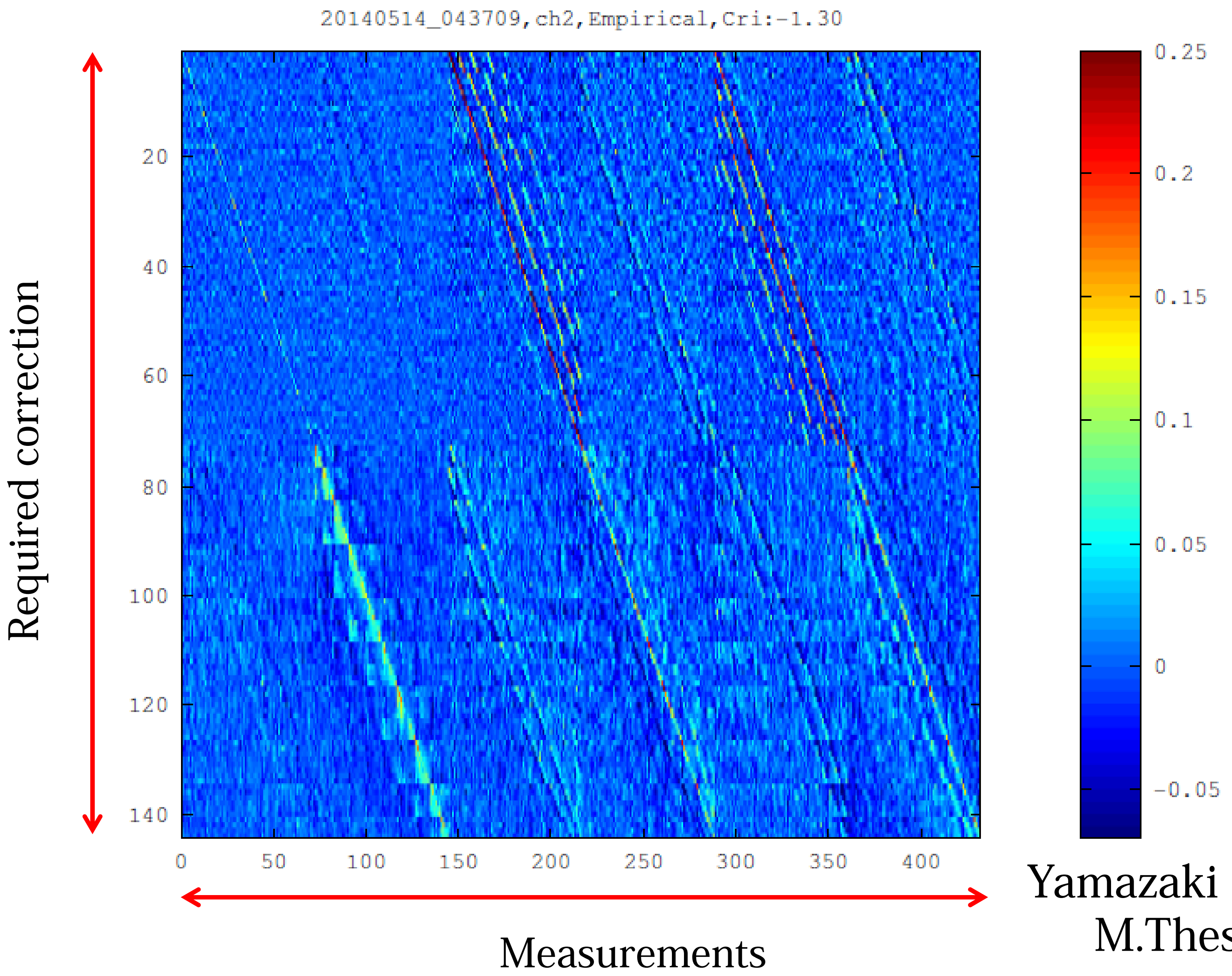
Tomography matrix : with atm. profiling



Yamazaki 2016
M.Thesis

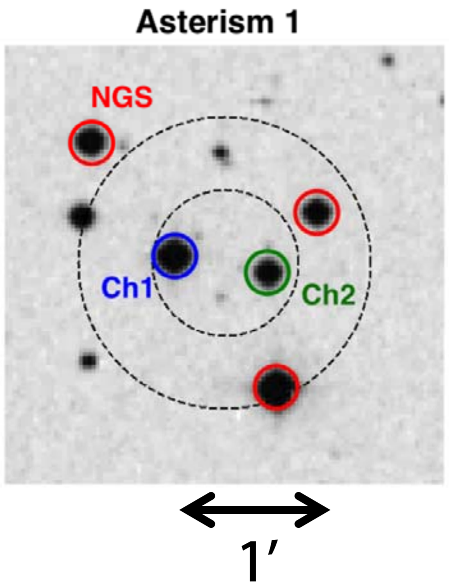
Tomography matrix : “cross-check”

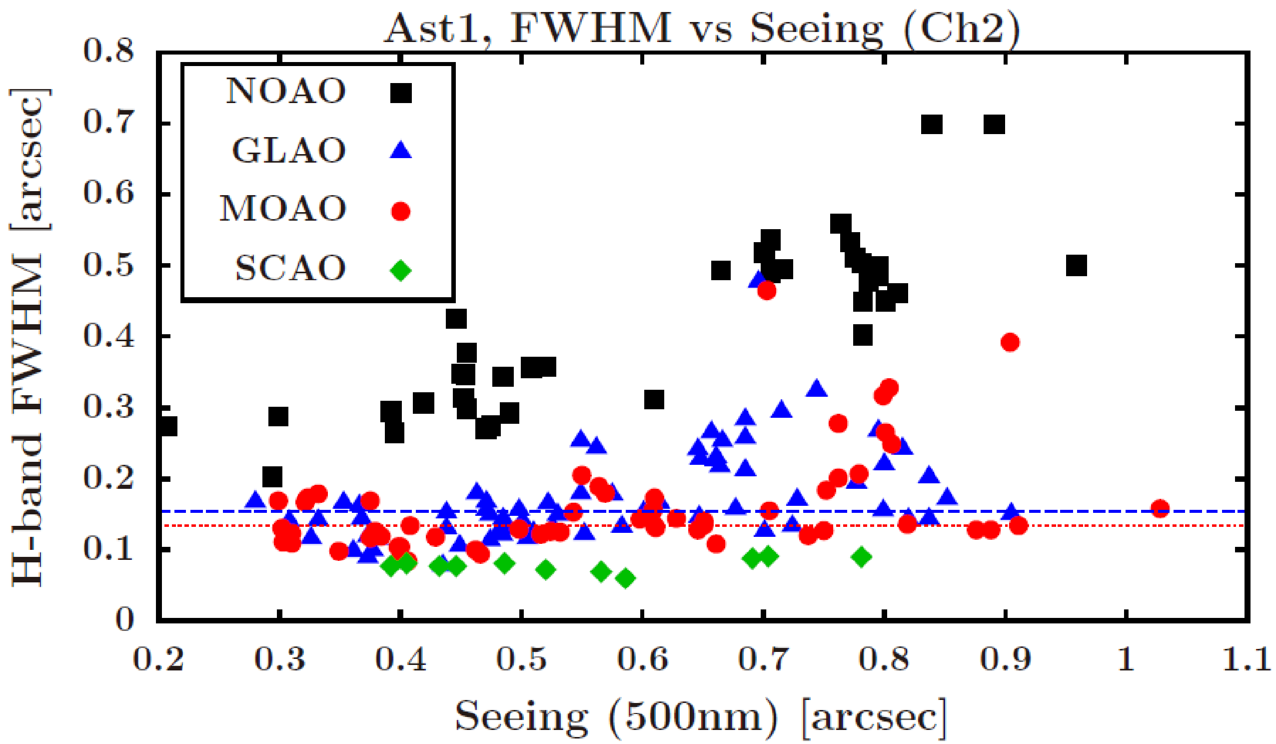


Yamazaki 2016 M.Thesis

RAVEN AO correction summary

- Correction performance in MOAO mode is similar to GLAO mode
  - Partly explained with strong ground-layer component.
  - Unstable DM reference shape affects both of the MOAO and GLAO modes, and results in similar performance.

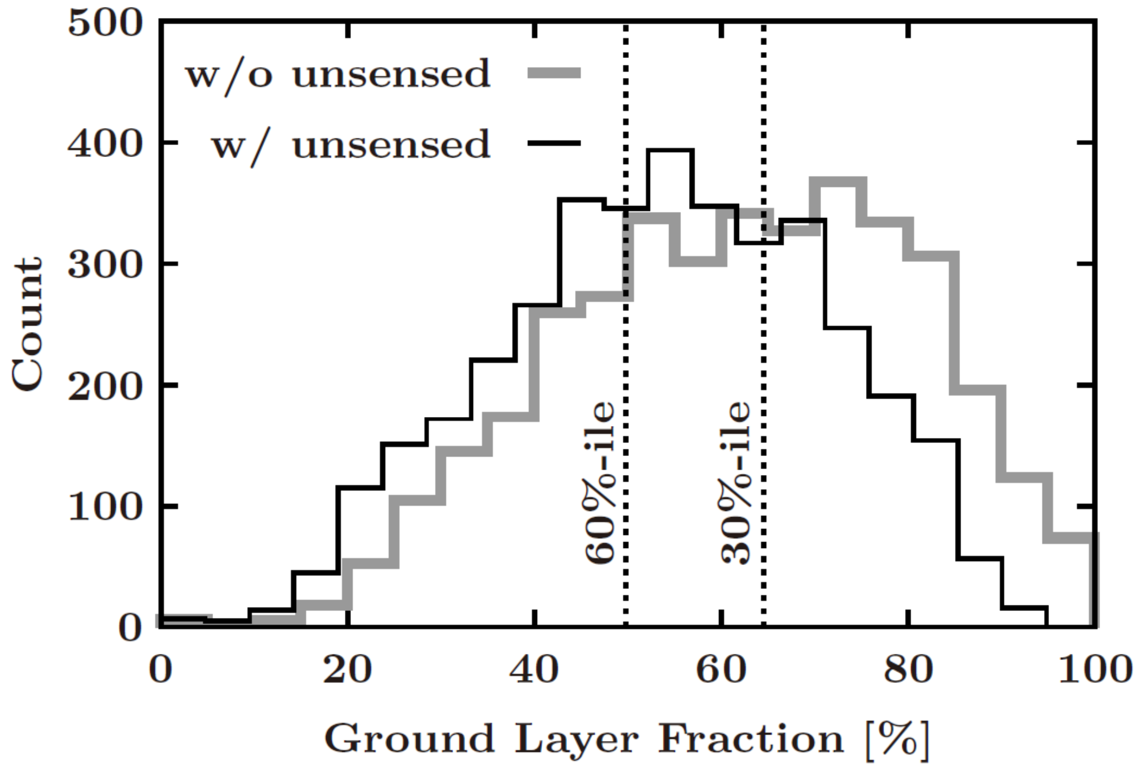


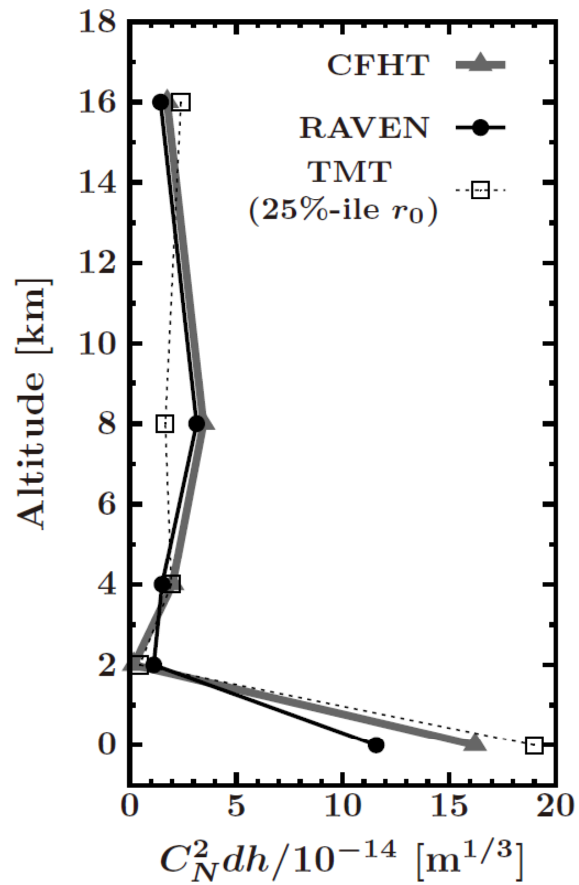


Ono et al. 2016, SPIE

Turbulence height profiling results

- RAVEN profiling confirms strong ground-layer component at Maunakea.





Ono et al. 2016, MNRAS, in press

TOMOGRAPHIC AO FOR ASTRONOMICAL OBSERVATIONS

Tomography AO path to the TMT (personal view)

- Tomographic AO experiment is directly connected to the ULTIMATE-Subaru development and TMT wide-field AO instrument (TMT-AGE).

1. RAVEN Tomography AO correction
with 3 NGSs

4 LGSs
+ WFS unit

2. Laser Tomography wavefront
Measurements with 4 LGSs

High-order DM

3. Laser Tomography AO correction
with 4 LGSs

Good AO correction
with LGS
Optical AO

Adaptive 2ndry

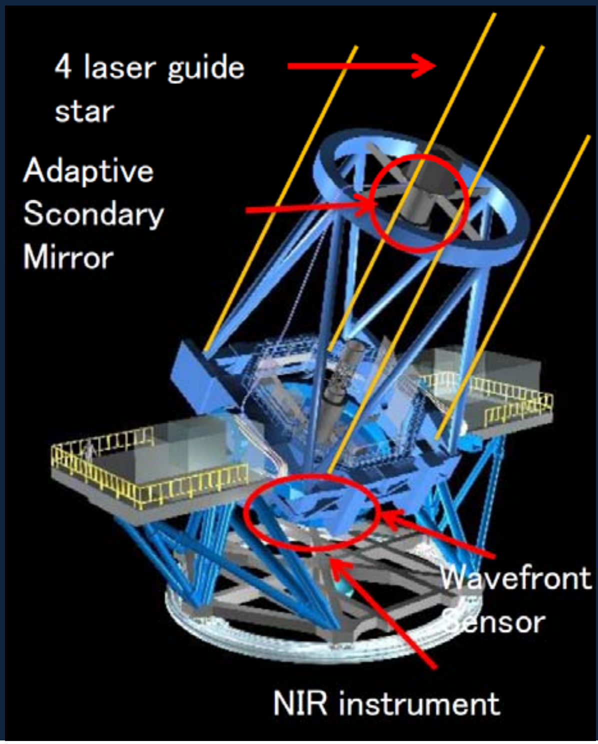
4. Ground-layer AO system
with 4 LGSs : ULTIMATE-Subaru

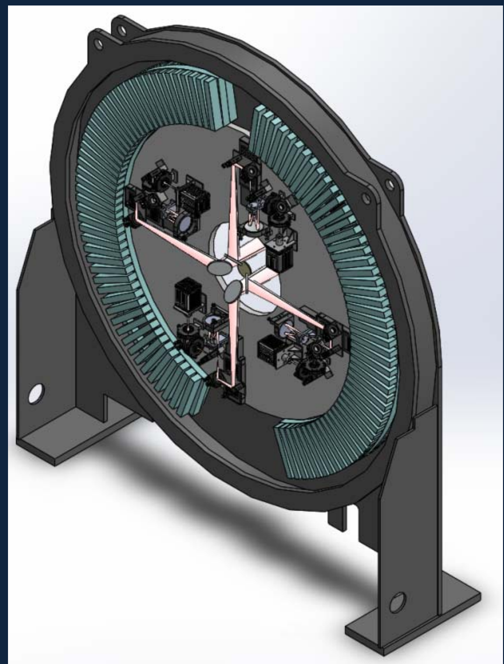
Wide-field AO
correction

5. Wide-field AO system
for TMT

Next generation tomographic AO system for Subaru telescope

- Tomographic AO system can achieve
  - Good AO correction in shorter wavelength range, laser AO system in the “optical” wavelength
  - Moderate AO correction in very wide-field of view

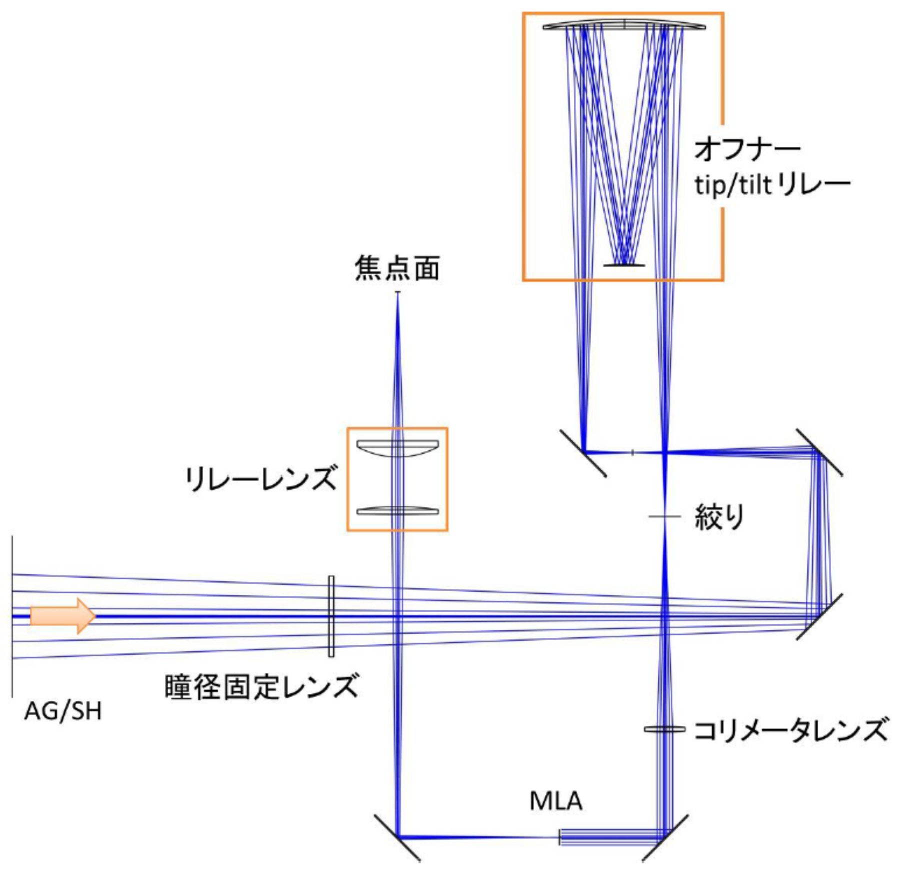




- Wavefront measurement unit with 4 WFSs.

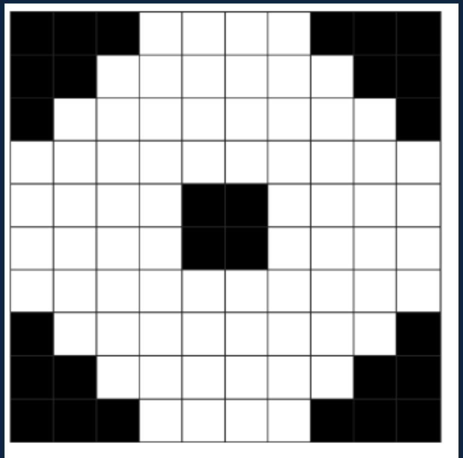
WFS design for tomographic AO experiment with LGSs

- Higher sampling than RAVEN can be achieved with bright LGSs.

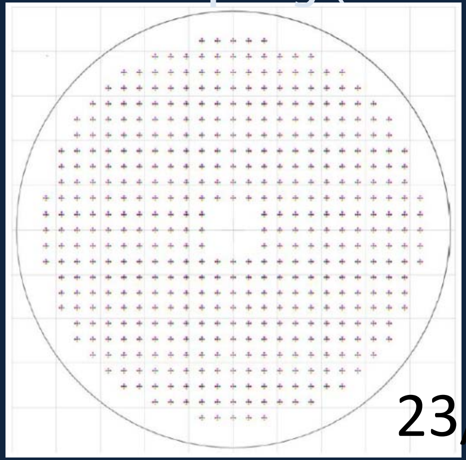


T.Watanabe : master student

RAVEN sampling (9x9~90cm)



NEW-WFS sampling (32x32~26cm)



Summary

- Tomographic AO system is a necessary system to achieve
  - good AO correction in optical wavelength and higher spatial resolution with Subaru.
- Tomographic AO concept is demonstrated on-sky with Subaru, and has been maturing.
- Tomographic AO system enables a variety of AO systems.
  - ULTIMATE-Subaru : AO not only for case studies, but also for explorations/surveys.
  - TMT-AGE : TMT as a spectrosopic surveyer

ACKNOWLEGEMENT

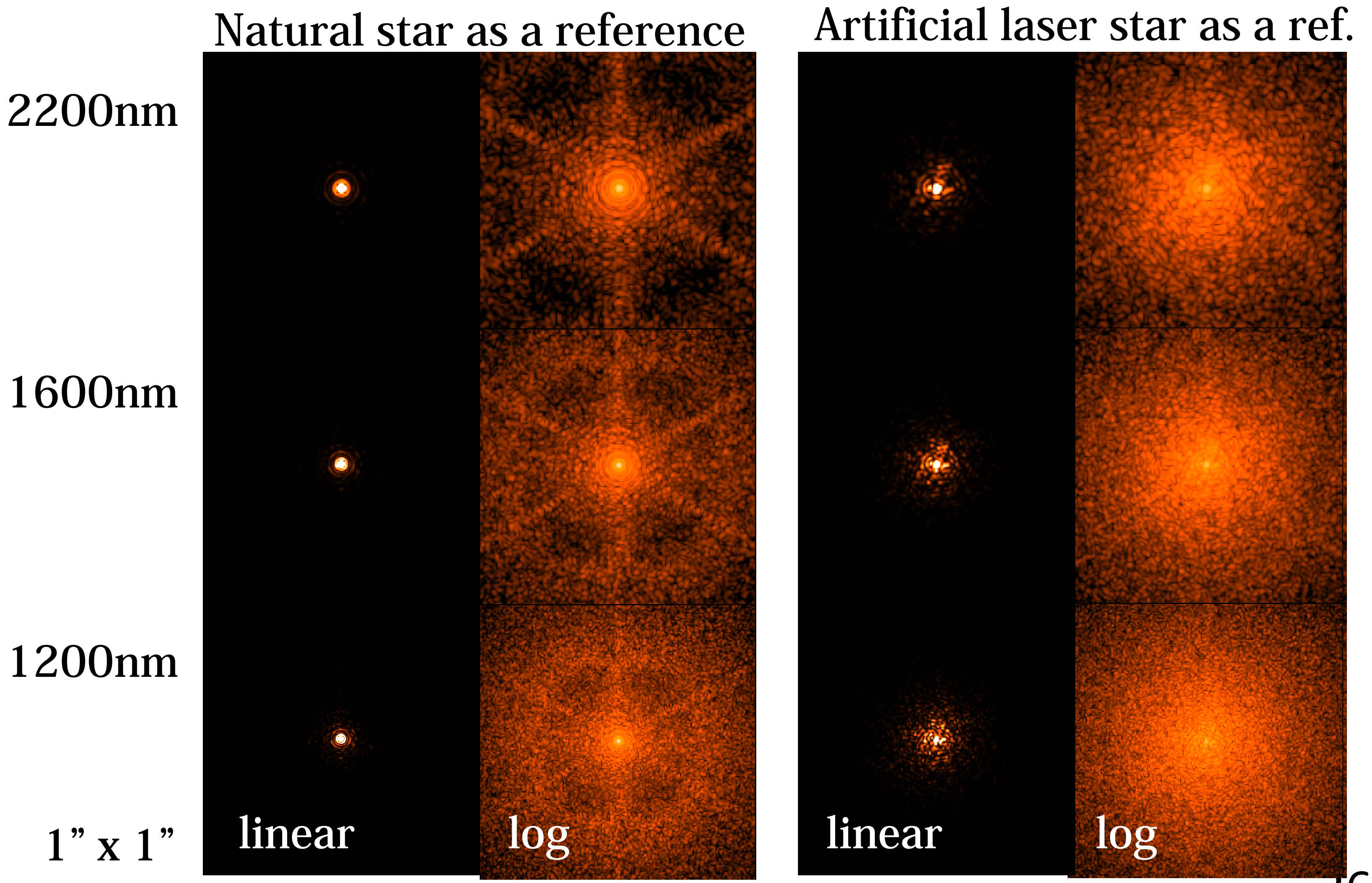
- RAVEN is a collaboration project among Univ. Victoria (Canada), NRC (Canada), Subaru telescope, and Tohoku Univ.
- We would like to thank all the members of the RAVEN project.

First run in May 2014.

Second run in Aug. 2014.

Limitation of a classical AO with one LGS

- Simulated on-axis image of a point source.



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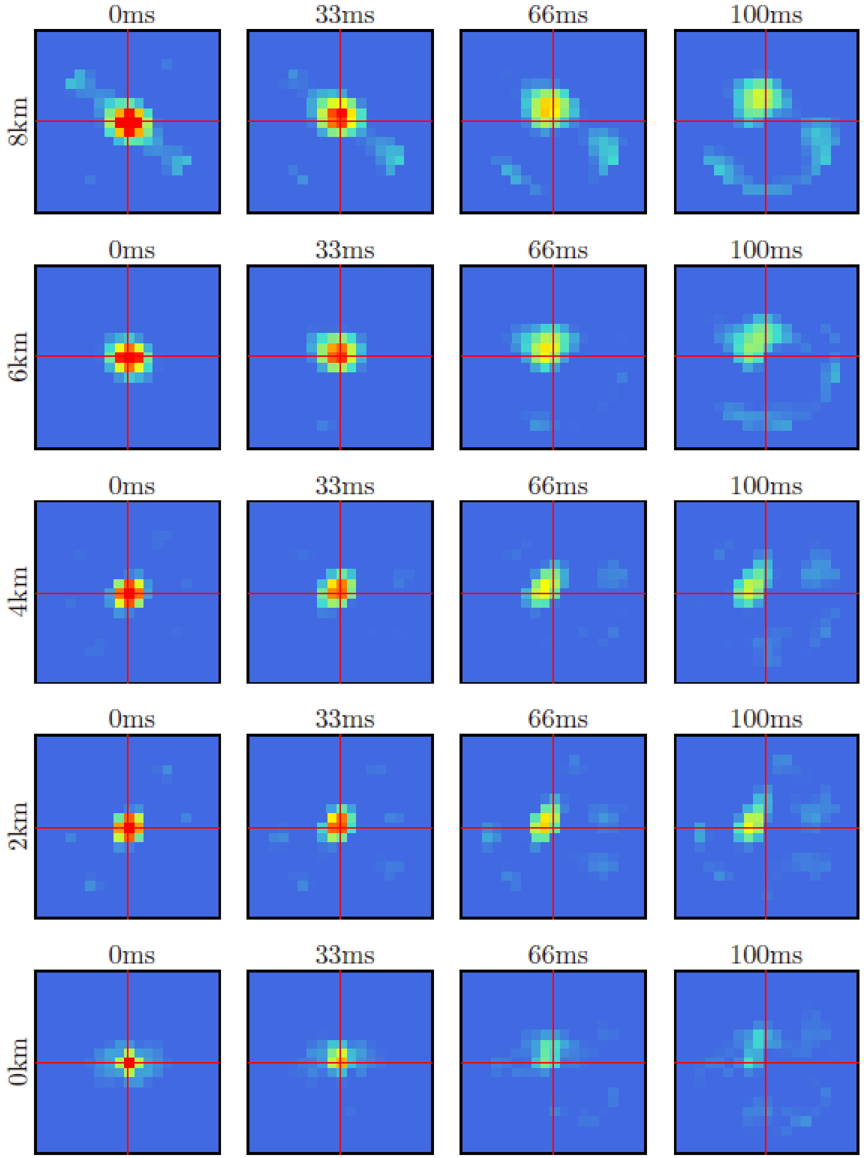
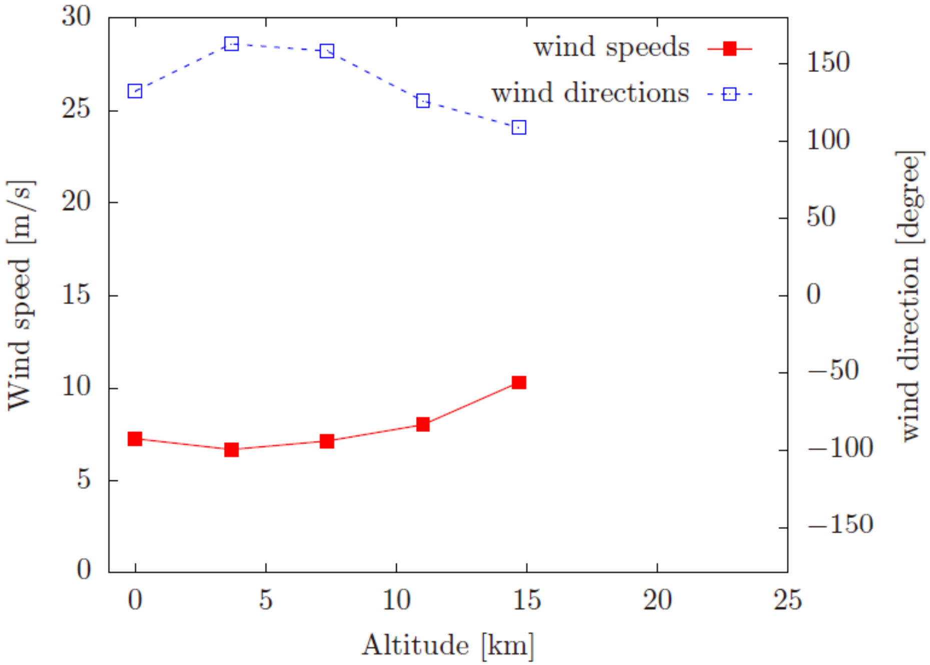
Tomography AO ingredient II : Wind profile



- Cross-correlation maps



Ono 2016

Turbulence height profiling results

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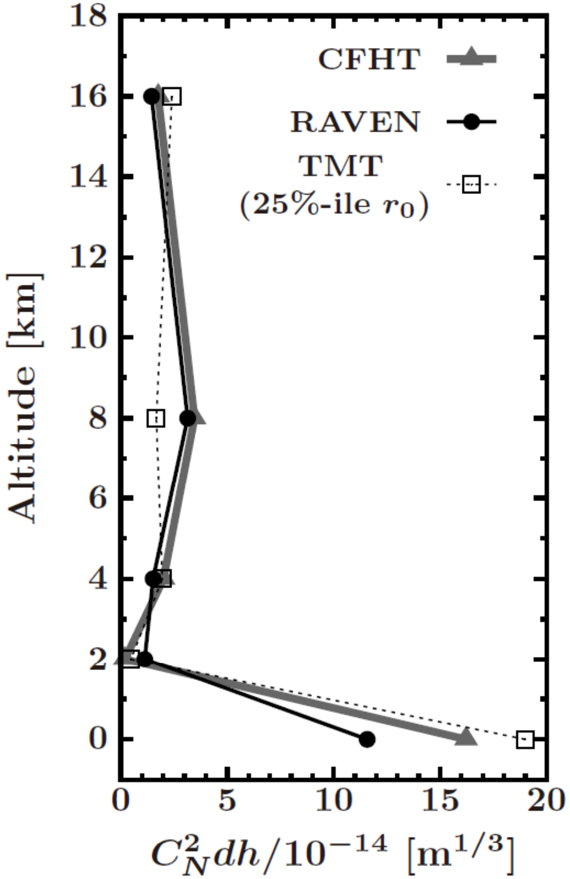
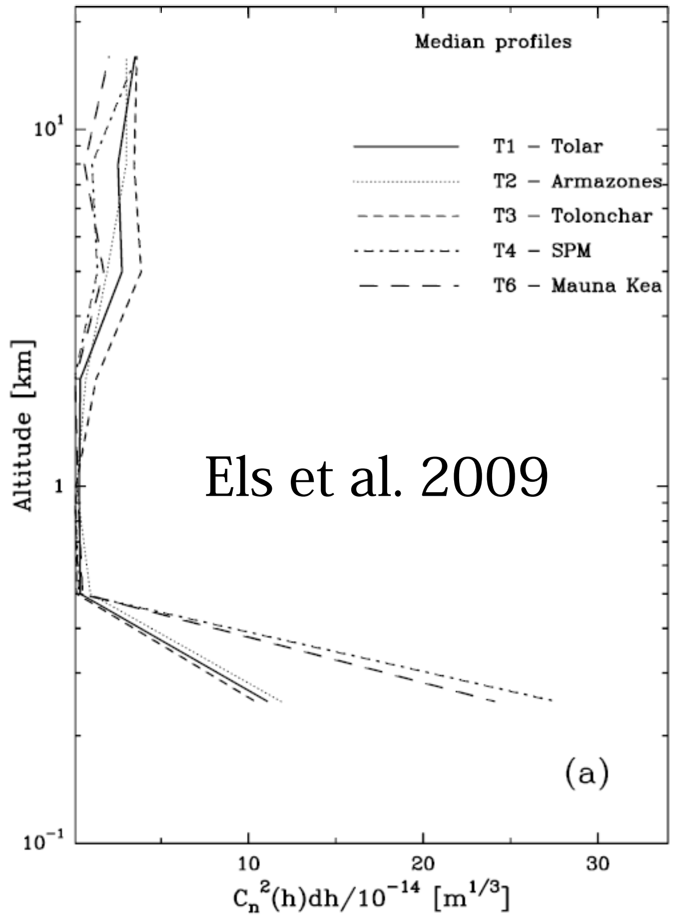


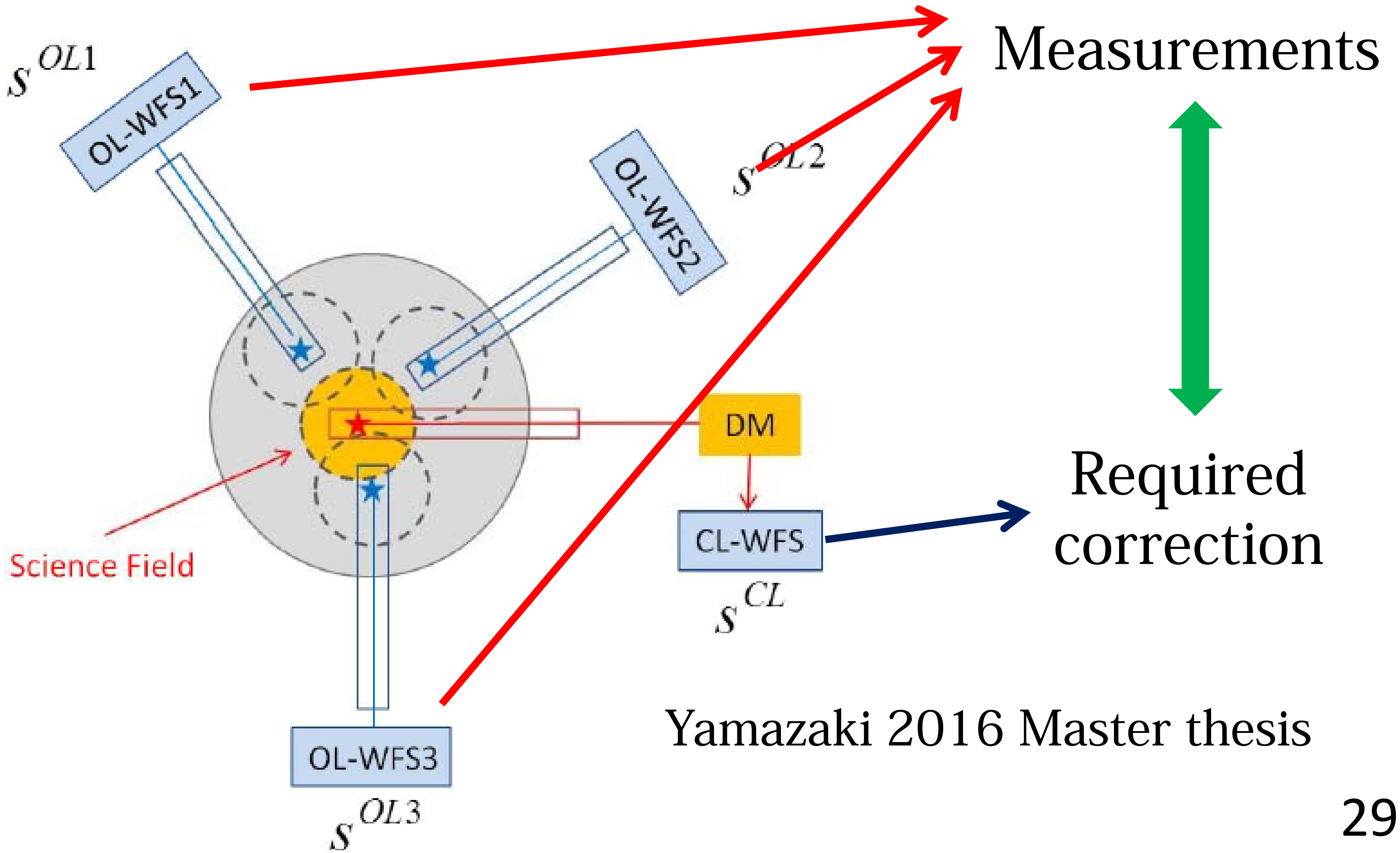


Els et al. 2009

Ono et al. 2016, MNRAS, in press

"Cross-check" the tomography matrix directly with measured dataset

- "Cross-check" tomography estimation with the WFS measurements from tomography WFSs and the WFS in the target optical path : "Learn & Apply" method.



Yamazaki 2016 Master thesis

Tomography matrix construction with the real-time measurement

- Tomography matrix are constructed with
  - Configurations of the reference light sources
  - Turbulence height profiles
  - Wind height profiles

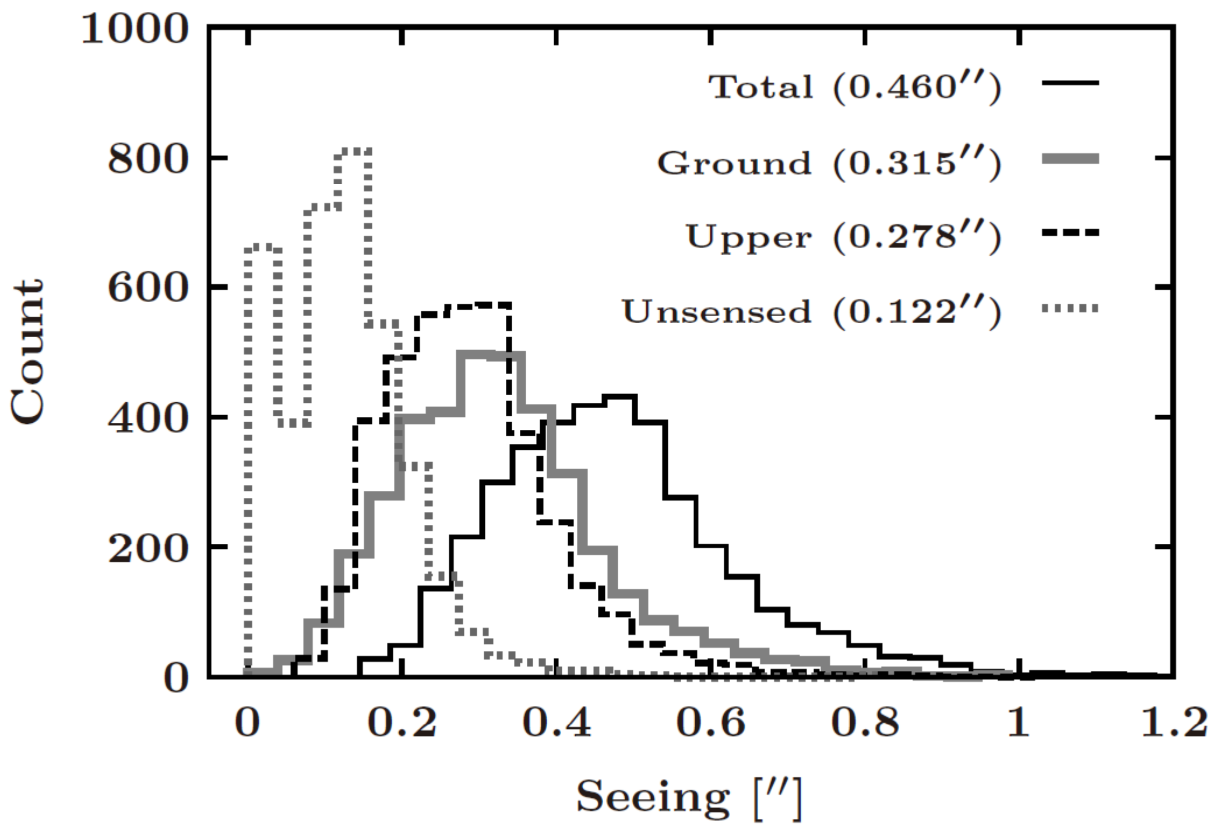
Updates every 10 min

The last two parameters are estimated in real-time atomospheric monitoring with the same WFS measurements

How to check whether the derived tomography matrix is optimal or not ?

Turbulence height profile: seeing

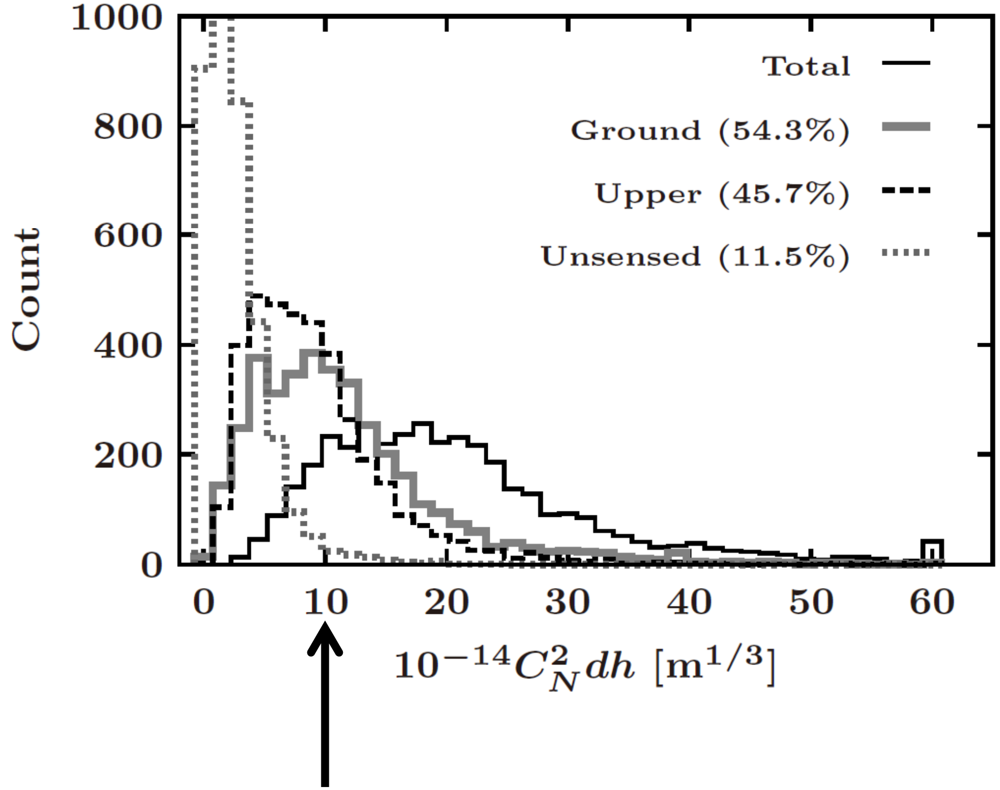
- Seeing value at 500nm :



Ono et al. 2016, MNRAS, in press

Turbulence height profile: seeing

- Contribution from the ground-layer (h<1.5km) component :



r0=32cm@500nm

Ono et al. 2016, MNRAS, in press

Turbulence height profile: seeing

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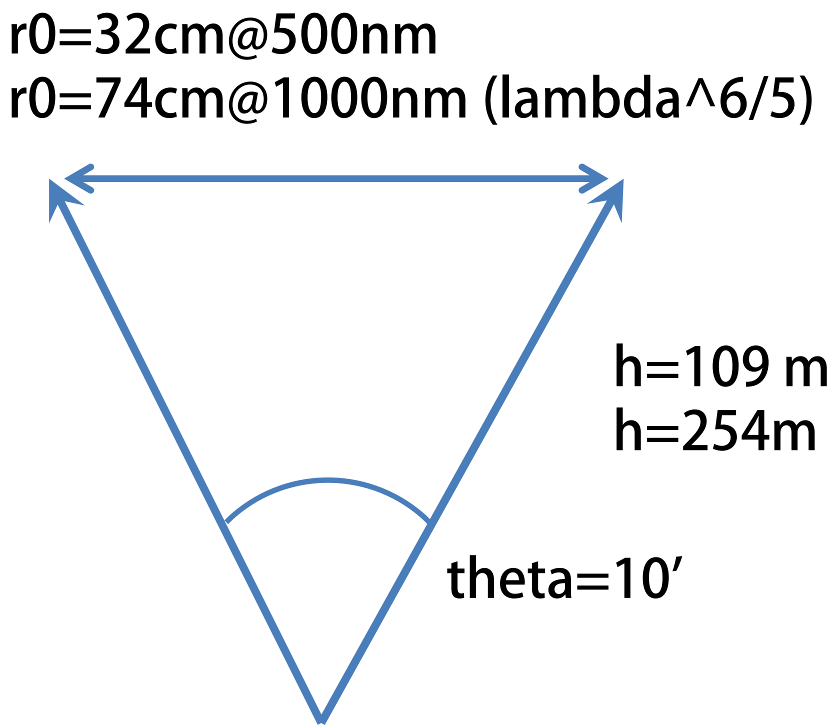

Ono et al. 2016, MNRAS, in press