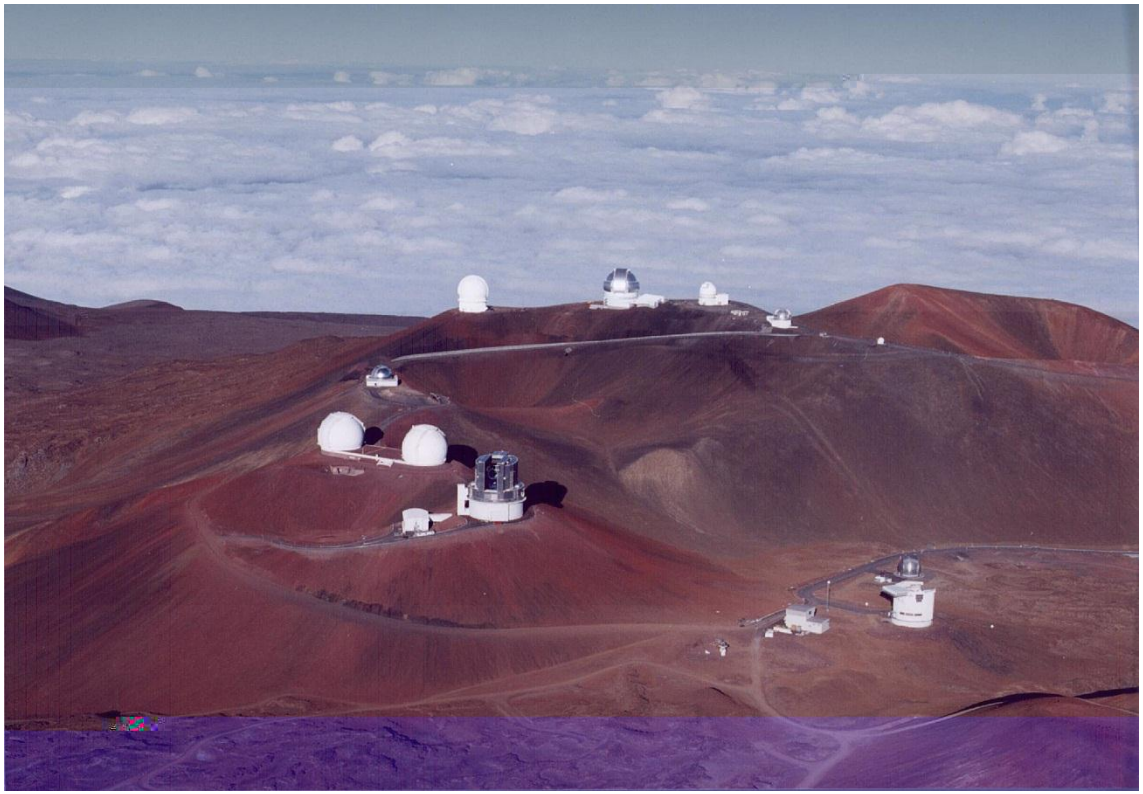
Subaru GLAO Simulation



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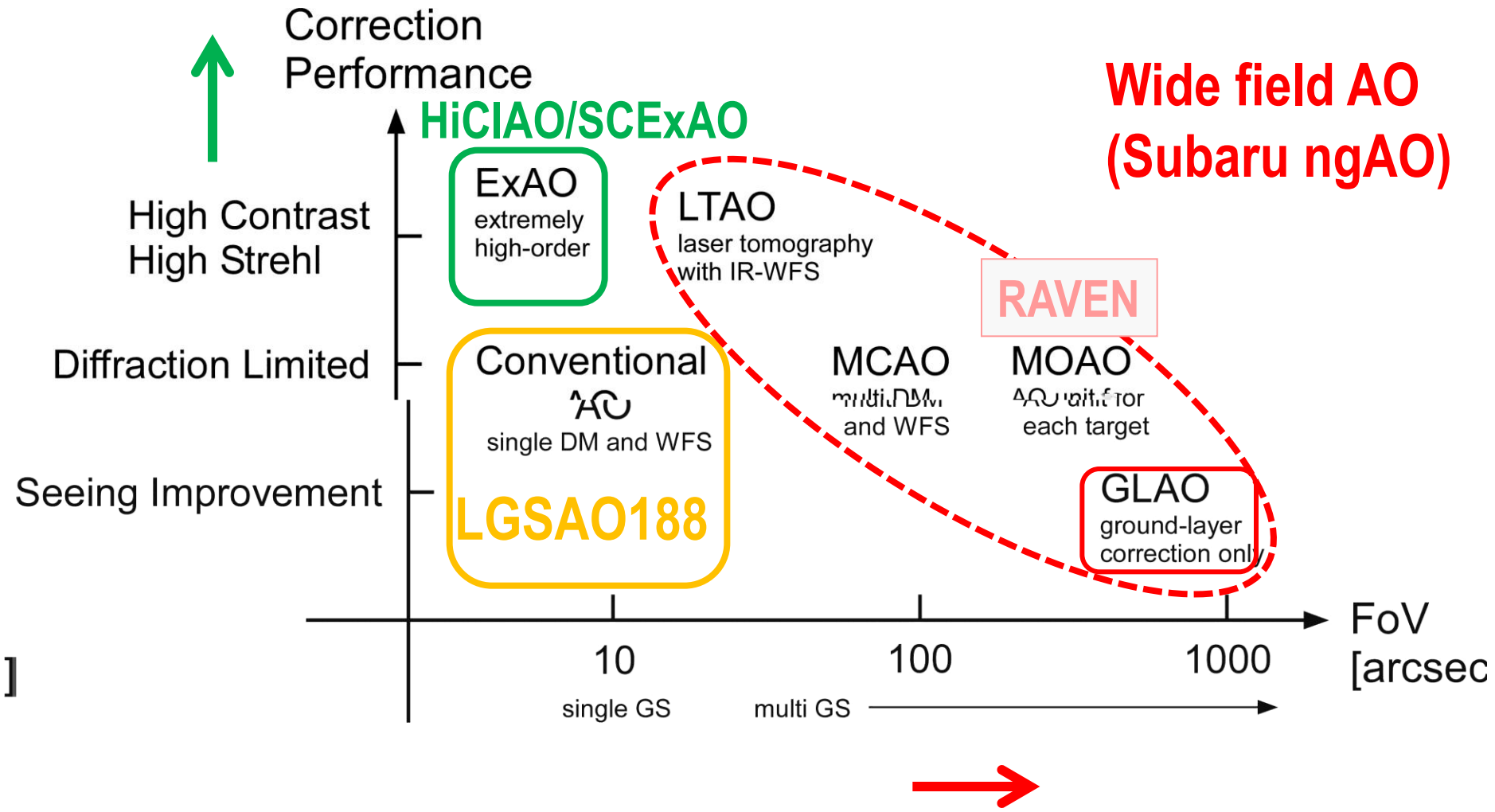
Outline

- What is Ground Layer Adaptive Optics (GLAO)?
  - a type of wide-field AO
  - Mauna Kea seeing (which determines GLAO performance)
- Simulation to evaluate performance
  - Code, seeing model, configuration
  - Correction
    - wavefront error (WFE)
    - profile (moffat FWHM; ensquared energy)
    - wavelength dependency
  - Field-of-View
    - mechanical limit: Cs 8.6'ϕ ⇒ 20' ϕ w/o ADC (cf. Ns 4'ϕ)
    - constraint from performance?
- Adaptive Secondary Mirror (ASM) application

AO types

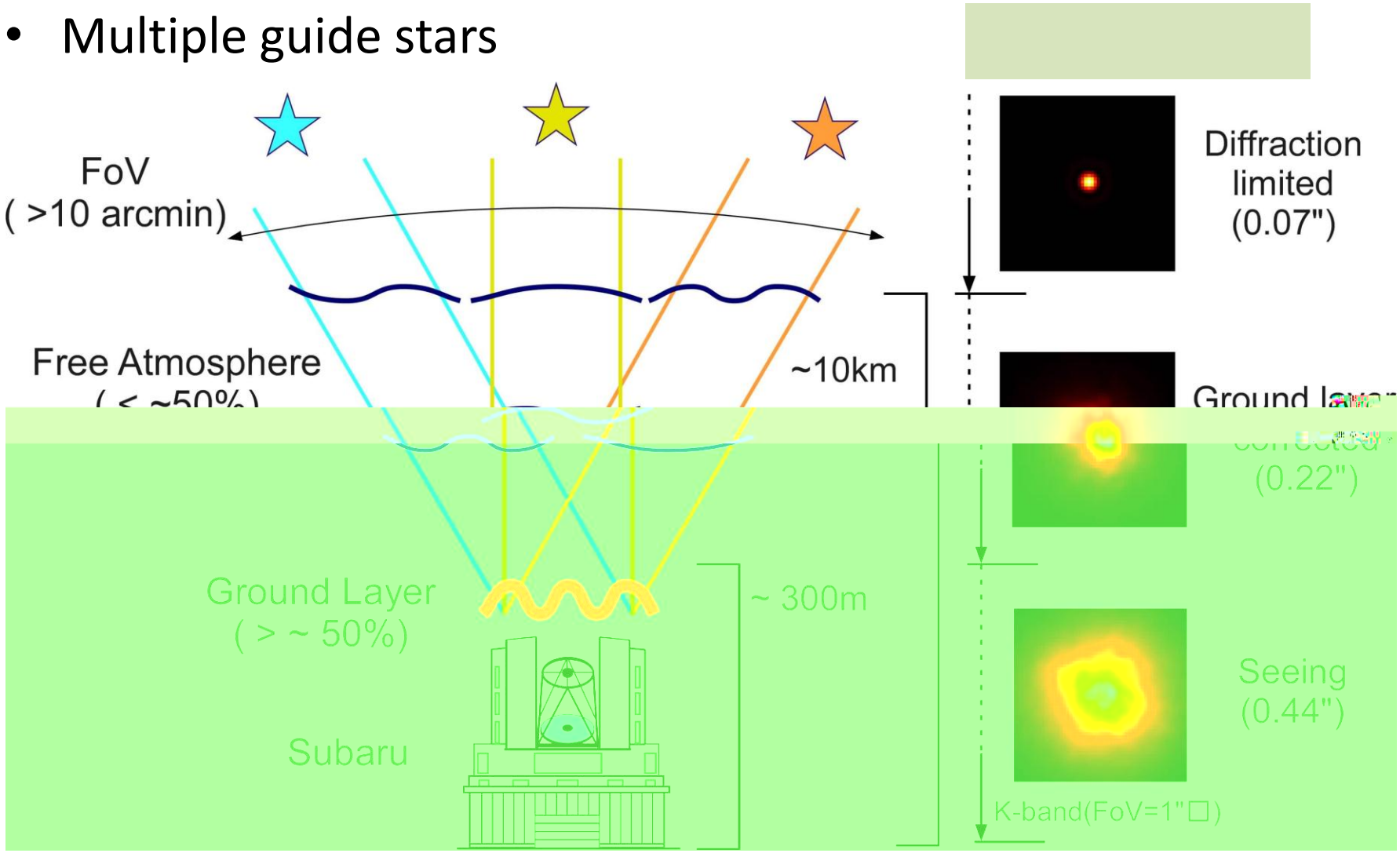

Correction
Performance
High Contrast
High Strehl
Diffraction Limited
Seeing Improvement
HiCIAO/SCExAO
ExAO
extremely
high-order
Conventional
AO
single DM and WFS
LGSAO188
LTAO
laser tomography
with IR-WFS
MCAO
multi DM
and WFS
MOAO
AO unit for
each target
RAVEN
GLAO
ground-layer
correction only
Wide field AO
(Subaru ngAO)
10
100
1000
FoV
[arcsec
single GS
multi GS

What is GLAO?

Wide-field AO (incl. GLAO) needs

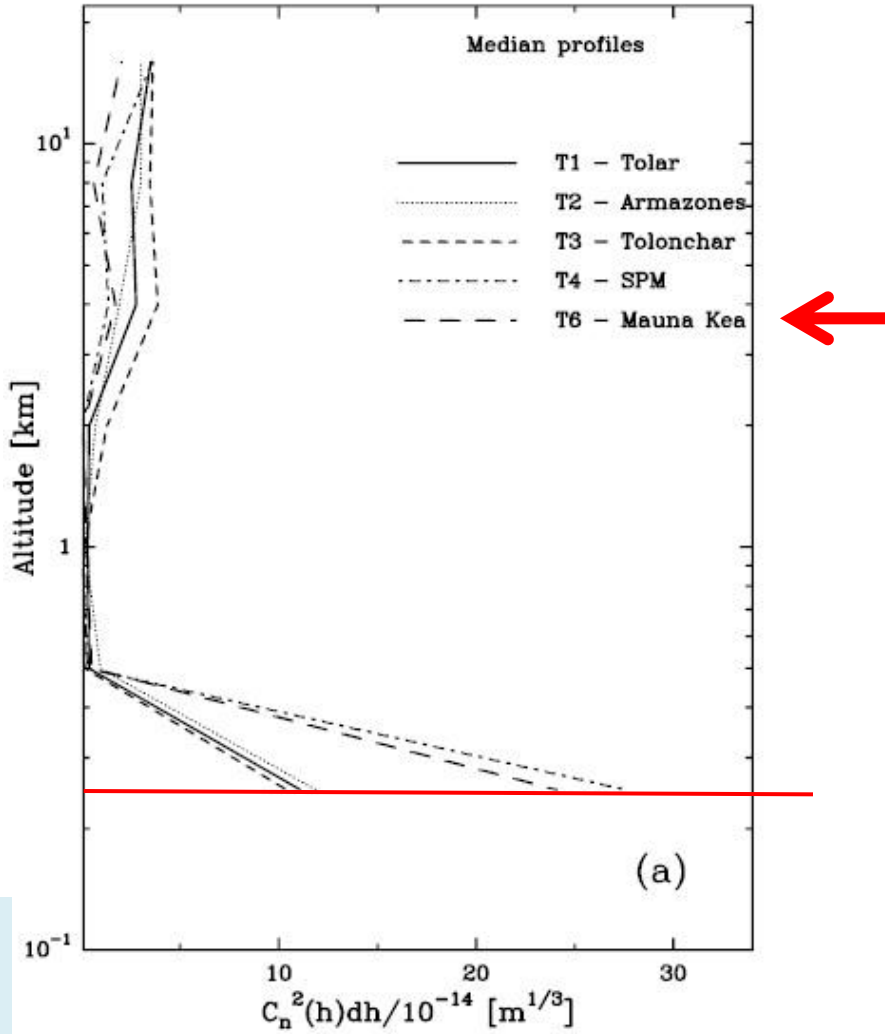
Tomography

- Considering 3D structure of atmospheric turbulence
- Multiple guide stars



Mauna Kea seeing: overall profile

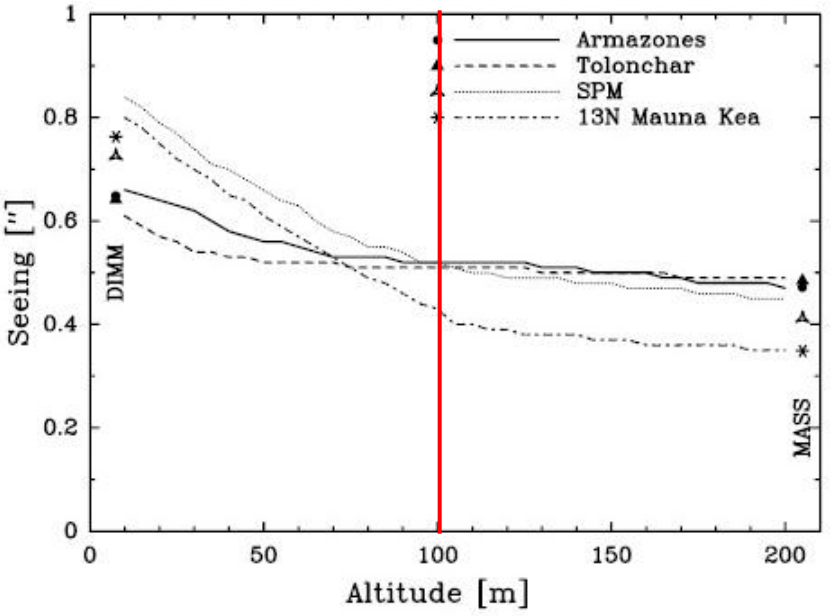
- Free atmosphere turbulence: weak
- Ground layer turbulence: strong



Mauna Kea Seeing: ground layer

– Concentrated close to the surface

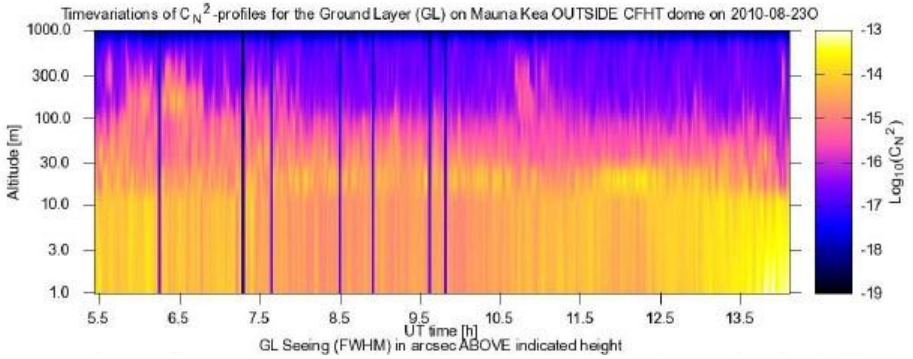
Altitude (m)	25 percentile	50 percentile	75 percentile
0.0	8.06E-14	1.04E-13	1.40E-13
15.0	3.31E-14	5.32E-14	8.56E-14
30.0	1.60E-15	1.41E-14	2.10E-14
45.0	0.00	6.34E-16	1.03E-14
80–160	5.20E-16	7.27E-15	2.43E-14
160–240	0.0	3.51E-15	1.01E-14
240–320	0.0	2.91E-15	9.01E-15
320–400	0.0	1.87E-15	6.91E-15
400–480	0.0	4.10E-16	4.97E-15
480–560	0.0	0.0	1.67E-15
560–640	0.0	0.0	0.0
FA	2.46e-13	1.57e-13	9.37e-14

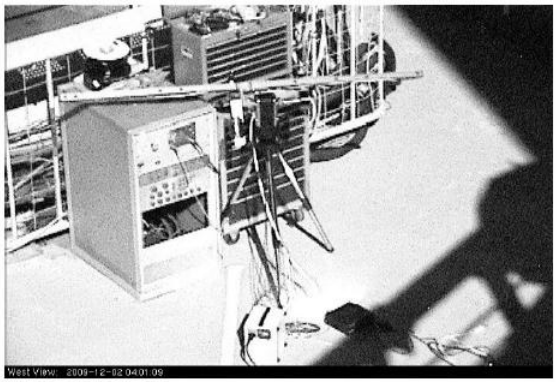


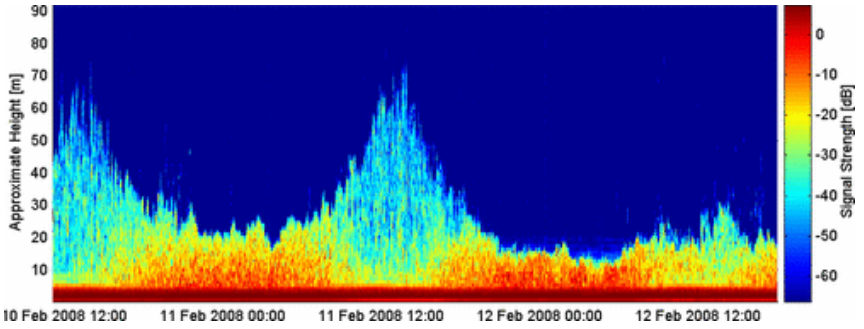
Seeing measurement plan at Subaru

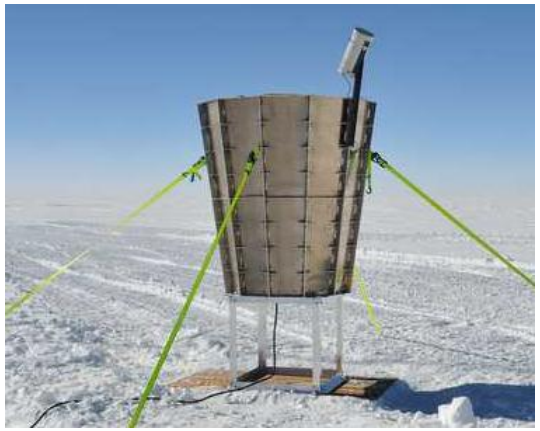
Local ground-layer at Subaru?

- 70m below and leeward of the ridge (laminar flow?)
- fine resolution data for more detailed simulation









Comparison of simulation codes

Comparison with Gemini GLAO simulation (Appendix F1)
validation of MAOS configuration: compared with other
check influence of gray-zone: same seeing (0.6" @ 0.5um), but different height (300m, 500m, 900m) and strength of gray-zone

MAOS additional conditions
wind speed: 6.5m/s @ < 1km, 15m/s @ 2km, 30m/s @ 10km (IMAKA model) ; direction: random
DM fitting: 10' square 5 points: (0' ,0'), (+/-5', +/-5')
Gain: 0.3
Noise free

FWHM

Code	Star Pos.	UA code 1	UA code 1	UD code	PAOLA	CIBOLA			(Gauss)	(Moffat)	MAOS		
Profile	[arcmin]	[arcsec]	[arcsec]	[arcsec]	[arcsec]	[arcsec]	ave	std	[arcsec]	[arcsec]	beta	ave	std
Uncorrected		0.359	0.357	0.353	0.349		0.355	0.004	0.347	0.340	3.083	0.344	0.005
low gz													
1	(0.0, 0.0)	0.258	0.224	0.235	0.221	0.220	0.235	0.017	0.215	0.209	1.70	0.212	0.004
1	(2.5, 0.0)	0.254	0.225	0.247	0.227	0.214	0.238	0.014	0.230	0.228	4.17	0.229	0.001
1	(5.0, 0.0)	0.256	0.228	0.252	0.230	0.214	0.242	0.015	0.234	0.227	1.62	0.231	0.005
1	(2.5, 2.5)	0.247	0.224	0.233	0.216	0.219	0.230	0.013	0.235	0.229	2.35	0.232	0.004
1	(5.0, 5.0)	0.263	0.222	0.253	0.235	0.230	0.243	0.018	0.250	0.246	2.66	0.248	0.003
ave		0.256	0.225	0.244	0.226	0.219	0.234		0.233	0.228	2.500	0.230	
std		0.006	0.002	0.009	0.007	0.007		0.015	0.013	0.013	1.031		0.012
medium gz													
2	(0.0, 0.0)	0.290	0.261	0.258	0.257	0.258	0.267	0.016	0.244	0.237	1.90	0.241	0.005
2	(2.5, 0.0)	0.282	0.260	0.263	0.261	0.252	0.267	0.010	0.262	0.259	5.77	0.261	0.002
2	(5.0, 0.0)	0.286	0.261	0.258	0.262	0.249	0.267	0.013	0.261	0.250	1.38	0.256	0.008
2	(2.5, 2.5)	0.282	0.257	0.258	0.251	0.255	0.262	0.014	0.243	0.243	1.80	0.243	0.000
2	(5.0, 5.0)	0.249	0.258	0.271	0.269	0.265	0.262	0.010	0.272	0.263	1.57	0.268	0.006
ave		0.278	0.259	0.262	0.260	0.256	0.263		0.256	0.250	2.484	0.253	
std		0.016	0.002	0.006	0.007	0.006		0.011	0.013	0.011	1.848		0.011
high gz													
3	(0.0, 0.0)	0.350	0.314	0.307	0.309	0.312	0.320	0.020	0.291	0.287	4.34	0.289	0.003
3	(2.5, 0.0)	0.336	0.314	0.310	0.312	0.307	0.318	0.012	0.301	0.300	5.33	0.301	0.001
3	(5.0, 0.0)	0.322	0.307	0.305	0.306	0.294	0.310	0.008	0.326	0.322	4.85	0.324	0.003
3	(2.5, 2.5)	0.334	0.311	0.305	0.304	0.305	0.314	0.014	0.312	0.306	2.97	0.309	0.004
3	(5.0, 5.0)	0.334	0.308	0.303	0.314	0.307	0.315	0.014	0.300	0.283	1.24	0.292	0.012
ave		0.335	0.311	0.306	0.309	0.305	0.313		0.306	0.300	3.746	0.303	
std		0.010	0.003	0.003	0.004	0.007		0.013	0.013	0.016	1.656		0.014

RAVEN seeing model

D. Andersen "RAVEN modeling note: Model Atmosphere"

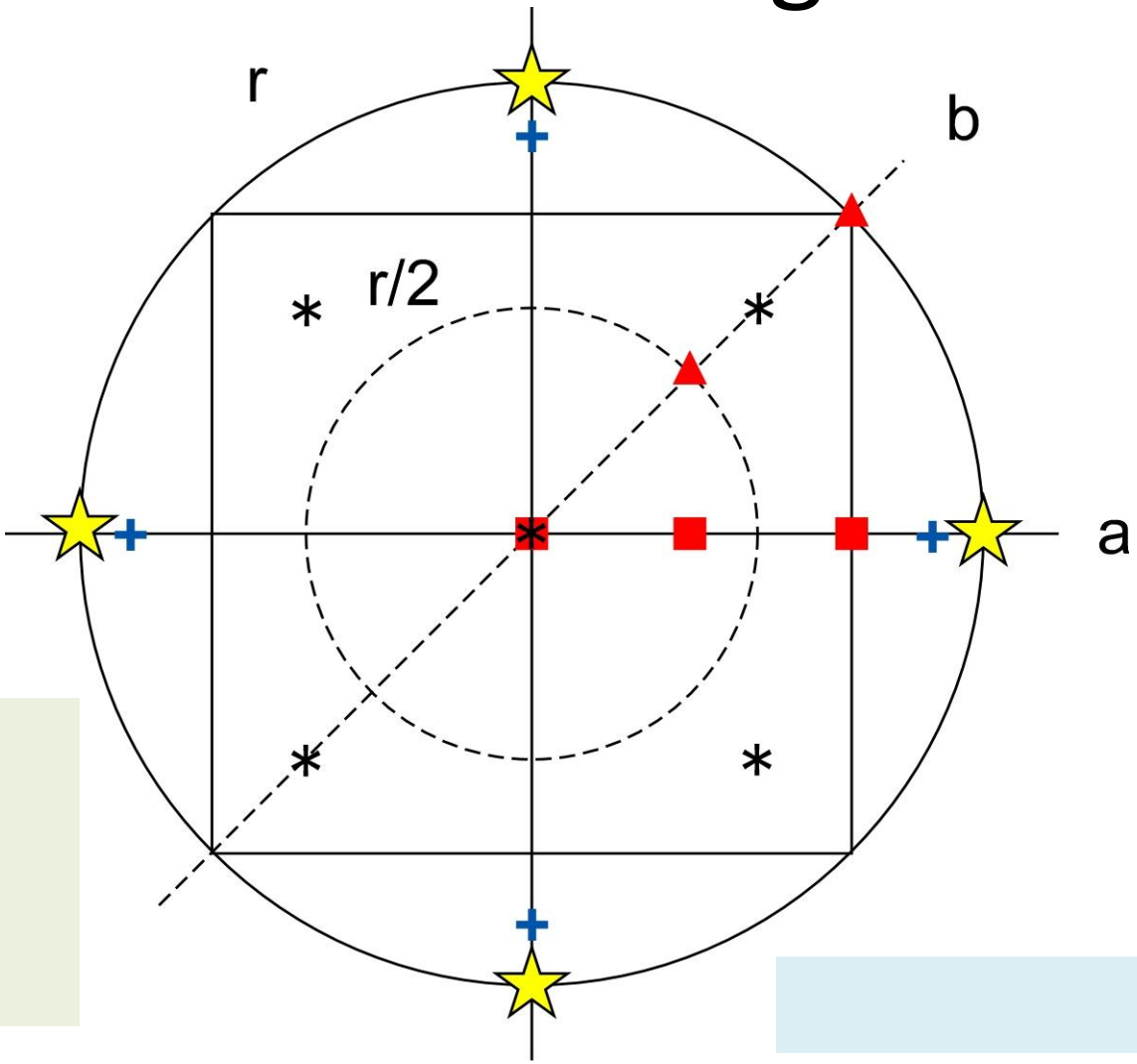
- based on TMT site testing profile at 13N (Els+09,PASP,121,527)

- IQ statistics difference between 13N profile and Subaru is attributed to ground layer

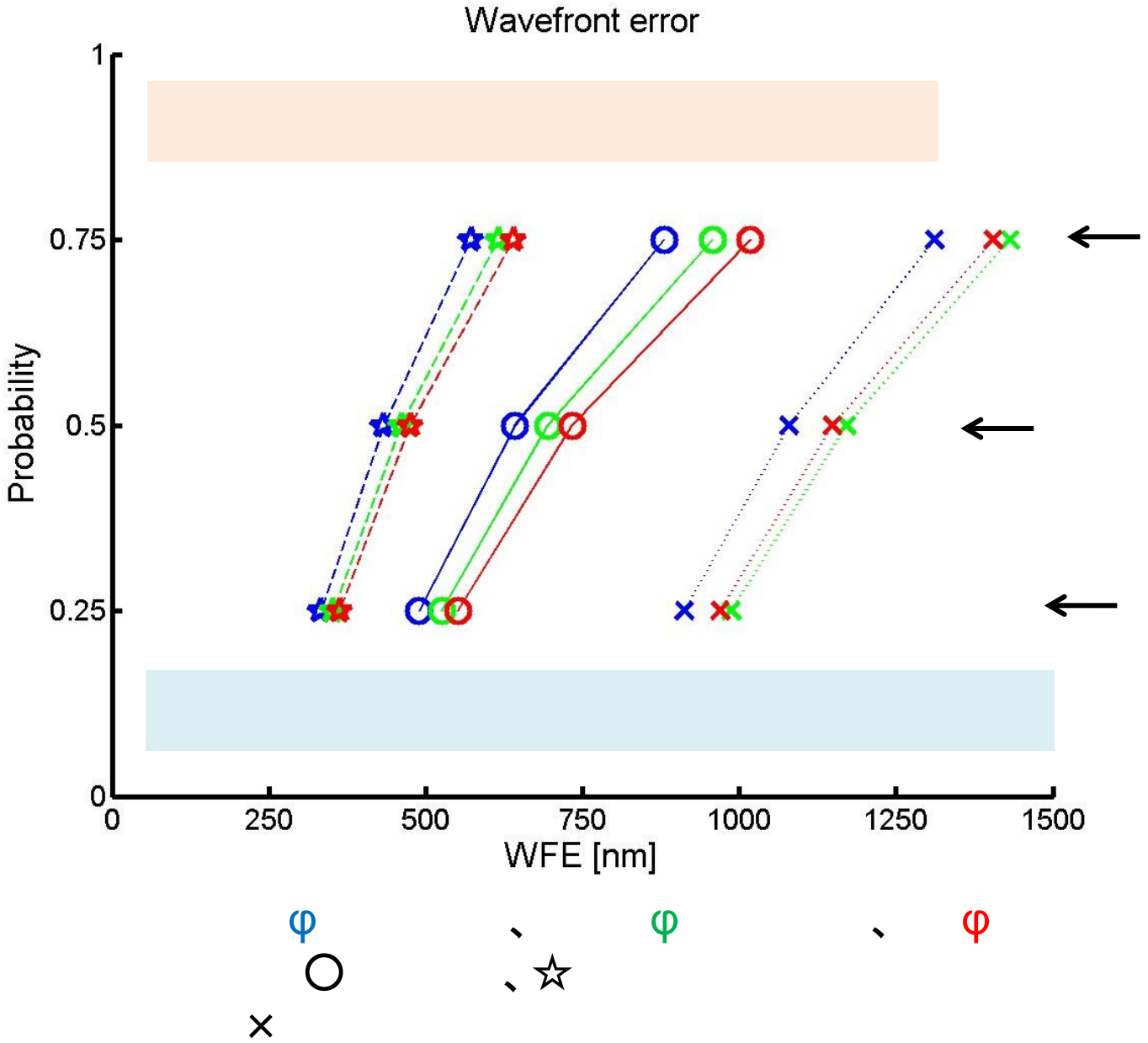
Fractional Layer Strength

h	seeing percentile		
km	25%	50%	75%
r_0	19.4 cm	15.6 cm	12.1 cm
fwhm	0.53"	0.66"	0.85"
0	0.6823	0.5960	0.4971
0.5	0.0611	0.0963	0.1382
1	0.0212	0.0325	0.0577
2	0.0172	0.0372	0.0642
4	0.0757	0.0869	0.0833
8	0.0486	0.0684	0.0895
16	0.0939	0.0826	0.0700

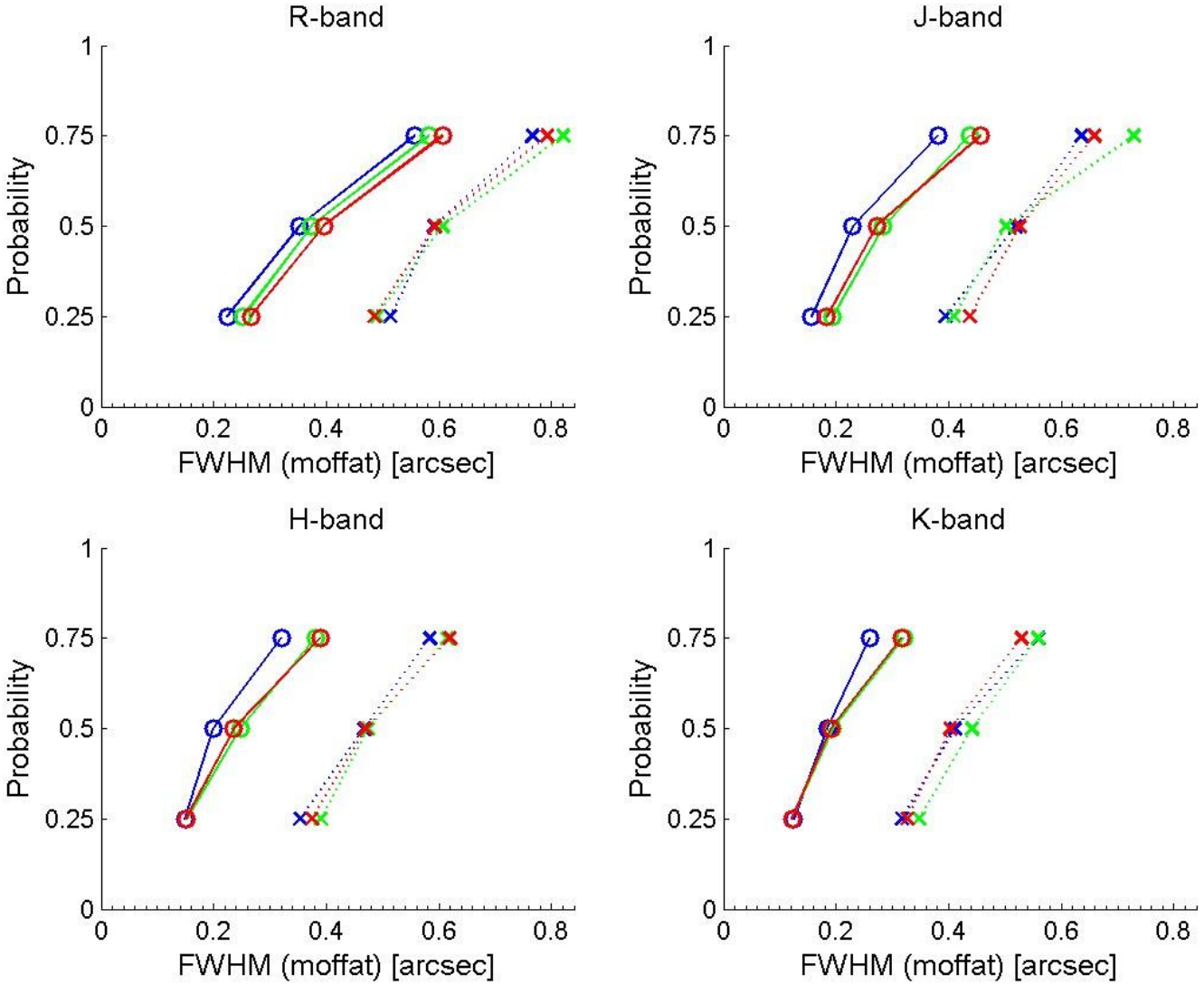
Subaru GLAO configuration



Seeing dependence of WFE



Seeing dependence of FWHM



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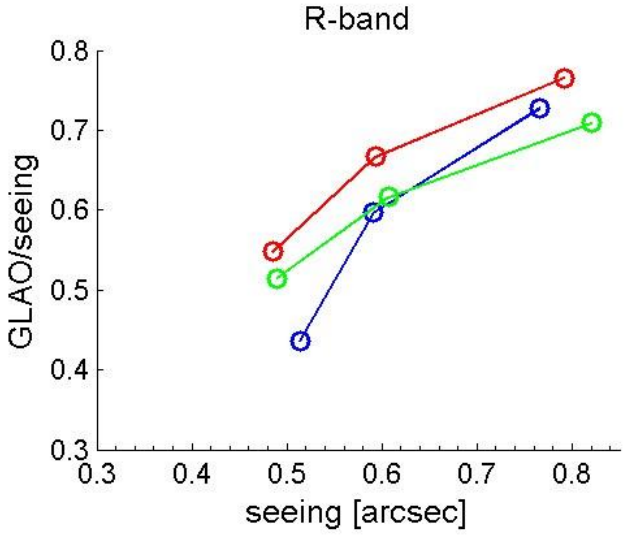
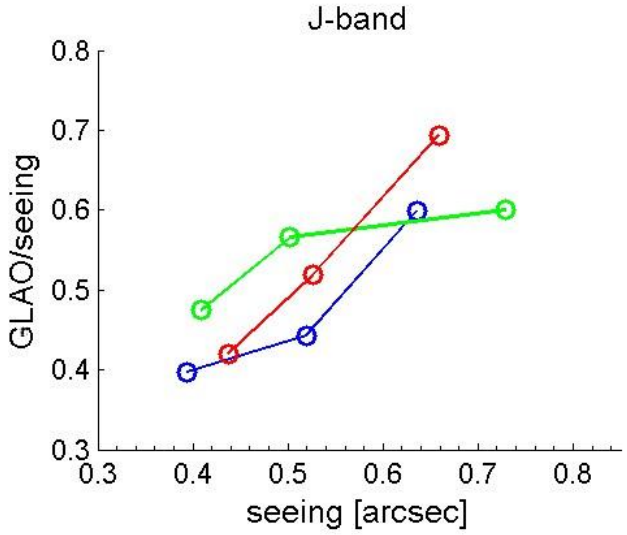
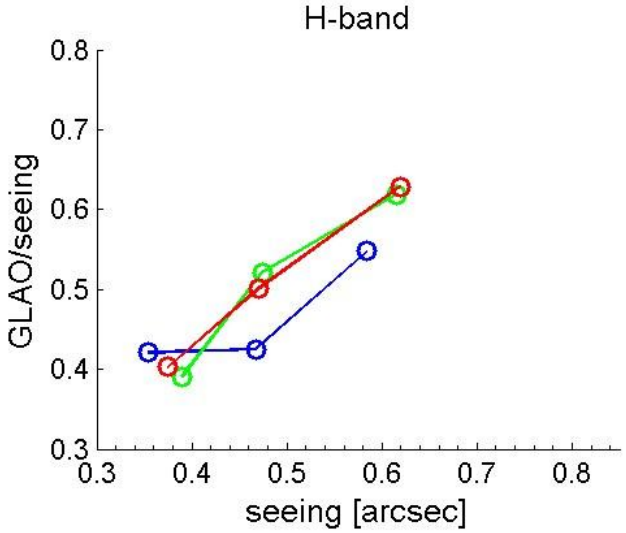
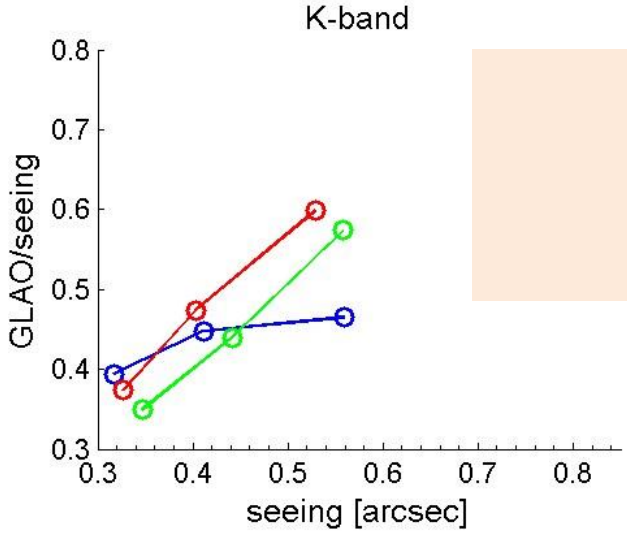
Seeing vs FWHM ratio (GLAO/seeing)



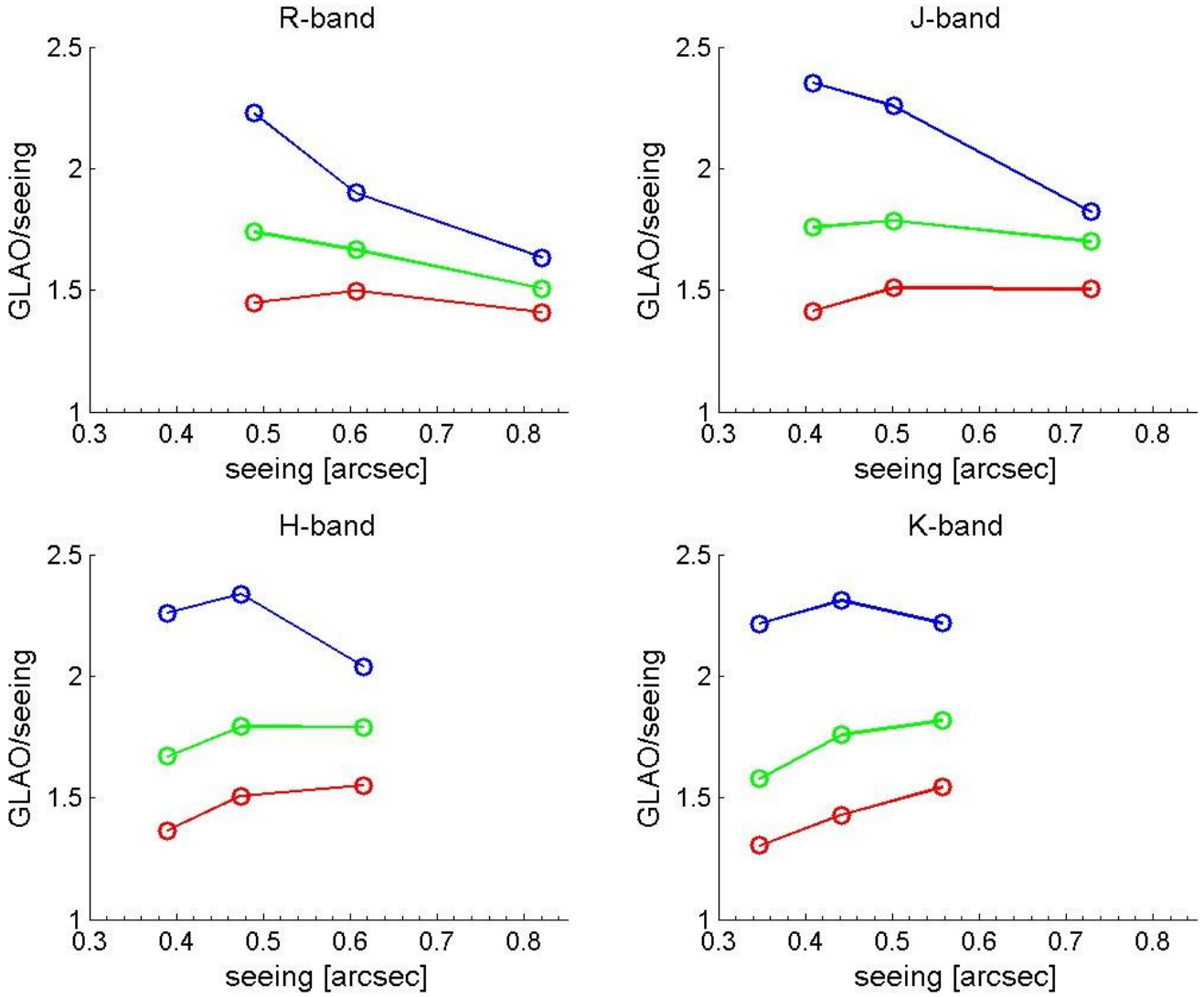






φ 、 φ 、 φ

Seeing vs EsqE ratio (GLAO/Seeing)



Comments on the noise

Seeing: $\sigma^2_{total} = \sigma^2_{atm}{}^{FA} + \sigma^2_{atm}{}^{GL}$

GLAO: $\sigma^2_{WFE} = \sigma^2_{atm}{}^{FA} + (\sigma^2_{sense} + \sigma^2_{fit} + \sigma^2_{delay} + \sigma^2_{etc})$

σ σ

WFE (σ_{WFE}) increase

- limit mag (σ_{sensor}): 8% by R=18 (TTF, 10mag LGS), RN limit
- HoWFS order (σ_{fit}): ~0% by 8x8 R=15 ⇔ 32x32 R=13
- frame rate (σ_{delay}): 8% by 200Hz ⇒ 50Hz (gain=0.5)

Bright NGS vs Typical LGS

typical case: moderate seeing (0.66"), FoV 15'ϕ

WFE [nm]: Tot: 1274±325, TT: 955±395, Ho: 802±129

- NGS sensor noise free (R=10)

  WFE [nm]: Tot: 737±95, TT: 515±122, Ho: 519±47

- LGS R=10, NGS(TTF) R=18mag

  WFE [nm]: Tot: 783±127, TT: 578±161, Ho: 517±47

WFS parameters: SH, 200Hz, gain=0.3, RN=0.1e-, 512x512pix

Possible observation modes by ASM

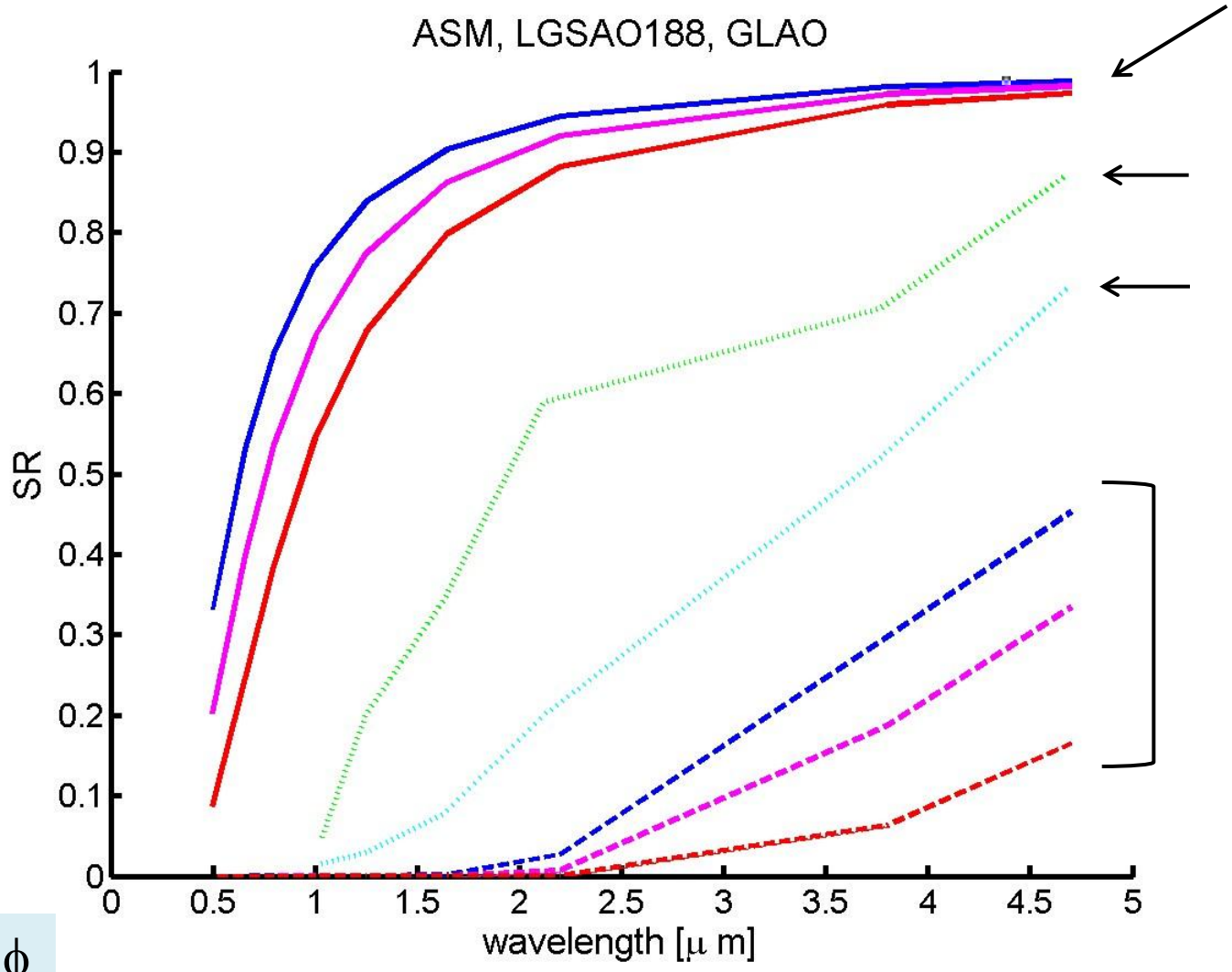
1. GLAO @ Cs
   - seeing improvement over wide FoV

2. On-Source Single NGS @ Cs, Ns
   - high SR for bright on-source NGS
   - reduction of thermal background at $\lambda > 2\mu m$

3. Single Conjugate Laser Tomography (SCLT) @ Cs,Ns
   - better SR than on-source single LGS
   - as close to on-source single NGS as possible

- Multi-Conjugate Laser Tomography (MCLT)?
  - to increase FoV > 1 arcmin

14. On-source bright NGS



ϕ

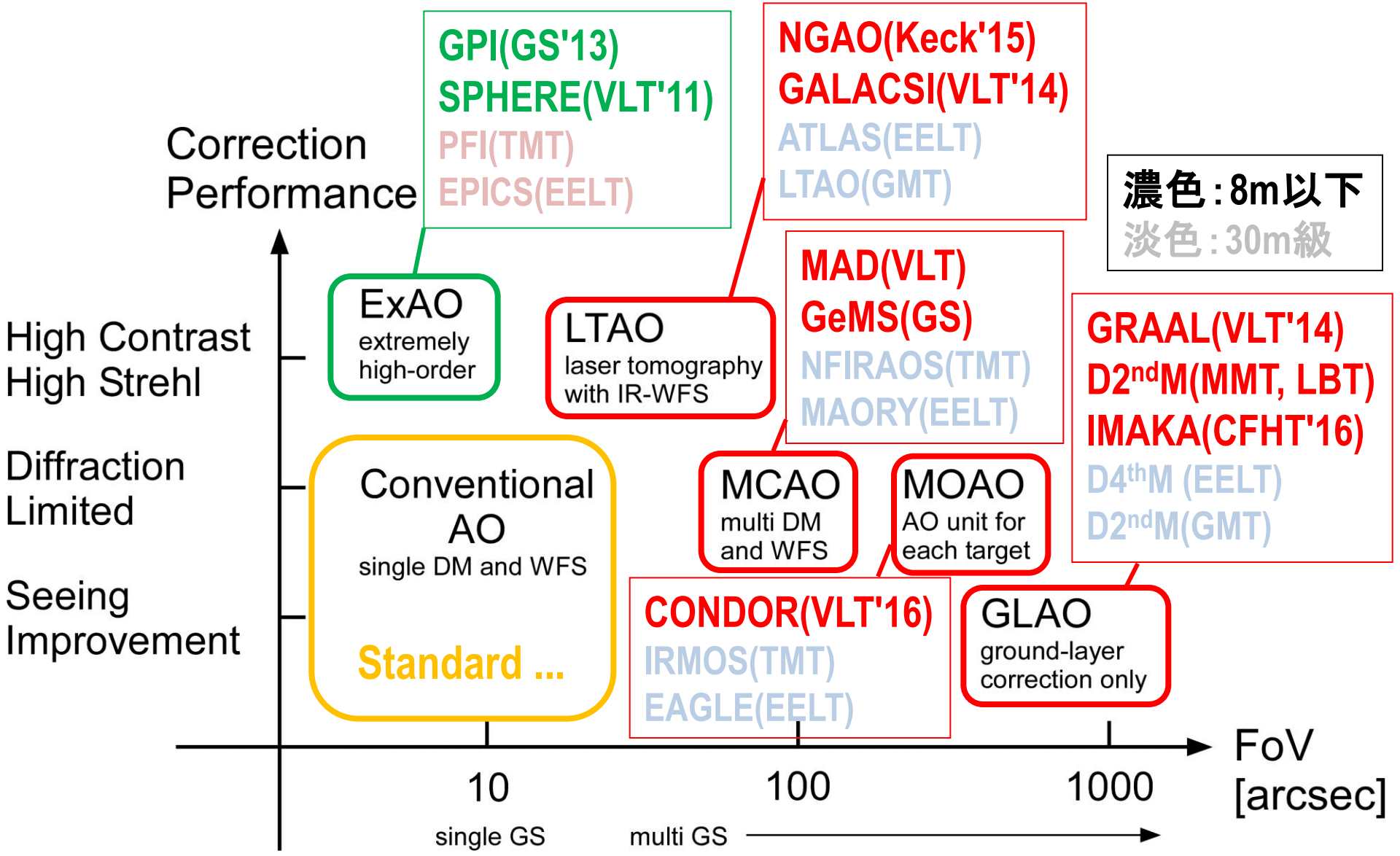
μ

Summary

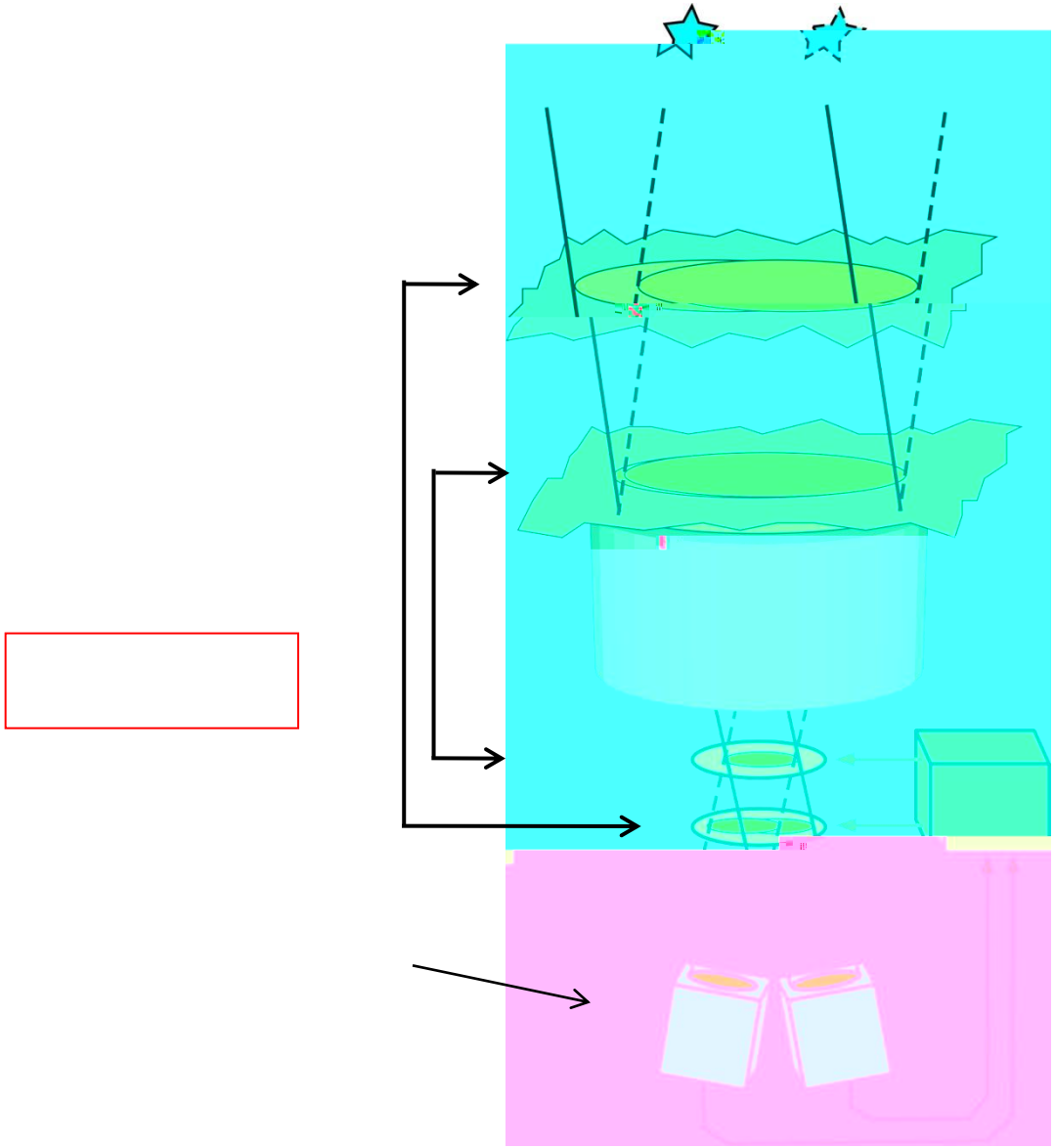
- GLAO: Ground Layer Adaptive Optics
  - a wide-field AO correcting ground-layer turbulence only
  - Mauna Kea seeing is suitable for GLAO
- Expected performance of GLAO by MAOS simulation
  - Seeing model: TMT (13N) + GL to match Subaru IQ statistics
  - Parameters: 32 elem, 4GS (NGS or LGS+TTF), 200Hz, 0.1e-RN
  - Correction
    - FOV: 15' Φ, FWHM < 0.2" @ K-band: 50%ile;0.65"@0.5μm
  - Field-of-View
    - mechanical vignetting by the telescope & optical design of the instrument limit FoV (not GLAO performance)
- Other possible observation modes by ASM
  - On-source bright NGS
    - FOV: 1' Φ, SR ~ 0.9 @ K-band : 50%ile;0.65"@0.5μm
  - Laser tomography
    - single conjugate (ASM only), multi conjugate (in future?)

Appendix

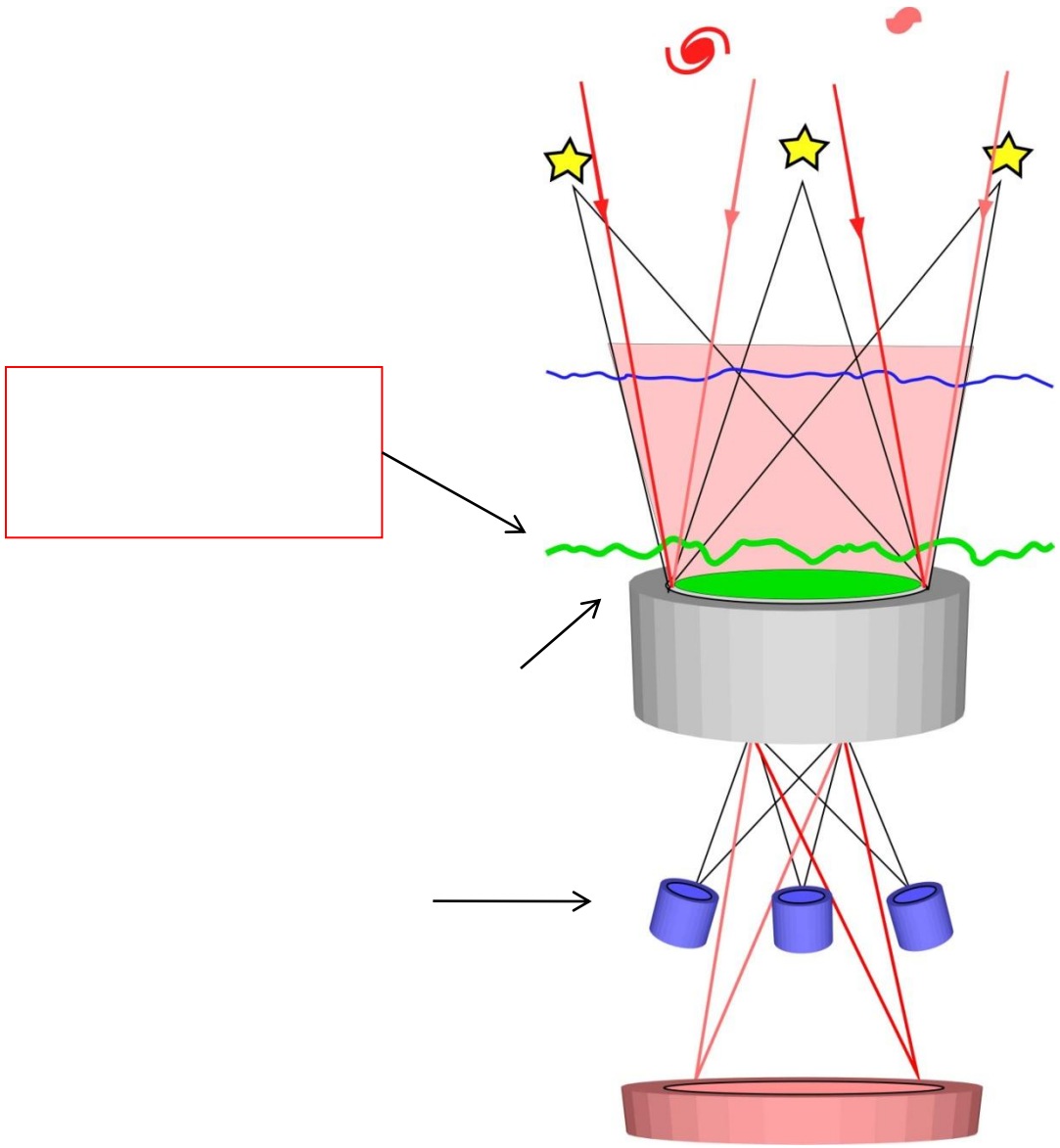
世界のAOの分布


GPI(GS'13)
SPHERE(VLT'11)
PFI(TMT)
EPICS(EELT)
NGAO(Keck'15)
GALACSI(VLT'14)
ATLAS(EELT)
LTAO(GMT)
濃色：8m以下
淡色：30m級
Correction Performance
High Contrast High Strehl
Diffraction Limited
Seeing Improvement
ExAO
extremely high-order
LTAO
laser tomography with IR-WFS
MAD(VLT)
GeMS(GS)
NFIRAOS(TMT)
MAORY(EELT)
GRAAL(VLT'14)
D2ndM(MMT, LBT)
IMAKA(CFHT'16)
D4thM (EELT)
D2ndM(GMT)
Conventional AO
single DM and WFS
Standard ...
MCAO
multi DM and WFS
MOAO
AO unit for each target
CONDOR(VLT'16)
IRMOS(TMT)
EAGLE(EELT)
GLAO
ground-layer correction only
10
100
1000
FoV [arcsec]
single GS
multi GS

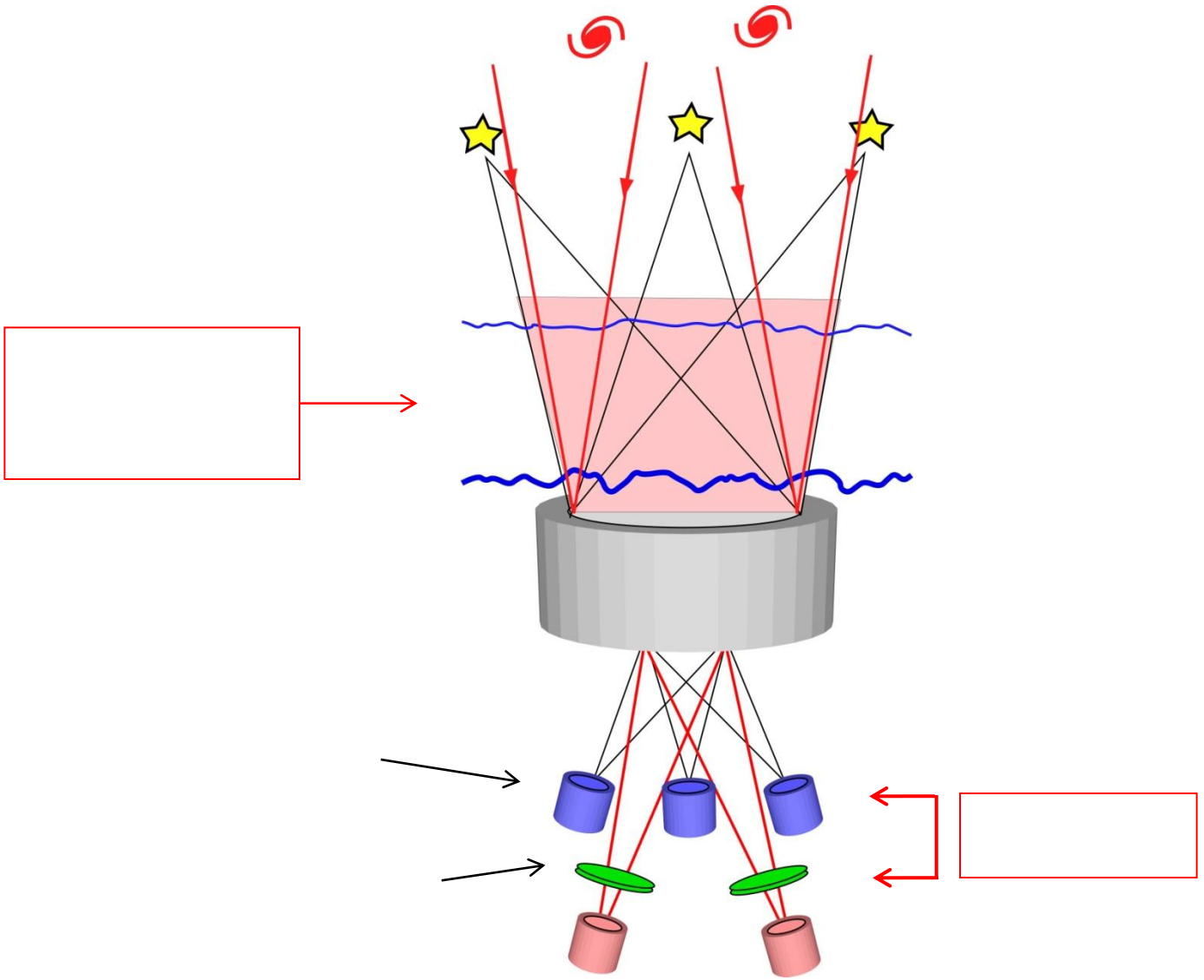
広視野AO: MCAO



広視野: GLAO

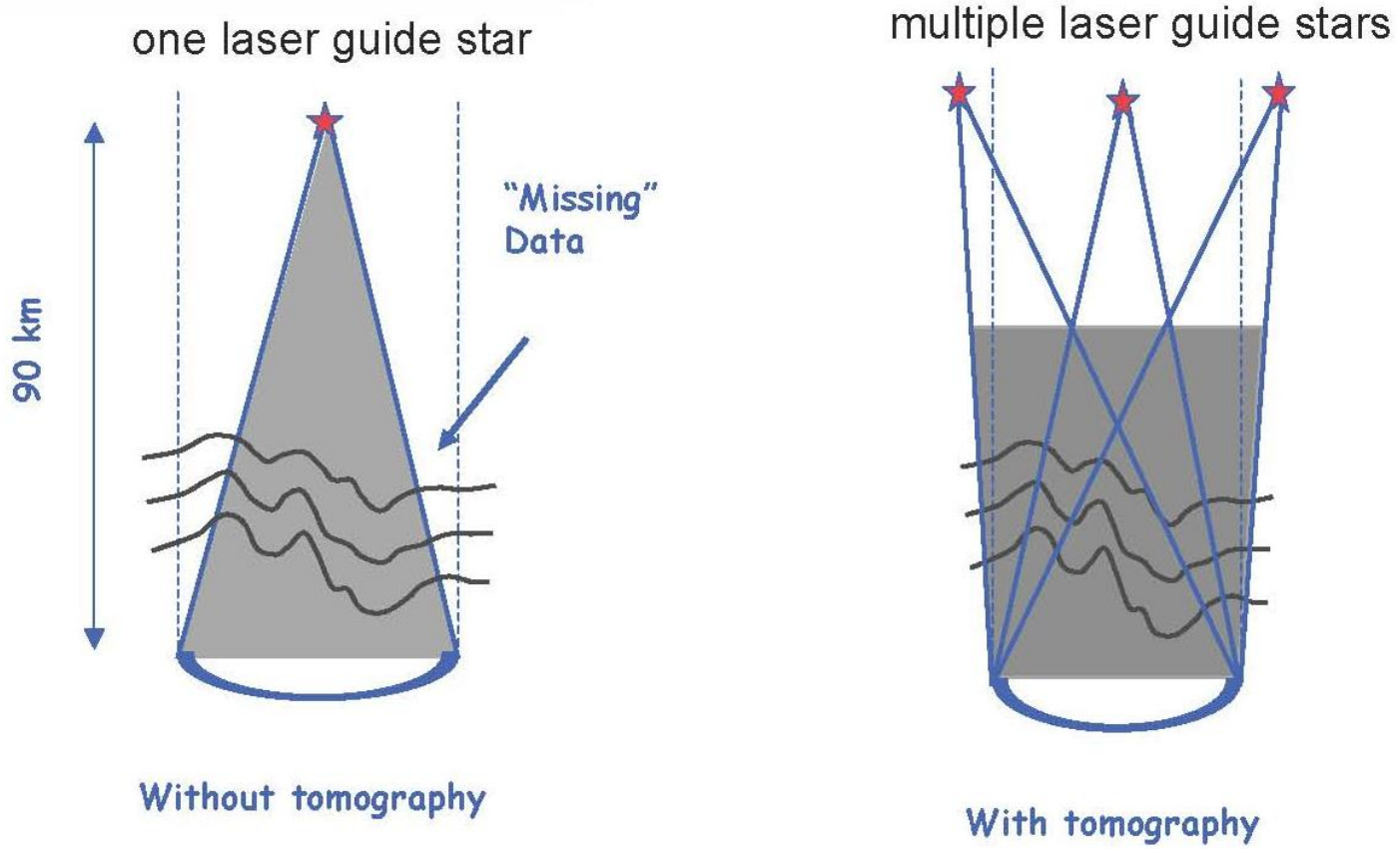


広視野AO: MOAO



LGSコーン効果の低減: LTAO

AO tomography: measure turbulence and correct for “cone effect”

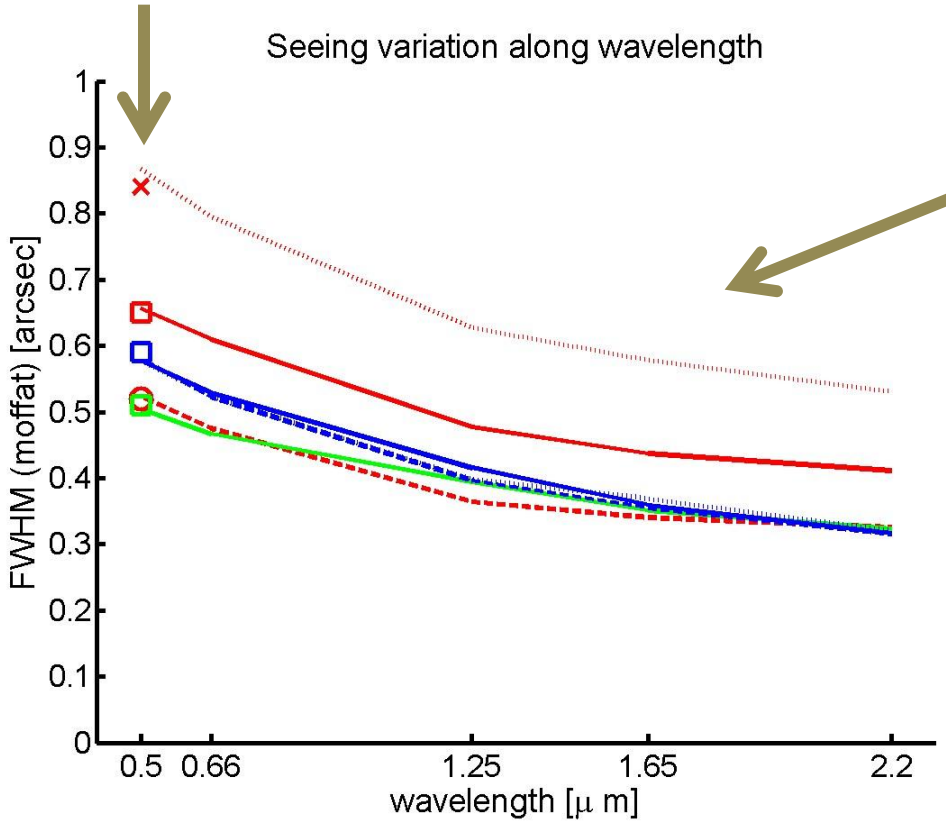


With AO tomography, measure 3D distribution of turbulence above telescope

Credit: ESO web page

3. Seeing simulation

μ



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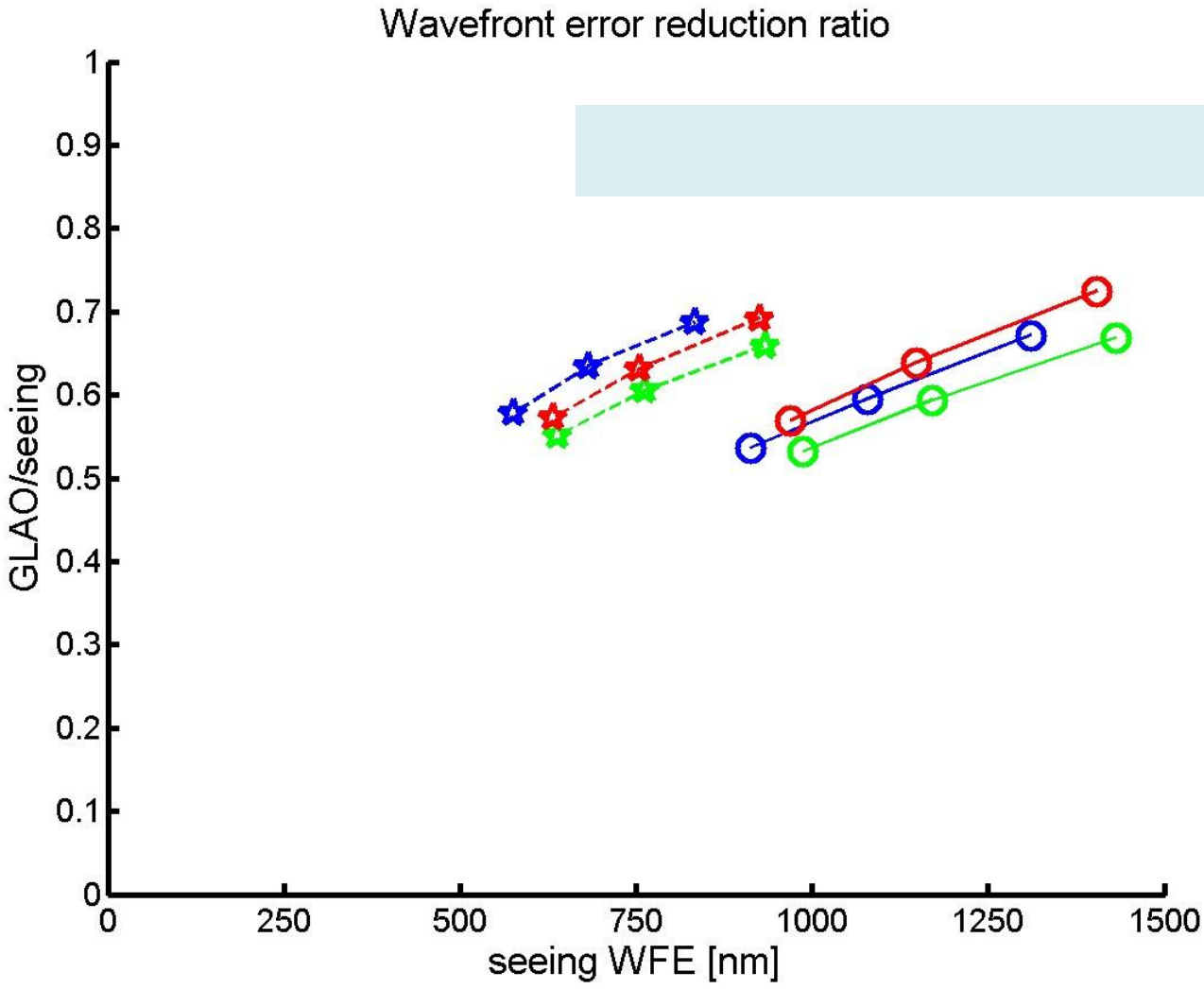
8. Seeing WFE vs WFE ratio (GLAO/Seeing)



φ 、 φ 、 φ

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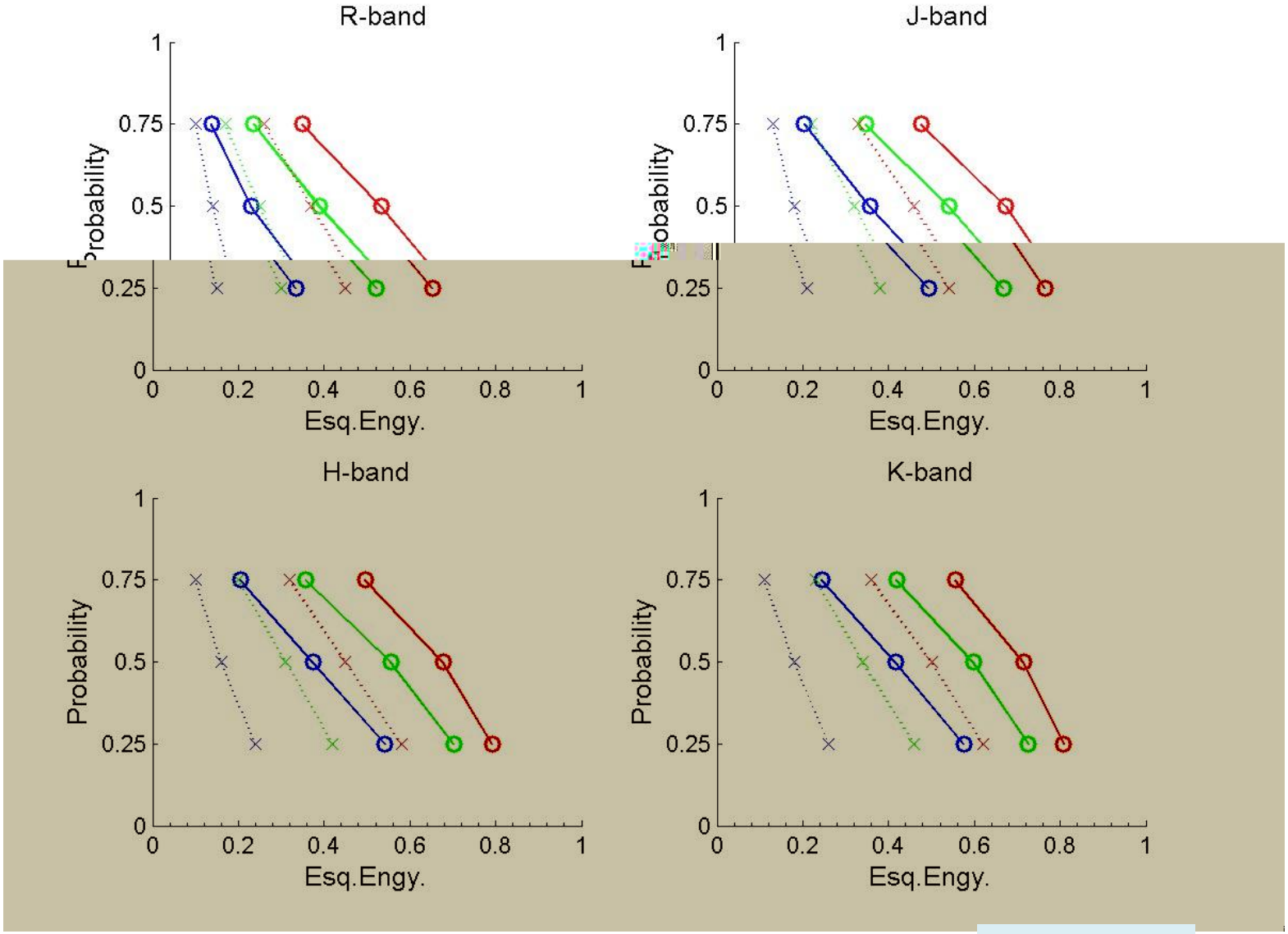
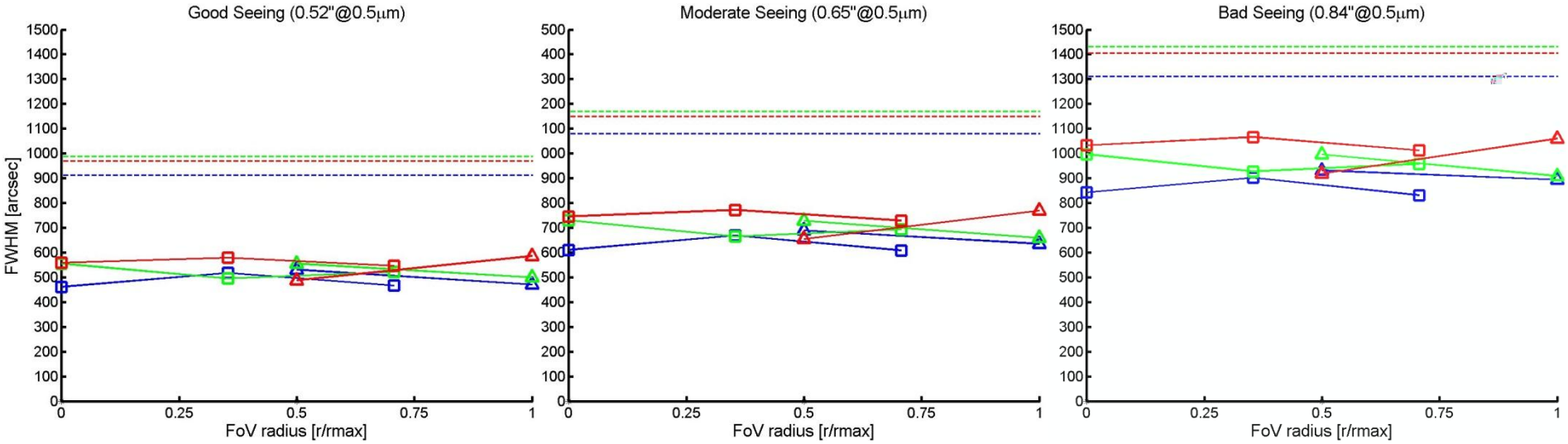
7. Seeing dependence of EsqE



ϕ

11. Field dependence of WFE



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□ 、△

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12. Dependence on the system order

ϕ