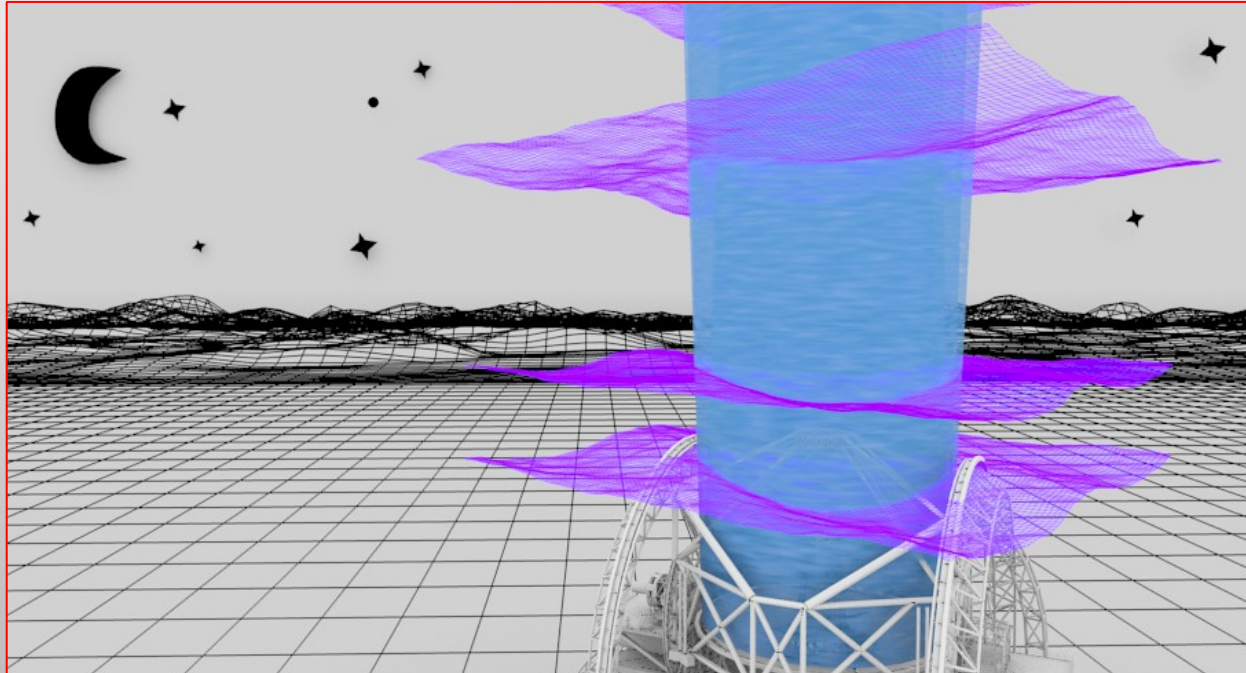


# Natural Guide Stars (NGS) only for Adaptive Optics (AO) on ELT



*Ismaning - Feb 28th 2013*

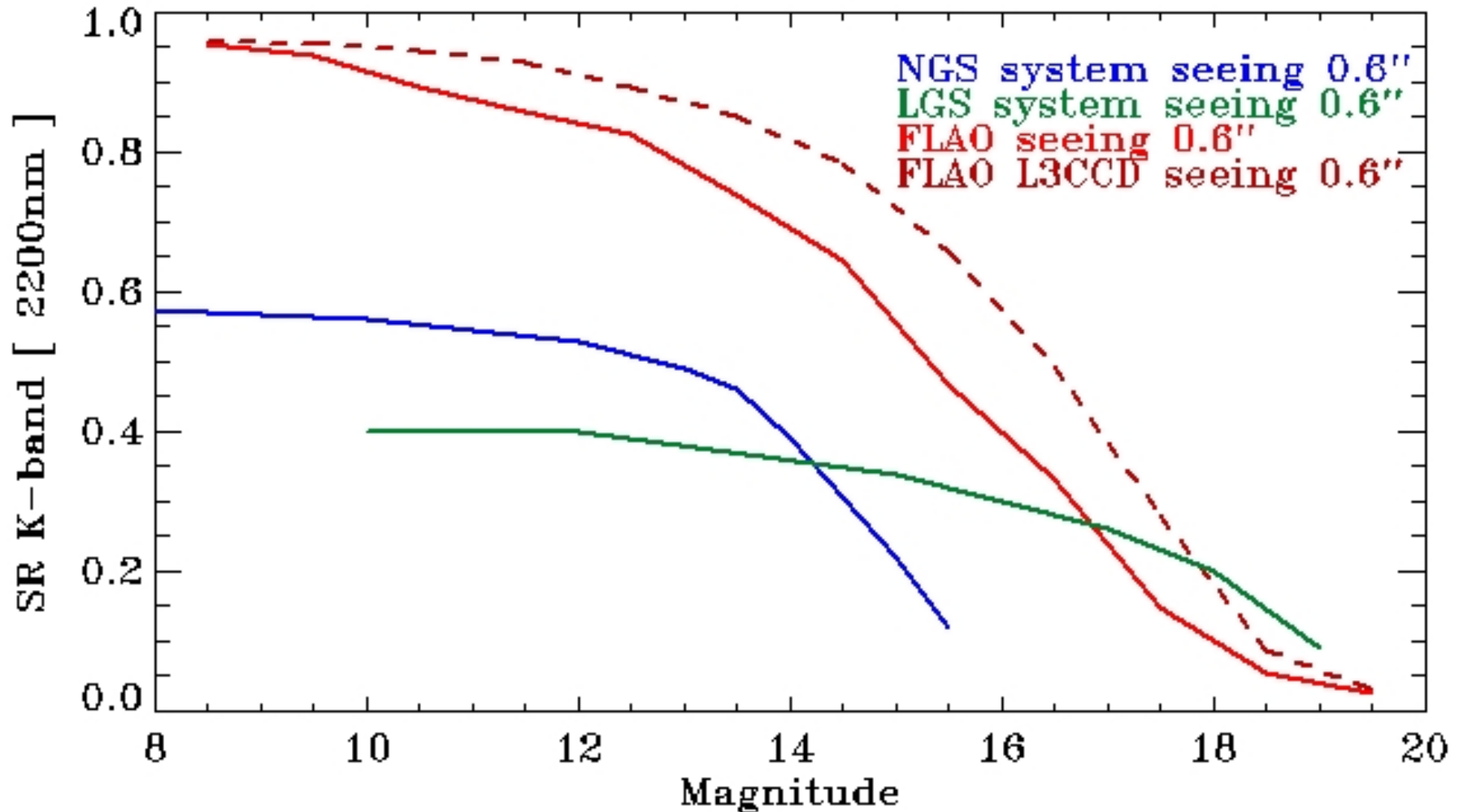
by R. Ragazzoni, C. Arcidiacono, M. Bergomi, M. Dima,  
J. Farinato, D. Magrin, L. Marafatto, V. Viotto

# Why NGSs for AO on ELT...?

- Because are cheaper than LGSs
- Because lim mag of Pyramid WFS pushed the limits of AO...
- Because the patrol field of E-ELT is huge
- Because the rays from LGSs will arrive nevertheless from a similarly skewed angle
- Because NGSs are less invasive then LGS
- Because MCAO can be extended a little into Global MCAO and making this true...

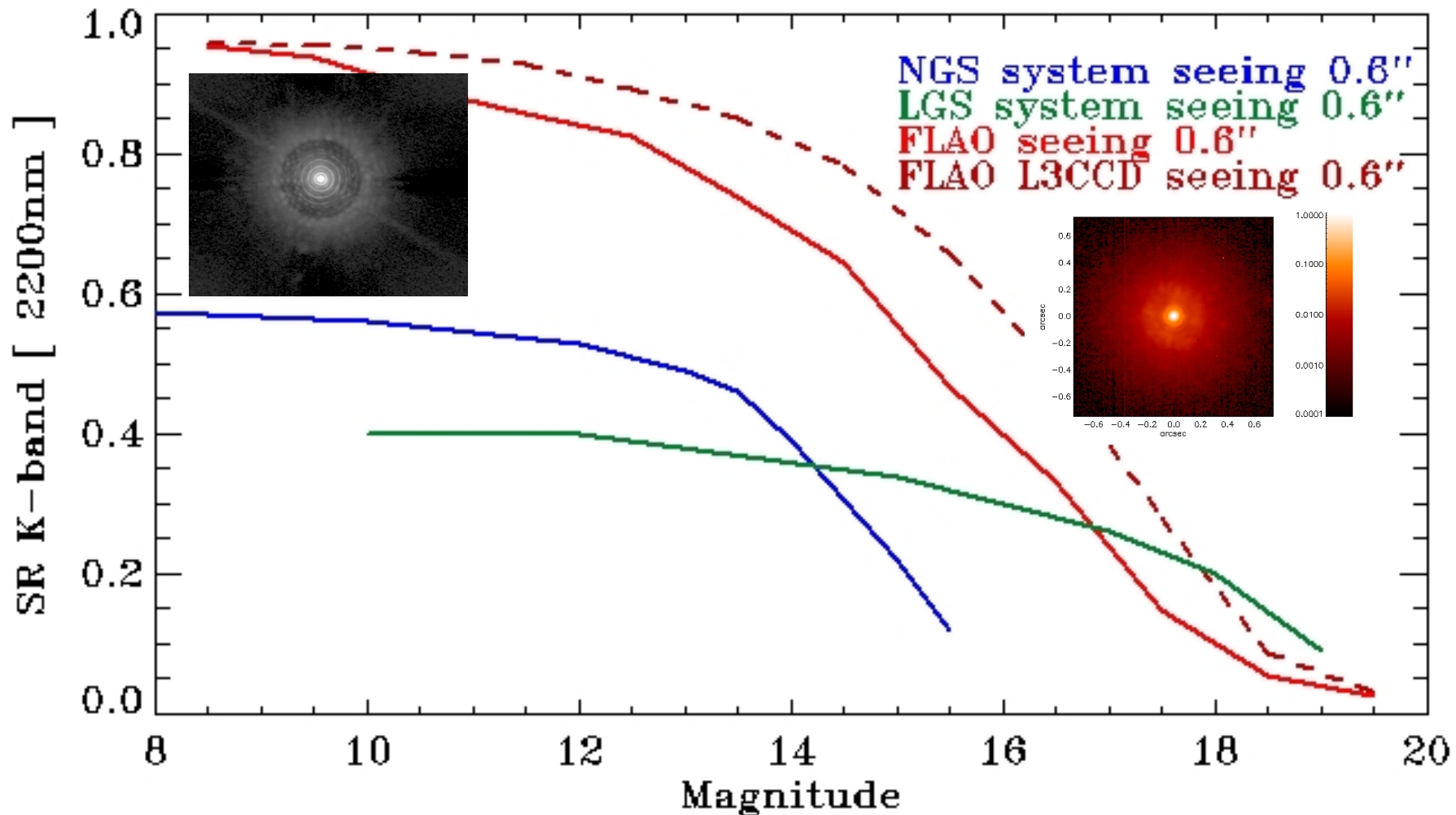
Courtesy S. Esposito - Based upon real LBT data

$L_0 = 40m$



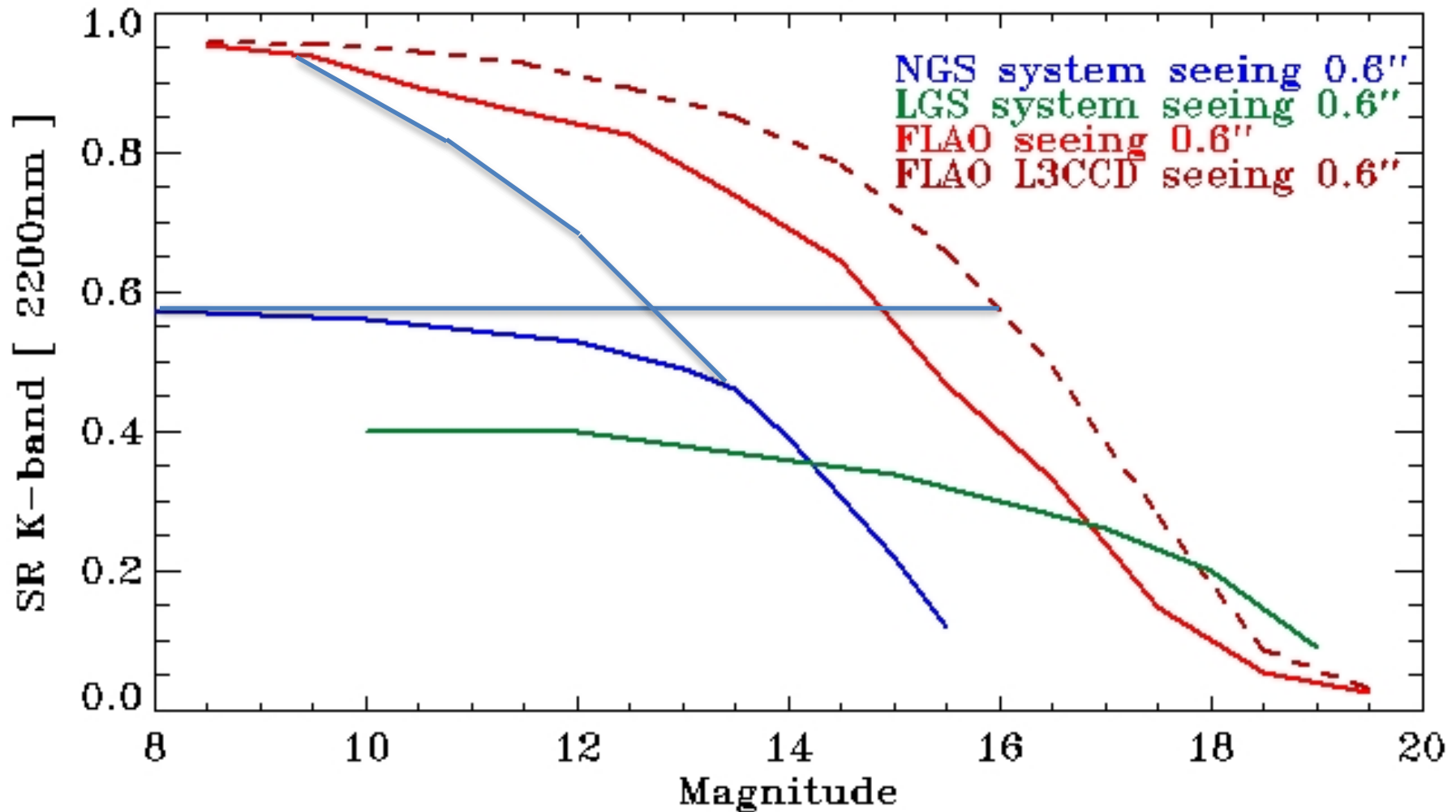
Courtesy S. Esposito - Based upon real LBT data

$L_0 = 40m$



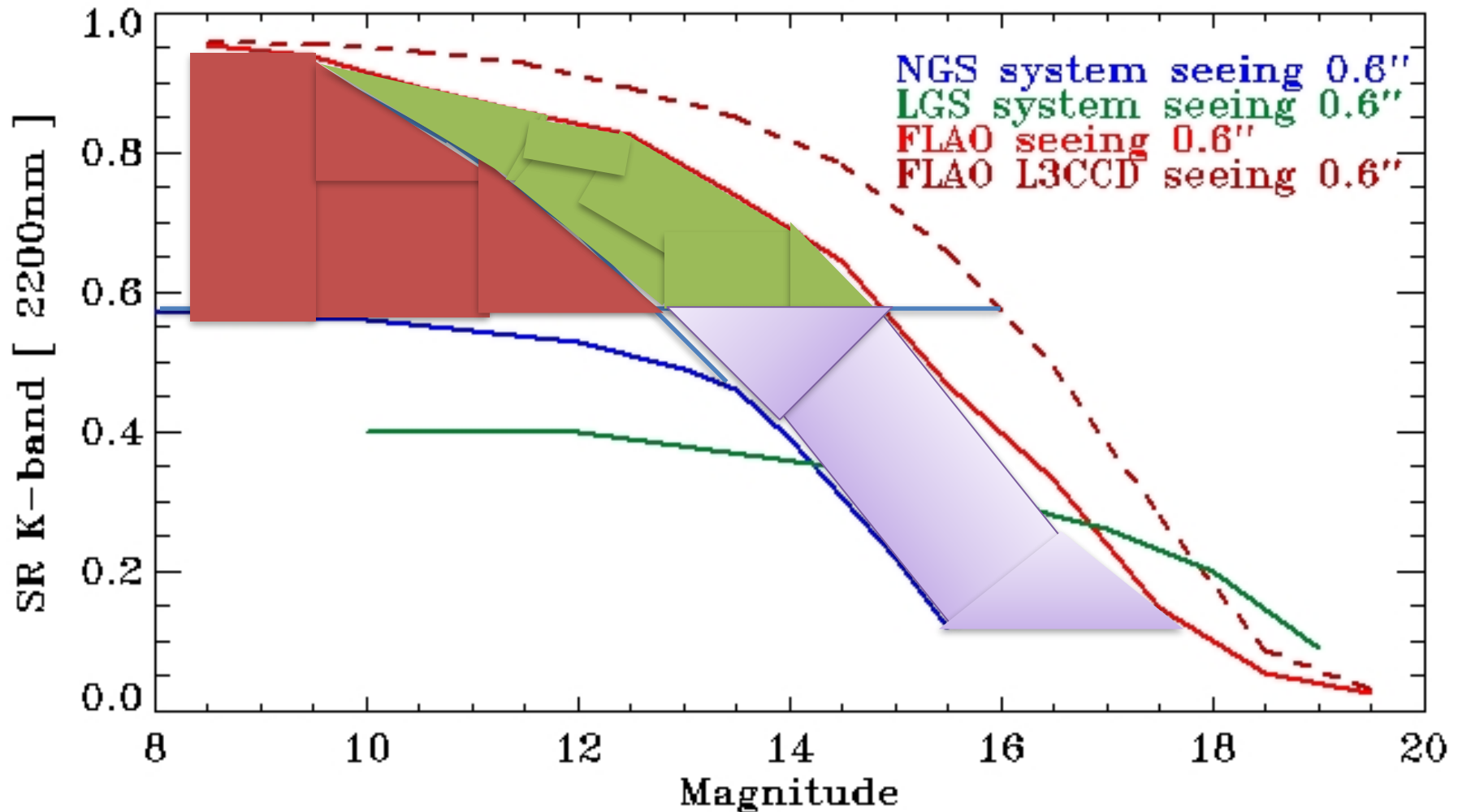
Courtesy S. Esposito - Based upon real LBT data

$L_0 = 40m$



Courtesy S. Esposito - Based upon real LBT data

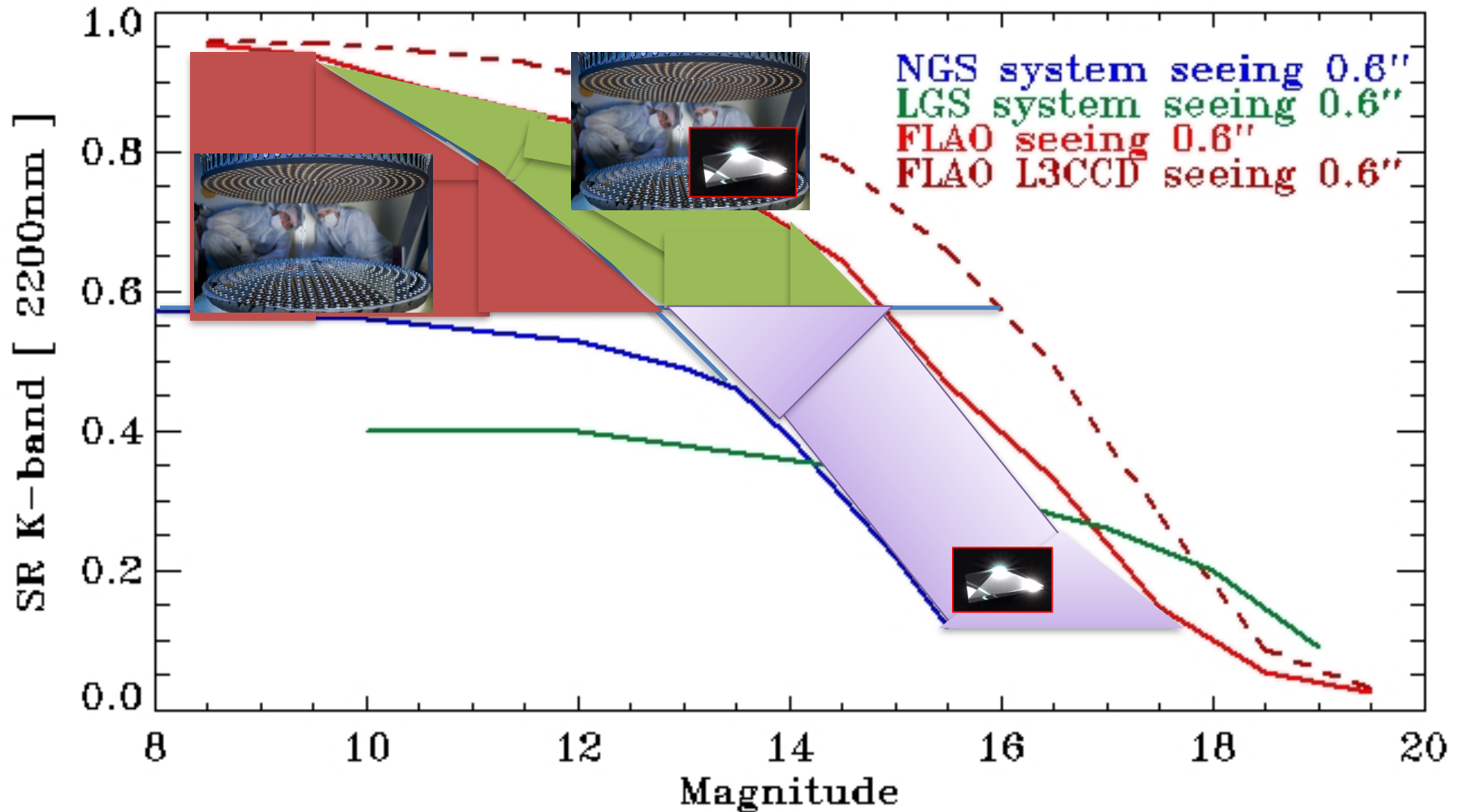
$L_0 = 40m$





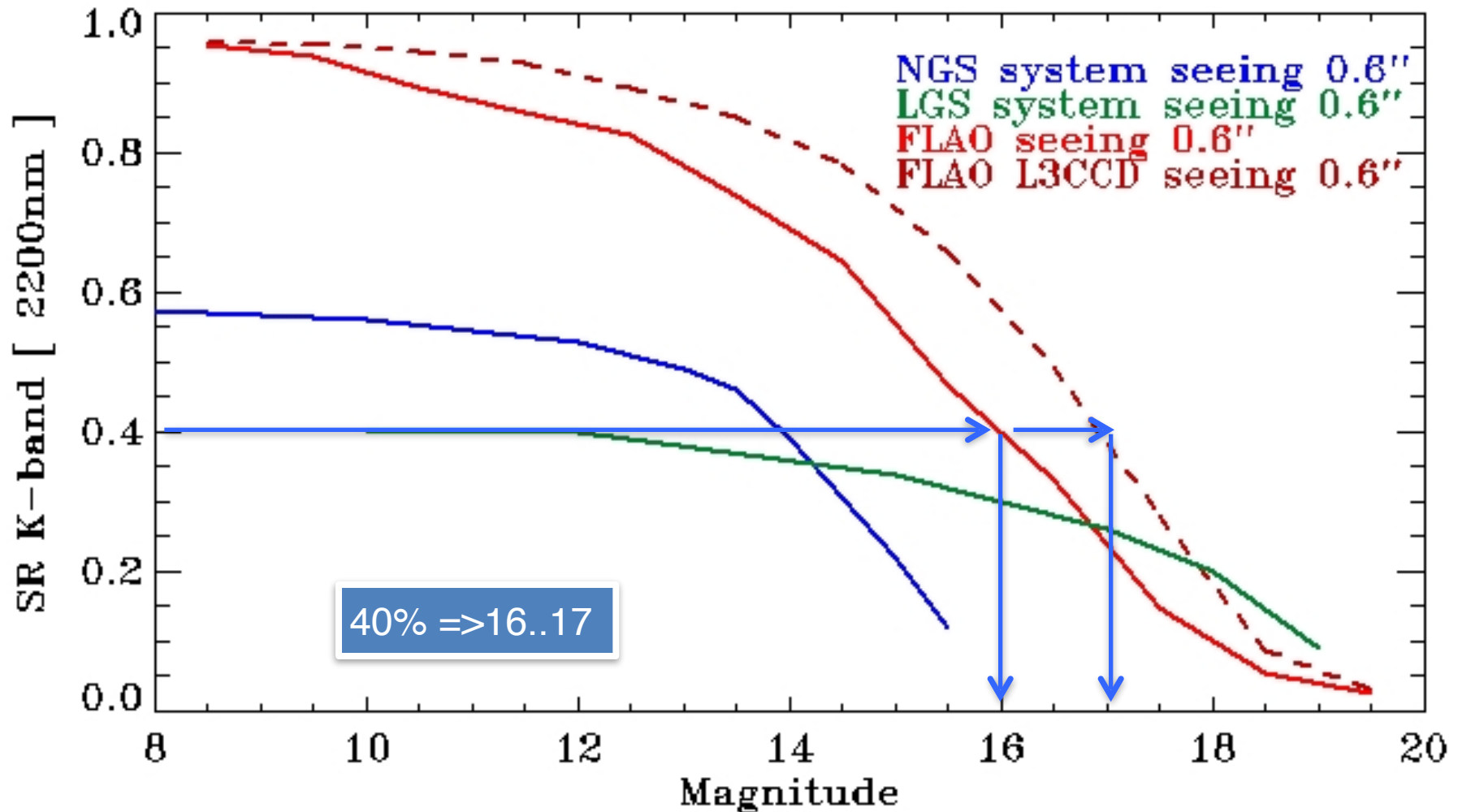
Courtesy S. Esposito - Based upon real LBT data

$L_0 = 40\text{m}$



Courtesy S. Esposito - Based upon real LBT data

$L_0 = 40m$



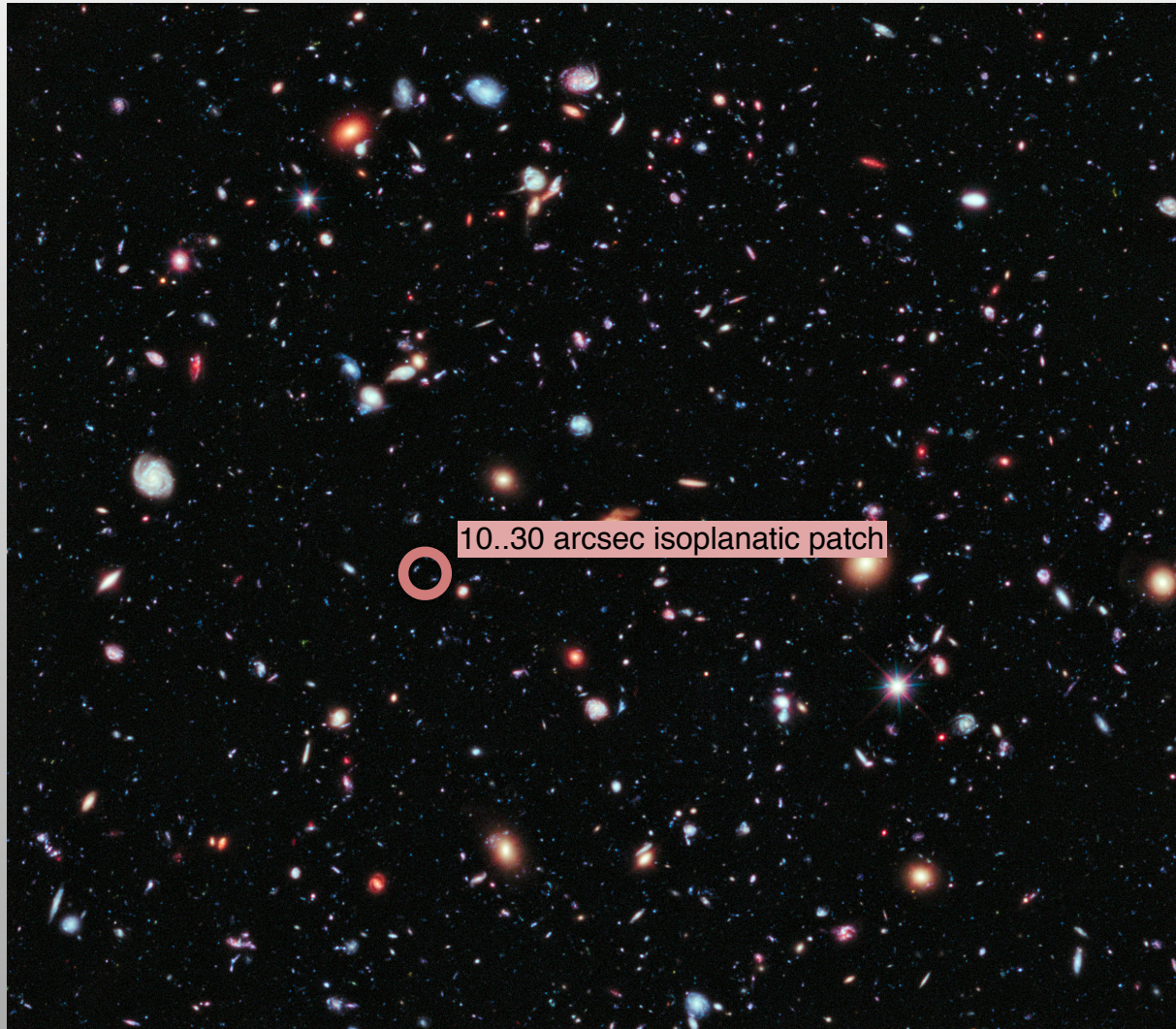


# Field of View comparison





# Field of View comparison





# Field of View comparison





# Field of View comparison

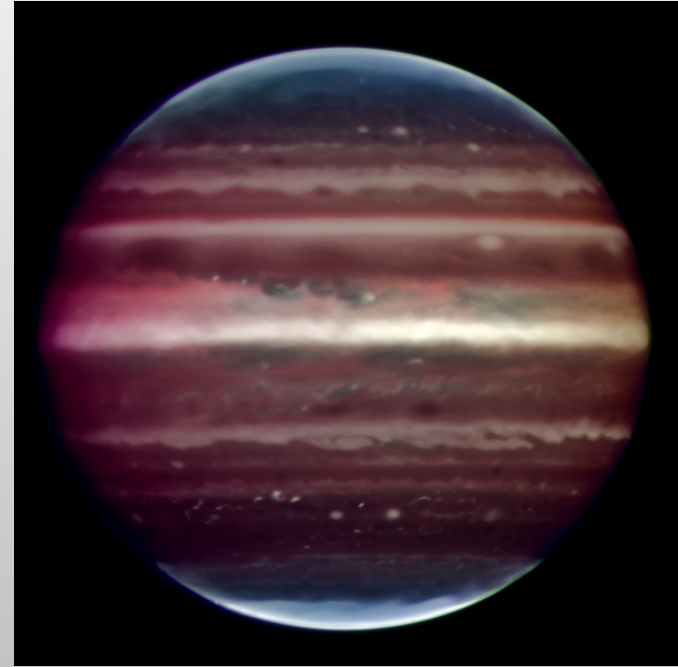


# Field of View

- SCAO: 10..30 arcsec
- MAD-like MCAO 2'
- x 16..144 wrt SCAO
- E-ELT patrol FoV 10'
- x 25 wrt MAD
- x 400..3600 wrt SCAO
- ....and sky coverages goes linearly with for a fixed number of stars (1 for SCAO, 2+ for MCAO likes...)
- Still using 3..5 stars makes a gain of  $\sim 100..1000$

# Field of View

- SCAO: 10..30 arcsec
- MAD-like MCAO 2'
- x 16..144 wrt SCAO
- E-ELT patrol FoV 10'
- x 25 wrt MAD
- x 400..3600 wrt SCAO
- ....and sky coverages goes linearly with for a fixed number of stars (1 for SCAO, 2+ for MCAO likes...)
- Still using 3..5 stars makes a gain of  $\sim 100..1000$







V	15	1.35 (2)
B		7.92 (1)
V	16	2.53 (2)
B		1.53 (2)
V	17	4.37 (2)
B		2.74 (2)
V	18	7.09 (2)
B		4.58 (2)

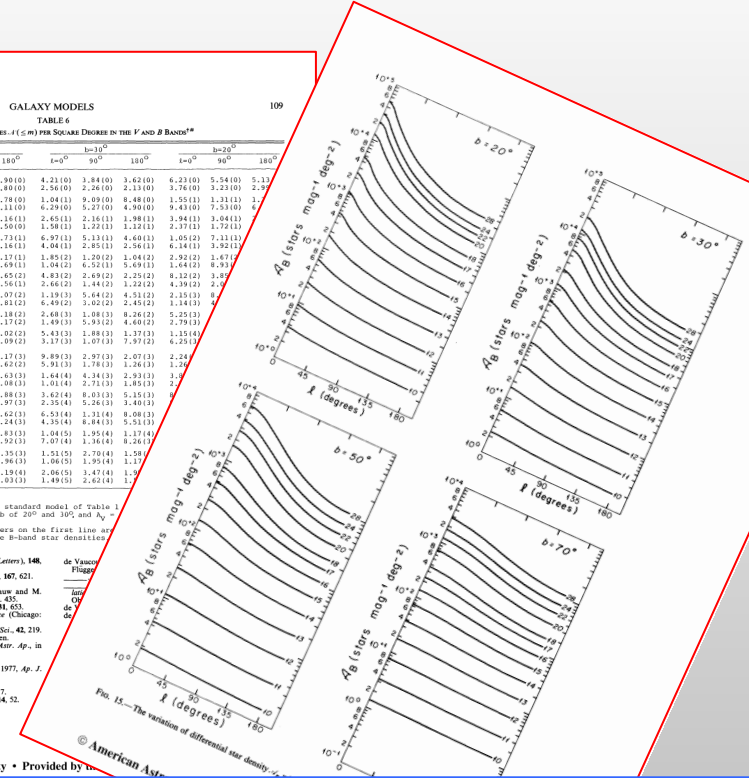
No. 1, 1980 GALAXY MODELS 109

TABLE 6  
INTEGRATED STAR DENSITIES  $\Sigma$  ( $\pm m$ ) PER SQUARE DEGREE IN THE V AND B BANDS\*

m	b=50°			b=10°			b=20°			
	0°	30°	180°	0°	30°	180°	0°	30°	180°	
V	2.10(0)	3.19(0)	3.01(0)	2.90(0)	4.21(0)	1.84(0)	3.42(0)	6.23(0)	5.54(0)	5.13
B	1.42(0)	2.61(0)	1.88(0)	1.80(0)	2.50(0)	2.26(0)	2.31(0)	3.76(0)	3.23(0)	2.7
V	5.46(0)	7.77(0)	7.13(0)	6.78(0)	1.04(1)	9.09(0)	8.48(0)	1.55(1)	1.31(1)	1.
B	3.24(0)	4.93(0)	4.14(0)	4.13(0)	6.29(0)	5.27(0)	4.90(0)	9.43(0)	5.23(0)	6.
V	1.31(1)	1.96(1)	1.72(1)	1.16(1)	2.65(1)	2.16(1)	1.98(1)	3.94(1)	3.04(1)	3.
B	7.88(0)	11.9(1)	1.02(1)	9.50(0)	1.98(1)	1.29(1)	1.21(1)	2.91(1)	1.74(1)	1.
V	3.03(1)	4.93(1)	4.08(1)	3.73(1)	6.97(1)	5.13(1)	4.60(1)	1.65(1)	1.13(1)	1.
B	1.76(1)	2.94(1)	2.37(1)	2.18(1)	4.08(1)	2.85(1)	2.56(1)	6.14(1)	3.92(1)	3.
V	4.64(1)	1.19(2)	9.20(1)	4.27(1)	1.85(2)	1.20(2)	1.04(2)	2.92(2)	1.67(2)	1.
B	3.84(1)	7.05(1)	5.29(1)	4.69(1)	1.04(2)	6.52(1)	5.69(1)	1.44(2)	0.93(2)	0.
V	1.35(2)	2.74(2)	1.93(2)	1.65(2)	4.63(2)	2.69(2)	2.25(2)	8.22(2)	2.87(2)	2.
B	7.92(1)	1.62(2)	1.11(2)	9.56(1)	2.66(2)	1.44(2)	1.22(2)	4.39(2)	2.67(2)	2.
V	2.53(2)	5.86(2)	3.72(2)	3.07(2)	1.19(3)	5.64(2)	4.53(2)	2.15(3)	1.5(3)	1.
B	1.53(2)	3.25(2)	2.19(2)	1.83(2)	6.49(2)	3.02(2)	2.45(2)	1.14(3)	0.7(3)	0.
V	4.37(2)	1.15(3)	6.54(2)	5.18(2)	2.48(3)	1.08(3)	8.26(2)	5.25(3)	3.7(3)	3.
B	2.74(2)	7.13(2)	4.08(2)	3.17(2)	1.89(3)	5.93(2)	4.60(2)	2.79(3)	1.9(3)	1.
V	7.09(2)	2.89(3)	1.04(3)	8.02(2)	5.43(2)	1.88(3)	1.37(3)	1.15(4)	0.7(4)	0.
B	4.58(2)	1.33(3)	6.71(2)	5.09(2)	5.17(3)	1.07(3)	7.97(2)	6.25(3)	4.3(3)	4.
V	1.10(3)	3.52(3)	1.61(3)	1.17(3)	9.89(3)	2.97(3)	2.07(3)	2.24(3)	1.36(3)	1.
B	7.58(2)	2.30(3)	1.09(3)	7.62(2)	5.31(3)	1.78(3)	1.26(3)	1.26(3)	0.7(3)	0.
V	2.64(3)	5.56(3)	2.33(3)	1.63(3)	1.64(4)	4.34(3)	2.93(3)	3.1(3)	1.9(3)	1.
B	1.09(3)	1.60(3)	1.55(3)	1.08(3)	1.01(4)	2.73(3)	1.85(3)	2.4(3)	1.4(3)	1.
V	3.26(3)	1.18(4)	4.39(3)	2.88(3)	3.62(4)	8.03(3)	5.15(3)	3.40(3)	2.2(3)	2.
B	2.22(3)	7.99(3)	5.00(3)	1.97(3)	2.55(4)	5.24(3)	3.40(3)	1.80(3)	1.1(3)	1.
V	9.66(3)	2.19(4)	7.35(3)	4.62(3)	6.53(4)	1.33(4)	8.08(3)	5.51(3)	3.3(3)	3.
B	3.94(3)	1.45(4)	5.12(3)	3.24(3)	4.35(4)	8.84(3)	5.91(3)	3.1(3)	1.9(3)	1.
V	0.85(3)	3.31(4)	1.22(4)	6.83(3)	1.04(5)	3.95(4)	1.17(4)	1.17(4)	0.6(4)	0.
B	6.27(3)	2.32(4)	7.30(3)	4.92(3)	7.07(4)	1.36(4)	8.26(3)	5.1(3)	3.1(3)	3.
V	3.27(4)	4.79(4)	1.57(4)	9.35(3)	1.51(5)	2.70(4)	1.58(4)	1.58(4)	0.8(4)	0.
B	9.21(3)	3.44(4)	1.15(4)	6.98(3)	1.96(5)	3.95(4)	1.17(4)	1.17(4)	0.6(4)	0.
V	1.70(4)	6.51(4)	2.96(4)	1.19(4)	2.86(5)	1.47(4)	1.9(4)	1.9(4)	1.0(4)	1.
B	1.28(4)	4.93(4)	1.55(4)	9.03(3)	1.49(5)	2.62(4)	1.1(4)	1.1(4)	0.6(4)	0.

\*These numbers were computed using the standard model of Table 1 for  $A_b = 0.20$  (equation 6) for latitudes  $b$  of 20° and 30°, and  $A_v = 0.10$  for each apparent magnitude; the numbers on the first line are the numbers on the second line are the b-band star densities.

Babcock, I. N., and Sargent, W. L. W. 1967, *Ap. J. (Letters)*, 148, L65.  
 Balmain, I. A., and Feast, M. W. 1974, *M.N.R.A.S.*, 167, 421.  
 Becker, F. 1939, *Zs. f. Ap.*, 19, 30.  
 Blaauw, A. 1965, in *Galactic Structure*, ed. A. Blaauw and M. Schmidt (Chicago: University of Chicago Press), p. 435.  
 Schmidt, T. J., and Weidman, D. W. 1978, *Ap. J.*, 231, 653.  
 Bok, B. J. 1977, *The Distribution of Stars in Space* (Chicago: University of Chicago Press).  
 Bok, B. J., and McClure, D. A. 1941, *Ann. N.Y. Acad. Sci.*, 42, 219.  
 Busca, A. 1978, Ph.D. thesis, University of Groningen.  
 Braccesi, A., Zwitter, F., and Formigini, L. 1980, *Astr. Ap.*, in press.  
 Brown, G. S. 1979, *A. J.*, 84, 1647.  
 Burbidge, G., R. Crowe, A. H., and Smith, H. E. 1977, *Ap. J. Suppl.*, 33, 111.  
 Burstein, D., and Heiles, C. 1978, *Ap. J.*, 225, 40.  
 Burstein, D., and McDonald, L. H. 1975, *A. J.*, 80, 17.  
 Chantrelin, J. W., and Allen, L. H. 1951, *Ap. J.*, 114, 52.  
 Chin, L. T. G. 1980, preprint.  
 Dieder, A., and Shubin, J. 1979, *Astr. Ap.*, 74, 186.



V=15	V=16	V=17	V=18	Galactic Pole
135	253	437	709	Stars per square deg
1.1	2.2	3.8	6.2	Stars in a 10' diameter
0.3	0.6	0.9	1.6	Stars in a 5' diameter

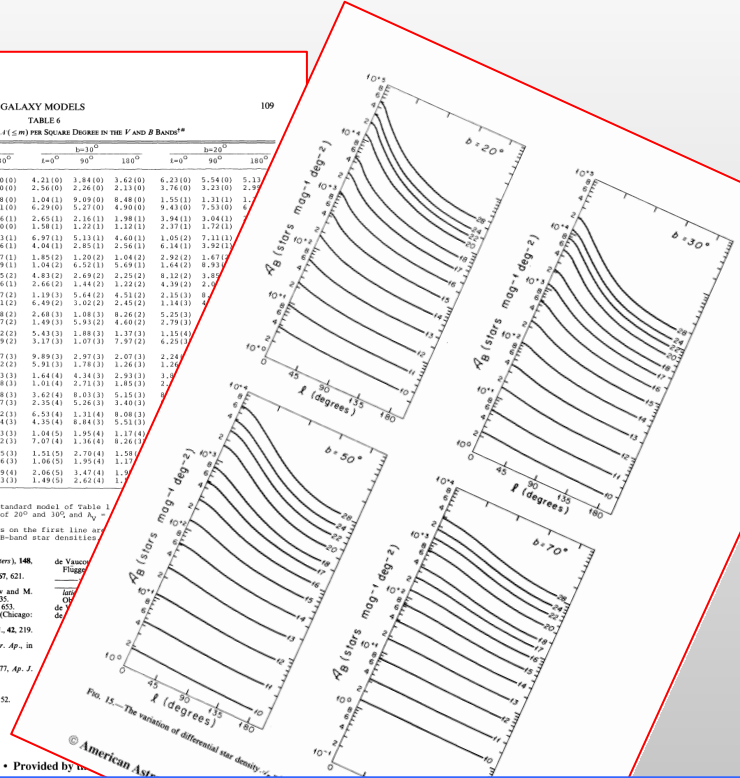


V	15	1.35 (2)
B		7.92 (1)
V	16	2.53 (2)
B		1.53 (2)
V	17	4.37 (2)
B		2.74 (2)
V	18	7.09 (2)
B		4.58 (2)

No. 1, 1980 GALAXY MODELS 109

INTEGRATED STAR DENSITIES  $\int (\leq m)$  PER SQUARE DEGREE IN THE V AND B BANDS\*

m	b=50°			b=10°			b=20°			
	0°	30°	180°	0°	30°	180°	0°	30°	180°	
V 10	2.10(0)	3.19(0)	3.01(0)	2.90(0)	4.21(0)	1.84(0)	3.42(0)	6.23(0)	5.54(0)	5.13
B 11	1.42(0)	2.61(0)	1.88(0)	1.80(0)	2.50(0)	2.26(0)	2.31(0)	3.76(0)	3.23(0)	2.7
V 11	5.46(0)	7.77(0)	7.13(0)	6.78(0)	1.04(1)	9.09(0)	8.48(0)	1.55(1)	1.31(1)	1.
B 12	3.24(0)	4.93(0)	4.14(0)	4.00(0)	6.29(0)	5.27(0)	4.90(0)	9.43(0)	5.23(0)	6.
V 12	1.31(1)	1.96(1)	1.72(1)	1.16(1)	2.65(1)	2.16(1)	1.98(1)	3.94(1)	3.04(1)	3.
B 13	7.88(0)	11.9(1)	1.02(1)	9.50(0)	1.98(1)	1.29(1)	1.21(1)	2.91(1)	1.74(1)	1.
V 13	3.03(1)	4.93(1)	4.08(1)	3.73(1)	6.97(1)	5.13(1)	4.60(1)	1.65(1)	1.13(1)	1.
B 14	1.76(1)	2.94(1)	2.37(1)	2.18(1)	4.08(1)	2.85(1)	2.56(1)	6.14(1)	1.92(1)	1.
V 14	6.44(1)	1.19(2)	9.20(1)	4.27(1)	1.85(2)	1.20(2)	1.04(2)	2.92(2)	1.47(2)	1.
B 15	3.84(1)	7.05(1)	5.29(1)	4.69(1)	1.04(2)	6.52(1)	5.69(1)	1.44(2)	0.93	1.
V 15	1.35(2)	2.74(2)	1.99(2)	1.65(2)	4.63(2)	2.69(2)	2.25(2)	8.22(2)	2.89	1.
B 16	7.92(1)	1.46(2)	1.11(2)	9.56(1)	2.66(2)	1.44(2)	1.22(2)	4.39(2)	2.69	1.
V 16	2.53(2)	5.86(2)	3.72(2)	3.07(2)	1.19(3)	5.64(2)	4.53(2)	2.15(3)	1.	1.
B 17	1.53(2)	3.25(2)	2.19(2)	1.83(2)	6.49(2)	3.62(2)	2.45(2)	1.14(3)	1.	1.
V 17	4.37(2)	1.15(3)	6.54(2)	5.18(2)	2.48(3)	1.08(3)	8.26(2)	5.25(3)	1.	1.
B 18	2.74(2)	7.13(2)	4.08(2)	3.17(2)	1.89(3)	5.93(2)	4.60(2)	2.79(3)	1.	1.
V 18	7.09(2)	2.89(3)	1.04(3)	8.02(2)	5.43(2)	1.88(3)	1.37(3)	1.15(4)	1.	1.
B 19	4.58(2)	1.33(3)	6.71(2)	5.09(2)	3.17(3)	1.07(3)	7.97(2)	6.25(3)	1.	1.
V 19	1.10(3)	3.52(3)	1.61(3)	1.17(3)	9.89(3)	2.97(3)	2.07(3)	2.24	1.	1.
B 20	7.94(2)	2.30(3)	1.09(3)	7.62(2)	5.31(3)	1.78(3)	1.26(3)	1.36	1.	1.
V 20	1.64(3)	5.56(3)	2.33(3)	1.63(3)	1.64(4)	4.34(3)	2.93(3)	3.	1.	1.
B 21	1.09(3)	1.69(3)	1.59(3)	1.08(3)	1.01(4)	2.73(3)	1.85(3)	2.	1.	1.
V 21	3.26(3)	1.18(4)	4.39(3)	2.88(3)	3.62(4)	8.03(3)	5.15(3)	1.	1.	1.
B 22	2.22(3)	7.99(3)	3.50(3)	1.97(3)	2.55(4)	5.24(3)	3.40(3)	1.	1.	1.
V 22	9.46(3)	2.19(4)	7.35(3)	4.42(3)	6.33(4)	1.33(4)	8.08(3)	1.	1.	1.
B 23	3.94(3)	1.45(4)	5.12(3)	3.24(3)	4.35(4)	8.84(3)	5.91(3)	1.	1.	1.
V 23	8.85(3)	3.31(4)	1.22(4)	6.83(3)	1.04(5)	3.95(4)	1.17(4)	1.	1.	1.
B 24	6.27(3)	2.32(4)	7.30(3)	4.92(3)	7.07(4)	1.36(4)	8.26(3)	1.	1.	1.
V 24	1.27(4)	4.79(4)	1.57(4)	9.35(3)	1.51(5)	2.70(4)	1.58	1.	1.	1.
B 25	9.21(3)	3.44(4)	1.15(4)	6.96(3)	1.96(5)	1.99(4)	1.17	1.	1.	1.
V 30	1.70(4)	6.51(4)	2.96(4)	1.19(4)	2.86(5)	1.47(4)	1.9	1.	1.	1.
B 31	1.26(4)	4.93(4)	1.55(4)	9.03(3)	1.49(5)	2.62(4)	1.9	1.	1.	1.

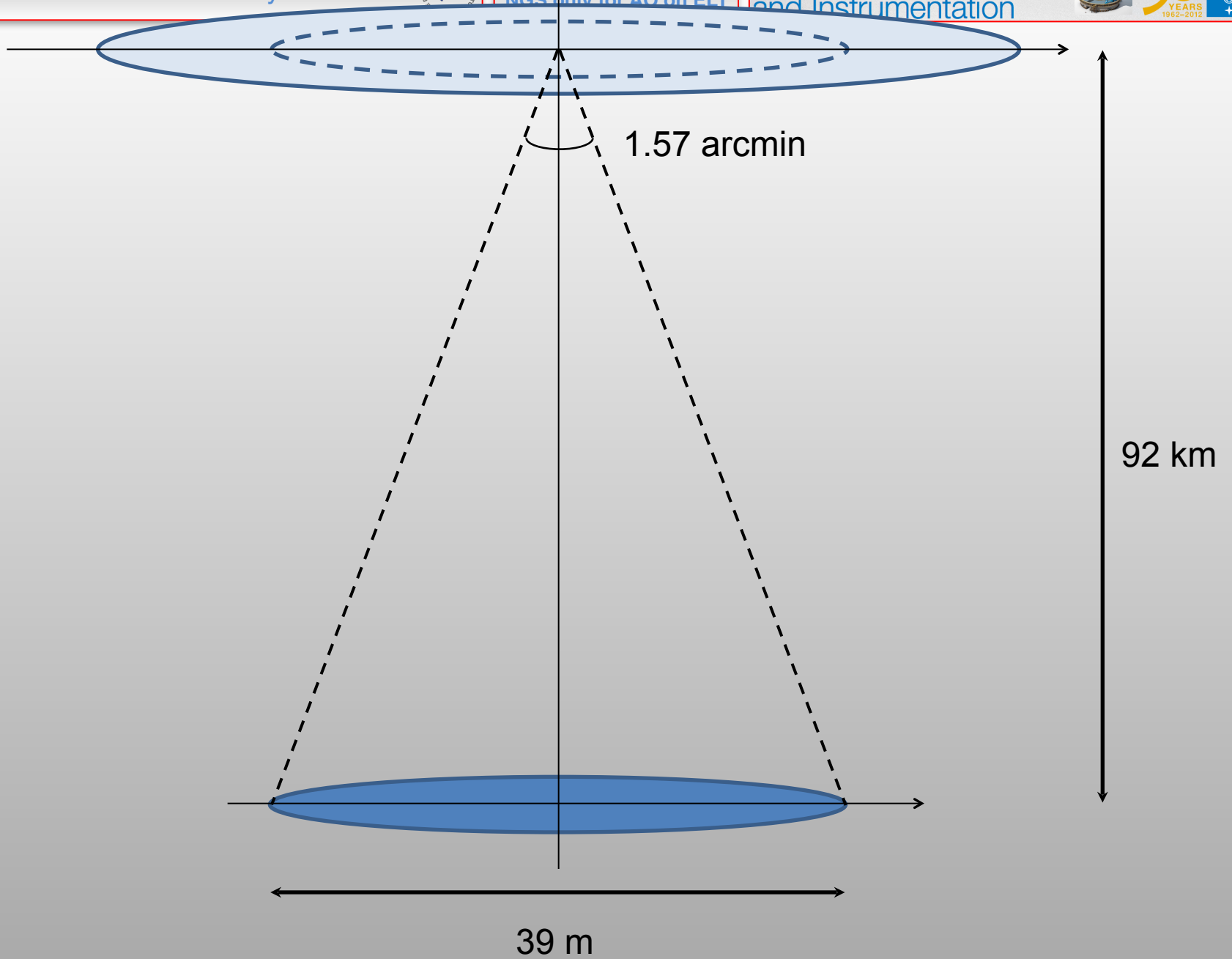


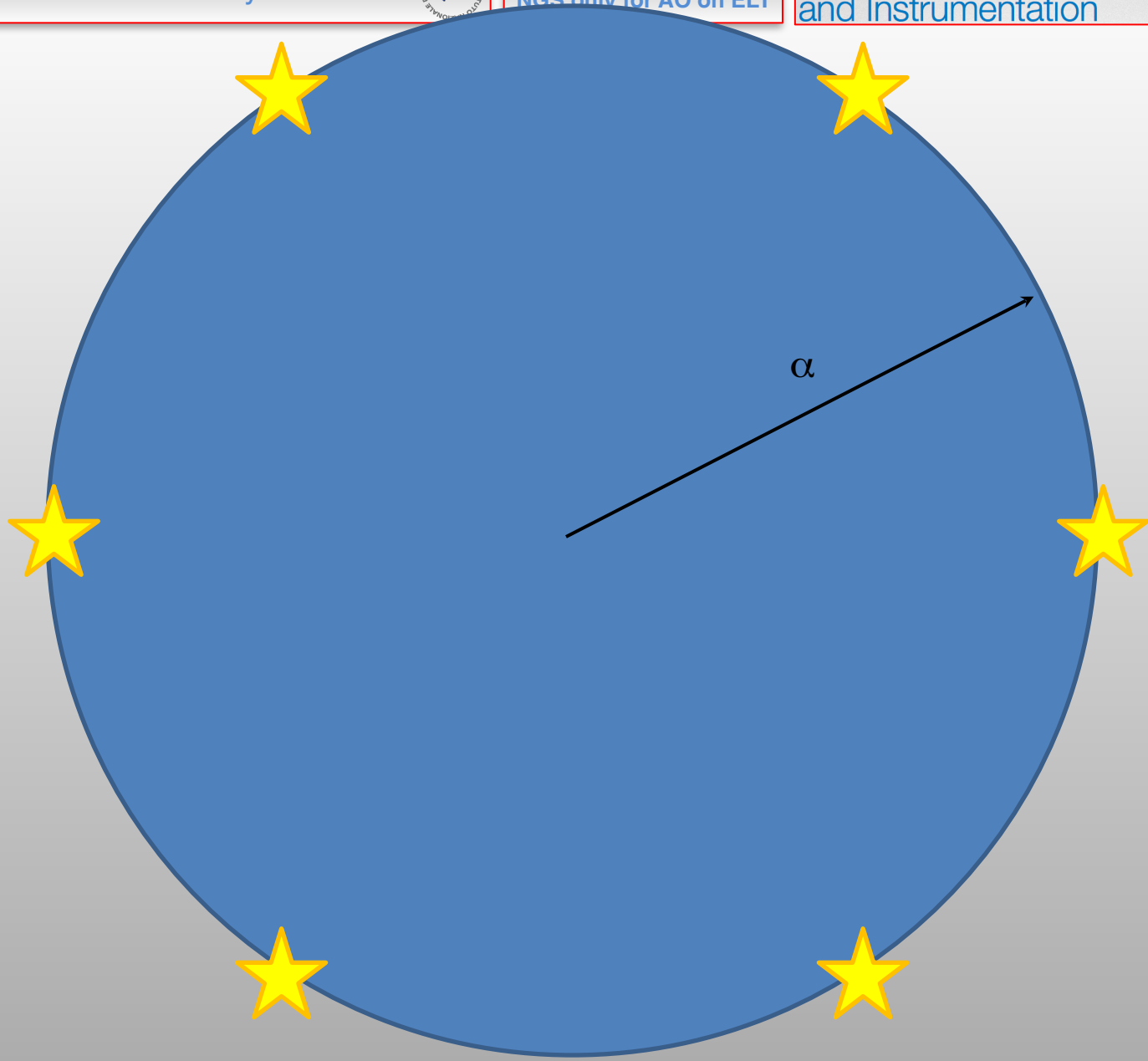
\*These numbers were computed using the standard model of Table 1,  $A_V = 0.20$  (equation 6) for latitudes  $b$  of 20° and 30°, and  $A_V = 0.10$  for each apparent magnitude; the numbers on the first line are the numbers on the second line are the  $b$ -band star densities.

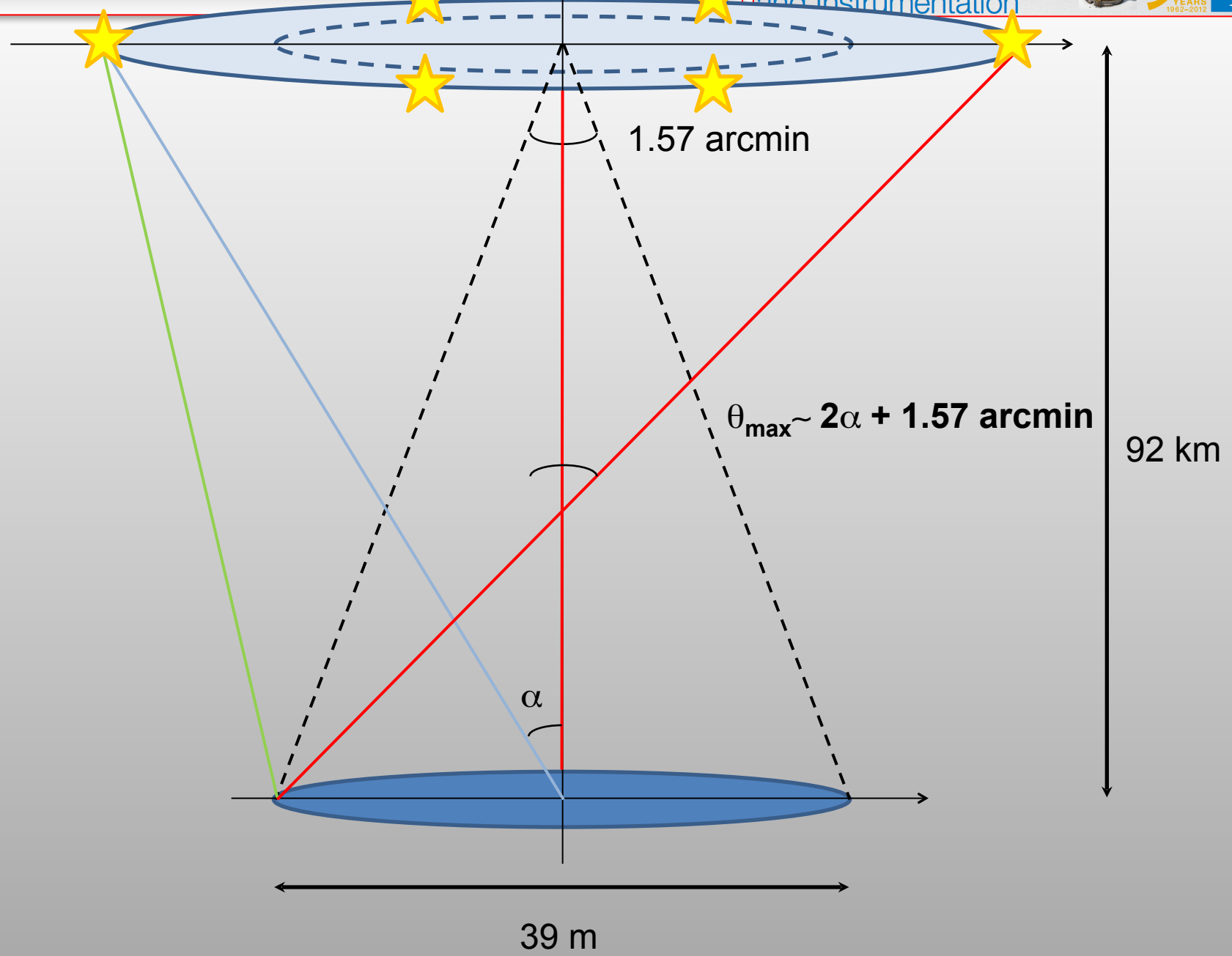
Babcock, J. N., and Sargent, W. L. W. 1967, *Ap. J. (Letters)*, 148, L65.  
 Balmain, L. A., and Frost, M. W. 1974, *M.N.R.A.S.*, 167, 421.  
 Becker, F. 1939, *Zs. f. Ap.*, 19, 30.  
 Blaauw, A. 1965, in *Galactic Structure*, ed. A. Blaauw and M. Schmidt (Chicago: University of Chicago Press), p. 435.  
 Schmidt, T. J., and Weidman, D. W. 1978, *Ap. J.*, 231, 653.  
 Bok, B. J. 1977, *The Distribution of Stars in Space* (Chicago: University of Chicago Press).  
 Bok, B. J., and McClure, D. A. 1941, *Ann. N.Y. Acad. Sci.*, 42, 219.  
 Bontas, A. 1978, Ph.D. thesis, University of Groningen.  
 Bracco, A., Zwitter, F., and Formigini, L. 1980, *Astr. Ap.*, in press.  
 Brown, G. S. 1979, *A. J.*, 84, 1647.  
 Burbidge, G., R. Crown, A. H., and Smith, H. E. 1977, *Ap. J. Suppl.*, 33, 111.  
 Burstein, D., and Heiles, C. 1978, *Ap. J.*, 225, 40.  
 Burstein, D., and McDonald, L. H. 1975, *A. J.*, 80, 17.  
 Chantrelin, J. W., and Allen, L. H. 1951, *Ap. J.*, 114, 52.  
 Chau, L. T. G. 1980, preprint.  
 Dolid, A., and Shaban, J. 1979, *Astr. Ap.*, 74, 186.

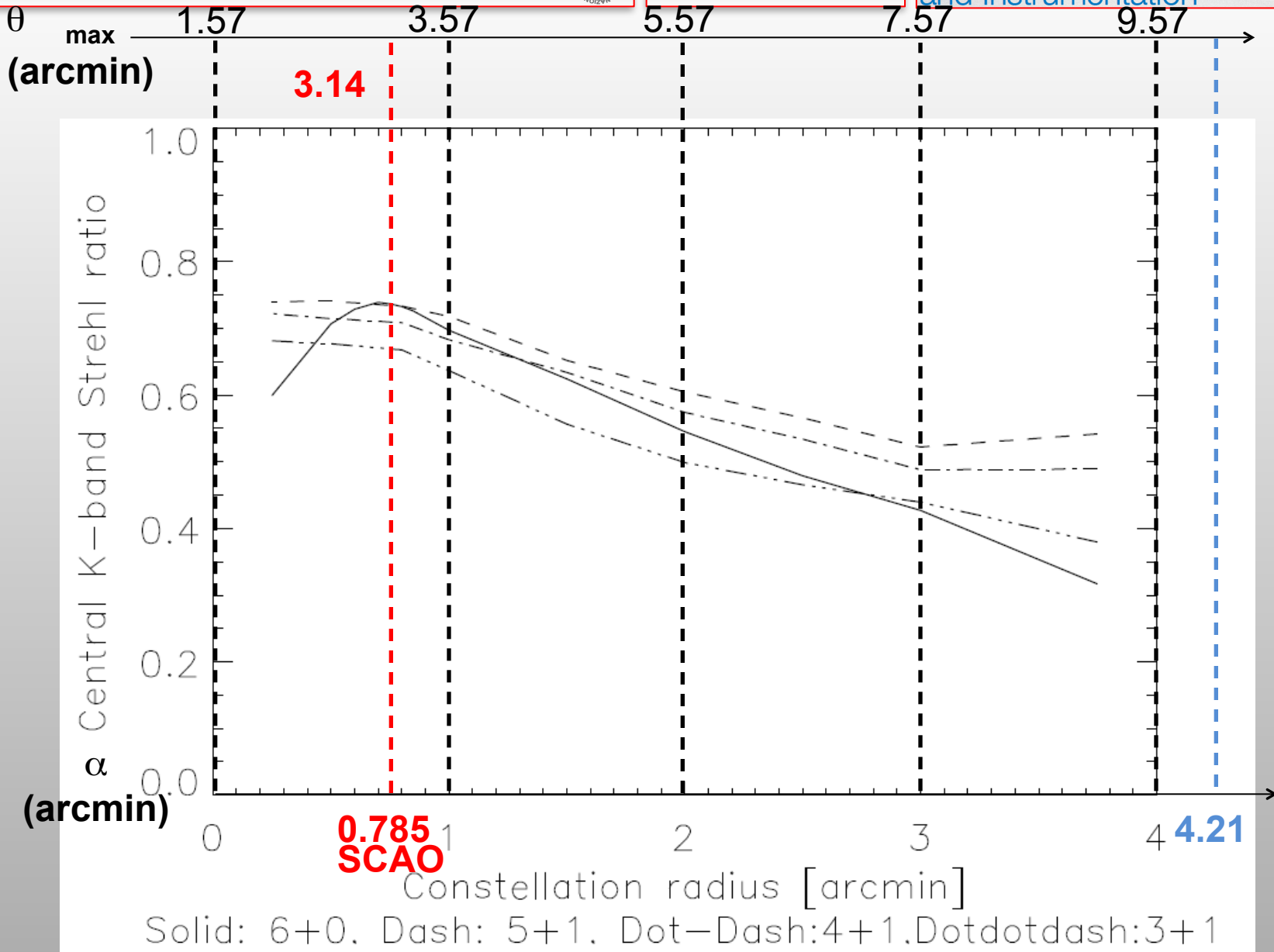
American Astronomical Society • Provided by American Astronomical Society

V=15	V=16	V=17	V=18	Galactic Pole
135	253	437	709	Stars per square deg
1.1	2.2	3.8	6.2	Stars in a 10' diameter
0.3	0.6	0.9	1.6	Stars in a 5' diameter



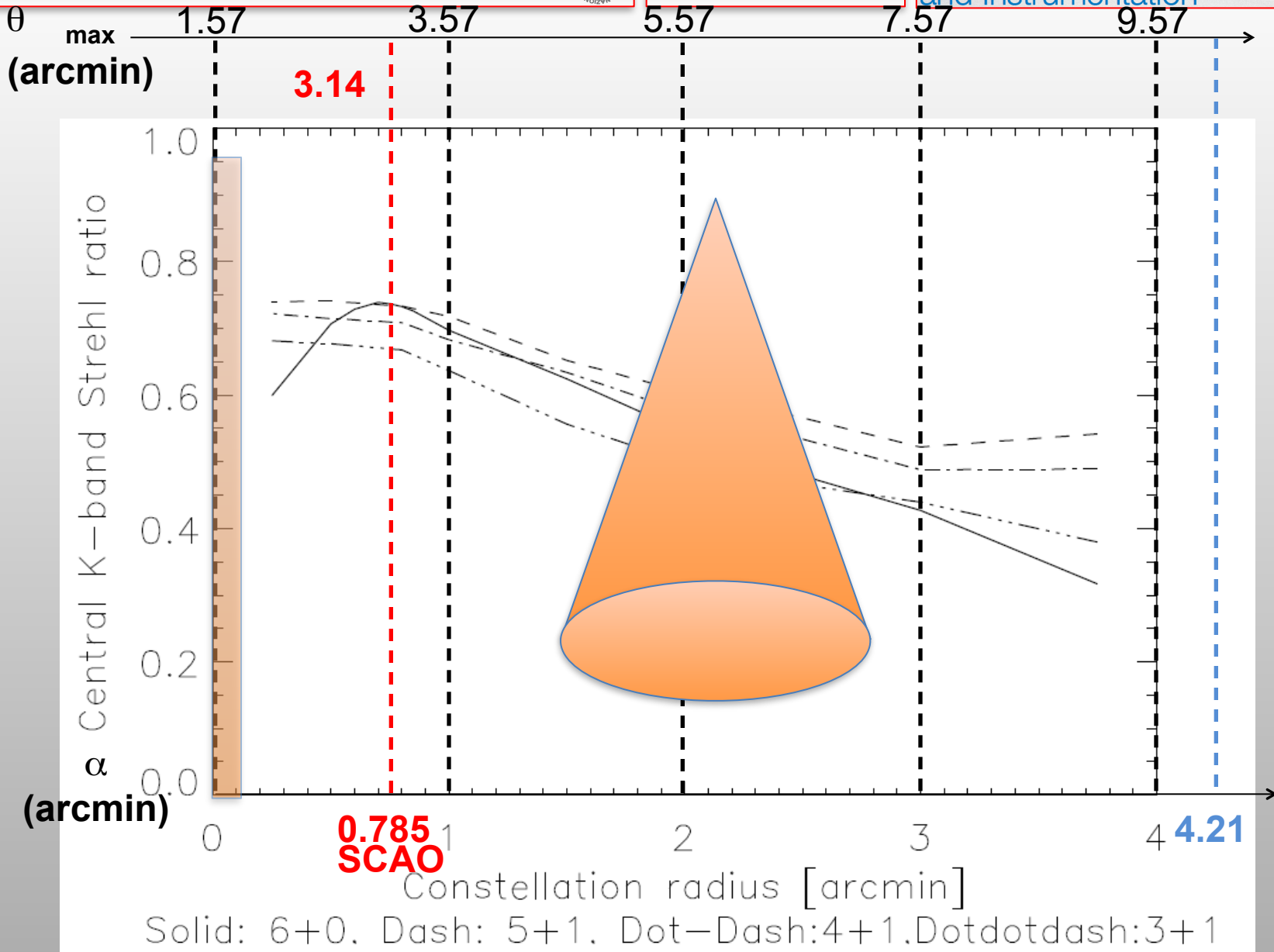




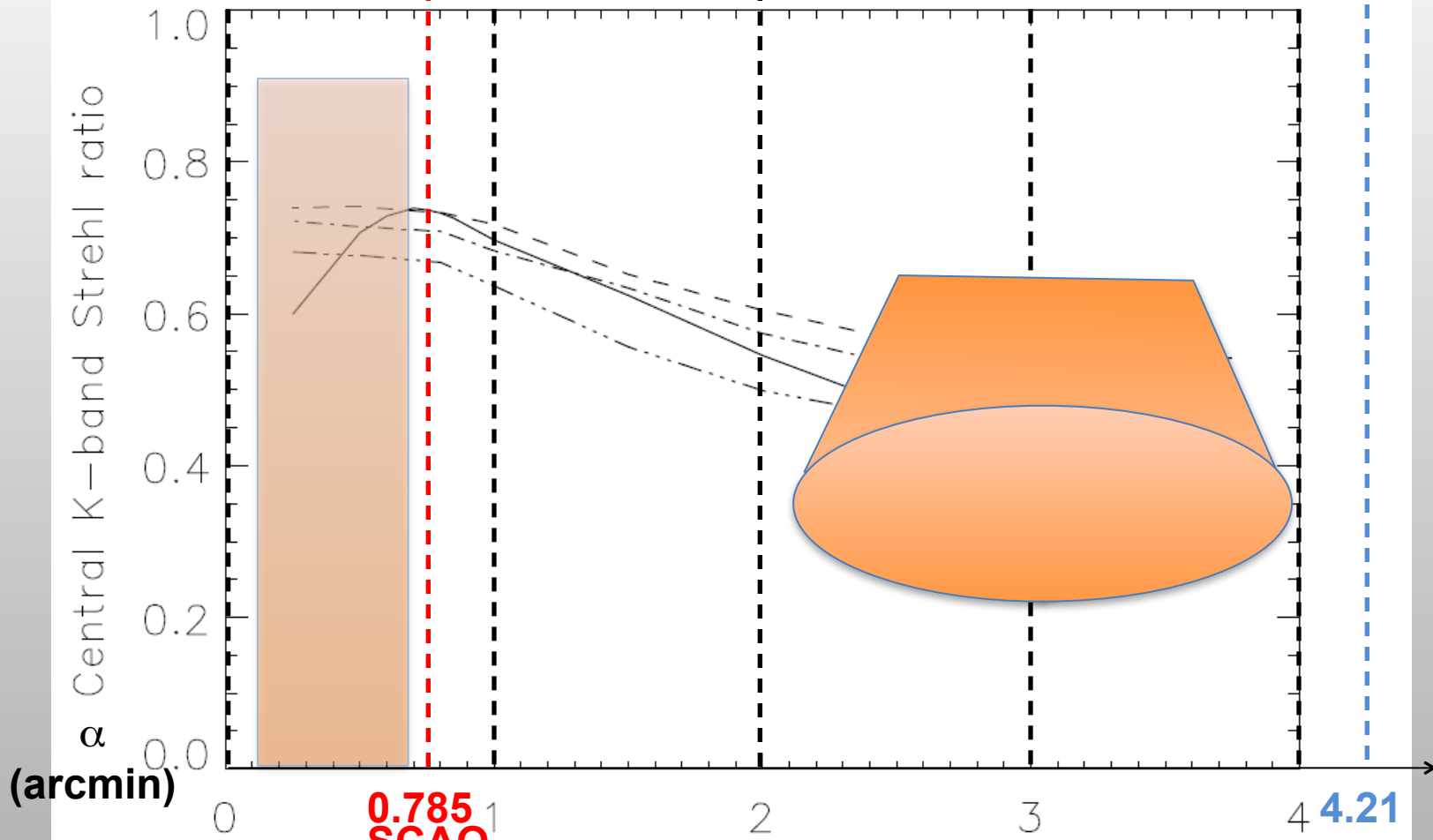
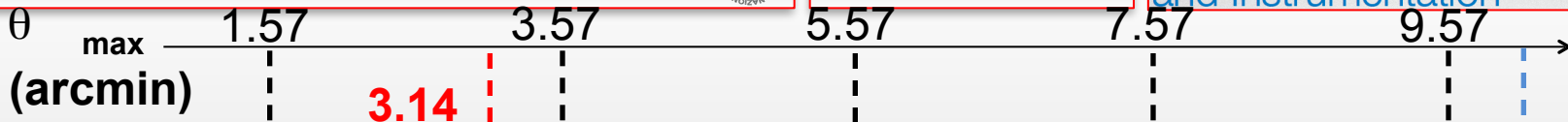


From M. Le Louarn - ELT AO LGSs simulations





From M. Le Louarn - ELT AO LGSs simulations

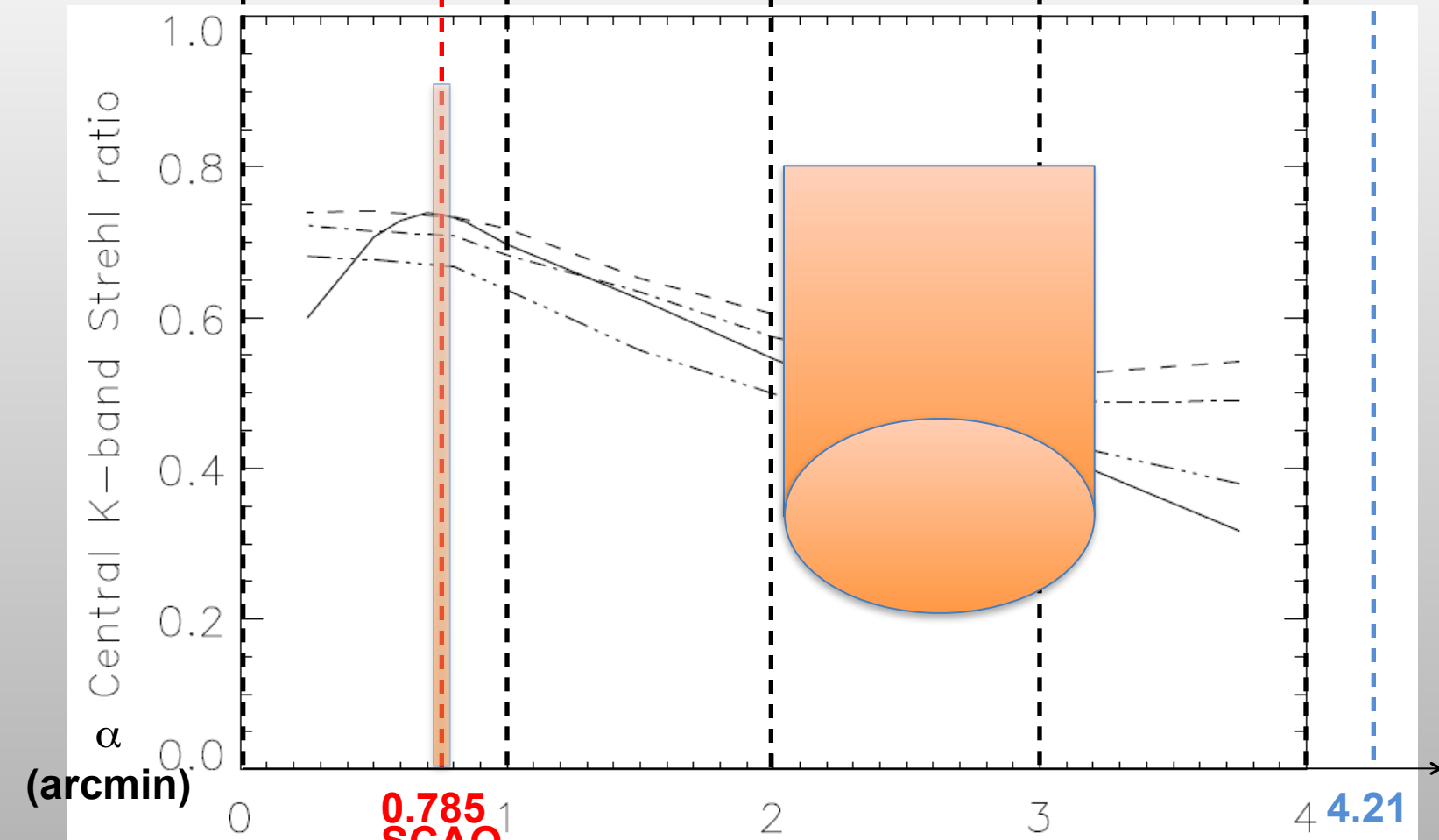


Constellation radius [arcmin]

Solid: 6+0. Dash: 5+1. Dot-Dash: 4+1. Dotdotdash: 3+1

From M. Le Louarn - ELT AO LGSs simulations

$\theta_{max}$  (arcmin) 1.57 3.57 5.57 7.57 9.57



Solid: 6+0. Dash: 5+1. Dot-Dash: 4+1. Dotdotdash: 3+1

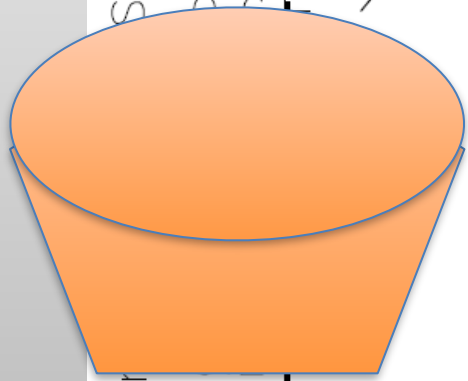
From M. Le Louarn - ELT AO LGSs simulations

$\theta_{max}$  (arcmin) 1.57 3.57 5.57 7.57 9.57

3.14

Strehl ratio

1.0  
0.8  
0.6  
0.4  
0.2  
0.0



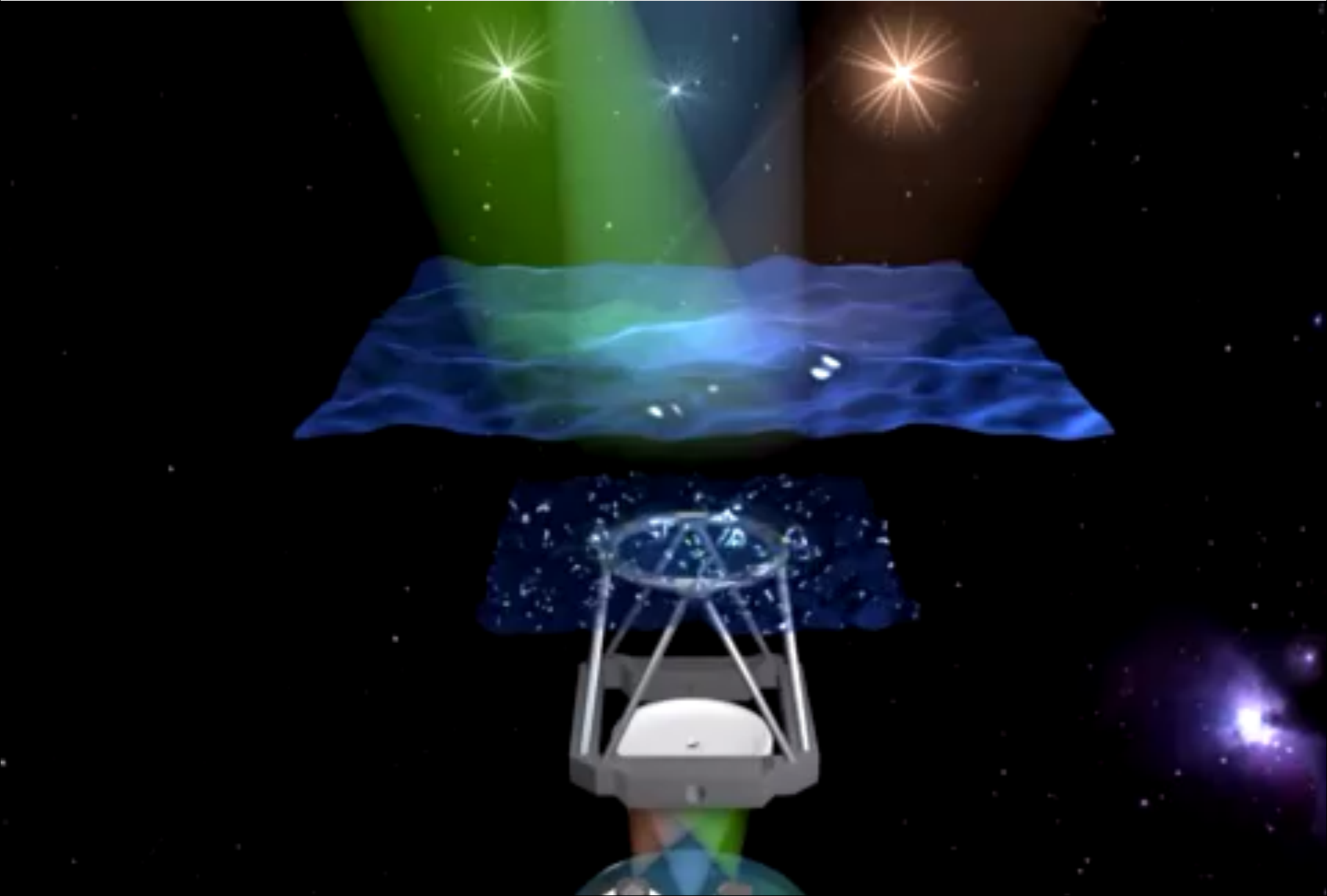
$\alpha$  (arcmin) 0.0

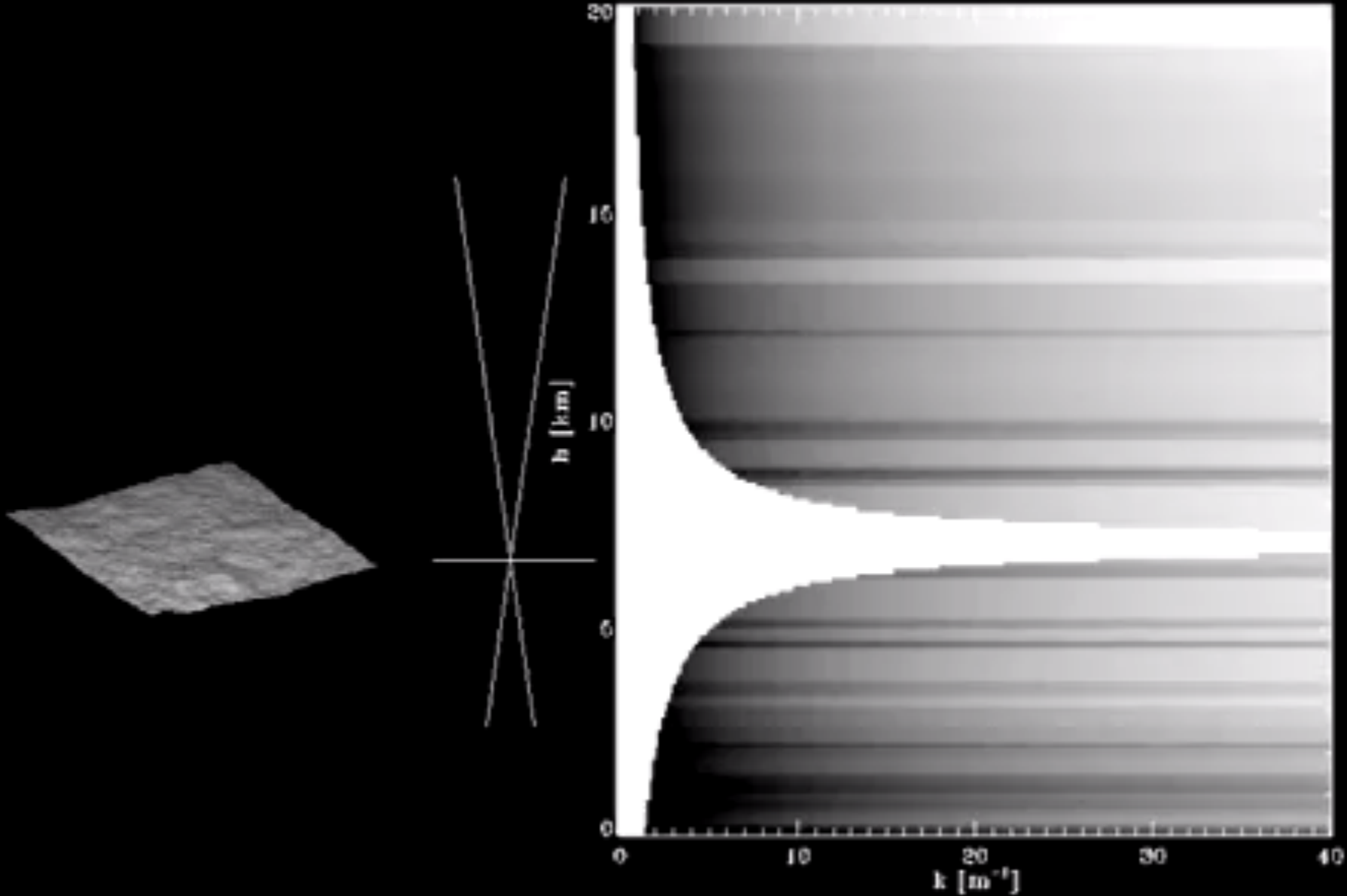
0.785  
SCAO

Constellation radius [arcmin]

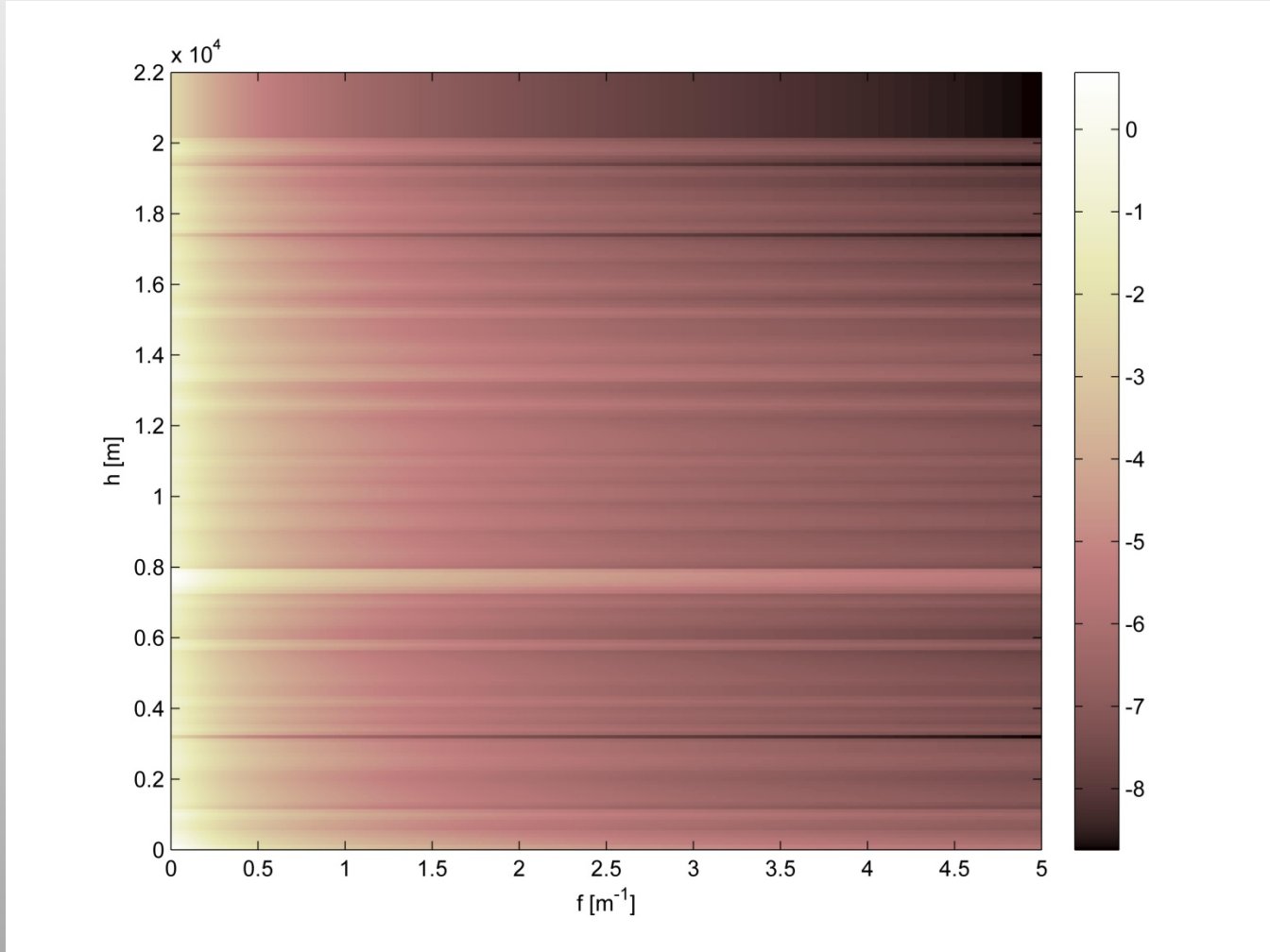
Solid: 6+0. Dash: 5+1. Dot-Dash: 4+1. Dotdotdash: 3+1

From M. Le Louarn - ELT AO LGSs simulations





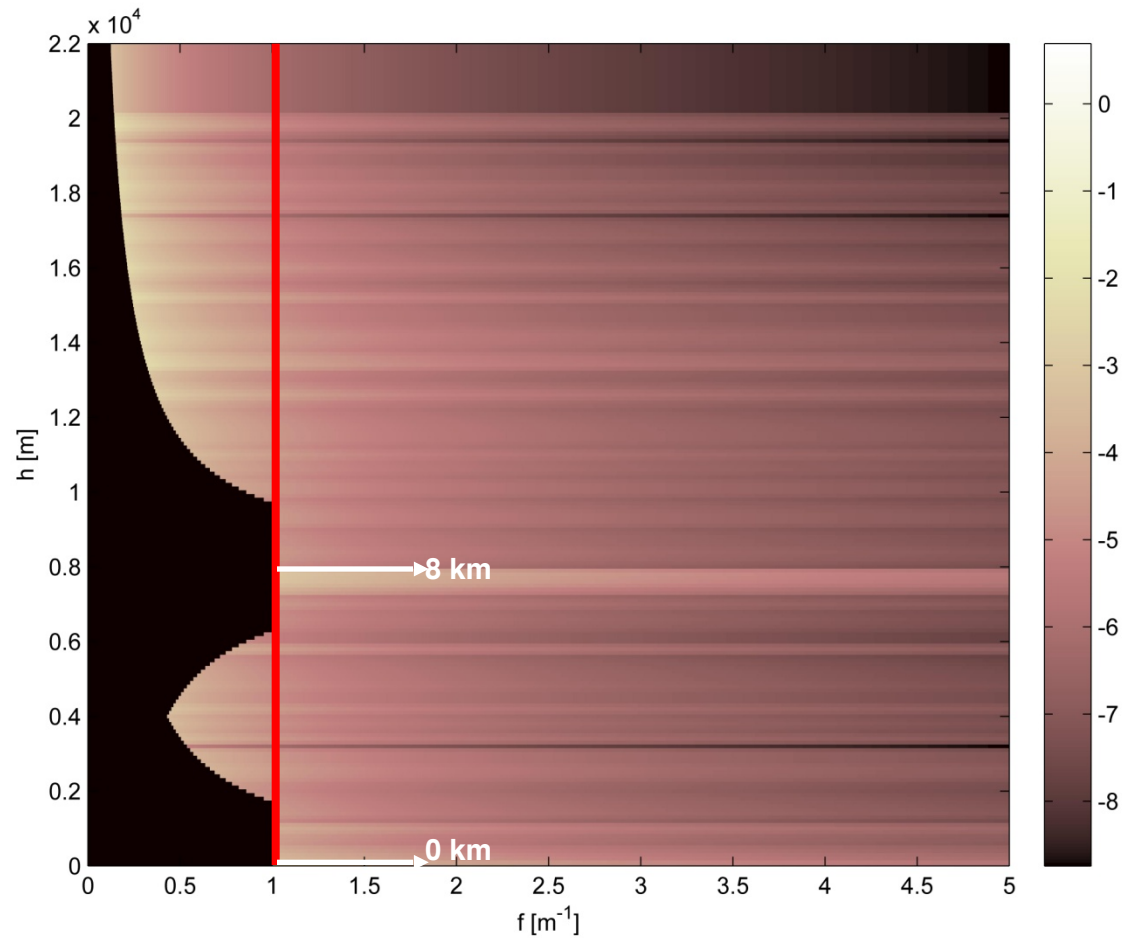




$D_{tel} = 8 \text{ m}$   
 N. DMs = 2  
 N. actuators = 8  
 Field of View = 2 arcmin

$$R = \sum_H \int_F \Phi_{\varphi}^{2D}(f) df$$

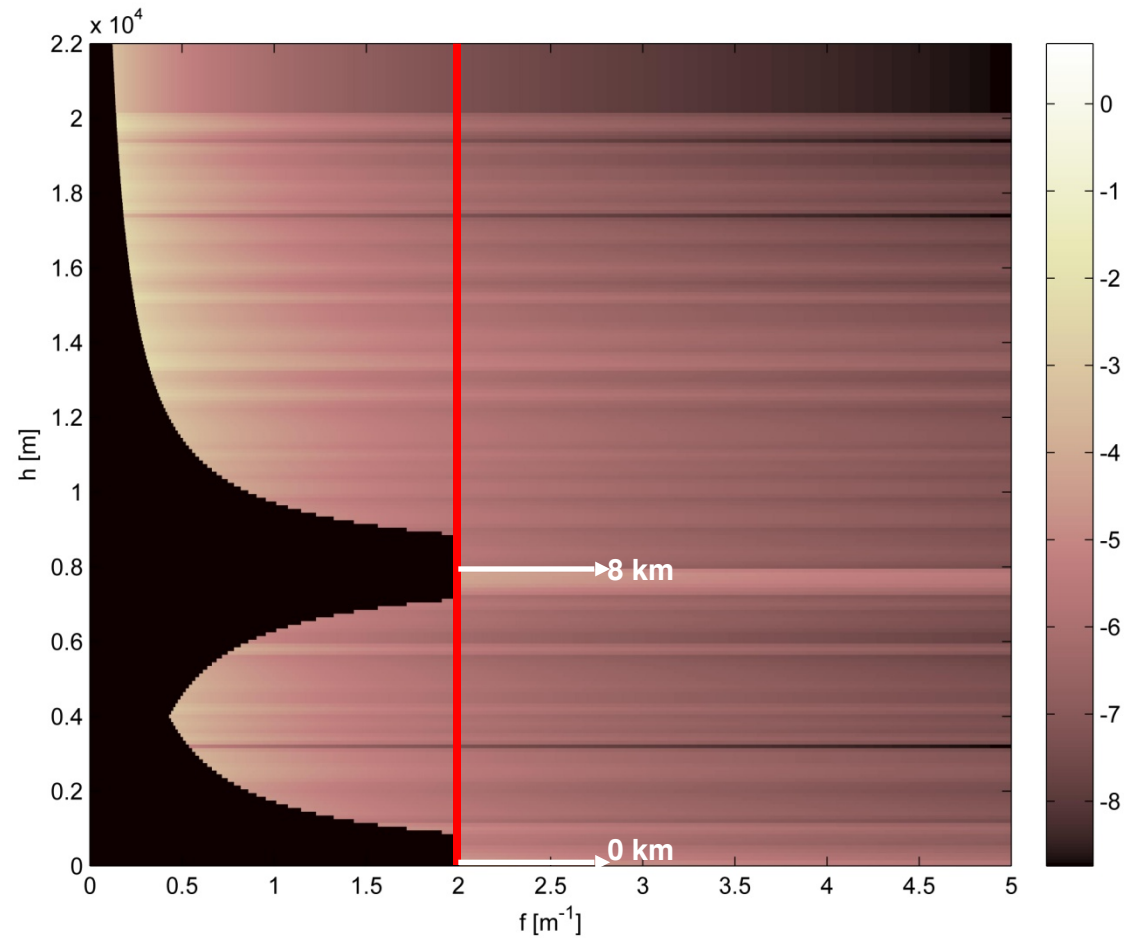
$$R_{MAD-8m} = 0.0262$$



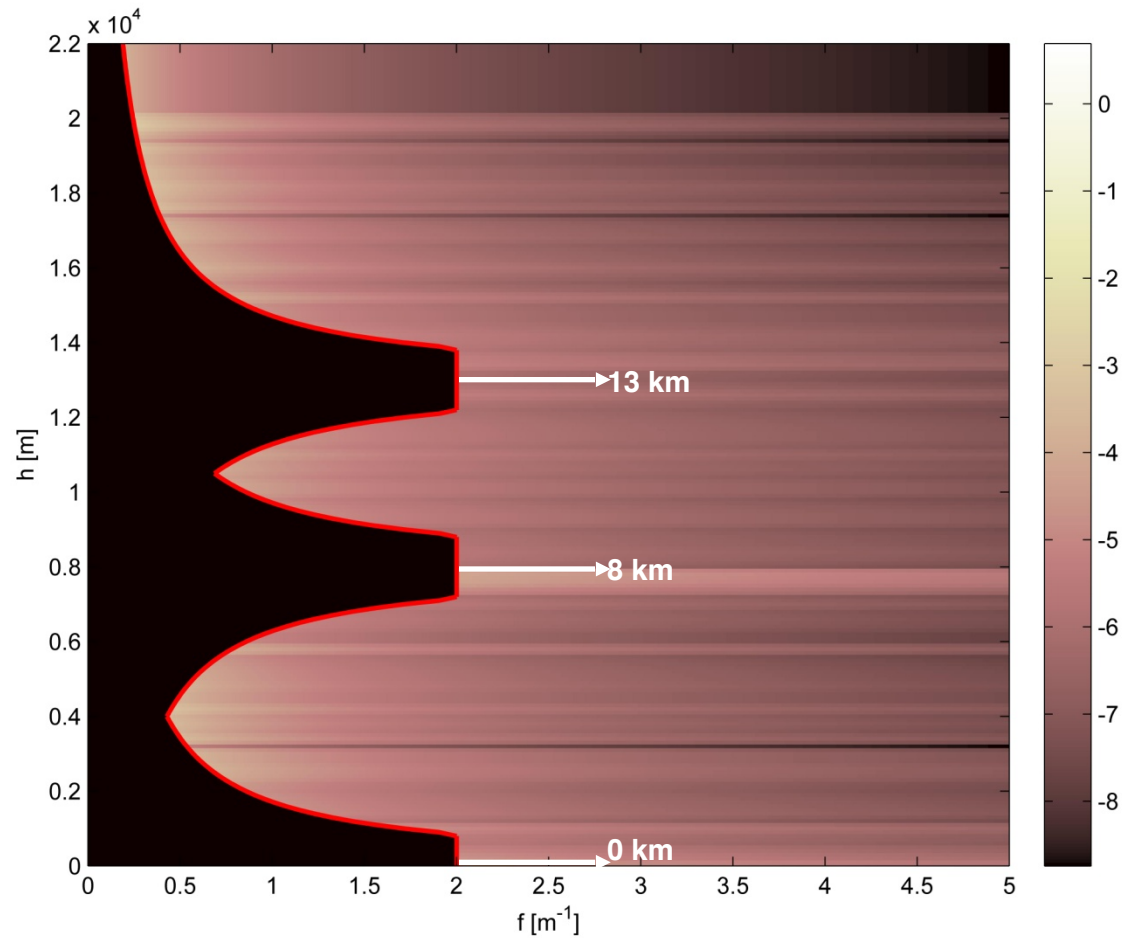
$D_{tel} = 40 \text{ m}$   
 N. DMs = 2  
 N. actuators = 80  
 Field of View = 2 arcmin

$$R = \sum_H \int_F \Phi_{\varphi}^{2D}(f) df$$

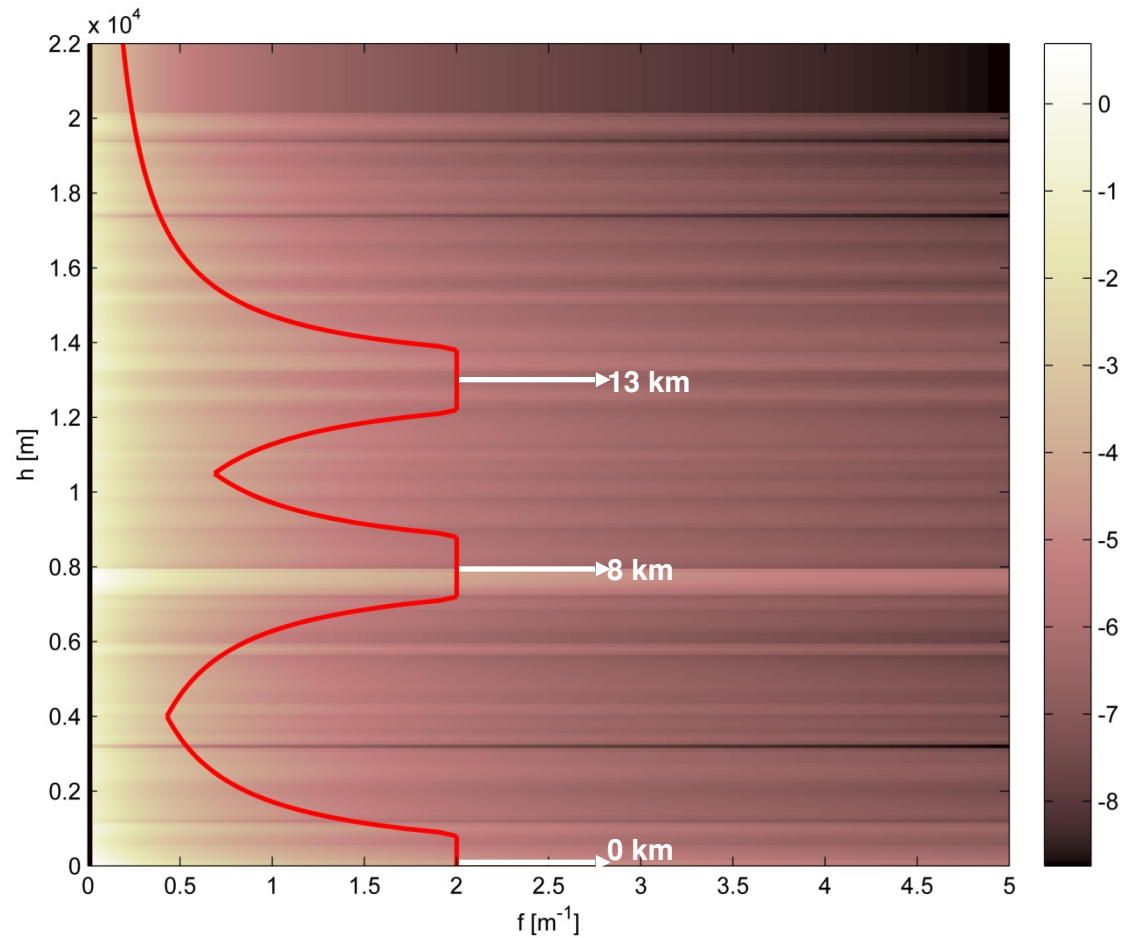
$$R_{MAD-40m} = 0.0239$$



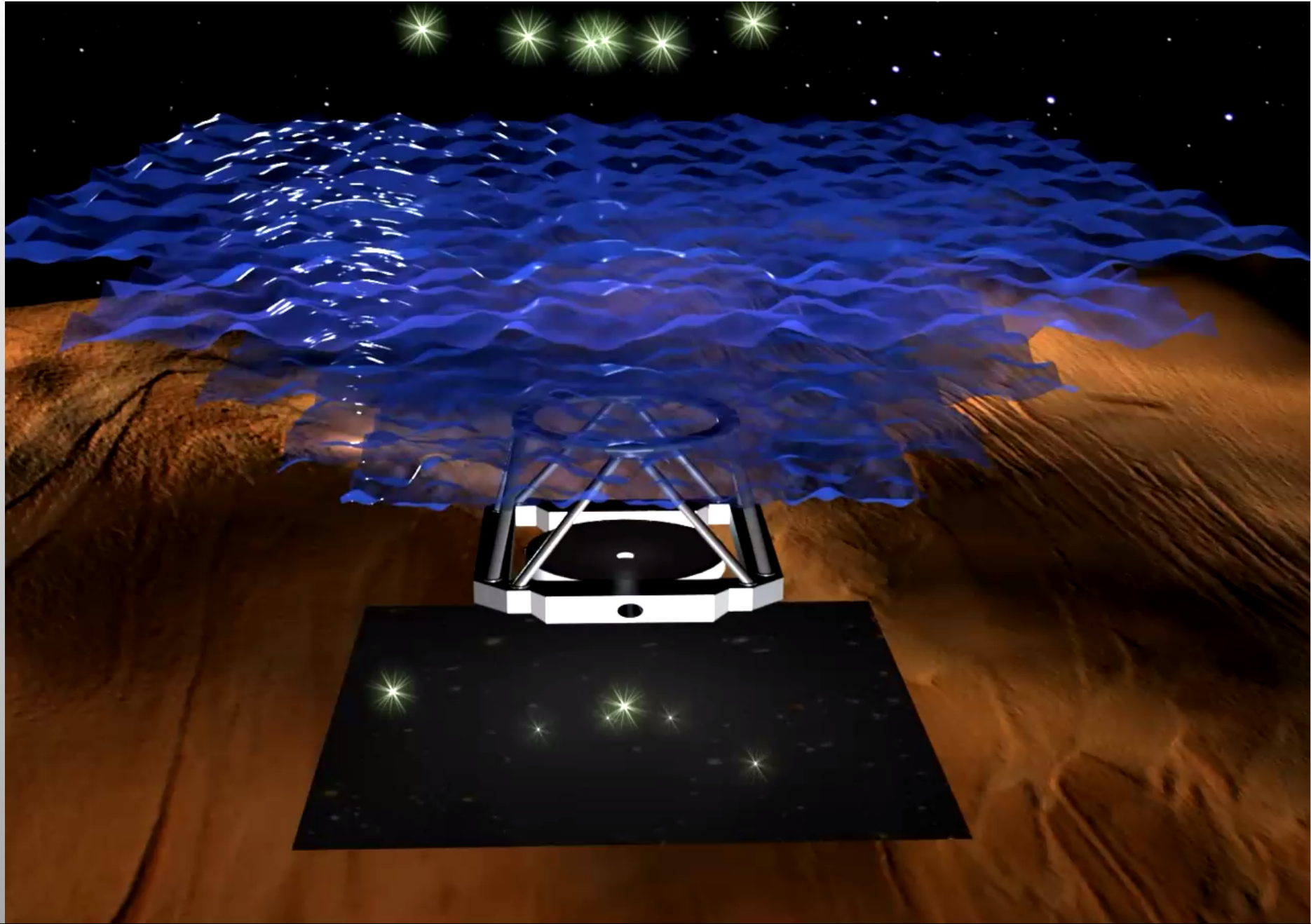
$D_{tel} = 40 \text{ m}$   
 N. DMs = 3  
 N. actuators = 80  
 Field of View = 2 arcmin



$D_{tel} = 40 \text{ m}$   
 N. DMs = 3  
 N. actuators = 80  
 Field of View = 2 arcmin  
  
 N.VDMs = 0

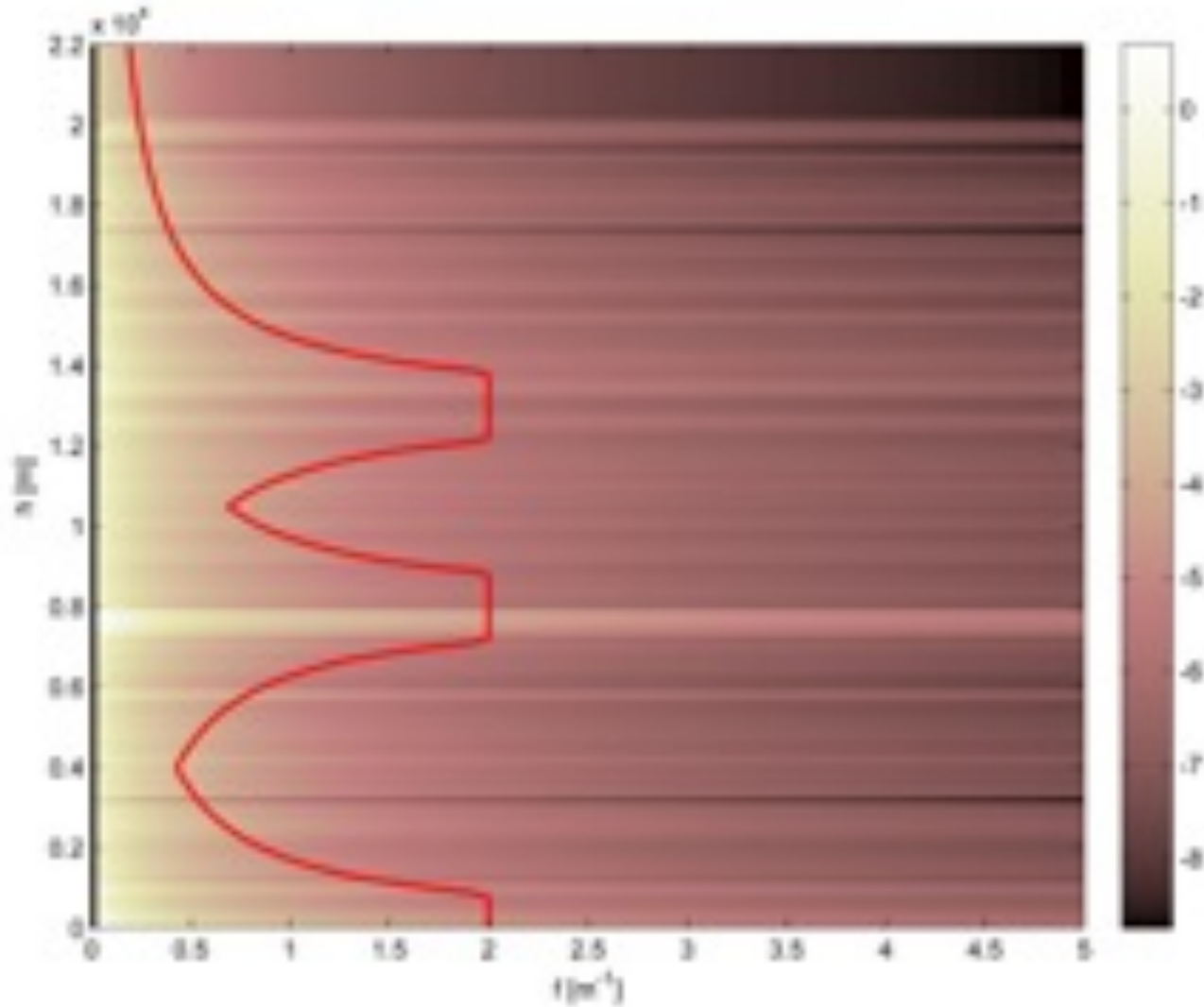




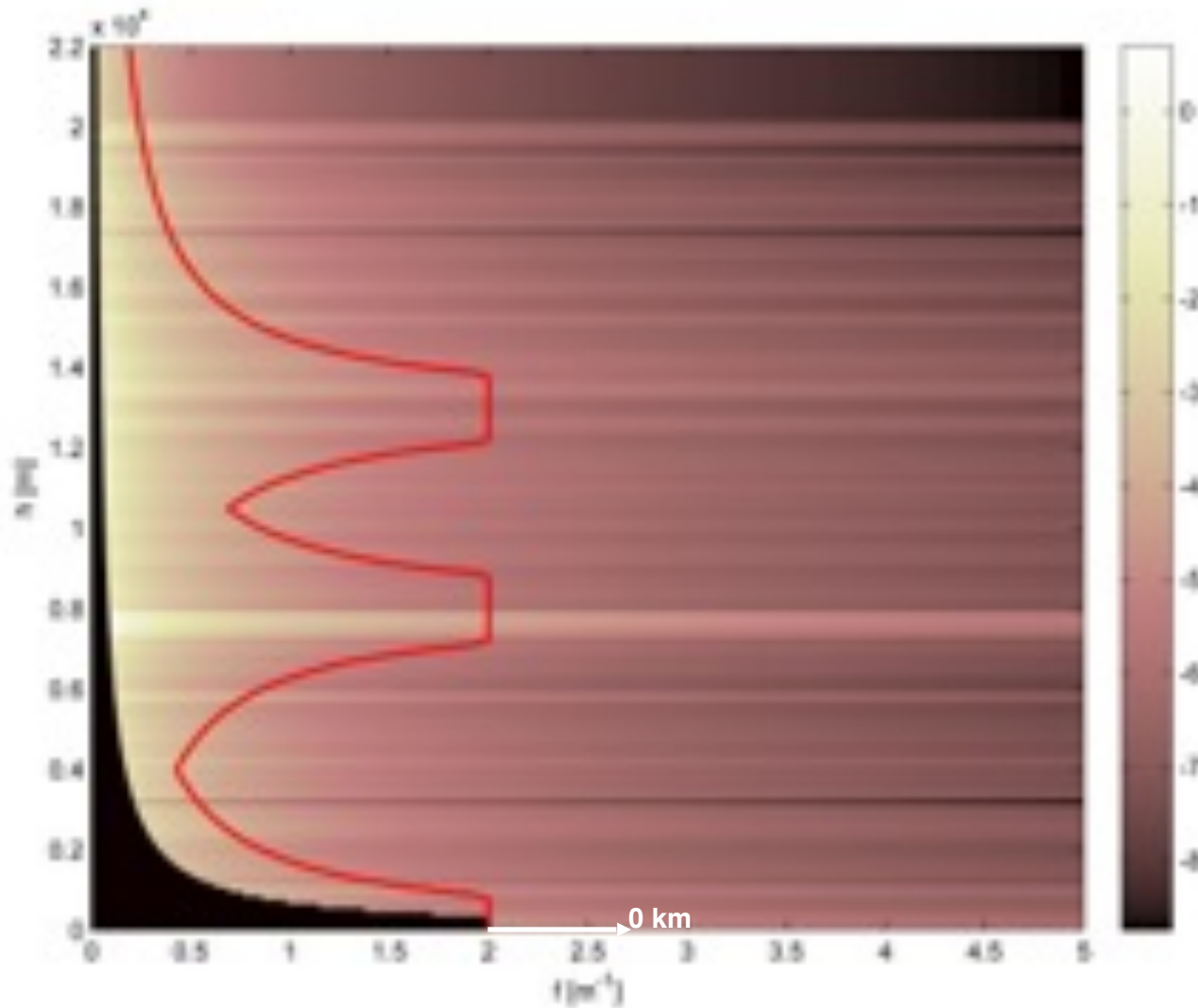




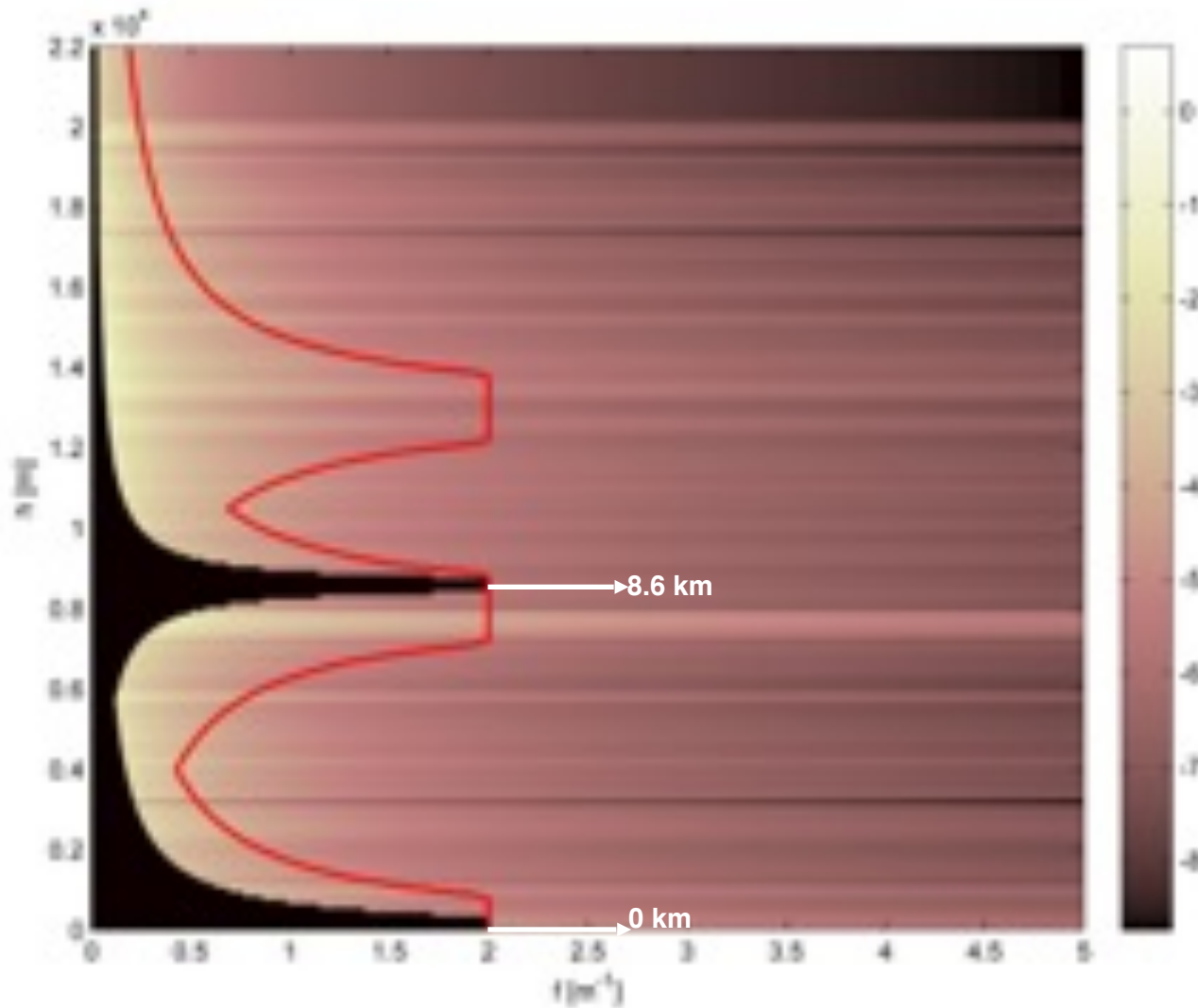
Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



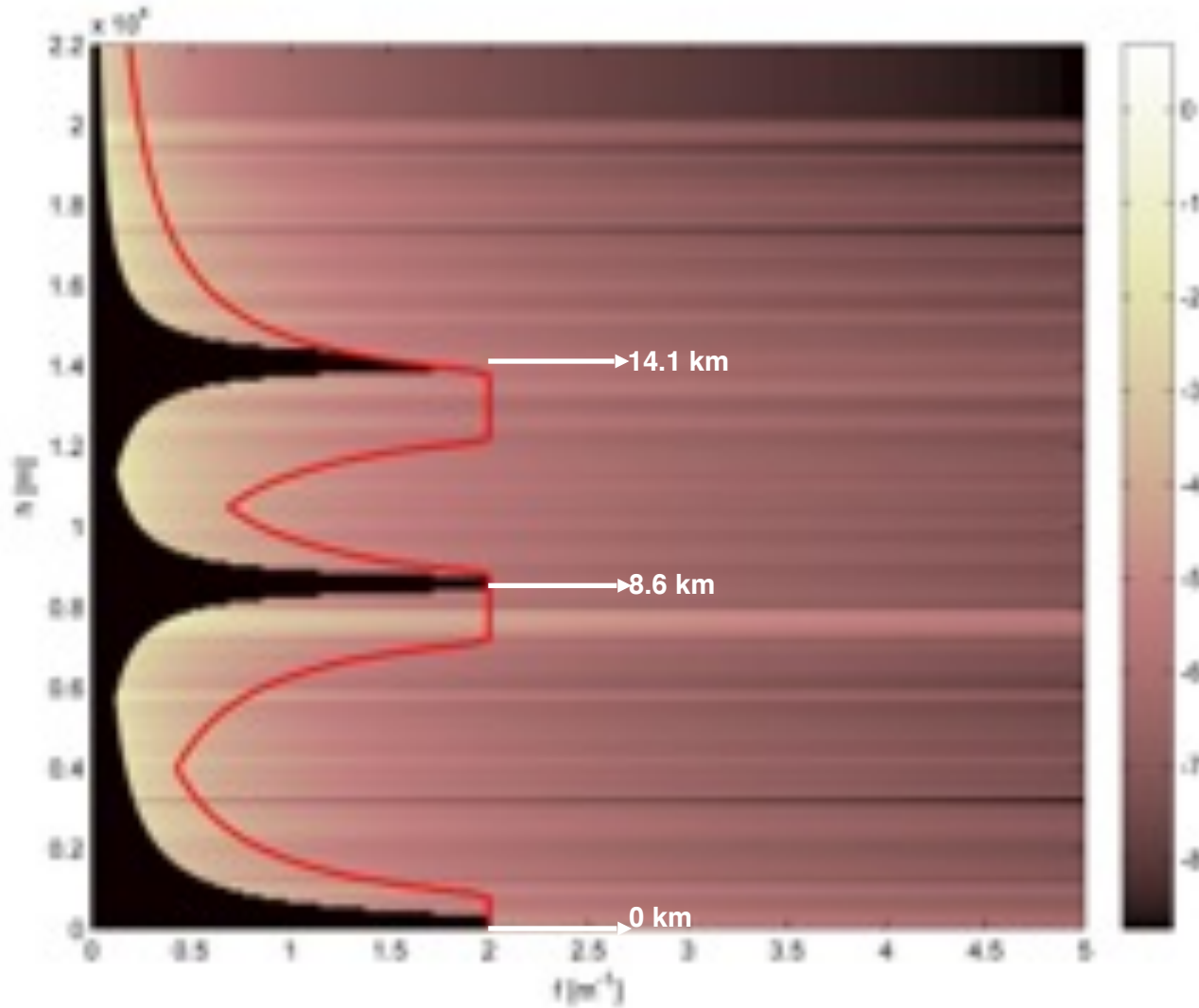
Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



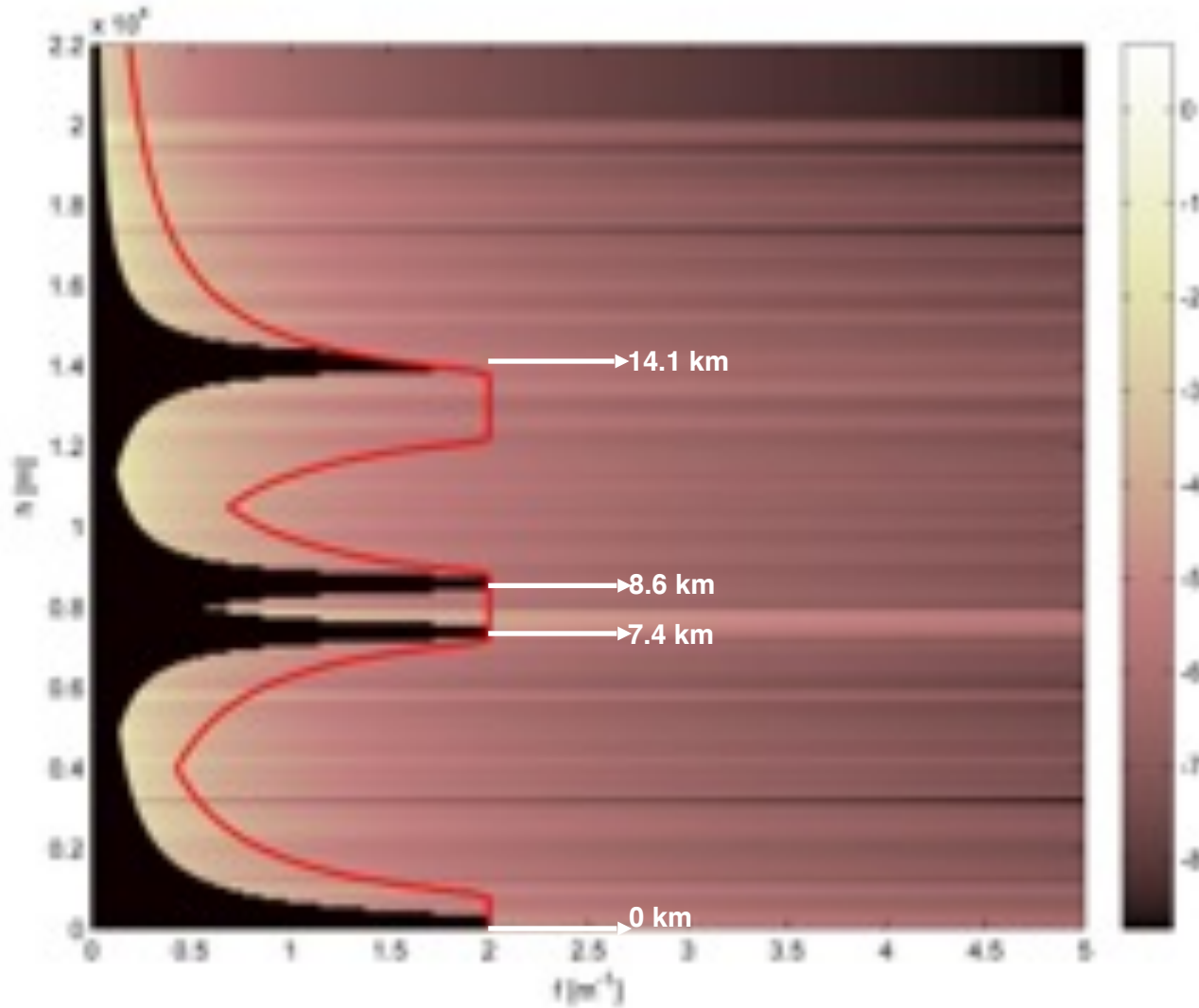
Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



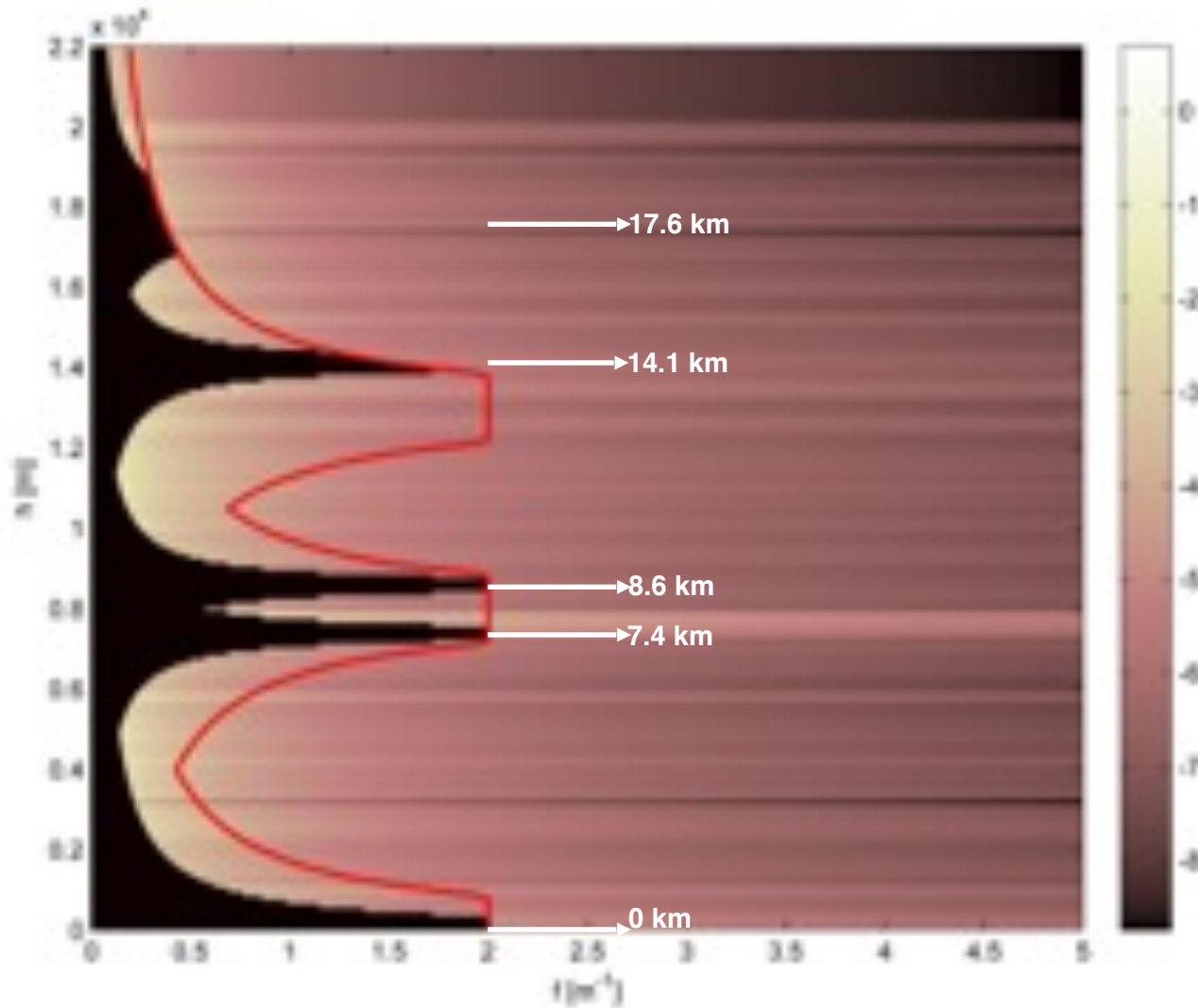
Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



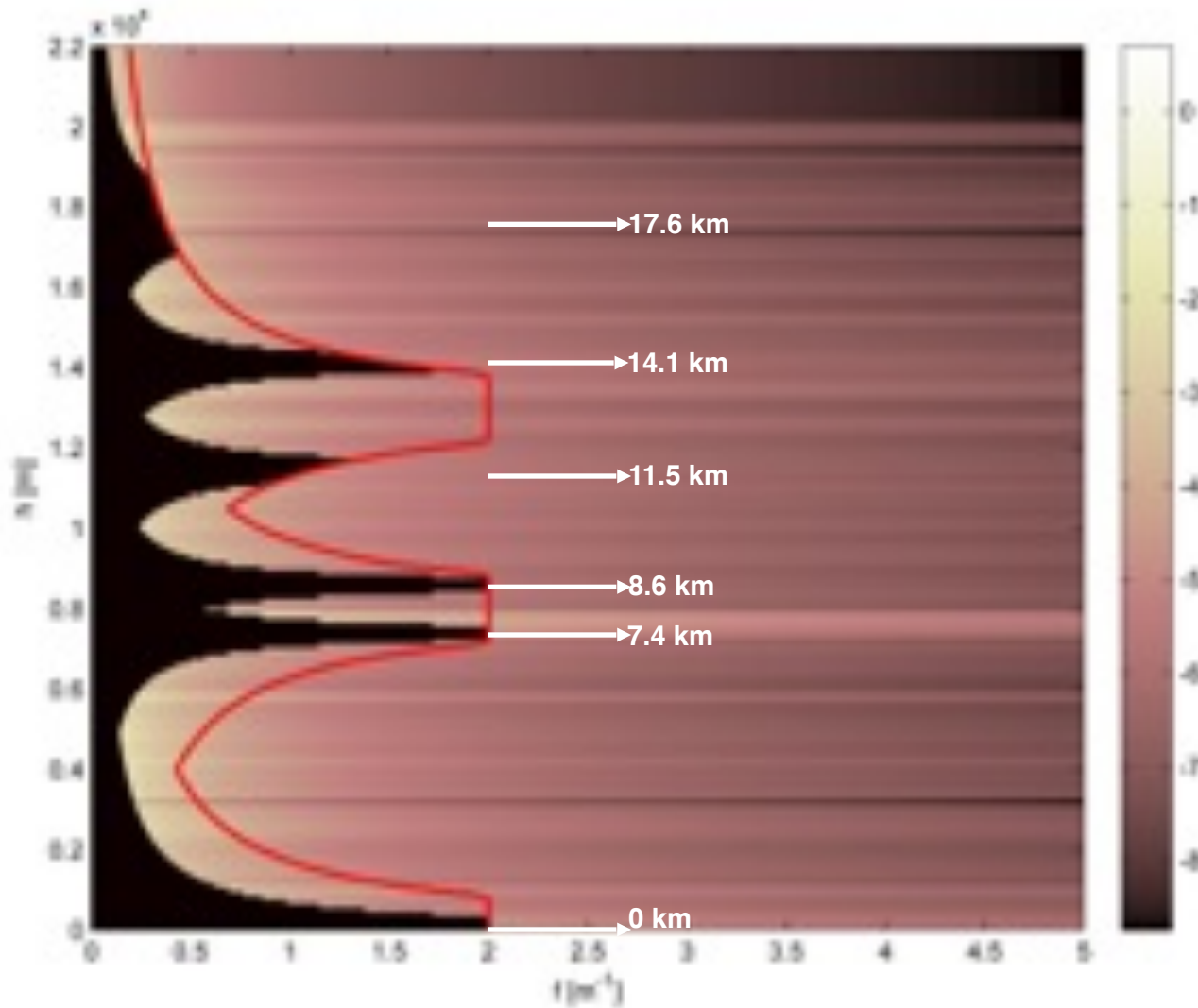
Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin

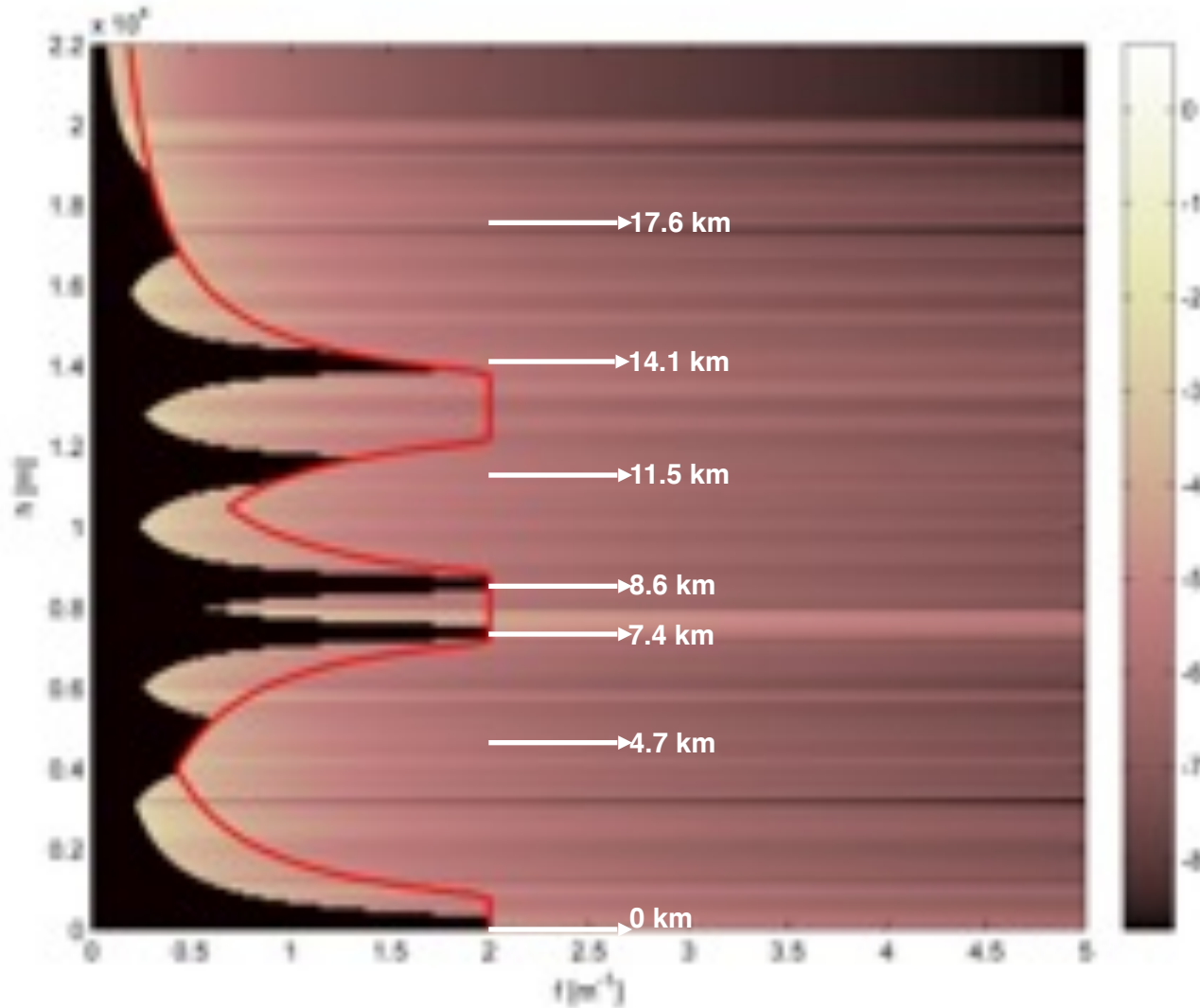


Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



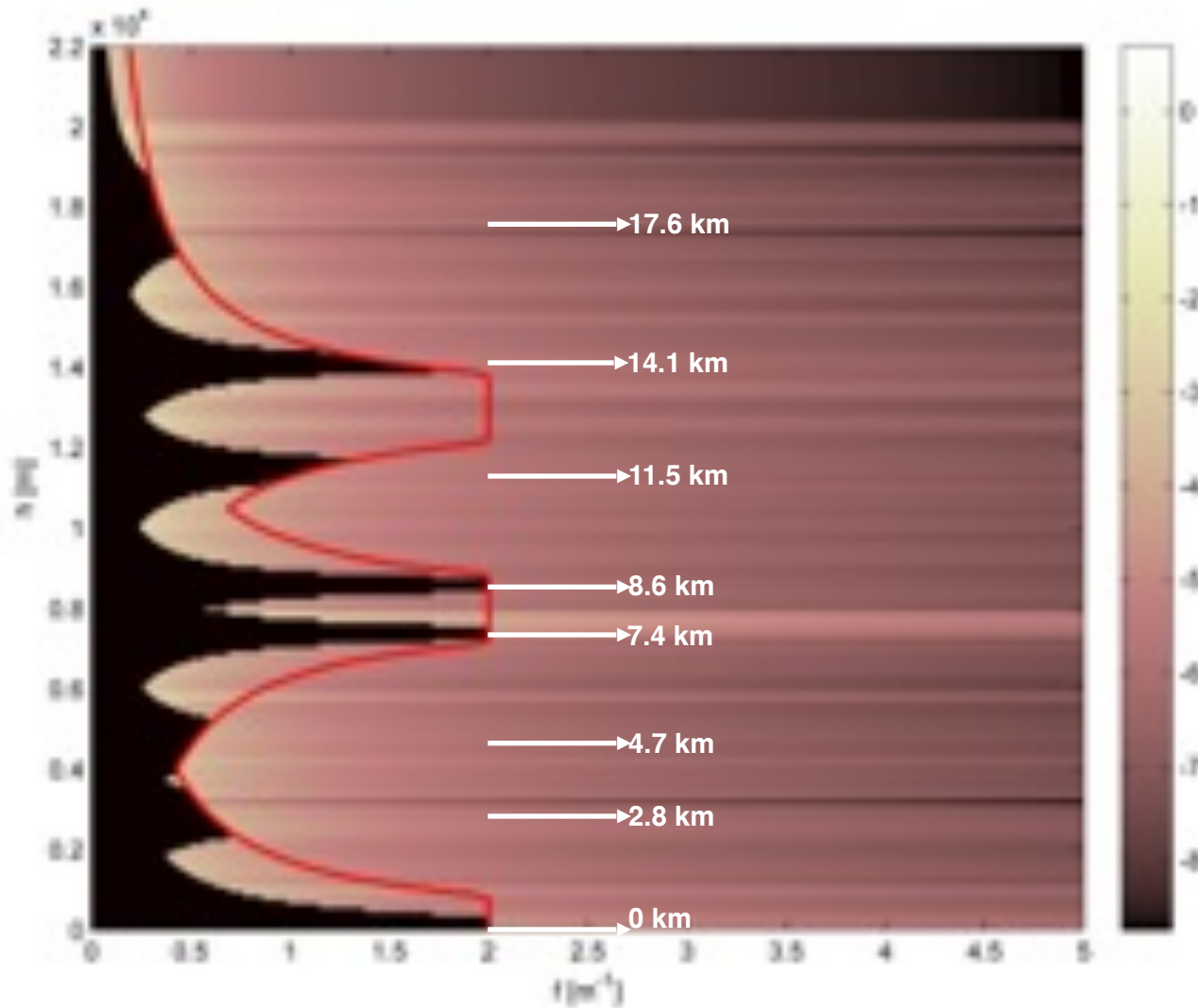


Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin

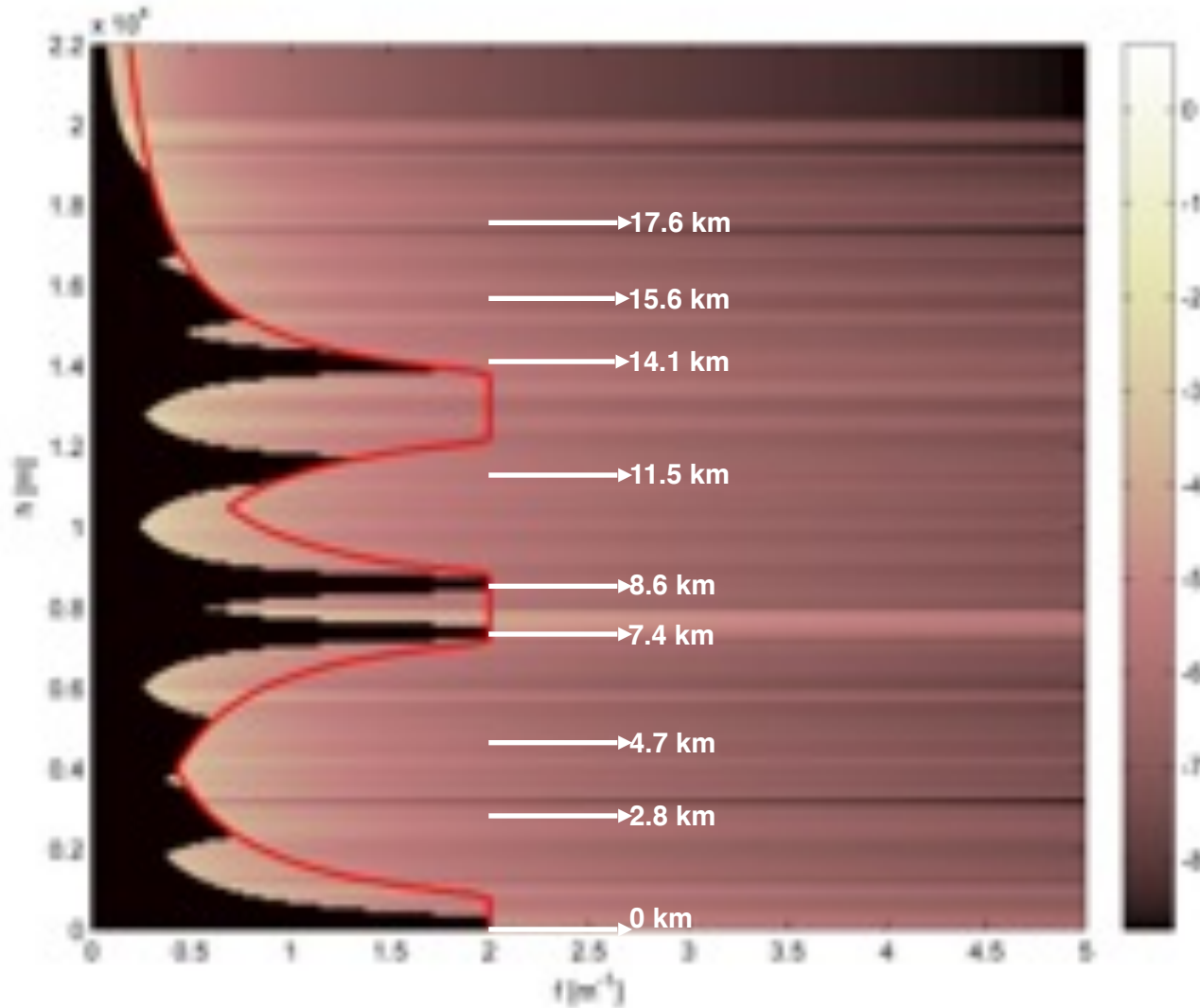




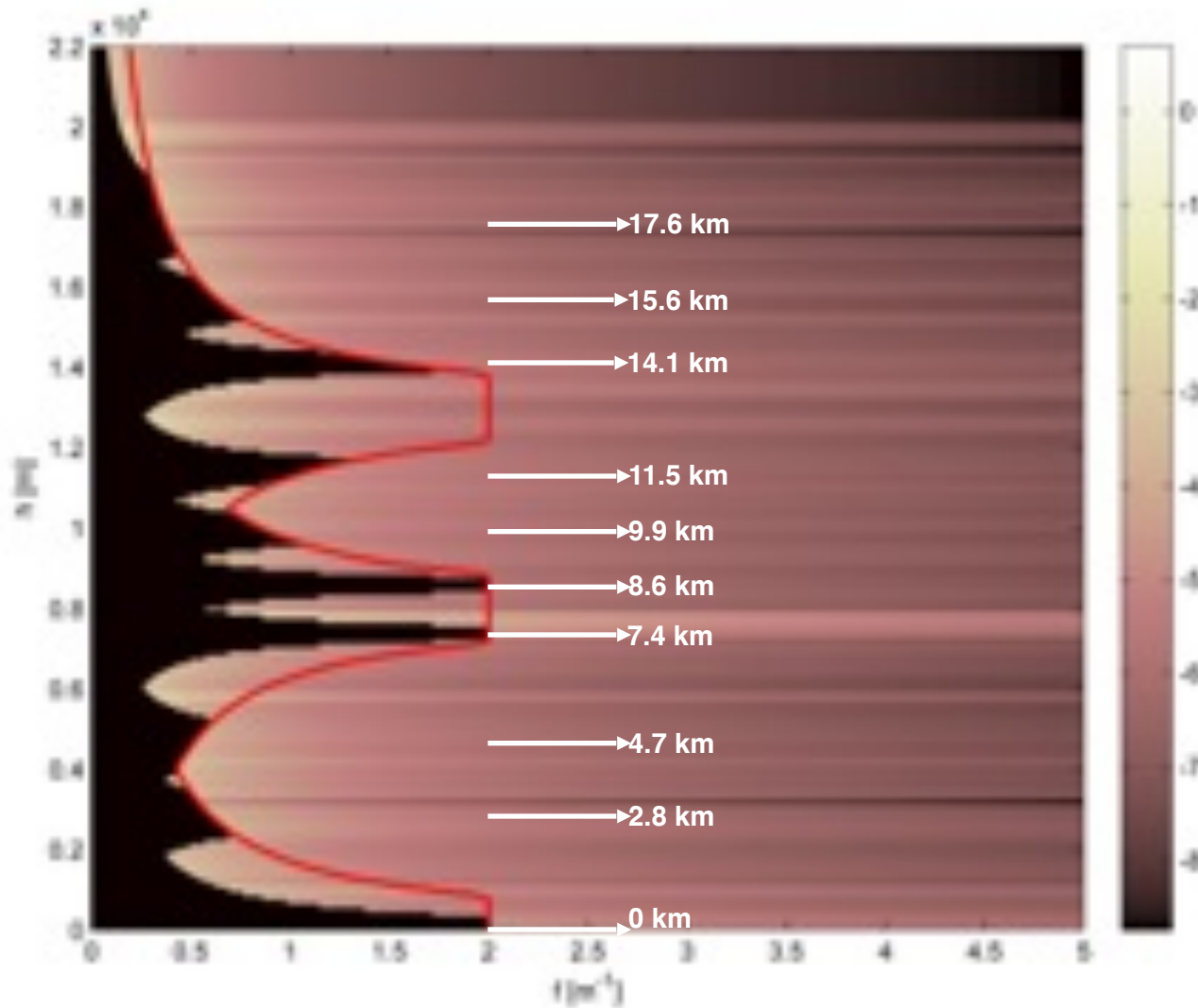
Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



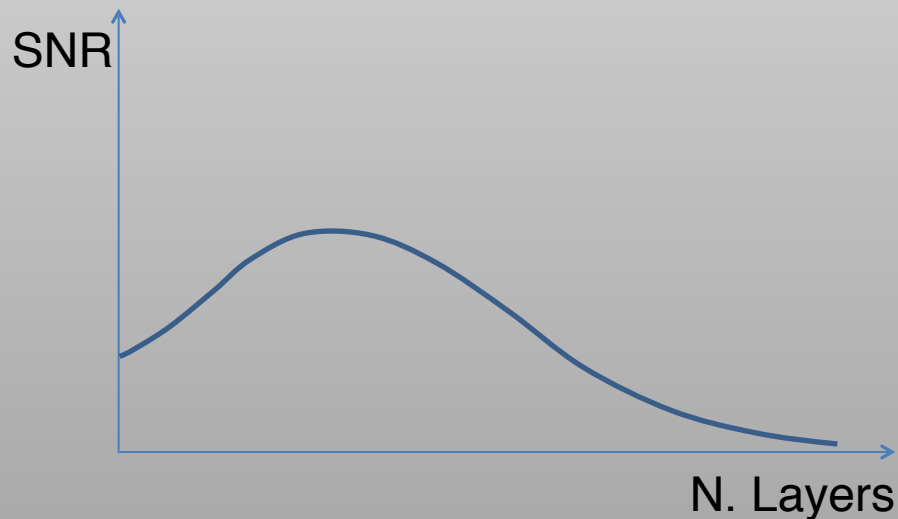
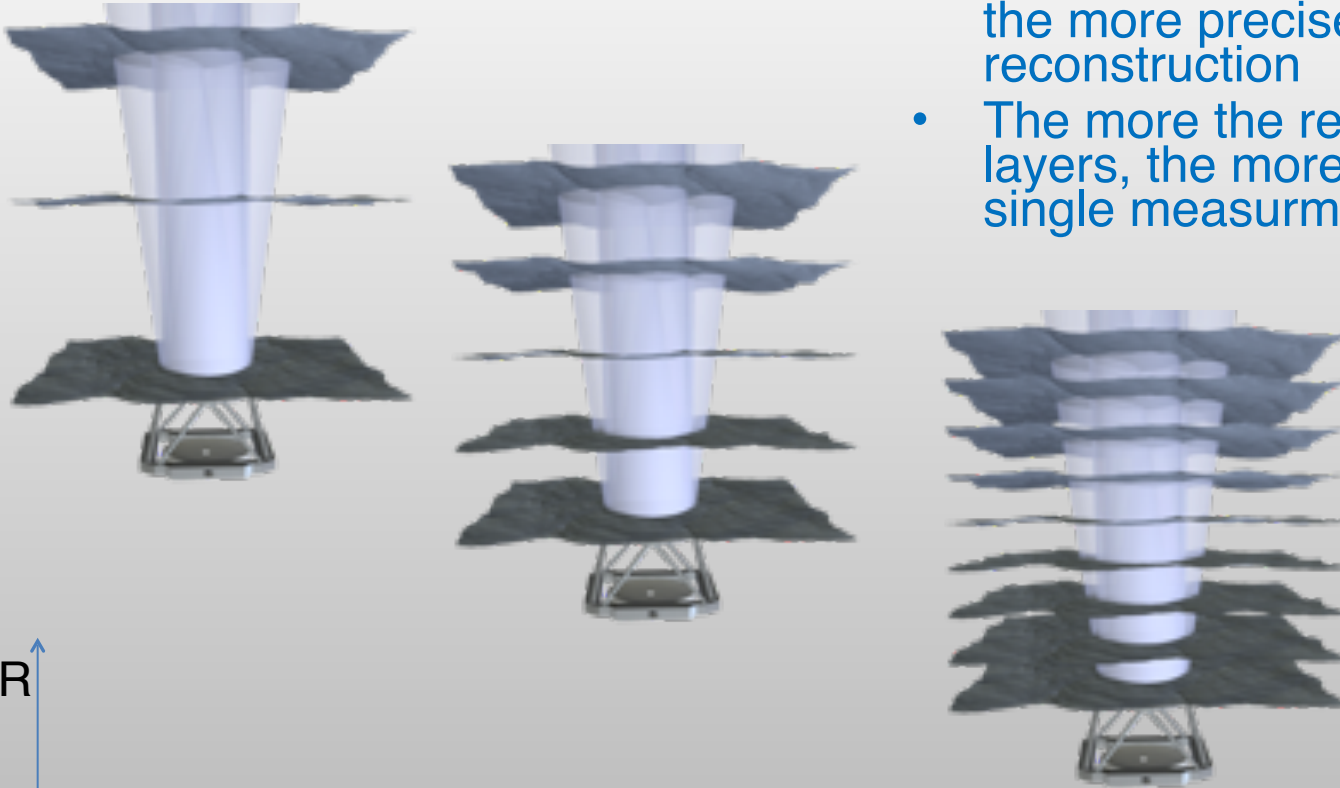
Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



Ground VDM FoV = 5 arcmin  
VDMs FoV = 10 arcmin



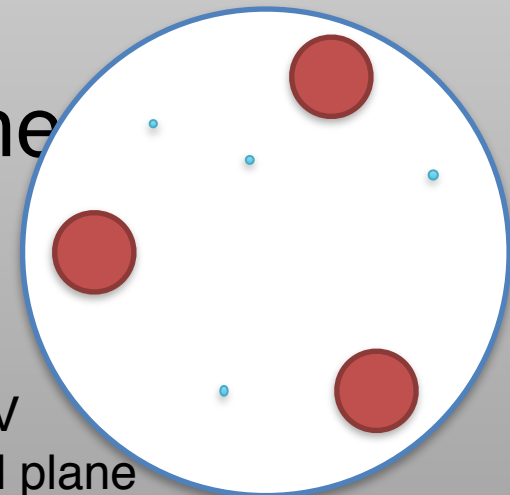
- The more the considered layers, the more precise the turbulence reconstruction
- The more the reconstructed layers, the more the noise from single measurements



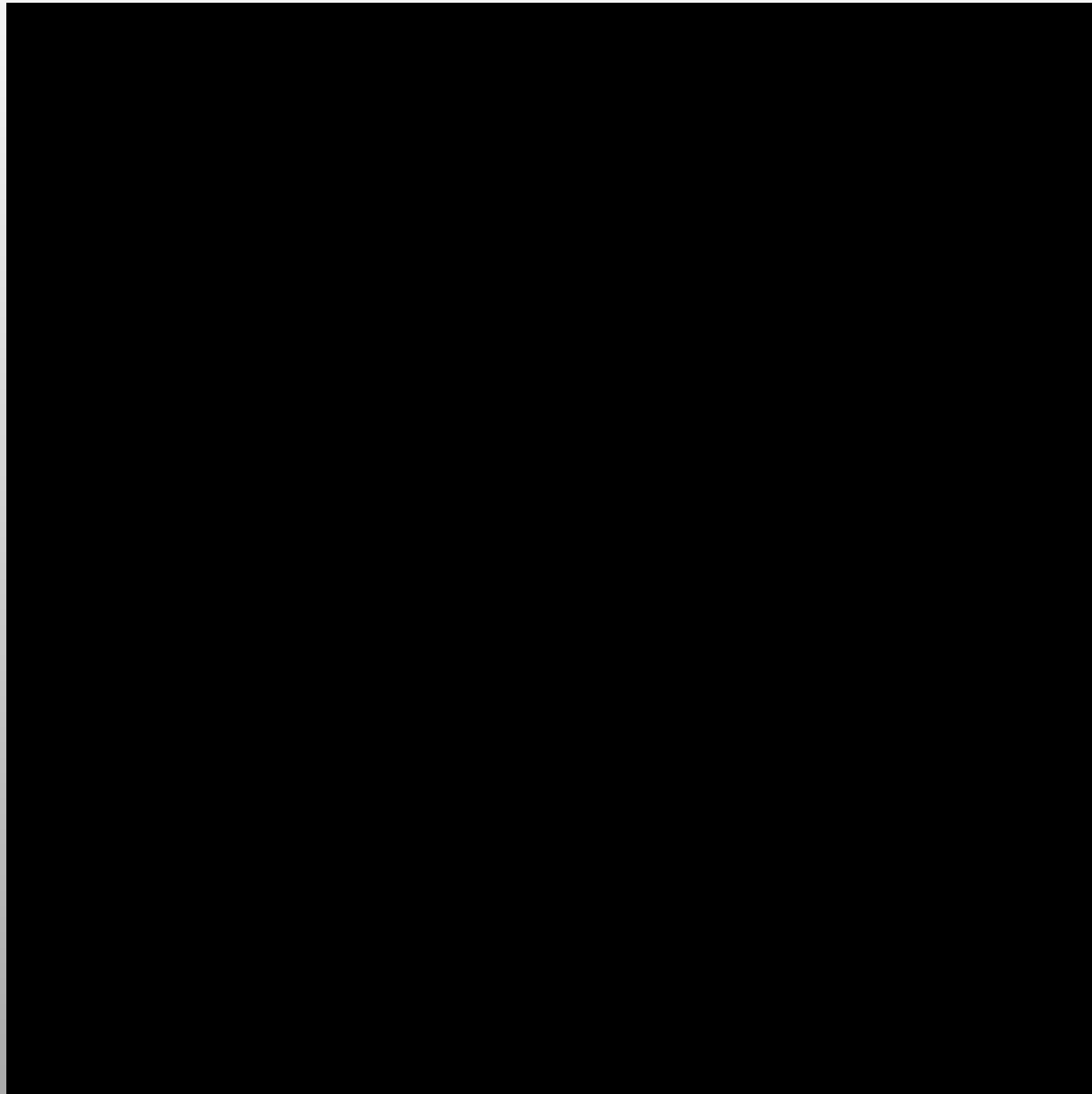
# Technology is at hands...

- Locally closed loop WFSs makes Pyramids working in (almost) closed loop
- These devices (we called Very Linear VL-WFSs) works around non zero
- Conceptually is exactly the same problem as MOAO
- NGSs are less invasive in the focal plane

Stars



10arcmin FoV  
Science focal plane



### THE E-ELT OPTICAL DESIGN.

**Fast's characteristics:**

- Variable gain in (0.001-100)
- 4-image approach
- Linearly linked (Ragazzoni, 1994)

**Advantages (1994):**

- Fast's structure (larger than needed for ELT) will be for NGS (0.001-100)

**Fast's structure:**

- Deformable Mirror (DM)
- Mirror slightly tilted (0.1°)
- Enables gain to use the same collimator

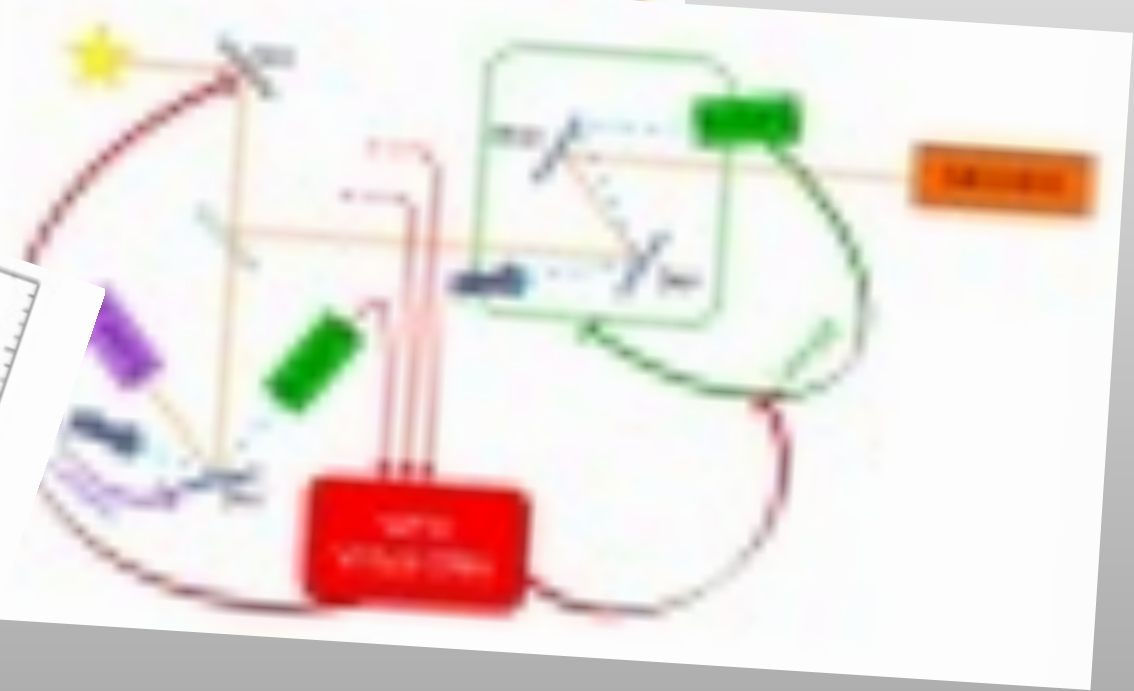
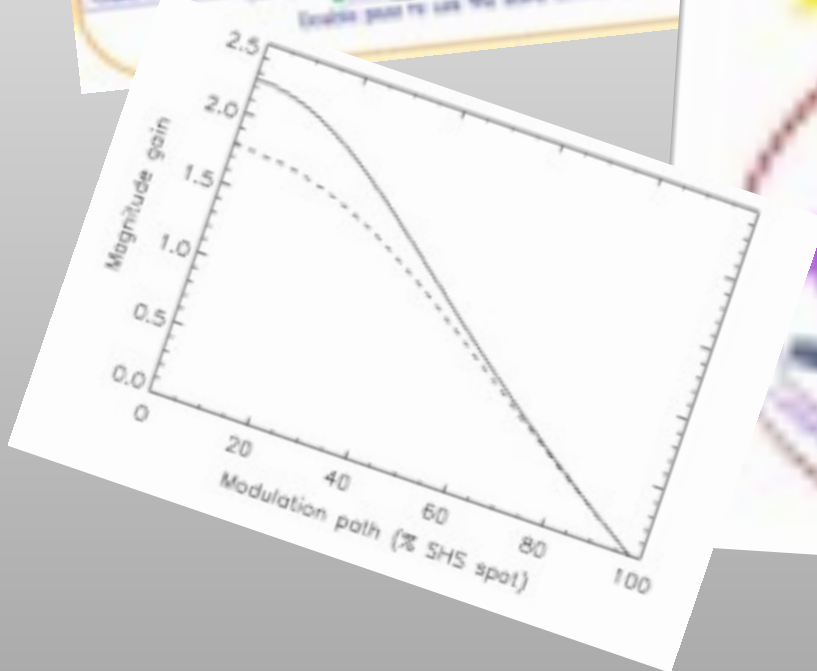
**1994:**

To combine the Pyramid Wavefront Sensor (PWS) with the Fast's Wavefront Sensor (WFS) in order to get the better of both of them.

WFS - Outputs are easy to combine. Needs to be similar image approach (Fast Design Sensors).

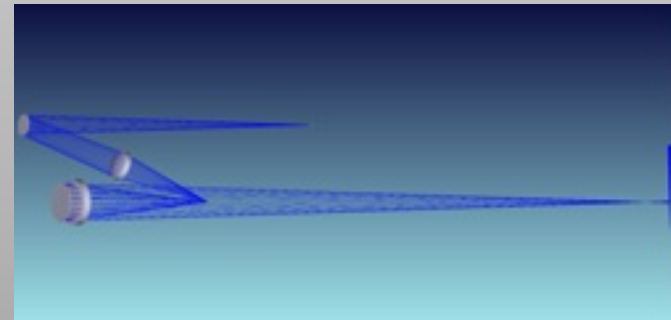
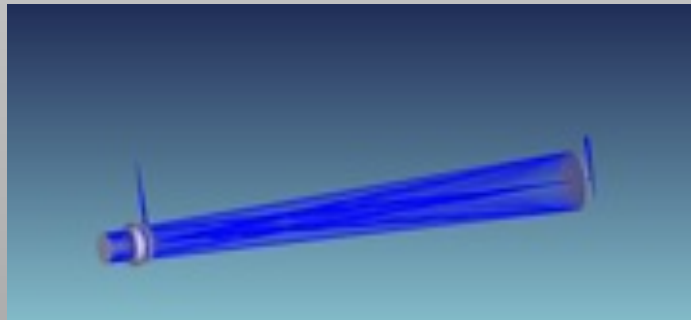
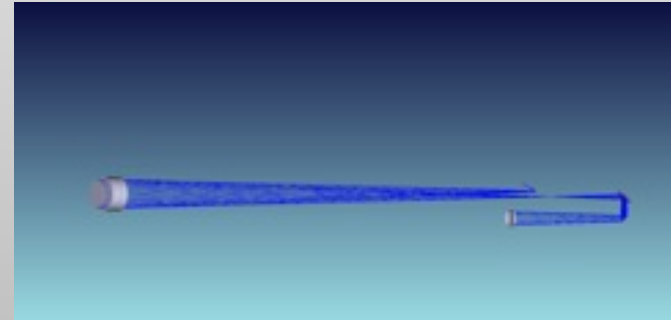
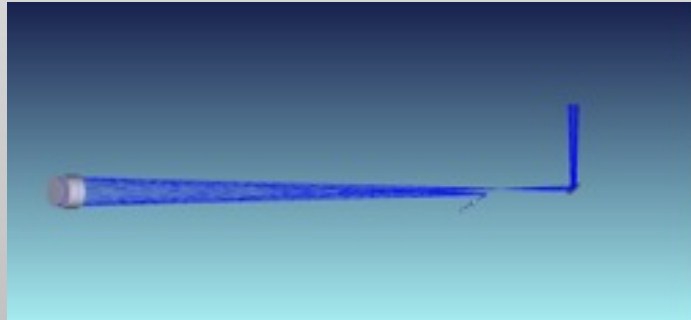
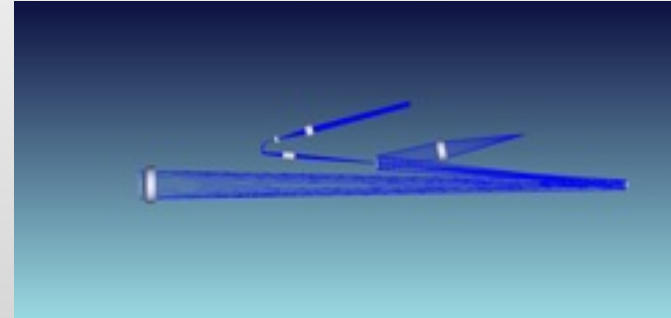
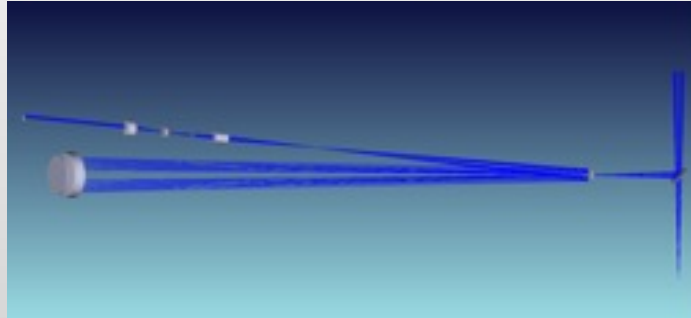
**Fast's characteristics:**

- Highly linear at a wide range
- 4-image approach
- No "intercept-point" effect (Ragazzoni et al., 2009)



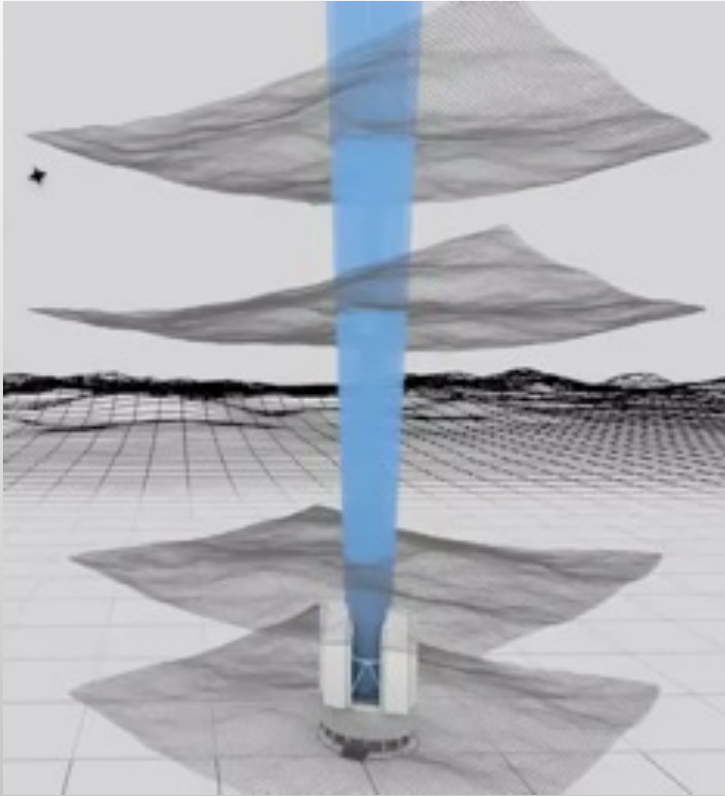


We are evaluating pro and cons of several different optical designs ...  
**work in progress**

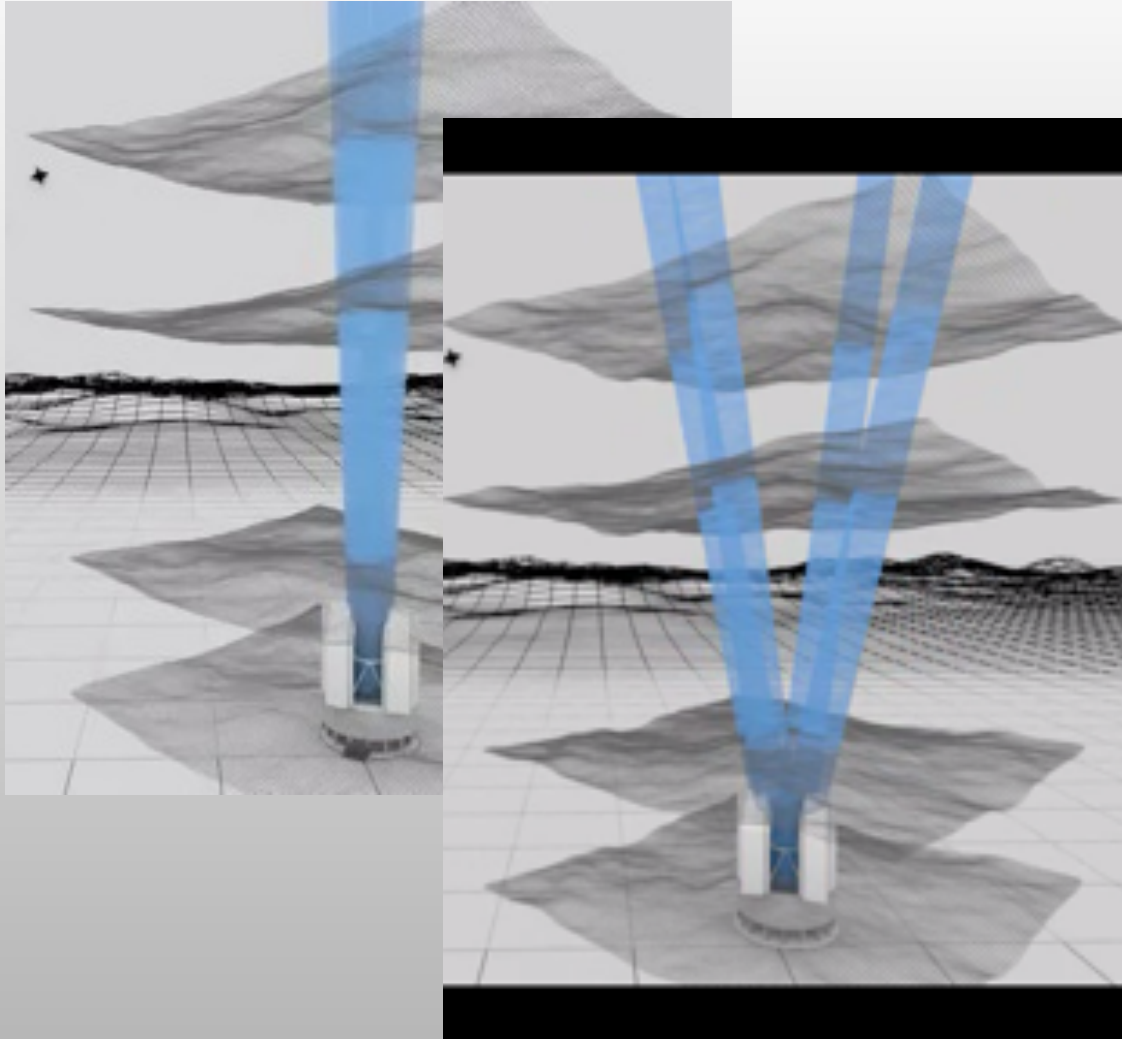




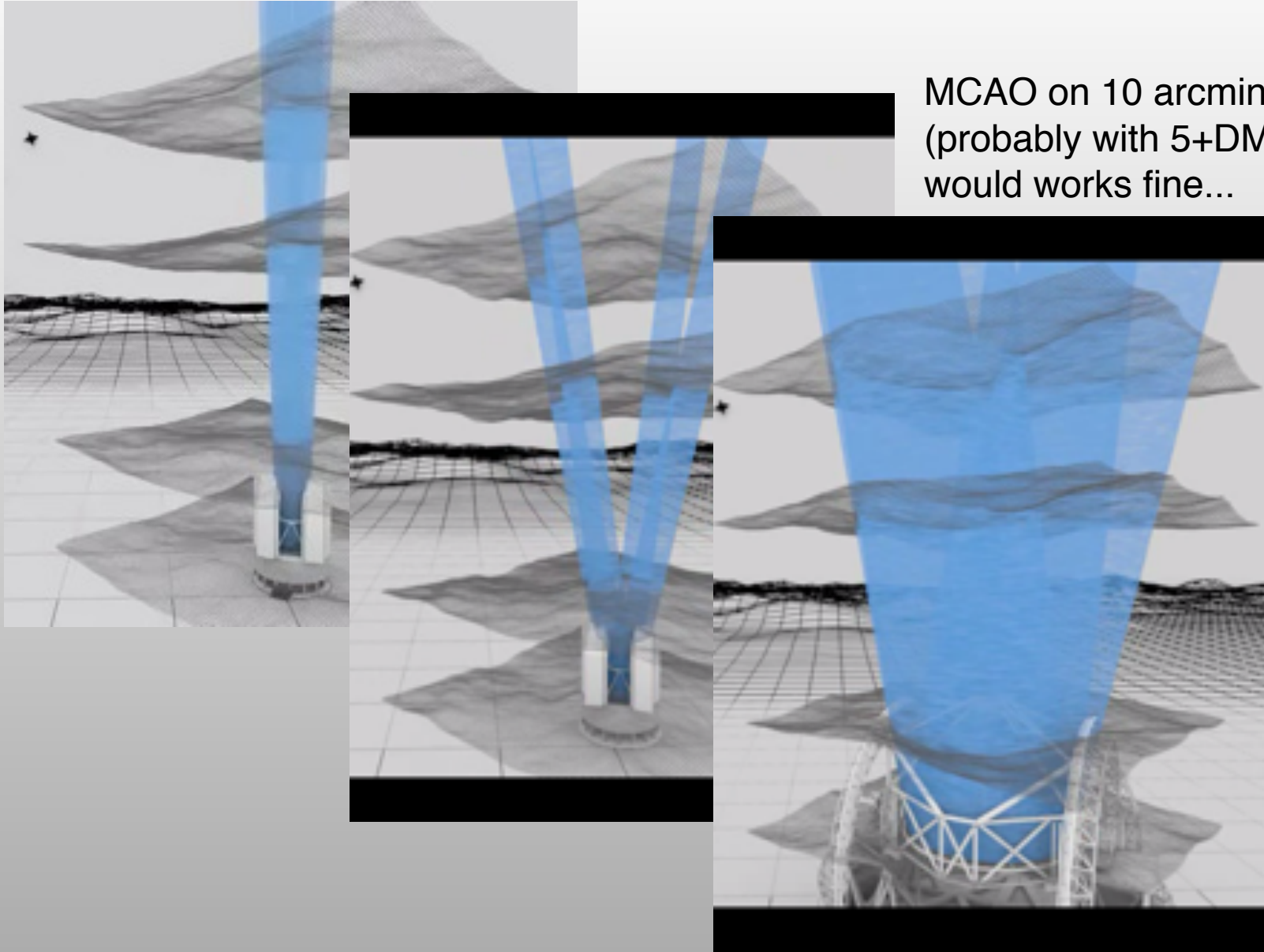




MCAO on 2 arcmin at an 8m

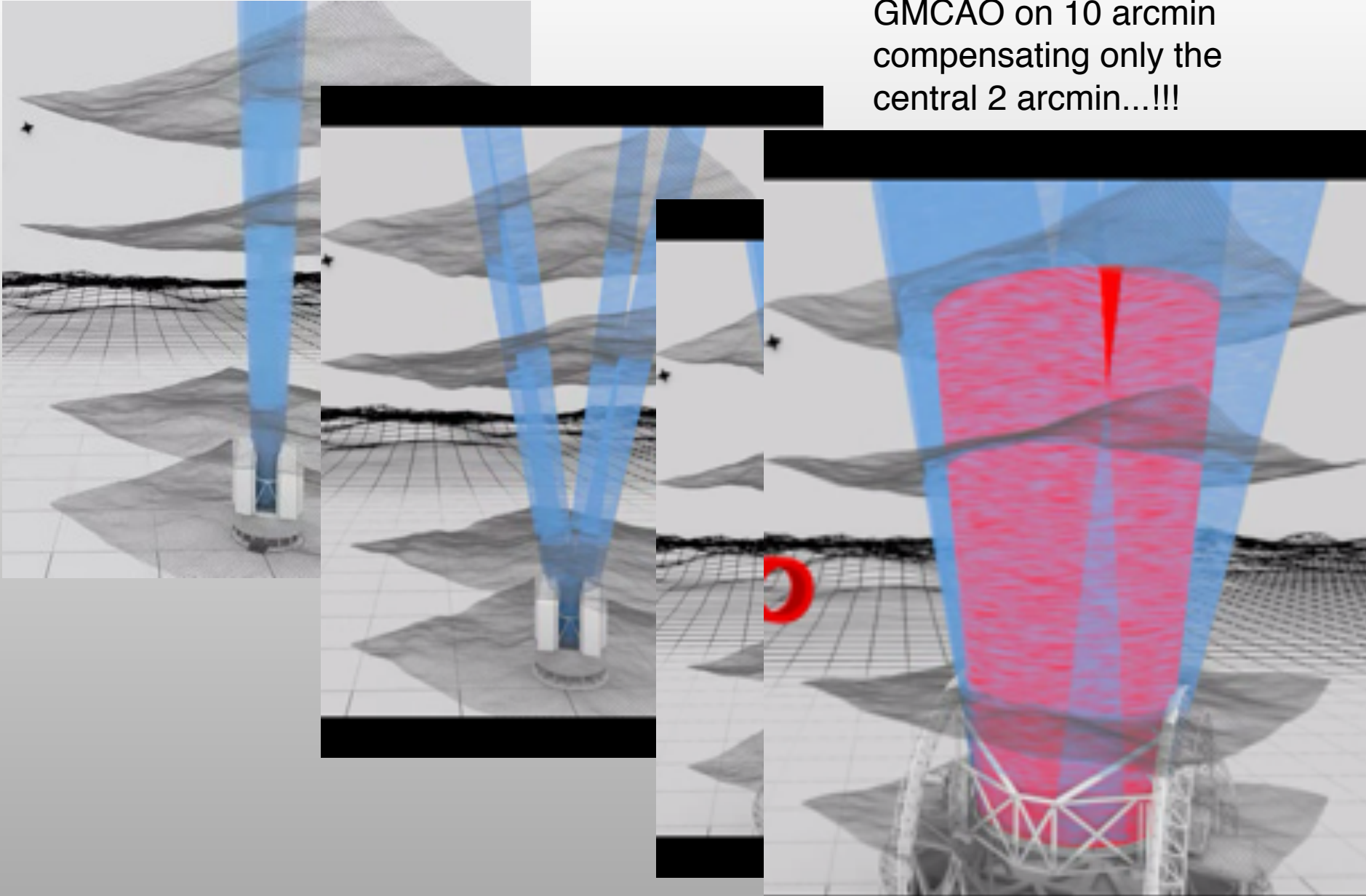


MCAO on 10 arcmin at an 8m  
would not give advantages  
other than for GLAO...



MCAO on 10 arcmin  
(probably with 5+DMs)  
would work fine...

GMCAO on 10 arcmin  
compensating only the  
central 2 arcmin...!!!



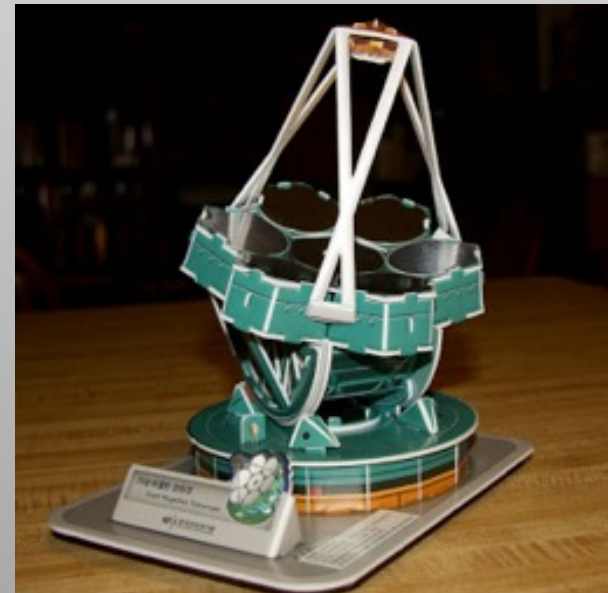


# Conclusions

- GMCAO can be used as back-up plan or...
- ...as performance mitigator (cyrrus, LGS failure...) and can coexists with LGSs.
- Performance assessment expected by AO4ELT3 in Florence late May

# Conclusions

- GMCAO can be used as back-up plan or...
- ...as performance mitigator (cyrrus, LGS failure...) and can coexists with LGSs.
- Performance assessment expected by AO4ELT3 in Florence late May
- We have got a GMT model so...



# Conclusions

- GMCAO can be used as back-up plan or...
- ...as performance mitigator (cyrrus, LGS failure...) and can coexists with LGSs.
- Performance assessment expected by AO4ELT3 in Florence late May
- We have got a GMT model so...

