NGAO System Design Phase

Trade study report

3.1 Systems Engineering

Trade study 3.1.2.3.3

LGS Asterism Geometry and Size

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Keck NGAO Team Meeting #2, Caltech, November 14, 2006

LGS asterism geometry & size

- From the NGAO SD SEMP WBS dctnry:
  - 3.1.2.3.3 LGS Asterism Geometry and Size

    Find the simplest LGS asterism geometry meeting the performance budget goals (e.g. quincunx, ring, 1+triangle, or hex) and the asterism radii. Consider optimization of the Strehl of the tip/tilt stars and the resultant sky coverage as well. Complete when LGS asterism, HO WFS, and LO WFS requirements have been documented.

LGS asterism geometry & size

- This trade study supplies:
  - some refinement to the wavefront error budget "Tomography error"
  - a basis for iterating on the wavefront error budget
  - support for other related trade studies (e.g. NGS, sky coverage)
  - a recommendation for potential LGS solutions for Keck NGAO
- The study does not:
  - by itself decide which LGS configuration should be adopted
  - by itself tell you what the sky coverage will be
  - .....

Contents

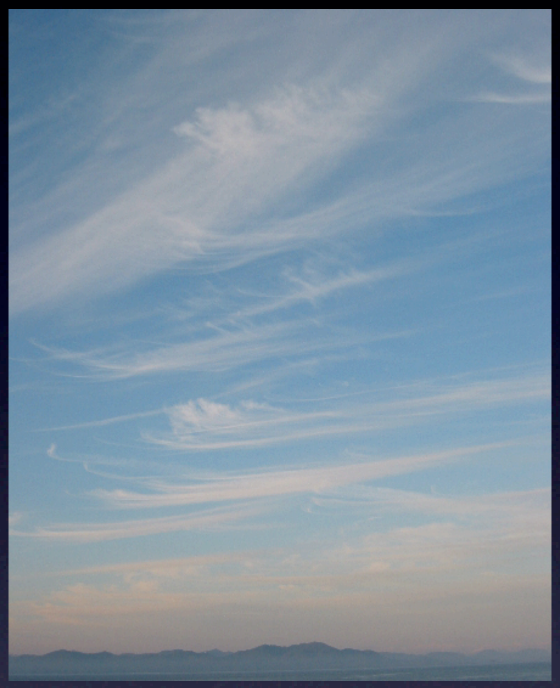
Tomography errors

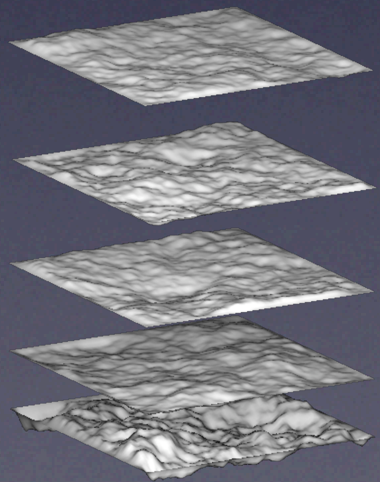
- In a multi-LGS AO system arise from:
  - Imperfect estimation of the science FoV volume turbulence, due to:
    - incomplete sampling of the volume turbulence, tomography only works where the beacons overlap *(sampling error)*
    - fitting a layered estimator model to a continuously distributed atmospheric turbulence profile *(estimator fitting error)*
    - invisible modes, LGS null-modes
  - Imperfect reconstruction of the estimated volume turbulence by having fewer corrector layers than estimation layers *(generalized anisoplanatism error)*

Tomography errors

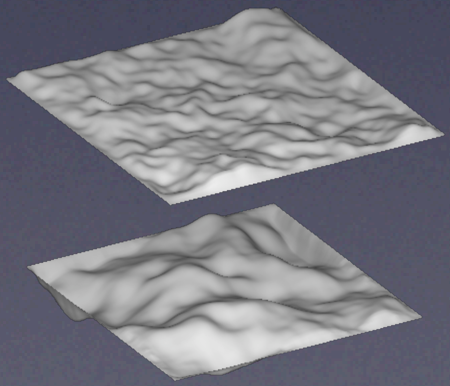
1 sampling

2 estimation


(real profile)


(estimated profile)

3 reconstruction


(corrected profile)

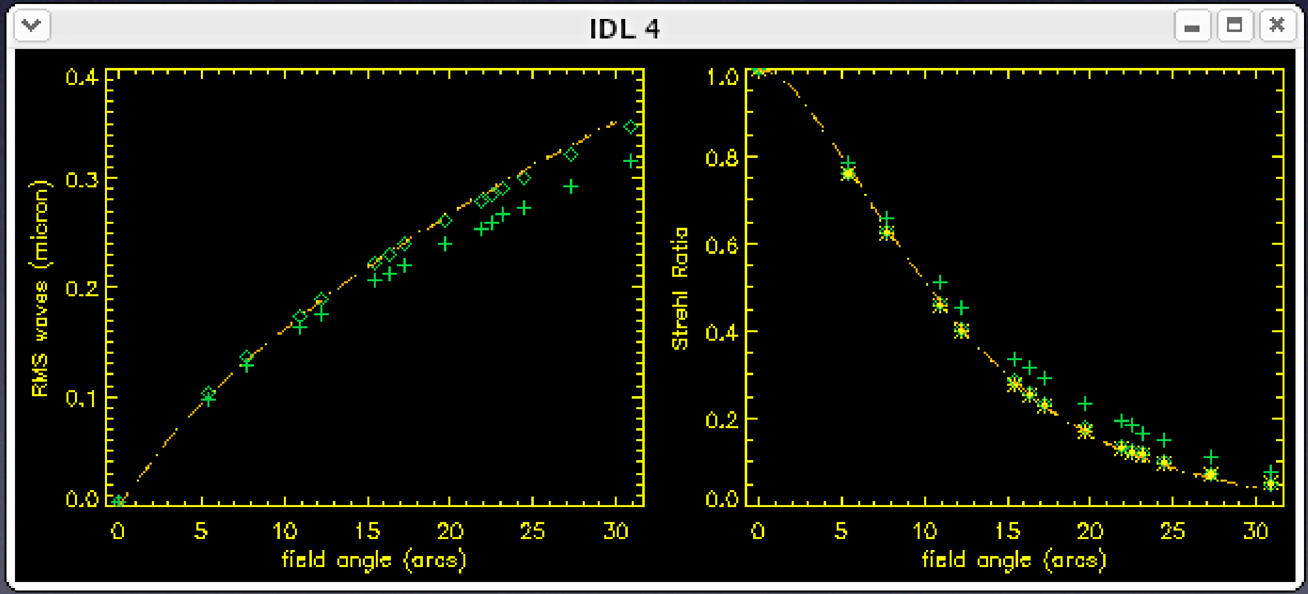
Tomography errors

- Design choices that influence these terms
  - Sampling :
    - LGS configuration, sub-aperture size
      (can not be zeroed in simulation)
  - Estimation :
    - algorithm (1), LGS configuration
      (can be made close to zero in simulation = "ideal")
  - Reconstruction :
    - DM configuration, algorithm (2)
      (can be made close to zero in simulation = "ideal")

Simulation tool

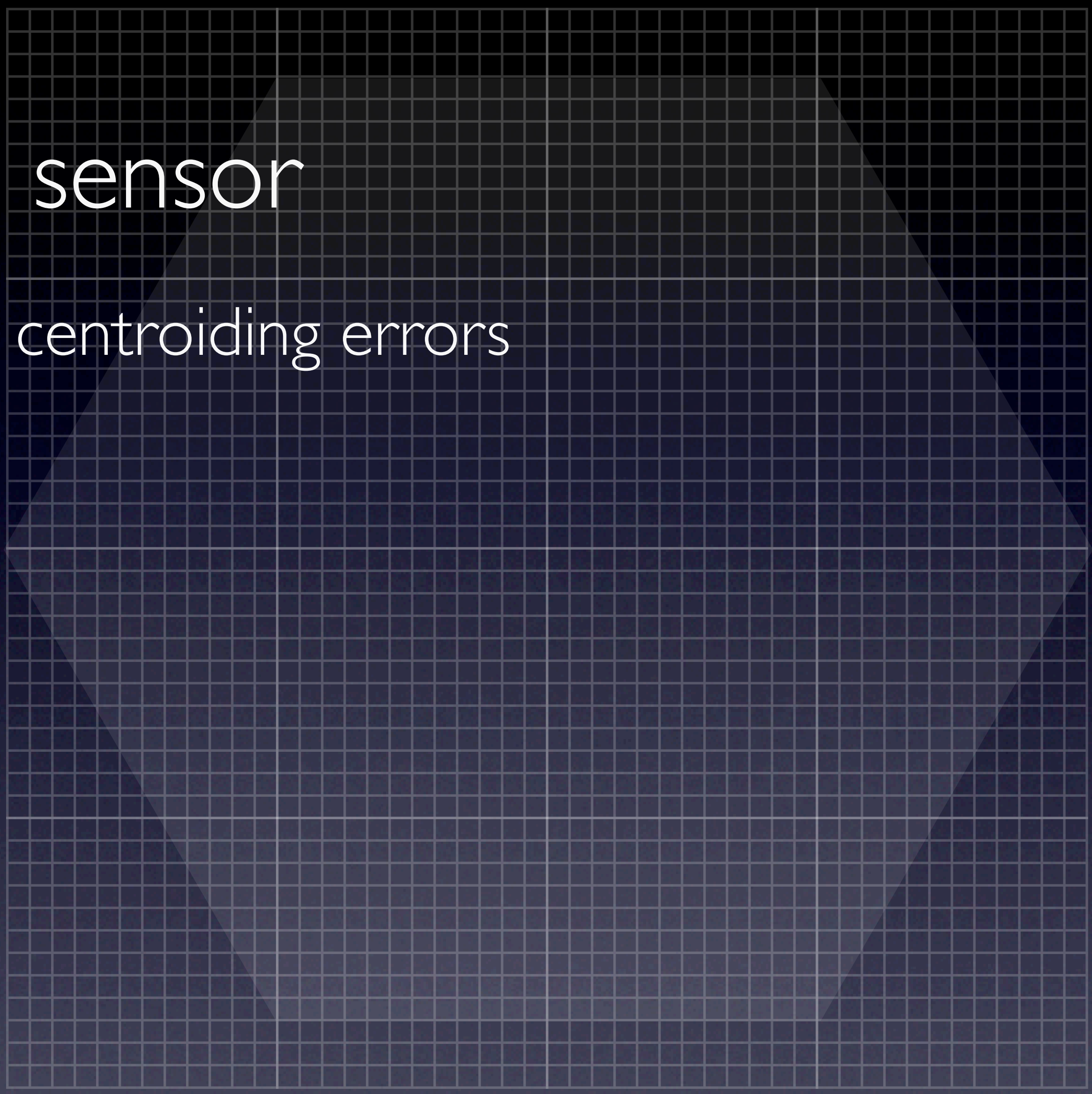
ref: Flicker, R. C. "Efficient first-order performance estimation for high-order adaptive optics systems," Astron. Astrophys. Vol 405, 2003.

- Method
  - Monte Carlo type, random draw Kolmogorov phase screens
  - Undersampled turbulence – no high-spatial-frequency errors are simulated (but can be emulated independently)
  - (SC, MC, LT, MO)AO
  - sparse MAP+PCG alg(1)
  - Used for Euro50 simul.



- Anchoring
  - Model reproduces canonical NGS and LGS anisoplanatism

System model (baseline)



- 48x48 sub-aperture slope sensor
  - geometrical, no aliasing, noise or centroiding errors
- 49x49 actuator corrector
  - no fitting error
- Open loop control
  - zero delay, no bandwidth error

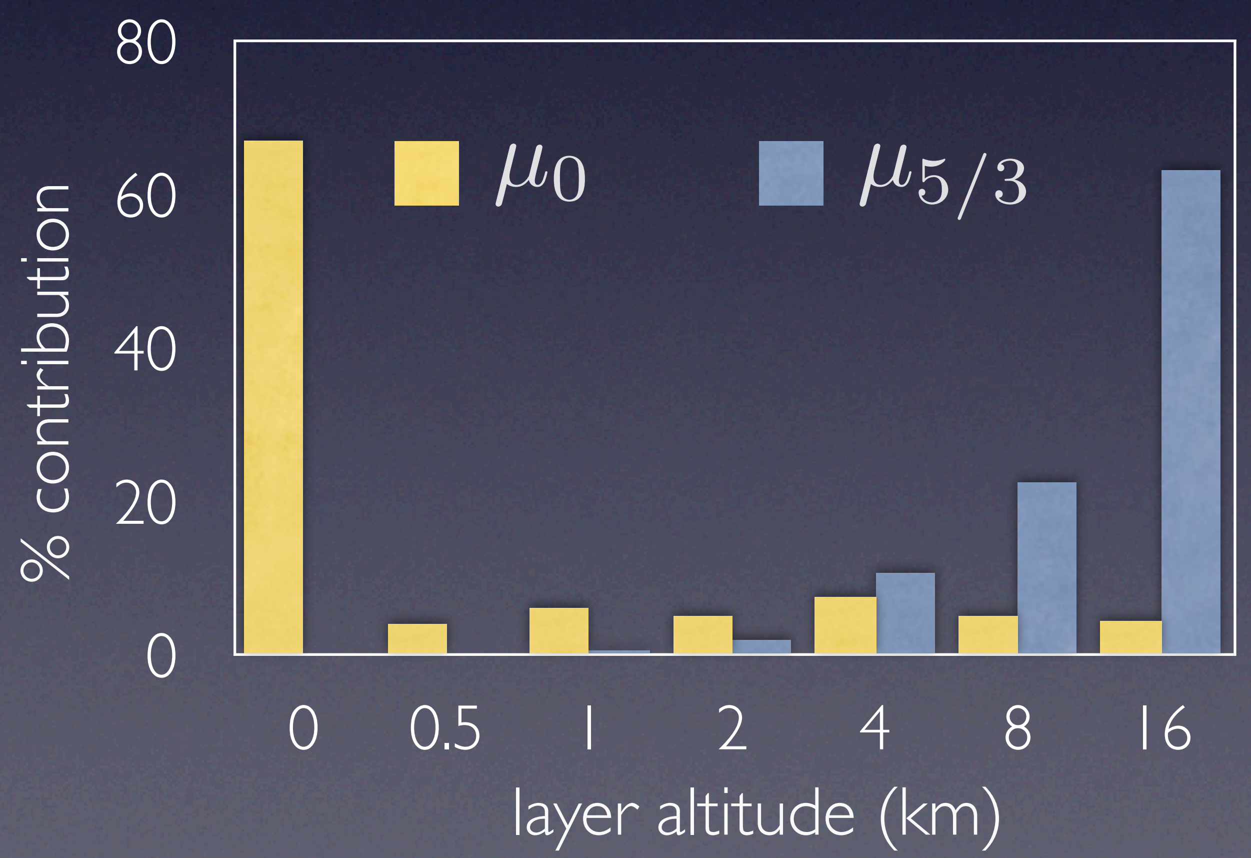
▸ Hence, the only things being simulated are tomography errors (sampling, estimation, reconstruction)

Turbulence model

- Mauna Kea equivalent median model atmosphere
  - Gemini GLAO FSR (seeing data from 2000 - 2004)
  - 13-North TMT MASS data (Dec 2005 - Oct 2006)

Further work on characterizing the 13N data is ongoing

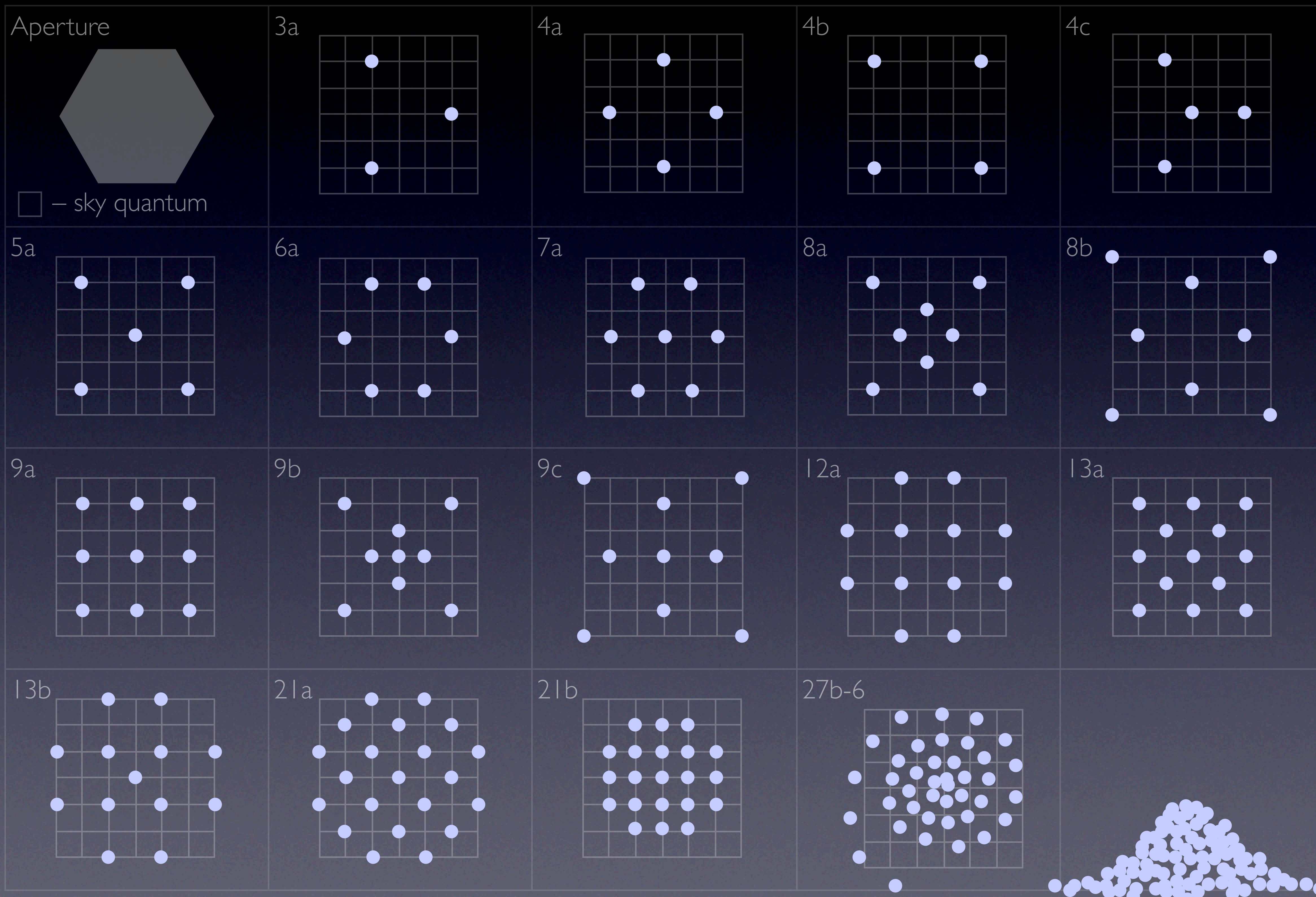
seeing	0.65"
r0	15.6 cm
theta0	3.10"
d0	5.60 m
hbar	3.26 km



Parameter studies

- For understanding the scaling laws, we wish to characterize the narrow-field and wide-field tomography wavefront error as a function of :
  - asterism geometry
  - seeing (r0)
  - asterism size
  - tomography assumptions (ideal / conservative)
    - ideal = ~ zero estimator fitting and generalized anisoplanatism
    - conservative = all terms included, ~ "worst case" scenario

Anatomy of an Asterism



Parameter: number of LGS

- On-axis tomography error vs. asterisms (all)
  - best fit (exponential):

$$f(x) = a_0 + a_1 e^{a_2 x}$$

  - NGS theory :

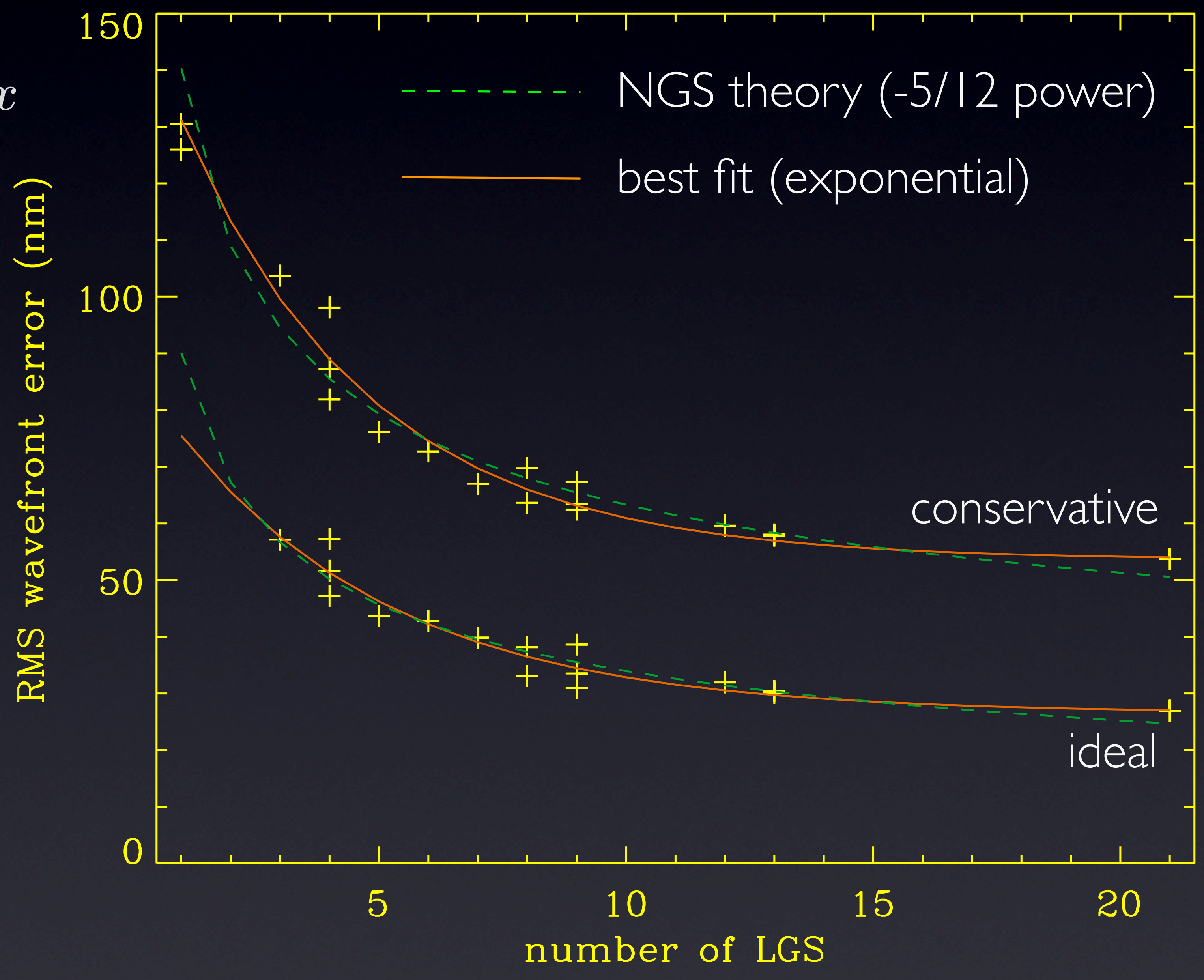
$$\sigma^2_{\mathrm{tom}} \propto \Theta^{5/3}$$

$$\Theta \overset{\propto}{\approx} \sqrt{N}$$

$$\sigma_{\mathrm{tom}} \propto N^{-5/12}$$

$$f(x) = a_0 + a_1 x^{-5/12}$$

not really a good comparison...



Parameter: r_0

- Tomography error vs. r_0 and asterism (4c, 5a, 8a)
  - Fit :

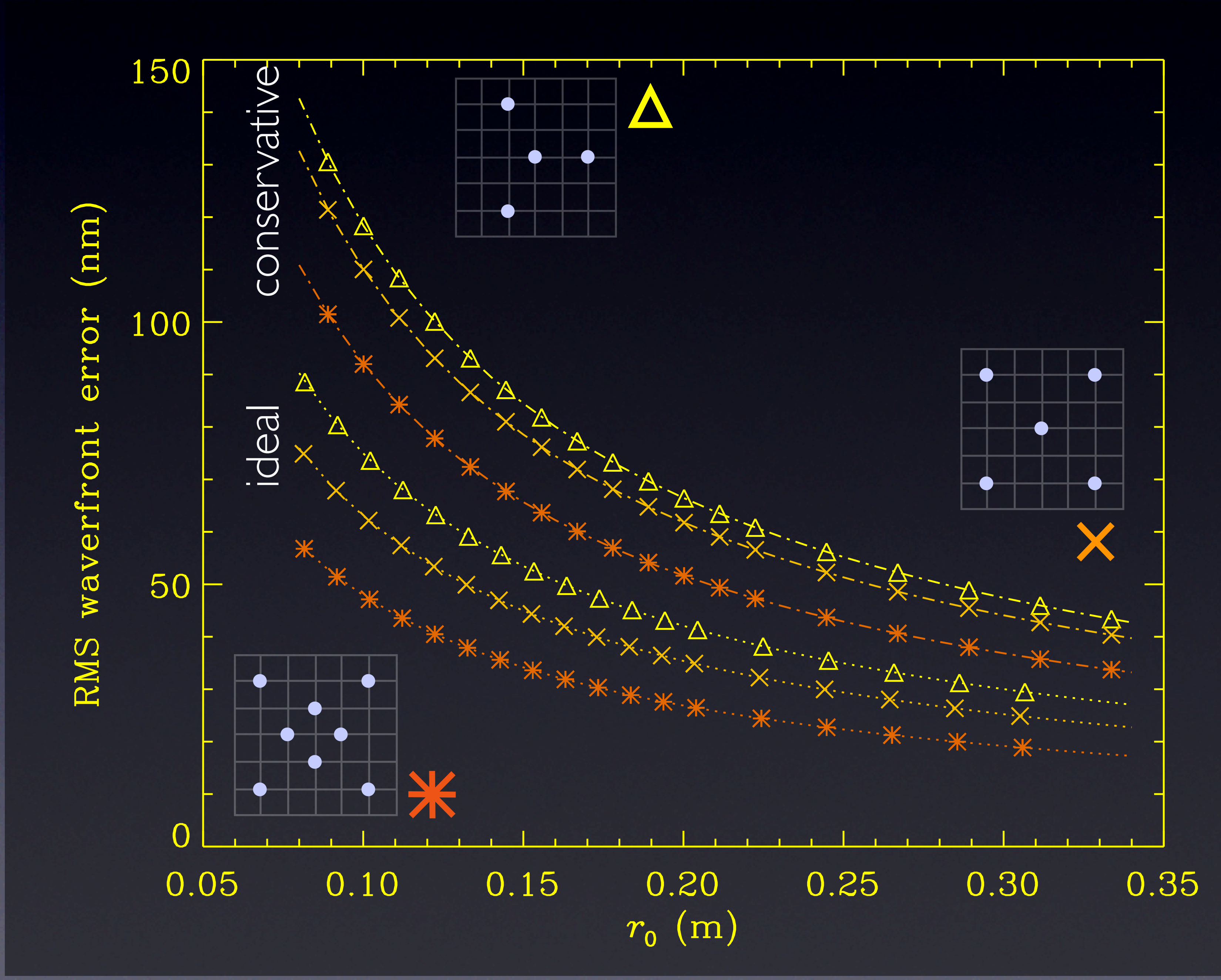
$$f(x) = a_0 x^{a_1}$$

$$a_1 = -0.833260 \pm 0.00018$$

  - Theory :

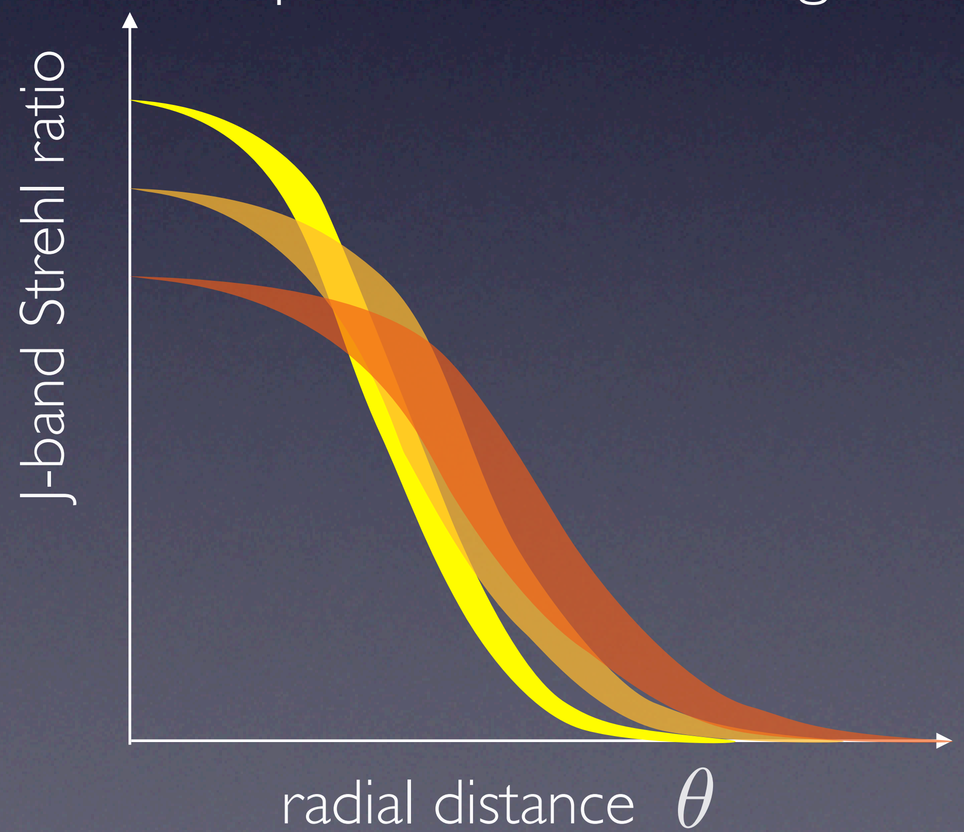
$$\sigma_{\rm tom} \propto r_0^{-5/6}$$

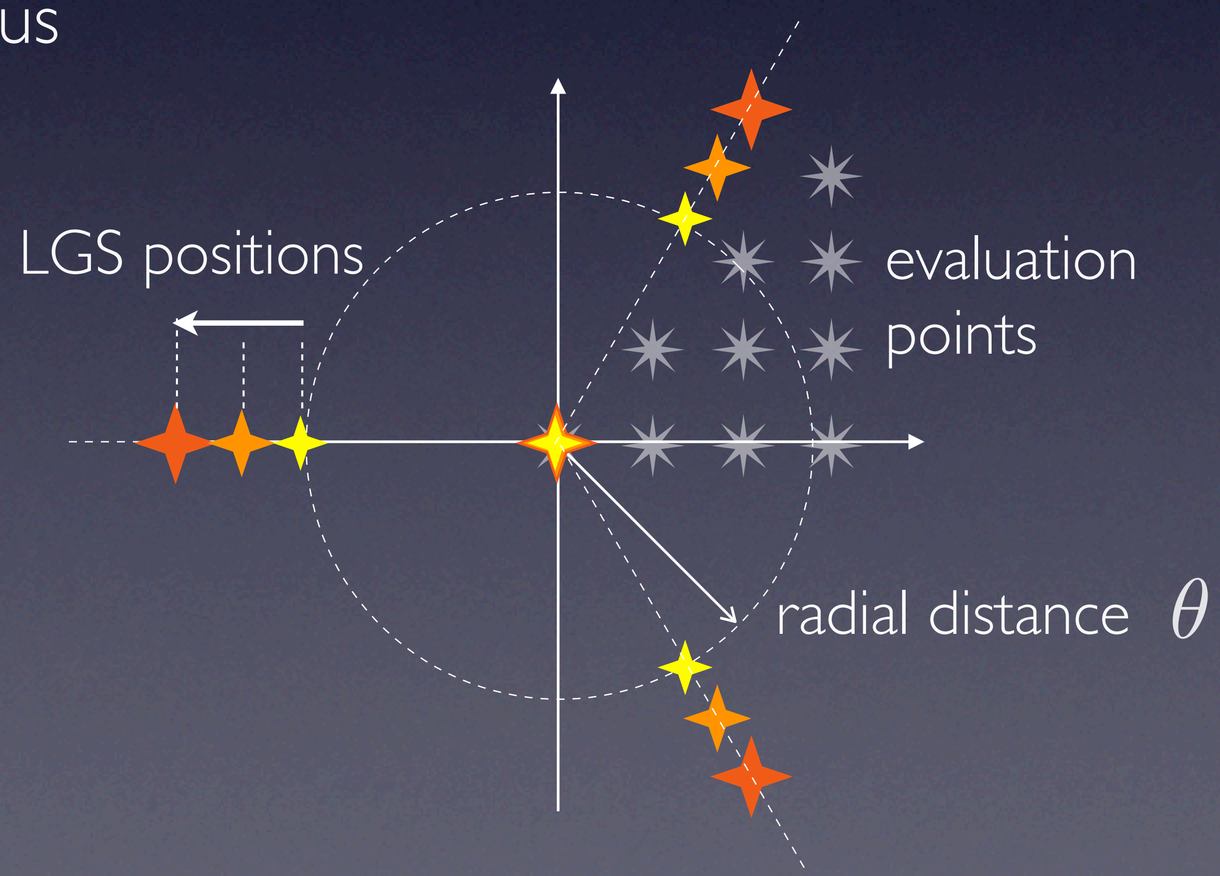
$$(5/6 = 0.83333\ldots)$$



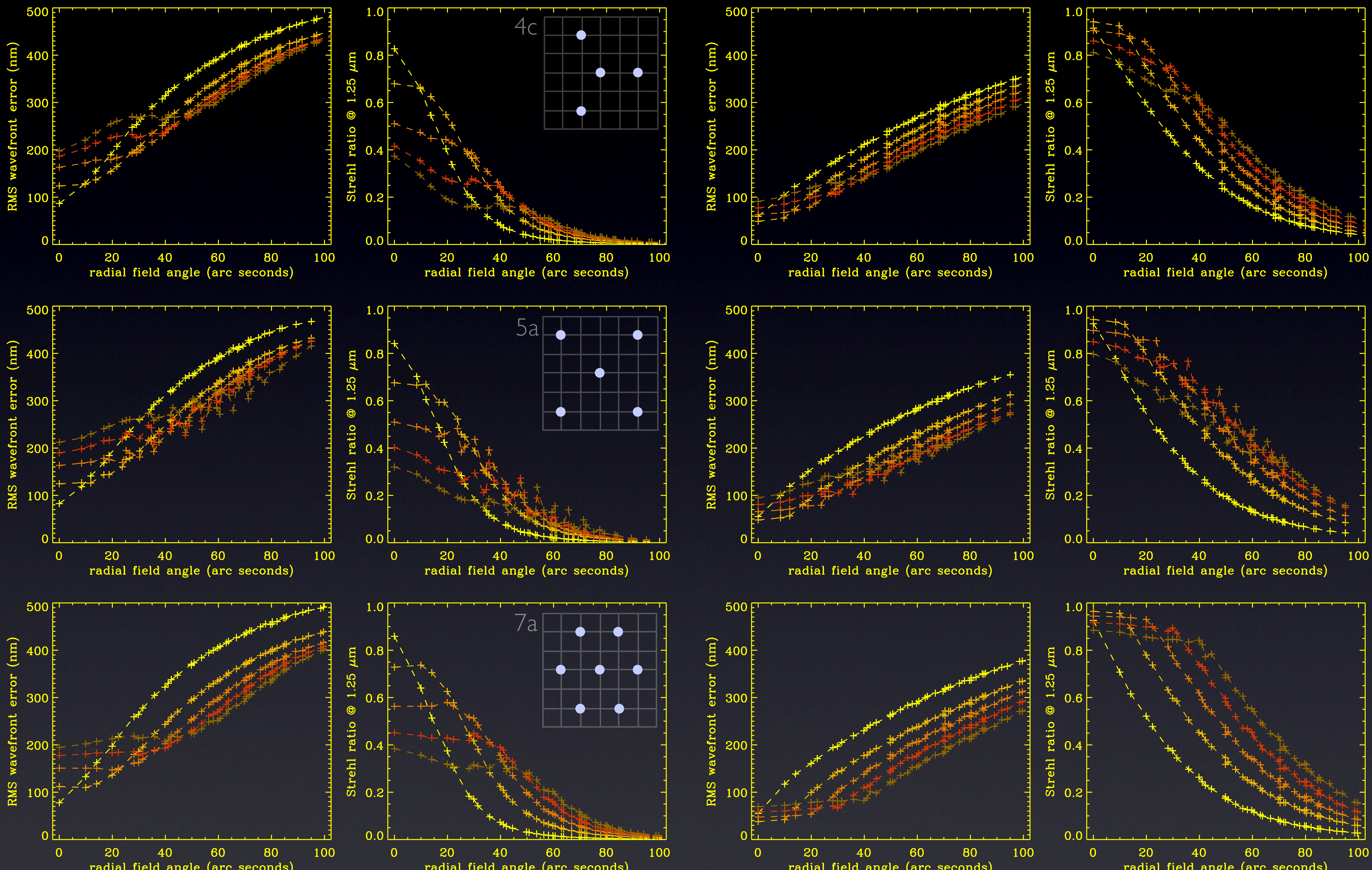
Parameter: asterism size (notes)

- Each curve : RMS wavefront error and J-band (1250 nm) Strehl ratio versus radial distance from central axis.
- Family of curves : function of LGS separation (in steps of ~ 10'' increments radially) for a given asterism.
- Columns (left/right) : conservative / ideal tomography assumptions
- Vertical spread of points indicate azimuthal variations of AO performance at a given radius

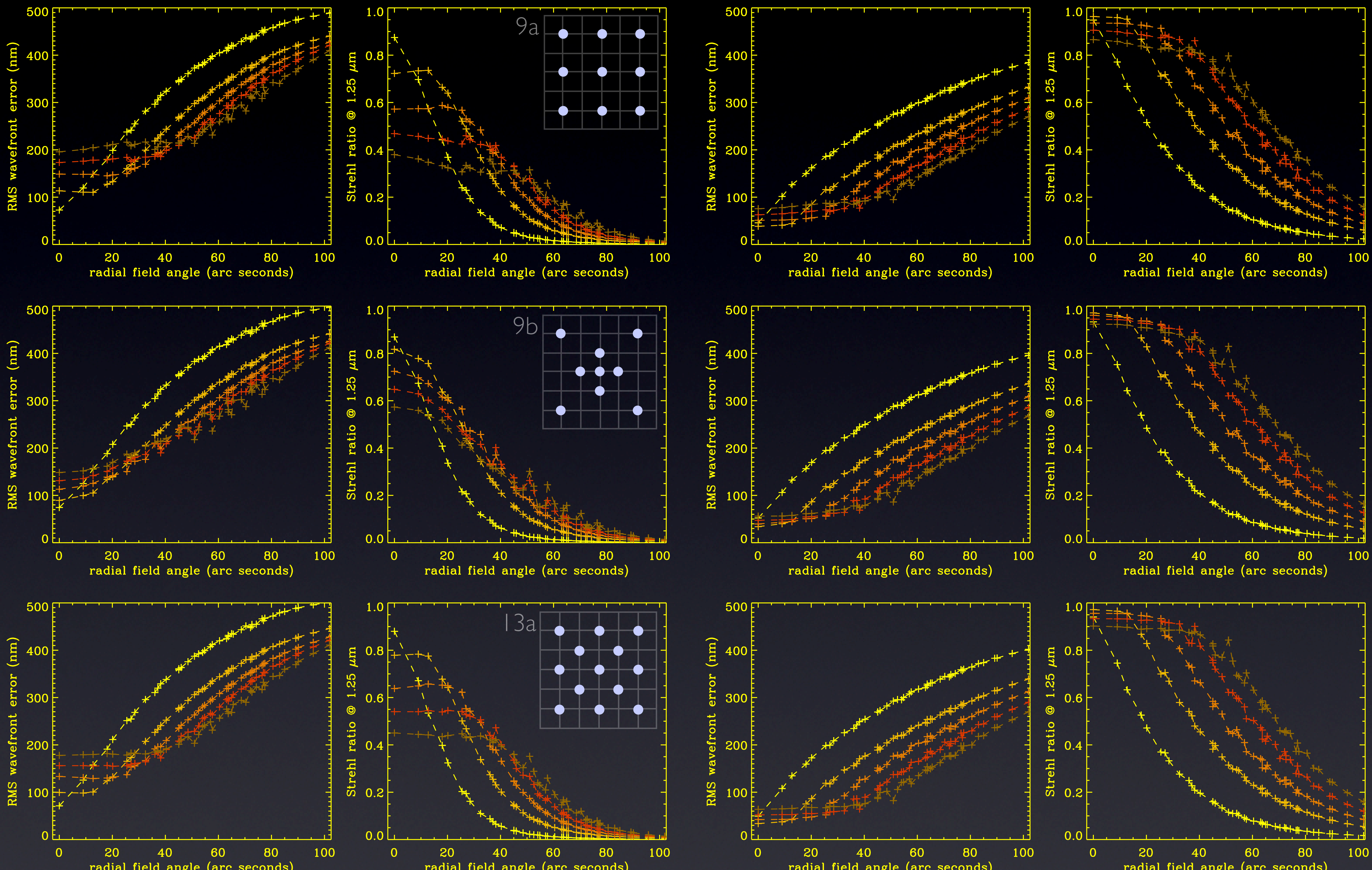




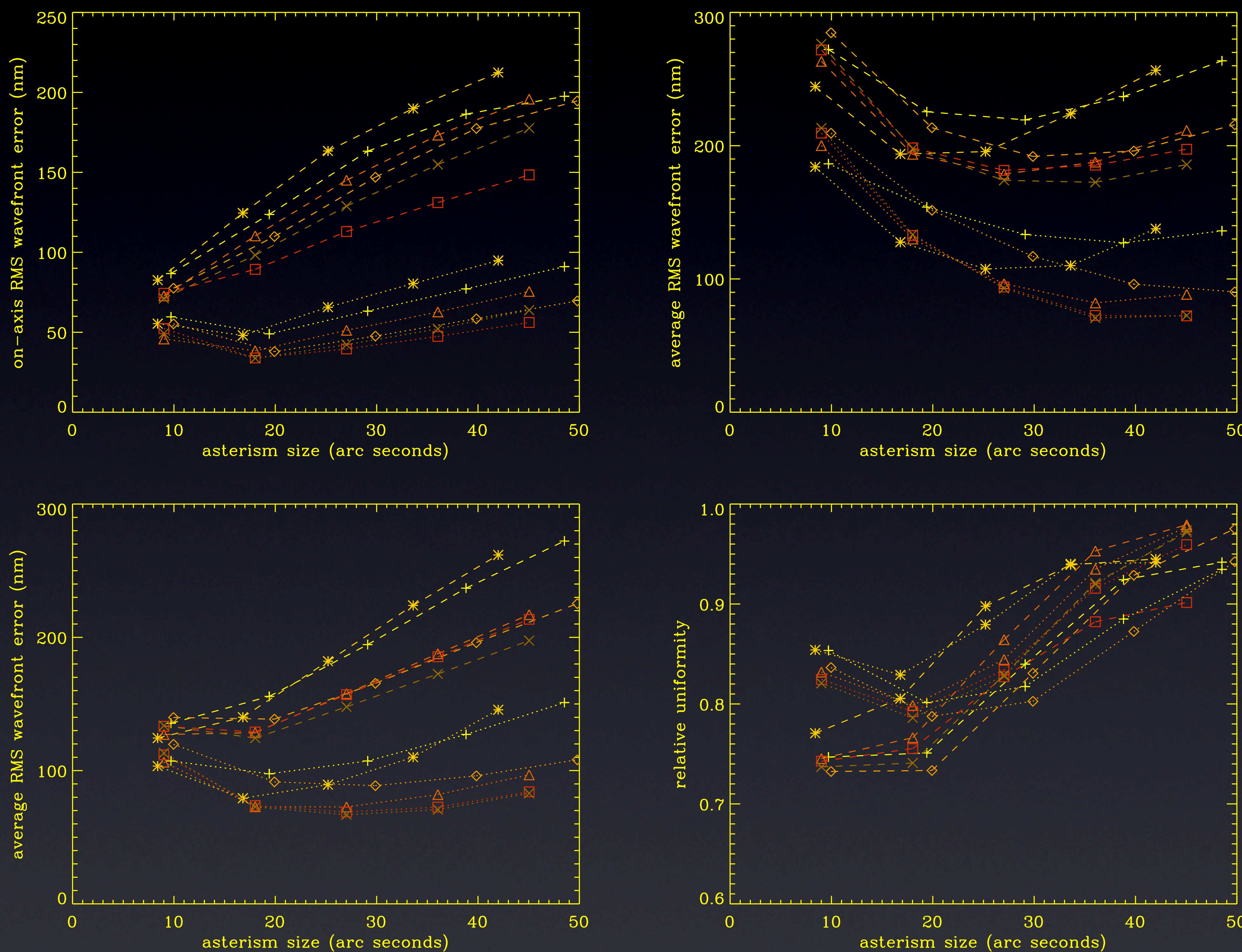
Parameter: asterism size



Parameter: asterism size



Parameter: asterism size



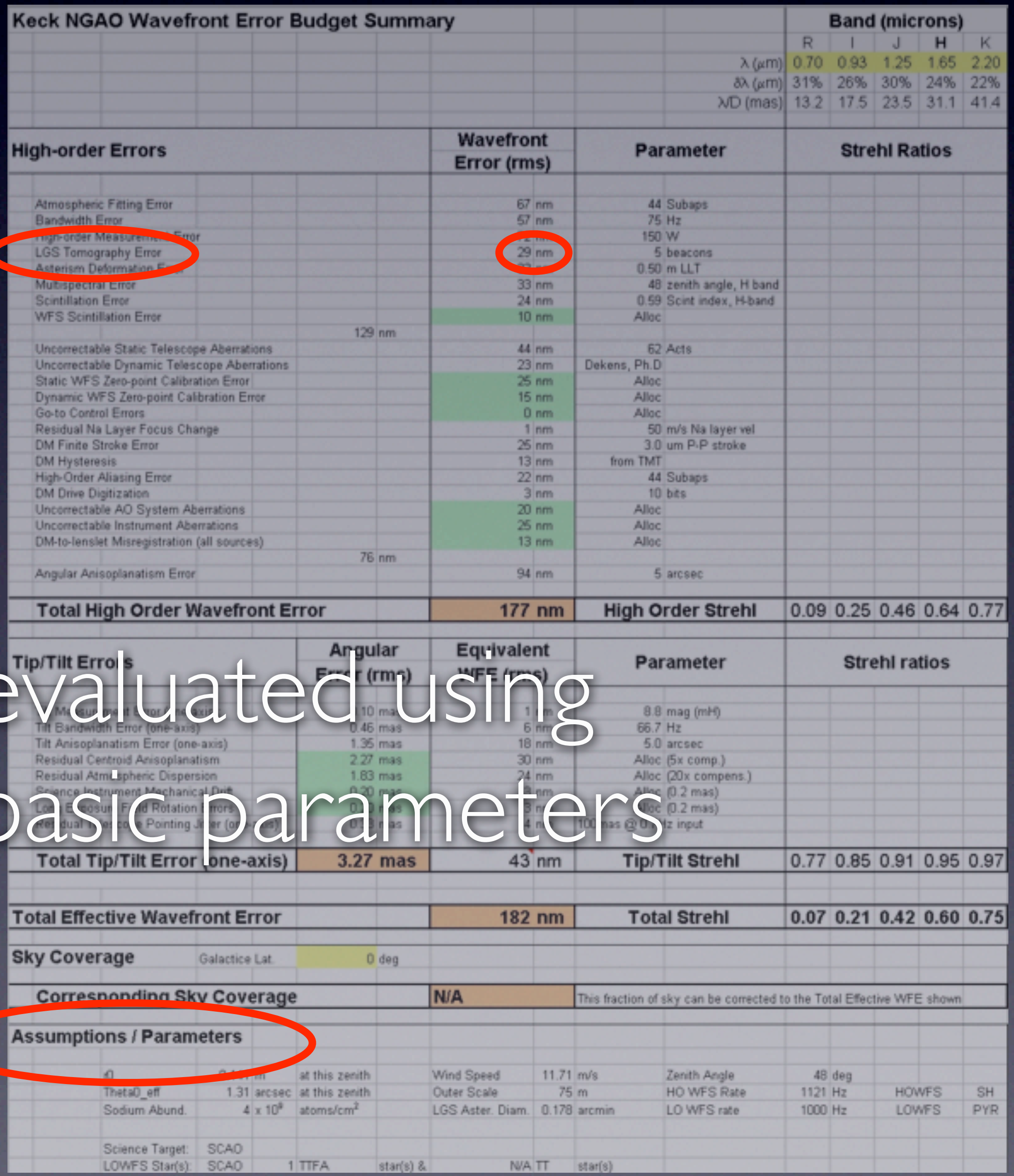
A lot of information in the previous plots...

Main utility of wide-FoV plots may be for finding the level of sharpening of NGS tip/tilt stars at a given field angle, for a given asterism/size.

This could be used in the NGS/sky coverage trade study.

Sample science cases

- From June 18 NGAO proposal:
  - KBO
  - optimal conditions NFAO
  - Galactic Center →
  - Field Galaxies
  - GOODS-N



Keck NGAO Wavefront Error Budget Summary

Band (microns)	R	I	J	H	K
λ (μm)	0.70	0.93	1.25	1.65	2.20
δλ (μm)	31%	26%	30%	24%	22%
λ/D (mas)	13.2	17.5	23.5	31.1	41.4

High-order Errors		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		67 nm	44 Subaps
Bandwidth Error		57 nm	75 Hz
High-order Measurement Error		[illegible]	150 W
LGS Tomography Error		29 nm	5 beacons
Asterism Deformation Error		[illegible]	0.50 m LLT
Multispectral Error		33 nm	48 zenith angle, H band
Scintillation Error		24 nm	0.59 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	129 nm		
Uncorrectable Static Telescope Aberrations		44 nm	62 Acts
Uncorrectable Dynamic Telescope Aberrations		23 nm	Dekens, Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		1 nm	50 m/s Na layer vel
DM Finite Stroke Error		25 nm	3.0 um P-P stroke
DM Hysteresis		13 nm	from TMT
High-Order Aliasing Error		22 nm	44 Subaps
DM Drive Digitization		3 nm	10 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		25 nm	Alloc
DM-to-lenslet Misregistration (all sources)		13 nm	Alloc
	76 nm		
Angular Anisoplanatism Error		94 nm	5 arcsec
Total High Order Wavefront Error		**177 nm**	**High Order Strehl**: 0.09 0.25 0.46 0.64 0.77

Tip/Tilt Errors	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)	0.10 mas	1 nm	8.8 mag (mH)
Tilt Bandwidth Error (one-axis)	0.46 mas	6 nm	66.7 Hz
Tilt Anisoplanatism Error (one-axis)	1.35 mas	18 nm	5.0 arcsec
Residual Centroid Anisoplanatism	2.27 mas	30 nm	Alloc (5x comp.)
Residual Atmospheric Dispersion	1.83 mas	24 nm	Alloc (20x compens.)
Science Instrument Mechanical Drift	[illegible]	[illegible]	Alloc (0.2 mas)
Long Exposure Field Rotation Errors	[illegible]	3 nm	Alloc (0.2 mas)
Residual Telescope Pointing Jitter (one-axis)	[illegible]	4 nm	100 mas @ [illegible] Hz input
Total Tip/Tilt Error (one-axis)	**3.27 mas**	**43 nm**	**Tip/Tilt Strehl**: 0.77 0.85 0.91 0.95 0.97

Total Effective Wavefront Error		**182 nm**	**Total Strehl**: 0.07 0.21 0.42 0.60 0.75
Sky Coverage	Galactice Lat. 0 deg		
Corresponding Sky Coverage		N/A	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	[illegible]	m	at this zenith	Wind Speed	11.71	m/s	Zenith Angle	48	deg			
Theta0_eff	1.31	arcsec	at this zenith	Outer Scale	75	m	HO WFS Rate	1121	Hz		HOWFS	SH
Sodium Abund.	4	x 10⁹	atoms/cm²	LGS Aster. Diam.	0.178	arcmin	LO WFS rate	1000	Hz		LOWFS	PYR
Science Target:	SCAO											
LOWFS Star(s):	SCAO	1	TTFA	star(s) &	N/A	TT	star(s)					

- Assumptions / Parameters →

- LGS tomography error re-evaluated using new simulation tool, same basic parameters

Sample science cases

- Before looking at the results:
  - If numbers do not conform what can you do?

1. Change asterism (more LGS)
   – *at the expense of system complexity and cost*
2. Change assumptions (improve seeing)
   – *at the expense of reduced science efficiency*
3. Turn the "tomography optimism" knob
   – *this really only puts your reputation on the line*
4. Find ways to lower other terms of the wavefront error budget
   (i.e. make it someone else's problem..)

Sample science cases

NGAO proposal ⇦ ⇨ new simulations

	mode	LGS[a] radius	zenith angle	$r_0(0)$ (m)	σ_{tom} (nm)	5a[d]	8a[d]	measured error at
KBO / Gal. Center	NFAO	10"	48°	0.18	29	89/59 74	69/36 52.5	0"
Best case	NFAO	10"	5°	0.40[b]	29	38/25 31.5	29/15 22	0"
Field Gal.	MOAO	21"	30°	0.18	118	175/105[c] 140	160/75[c] 117.5	25"
GOODS-N	MOAO	33"	45°	0.18	160	280/170[c] 225	240/100[c] 170	30"

[a] In simulation, the LGS positions were adjusted for zenith angle to preserve the asterism size

[b] In the tail of the CDF, this happens very rarely (probably < 1% of the time)

[c] See Appendix page 27 for full details (on-axis and field-averaged performance values)

[d] Values reported are: conservative / ideal, and their average (below, colored) in nm RMS

Sample science cases

- Preliminary conclusions
  (based on non-ideal, non-conservative tomography assumptions)
  - Quincunx asterism (5a) fails to deliver required performance in all cases
  - Asterism 8a performs mostly ok
  - Must relax requirement on tomography error for the KBO / Galactic Center science cases
    - 29 nm RMS at 1.5 air masses (r_0 ~ 14 cm) appears to be too costly to reach even in the most optimistic estimate

Summary

The following summary is based on performance levels interpolated half-way between the "ideal" and "conservative" tomography cases, thus representing an average condition that is neither too optimistic nor too pessimistic.

$$$

	Science case score (5 max)	50 nm RMS[b] NF r_0 (cm)	Wide-FoV[c] Strehl > 0.2	need flexible LGS pos.	type
4c	0[a]	22.1	61"	yes	tetrapod
5a	0.5	19.5	71"	yes	quincunx
7a	>1[a]	-	77"	probably	heptapod
8a	2.5	15.2	-	possibly	square (bimodal)
9a	2.5[a]	-	79"	possibly	square (sparse)
13a	>2.5[a]	-	79"	probably not	square (dense)

[a] Conjecture, specific case not simulated

[b] Interpolated from figure on page 14

[c] Interpolated from figures on pages 16-17

Appendix

Additional simulation details

7-layer NFAO mmod-optimization

Asterism #LGS / type	mmod	dtheta	malt	sigma*	NTRMS on-axis	NTRMS avg	NTRMS nm/as^2	NTRMS avg	NTRMS rms
1a	–	–	7500	0.001	130.5	180.2	25/119	–	–
3a	2.2	4.7314	8250	0.5/0.1					
4a	2.1	4.9794	7875	0.05/1.0					
4b	2.45	4.1999	9187.5	0.75/0.1					
4c	2.15	4.8525	8062.5	0.05/0.5					
5a	2.45	4.1999	9187.5	0.1/1.0					
6a	2.15	4.8525	8062.5	0.05/1.0					
7a	2.1	4.9794	7875	0.05/1.0					
8a	2.3	4.5049	8625	0.05/1.0					
8b	3.2	3.1036	12000	0.05/1.0					
9a	2.3	4.5049	8625	0.05/1.0					
9b	2.3	4.5049	8625	0.02/1.0					
9c	3.2	3.1036	12000	0.02/1.0					
12a	2.9	3.4741	10875	0.05/0.5					
13a	2.3	4.5049	8625	0.05/1.0					
13b	2.85	3.5434	10687.5	0.05/1.0					
21a	2.8	3.6152	10500	0.05/1.0					
21b	2.15	4.8525	8062.5	0.05/0.5					

See Figure 1

* first cut / second optimization with 2-layer atm.

2-layer NFAO sigma-optimization

Asterism #LGS / type	[f1,f2]	theta0	d0	hbar	NTRMS on-axis	NTRMS avg	NTRMS nm/as^2	NTRMS avg	NTRMS rms
1a	0.75, 0.25*	3.04	5.16	3.26	125.4	185.1	30/119	–	–
3a	0.79 , 0.21	3.13	5.38	3.23					
4a	0.77 , 0.23	3.10	5.30	3.26					
4b	0.82 , 0.18	3.08	5.38	3.28					
4c	0.78 , 0.22	3.11	5.33	3.25					
5a	0.82 , 0.18	3.08	5.38	3.28					
6a	0.78 , 0.22	3.11	5.33	3.25					
7a	0.77 , 0.23	3.10	5.30	3.26					
8a	0.80 , 0.20	3.08	5.33	3.28					
8b	0.88 , 0.12	3.01	5.48	3.36					
9a	0.80 , 0.20	3.08	5.33	3.28					
9b	0.80 , 0.20	3.08	5.33	3.28					
9c	0.88 , 0.12	3.01	5.48	3.36					
12a	0.86 , 0.14	3.02	5.42	3.34					
13a	0.80 , 0.20	3.08	5.33	3.28					
13b	0.86 , 0.14	3.08	5.50	3.29					
21a	0.85 , 0.15	3.01	5.36	3.36					
21b	0.78 , 0.22	3.11	5.33	3.25					

See Figure 1

* adopted model

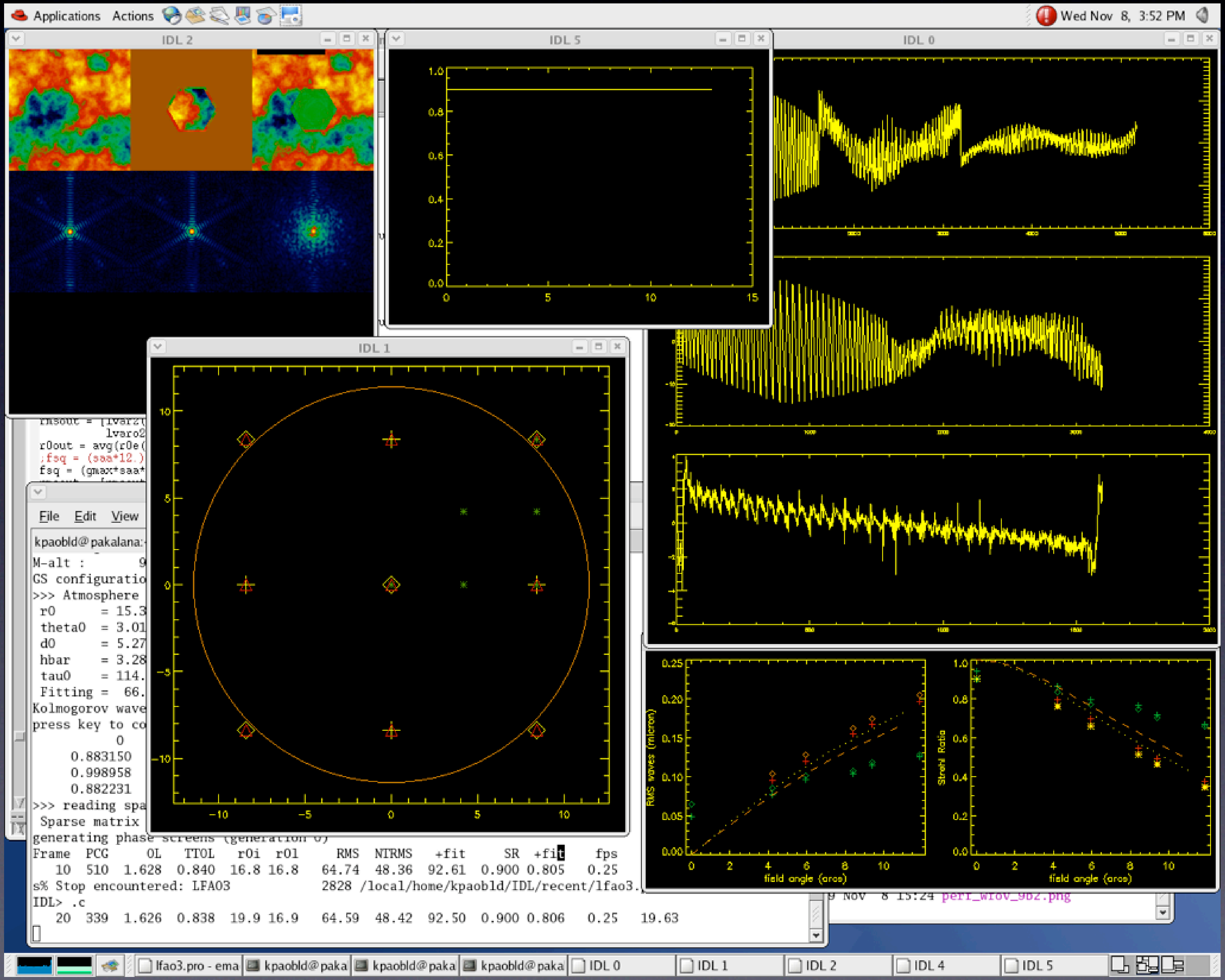
Canonical NFAO cases

- 7-layer loop parameters (mmod optimiz.) :
  - niter = 80 ; nits = 4 ; skipevery = 20 ; skipn = 400 ; skip = 5
  - acoeff = 1/6 ; r0(in) = 0.14 ; r0(out) = 0.156
- 2-layer loop parameters (sigma optimiz.) :
  - niter = same as above
  - r0(in) = 0.153 ; r0(out) = 0.156
  - Preserving turbulence statistics: theta0 and d0 are tuned by adjusting the DM2 altitude and the ratio f1/f2

	0	avg	25'' 30''	0	avg	25'' 30''		
	5a	5a	5a	8a	8a	8a		
								gmax
Field Gal.	155/61	169/90	175/105	121/40	150/68	160/75	118	6/3
GOODS-N	224/100	270/150	280/170	186/66	226/93	240/100	160	10/5

Simulation tool

- IDL code (requires SOI package)



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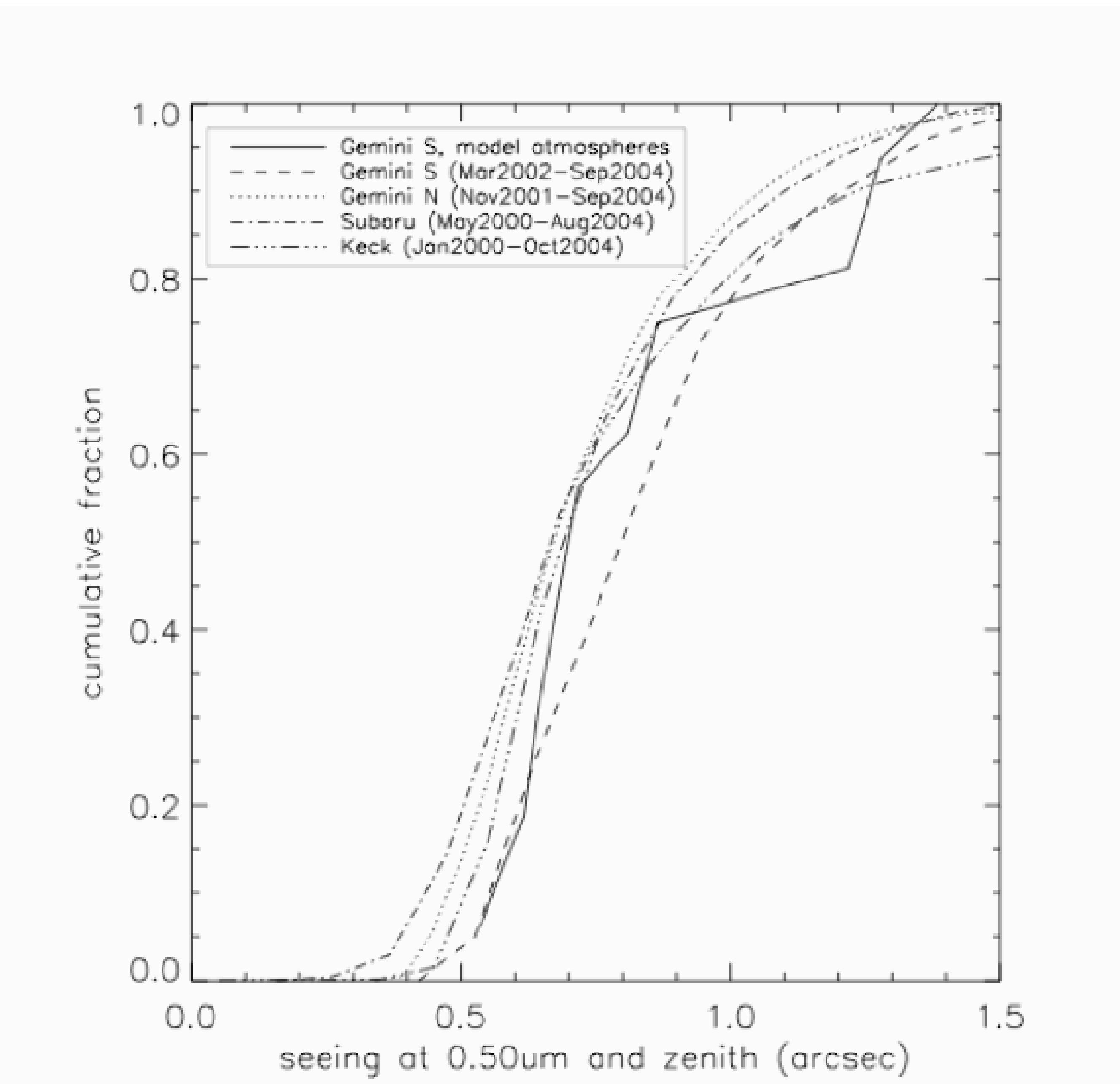

Figure 4. Seeing statistics for observatories located on Mauna Kea and Gemini-S. The solid line is the prediction of the atmospheric models for Gemini-S. The model atmospheres are in good agreement with the seeing statistics. Mauna Kea observatories, including Gemini-N, are shown to be in good agreement as well.