Raven MOAO science and technology demonstrator for Subaru 8m telescope

http://web.uvic.ca/~ravenmoa/

Kate Jackson and Carlos M. Correia
on behalf of the Raven team

Adaptive Optics Tomography Workshop
Edinburgh, 25-26 March 2014

University of Victoria AO Lab

TOHOKU UNIVERSITY

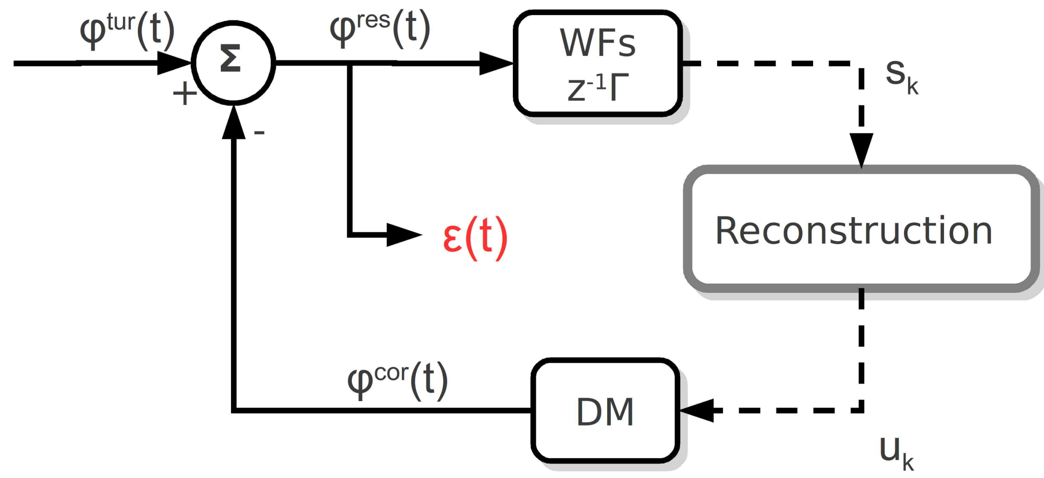
Outline

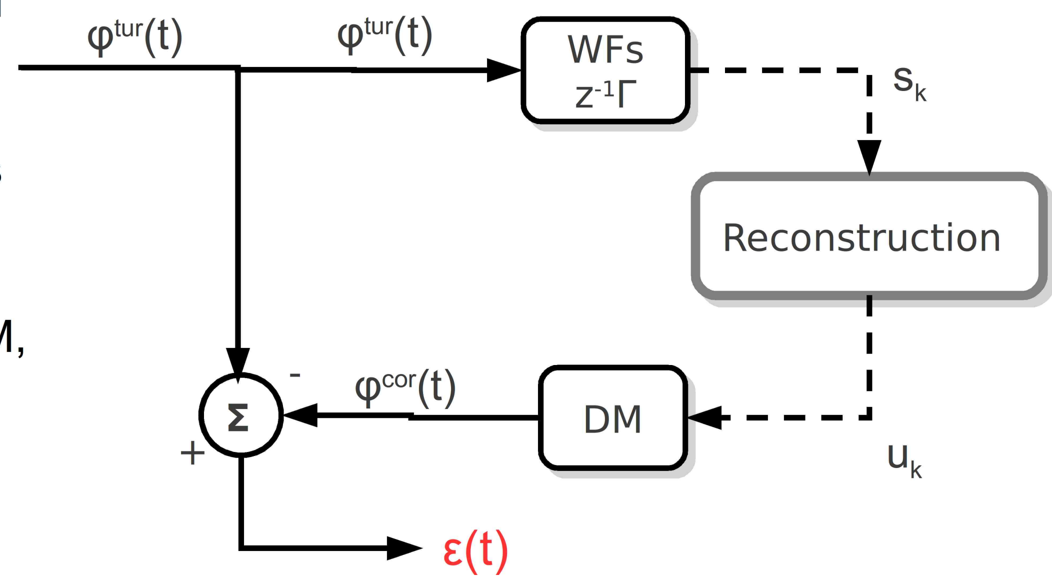
- **MOAO rationale**
  - Why open-loop AO?
- **TLR**
  - Science and technological drivers
  - System design and performance budgeting
- **Wide-field Tomography and real-time implementation (Kate Jackson's PhD)**
  - Spatio-angular tomography
  - Temporal prediction
  - Sky-coverage improvement

Multi-object adaptive optics: rationale

- **Increase the corrected field to several arcmins → many DMs to overcome FoV vs. thickness rule**

- **MOAO**
  - Tomographic reconstruction as in MCAO
  - Multiple science pick-off arms are placed on the scientifically interesting targets in the field
  - Each science channel contains a DM that makes the optimal turbulence correction in its science direction
  - Open-loop AO (WFS placed in front of the DM, unlike MCAO)
  - Calibration becomes a challenge
    - Misregistrations, field-depedent distortions, irregular sensitivity, DM non-linearity, hysteresis



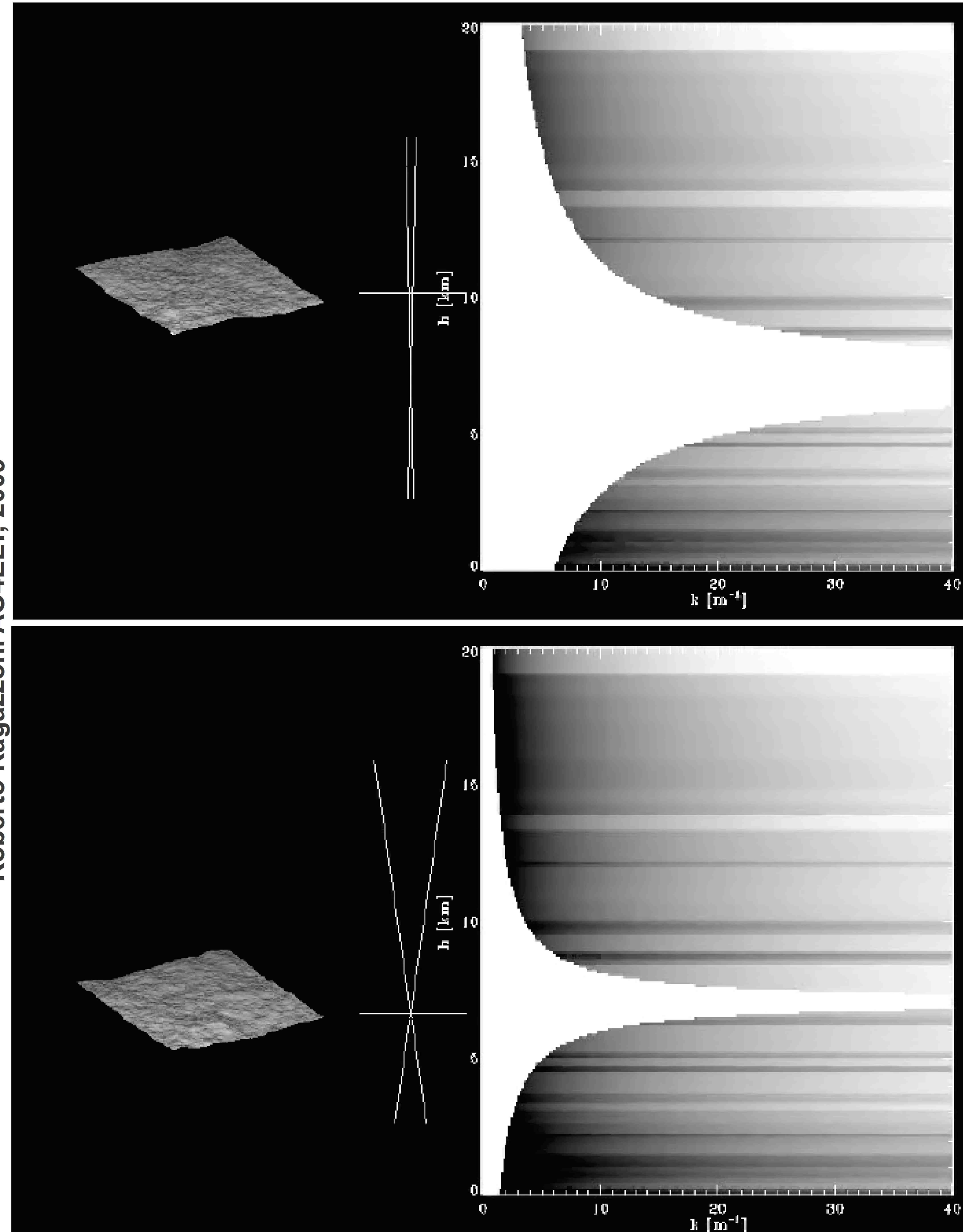


FoV vs. thickness rule

What is the FoV vs t. rule?

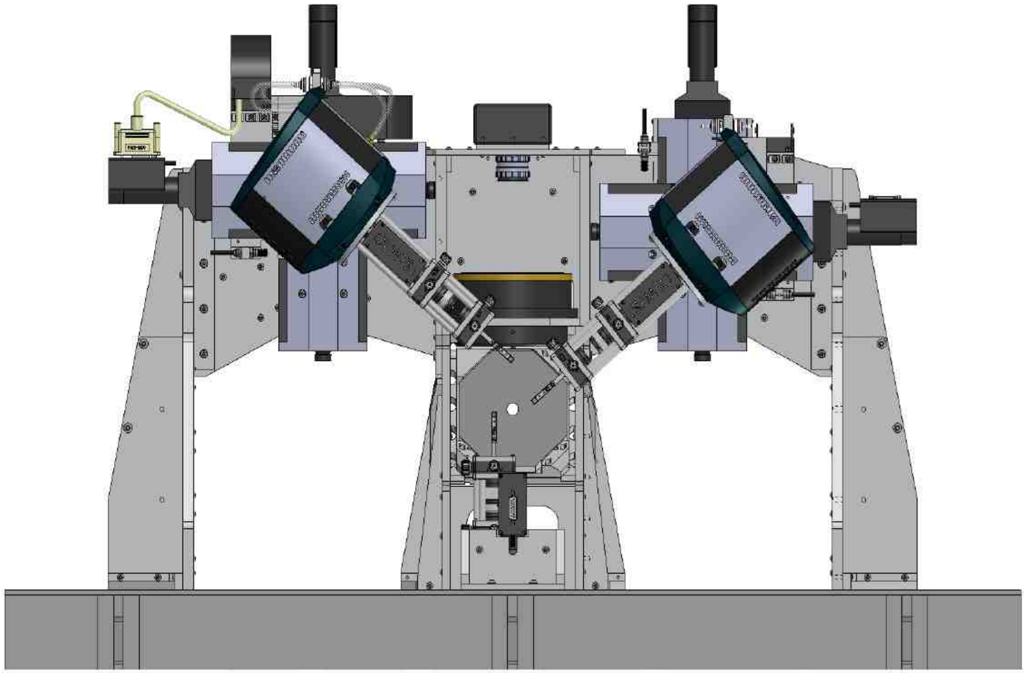
- It is an approximation of the maximum spatial scale that can be corrected at a given distance from a DM…
- A DM can correct all the spatial scale it can fit at its height of conjugation…
- …and only a limited spatial scale at a certain distance…
- …whose linearly deteriorate with a coefficient given by the FoV

Roberto Ragazzoni AO4ELT, 2009



Raven in a nutshell...

- **1st Multi-Object Adaptive Optics (MOAO) technical and science demonstrator installed on an 8 m class telescope**
- **Partnership**
  - Subaru Telescope
  - National Astronomical Observatory of Japan (NAOJ),
  - Herzberg Institute of Astrophysics
  - University Victoria
  - Tohoku University
- **Project start: 2010**
- **On-sky ~mid 2014**
- **Precursor of ELT's NIR multi-IFU**



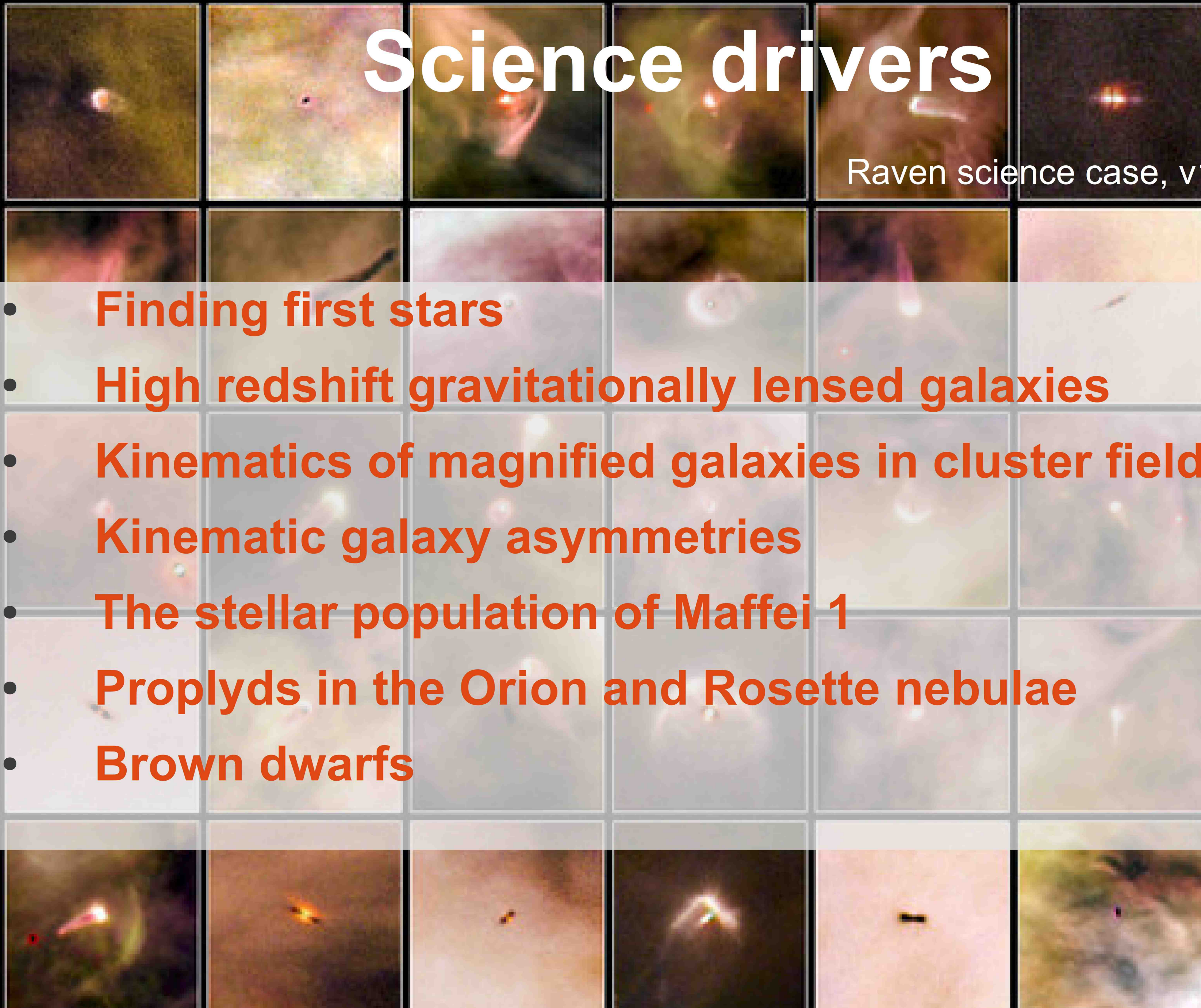
University of Victoria AO Lab

TOHOKU UNIVERSITY

Science drivers

Raven science case, v1.0, (2012)

- **Finding first stars**
- **High redshift gravitationally lensed galaxies**
- **Kinematics of magnified galaxies in cluster fields**
- **Kinematic galaxy asymmetries**
- **The stellar population of Maffei 1**
- **Proplyds in the Orion and Rosette nebulae**
- **Brown dwarfs**



Science case overview

- **As a science demonstrator → designed to maximize sky coverage (given the limitations of NGS tomography) and deliver performance comparable to AO188.**

- **Sky coverage has been increased by:**
  - 1 on-axis LGS
  - Large 3.5' FOR
  - Relatively large subapertures (10x10 OL WFSs effectively collect light from 0.8x0.8m2) → an acceptable loss in AO correction because of this choice.
  - Large free spectral range and high throughput of the OL WFSs (450 nm < λ < 850 nm).
  - The relatively large pixel size of the OL WFSs (0.4"/pixel).
  - The adoption of correlation centroiding (works with spots at a lower S/N).
  - The adoption of LQG optimal control schemes (predictive control allows the loops to run slower allowing for longer integration times).

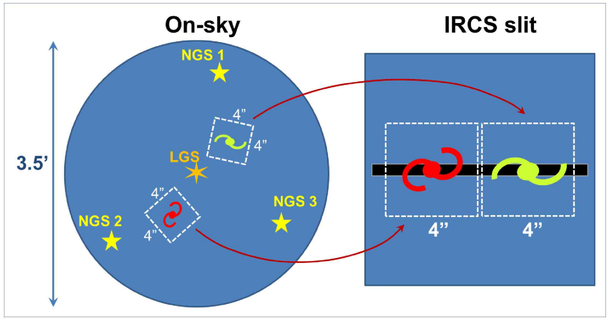
- **Still, sky coverage is relatively low compared to LGS AO systems ~ few %.**

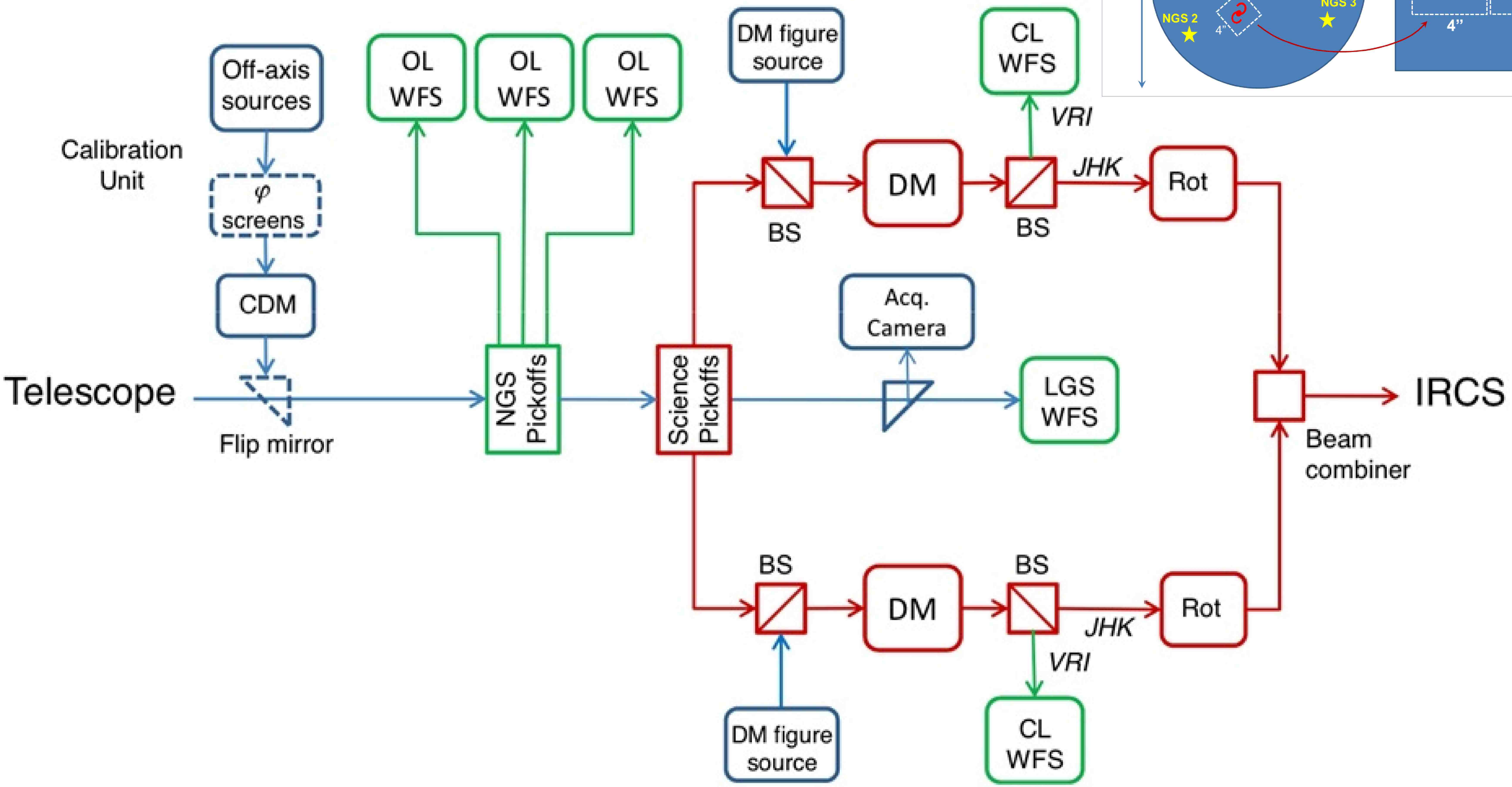
- **2 NGS brighter than 14 required for little loss in performance (down to R < 15 with some loss in performance).**

System overview

Parameter	Requirement
AO System	MOAO operation with tomographic reconstructor
Calibration System	Capable of testing MOAO during daytime and in lab
Science Instrument	Capable of feeding IRCS in imaging, grism and echelle modes
Science spectral range	0.9 - 4 microns
# of science channels	2, 11x11 DMs
# of WFS	3 NGS + 1 on-axis LGS (10x10)
Field of Regard	3.5 arcminutes diameter
Science Field of View	4 arcseconds diameter per science pick-off
Delivered EE	> 30% in 140mas in H-band for r_0 = 15 cm
Throughput	80% of AO188
Image rotation	Ability to align each source to the IRCS slit
Zenith angle	< 60 degrees
WFS limiting mag	R < 14 (goal of R < 15)

Functional block diagram



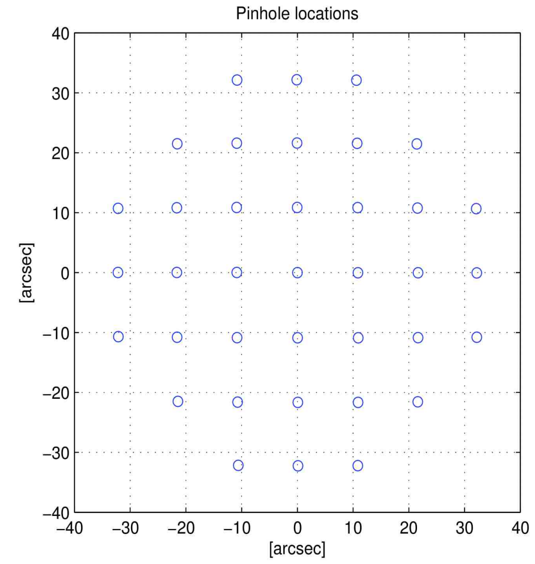


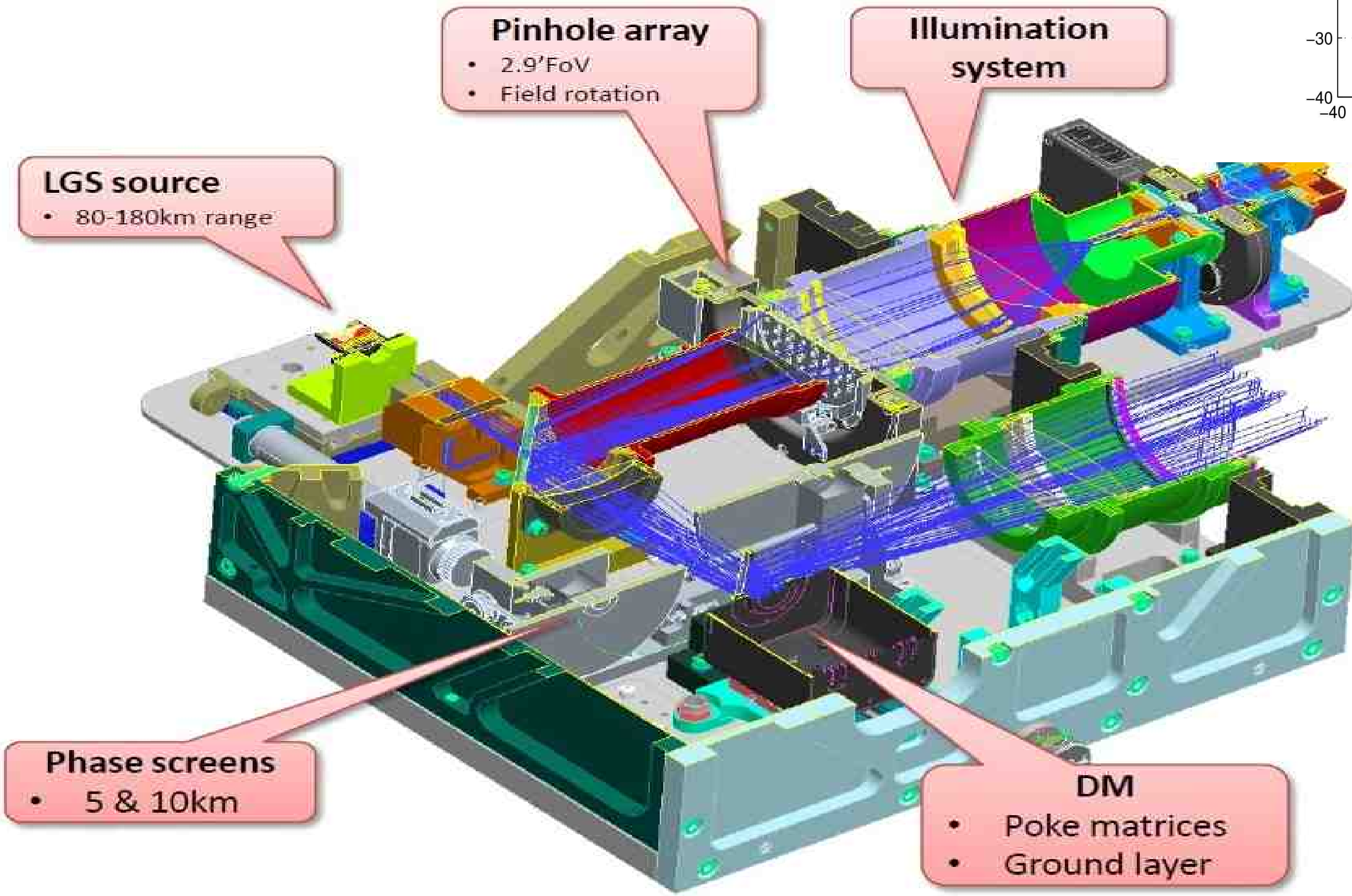
Functional optical block diagram of Raven.

Error budget

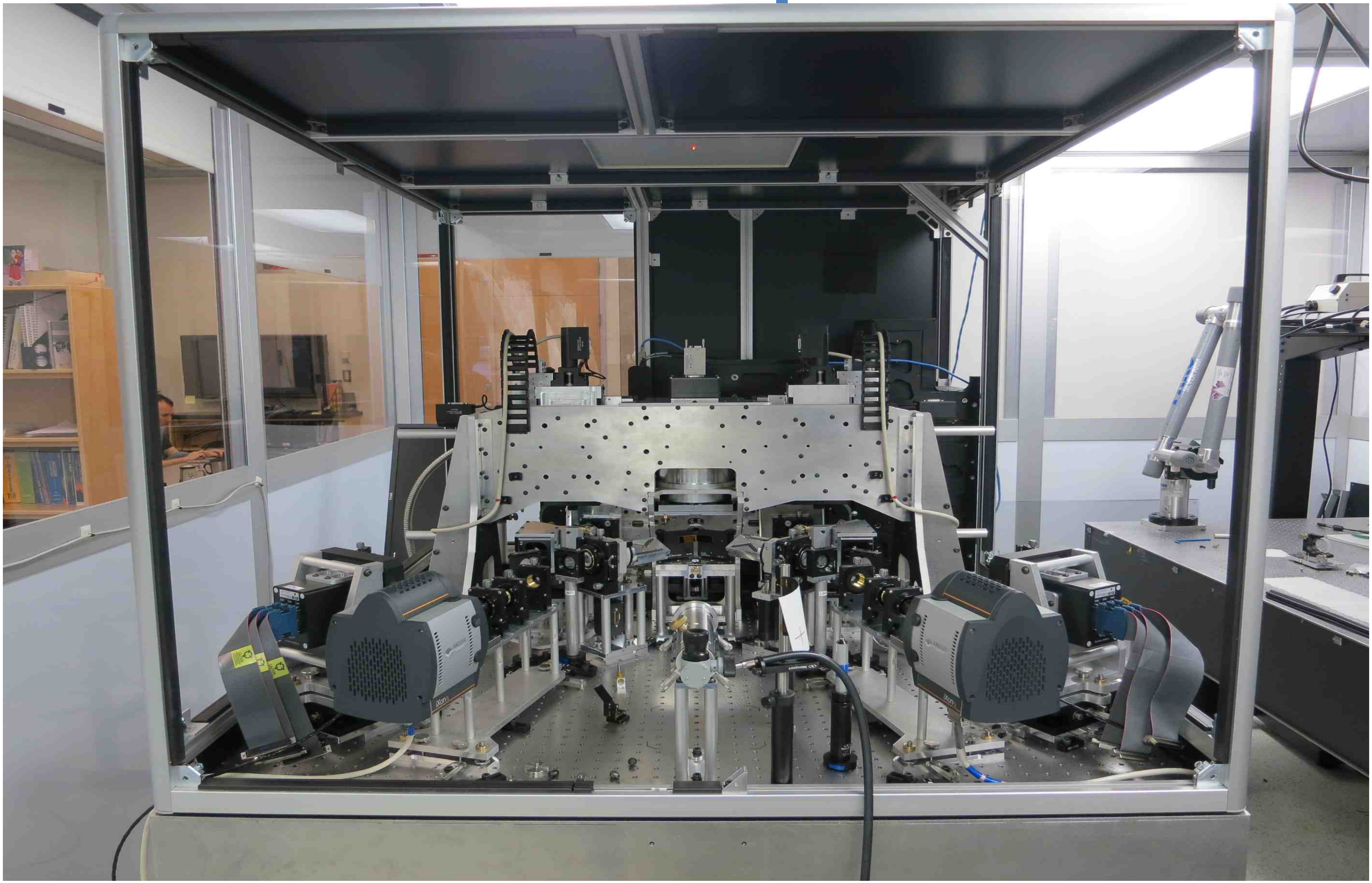
Term	3 NGS (nm)	3NGS +LGS (nm)
Tip/tilt removed Tomography (asterism + atm)	175	105
WFS Sampling - $\sigma^2=0.25(d/r_0)^{5/3}$	155	145
DM Fitting - $\sigma^2=0.1(d/r_0)^{5/3}$	103	112
WFS Pixel sampling (tip/tilt removed)	72	62
WFS Noise (m=12; fs=500 Hz) (tip/tilt removed)	54	83
WFS Noise (m=14; fs=180 Hz) (tip/tilt removed)	95	96
Total (m=12)	271	236
Total (m=14)	280	241

Calibration unit

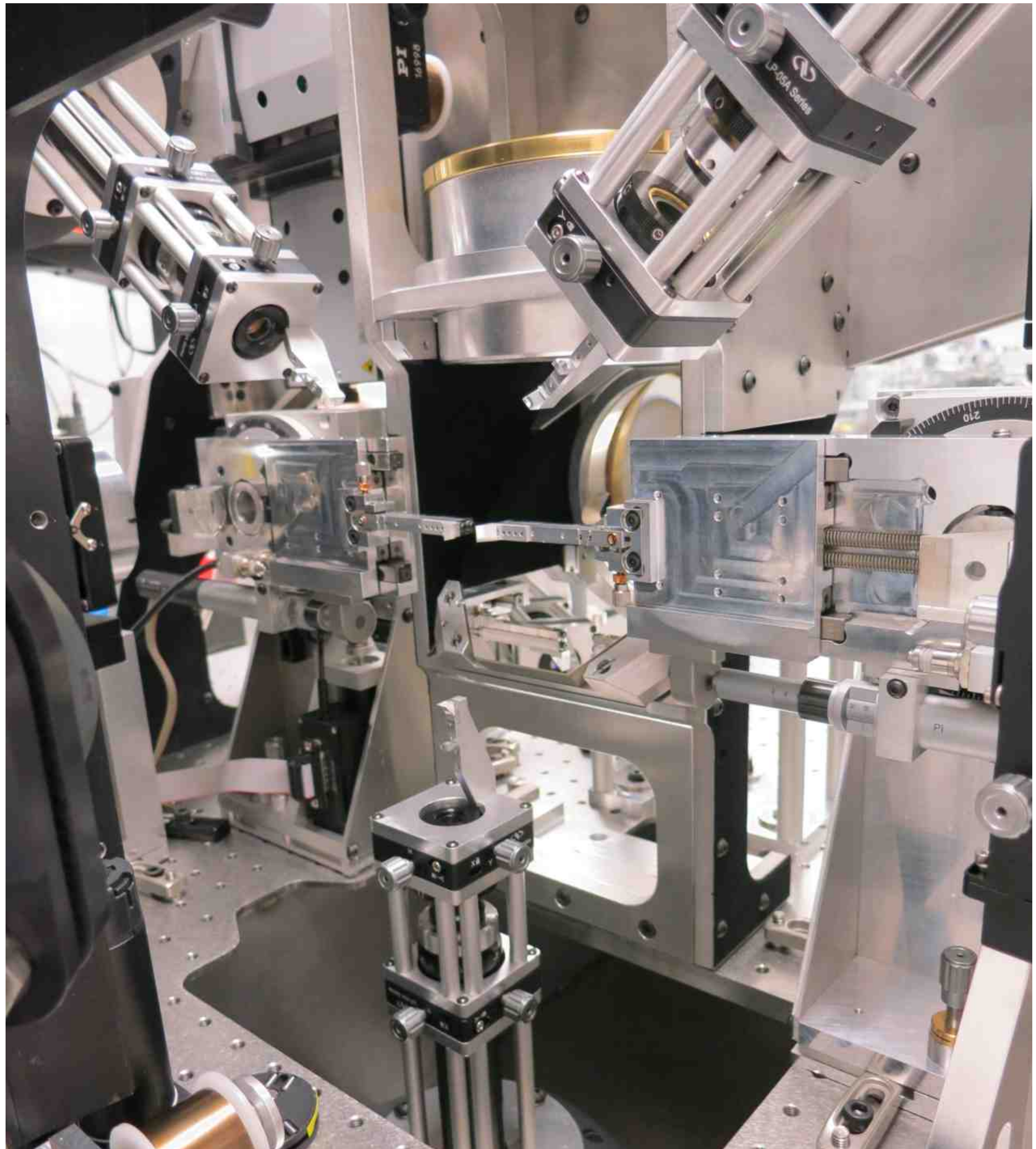




Raven snapshot



Raven snapshot



All-on-one equation...

Calibrated command matrix

Transformation matrix

$$u = \mathrm{M}_{\mathrm{com}} \mathrm{W}_{\mathrm{tomo}} \mathrm{T}(s - s_0) + u_0$$

➔ Tomographic reconstructor

Offsets (ncpa)

Flattening

SDM commands ↔ WFS measurements

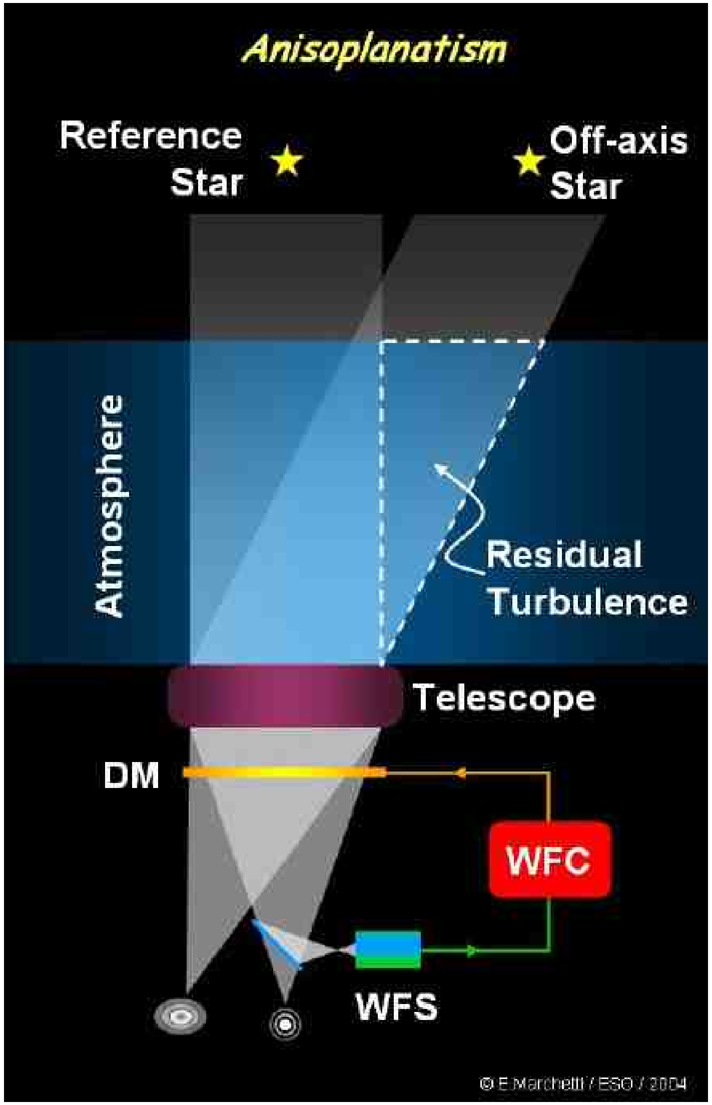
- **Calibration**
- **Model-based (fully, hybrid model/data)**

Beating down angular anisoplanatism

- **Off-axis NGS-SCAO**
  - Measure in direction dα
  - Correct in direction dβ
- **Follow on Whiteley et al, JOSA-A, 1998**
  - **Solution involves Spatio-angular covariance matrices**
    - Known analytically

$$\mathcal{E}\{\phi_\beta | s_\alpha\} \triangleq \Sigma_{(\phi_\beta, s_\alpha)} \Sigma_{s_\alpha}^{-1} s_\alpha = \widehat{\phi}_\beta$$

  - Post-processing cov matrices reveals atmospheric parameters: Cn², r0, etc
- **Open-loop allows for directly register such matrices from data**
  - Data-driven (self-calibrating) AO system



Jackson&Correia, AO Tomography workshop, Edinburgh, March 2014

Tomographic reconstruction

(static, predictive, model-based/hybrid)

- **Pupil-plane (spatio-angular) -MMSE**

$$\mathcal{E}\{\phi_\beta | s_\alpha\} \triangleq \Sigma_{(\phi_\beta, s_\alpha)} \Sigma_{s_\alpha}^{-1} s_\alpha = \widehat{\phi}_\beta$$

- **Explicit -MV**

$$\widehat{\phi}_\beta = \mathbf{P}_\beta \mathbf{E} s_\alpha$$

$$= \mathbf{P}_\beta \left\langle \varphi\varphi^\mathsf{T} \right\rangle \mathbf{P}_\alpha^\mathsf{T} \Gamma^\mathsf{T} \left(\Gamma \mathbf{P}_\alpha \left\langle \varphi\varphi^\mathsf{T} \right\rangle \mathbf{P}_\alpha^\mathsf{T} \Gamma^\mathsf{T} + \left\langle \eta\eta^\mathsf{T} \right\rangle \right)^{-1} s_\alpha$$

→ Focus is now #GS instead #layers

→ Part of reconstructor from data

- **Embed temporal prediction**

$$\widehat{\phi}_{\beta_j, k+1} = \mathbf{P}_{\beta_j} \mathcal{P} \mathbf{E} s_\alpha \qquad \widehat{\phi}_{\beta_j, k+1} = \mathbf{P}_{\beta_j} \mathcal{P} [\widehat{\varphi}_k, \widehat{\varphi}_{k-1}, \cdots, \widehat{\varphi}_{k-n}]$$

Predictive models

- **Increase in sky-coverage**
  - use fainter stars → lower SNR regime
  - Decrease frame-rate → Beat down temporal-lag error
- **Auto-Regressive, diagonal models**

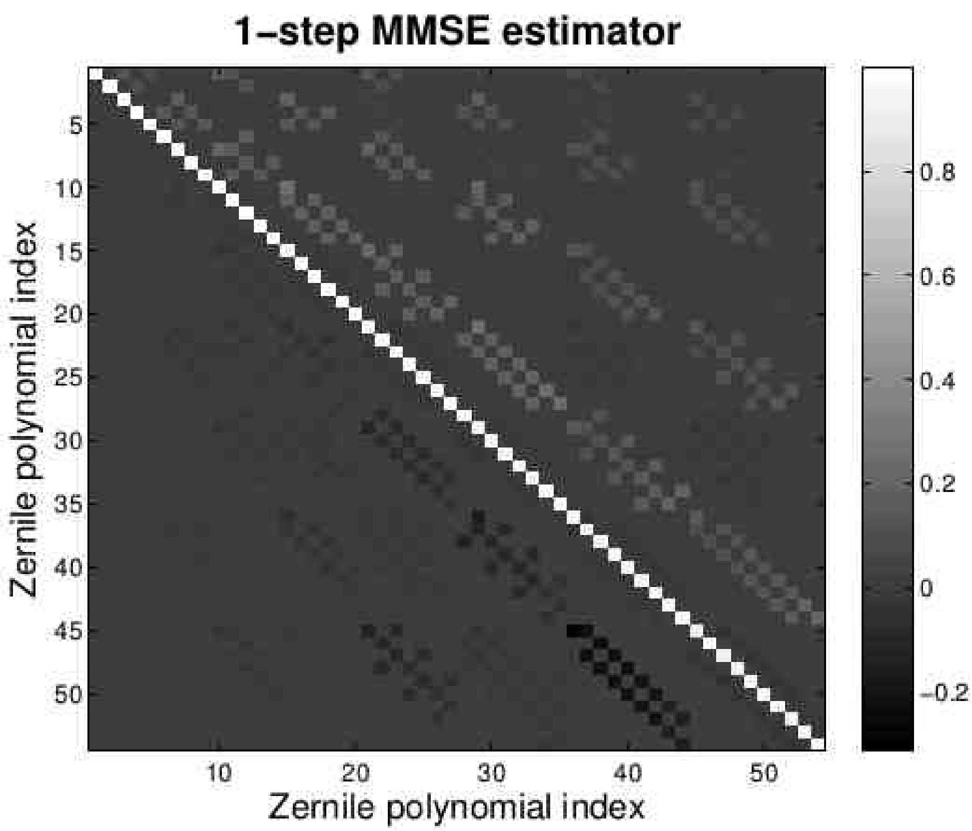
$$\widehat{\phi}_{\beta_j,k+1} = \mathbf{P}_{\beta_j}\mathcal{P}[\widehat{\varphi}_k, \widehat{\varphi}_{k-1}, \cdots, \widehat{\varphi}_{k-n}]$$

  - Orders 1, 2, 3
  - Assume Zernike polynomial expansion
- **1-step Spatio-Angular predictor**

$$\mathcal{A}_\tau = \arg\min_{\mathcal{A}'_\tau} \left\langle \|\varphi(t+\tau) - \mathcal{A}'_\tau\varphi(t)\|^2_{L_2(\Omega)} \right\rangle$$

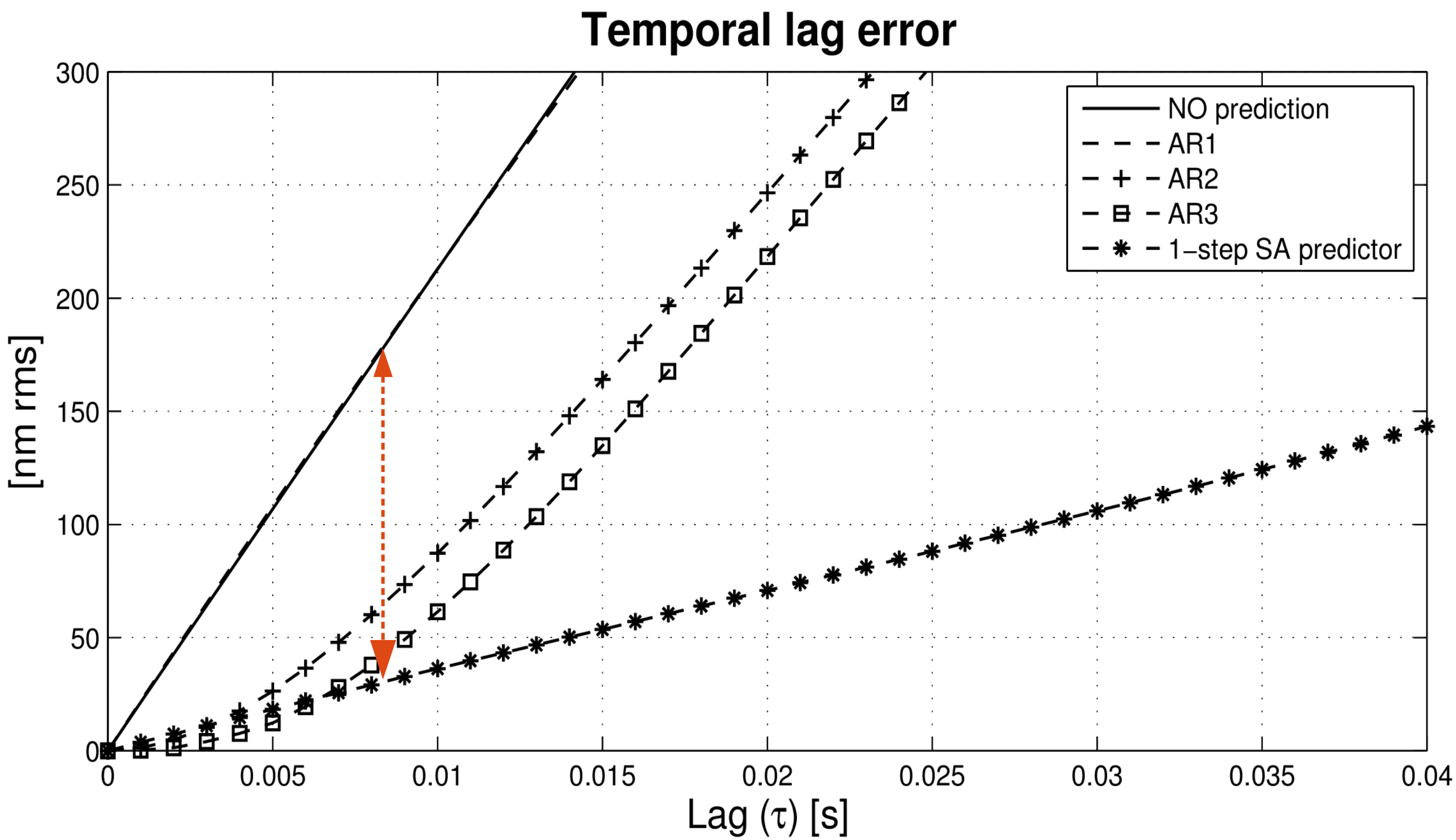
$$\mathcal{A}_\tau \triangleq \left\langle \varphi_{k+1}\varphi_k^\top \right\rangle \left\langle \varphi_k\varphi_k^\top \right\rangle^{-1}$$

  - Use frozen-flow hypothesis
  - Markovian → asynchronous WFS/DM case easily dealt with



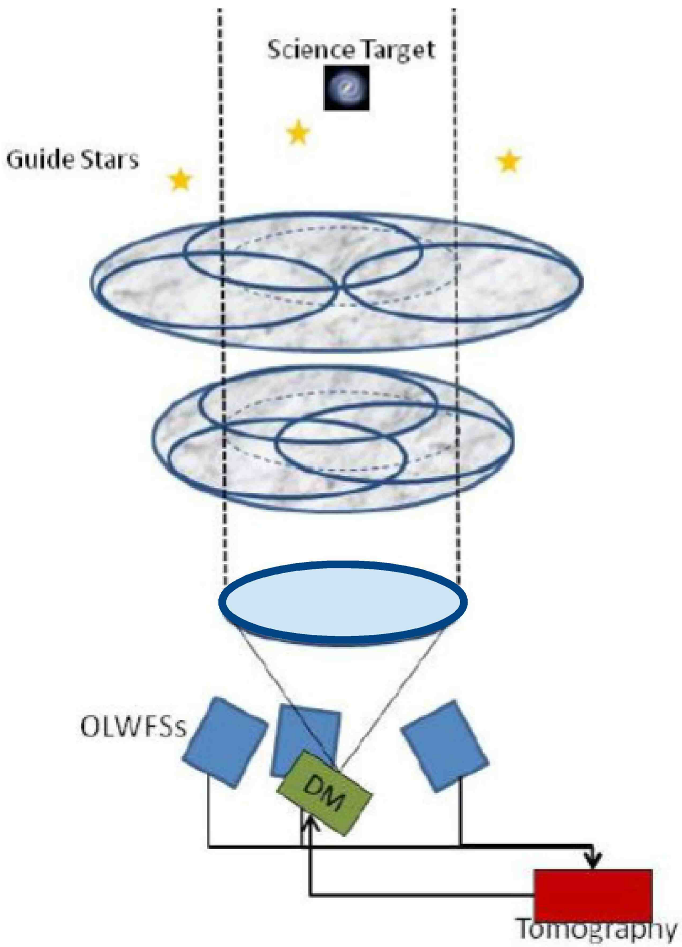
Predictive reconstruction

- **Analytical temporal structure functions of predictive models (using frozen-flow hypothesis)**



→ Correia et al, *Static and predictive tomographic reconstruction for wide-field multi-object adaptive optics systems*, JOSAA, 31 (1), 2014

Simulation and experiment parameters

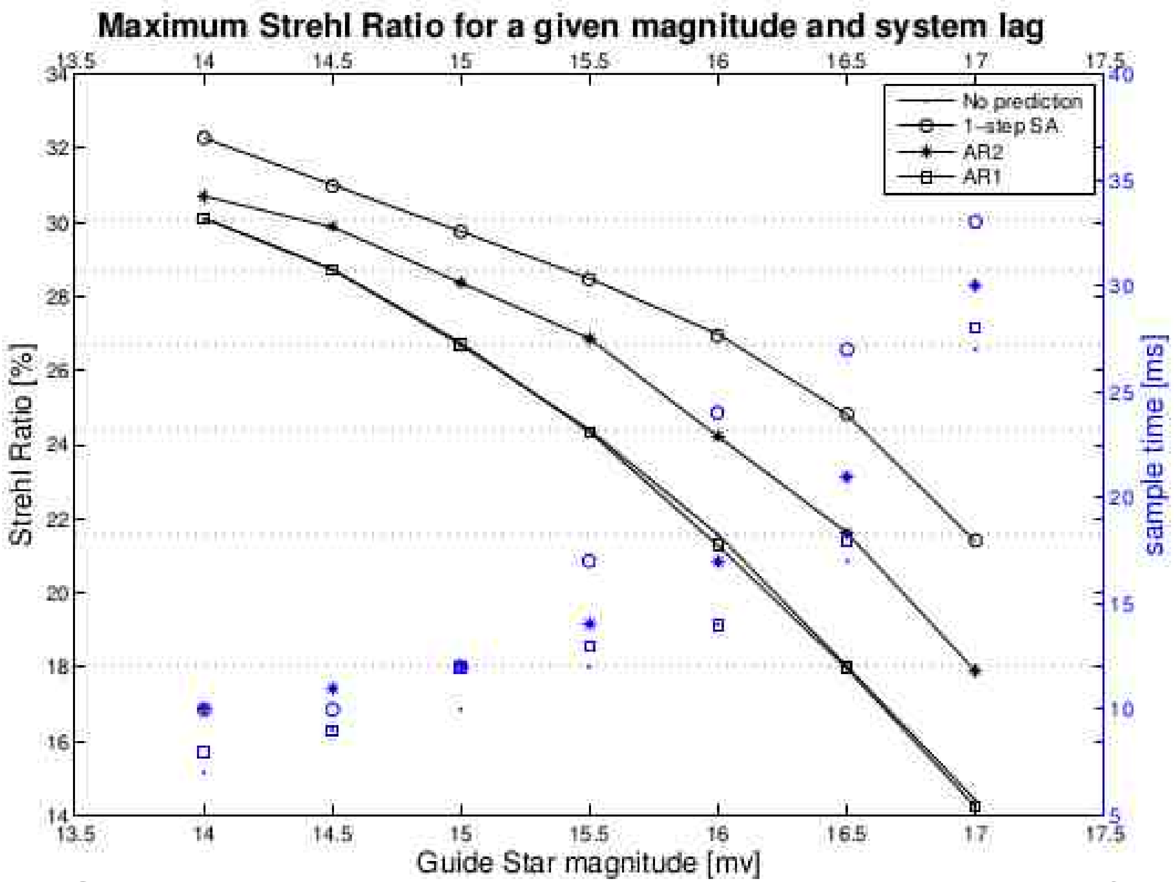


- **Cn2 profile**
  - Two layers of turbulence at 5km and 10km
  - r0 = 0.155m, L0 = 25m
  - Fractional r0 in simulation:
    0.6,0.22,0.18
  - Fractional r0 in lab:
    0.9, 0.055, 0.045

- **OOMAO, Matlab-based E2E simulator**
  - https://github.com/rconan/OOMAO/
  - Poster at PIE

Increased limiting magnitude

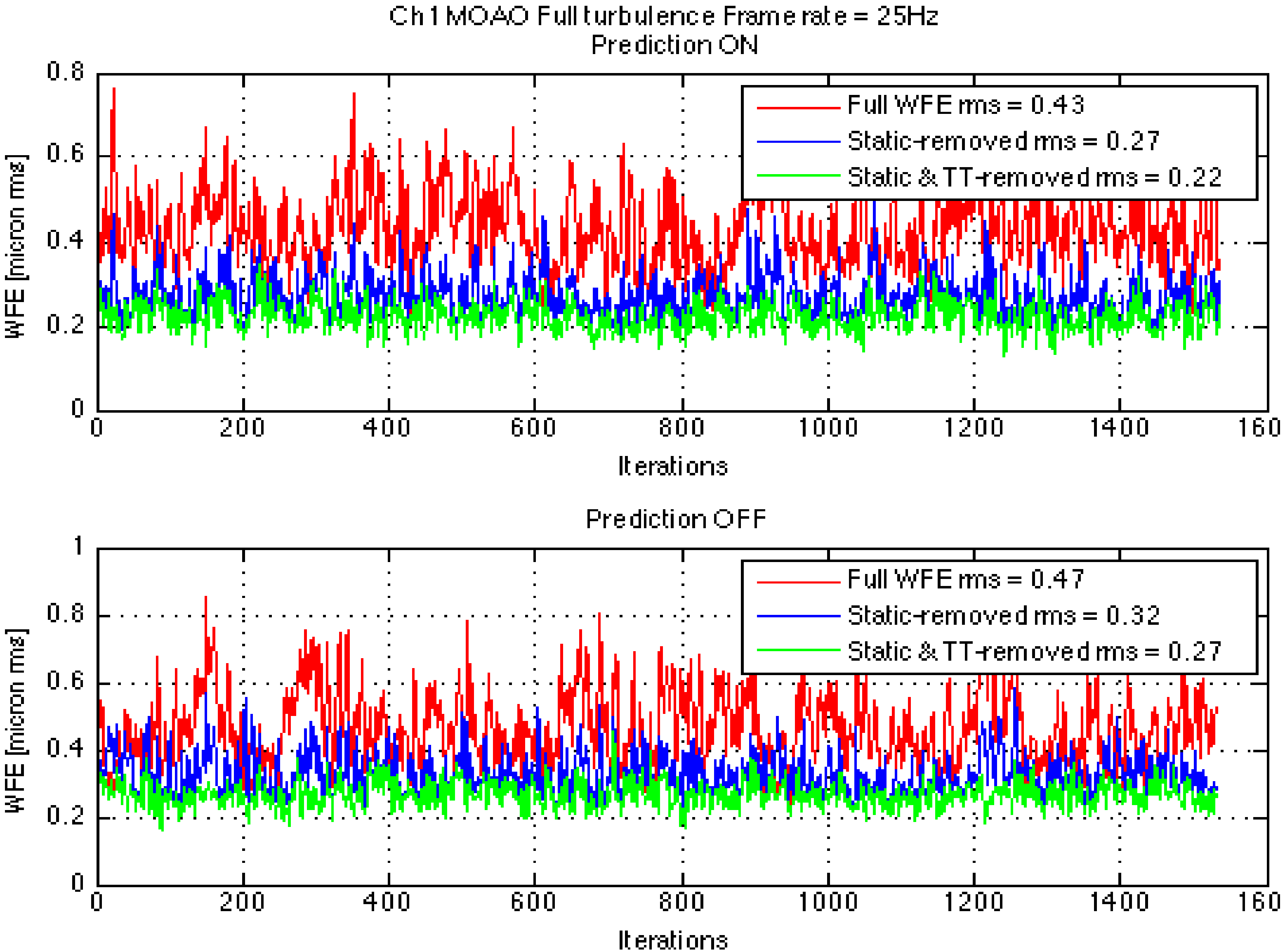
- **AR2: ~0.5 magnitudes fainter**
- **1-step SA predictor: ~1 mag fainter**



Correia et al, *Static and predictive tomographic reconstruction for wide-field multi-object adaptive optics systems*, JOSAA, 31 (1), 2014

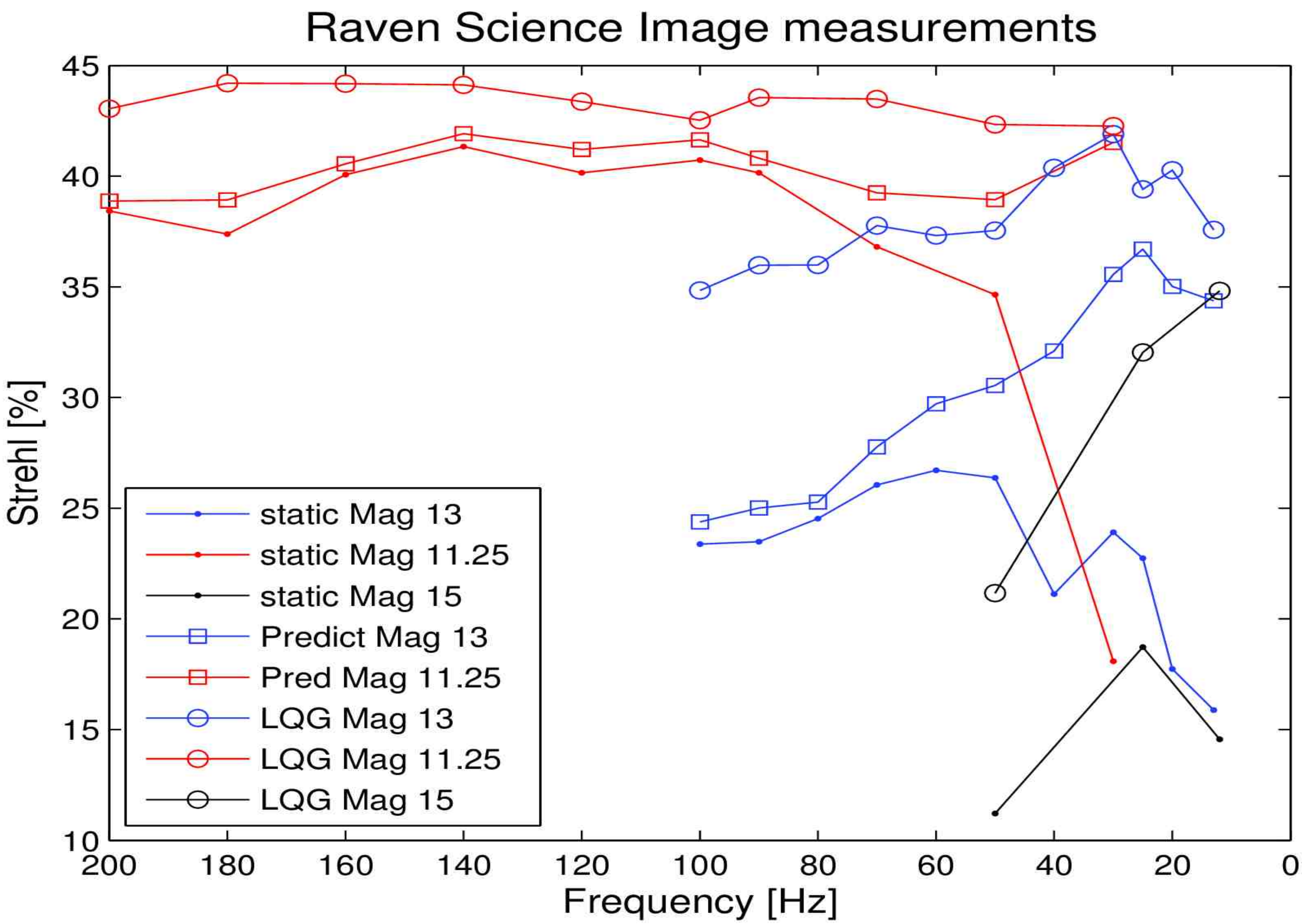
Static vs predictive

Wind directions: 90, 180, 180 degrees
Wind speeds: 5.68, 6, 17 m/s

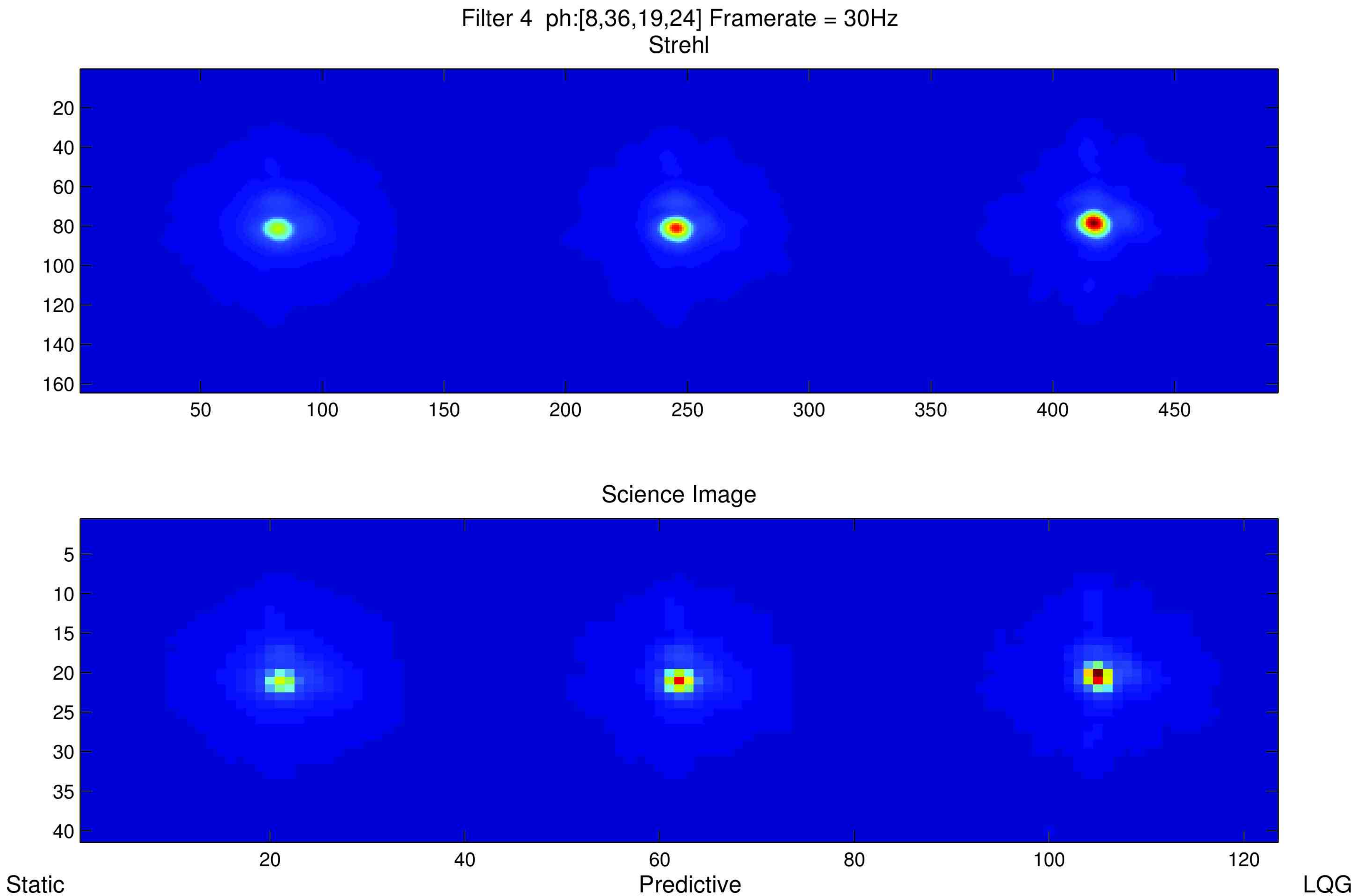


Static vs predictive vs SA-LQG

Exposure times: 120 seconds



Static vs predictive vs SA-LQG



Conclusions and outlook

- **Spatio-Angular formulation**
  - Natural generalization of off-axis MMSE to multiple #WFSs and #DMs
    - Fully model-based or partly data-driven
- **Temporal prediction can be straightforwardly embedded**
  - Can use as finely discretized Cn2 profile as wanted
  - Leads to 1 mag increase in limiting magnitude
  - RTC requirements ~3x160 slopes X 2x97 DM actuators ~47MFLOPS
  - Robustness under assessment
- **1st experimental setup of LQG formulation**
  - Provides extra 1 mag in limiting magnitude
  - OL/CL extension requires multi-rate processing
  - RTC requirements increase ~2x
- **Outlook**
  - **May 2014:** First engineering night at Subaru Telescope