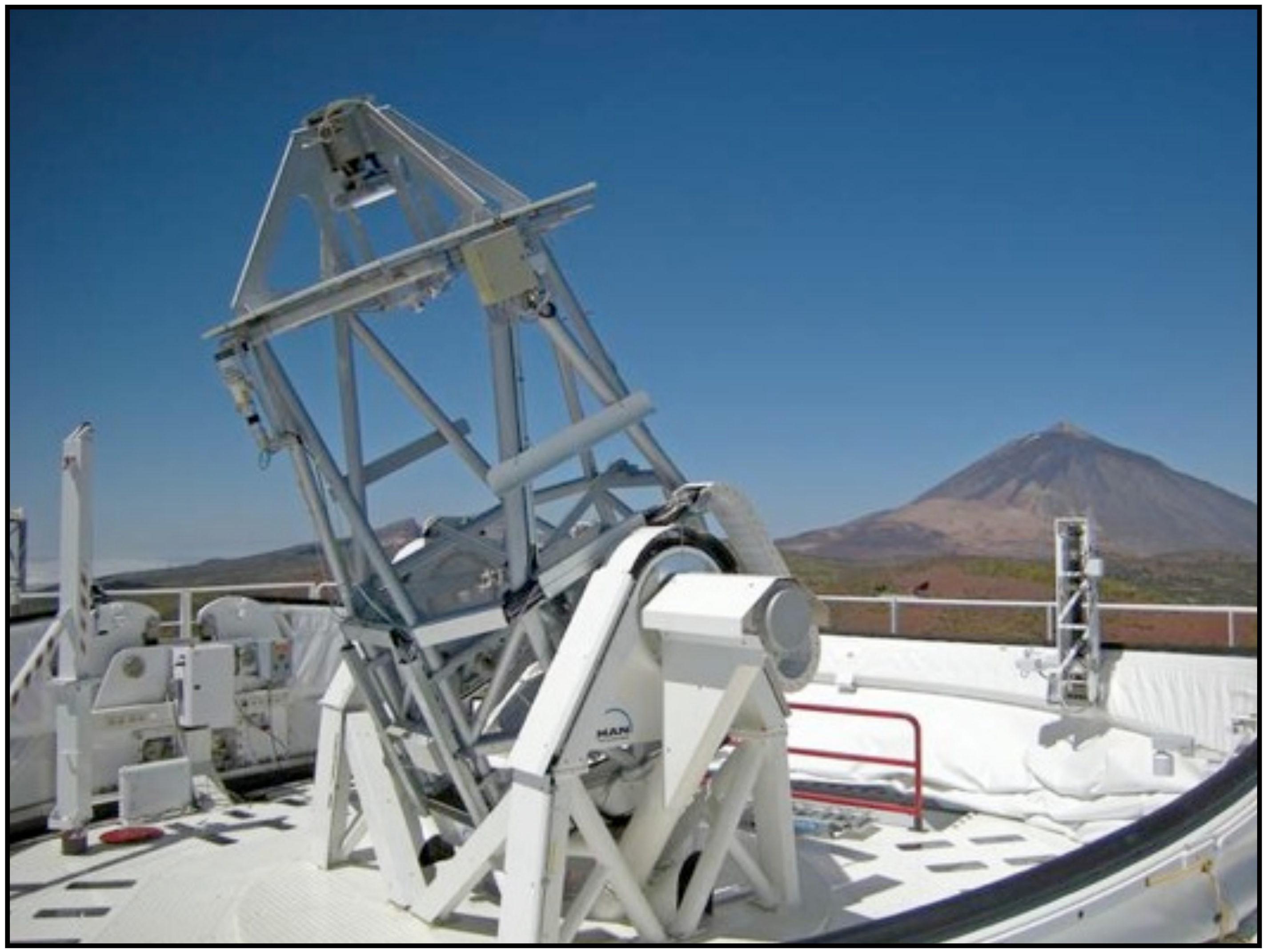
Tomography and first On-Sky Results of the MCAO at the 1.5m GREGOR Solar Telescope



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Outline

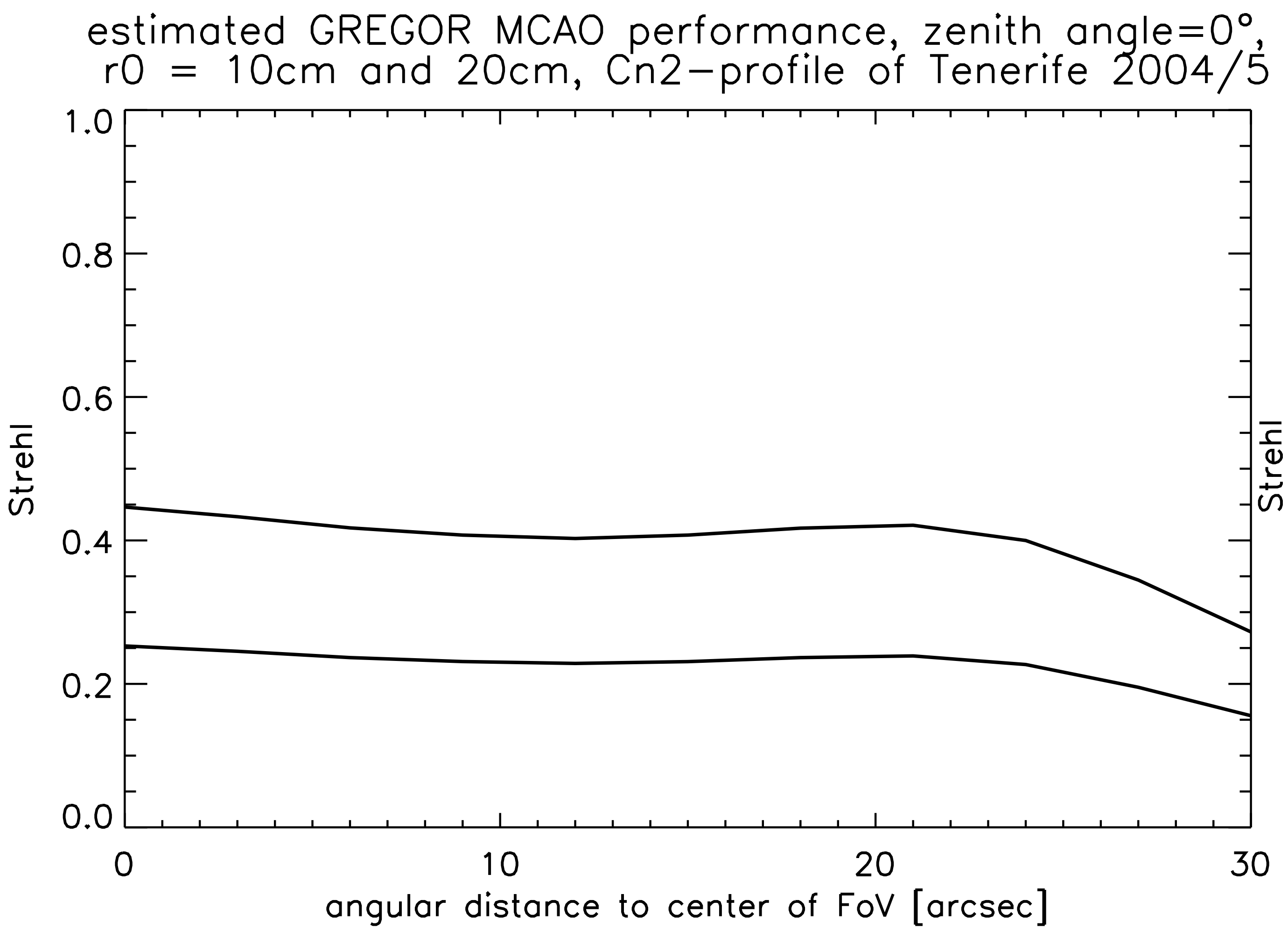
1. differences of night-time and solar MCAO
2. specs and system setup of the GREGOR MCAO
3. wavefront reconstruction scheme
4. on-sky results and lessons learned
5. changes for future observations
6. outlook

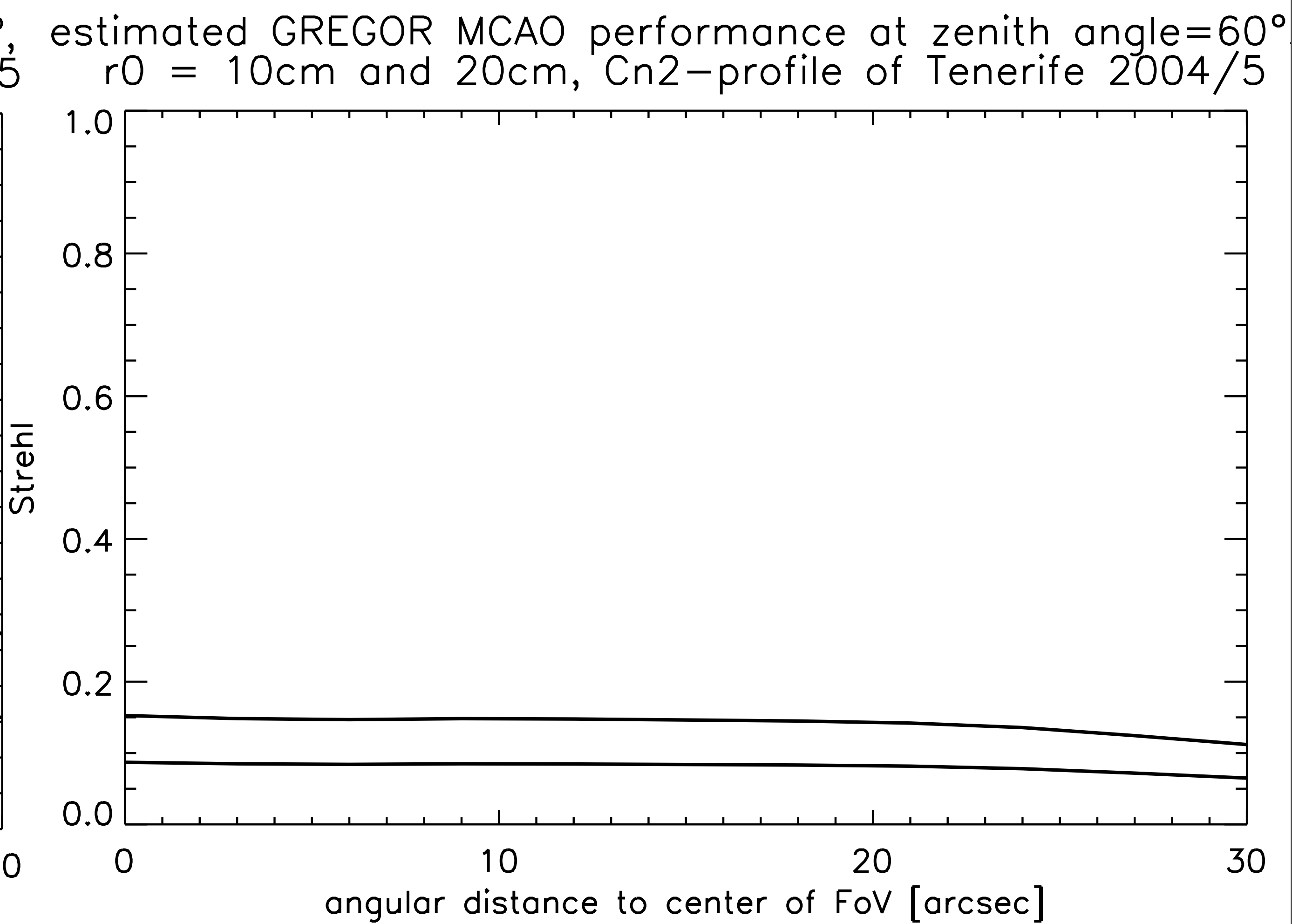
1. Advantages of Solar MCAO

+ plenty of photons
+ (almost) complete sun coverage, plenty of guide regions
  no open loop MOAO
+ no laser guide stars and their problems

I. Disadvantages of solar MCAO

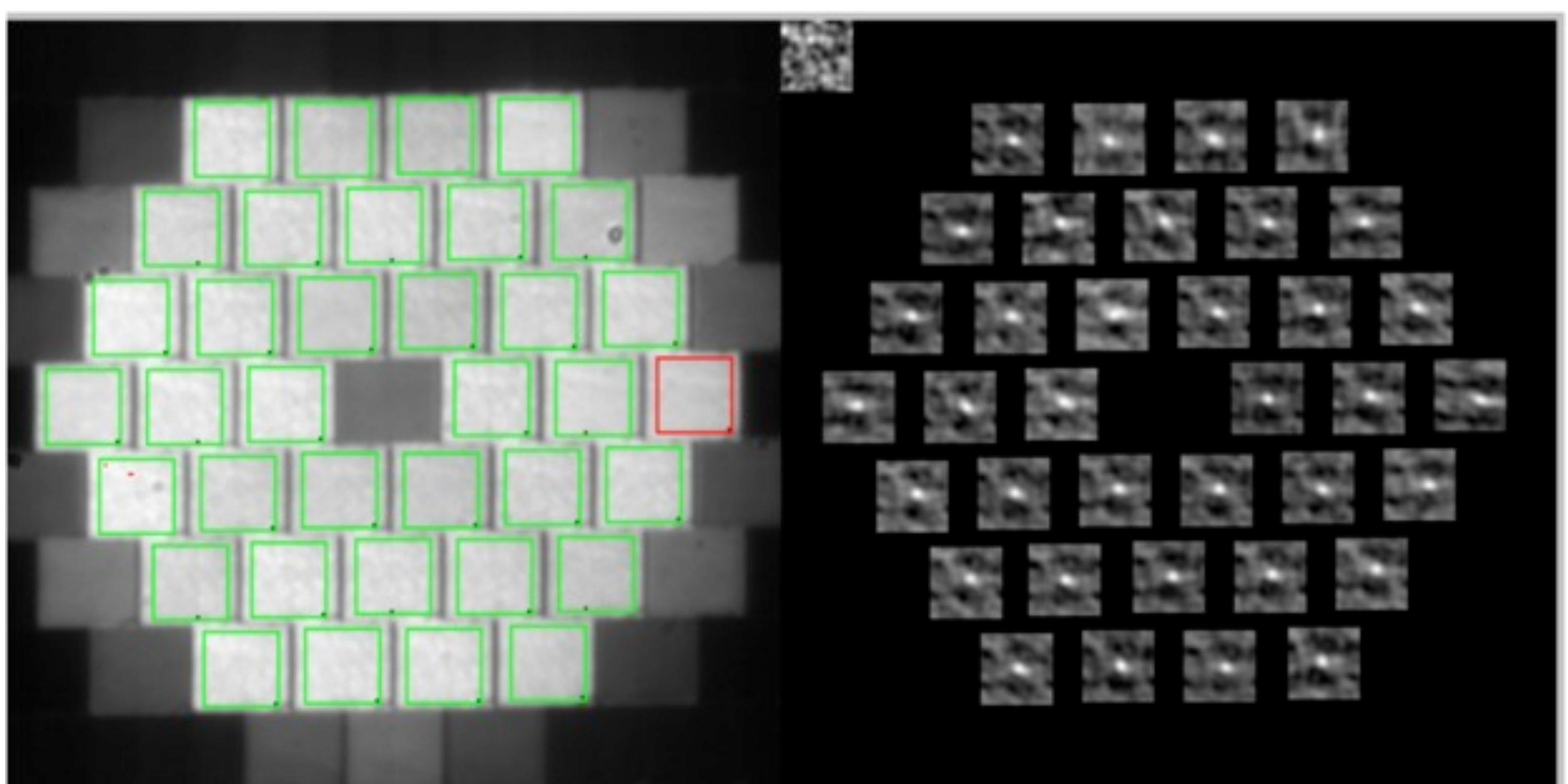
- observations are mostly done in the visible
- observations are mostly done at high air masses





1. Disadvantages of solar MCAO

- observations are mostly done in the visible
- observations are mostly done at high air masses
- only correlating Shack-Hartmann sensors useable, its FoV of 10´´-15´´ leads to GLAO-type wavefront sensing



example:
WFS of the VTT

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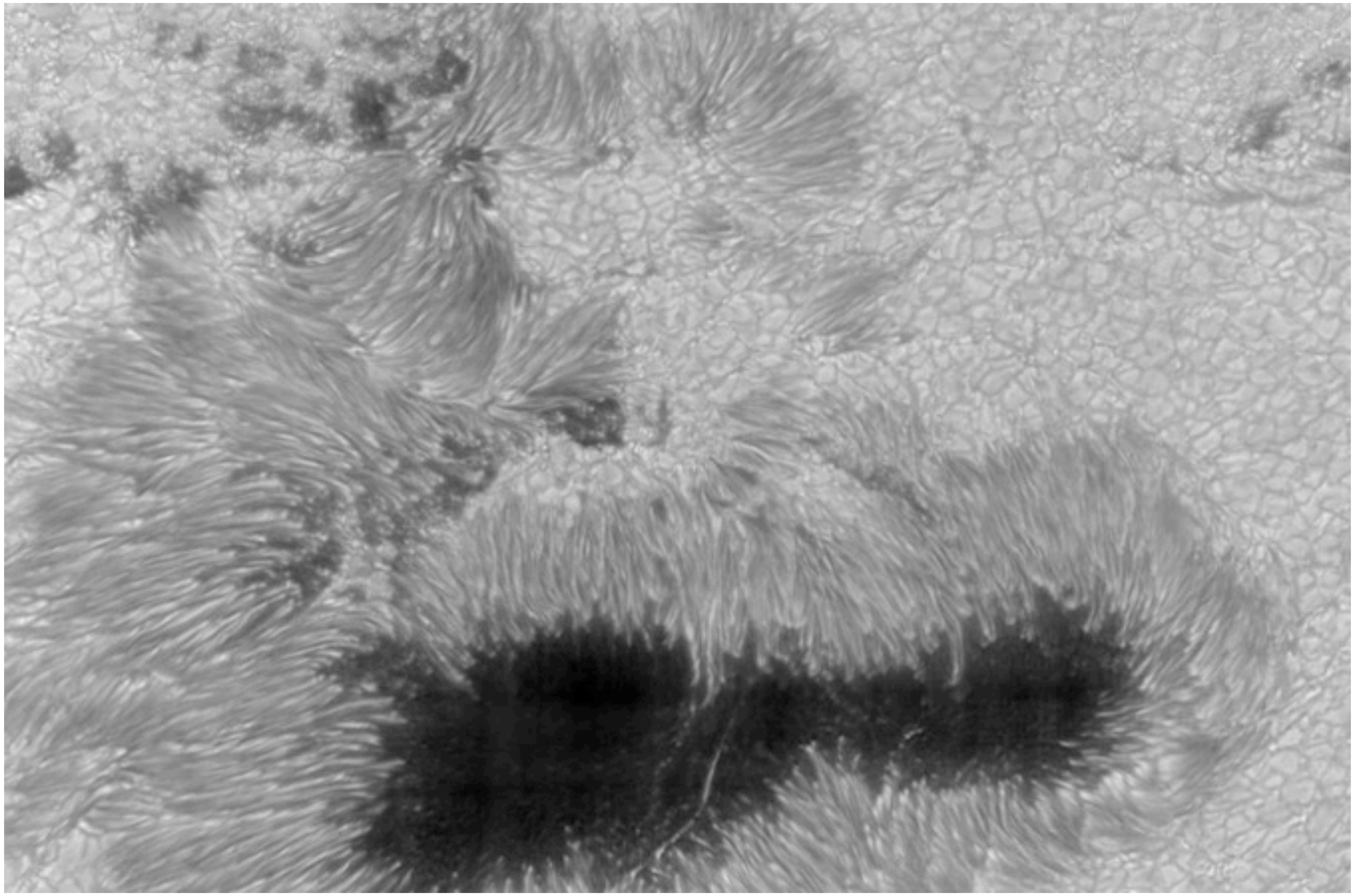
- only correlating Shack-Hartmann sensors useable, its FoV of 10´´-15´´ leads to GLAO-type wavefront sensing
- CMOS camera development leads to smaller and smaller full well capacities, no binning

2. Specs of the GREGOR MCAO

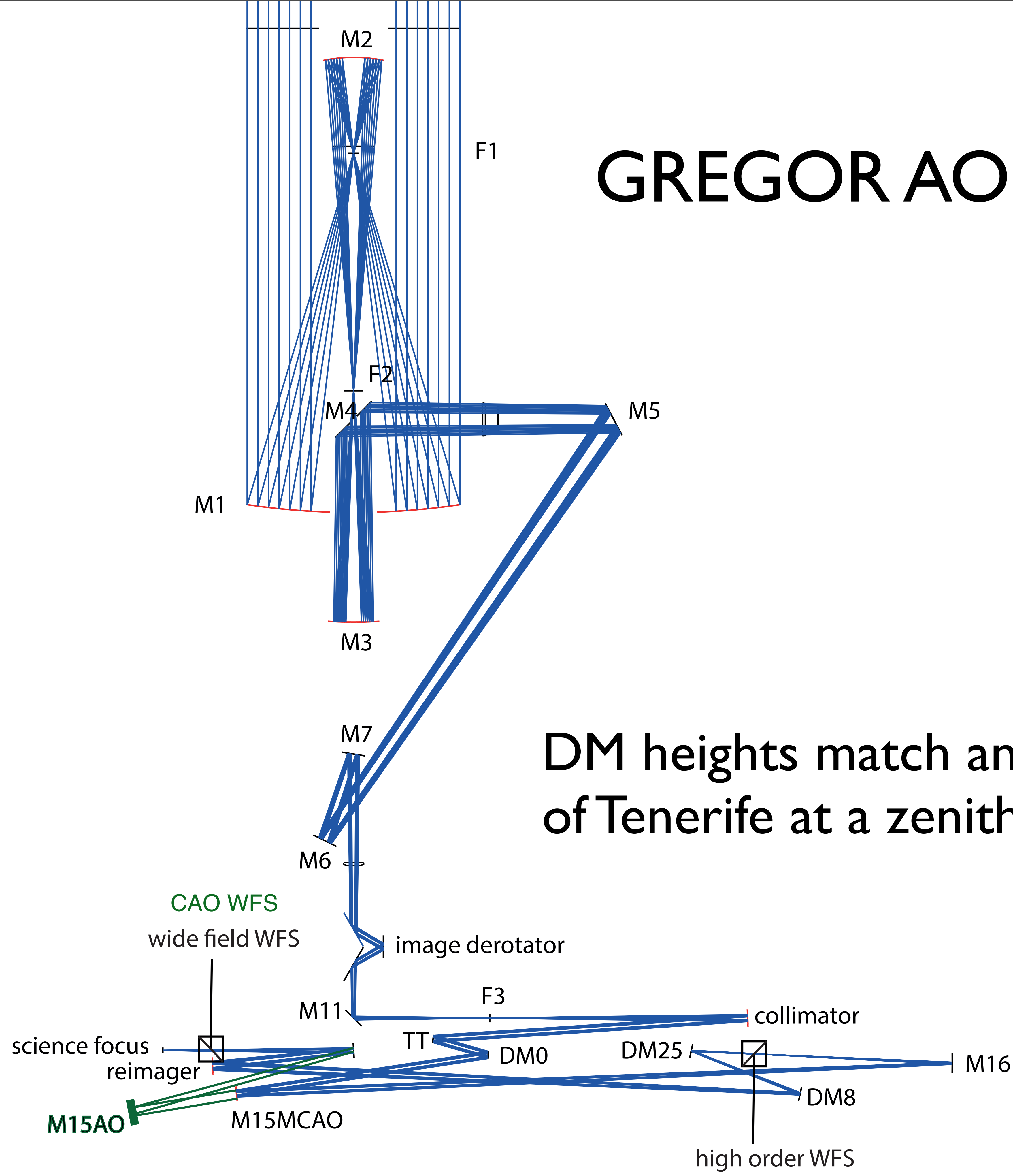
- corrected FoV 60´´ (sunspots)



2. Specs of the GREGOR MCAO

- corrected FoV 60´´ (sunspots)
- extension of the CAO system
  (135 corrected KL modes, 100 Hz bandwidth (0db))
- CAO and MCAO must be easily switchable
- low number of additional mirrors
- f-ratio, science focus and exit pupil must coincide with CAO

GREGOR AO / MCAO optics



DM heights match an averaged Cn2-profile of Tenerife at a zenith angle of ~55 deg

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  (135 corrected KL modes, 100 Hz bandwidth (0db))
- CAO and MCAO must be easily switchable
- low number of additional mirrors
- f-ratio, science focus and exit pupil must coincide with CAO
- optical scheme must provide a constant metapupil
  (allows changing the heights of the layer DMs)
- three DMs are the maximum doable right now

2. Specs of the GREGOR MCAO

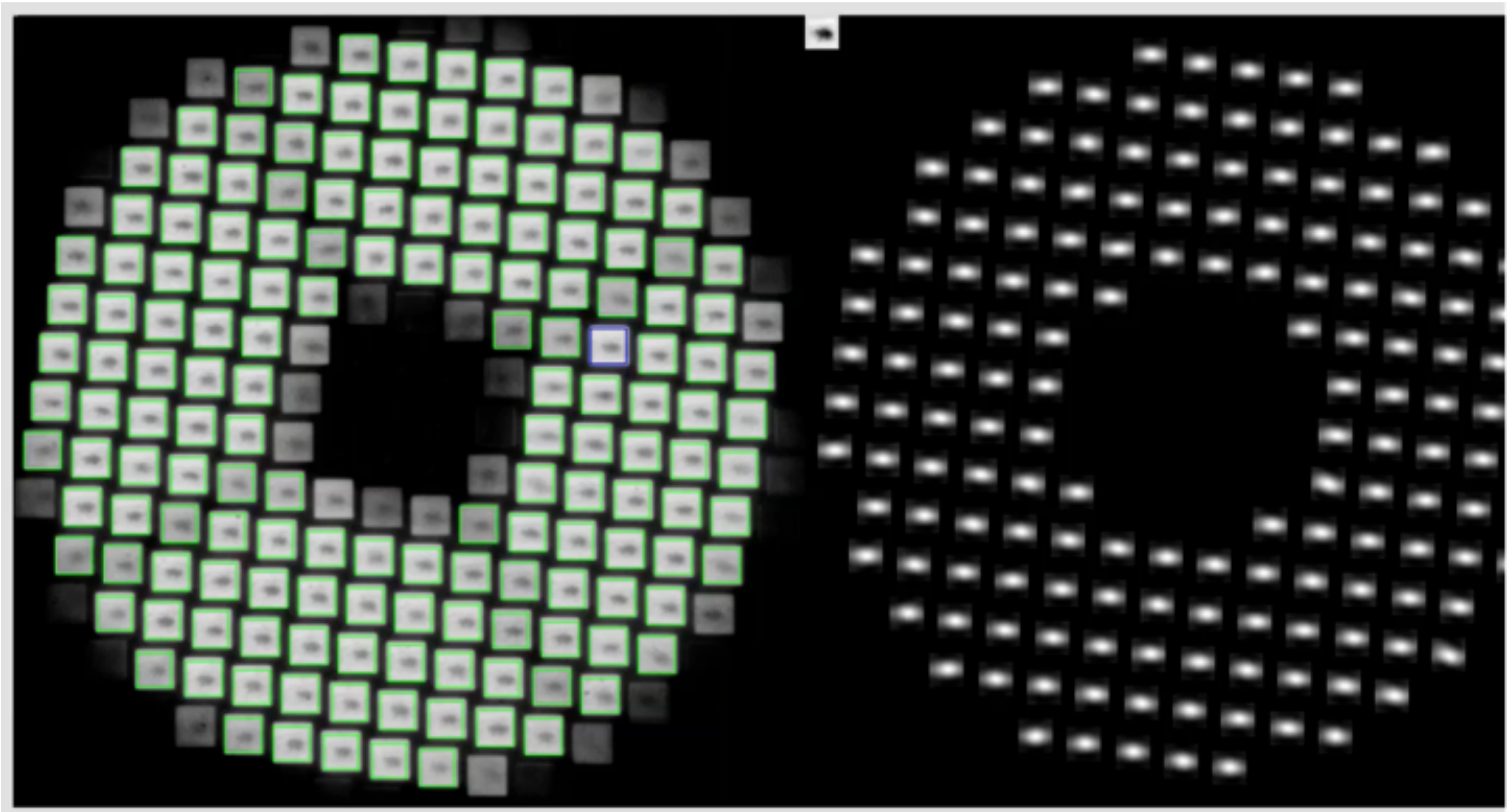
no spec for Strehl !

- best effort
- solar MCAO still experimental

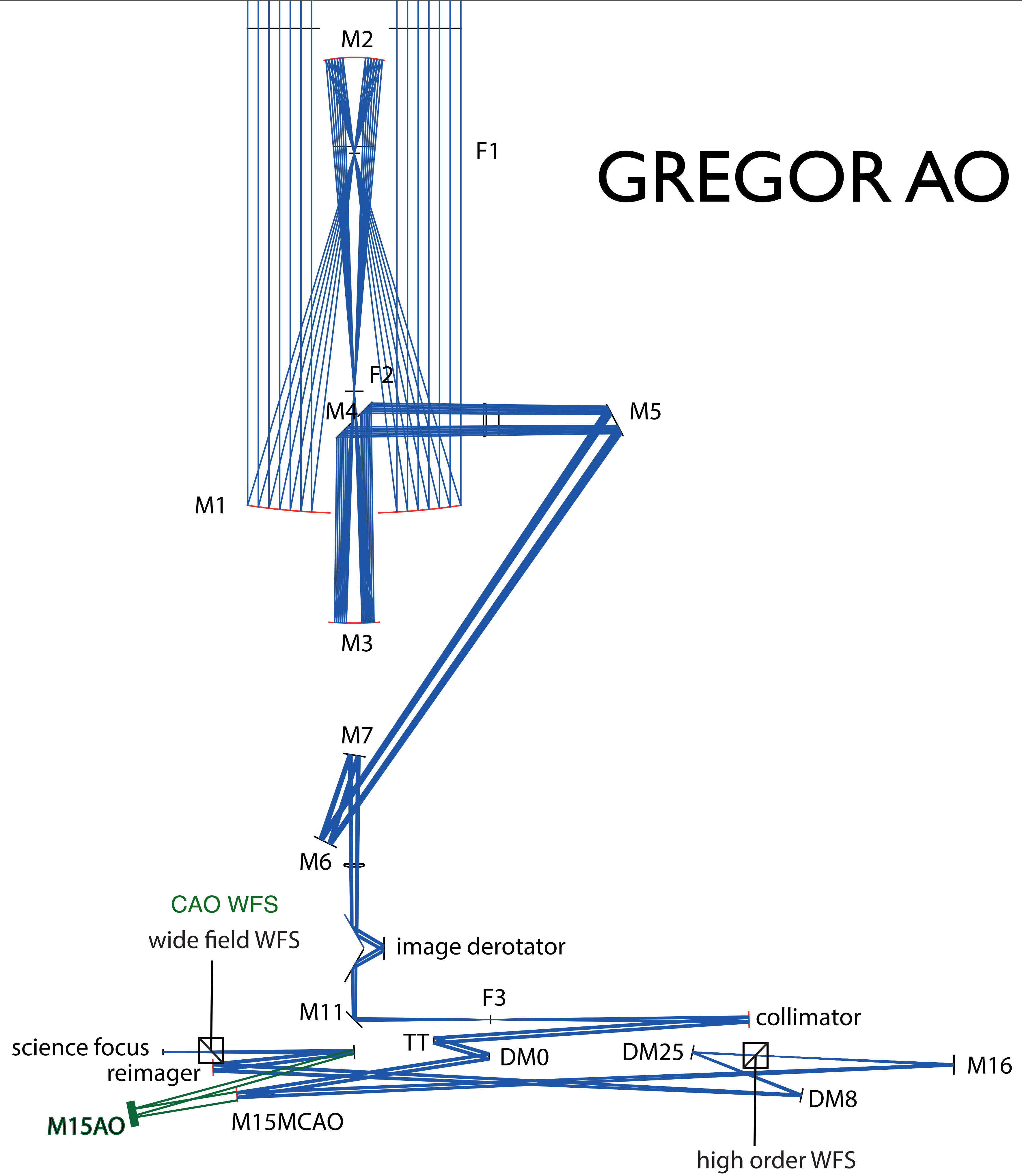
2. WFSs of the GREGOR MCAO

1) HOWFS: high order (on axis, same as CAO) WFS

- high spatial resolution (156 subapertures, 10cm /subap)
- only one viewing direction (on-axis), 12´´FoV (24x24 pix)
- senses the low altitude high spatial frequencies



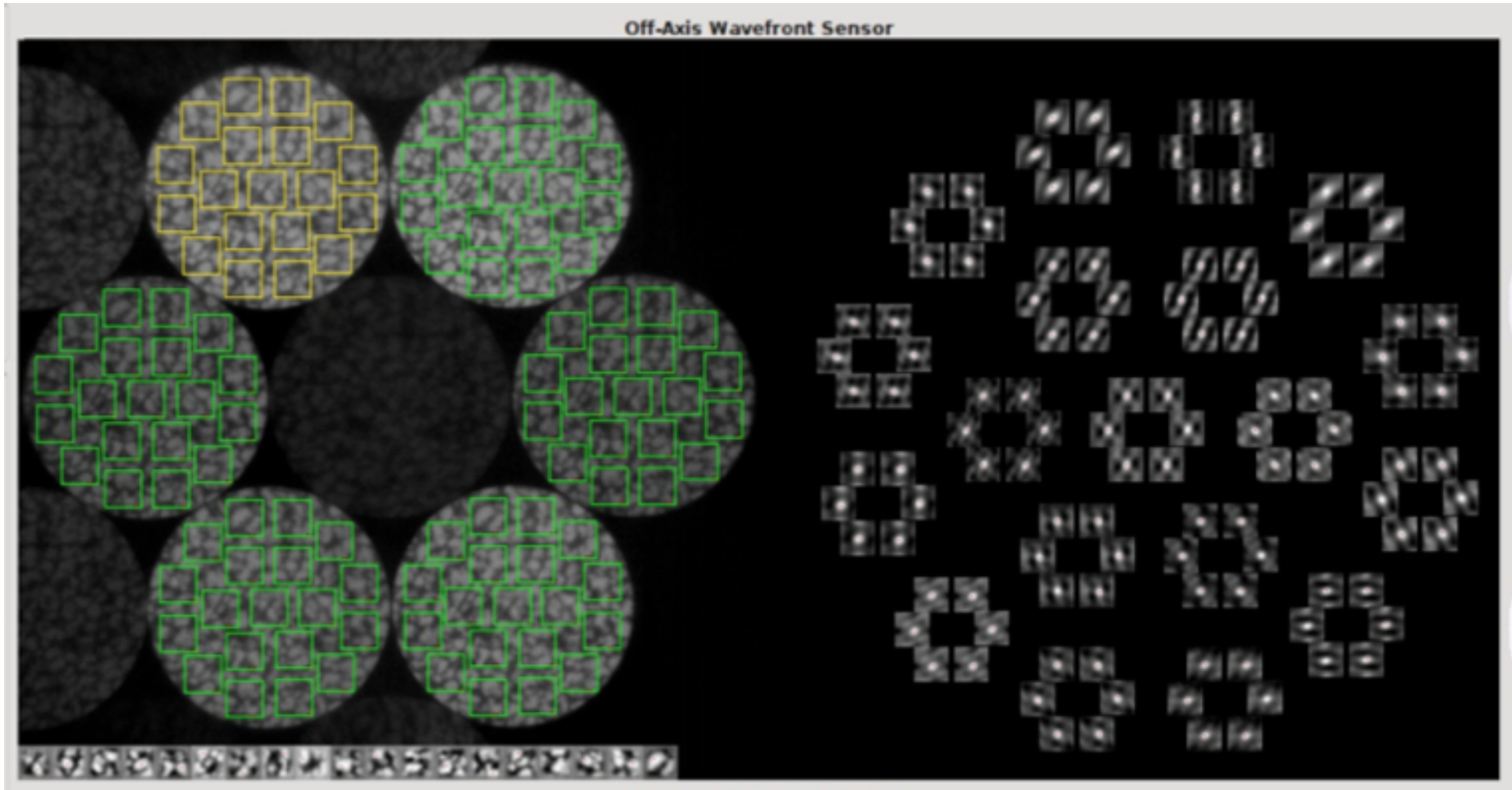
GREGOR AO / MCAO optics



2. WFSs of the GREGOR MCAO

2) WFWFS: wide field (low order) WFS

- low spatial resolution (6 subapertures, 48cm /subap)
- large (74´´) FoV, 19 subfields (12´´each) cover the corrected FoV
- senses the field dependent low order high altitude seeing



2. DM / WFS Order in the GREGOR MCAO

- DM0 - HOWFS - DM25 - DM8 - WFWFS
  present solution, extension of the CAO system
- DM0 - DM25 - DM8 - WFWFS / HOWFS

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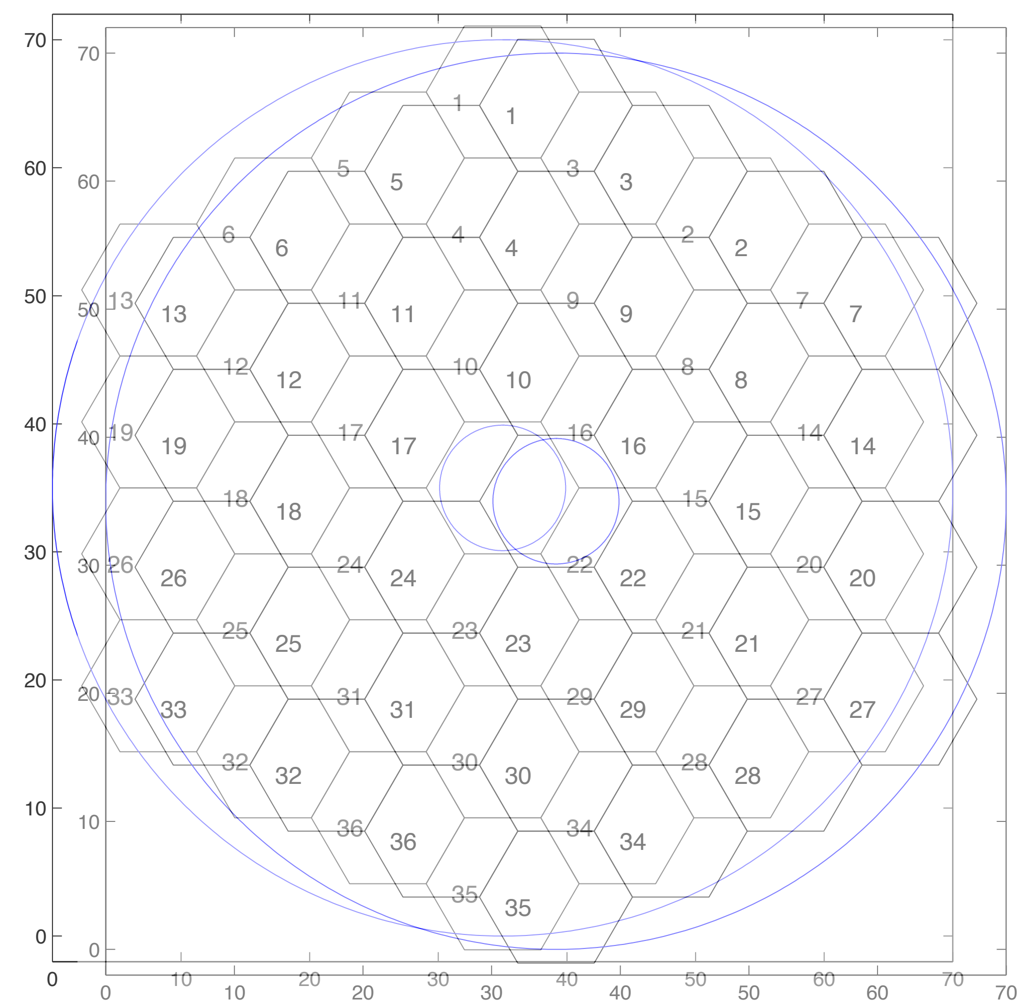
- high altitude DMs (close to the focus) warp the pupil on the following light paths (and DMs / Lenslets)
- for AO loops, pupil misregistration between DMs and Lenslets is a problem for high spatial frequencies, i.e. DM0 and the HOWFS



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- high altitude DMs (close to the focus) warp the pupil on the following light paths (and DMs / Lenslets)
- for AO loops, pupil misregistration between DMs and Lenslets is a problem for high spatial frequencies, i.e. DM0 and the HOWFS
- no high altitude DM between DM0 and the HOWFS !!
- no problem for the large subapertures of the WFWFS

2. DM / WFS Order in the GREGOR MCAO

- DM0 - HOWFS - DM25 - DM8 - WFWFS
  present solution, extension of the CAO system
- DM0 - DM25 - DM8 - WFWFS / HOWFS
  problem of dynamic pupil misregistration
- DM25 - DM8 - DM0 - WFWFS / HOWFS
  requires completely new AO/MCAO train - good reasons ?
- DM25 - DM8 - DM0 - several HOWFS (Gemini, VLT)
  requires completely new AO/MCAO train - good reasons ?
  many WFSs / -cameras

2. Technical Details

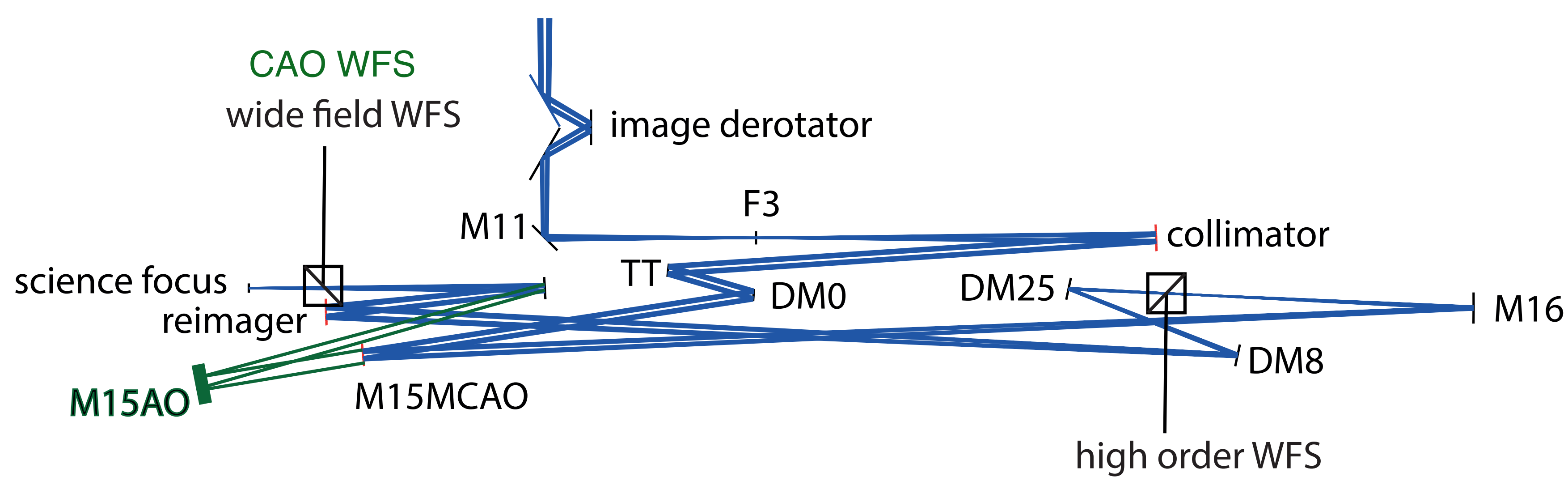
- WFS-cameras: Mikrotron Eosens CL
  ROI 560x560 pix, 8 bit/pix, 1.6 kHz frame rate
- DM0: CILAS stacked piezo, 256 actuators
- DM8/25: Flexible Optics, 69 actuators each

3. Calibration - Internal Reference

- pinhole at the WFS entrance focus gives the internal reference for the perfect wavefront
- for the WFWFS, a pinhole pattern corresponds to the guide region positions on sky

3. Calibration - Interaction Matrices

- DM0 to HOWFS: pinhole at the F3 focus (before all DMs), poking DM0 using a hadamard pattern



3. Calibration - Interaction Matrices

- DM0 to HOWFS: pinhole at the F3 focus (before all DMs), poking DM0 using a hadamard pattern
- TT/DMs to WFWFS: pinhole pattern at the F3 focus, poking the TT and all DMs using hadamard patterns
- alternatively, an extended target in F3 and crosscorrelation techniques can be used instead of the pinhole pattern, avoiding mismatch with respect to the reference pinhole pattern

3. Wavefront Reconstruction

- two reconstruction steps: shifts ⇒ modes ⇒ actuators
- modal basis: KL modes projected onto the DMs, matrix modes ⇒ actuators is fixed (but modal gains exist)
- wavefront reconstruction: find matrix shifts ⇒ modes

3. Wavefront Reconstruction

- modal selection
  - aliasing analysis for HOWFS / DM0: 135 usable modes,
  - DM8/25: first 40-50 KL modes each

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- #modes reduced in case of bad seeing (DM0) or strong differential (field dependent) errors (DM25)

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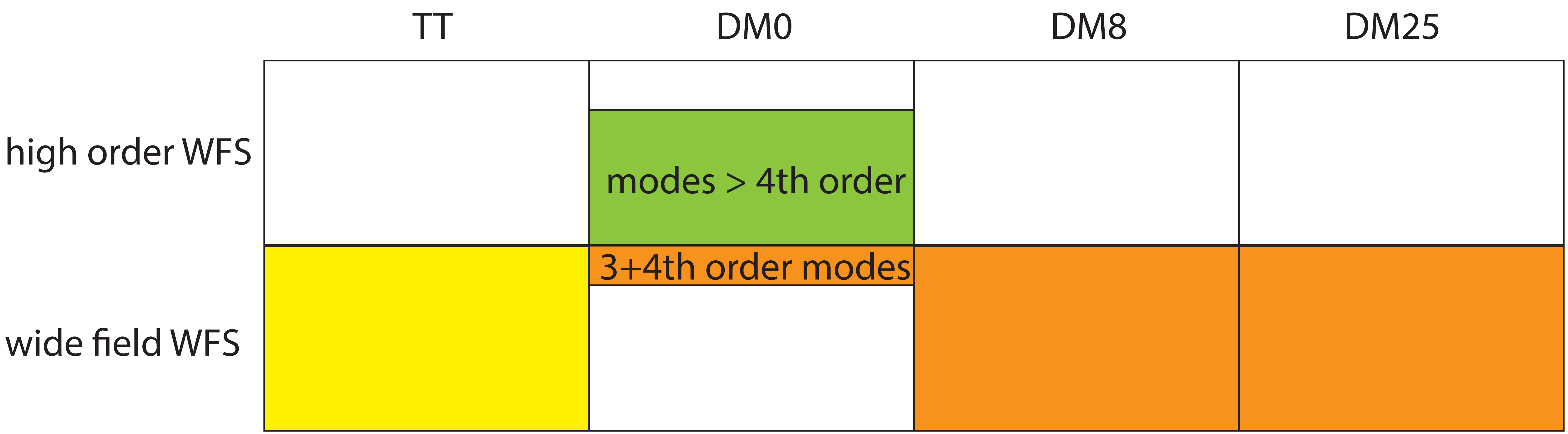
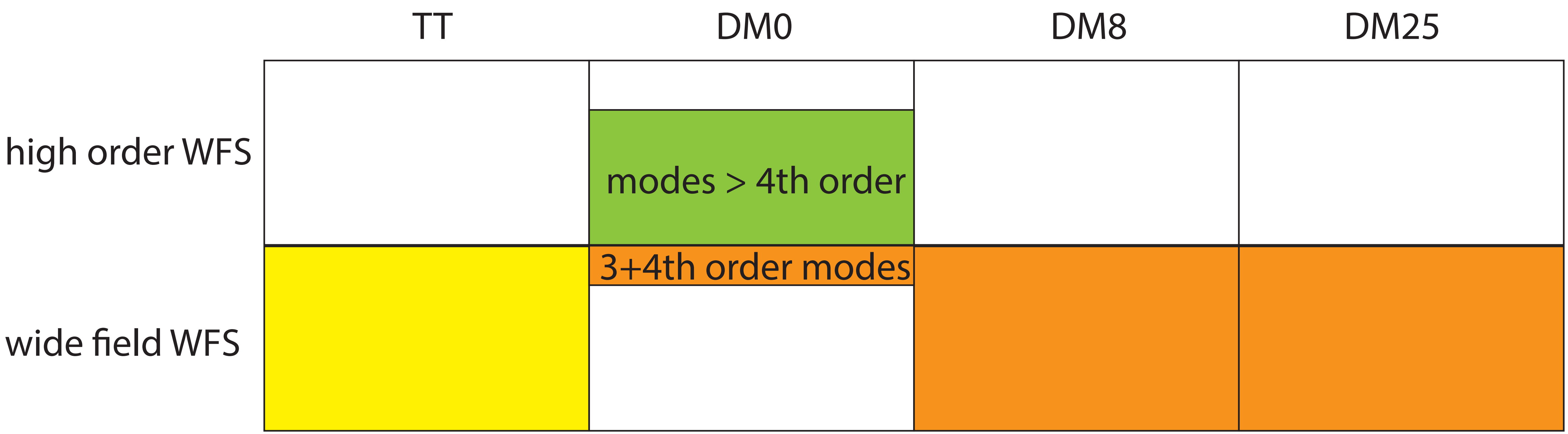


differential image drift is removed due to evolving solar granulation

3. Wavefront Reconstruction



crosstalk of low order modes in the
global inversion of the WFWFS (orange)

- lab test: only separating focus of DM8/25 posed a problem
- on-sky: wrong ground layer focus

4. On-Sky Results

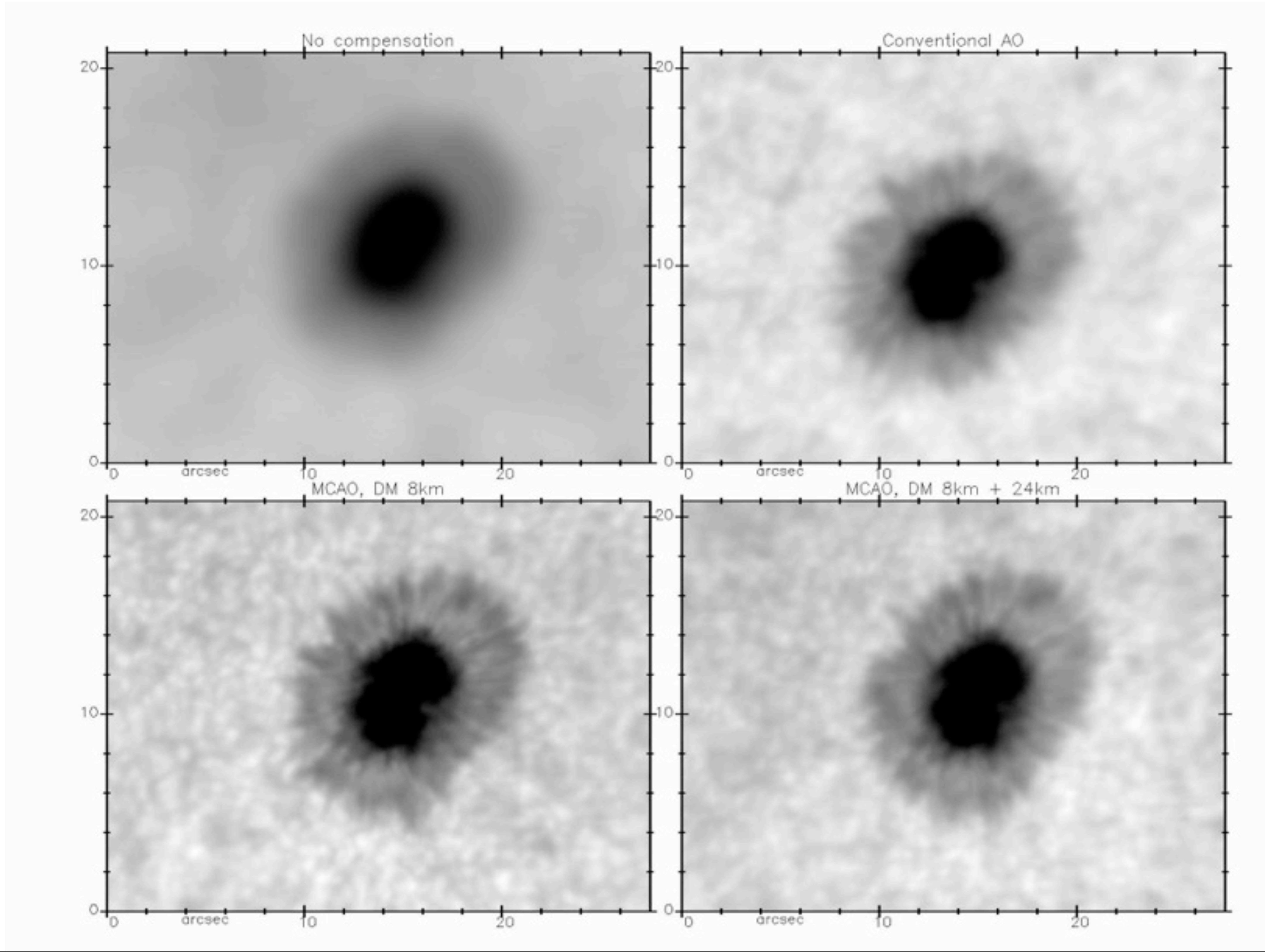
- observing run Nov. 2013: settings things up, closed loop during the last morning
- observing run Jan. 2014: mostly cloudy

⇒ two observing days with bad seeing in total

4. On-Sky Results

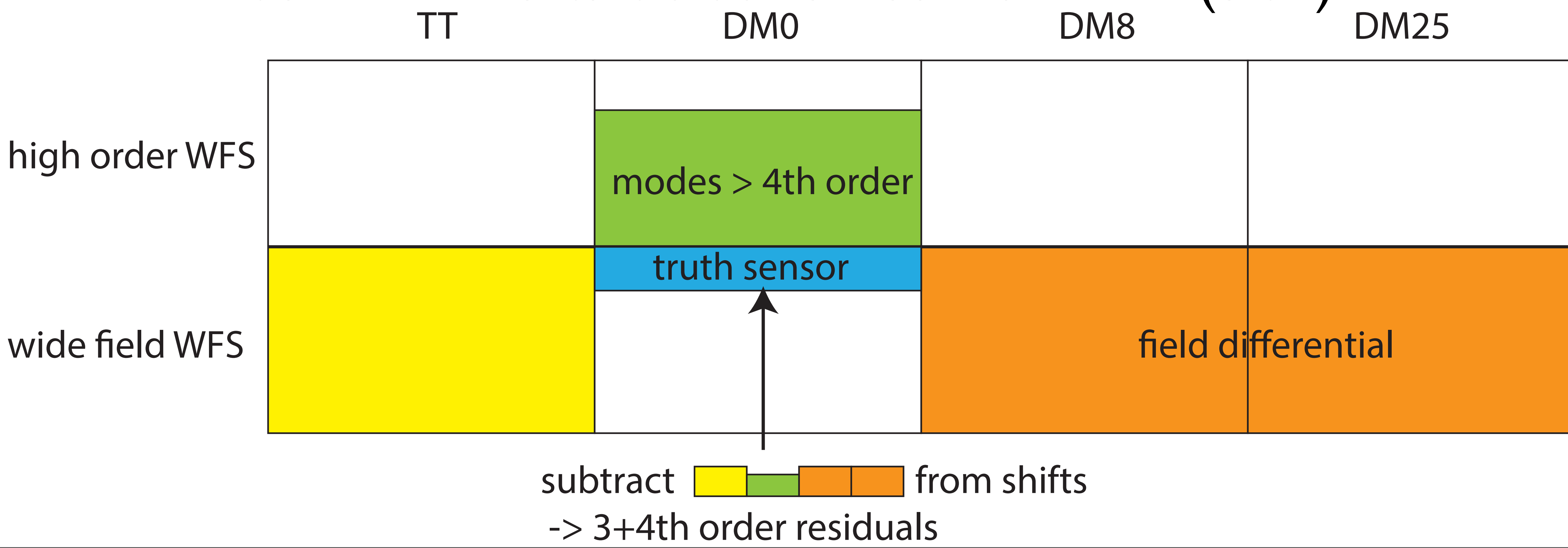
- movie missing -

4. On-Sky Results



4. On-Sky Results: Lessons Learned

- wrong ground layer focus due to crosstalk: modify reconstructor similar to the one used during the successful on-sky tests at the VTT in 2005/6
  - use DM8/25 to correct field-dependent aberrations
  - use DM0 to correct field-independet aberrations
  - use WFWFS as a truth-sensor for DM0 (blue)



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  - use DM8/25 to correct field-dependent aberrations
  - use DM0 to correct field-independet aberrations
  - use WFWFS as a truth-sensor for DM0 (blue)
- measurement of WFWFS interaction matrices: try extended target instead of pinhole pattern in F3 to avoid mismatch with reference pinhole pattern

to be changed for observing campaign in May

5. Changes for Future Observations

later this year...

- change WFWFS from 6 to 18 subapertures (29cm diam.)
  - to have a higher accuracy on field-dependent aberrations
  - to have a higher accuracy on the residual DM0 correction
- use the new reconstructor plugin possibility
  to try completely different reconstructors
- use the new simulator capability of the control loop

5. New simulator capability of the control loop

- set of phase screens mimic a Cn2-profile, including wind etc
- an artificial solar image gets propagated and disturbed and is fed into the camera framebuffers
- normal operation of the control loop
- DM commands are subtracted from the phase screens (selectable frame delay)

⇒ **test tomographic reconstruction**

5. Changes for Future Observations

wish list...

- we need more actuators on DM8/25... (according to the Cn2-profile),
- DMs should have surface without inherent curvature (focus change due to solar heating)
- easier switching between CAO and MCAO
  - allows to do tests during the scientifically unused afternoons
  - requires motorized mirror stages
- realtime-measurement of the Cn2-profile (Shabar)

6. Outlook

we are confident to get a good and stable MCAO loop in May
⇒ talk at SPIE Montreal by Dirk Schmidt

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funding proposal to the Leibniz Society

- to buy two DMs with approx. 150 actuators each, to either get the first 4+1 DM-MCAO or a better 2+1 DM-MCAO
- get a postdoc for two years to work on the topics mentioned, especially wavefront reconstruction

testbed for 4m solar telescopes ATST and EST