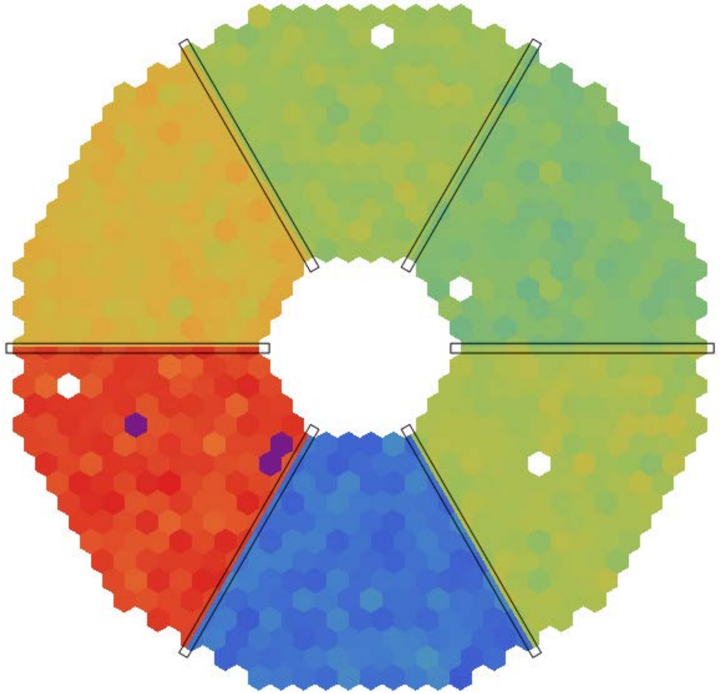
Simulation Environment for Segment and Petal Phasing of Large Telescopes



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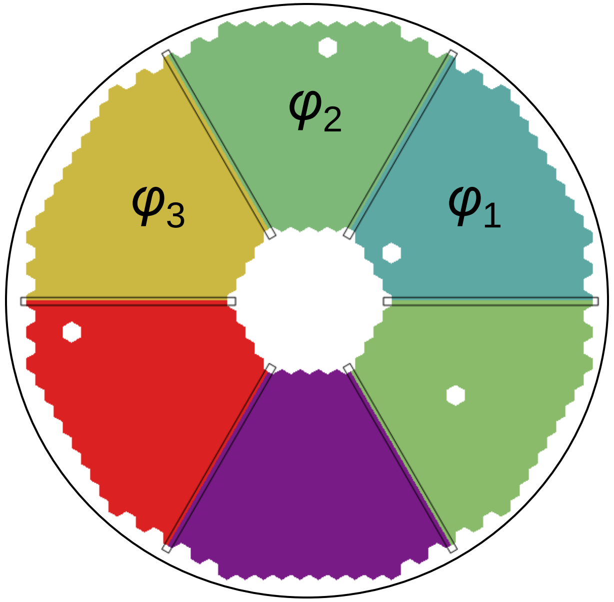
Wavefront Sensing Workshop

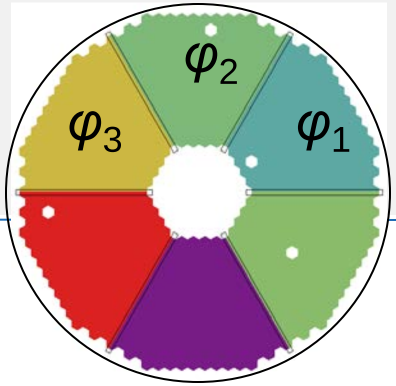
Oct 2019



Physical Optics Simulation Environment

- Continuous need in ESO’s Optics Department to simulate optical subsystems, often involving diffraction effects and turbulence
- “Numerical Test Bench”: Deepen understanding of optical performance, compare technical options, ability to validate technical requirements, develop algorithms
- Fourier optics code, implemented in *Mathematica*
- Take advantage of *Mathematica’s* strong analytical math capabilities, rapid code development, integrated graphical output, multiprocessing
- We welcome comparison of algorithms and results with OOMAO, YAO

Test Case: Petal Phase Offsets



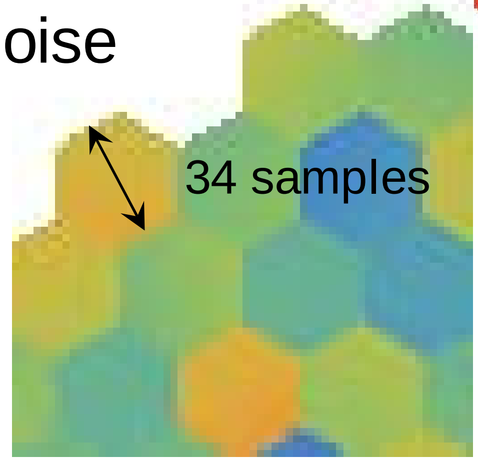
- The ELT adaptive mirror M4 consists of 6 petals (disconnected shells) whose edges are aligned with the spider shadows
- Baseline: Petal-to-petal OPD is calibrated on test tower to ~20 nm PtV, but may drift over the years (capacitive sensors)
- Petaling can exacerbate the “Island Effect” / pupil fragmentation on M1
  ➔ Distorts the PSF when AO is running and/or at large wavelength
- The spiders are 530 mm wide, exceeding r_0 in most bands (w/o AO)
  ➔ challenging to sense reliably across the spider
- Studies on K-band pyramid WFS to sense petaling are ongoing, e.g.

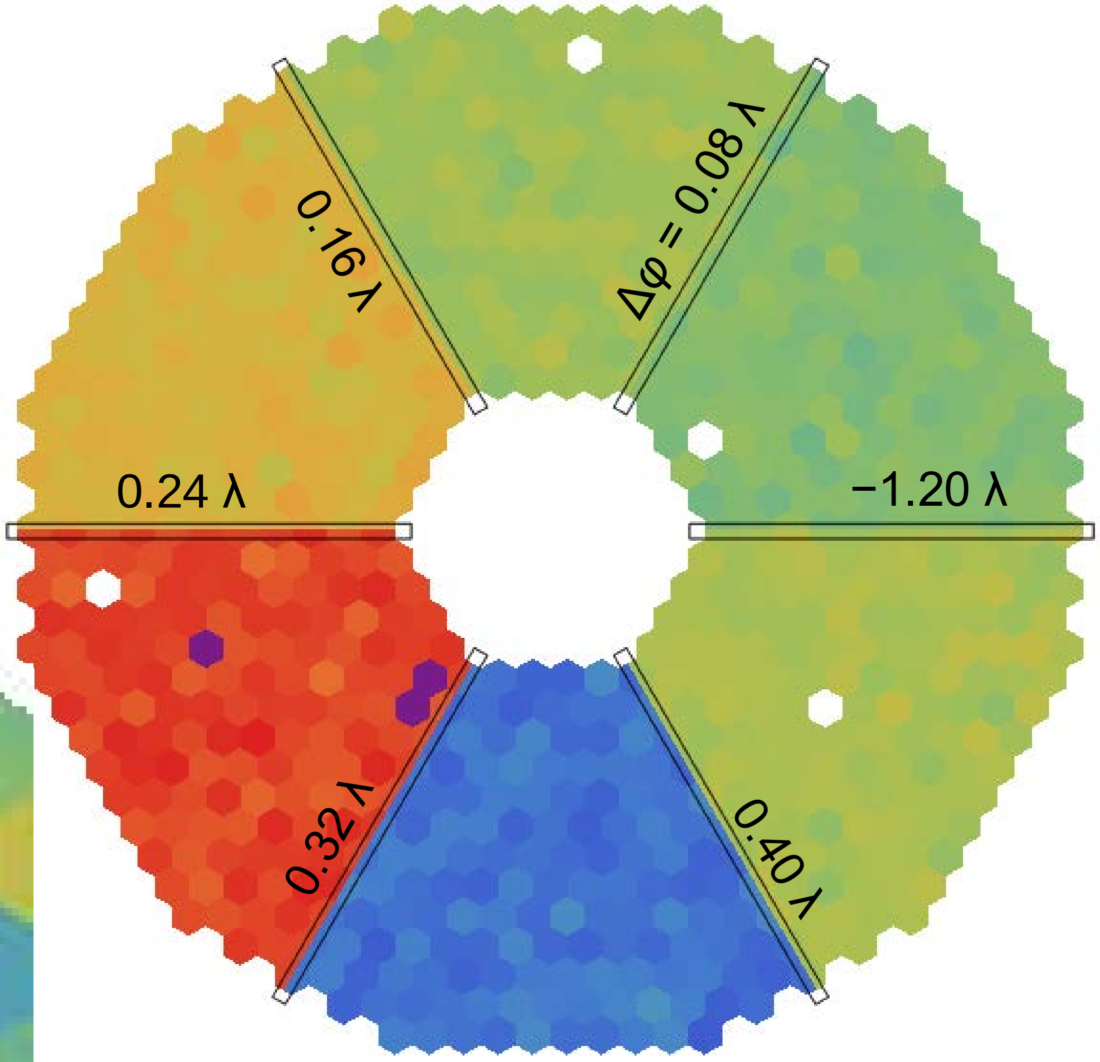
S. Hippler *et al*., “Single conjugate adaptive optics for the ELT instrument METIS”, Exp. Astron. **47** (2019)
V. Hutterer *et al*., “Advanced WF reconstruction methods for segmented ELT pupils using PWFS”, JATIS **4** (2019)

Simulations

- Monochromatic physical optics with FFT size ≥ 1176^2, non-elongated point source, average over 4000 independent phase screens
- 798 ELT-size hexagonal segments (1.22 m edge-to-edge), 2 edges aligned with pixel grid
- Simulate increasing petal phase offsets →
- Additional small Gaussian random distribution of piston misalignments (λ/30 RMS)
- No sky background / detector noise
- Compare pyramid, phase contrast, shearing WFS
- Resolution:

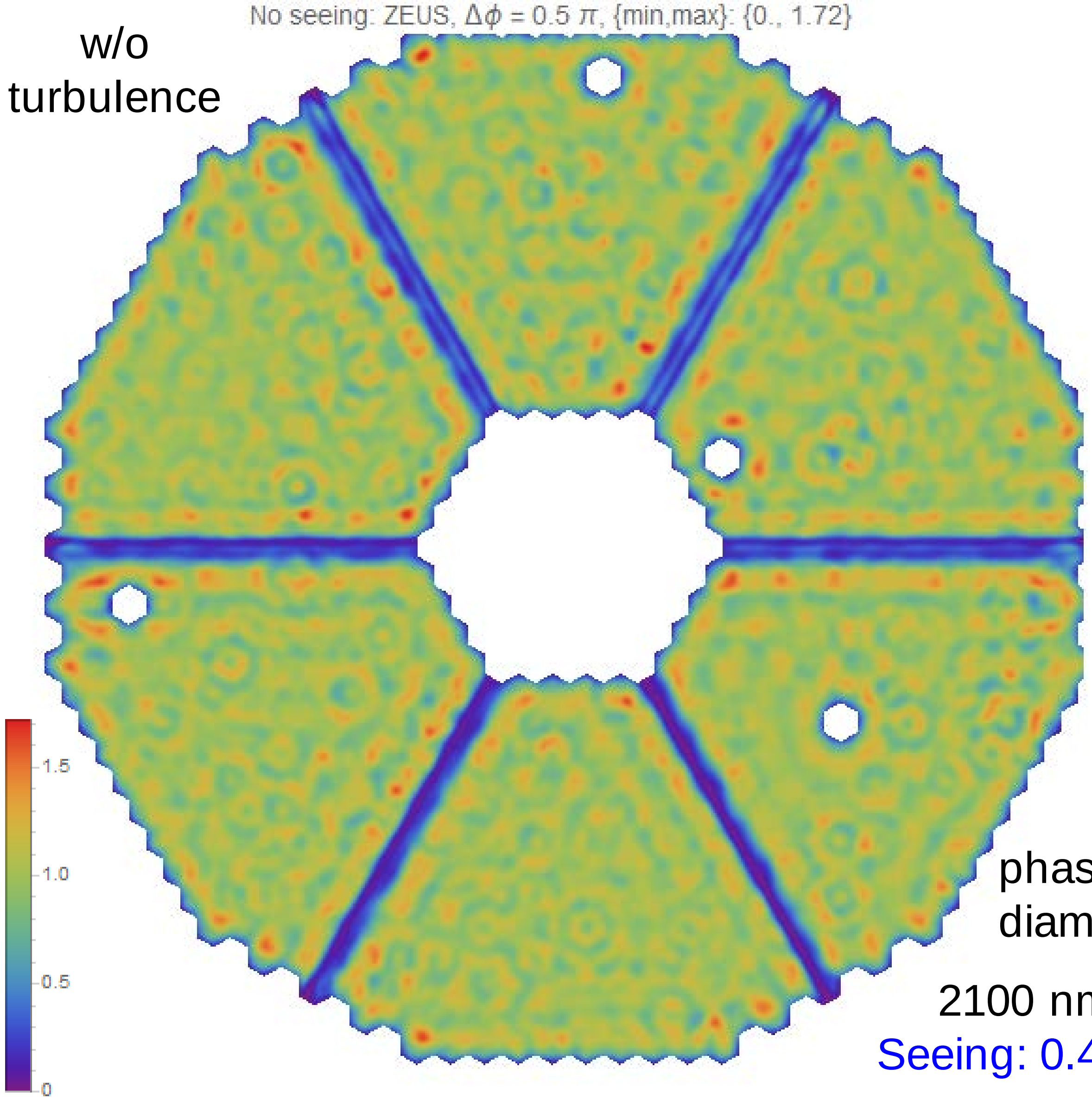
3.6 cm, angle: 8.6 mas

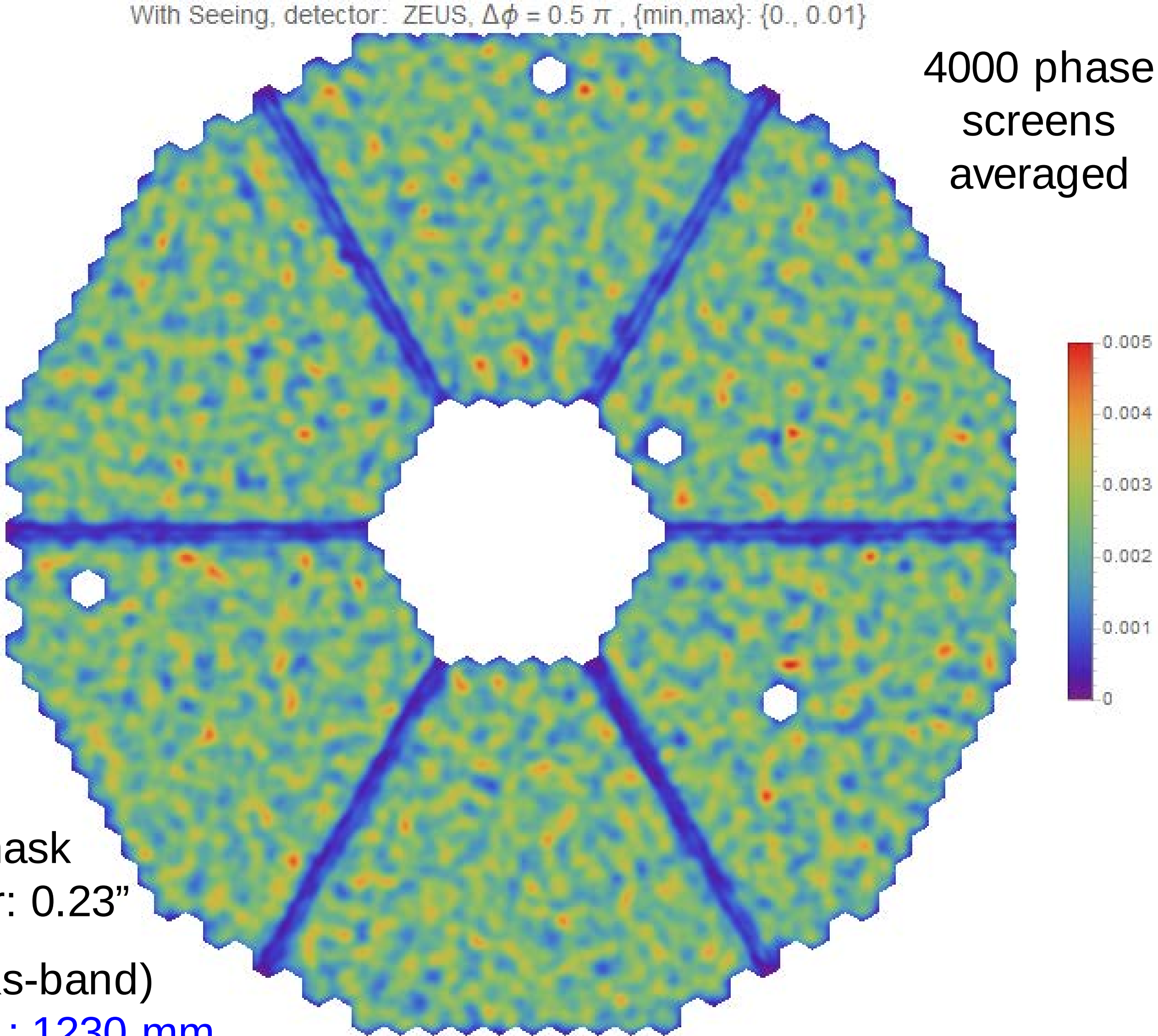




Phase Contrast WFS Response to Petaling
(ZEUS)

w/o turbulence





4000 phase screens averaged

phase mask diameter: 0.23”

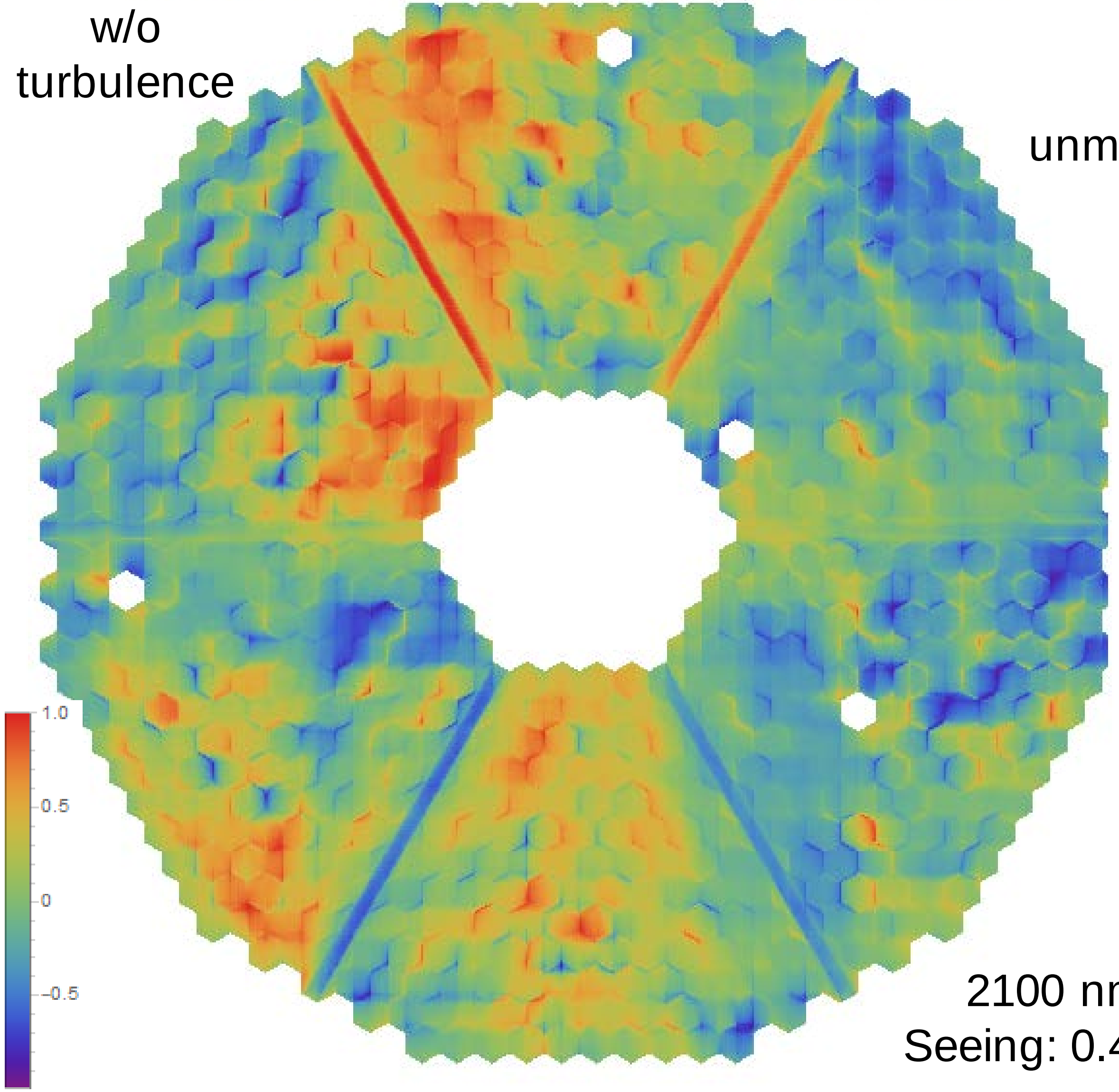
2100 nm (Ks-band)

Seeing: 0.4”, r_0: 1230 mm

Pyramid WFS: X Slopes, Unmodulated

No seeing: Unmodulated Pyramid WFS, X Slopes, {min,max}: {−0.99, 1.}

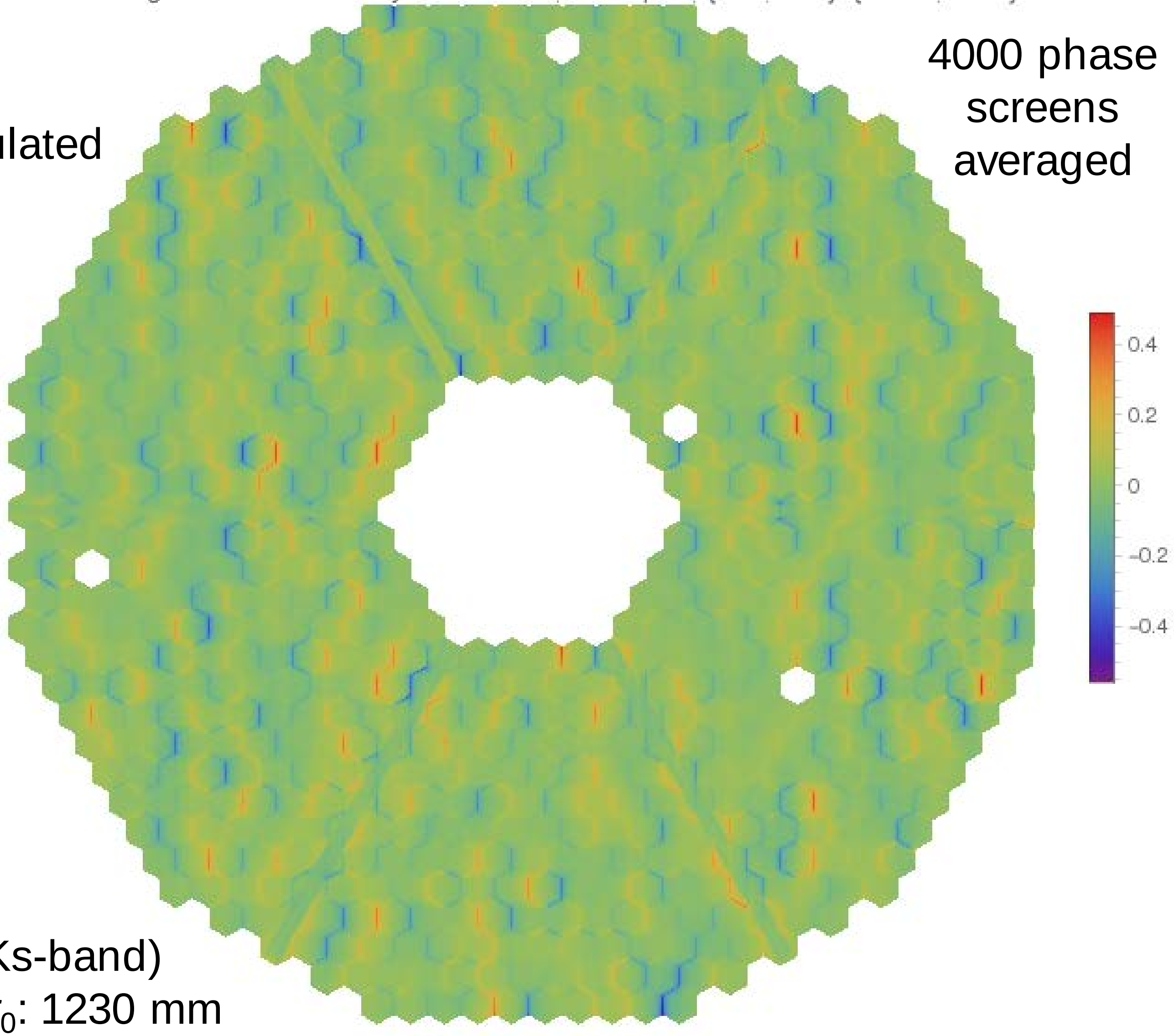
w/o
turbulence



S_x
unmodulated

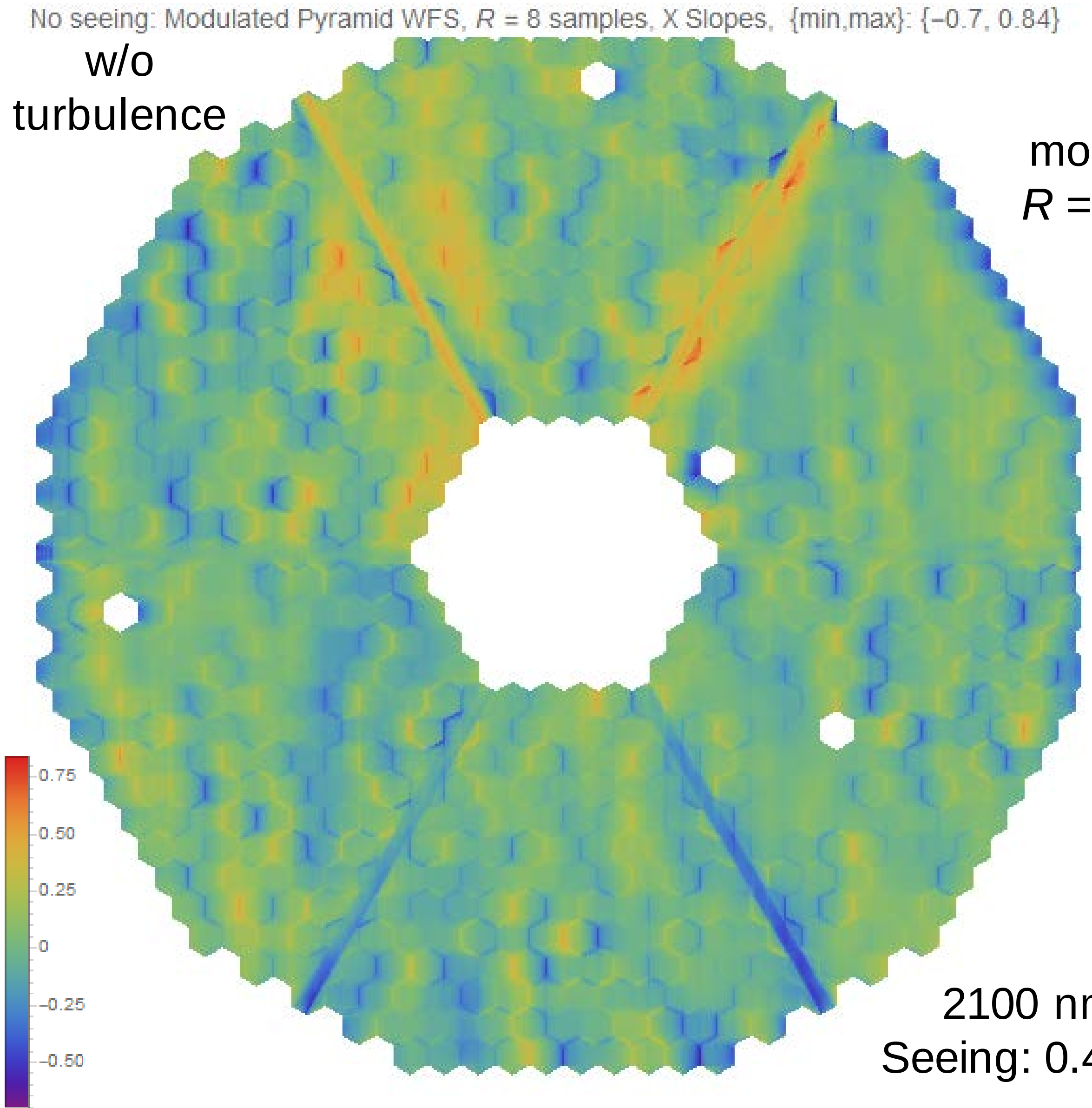
With Seeing: Unmodulated Pyramid WFS, X Slopes, {min,max}: {−0.56, 0.49}

4000 phase
screens
averaged



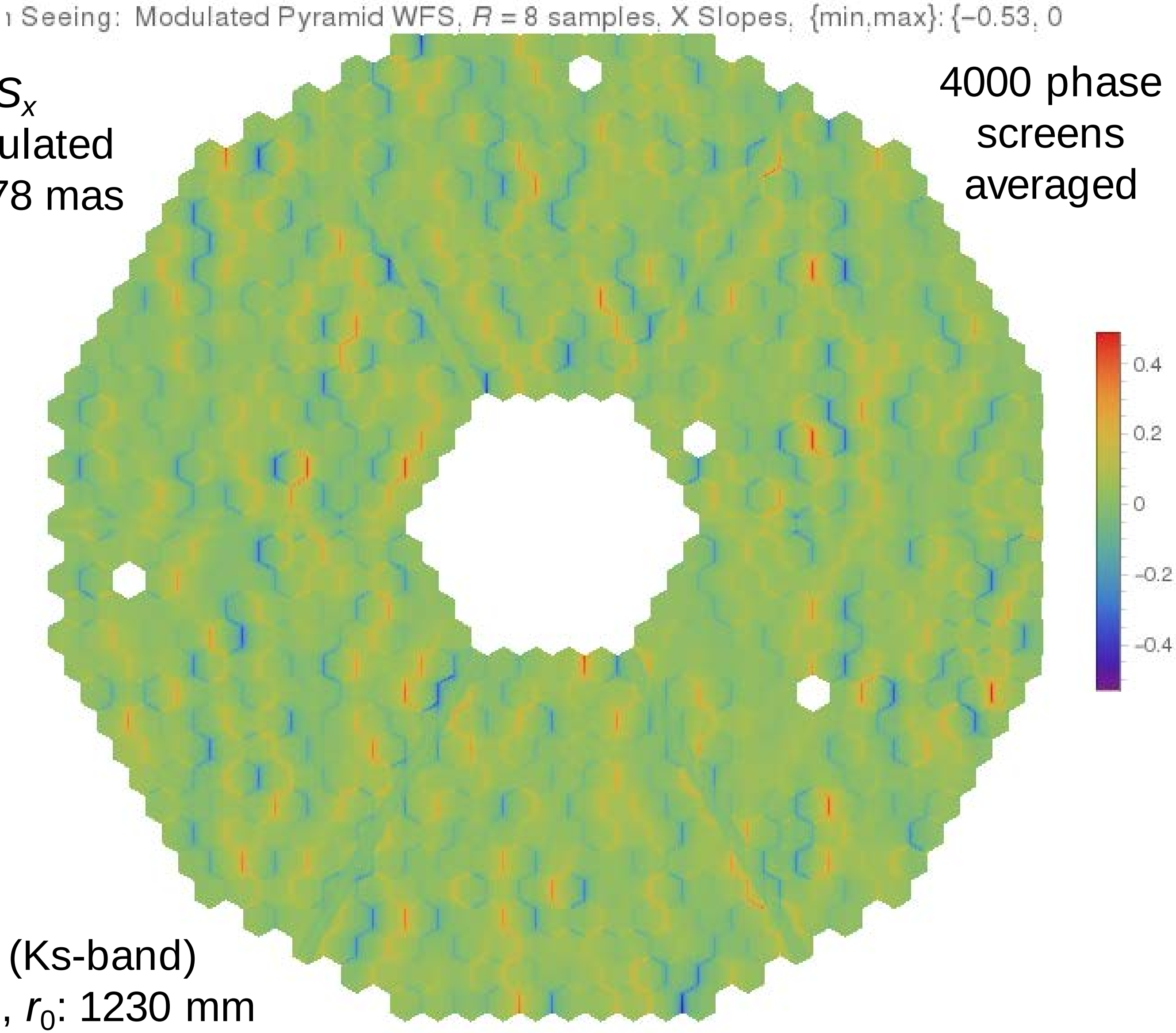
2100 nm (Ks-band)
Seeing: 0.4”, r_0: 1230 mm

Pyramid WFS: X Slopes, Weakly Modulated



w/o turbulence

S_x modulated
R = 78 mas

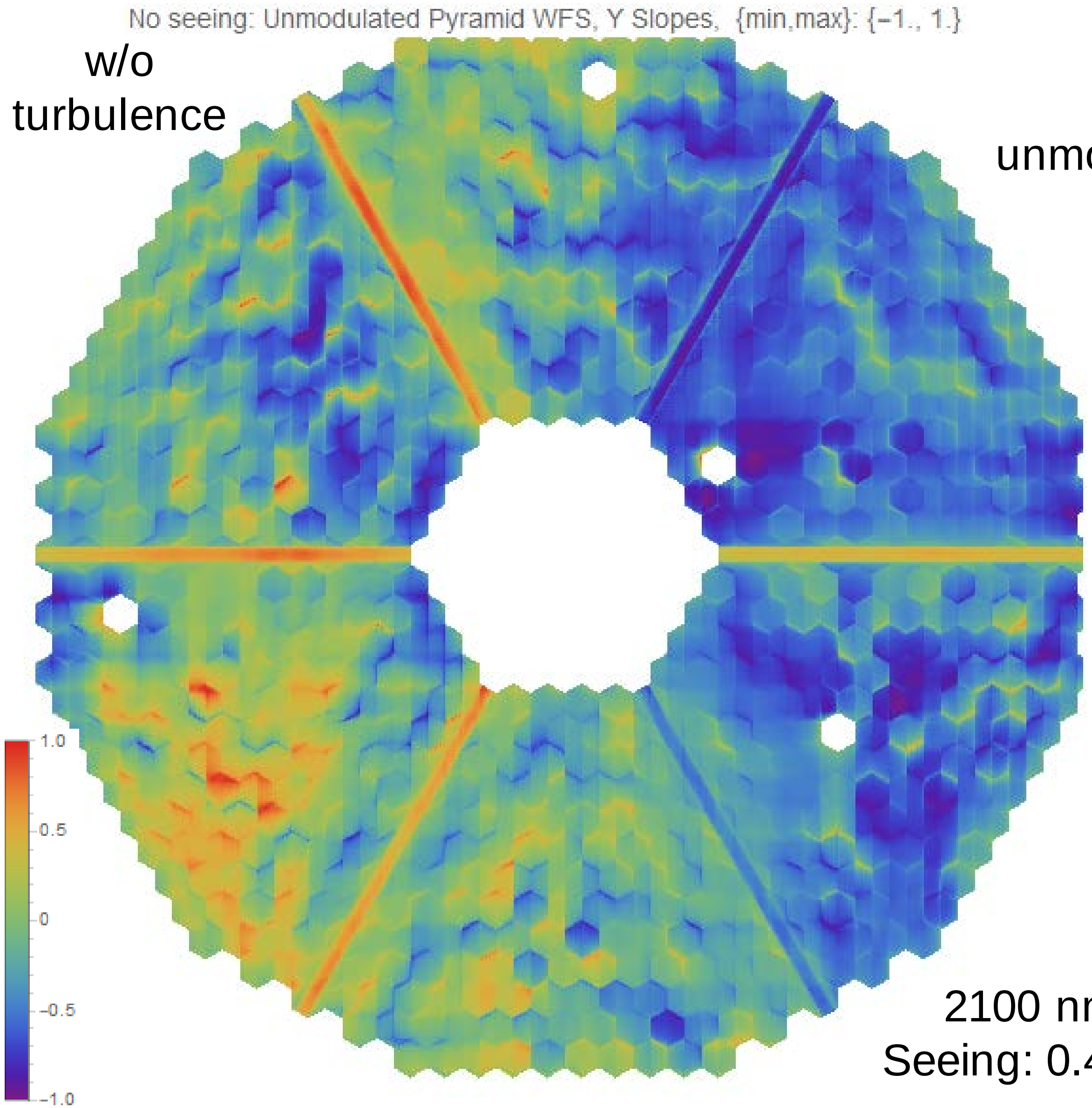


4000 phase screens averaged

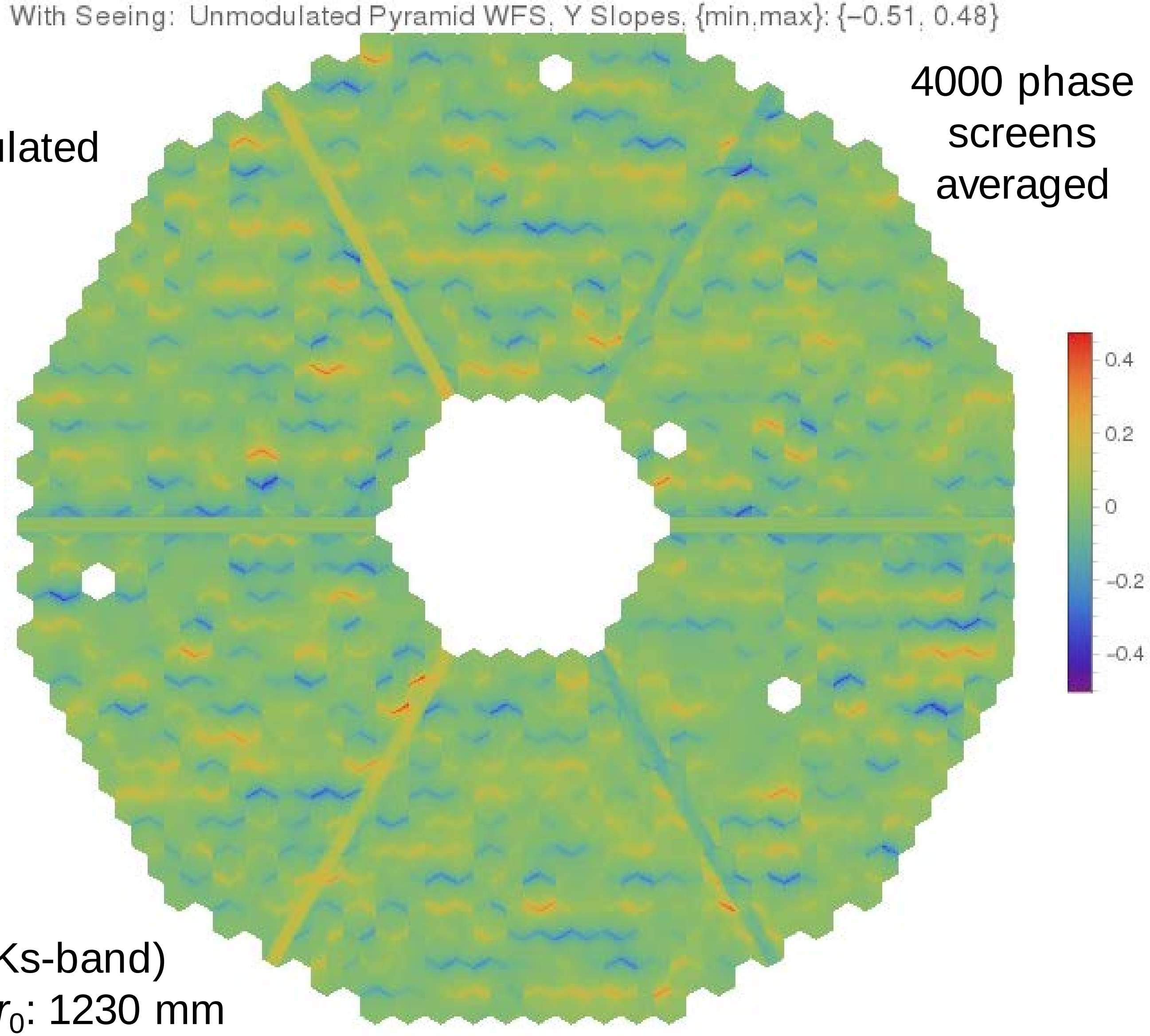
2100 nm (Ks-band)
Seeing: 0.4”, r_0: 1230 mm

Pyramid WFS: Y Slopes, Unmodulated

w/o turbulence



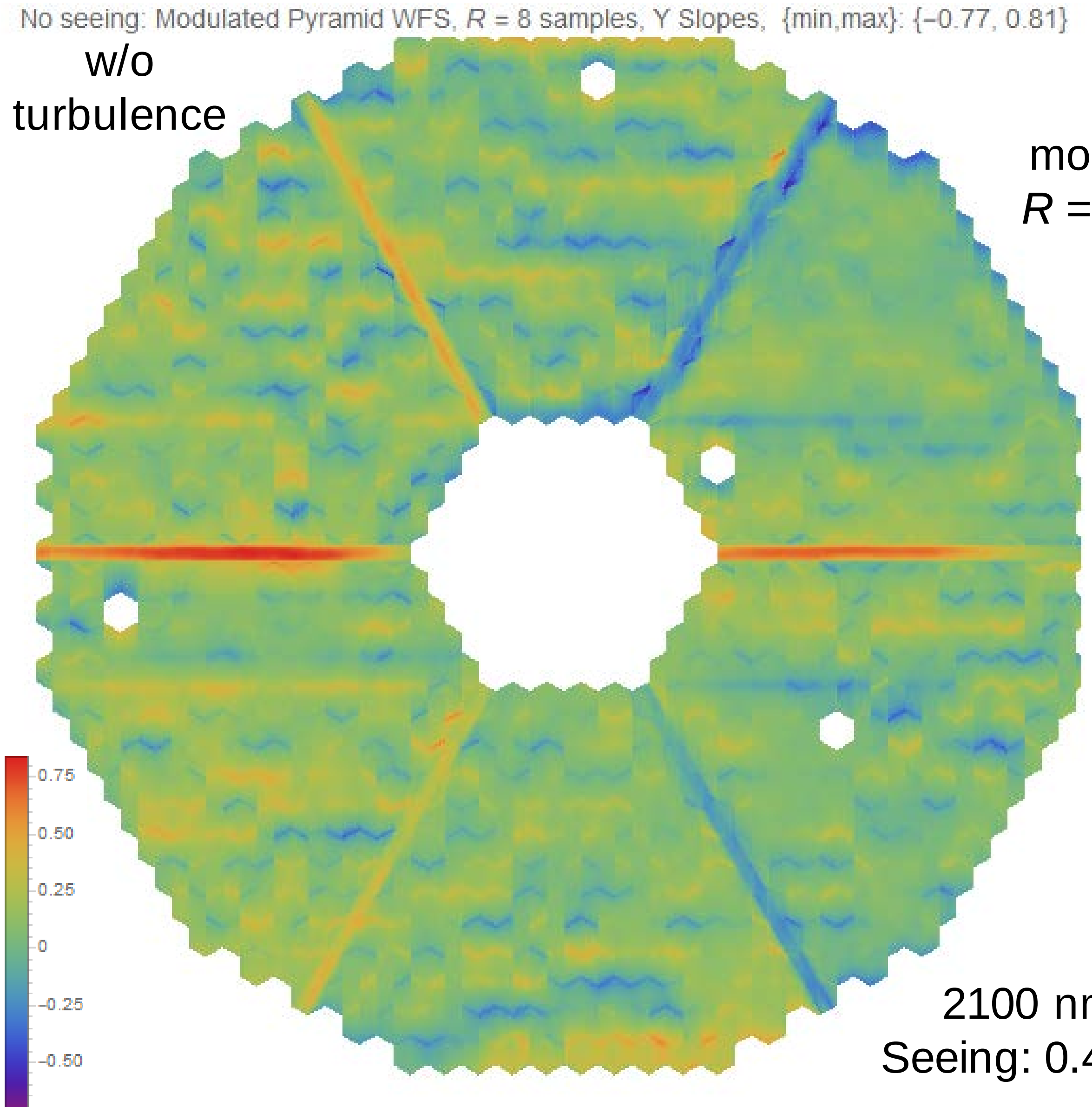
S_y
unmodulated



4000 phase screens averaged

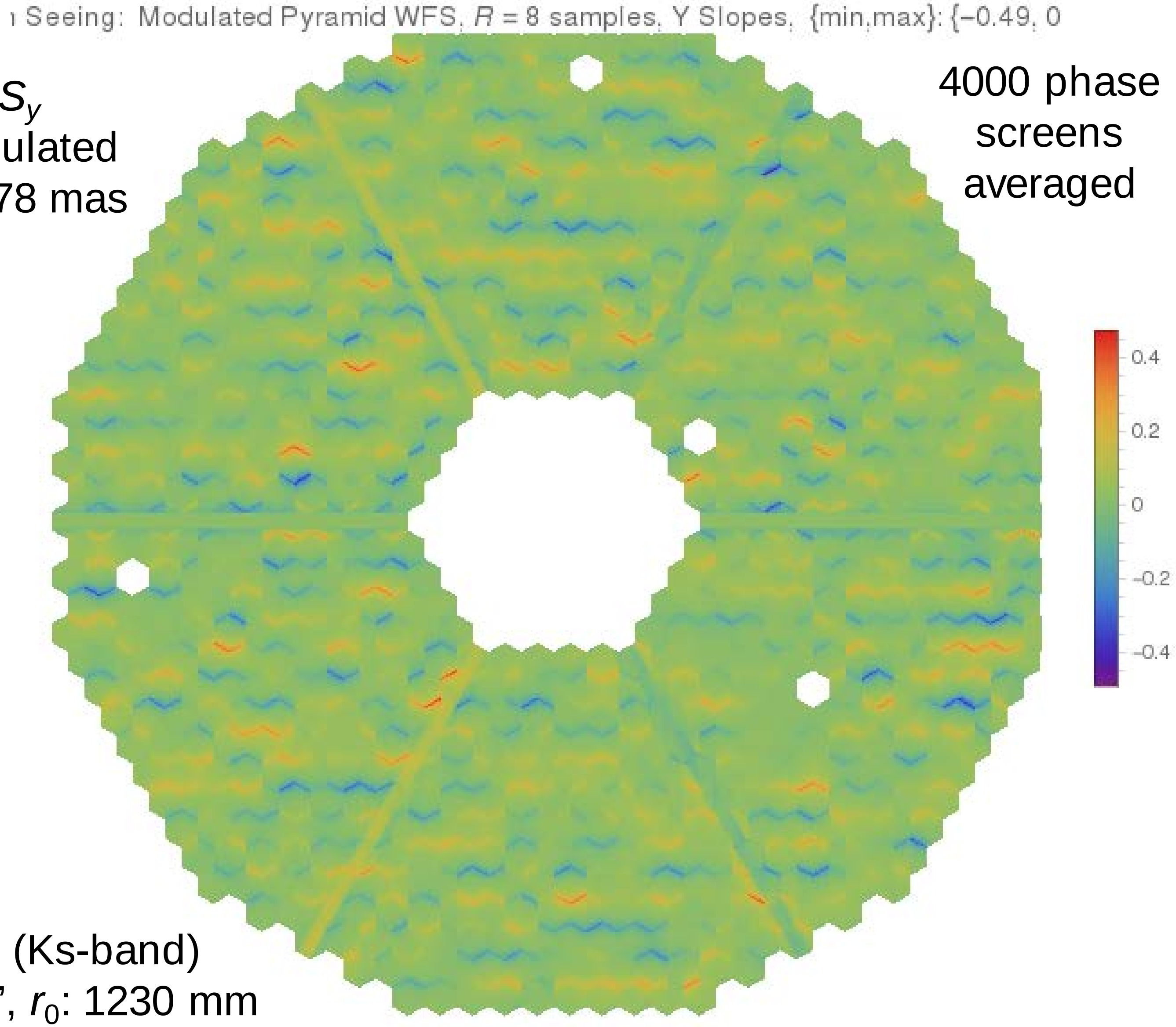
2100 nm (Ks-band)
Seeing: 0.4”, r_0: 1230 mm

Pyramid WFS: Y Slopes, Weakly Modulated



w/o turbulence

S_y modulated
R = 78 mas

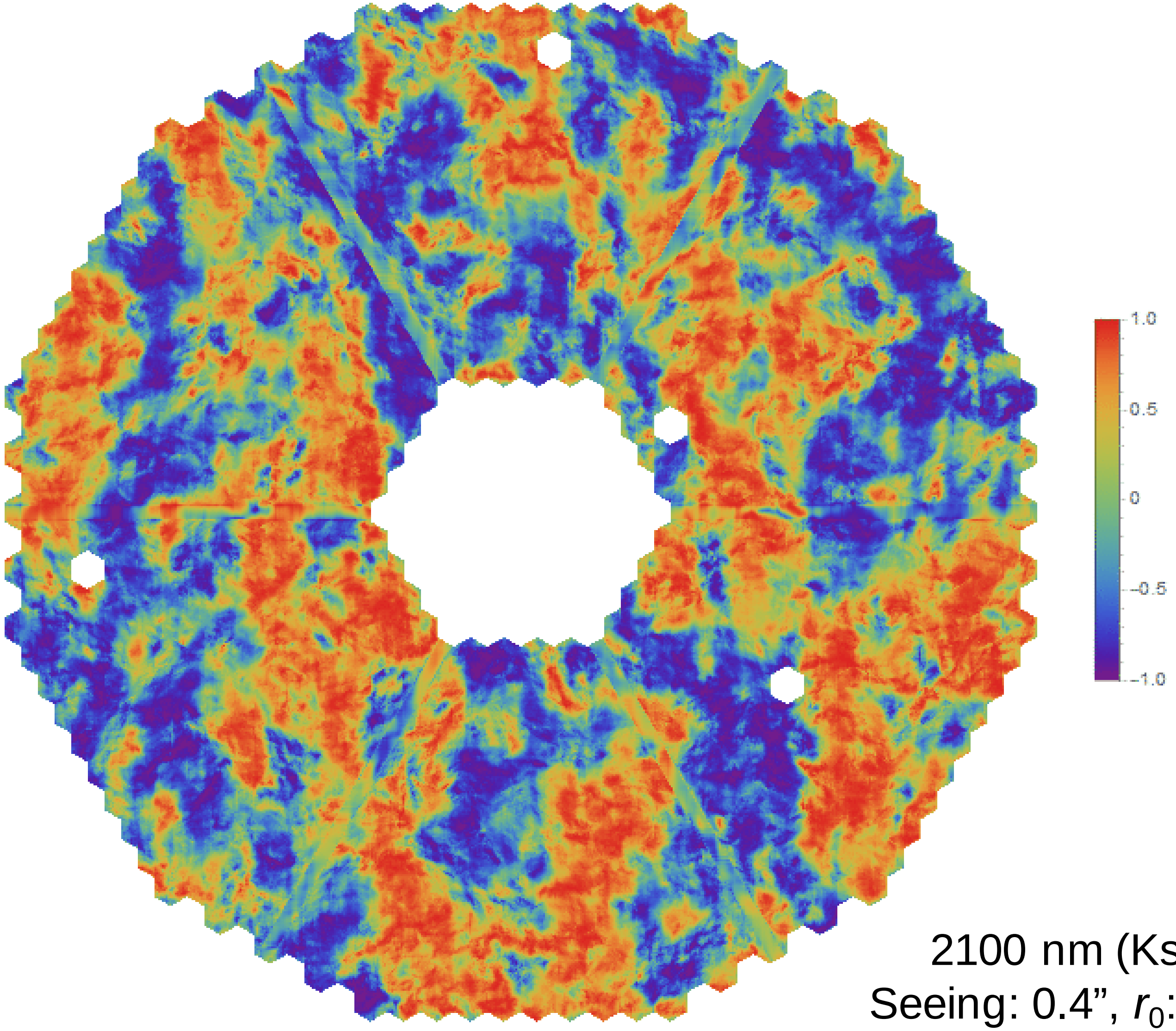


4000 phase screens averaged

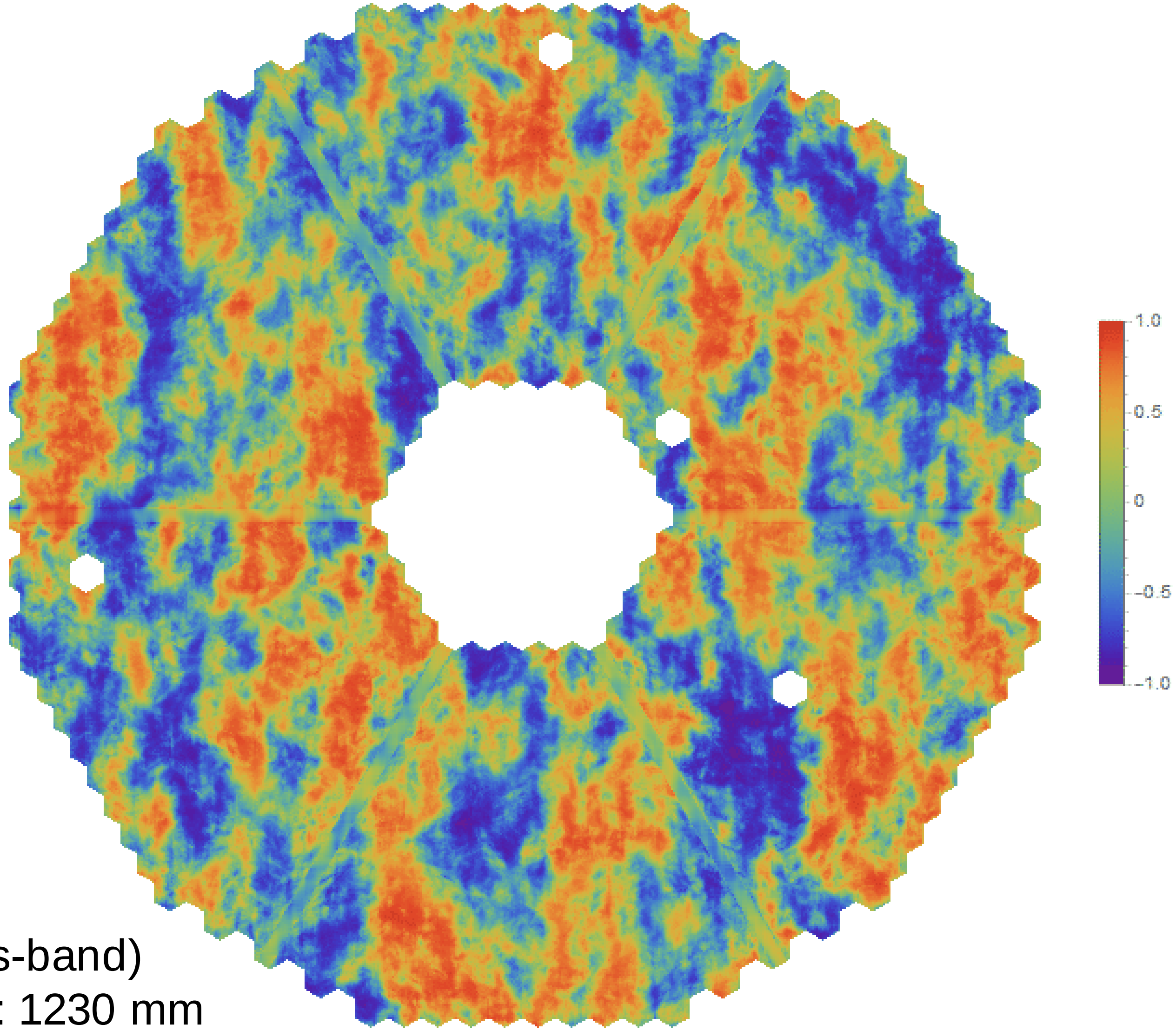
2100 nm (Ks-band)
Seeing: 0.4”, r_0: 1230 mm

Pyramid WFS: X Slopes

unmodulated



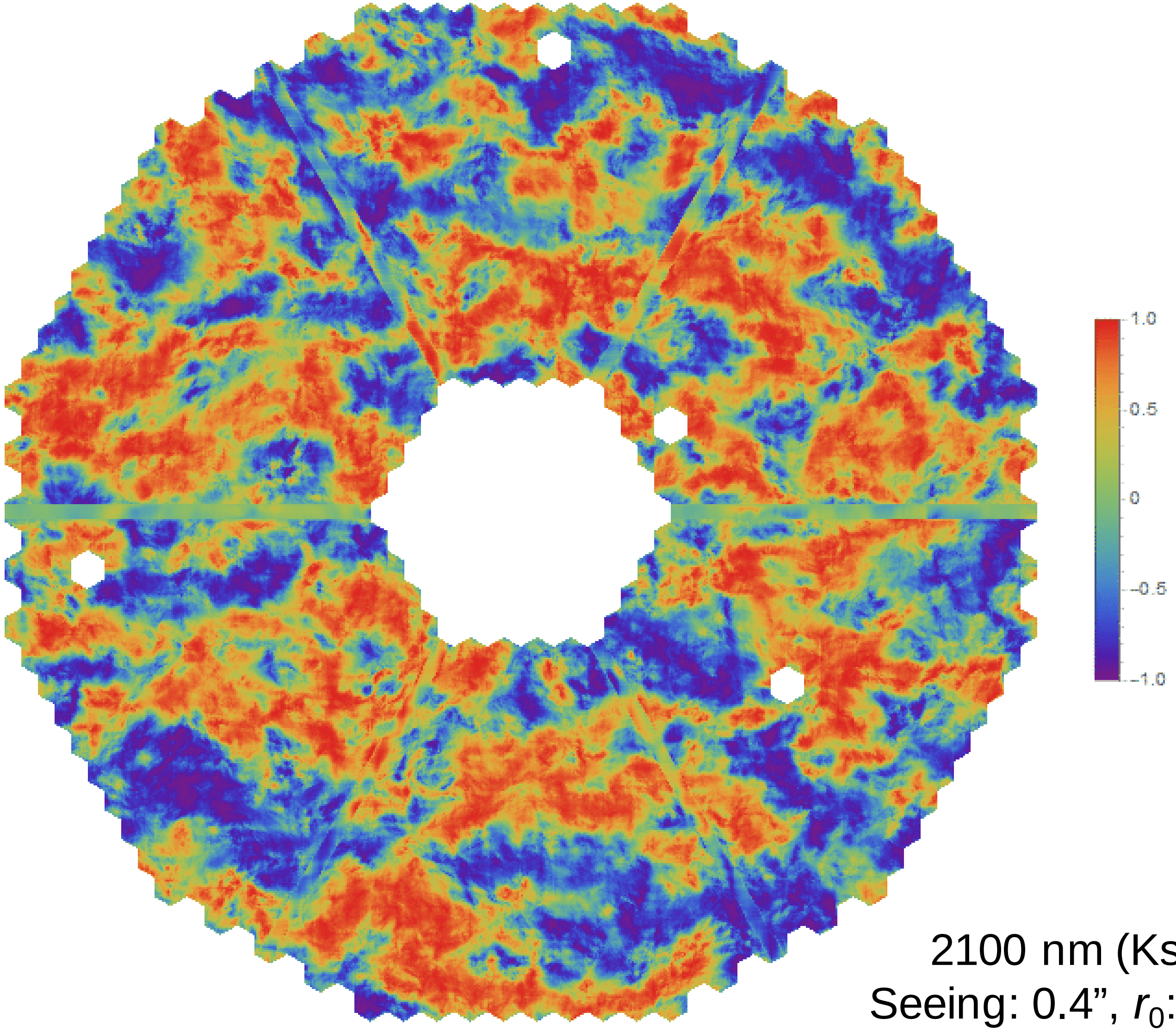
weakly modulated



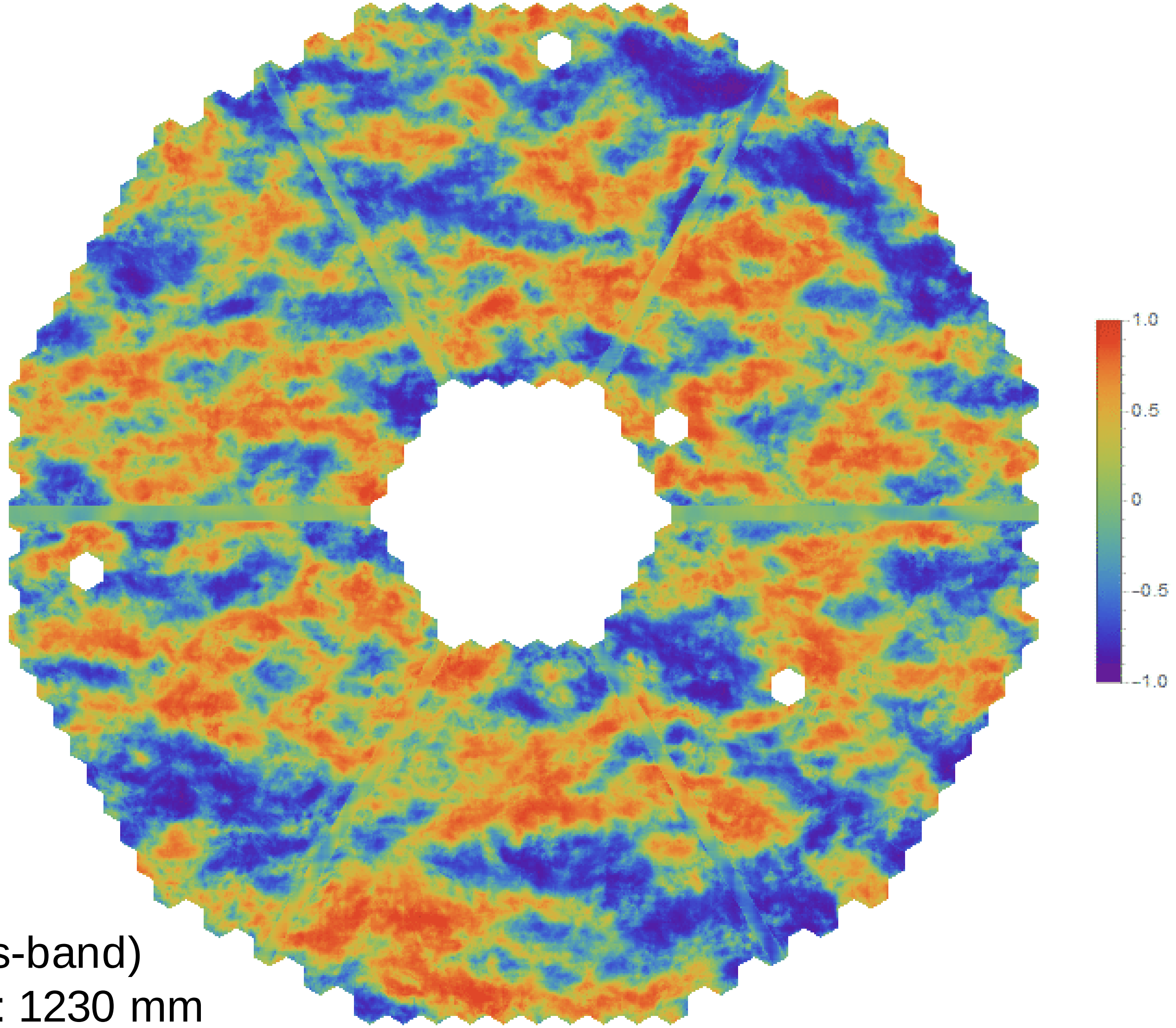
2100 nm (Ks-band)
Seeing: 0.4”, r_0: 1230 mm

Pyramid WFS: Y Slopes

unmodulated



weakly modulated

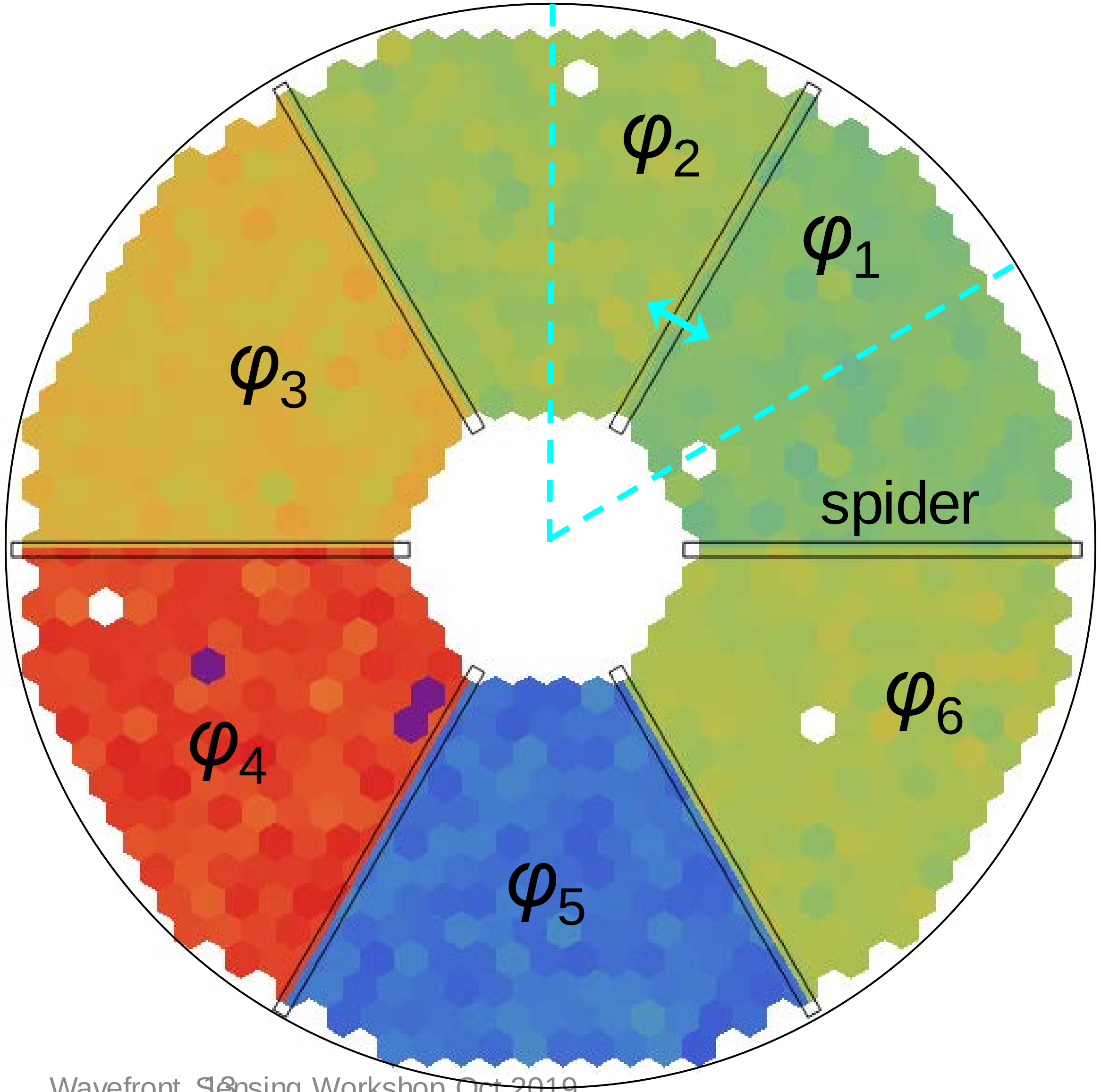


2100 nm (Ks-band)
Seeing: 0.4”, r_0: 1230 mm

Some Intermediate Observations

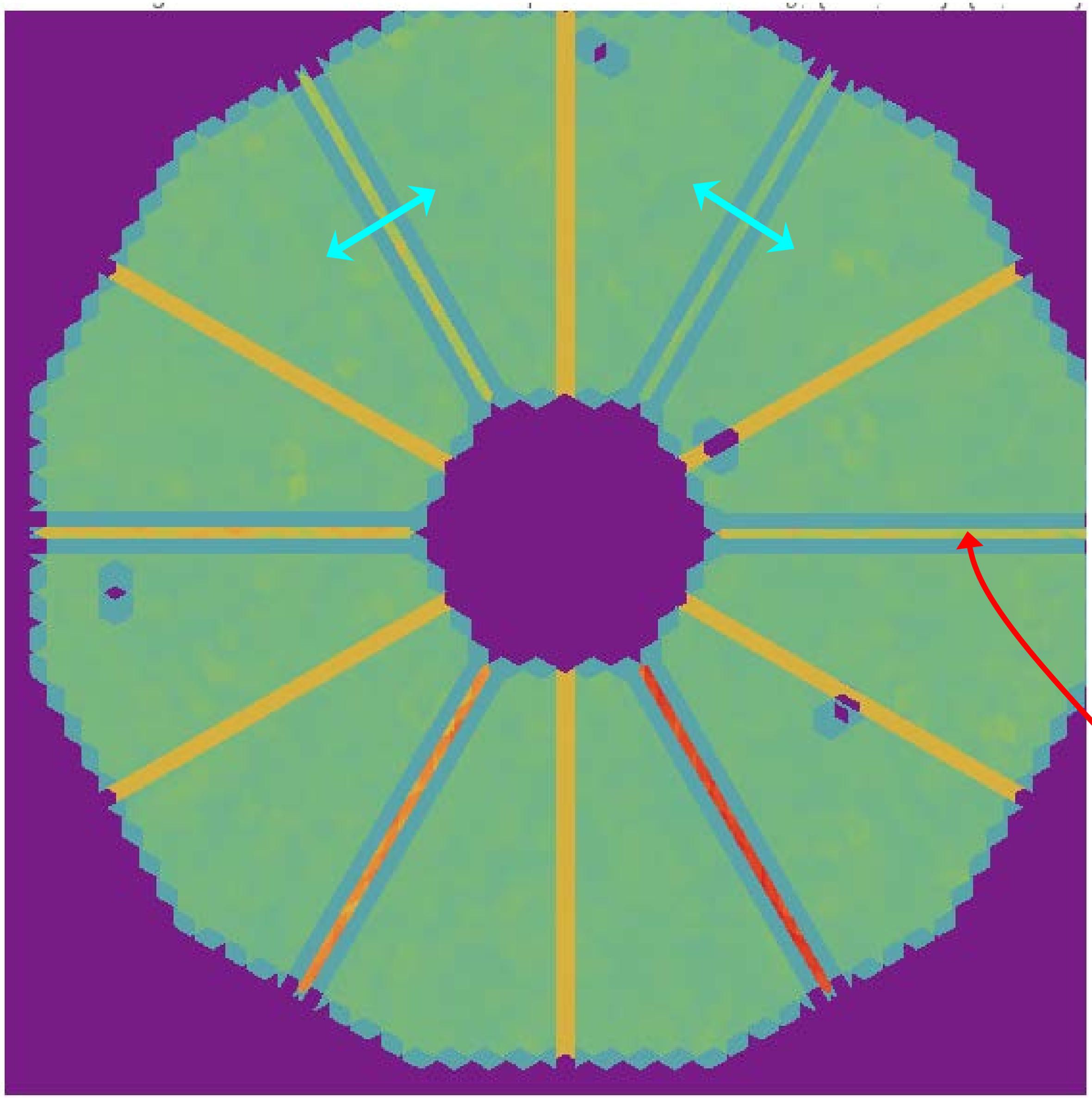
- Phase contrast WFS response to petal phase step is smeared out; seeing/phase mask dependent
- Pyramid WFS response without turbulence…
  - …is strongest in the shadow region (slopes up to +/−1, hence maximum)
  - Strongly diminished even by small modulation
- Pyramid WFS response with turbulence…
  - …is weak(er); nearly vanishes in long exposure
  - Not much more diminished by small modulation
- However, simulation studies show that closed-loop AO with K-band pyramid can “de-petal” (Hutterer, *et al.*)

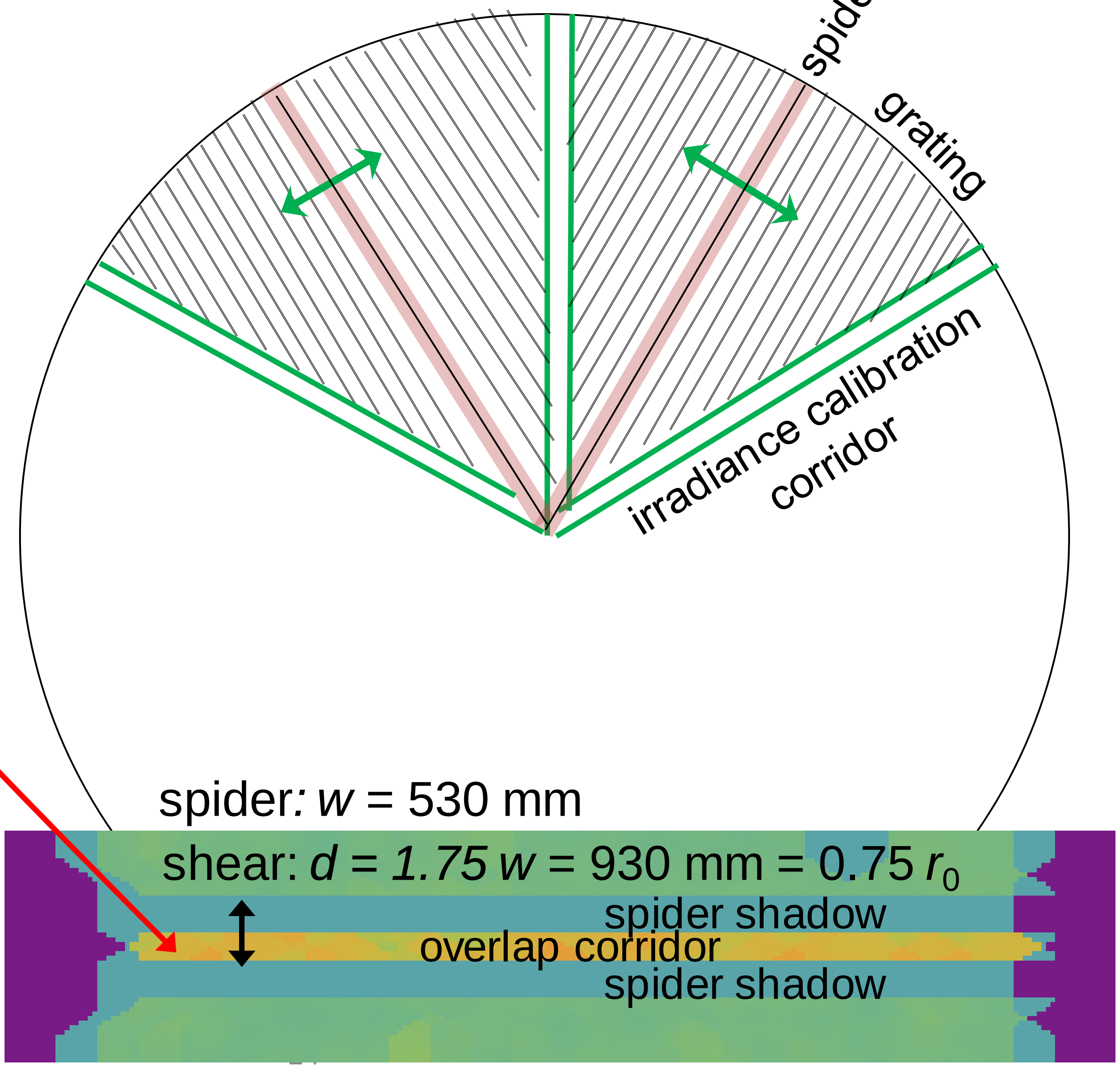
Idea: “Windmill” Shearing WFS as Petalometer



Molino de Tefía, Fuerteventura

Conceptual Shearing Mask





Reconstruction

- Shear optical fields left and right of the spider, petal phases φ_L and φ_R :

$$I_{\text{det, LR}} = \eta |E_0|^2 \left\langle \left| \exp\left[i\left(\varphi_L + \psi(x)\right)\right] \mp \exp\left[i\left(\varphi_R + \psi(x+d)\right)\right] \right| \right\rangle^2$$
$$= 2\eta |E_0|^2 \left[\, 1 \mp \cos(\varphi_L - \varphi_R) \left\langle \exp[i\,\psi(x)]\exp[-i\,\psi(x+d)] \right\rangle \,\right]$$
$$= 2\eta |E_0|^2 \left[\, 1 \mp \cos(\varphi_L - \varphi_R)\, \Gamma_2(d) \,\right]$$

ψ: turbulence, Γ_2: mutual coherence

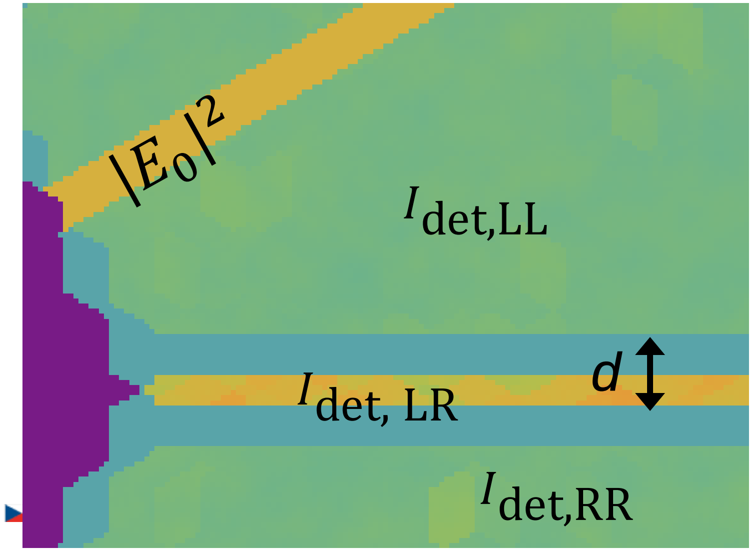
η: grating diffraction efficiency

- Shearing in between spiders is similar, but smaller phase variance $\Delta\varphi$:

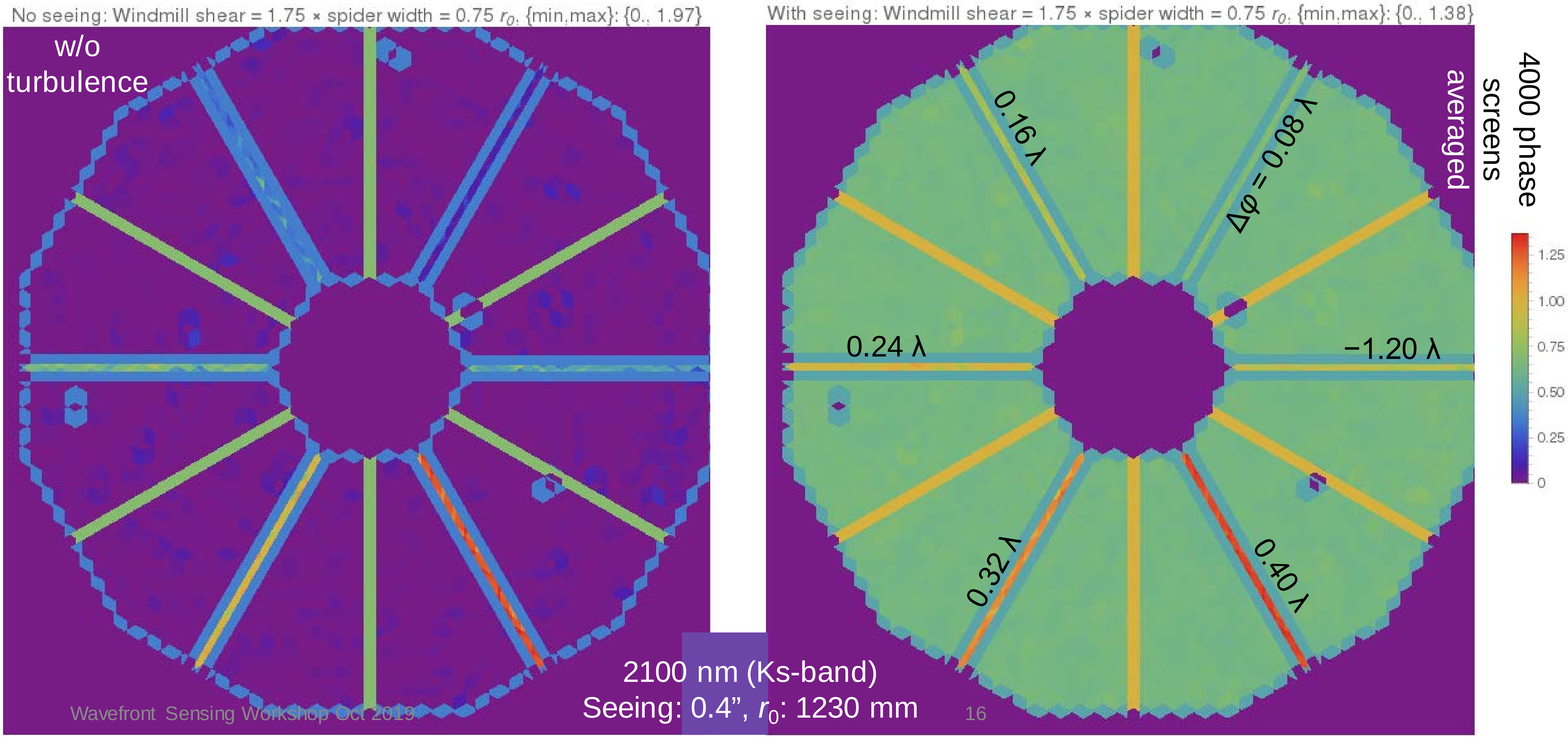
$$I_{\text{det,LL}} = I_{\text{det,RR}} = 2\eta |E_0|^2 \left[\, 1 \mp \cos(\Delta\varphi)\, \Gamma_2(d) \,\right]$$

- The phase step across the spider is then

$$\varphi_L - \varphi_R = 2\pi n \pm \arccos \frac{\cos(\Delta\varphi)\left(\left\langle I_{\text{det, LR}} \right\rangle - 2\eta |E_0|^2\right)}{\left\langle I_{\text{det, LL}} \right\rangle - 2\eta |E_0|^2}$$



Windmill Shearing WFS Response to Petaling



Reconstruction and Beyond

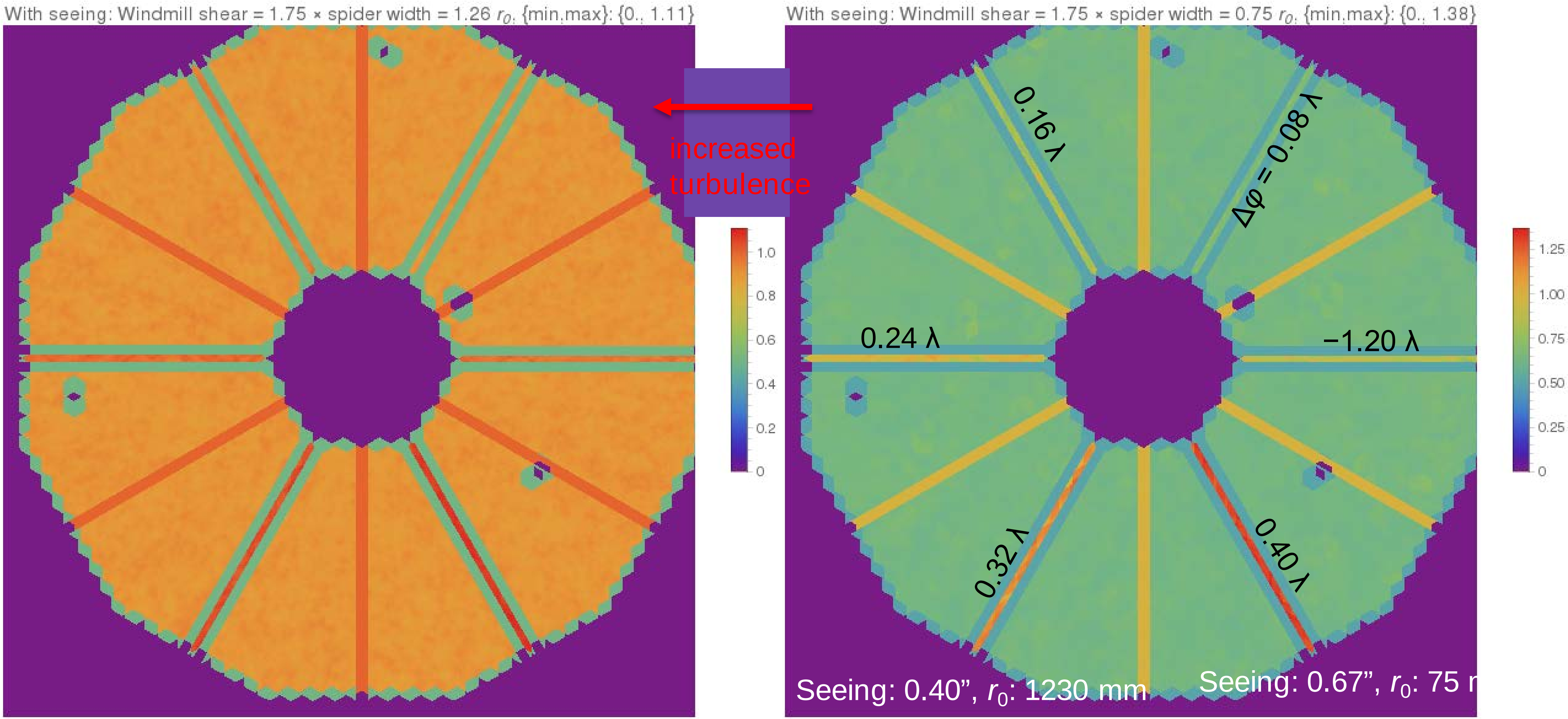
- Example for subtractive gratings, generating the sole orders +1, −1
- Commanded phase steps: {0.08, 0.16, 0.24, 0.32, 0.40, −1.20} waves
- Reconstructed: {0.078, 0.167, 0.235, 0.307, 0.398, −1.197} waves
- Errors: {−2.22, 6.94, −5.39, −12.58, −2.23, 3.11}/1000 waves
  ➔ 0.016 waves RMS = $\lambda/62$ (assuming we pick the right solution *n*)
- Tolerant to imperfect M1 segment phasing
- Shearing distance can be tuned (piston grating mask vs. detector)
- Slight disadvantage: Grating mask must be rotated with the pupil (but not aligned to high accuracy)

Conclusions

- Building up / extending a physical optics simulation environment
- Based on Fourier optics, Monte Carlo simulations (turbulence)
- Test case: Petaling
  - Phase contrast WFS response to petal phase step is unclear
  - Pyramid WFS response strong w/o turbulence and modulation, but small(er) otherwise
    - However, closed-loop AO can "de-petal" M4 in simulation (Hutterer, *et al*.)
  - Windmill shearing
    - Shows solid signal w/o turbulence and with turbulence in long exposure
    - Simple reconstruction, yields accurate petal phase steps in simulation
    - Feasibility and practical implementation TBD
- Possible additional study case:
  - sensing of wavefront errors from spider subcooling

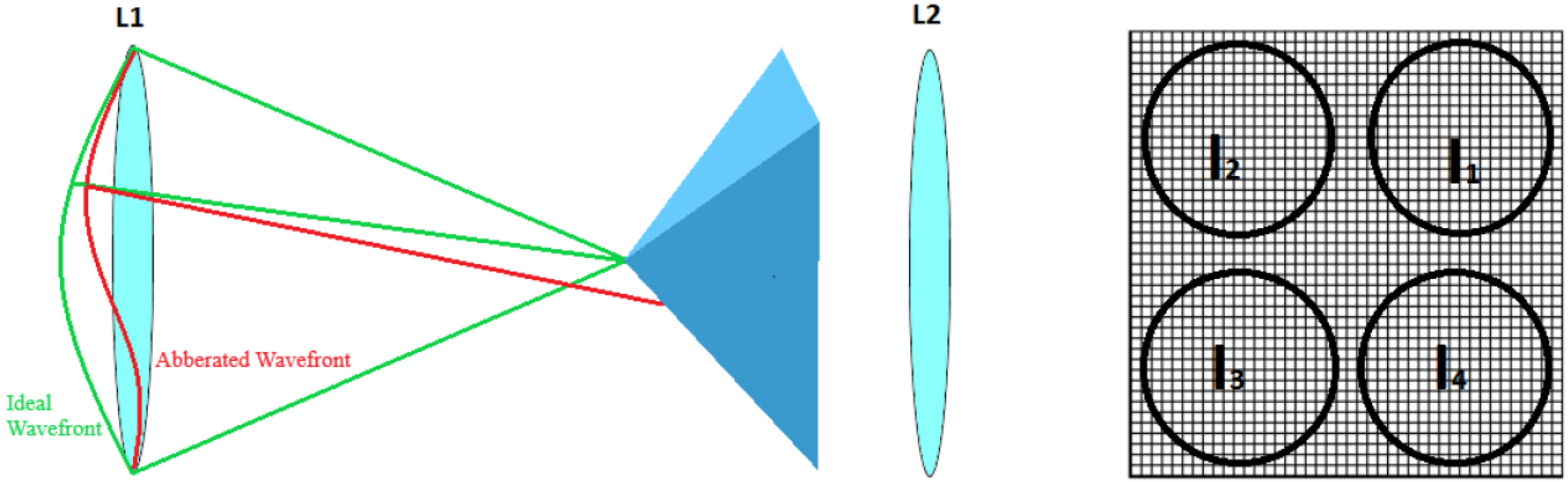
BACKUP SLIDES…

Turbulence Reduces Contrast



Pyramid WFS

Pyramid WFS setup



$$Sx(x,y) = \frac{(I1(x,y) + I2(x,y)) - (I3(x,y) + I4(x,y))}{Iavg}$$

$$Sy(x,y) = \frac{(I1(x,y) + I4(x,y)) - (I2(x,y) + I3(x,y))}{Iavg}$$

$$Iavg(x,y) = I1(x,y) + I2(x,y) + I3(x,y) + I4(x,y)$$

Source:
Jacob *et al.*, SPIE 107001 (2018)