LABORATORY RESULTS OF A DARK HOLE MAINTENANCE ALGORITHM FOR HIGH CONTRAST IMAGING

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OVERVIEW

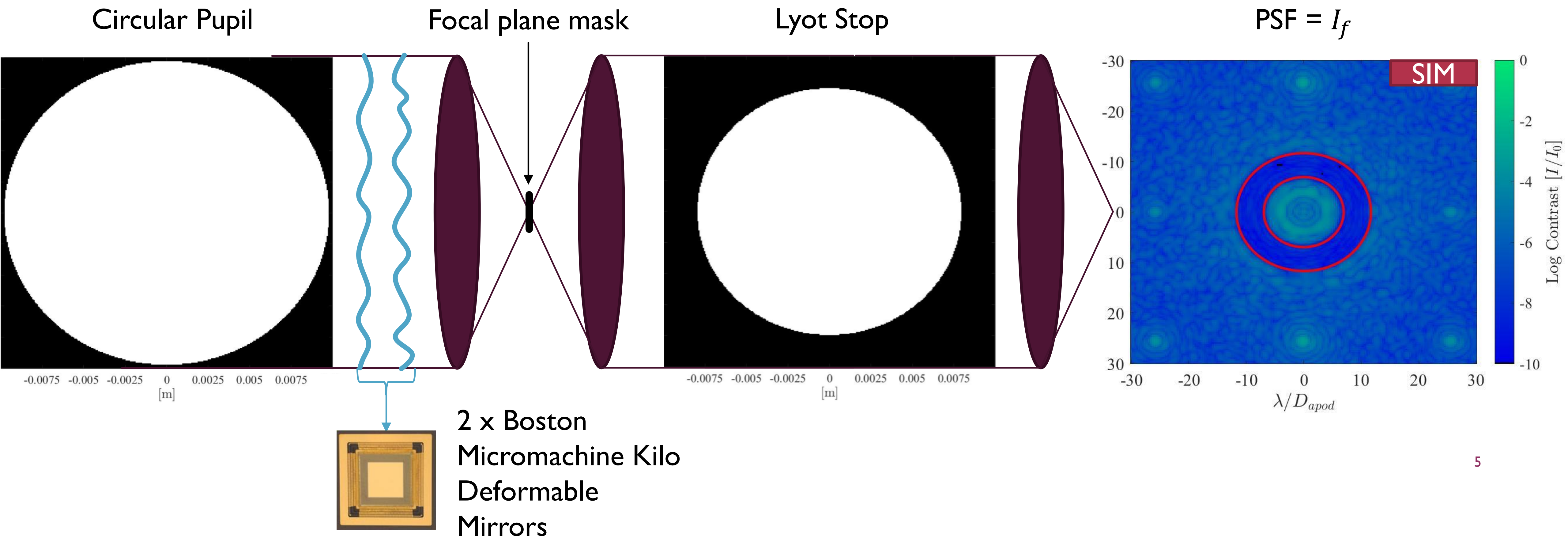
- **Background**: Direct Imaging of Exoplanets
- **Motivation**: Wavefront Error Drifts
- **Implementation**: How does the algorithm work?
- **Results**: Experiments on the High-contrast imager for Complex Aperture Telescopes (**HiCAT**) at the Space Telescope Science Institute

DIRECT IMAGING OF EXOPLANETS

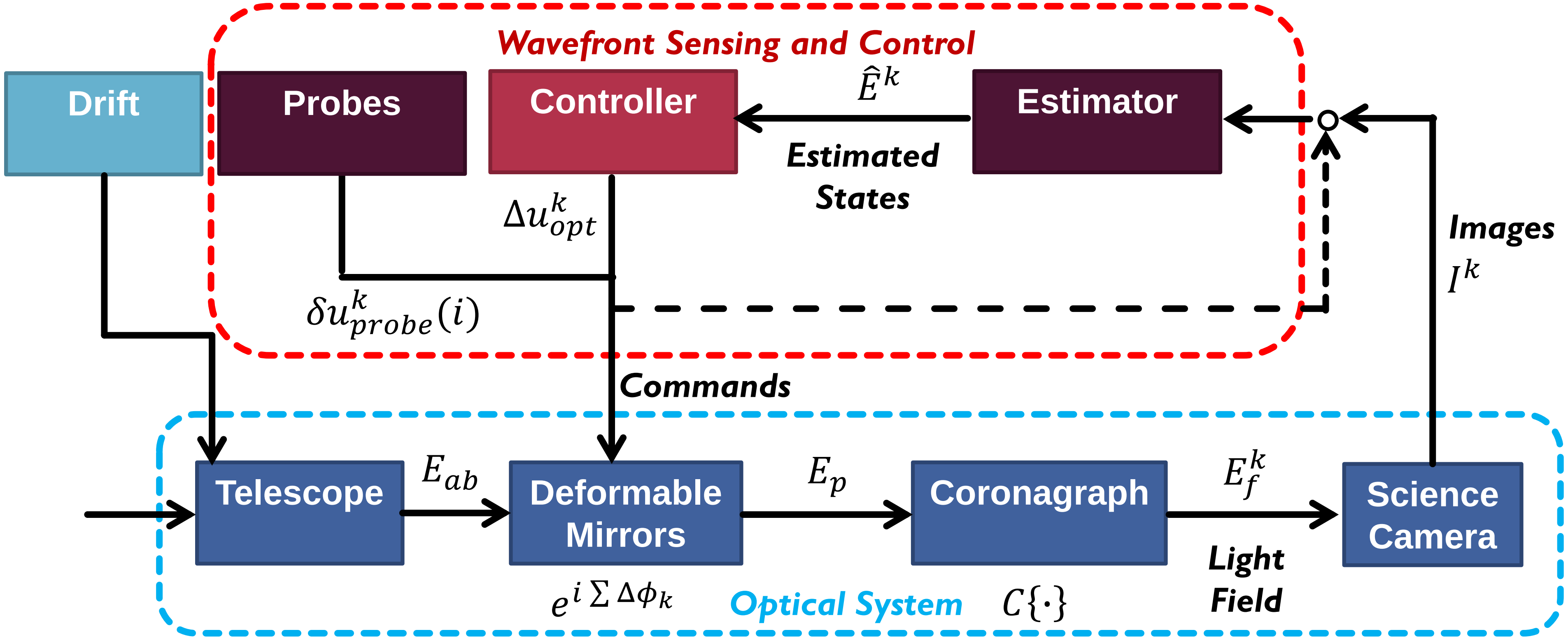
CREATING HIGH CONTRAST REGION: HICAT HARDWARE

High-contrast imager for complex aperture telescopes
Soummer 2019, Moriarty 2019

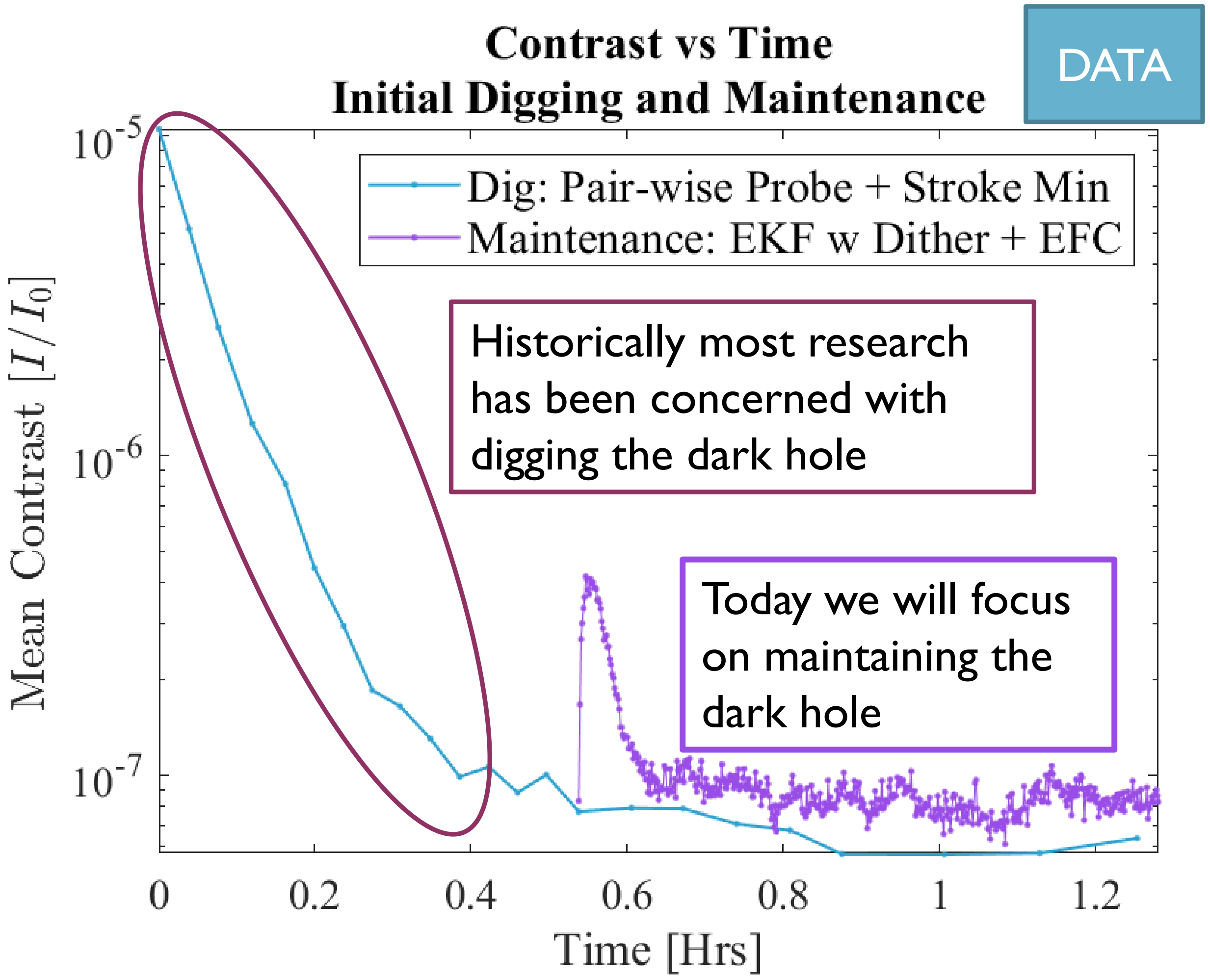
CREATING HIGH CONTRAST REGION: HICAT HARDWARE



FOCAL PLANE WAVEFRONT CONTROL (FPWC)

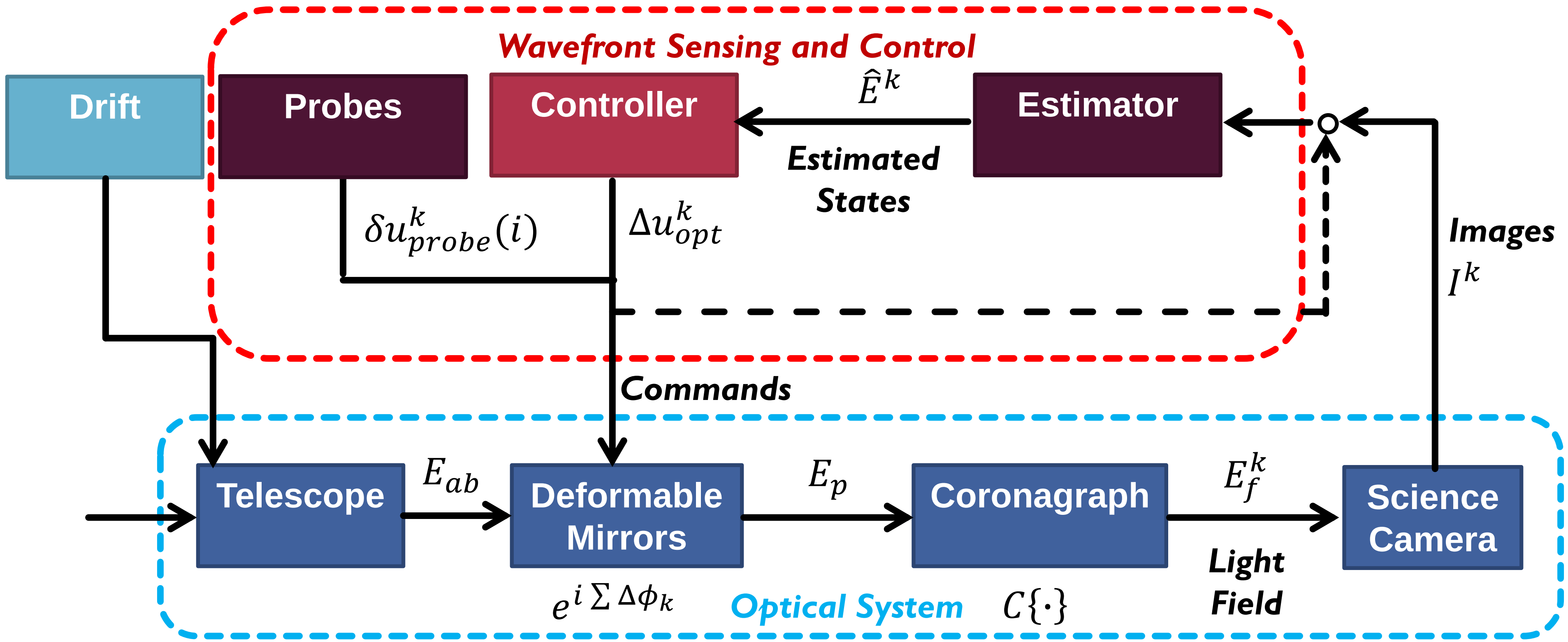


FPWC IN ACTION



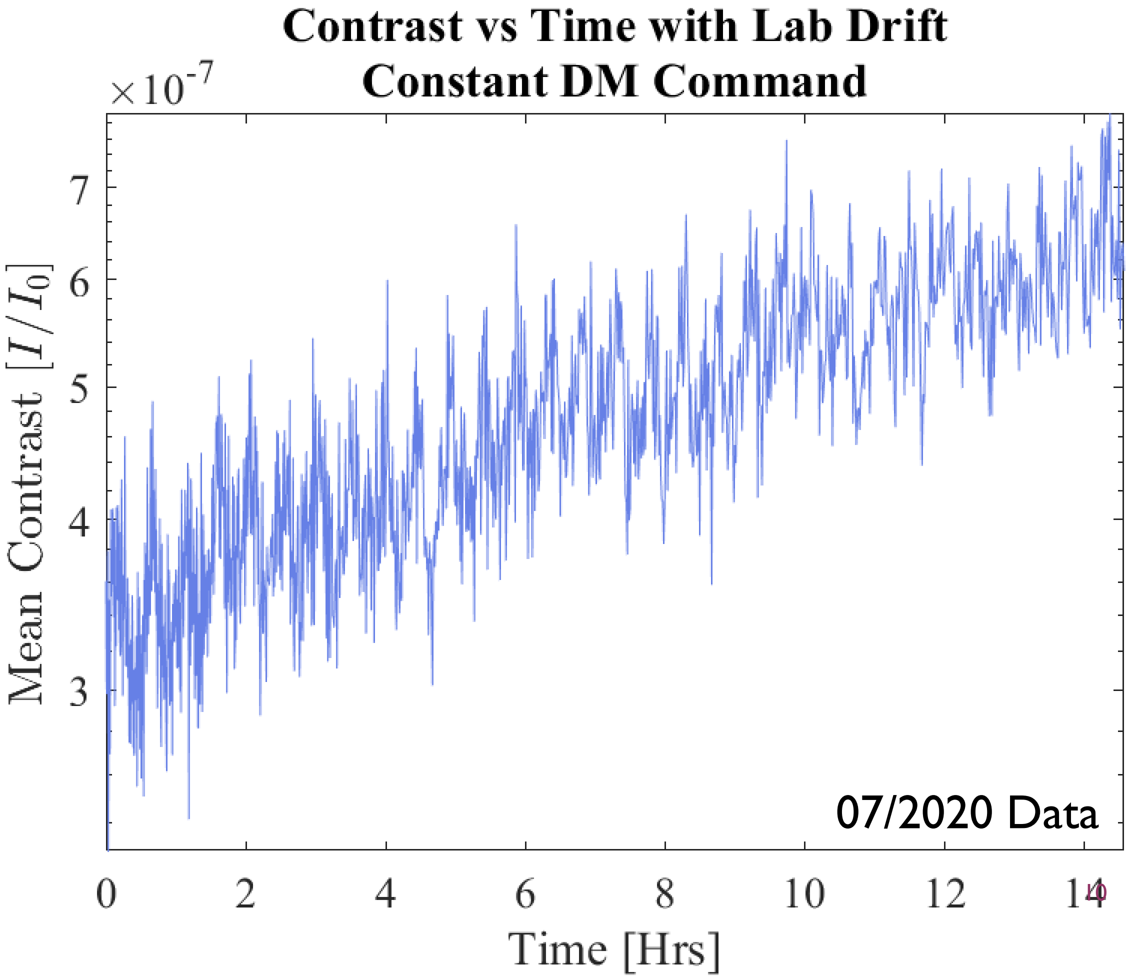
WAVEFRONT ERROR DRIFTS

SYSTEM DRIFTS

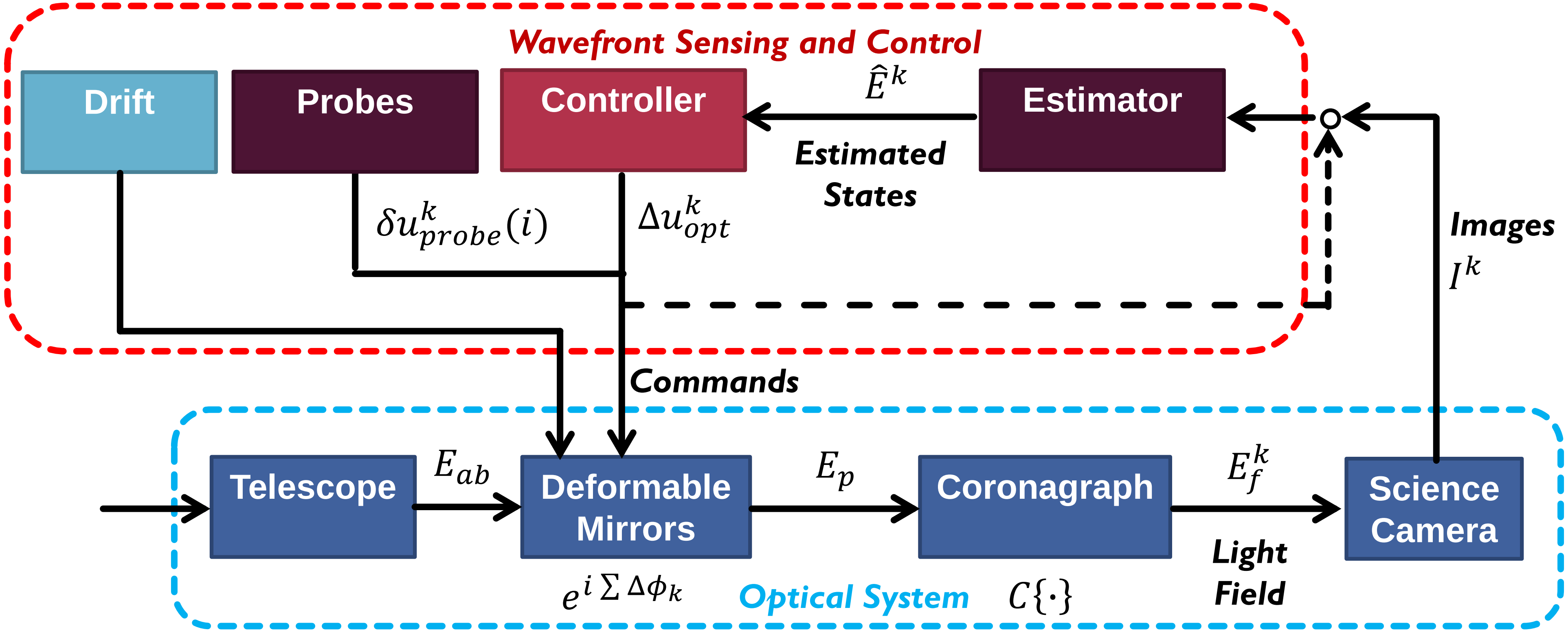


SLOW SYSTEM DRIFTS IN HICAT

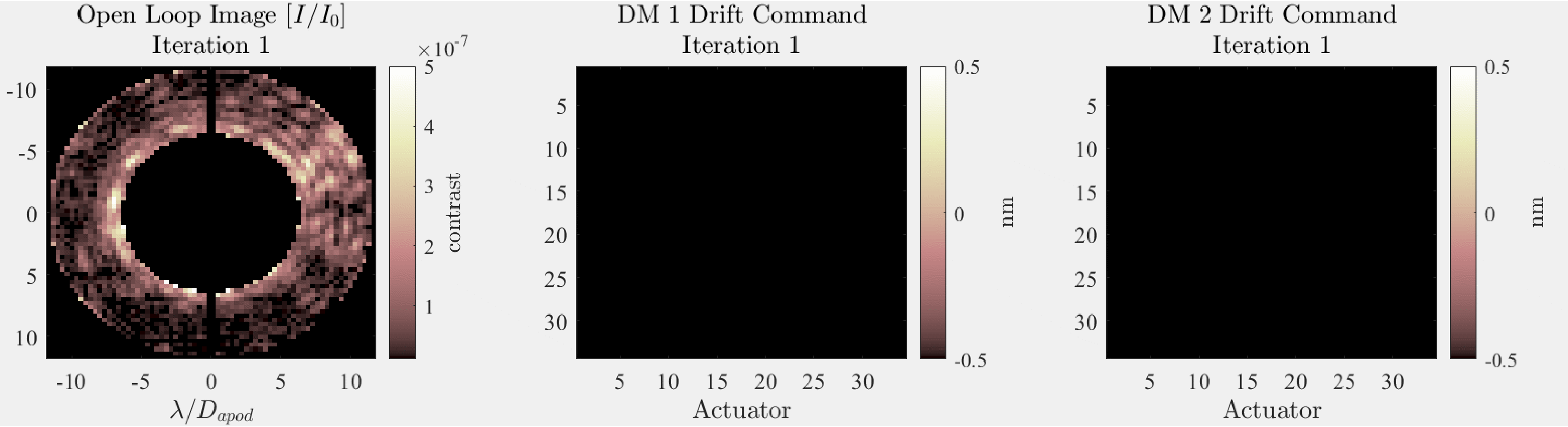
- Slow system drifts are present in every optical system
- Degradation of contrast makes detection and characterization of exoplanets more difficult
- Common causes:
  - Thermal diffusion
    - Time to reach thermal steady state
  - Thermal gradient changes
    - Changing telescope roll angle
  - Gravity (ground telescopes)
    - Change in elevation angle



MANUALLY ADDED DRIFT



DEFORMABLE MIRROR ACTUATOR RANDOM WALK DRIFT

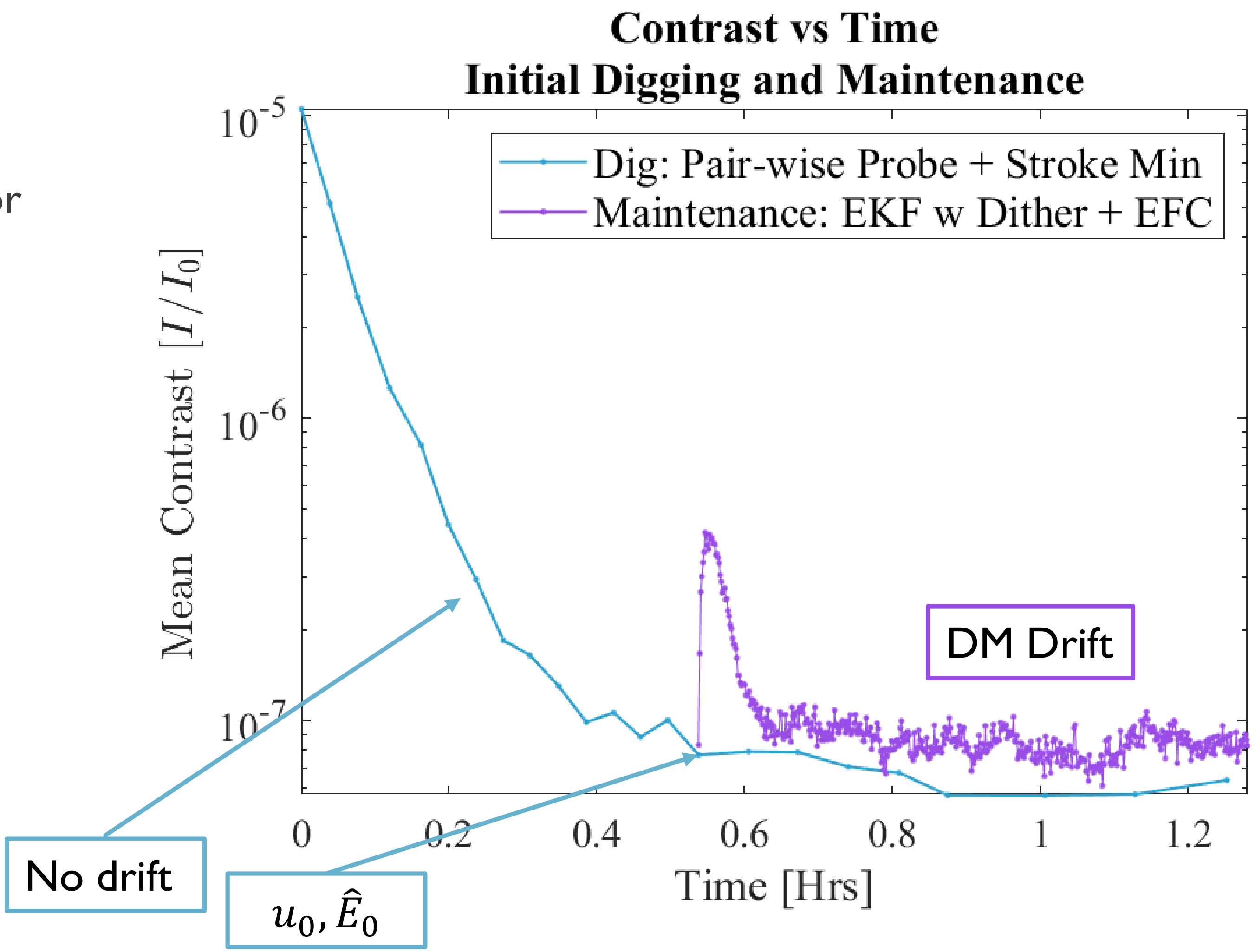


- $u_{\text{open loop}}^{k+1} \mathrel{+}= \mathcal{N}(0, \sigma_{drift}^2 \boldsymbol{I})$
- Each actuator does a random walk with standard deviation of $\sigma_{drift} = 0.01\ nm/iteration$ starting at the final Stroke-Min DM command
- Contrast degrades by a factor of 2 in 1.5 hrs

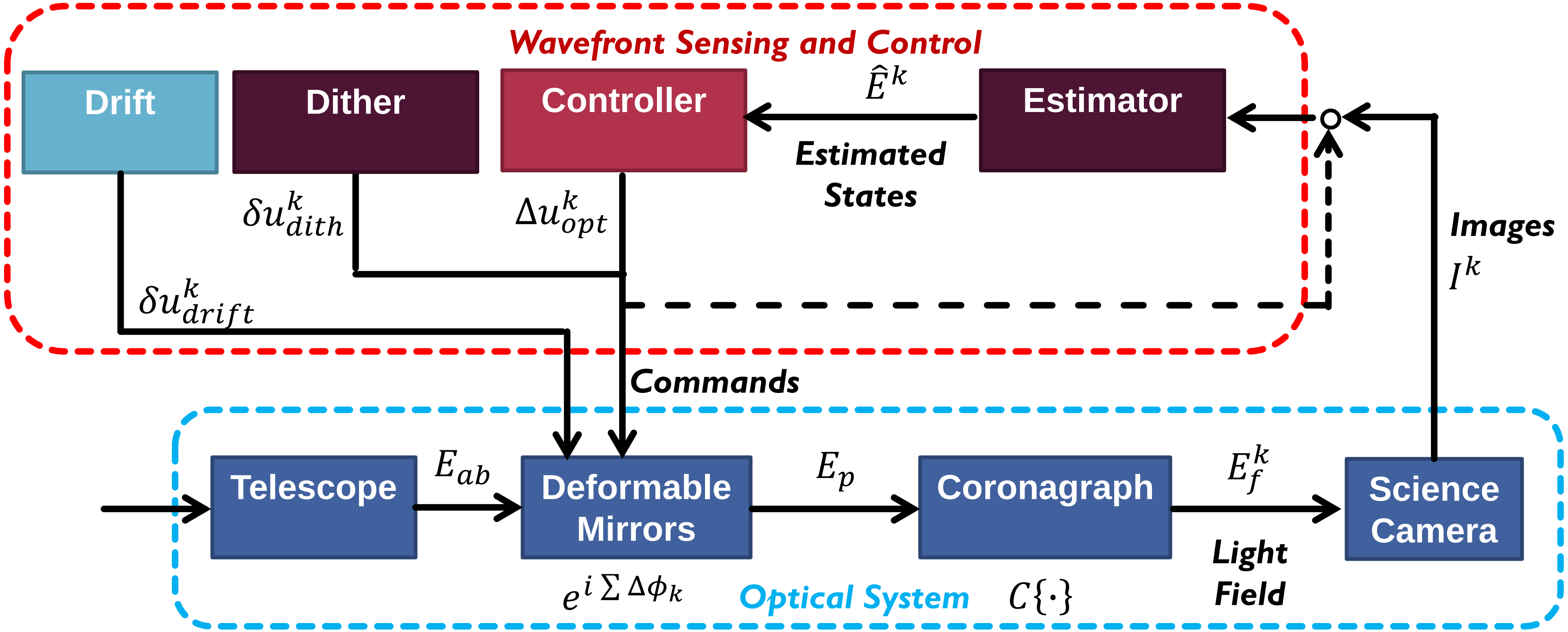
IMPLEMENTATION OF THE DARK HOLE MAINTENANCE ALGORITHM

HIGH LEVEL MAINTENANCE PROCEDURE (POGORELYUK 2019)

- Dig dark hole
- Use final DM command (u_0) and Electric Field Estimate ($\hat{E}_0$) as initial conditions for maintenance algorithm
- Turn on DM random walk drift and start maintenance algorithm
- Advantages:
  - More science images
  - Easier post-processing (Pogorelyuk, 2019)
  - Can use shorter exposures



FPWC WITH DM ACTUATOR RANDOM WALK DRIFT

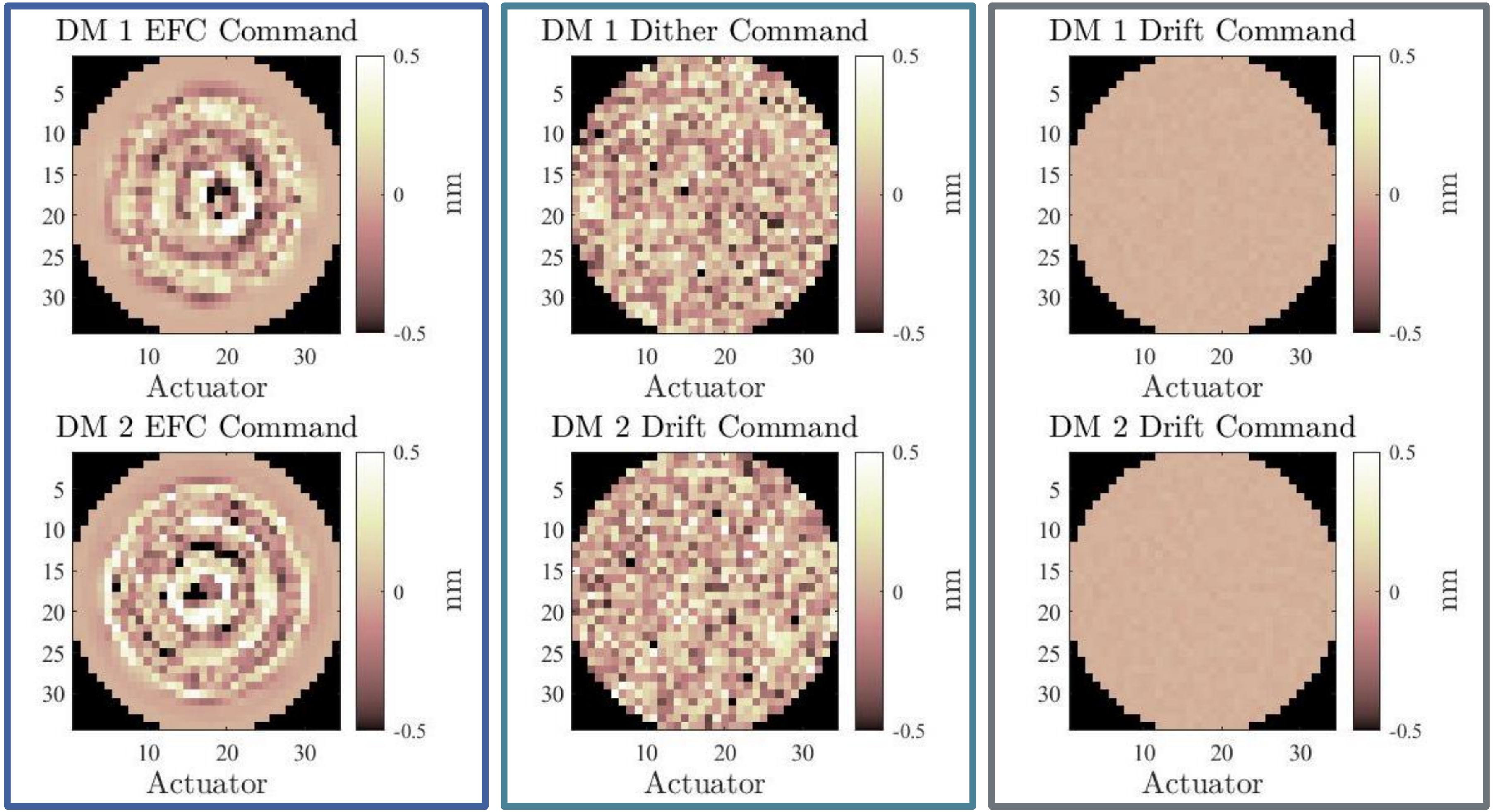


States: Electric field at each pixel in the dark hole on the science camera

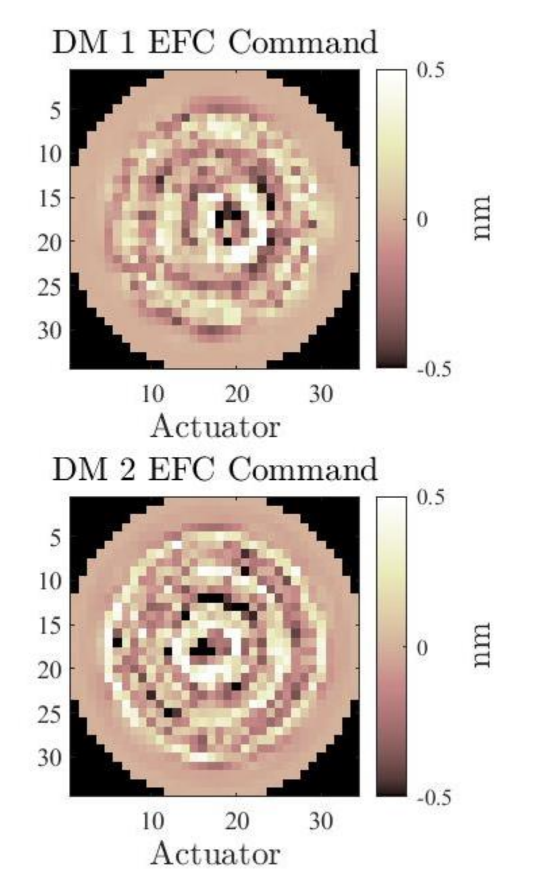
Control: 2 x 952 Deformable Mirror actuators

Measurement: Intensity at each science camera pixel

STEP 2: APPLY CONTROL: $u_{tot}^{k+1} = u_0 + \Delta u_{opt}^{k+1} + \delta u_{dith}^{k+1} + \delta u_{drift}^{k+1}$



STEP 2: ELECTRIC FIELD CONJUGATION



Electric Field Conjugation:

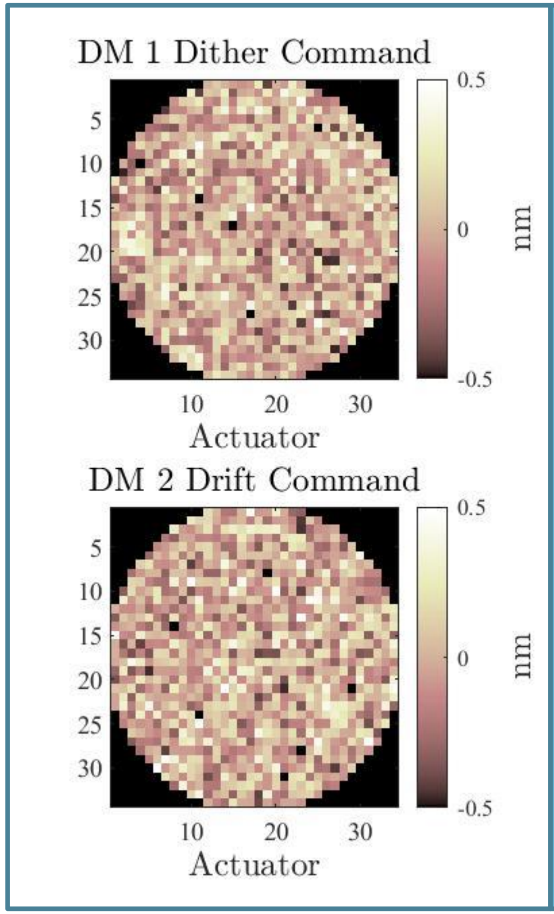
$$\Delta u_{opt}^{k+1} = -\left(\mathbf{G}\mathbf{G}^{T} - \alpha\mathbf{I}\right)^{-1} G^{T}\, \hat{E}^{k}$$

Jacobian

Regularization Parameter

Estimate

STEP 2: DITHER

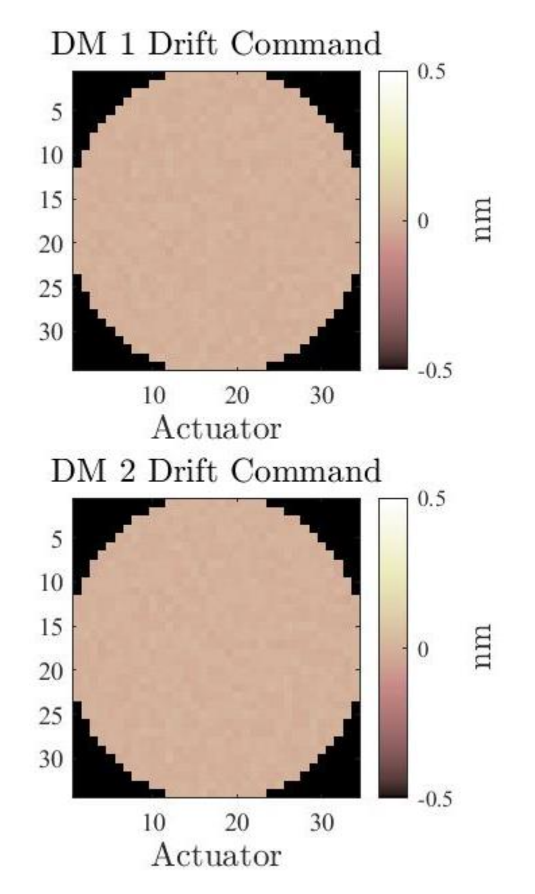


Dither Command:

- Acts as a 'probe'
- Increases phase diversity to improve estimate
- Random displacement applied to each actuator with standard deviation σ_{dith}

$$\delta \mathrm{u}_{\mathrm{dith}}^{k+1} \sim \mathcal{N}(0, \sigma_{dith}^2 \boldsymbol{I})$$

STEP 2: DRIFT

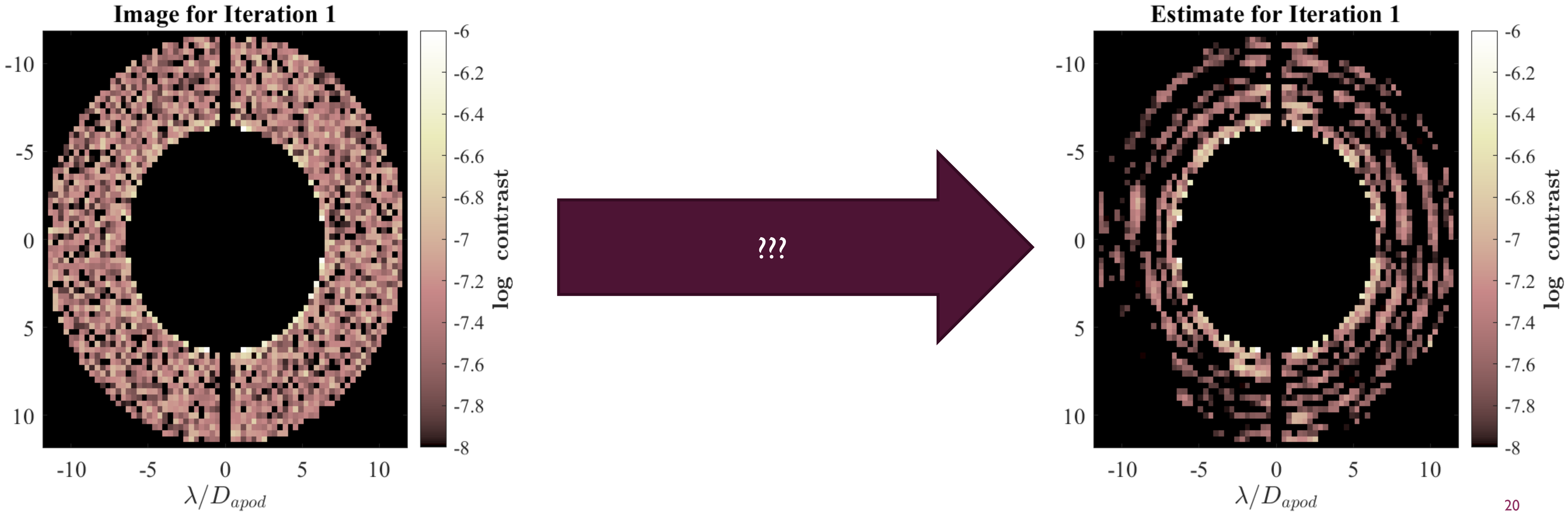


Drift Command:

- Manually inputs a drift/instability into the system
- Simple case: each actuator does a random walk from a normal distribution with standard deviation σ_{drift}
- Future drifts could be Zernike modes, lab temperature, etc.

$$\delta \mathrm{u}_{\mathrm{drift}}^{k+1} = \delta \mathrm{u}_{\mathrm{drift}}^{\mathrm{k}} + \mathcal{N}(0, \sigma_{drift}^2 \boldsymbol{I})$$

STEP 1: ESTIMATE



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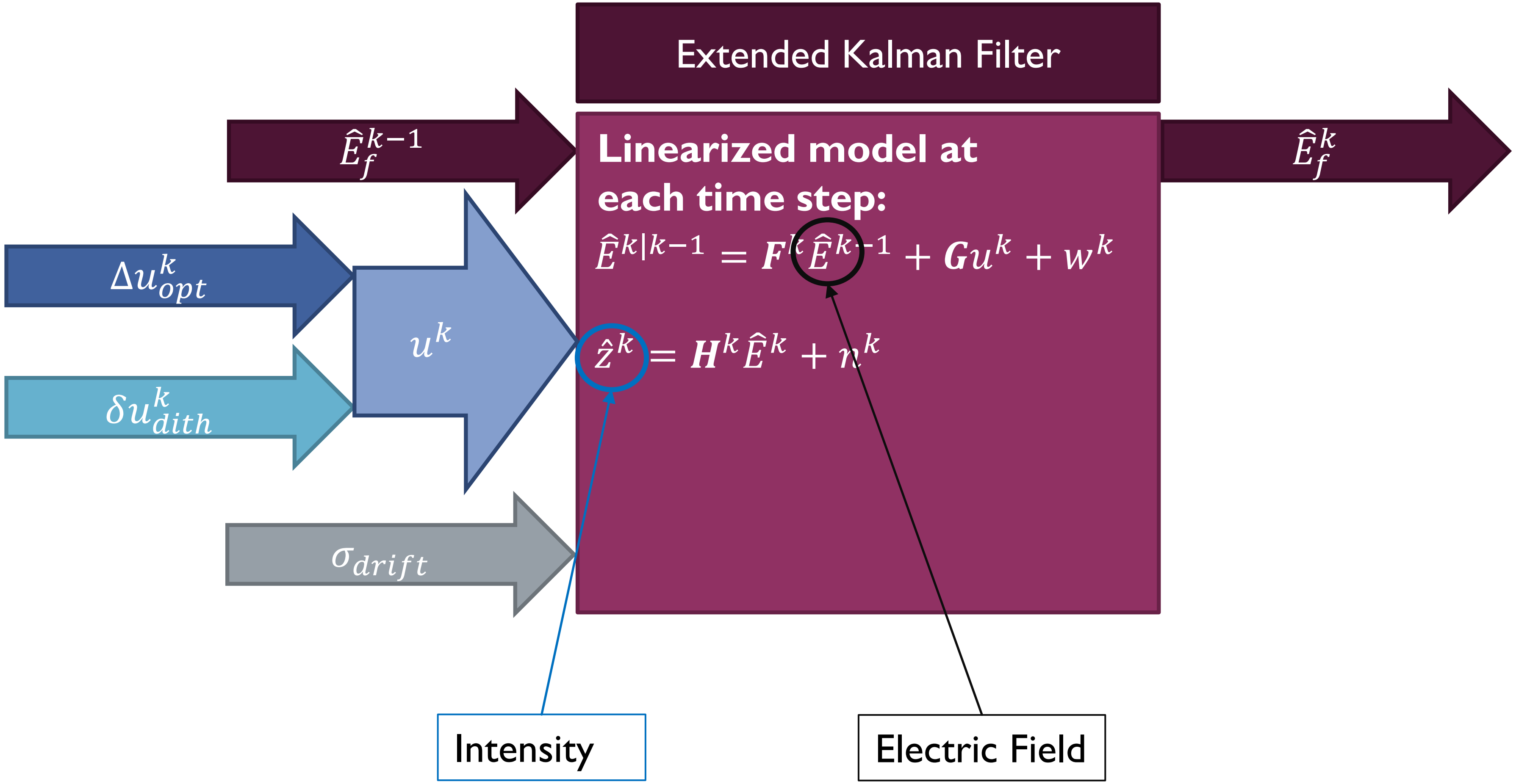

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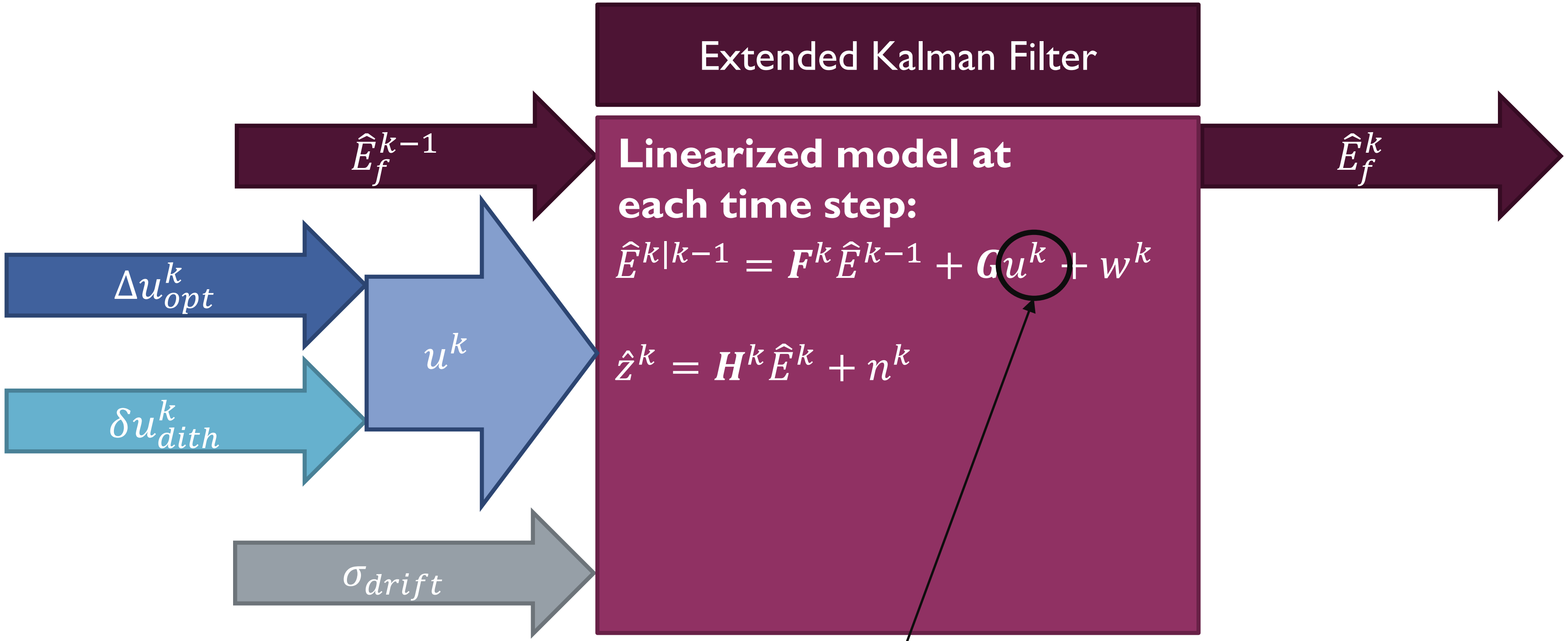
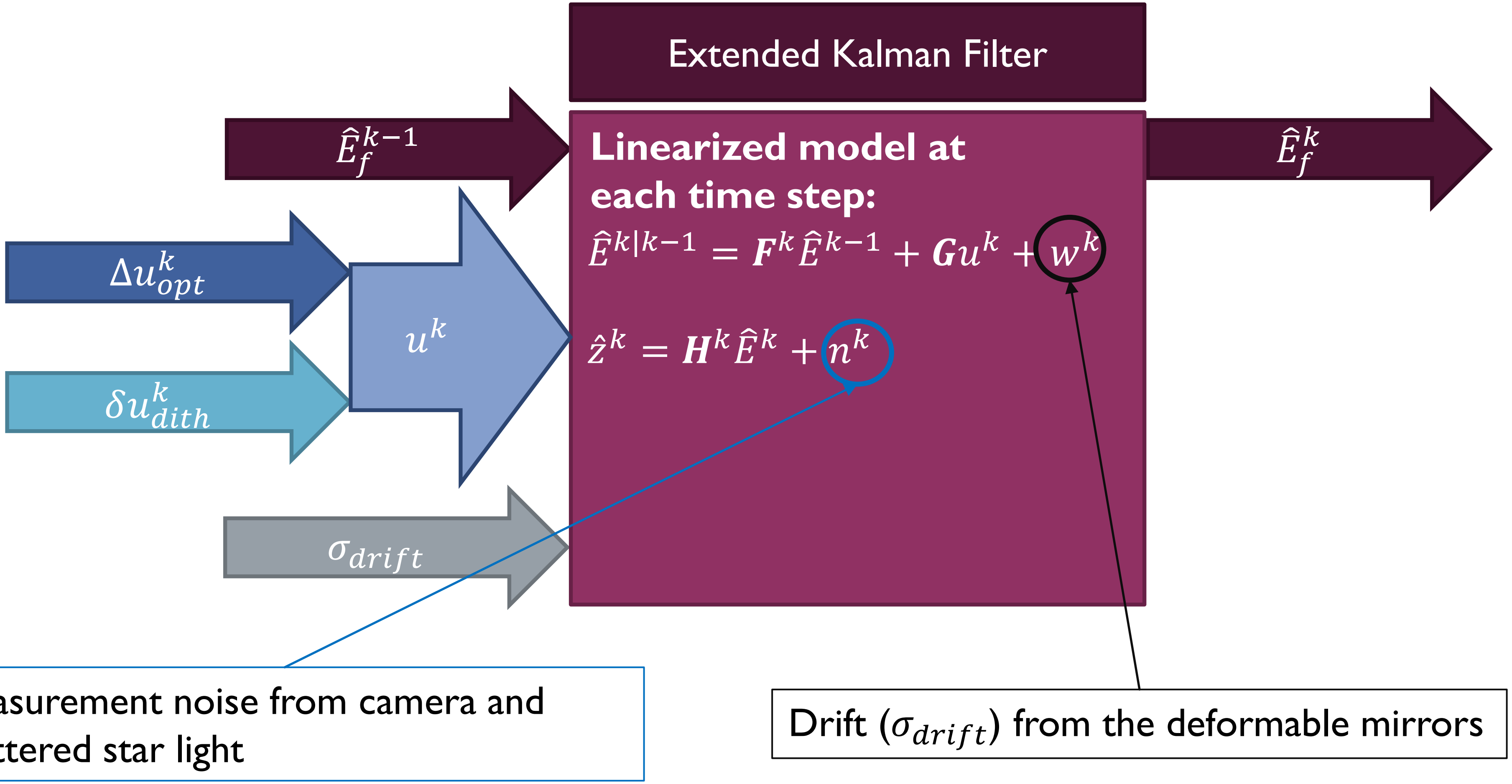


- $\mathrm{u}^k = \Delta \mathrm{u}_{\mathrm{opt}}^k + \delta \mathrm{u}_{\mathrm{dith}}^k$
- Need $\delta \mathrm{u}_{\mathrm{dith}}^k$ to avoid estimate converging to incorrect value (Riggs, 2016)

STEP 1: ESTIMATE



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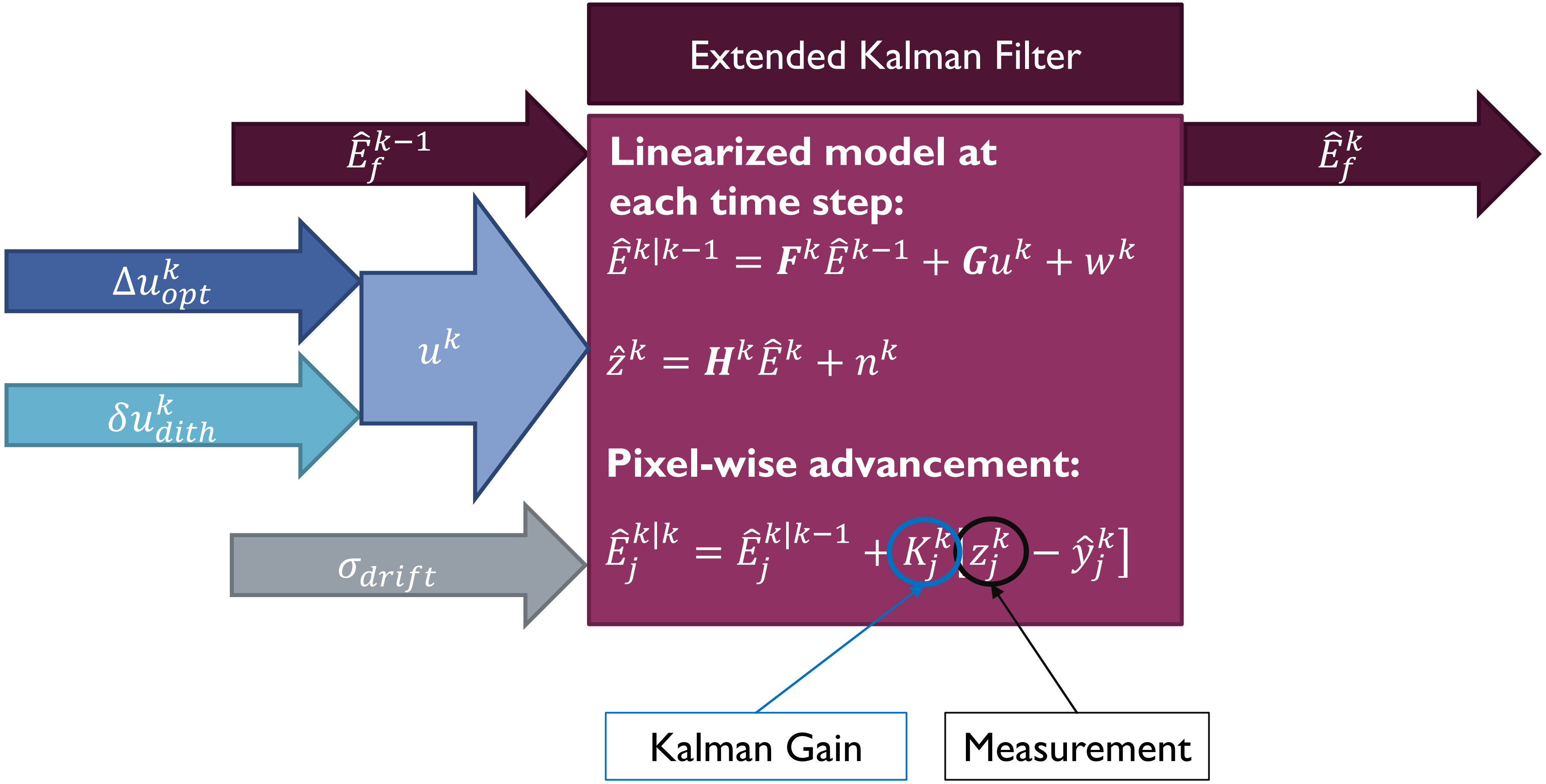

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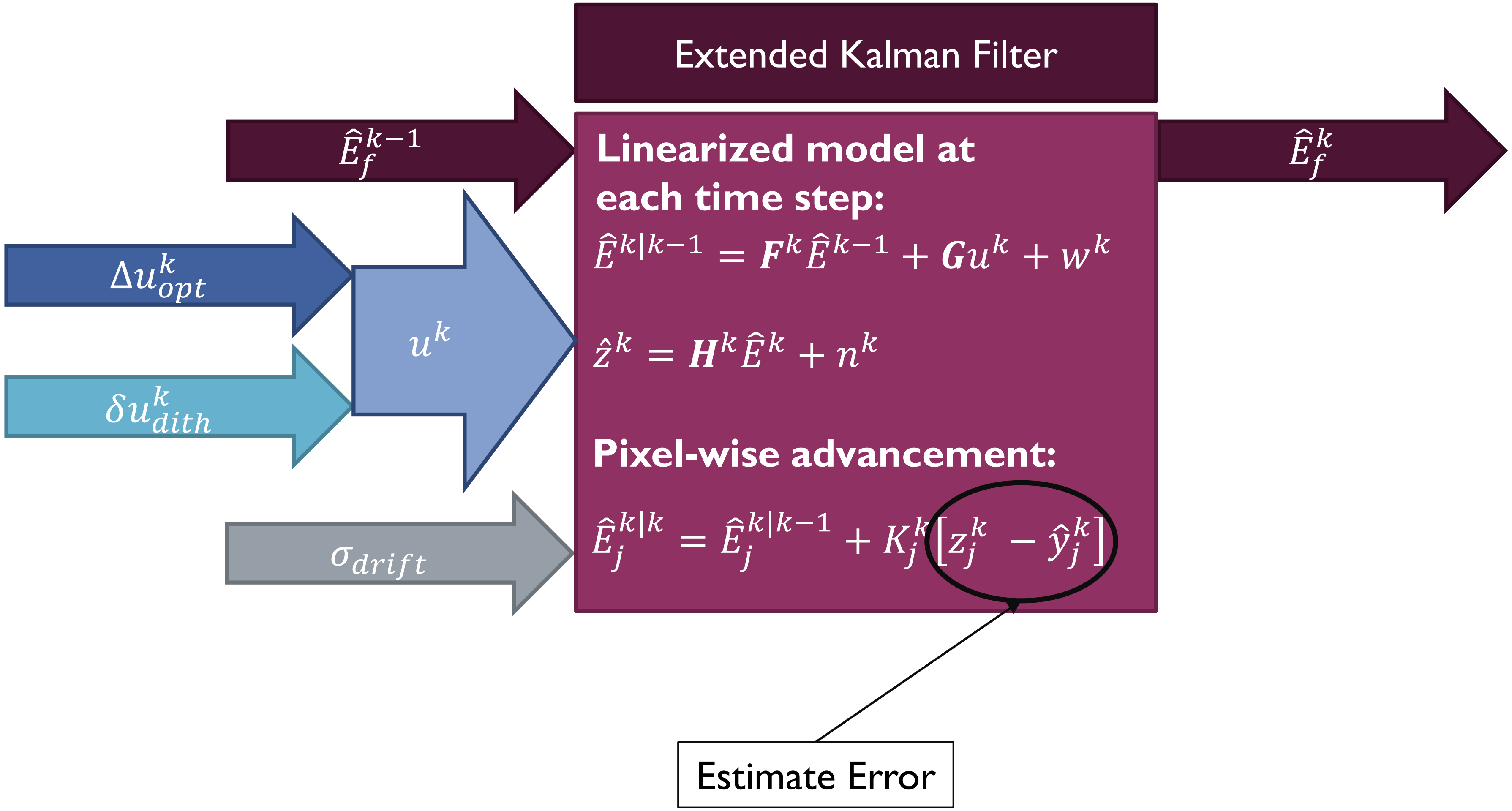
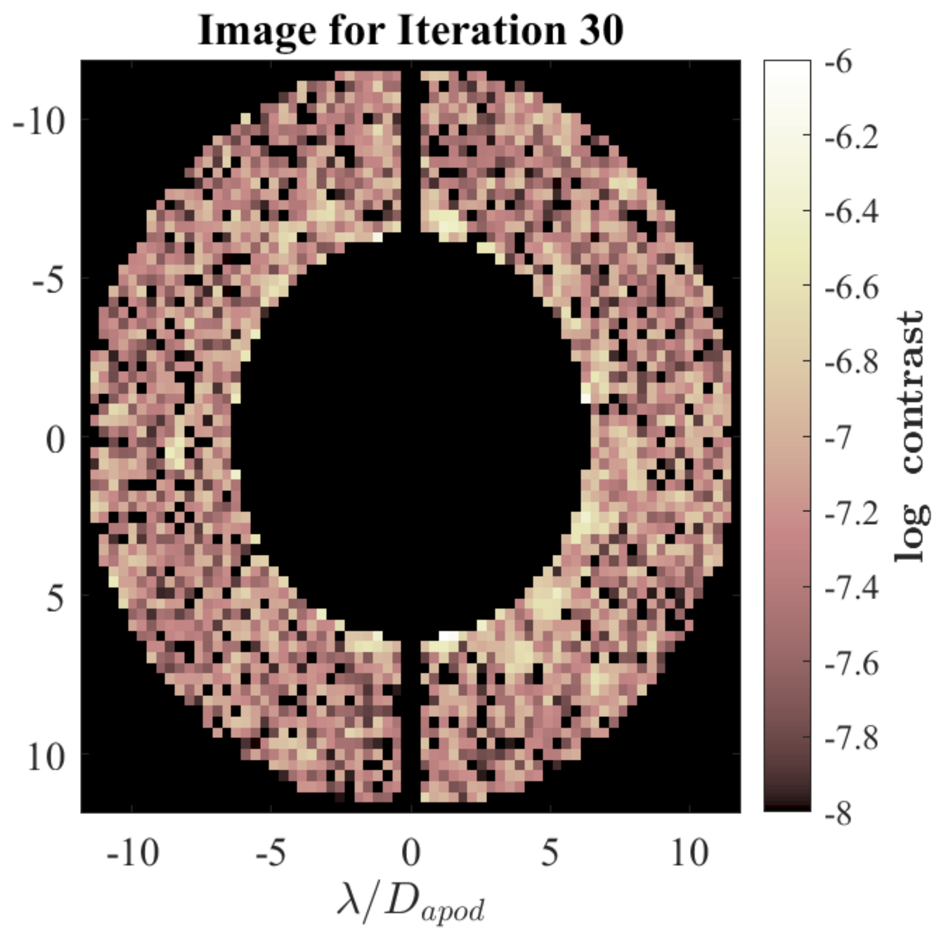
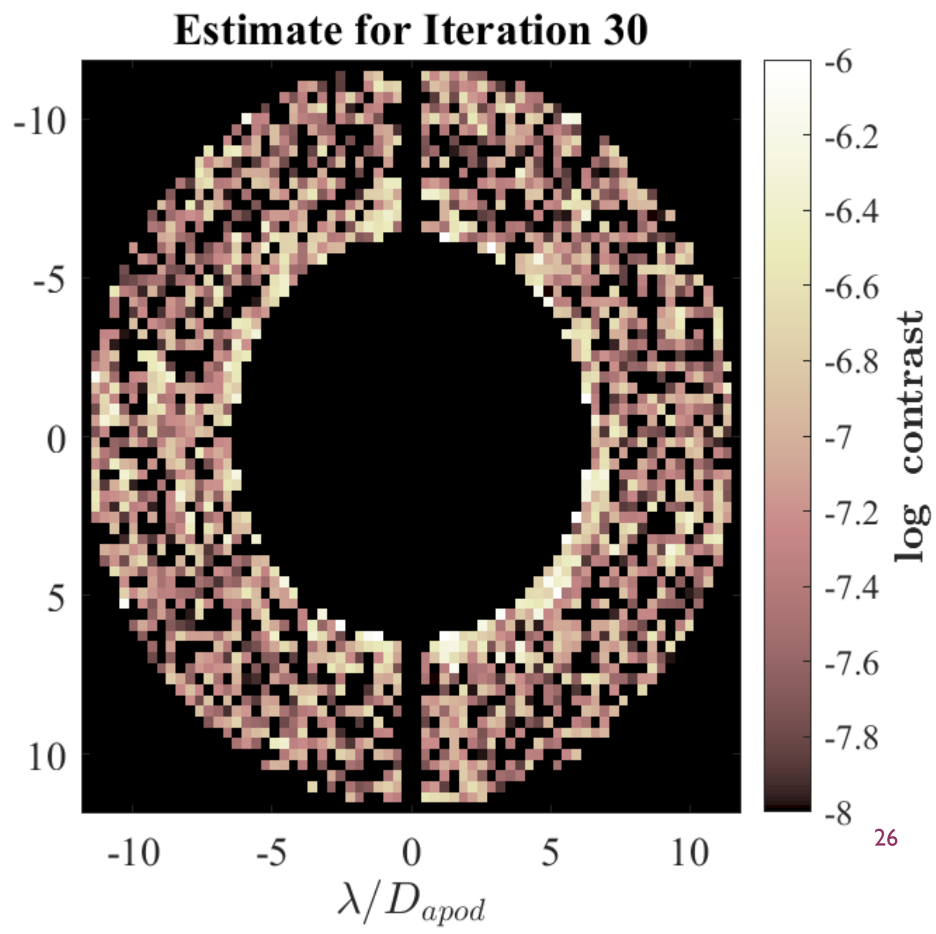


STEP 3: REPEAT AS DESIRED

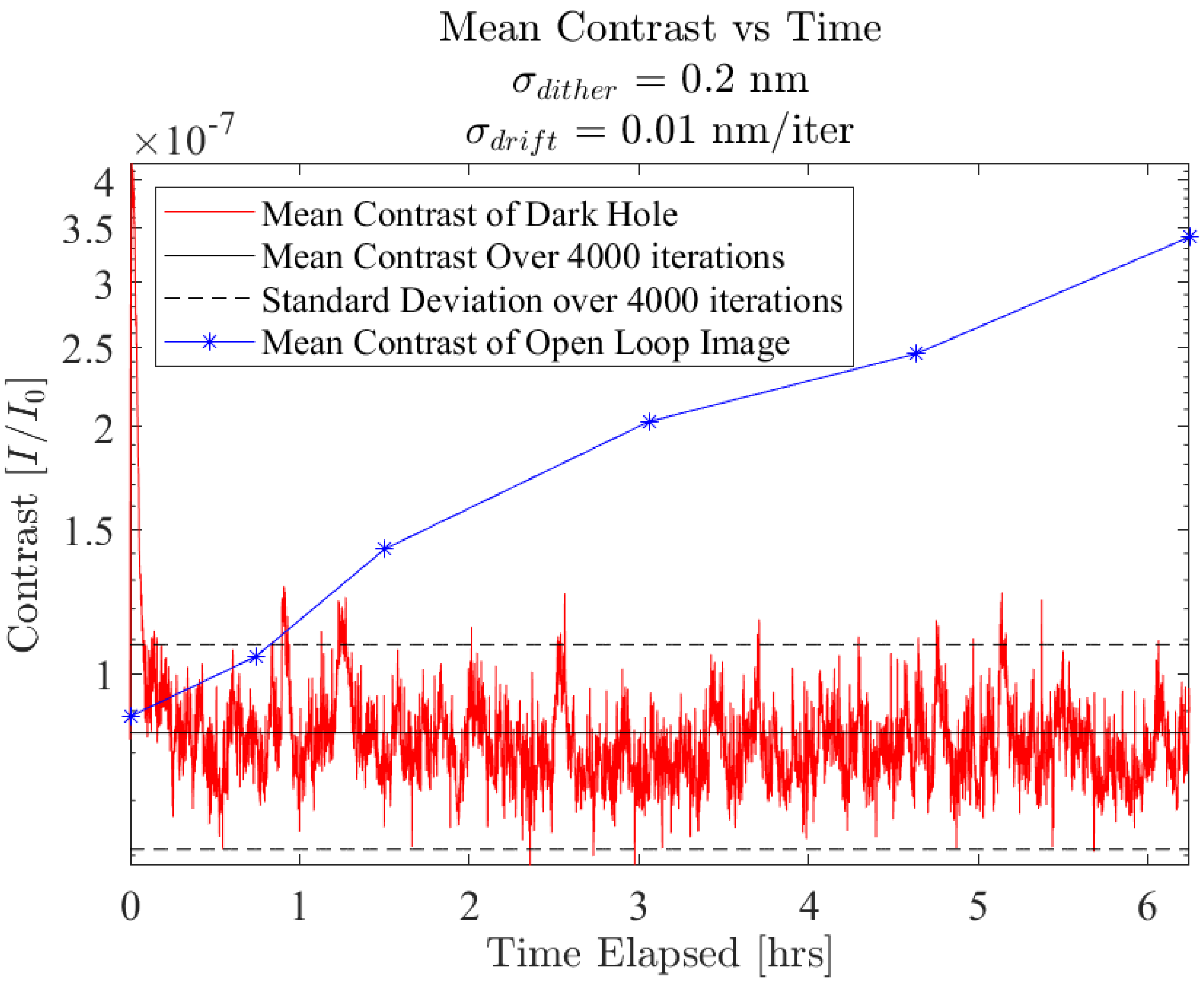


Estimator tends to converge within ~30 iterations using an appropriate dither value



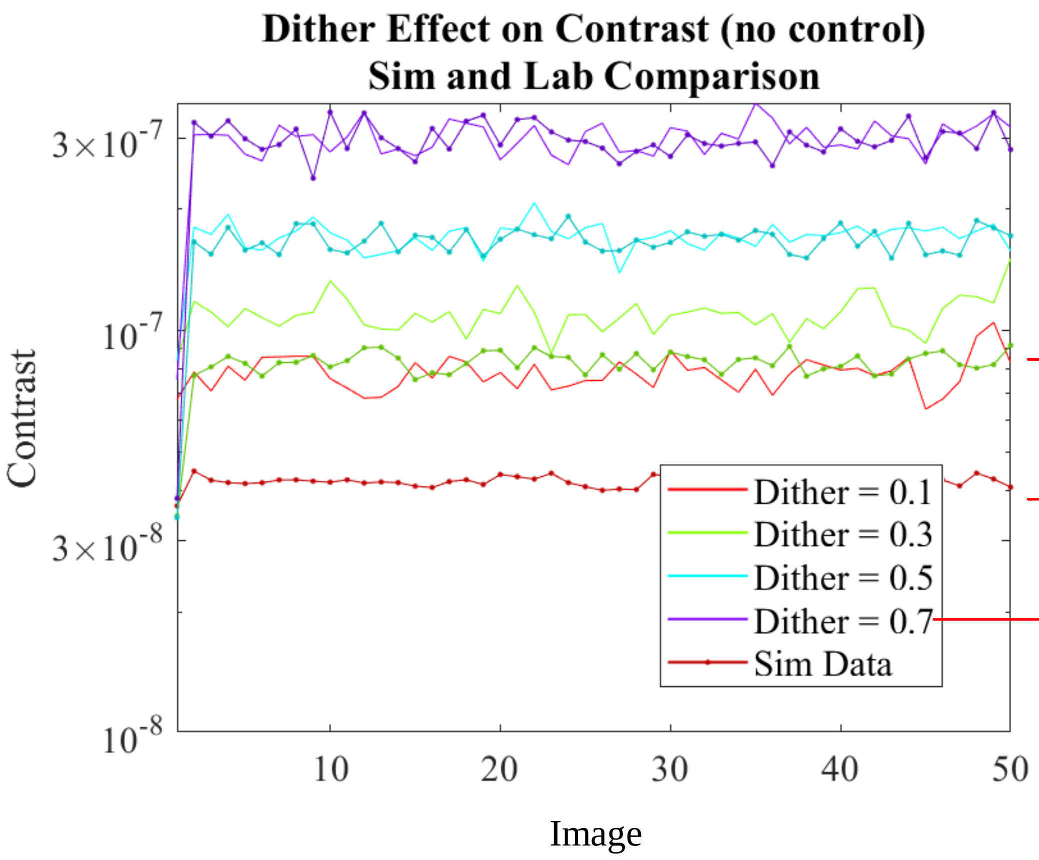
HICAT RESULTS

LONG MAINTENANCE RUN PERFORMANCE



- Open loop mean contrast degrades by a factor of 4 over the six hour experiment
- Closed loop mean contrast is maintained at 8.5×10^{-8} within a standard deviation of 2.4×10^{-8}

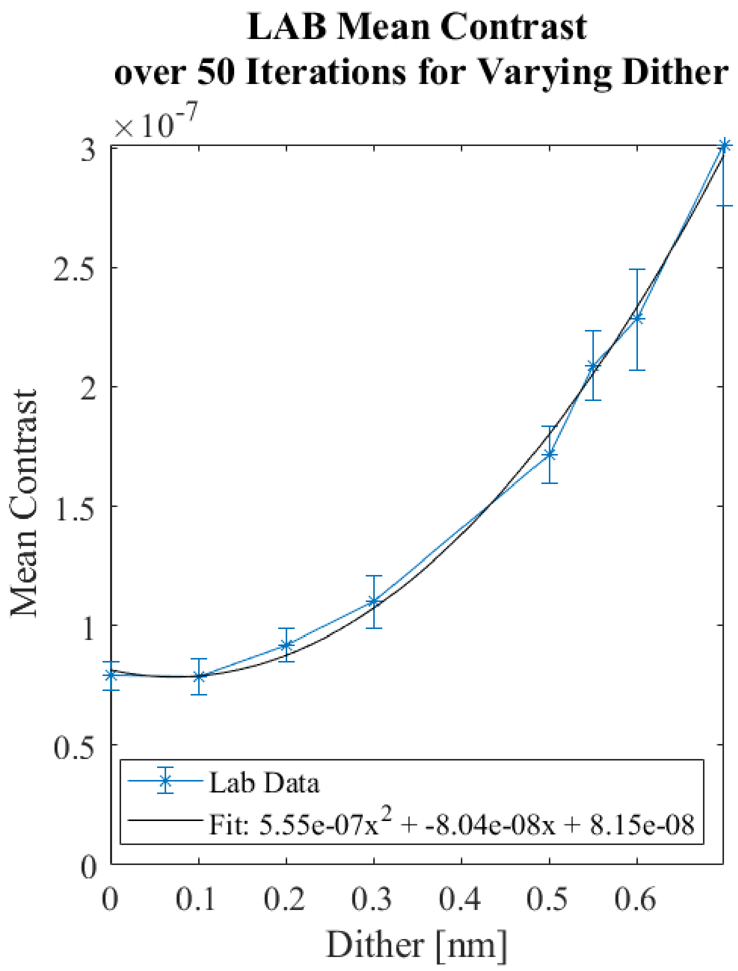
RAW EFFECT OF DITHERING DMS WITHOUT CONTROL



- Without any control, dithering the DMs degrades the contrast*
  - $u = u_0 + \mathcal{N}(0, \sigma_{dith}^2 \boldsymbol{I})$
  - *This depends on the initial contrast, if the dither is below a certain threshold the contrast does not change

σ_{dith} $[nm]$

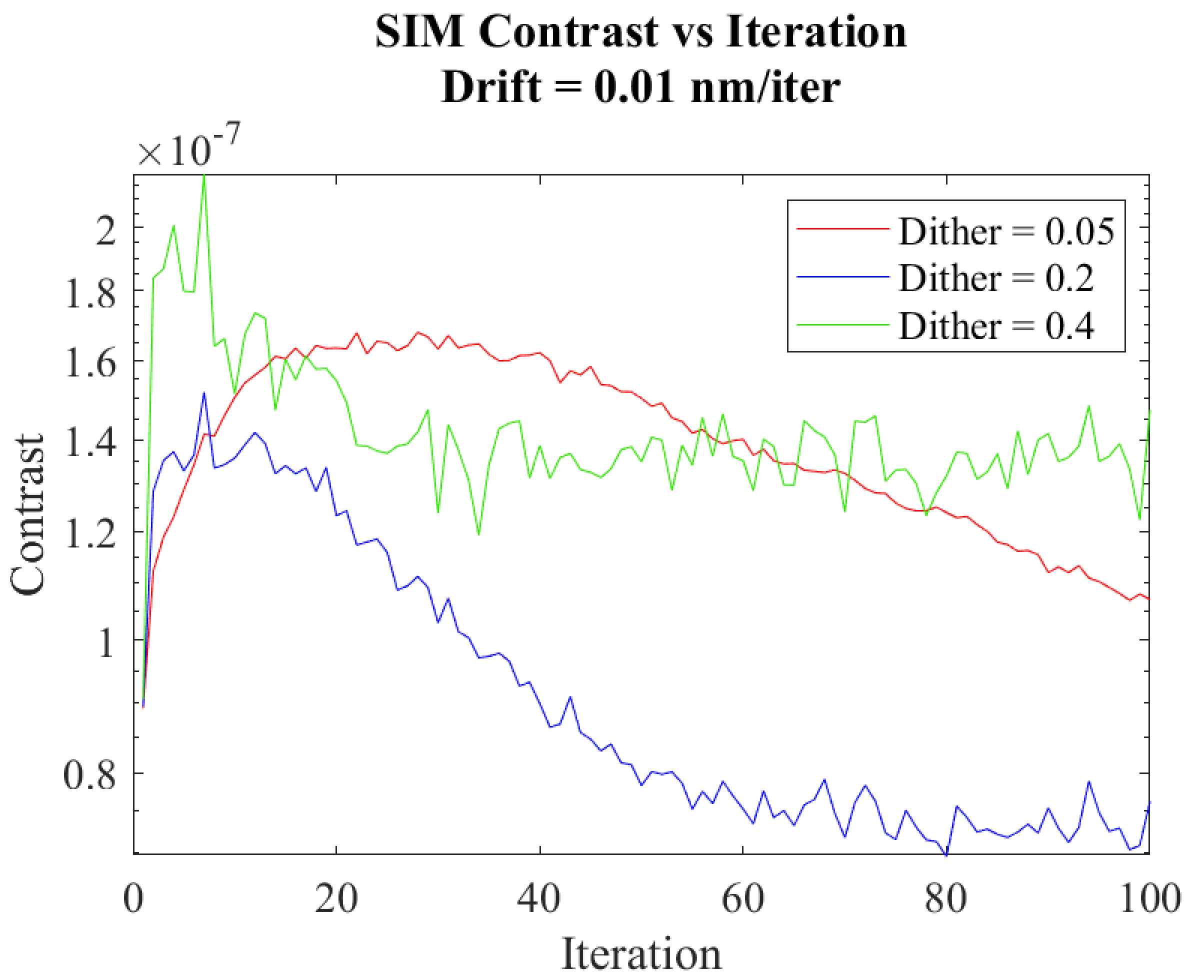
RAW EFFECT OF DITHERING DMS



- We can then fit the data and predict the 'limiting' contrast based on the dither
- This would suggest that we want to choose a dither of zero BUT this is not the whole story, we have an estimator and control loop too!

EFFECT OF DITHER ON MAINTENANCE PERFORMANCE

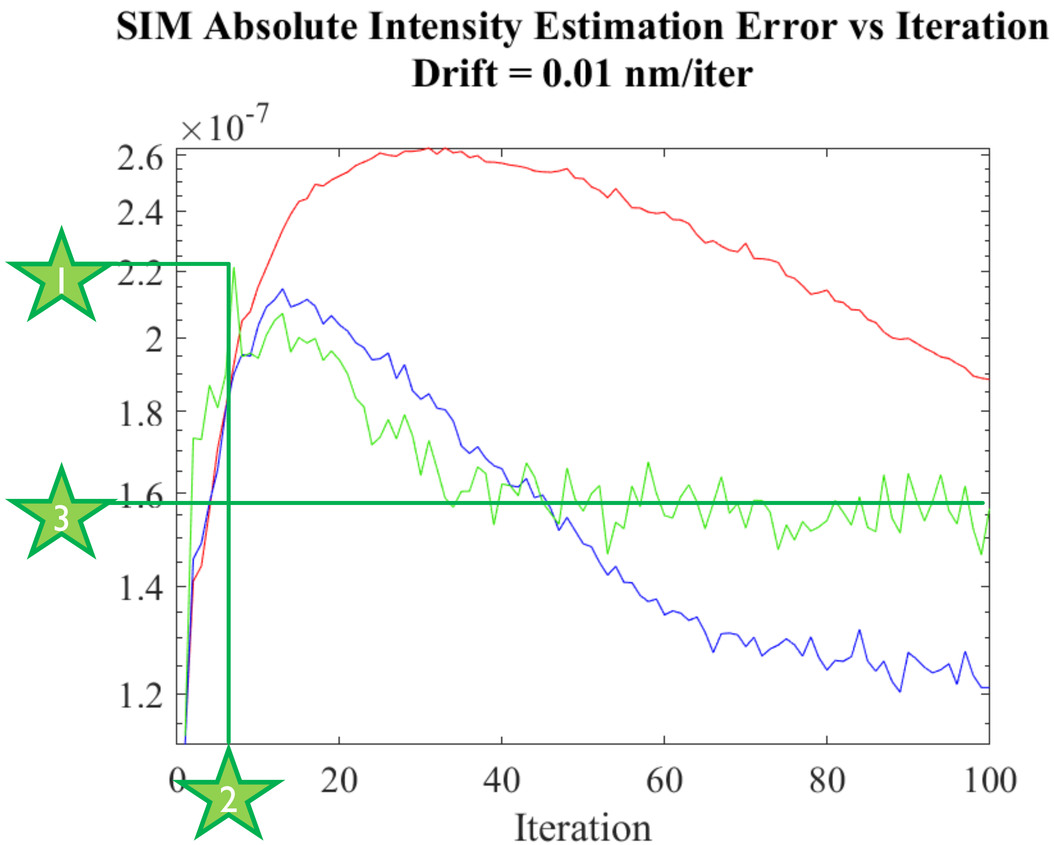
- Small dither ($5 \times \sigma_{drift}$):
  - Shallow slope
  - Takes longer to shoot off and recover
  - Reaches original contrast at ~200 iterations
- Large dither ($40 \times \sigma_{drift}$):
  - Steep slope pre and post contrast
  - Asymptotes to higher final contrast
- Medium dither ($20 \times \sigma_{drift}$):
  - Smaller offshoot than large dither
  - Steeper slope than small dither
  - Asymptotic contrast is on par with original state



DITHER AND ESTIMATE CONVERGENCE

Note: Estimate error has same trend as contrast. The better the estimate, the more effective the control and the better the contrast.

DITHER AND ESTIMATE CONVERGENCE

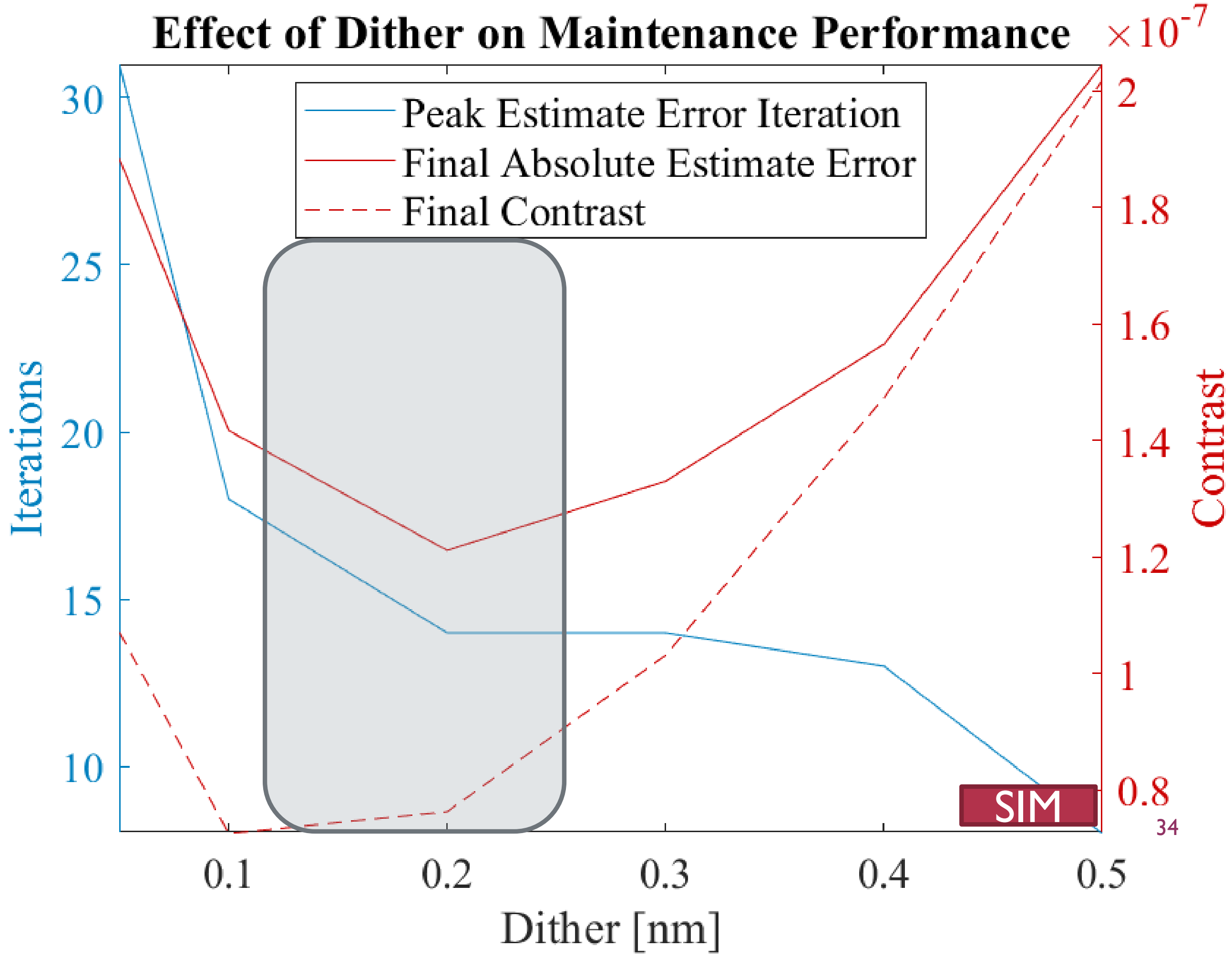


- Looking at three main parameters:
  1. Peak estimation error [contrast]
  2. Number of iterations until peak [iterations]
  3. Asymptotic estimation error [contrast]

CHOOSING THE 'BEST' DITHER

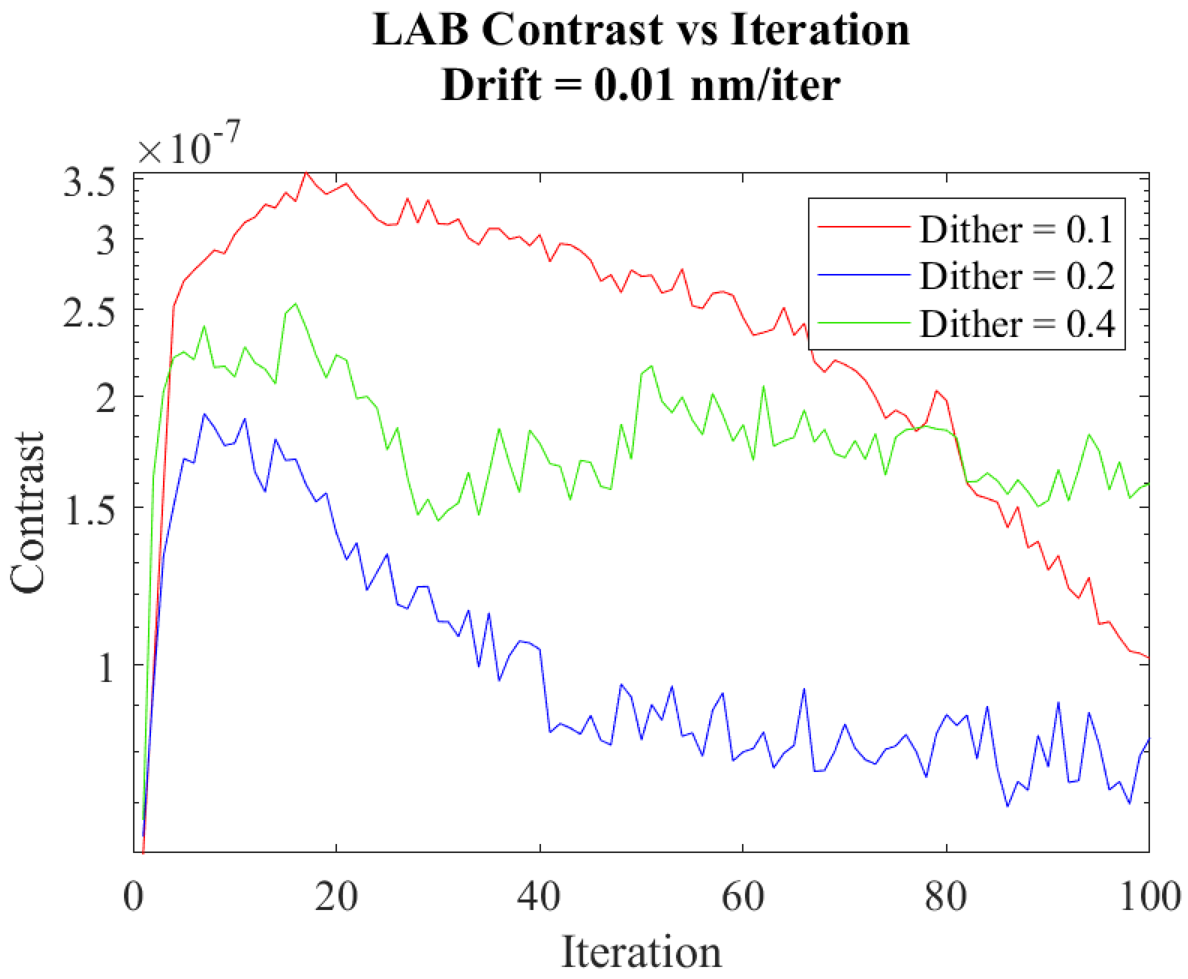
- Ultimate Goal:
  - Estimator converges fast
  - Estimate error is small
  - Final Contrast is small
- Caveats:
  - This is for a single DM drift
    - $\sigma_{drift} = 0.01\ nm/iter$
  - Repeating this process for various drifts shows that for best performance:

$$\sigma_{dither} \approx 20 \times \sigma_{drift}$$



LAB VERIFICATION!

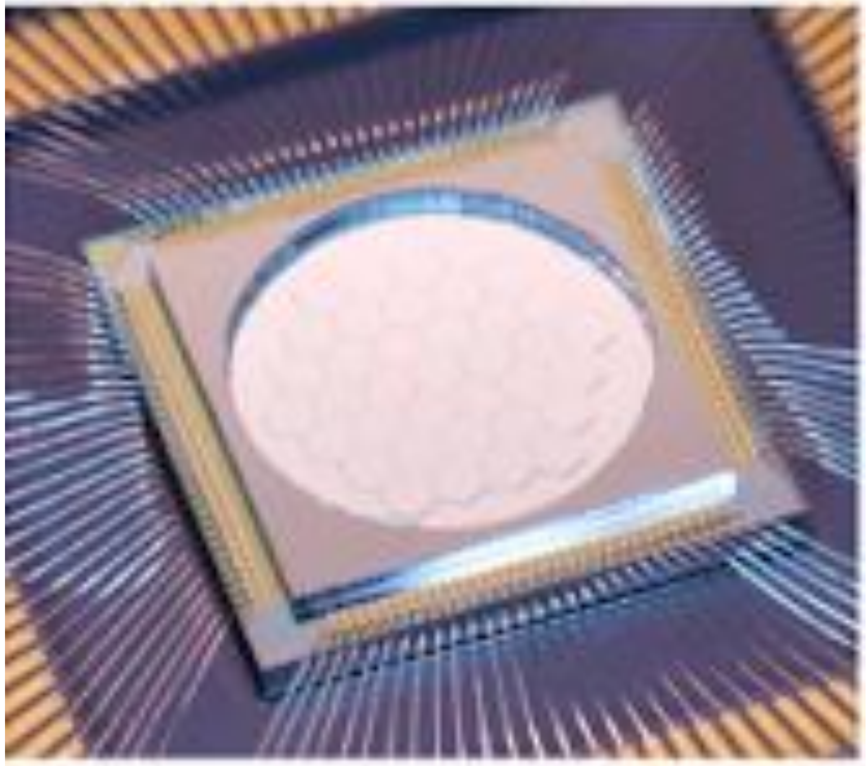
- The same trend is observed in the lab!
- Large dither limits steady state contrast
- Small dither takes a long time to recover
- $\sigma_{dither} \approx 20 \times \sigma_{drift}$ performs the best



SUMMARY AND FUTURE WORK

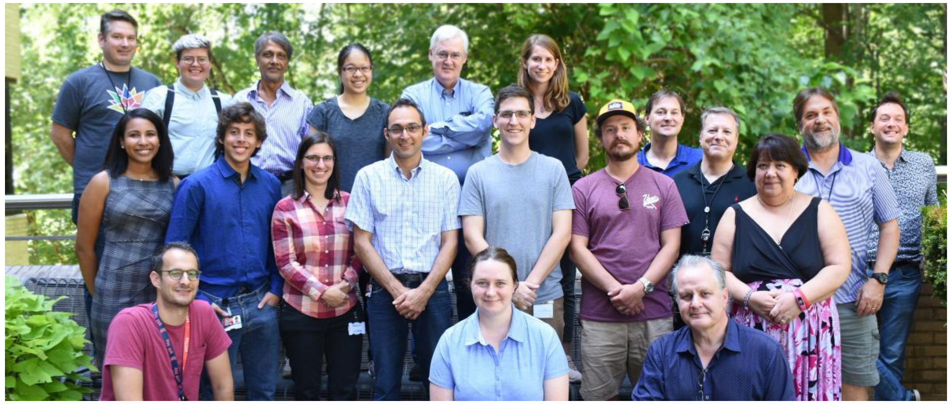
SUMMARY AND FUTURE WORK

- The EKF + EFC dark hole maintenance algorithm presented here can maintain contrast levels of 7×10^{-8} in the presence of a DM random walk drift for thousands of iterations / 6 hrs
- Next steps:
  - Use the recently installed an Iris AO Deformable primary mirror to introduce drifts
  - Drift using Zernike modes instead of random walk of each actuator
  - Use the temperature as the drift
  - Add broadband capabilities
  - Translate testbed results into mission implications



IRIS AO Segmented Mirror

ACKNOWLEDGEMENTS



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QUESTIONS?

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VALIDATION OF REAL TIME DRIFT CORRECTION

- Goal: Show that the open loop electric field is drifting and the estimator+controller is correcting for it in real time.
- Algorithm:

1. Take close loop image
   a. Apply closed loop DM command: $u^{CL}(k+1) = u_0 + \Delta u_{opt}(k) + \delta u_{dith}(k) + \delta u_{drift}(k)$
   b. Take image
2. Take open loop image
   a. Apply open loop DM command: $u^{OL}(k+1) = u_0 + \delta u_{drift}(k)$
   b. Take image
3. Advance Estimator using closed loop data
4. Obtain new optimal DM command using closed loop data
5. Repeat

VALIDATION OF REAL TIME DRIFT CORRECTION

$\Delta u_{opt}(k) + \delta u_{dith}(k) + \delta u_{drift}(k)$

$\delta u_{drift}(k)$