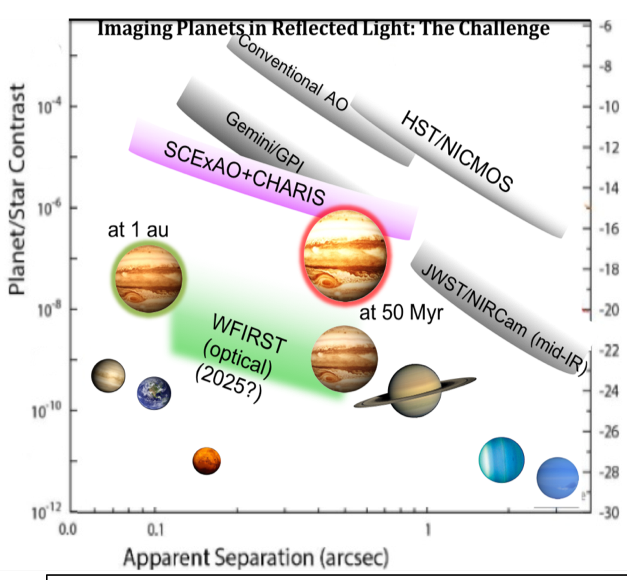
# Laboratory Demonstration of Spatial Linear Dark-Field Control for Imaging Extrasolar Planets in Reflected Light

*Thayne Currie[1,2], Eugene Pluzhnik[1], Olivier Guyon[2,3] Ruslan Belikov[1], Kelsey Miller[4], Steven Bos[4]*
*1. NASA-Ames Research Center, 2. Subaru Telescope, 3. University of Arizona, 4. Leiden Observatory*

## MOTIVATION: WHY LDFC?

Directly detecting and characterizing the spectrum of an Earth-like planet with a future space mission requires suppression of noisy, scattered halo of starlight better by a factor of $10^{10}$. While high-contrast imaging testbeds simulating space-based high-contrast imaging have demonstrated significant progress towards this goal, *maintaining* this dark hole (DH) requires extremely precise stellar halo measurements. If the halo itself is dark/low in flux because focal-plane wavefront control (FPWFC) methods like EFC are applied in the first place), the DH can degrade due to dynamic aberrations. Furthermore, by *modulating* the deformable mirror (DM) to determine and update the estimate of the electric field, FPWFC methods like EFC *perturb* science exposures, potentially limiting exposure times and the effectiveness of post-processing methods to further remove the stellar halo.



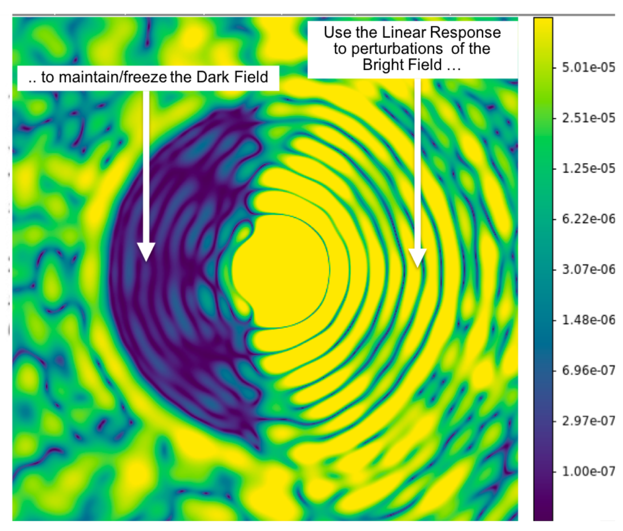




Fig. 1 – Imaging solar system-like planets requires maintaining a static dark hole (shown as "the dark field" or DF). LDFC utilizes the linear response of the region outside the dark hole which has far larger signal (the ``bright field" or BF) to wavefront perturbations that affect both the BF and the DF ([1], [2]). LDFC does not require modulation.

**Spatial Linear Dark Field Control (LDFC) is a promising wavefront control method that can maintain a static, deep DH that is first generated from FPWC methods ([2]).**

### Mathematical Premise Behind LDFC

Electrical Field in image plane = initial pupil plane field + small change in complex amplitude induced by DM (1); resulting intensity is given by three terms (2, 3)…

$$E_t \approx E_0 + E_{DM} \quad (1)$$

$$I_t = |E_t|^2 \quad (2)$$

$$I_t \approx |E_0|^2 + |E_{DM}|^2 + 2\langle E_0, E_{DM}\rangle \quad (3)$$

In the DF, intensity is dominated by DM term (4); in BF, the initial field dominates (5)

$$|E_{DM}|^2 \gg |E_0|^2 \quad (4)$$

$$|E_0|^2 \gg |E_{DM}|^2 \quad (5)$$

Signal used by LDFC to drive DF back to its initial state is (6)

$$\Delta I_t = I_t - I_{ref} \approx 2\langle E_0, E_{DM}\rangle \quad (6)$$

DM shape that restores deep DH is then (7), where M is the pseudo-inverse of the Response Matrix (i.e. Control Matrix)

$$u_t = -(M^T M)^{-1} M^T \, \Delta I_{t,n} \quad (7)$$

## SETUP

To provide first empirical test of LDFC, we used the Ames Coronagraph Experiment (ACE) laboratory at NASA-Ames Research Center.

Experimental Setup:

S1FC635 laser centered on ~635nm; ~1nm bandpass; PIAA coronagraph
One-sided dark hole created using Speckle Nulling ([3]) using an implementation of the Gerchberg-Saxton method for phase retrieval ([3])
Starting contrast of ~1e-3--1e-4, final DH contrast of ~5 to 8e-7 (1.2-4.5 lambda/D)

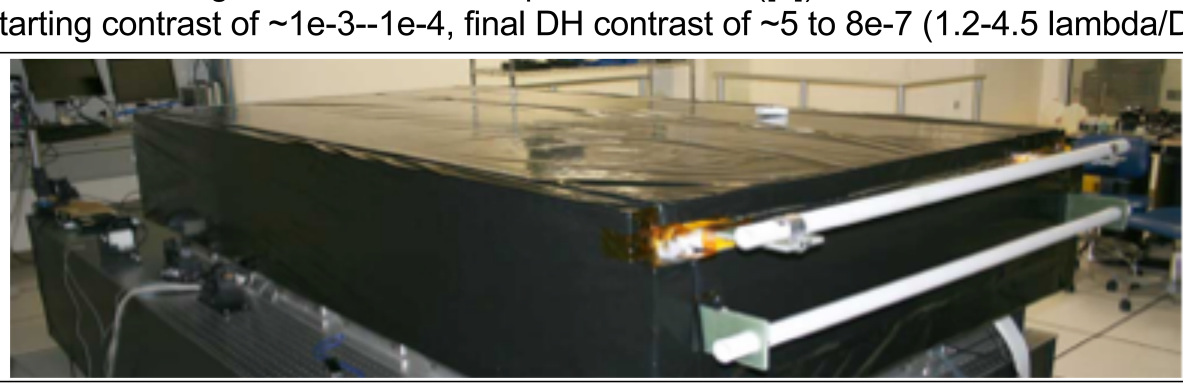


Fig 3 – ACE lab setup

## Methods

### Response and Control Matrix Calculations and Wavefront Control Loop

**- We calculate the LDFC Response Matrix (RM) by poking *m* actuators and recording the intensity over *n* BF pixels using two different patterns, a and b:**
**$RM(n,m) = 0.5*[(I_{a1}-I_{a2})+(I_{b1}-I_{b2})]/2*ampl_{poke}$**
**- We compute the Control Matrix (CM) as the pseudo-inverse of the RM using eigenvalue truncation, typically at 250—300 modes (out of 1024)**

## RESULTS:

**We obtained the first closed-loop lab demonstrations of LDFC at a contrast level relevant for imaging planets in reflected light**

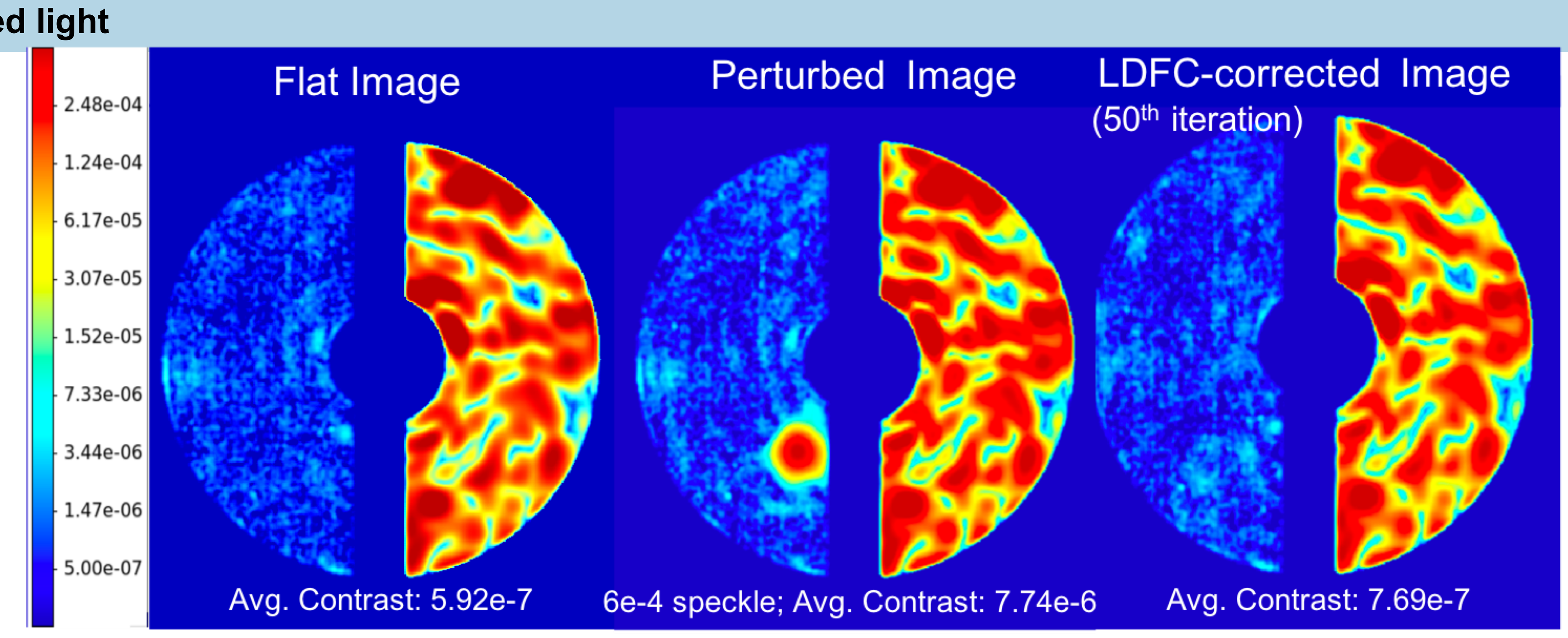
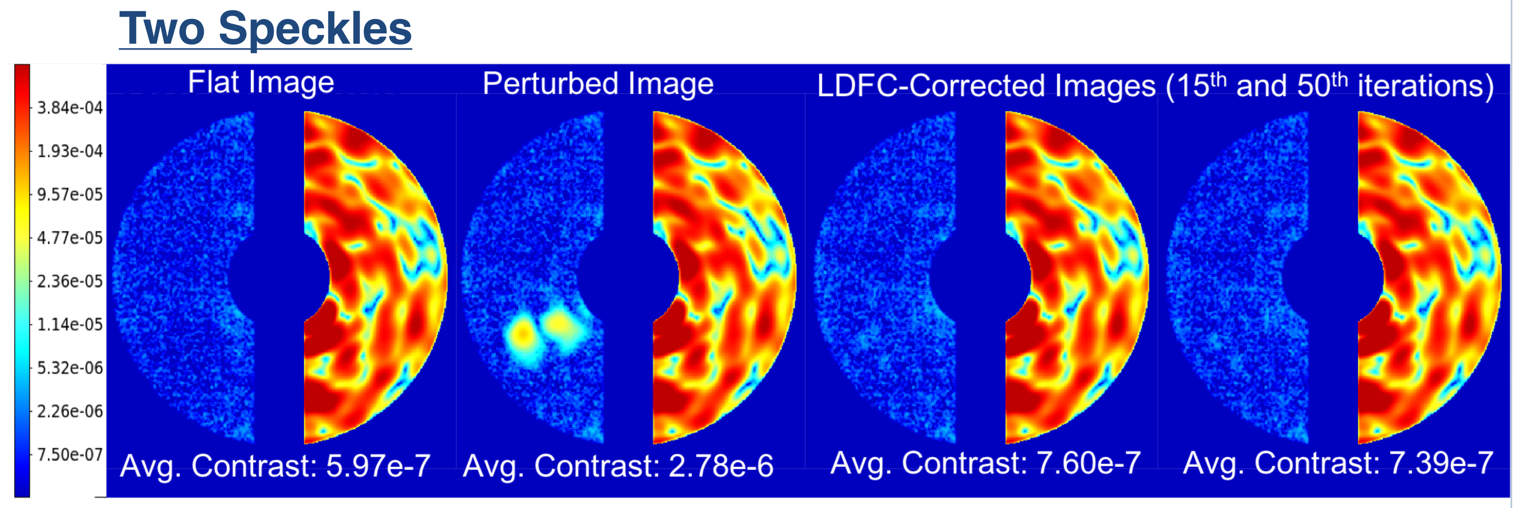


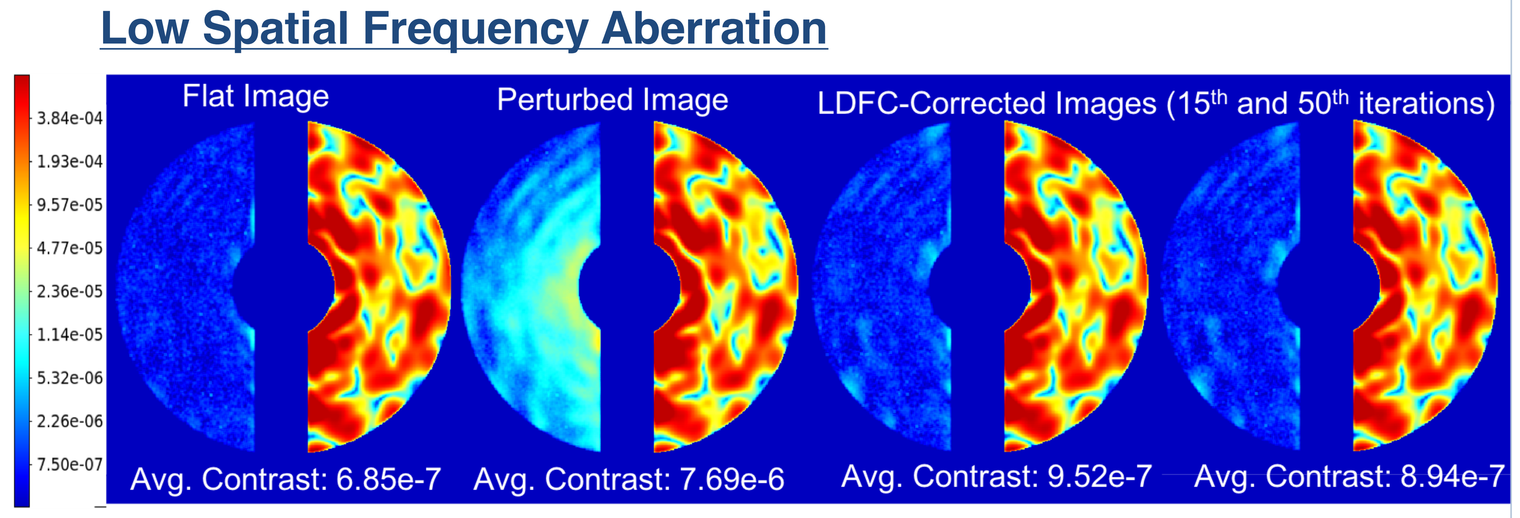

Fig 4 – Demonstration of LDFC. After producing a 5.9e-7 dark hole, we introduced a sine wave perturbation to produce a pair of 6e-4 speckles, degrading the average contrast to 7.7e-6. After 15 iterations our LDFC loop nulls the speckles and returns the dark hole to near nearly its original state. The dark hole stays frozen through 125 iterations.

**LDFC can correct different types of perturbations**

### Two Speckles




### Low Spatial Frequency Aberration




### Complex Aberrations

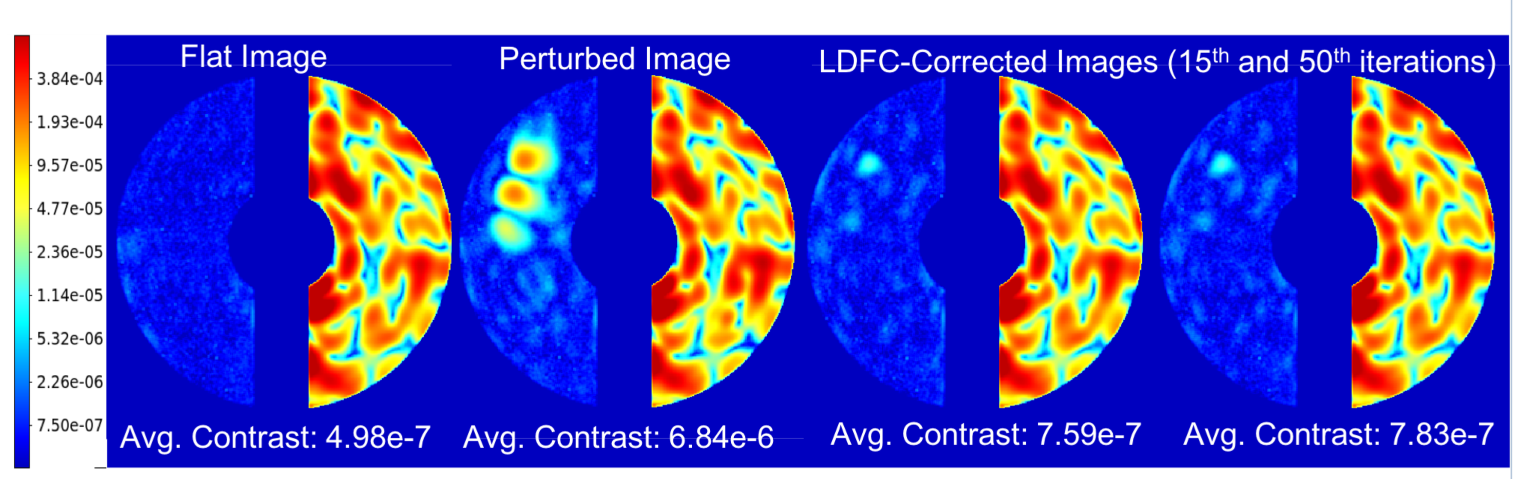



Fig 4 – Performance of LDFC for a range of different aberrations

**LDFC may be more efficient than standard DM probing methods like Speckle Nulling**

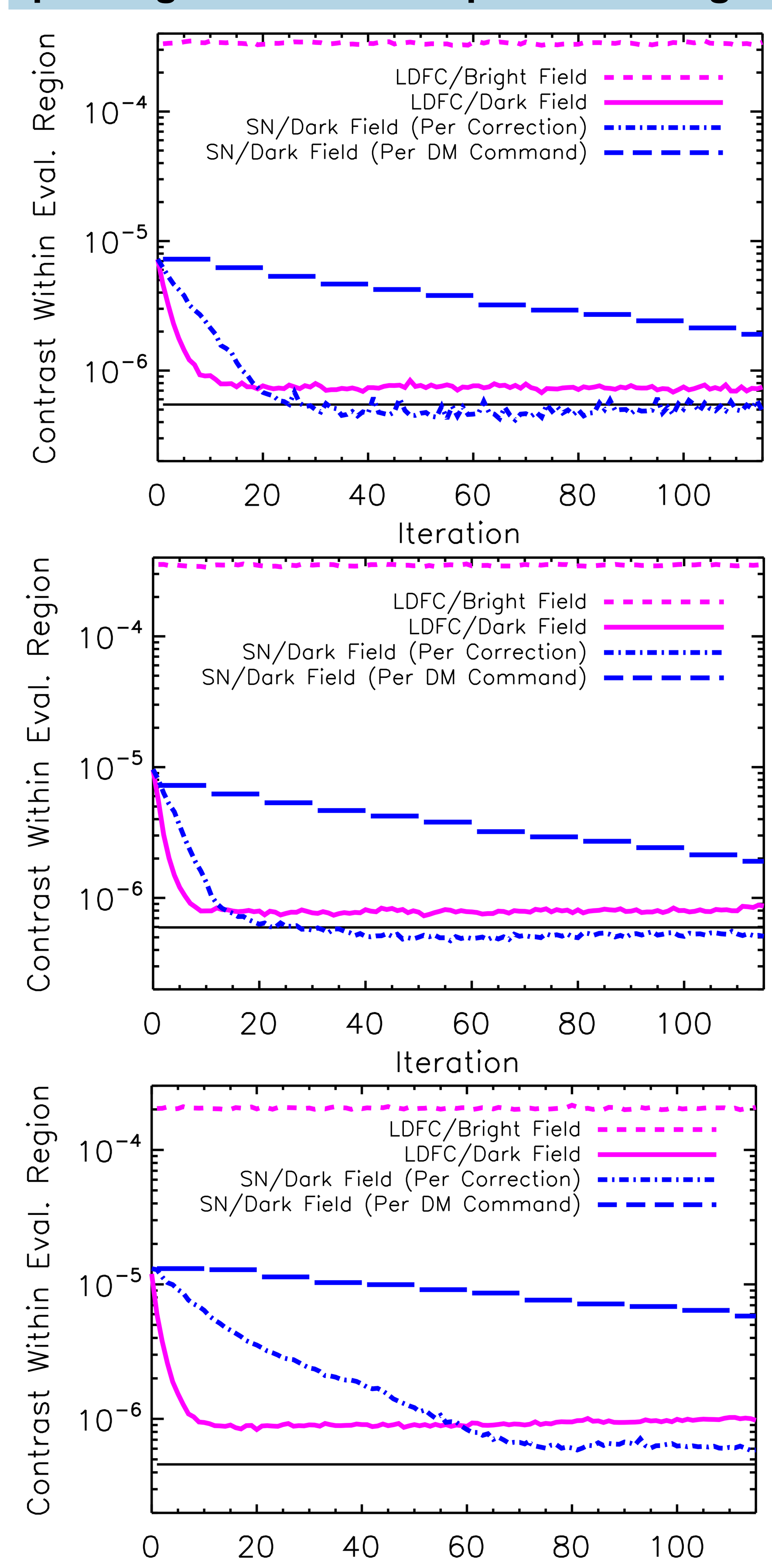



Fig 5 – Efficiency and stability of LDFC vs. Classical Speckle Nulling

## REFERENCES

1. Miller et al. 2017, JATIS, 3, 9002
2. Guyon et al. 2017, arxiv:1706.07377
3. Pluzhnik et al. 2017, SPIE, 10400, 1040024
4. Currie et al. 2019, SPIE

*For more information, contact Thayne Currie: currie@naoj.org*

**Now published in Currie et al. 2020, PASP, 132, 4502**