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Speckle nulling with space-based coronagraphs

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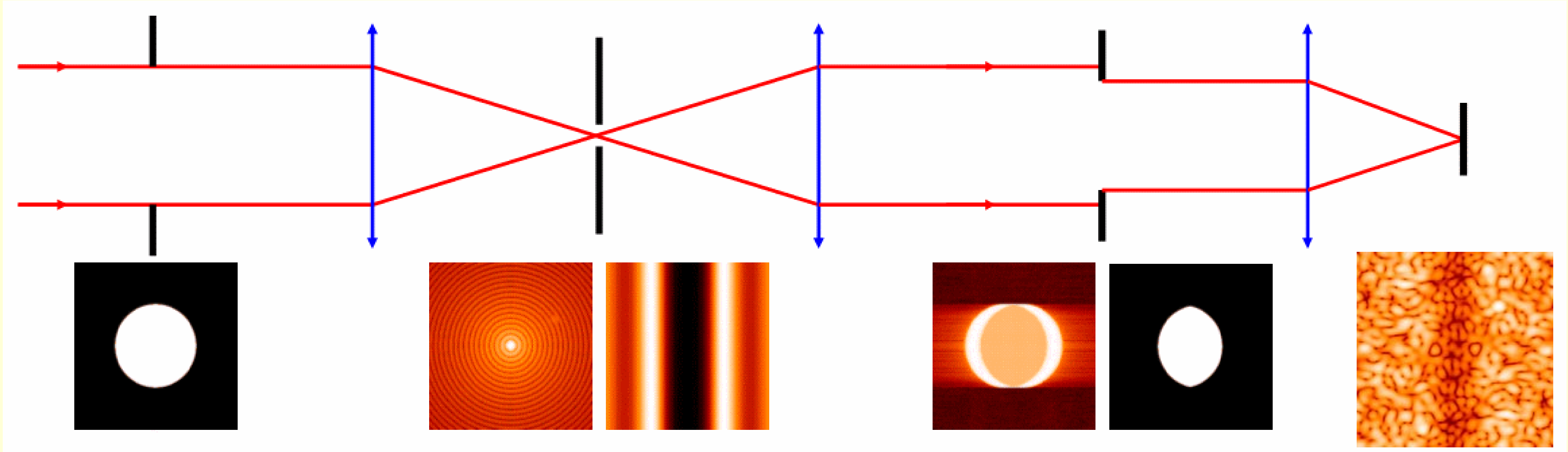
Outline

1. Speckle noise in coronagraphs
2. Combining coronagraphs & AO
3. Wavefront sensing using science focal plane
4. Algorithms for wavefront control
5. Simulations

Example of coronagraph

Lyot coronagraph with band-limited mask

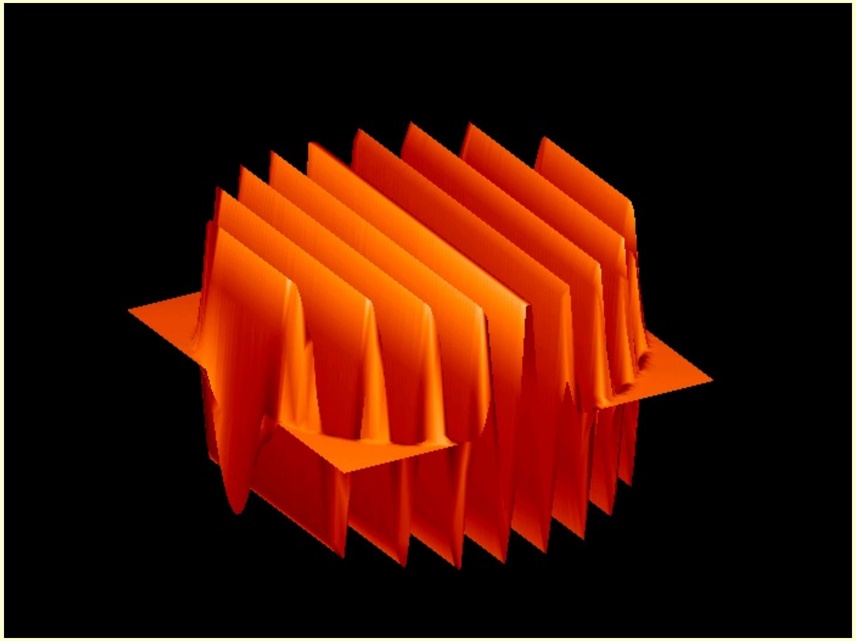
Kuchner & Traub, ApJ, 2002



Wavefront aberrations cause speckle noise

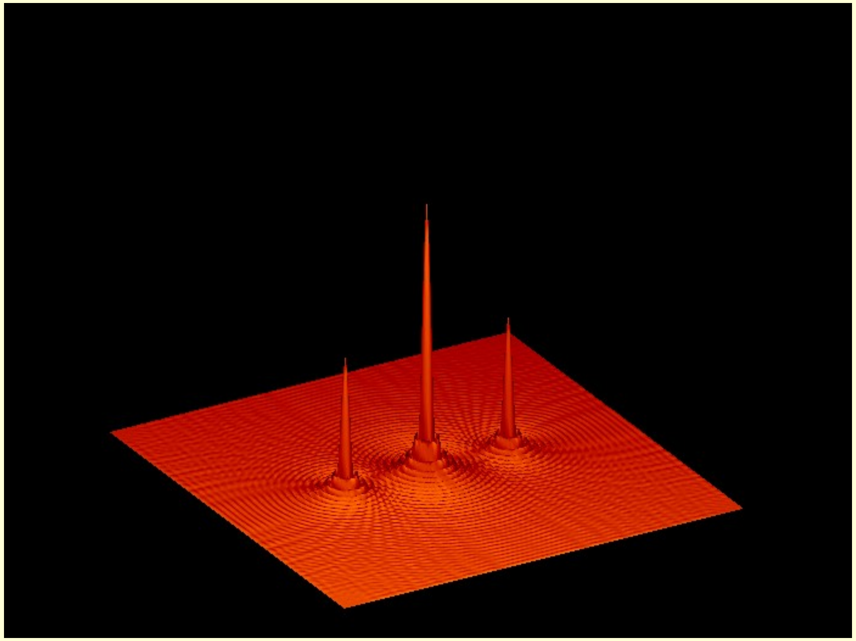
Understanding speckles

Pupil plane



Physical ripple on mirror
⇨ phase grating

Image plane



The central star is replicated
⇨ two symmetric speckles

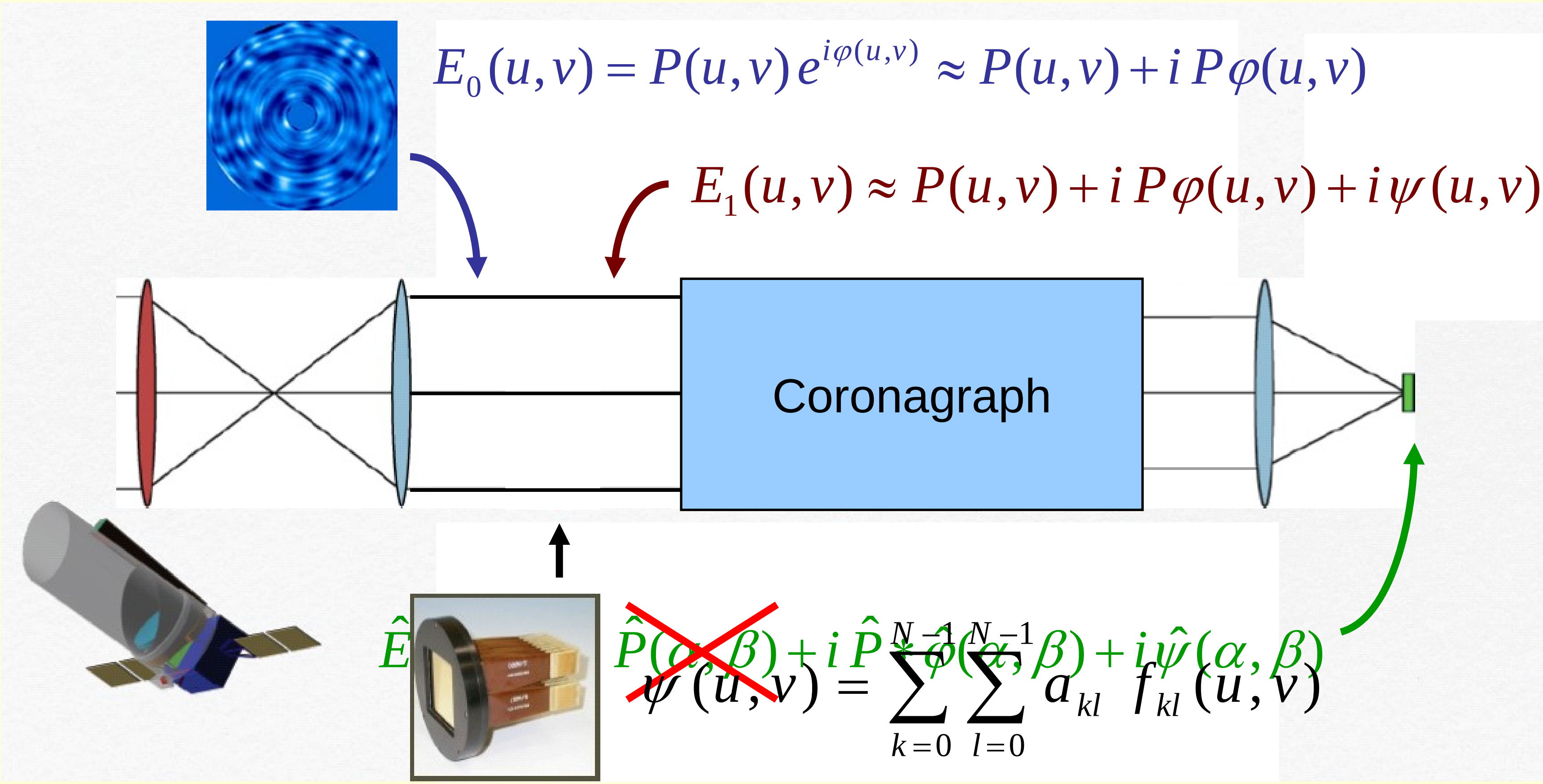
Framework of the study

- Following the tracks of Malbet, Yu & Shao (1995)
- Algorithms to be tested at JPL on the HCIT (Trauger et al.)
- Goal: reduce the number of iterations needed to obtain the dark hole by targeting all speckles at once

Coronagraph & AO

$$E_0(u,v) = P(u,v)\,e^{i\varphi(u,v)} \approx P(u,v) + i\,P\varphi(u,v)$$

$$E_1(u,v) \approx P(u,v) + i\,P\varphi(u,v) + i\,\psi(u,v)$$



$$\hat{E}(\alpha,\beta) \approx \hat{P}(\alpha,\beta) + i\,\hat{P}*\hat{\varphi}(\alpha,\beta) + i\,\hat{\psi}(\alpha,\beta)$$

$$\psi(u,v) = \sum_{k=0}^{N-1}\sum_{l=0}^{N-1} a_{kl}\, f_{kl}(u,v)$$

Speckle field measurement

$$\left\{\begin{array}{l} \left(\widehat{\delta\psi_1}\right)^* \left(\widehat{P\phi}+\widehat{\psi}_0\right) + \widehat{\delta\psi_1}\left(\widehat{P\phi}+\widehat{\psi}_0\right)^* = I_1 - I_0 - |\widehat{\delta\psi_1}|^2 \\ \left(\widehat{\delta\psi_2}\right)^* \left(\widehat{P\phi}+\widehat{\psi}_0\right) + \widehat{\delta\psi_2}\left(\widehat{P\phi}+\widehat{\psi}_0\right)^* = I_2 - I_0 - |\widehat{\delta\psi_2}|^2 \end{array}\right.$$

$$\Delta \equiv \left(\widehat{\delta\psi_1}\right)^* \widehat{\delta\psi_2} - \widehat{\delta\psi_1}\left(\widehat{\delta\psi_2}\right)^*$$

$$\widehat{P\phi} = \frac{\widehat{\delta\psi_2}\left(I_1 - I_0 - |\widehat{\delta\psi_1}|^2\right) - \widehat{\delta\psi_1}\left(I_2 - I_0 - |\widehat{\delta\psi_2}|^2\right)}{\Delta} - \widehat{\psi}_0$$

Speckle field nulling

- Cancel speckle field in the dark hole

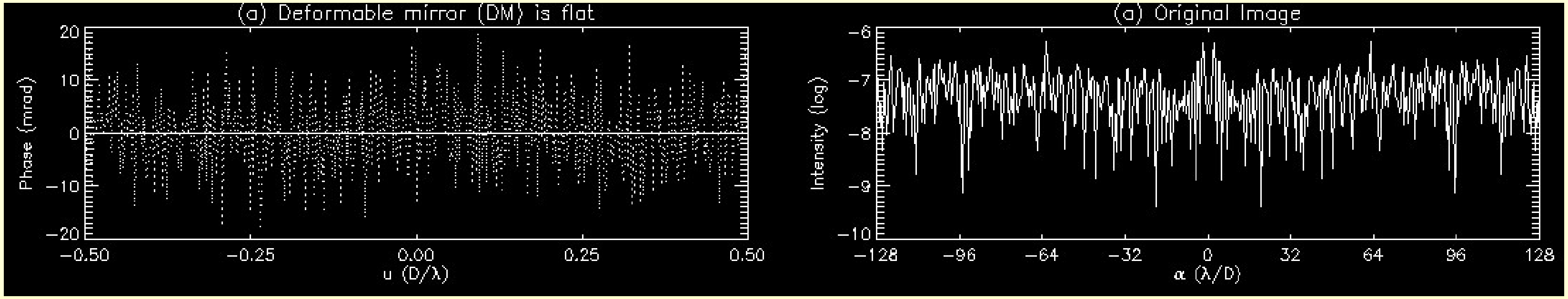
$$\hat{E}(\alpha,\beta) = \hat{P} * \hat{\varphi}(\alpha,\beta) + \sum_{k=0}^{N}\sum_{l=0}^{N} a_{kl}\,\hat{f}_{kl}(\alpha,\beta) = 0$$

$$\sum_{k=0}^{N}\sum_{l=0}^{N} a_{kl} e^{-i\frac{2\pi d}{\lambda}(k\alpha+l\beta)} = -\frac{\hat{P} * \hat{\varphi}(\alpha,\beta)}{\hat{f}(\alpha,\beta)}$$

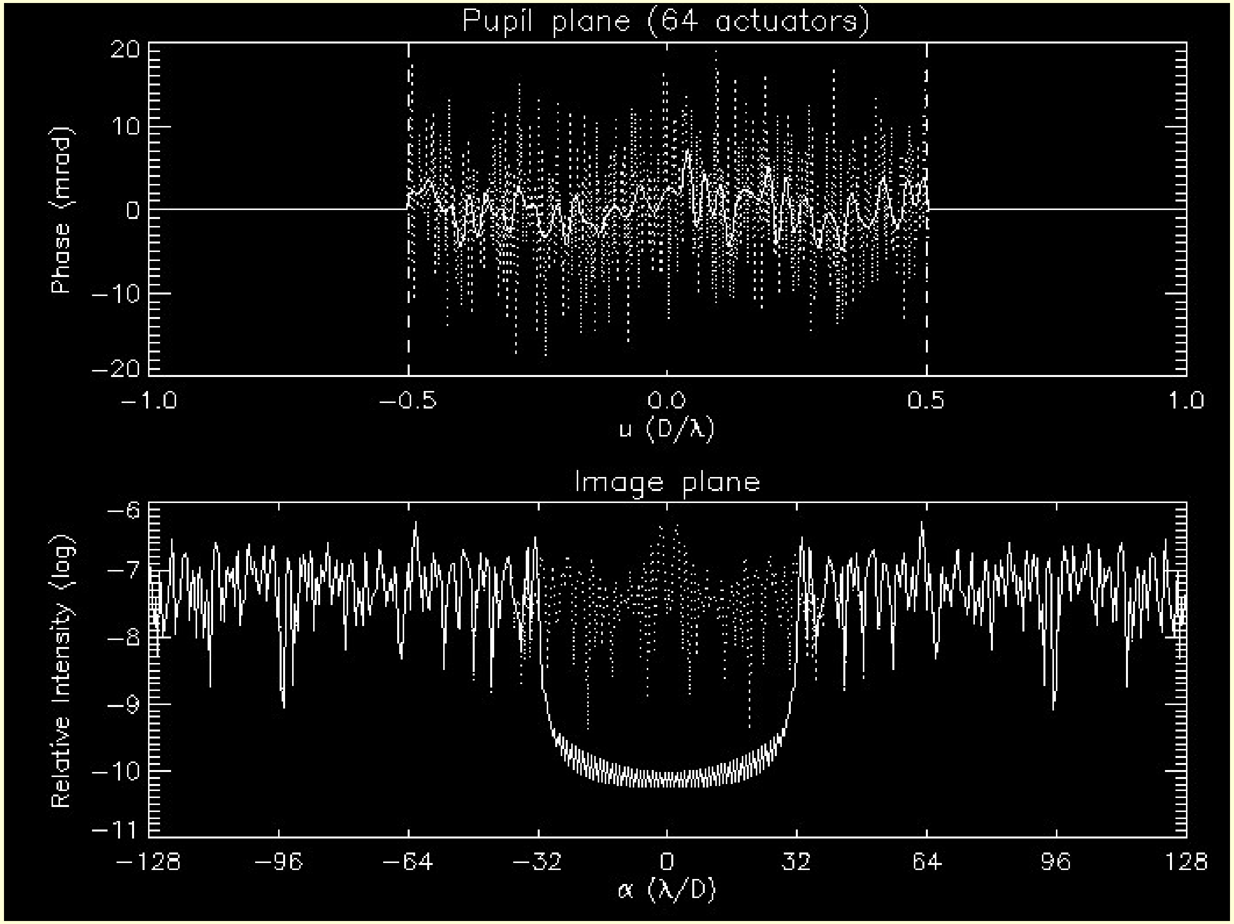
Fourier expansion: $$a_{kl} = \frac{2d^2}{\lambda^2}\iint_H -\frac{\hat{P} * \hat{\varphi}(\alpha,\beta)}{\hat{f}(\alpha,\beta)}\, e^{i\frac{2\pi d}{\lambda}(k\alpha+l\beta)}\, d\alpha\, d\beta$$

Fast algorithm thanks to FFTs

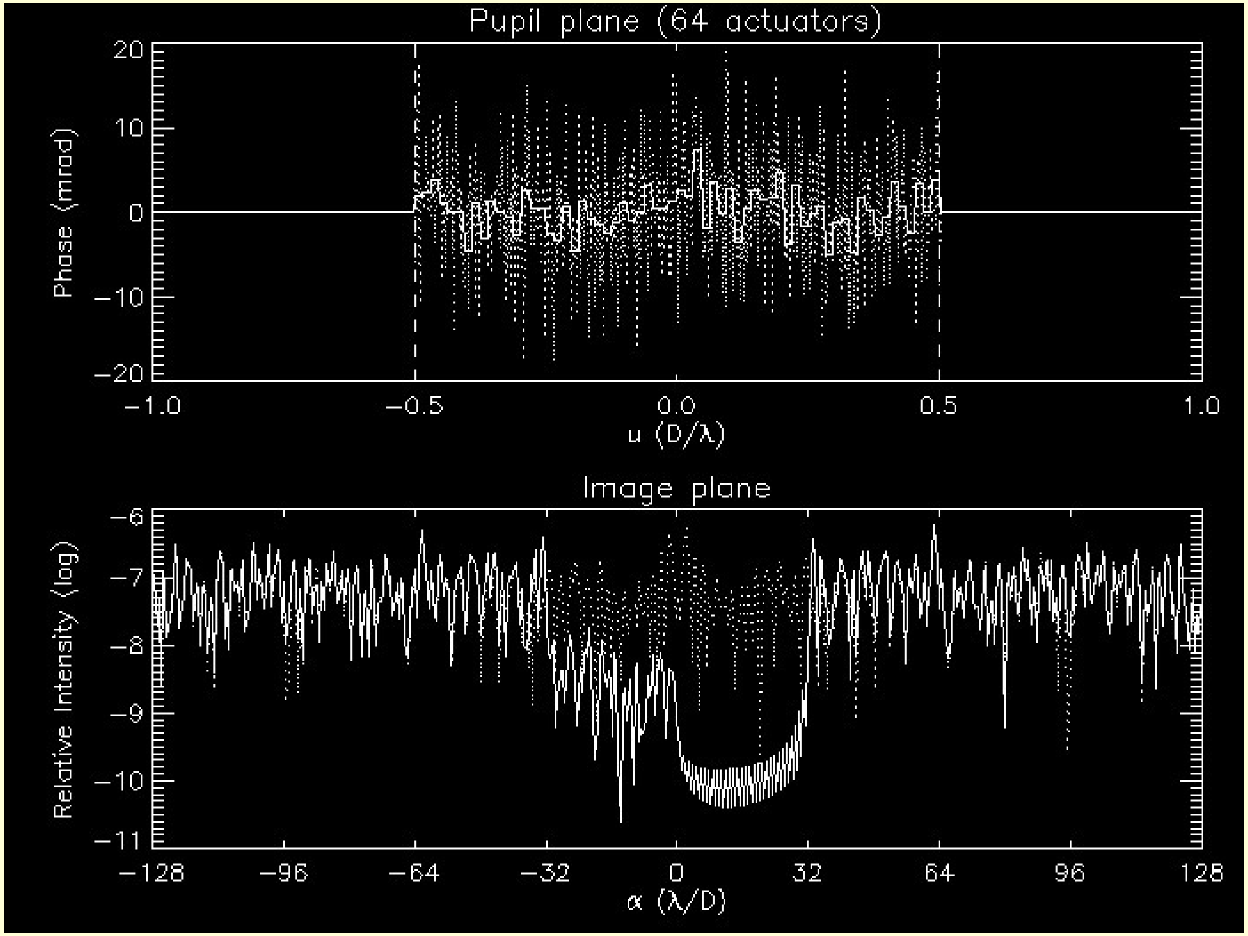
Measurement simulation



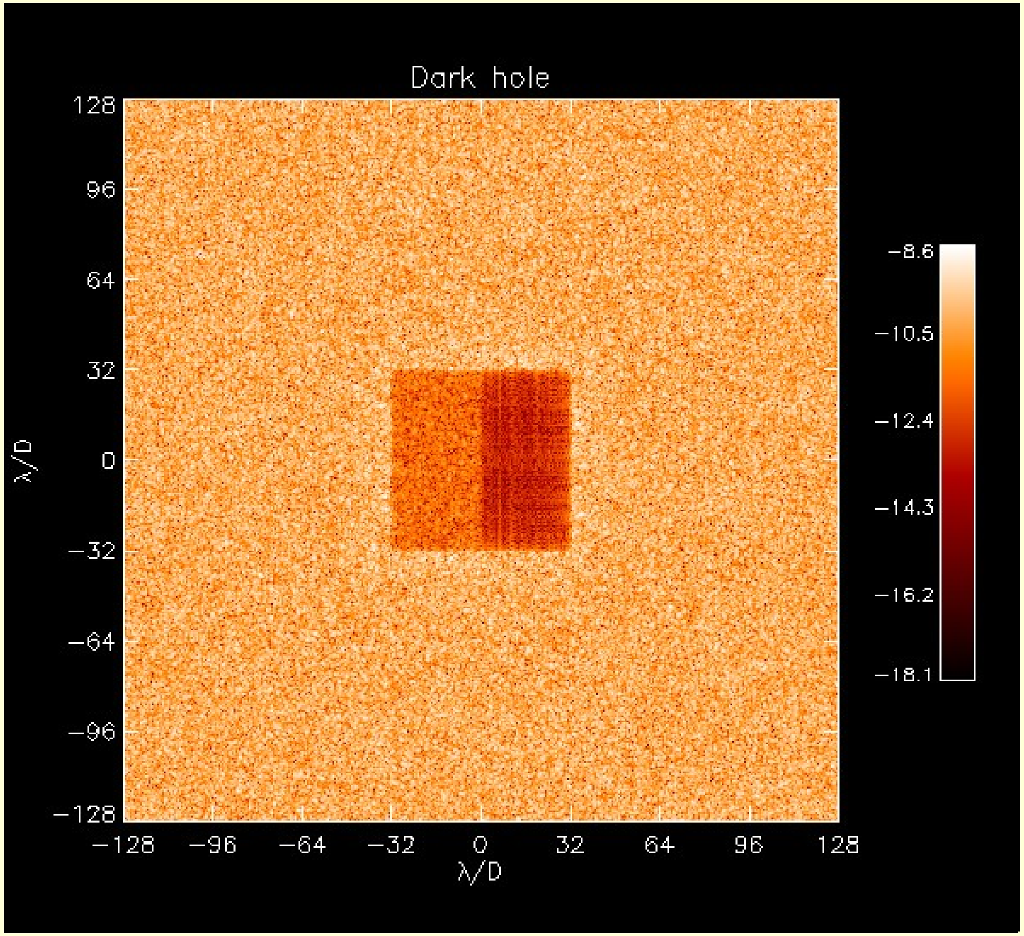
Field nulling simulation



Amplitude aberrations



Field nulling simulation (2D)



Energy minimization

- Minimize speckle energy in the dark hole

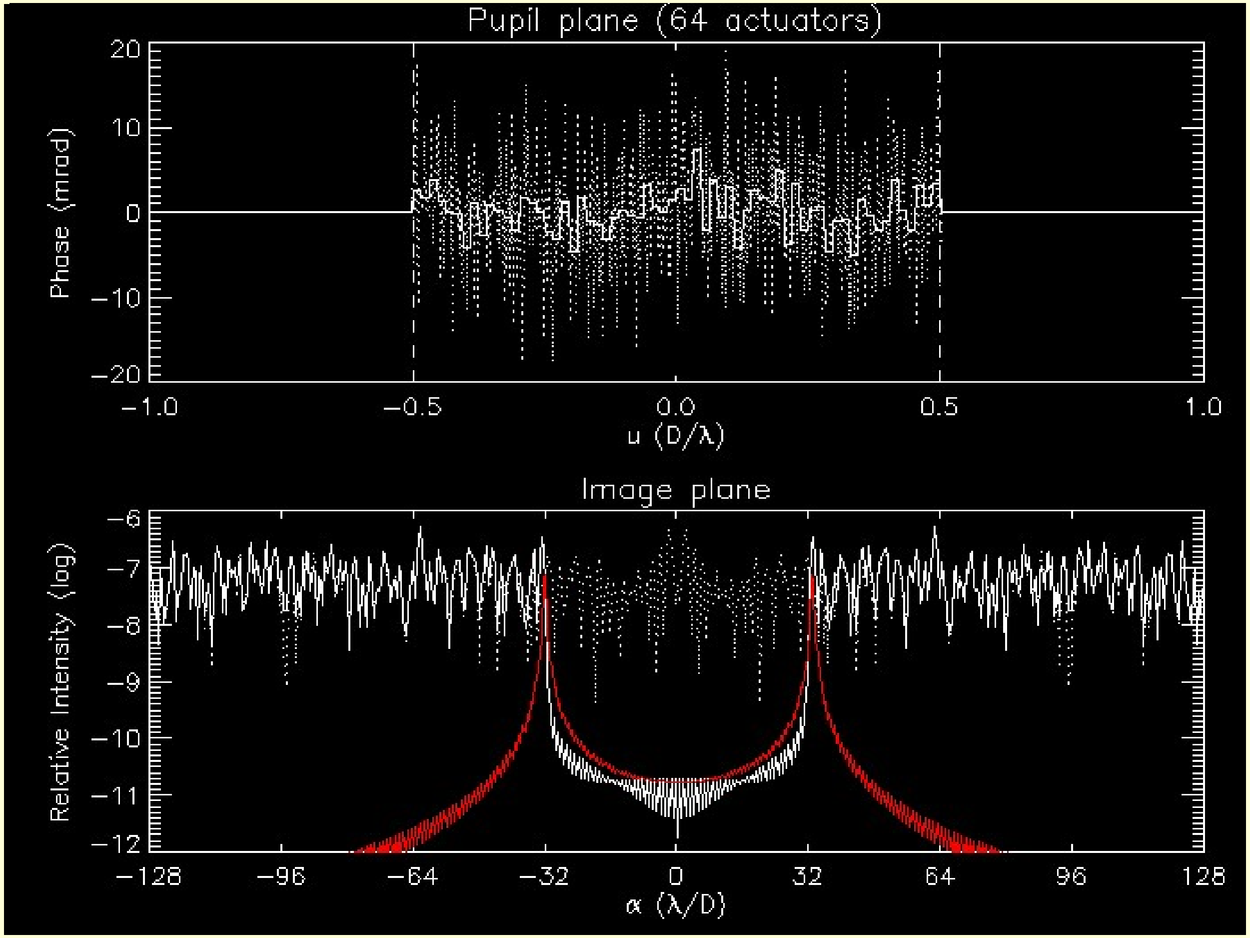
$$\mathcal{E} = \iint_H \left| \hat{P} * \hat{\varphi}(\alpha,\beta) + \hat{\psi}(\alpha,\beta) \right|^2 d\alpha\, d\beta$$

$$\forall (k,l),\ \frac{\partial \mathcal{E}}{\partial a_{kl}} = 0 \quad \Leftrightarrow \quad \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} a_{nm} \iint_H \hat{f}_{nm}\, \hat{f}_{kl}^{*} = -\mathrm{Re}\left(\iint_H \hat{P} * \hat{\varphi}\ \hat{f}_{kl}^{*} \right)$$

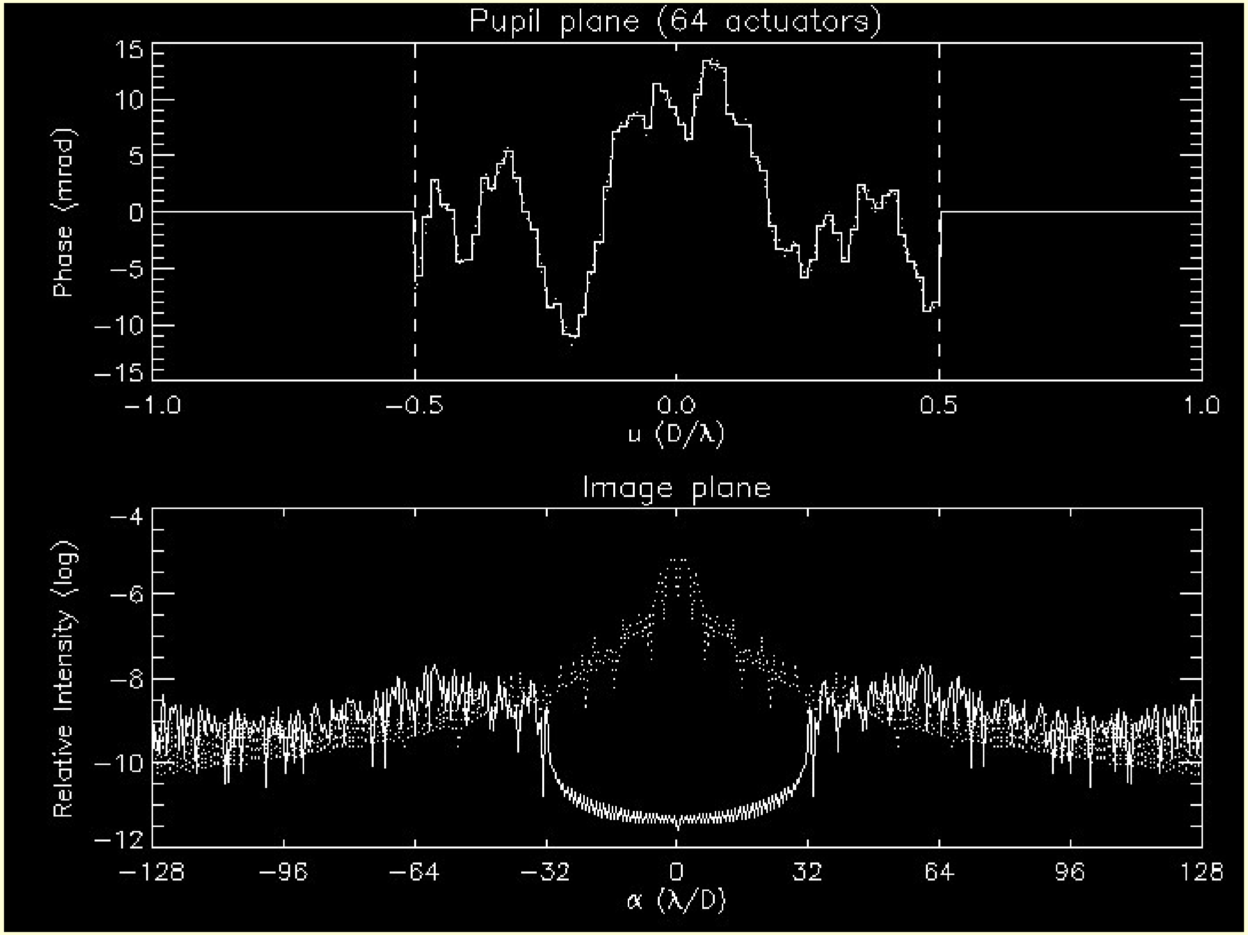
$$FA = \Phi \quad \Leftrightarrow \quad A = F^{-1}\Phi$$

If $\quad f_{kl}(u,v) = g_k(u)\, g_l(v) \quad$ then $\quad GAG = \Phi \Leftrightarrow A = G^{-1}\Phi G^{-1}$

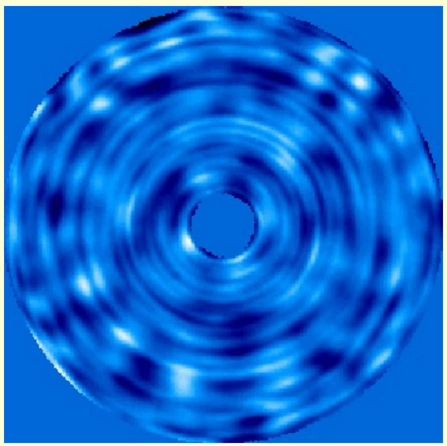
Energy minimization simulation



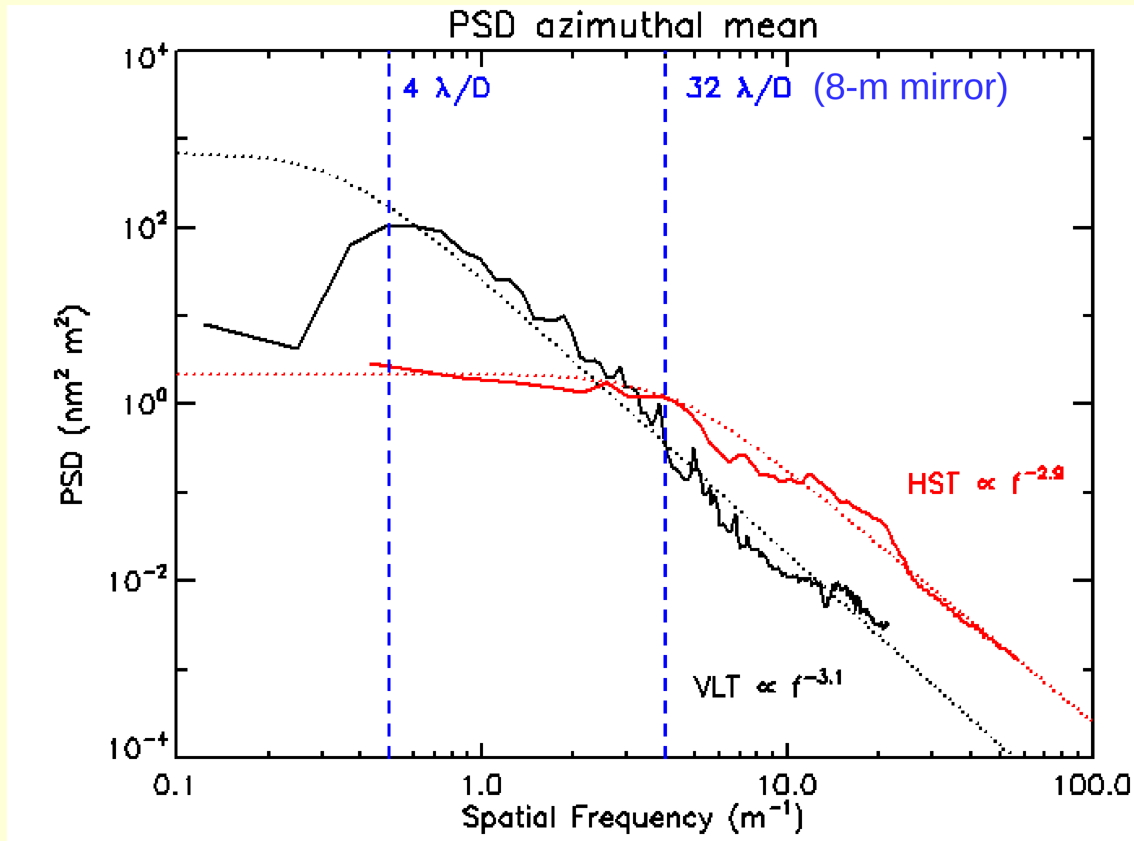
Colored speckle noise (1/f^3)



8-m mirror surface errors



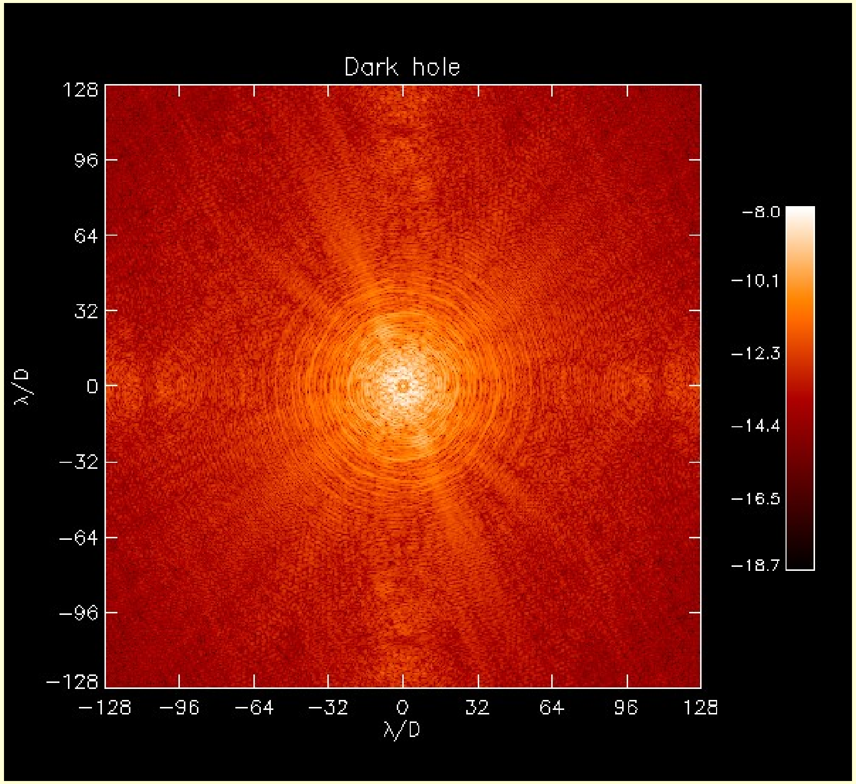
8.2-m VLT primary
(active mode)
43 nm rms



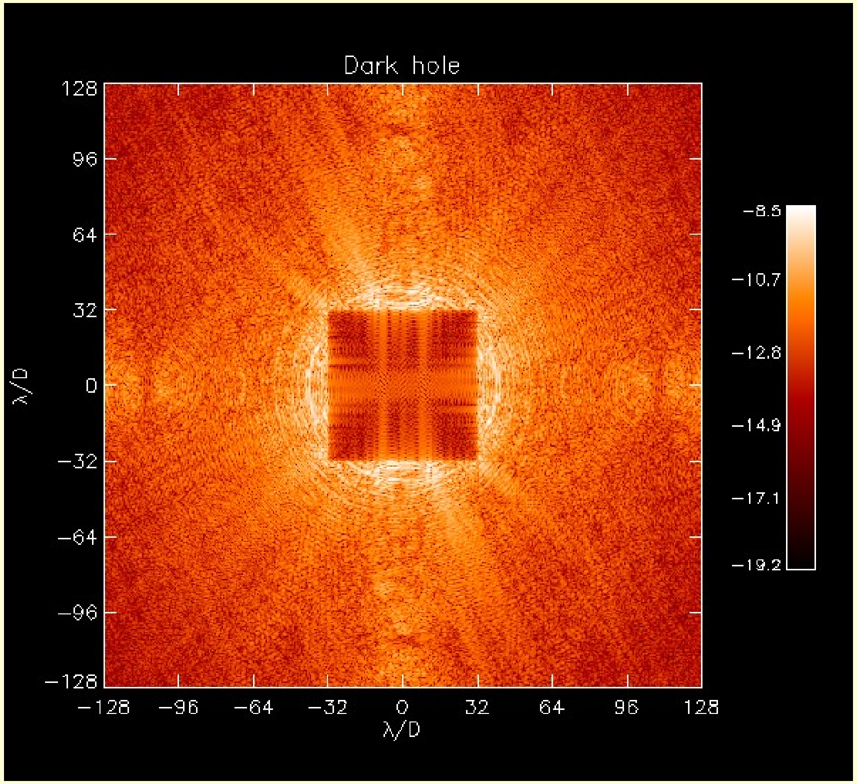
Simulation parameters

- VLT 8-m primary mirror phase map scaled to $\lambda/1000$ rms phase errors
- 64×64-actuator deformable mirror
- Actual HCIT influence functions
- 2 detector pixels per λ/D
- No photon noise, no read-out noise

Simulation results #1

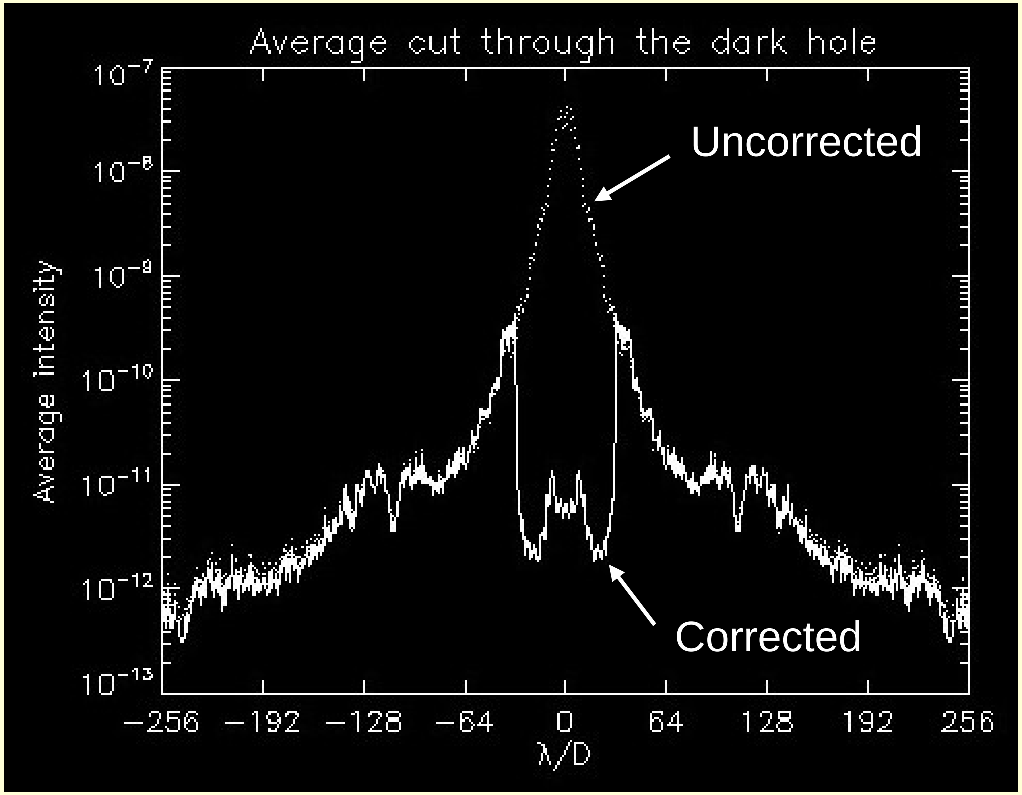


Uncorrected coronagraphic image



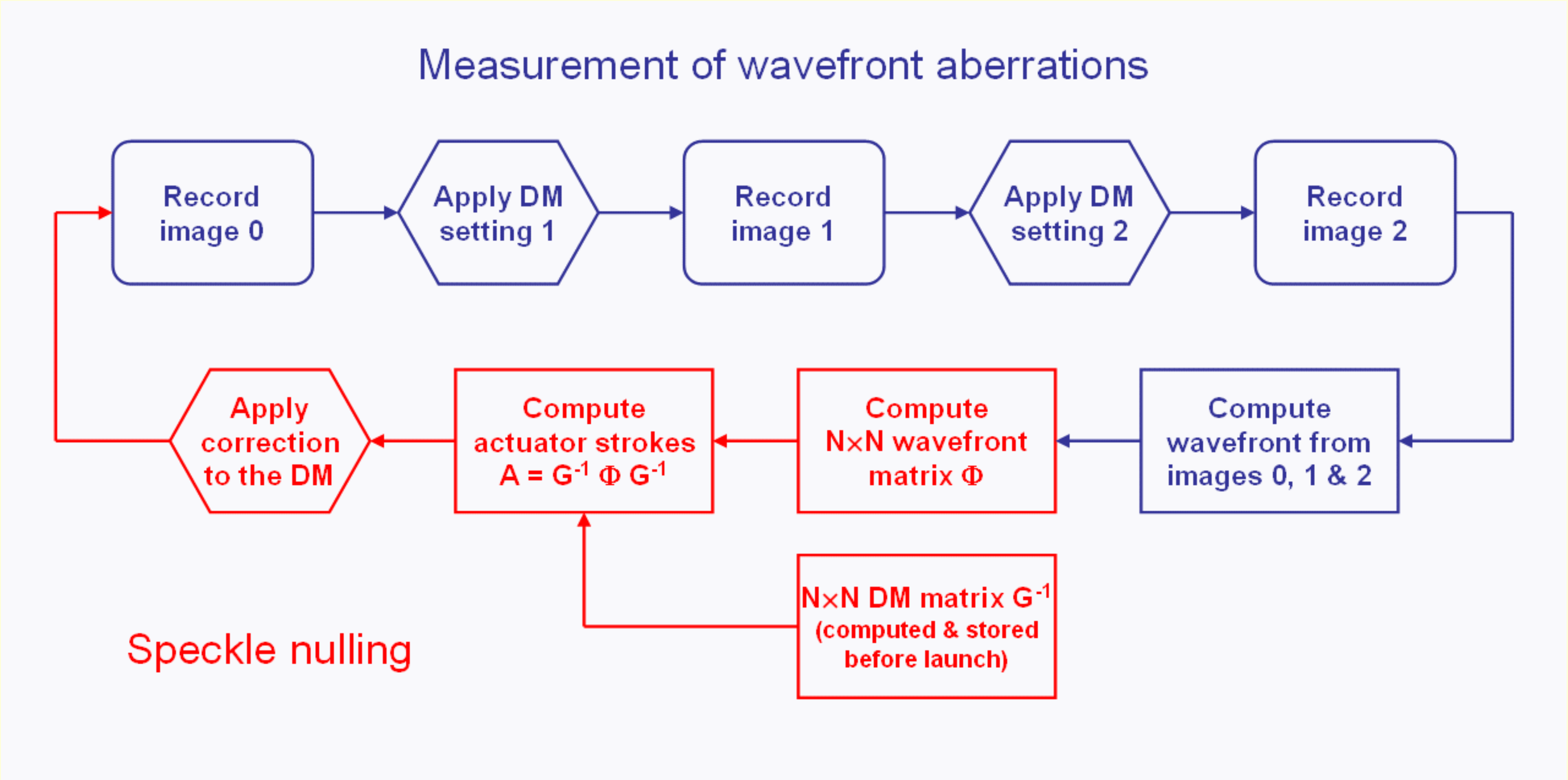
Corrected coronagraphic image

Simulation results #2



Mean dark hole is 6×10^{-12}

Summary



Measurement of wavefront aberrations
Record image 0
Apply DM setting 1
Record image 1
Apply DM setting 2
Record image 2
Compute wavefront from images 0, 1 & 2
Compute N×N wavefront matrix Φ
Compute actuator strokes A = G-1 Φ G-1
Apply correction to the DM
N×N DM matrix G-1 (computed & stored before launch)
Speckle nulling

Conclusion

- Wavefront aberrations (amplitude & phase) measured with the first 3 images, corrected in the 4th image
- Would work with most coronagraphic concepts
- Dark hole depth strongly depends on mirror PSD and nb of actuators
- Algorithms will soon be tested on HCIT
- Bordé & Traub, to appear in ApJ (February 2006)