Wavefront control for high-contrast imaging

Lisa A. Poyneer

In the Spirit of Bernard Lyot: The direct detection of planets and circumstellar disks in the 21st century.

Berkeley, CA, June 6, 2007

UCRL-PRES-231448

Gemini Planet Imager

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We need wavefront control

- Coronagraph can reduce diffracted star light
- Wavefront control can reduce light scattered by wavefront phase and amplitude errors

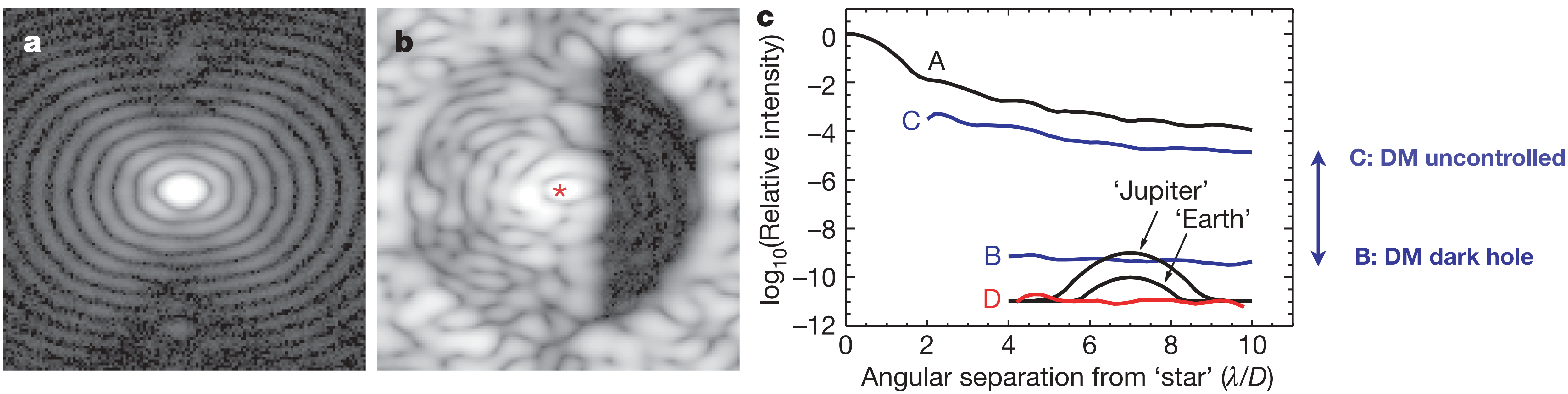
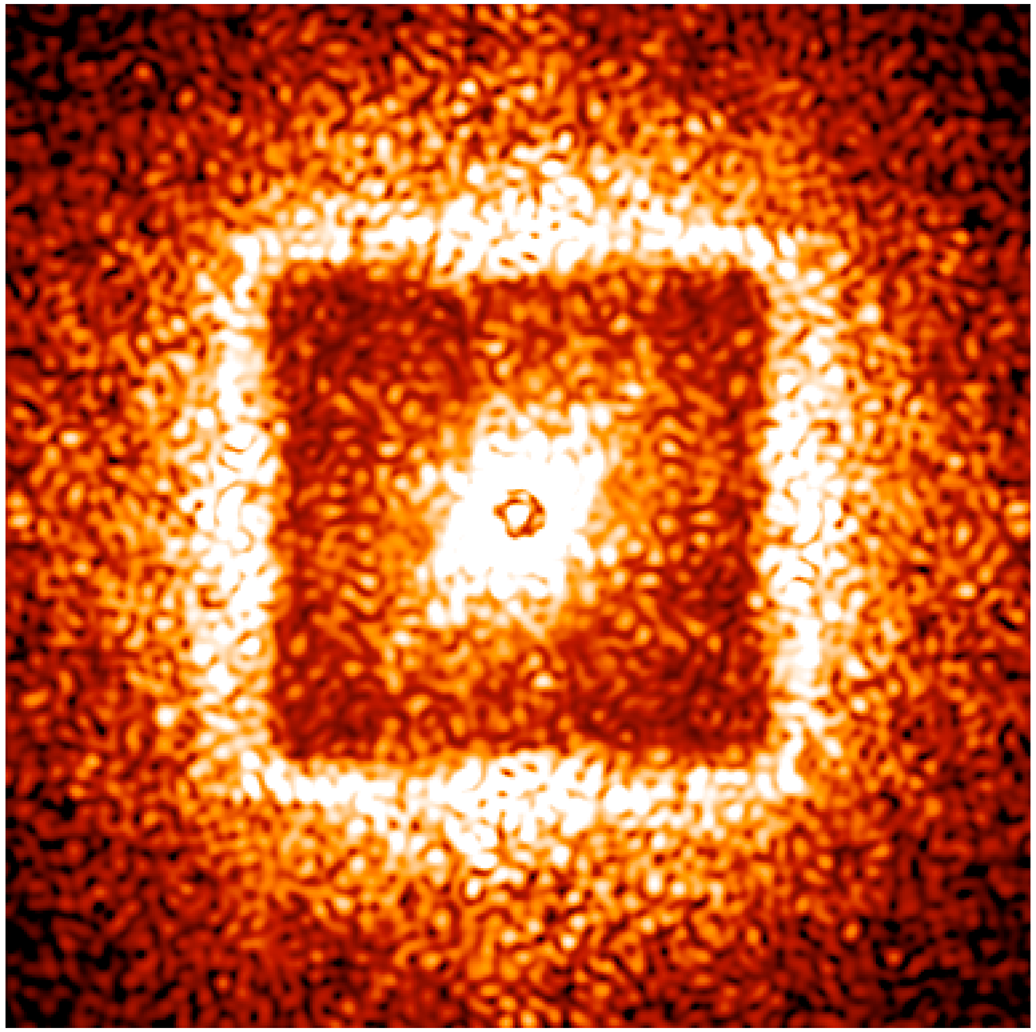


Figure taken from J. T. Trauger and W. A. Traub, "A laboratory demonstration of the capability to image an earth-like extrasolar planet," *Nature* **446**, 771–773 (2007).

Two aspects to PSF after wavefront control

- The level of scattered light must be low
- The variance of the scattered light must be low

GPI with H-band APLC, 14.5 cm r_0, I=6



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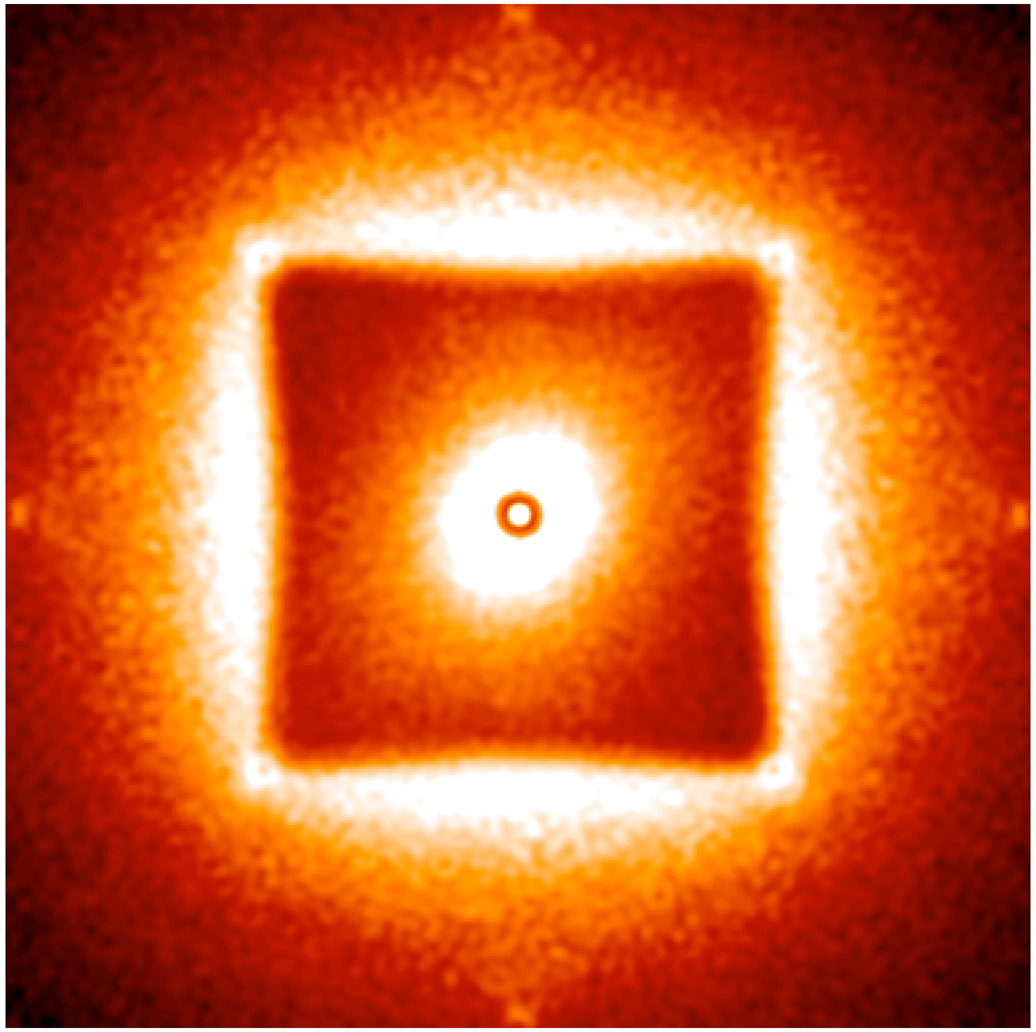

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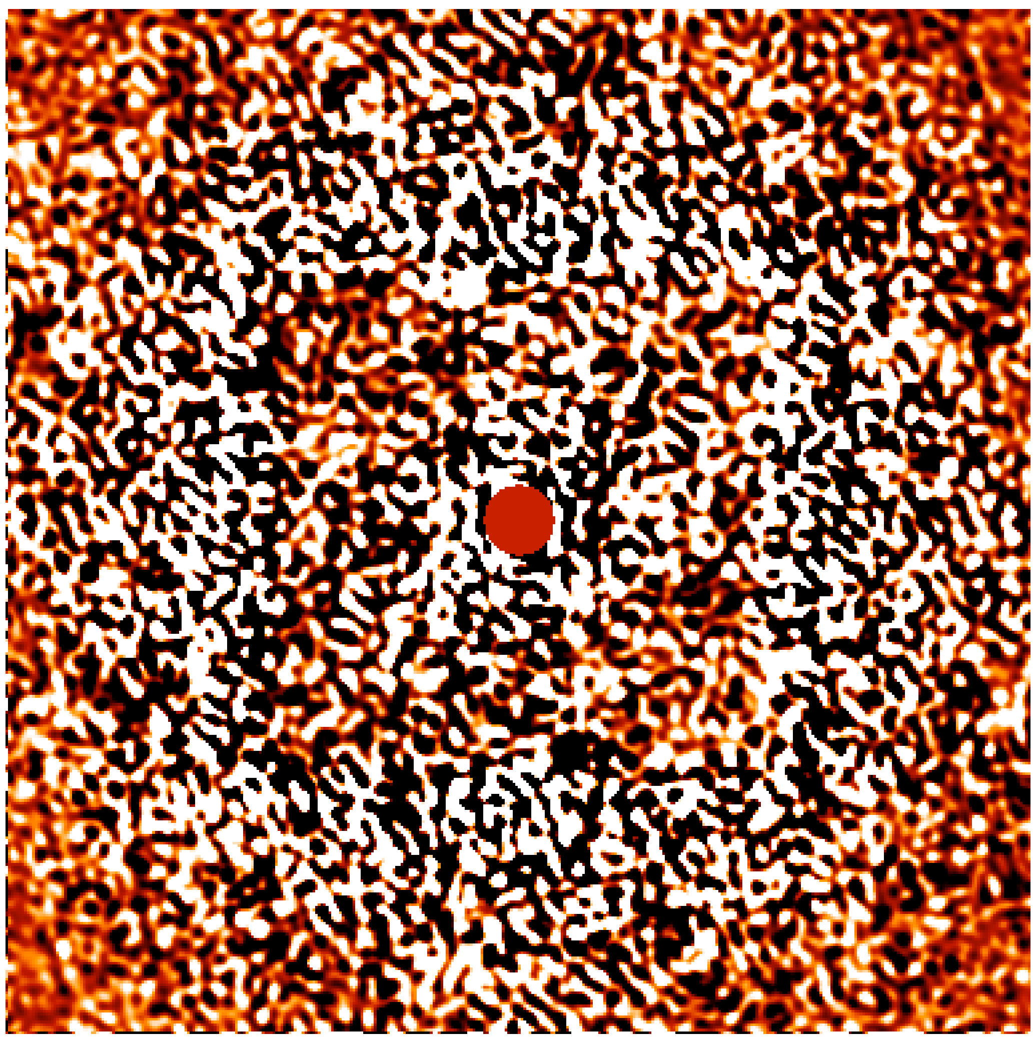

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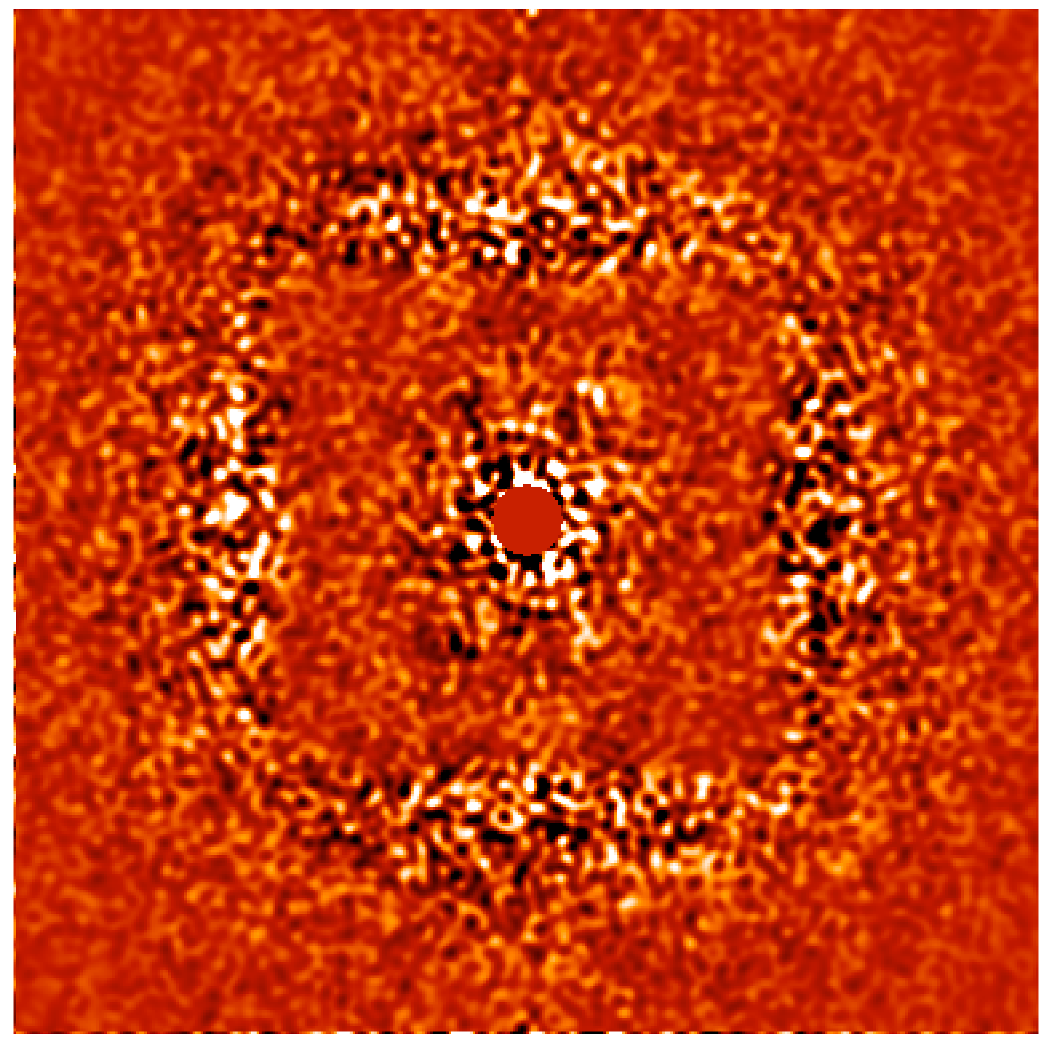

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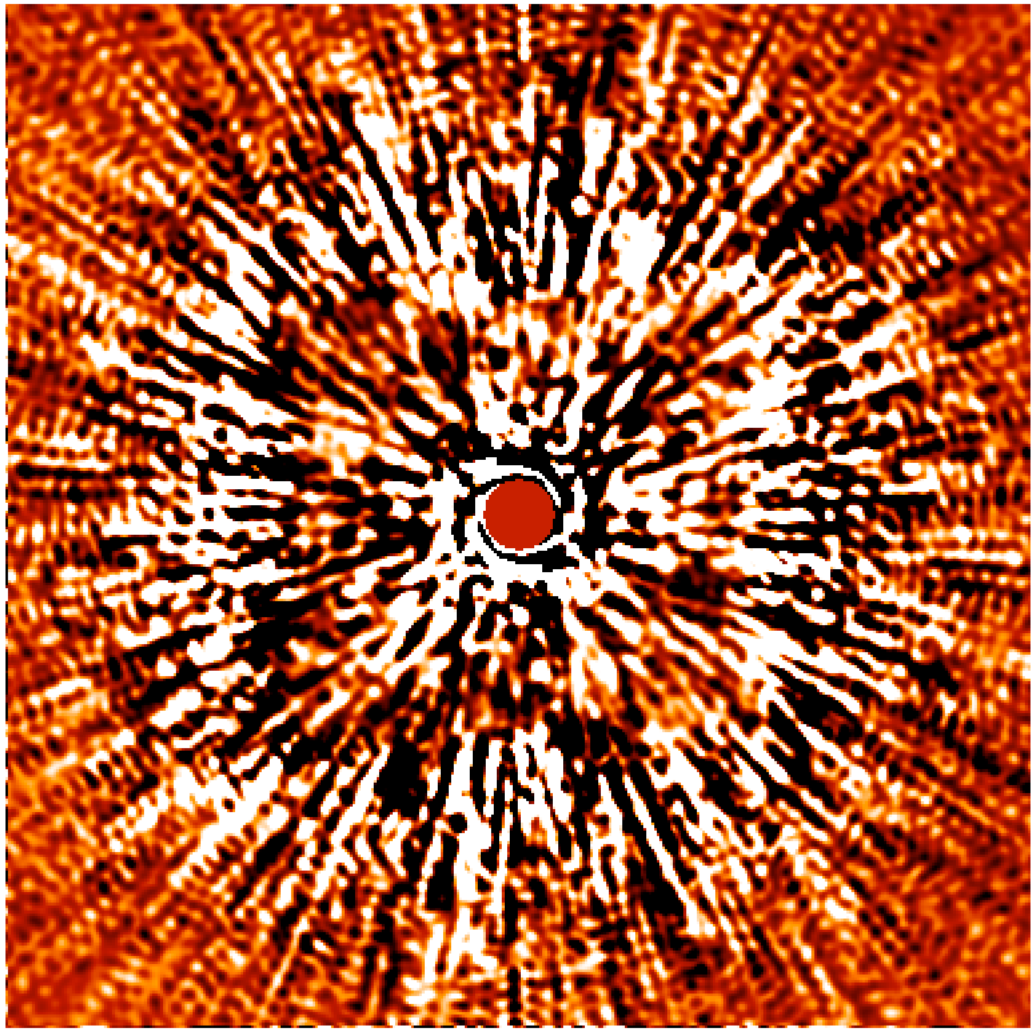

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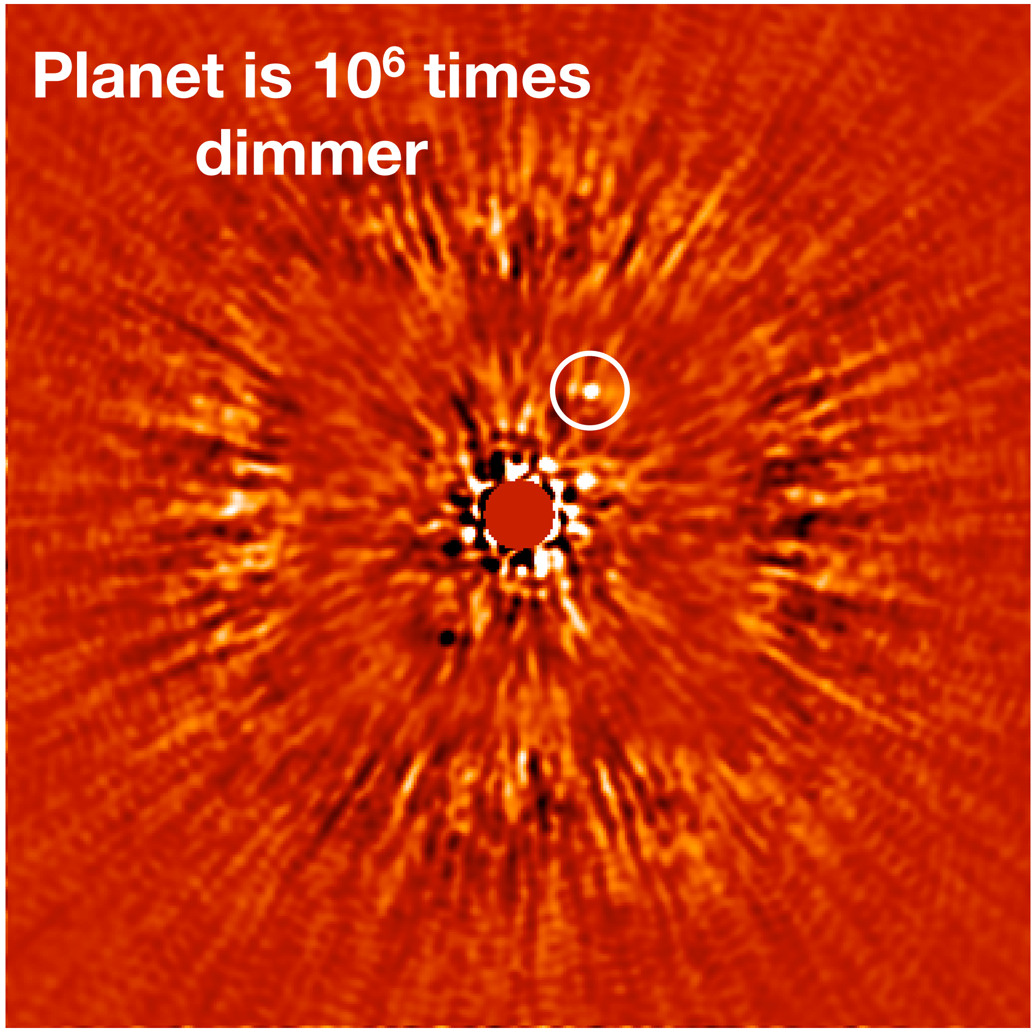

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PSF expansion allows analysis of structure

- Express amplitude and phase with Taylor expansion*

$$a \exp(j\phi) = a\left(1 + j\phi - \frac{\phi^2}{2} + \cdots\right)$$

- Image plane field is convolutions of Fourier transforms

$$A + jA * \Phi - \frac{1}{2}A * \Phi * \Phi + \cdots$$

- Image plane intensity has several important terms
  - Diffraction pattern: $|A|^2$
  - Pinned speckles: $-2\mathrm{Im}\{A^*(A * \Phi)\}$ $-\mathrm{Re}\{A^*(A * \Phi * \Phi)\}$
  - Power Spectrum (PSD): $|A * \Phi|^2$
  - Folding term: $\frac{1}{4}|A * \Phi * \Phi|^2$

*see Sivaramakrishnan *et al* (ApJ 2002) and Perrin *et al* (ApJ 2003)

Power spectral approach for random errors

- Evaluate PSD term of PSF expansion
- This tells us the expected halo intensity in an infinitely long exposure
- Several treatments exist, including Ellerbroek; Guyon; Jolissaint *et al*

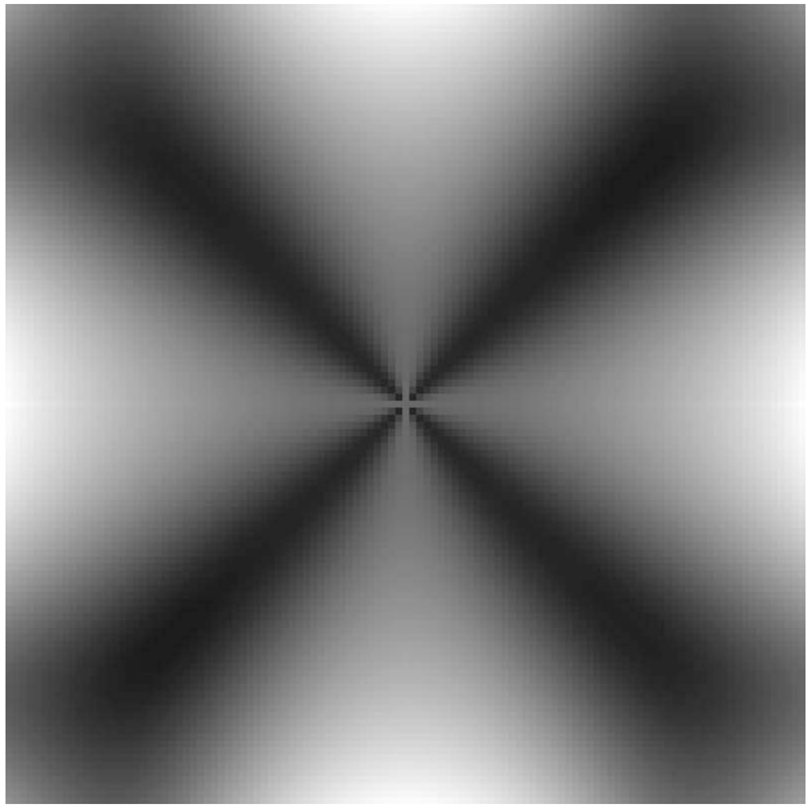
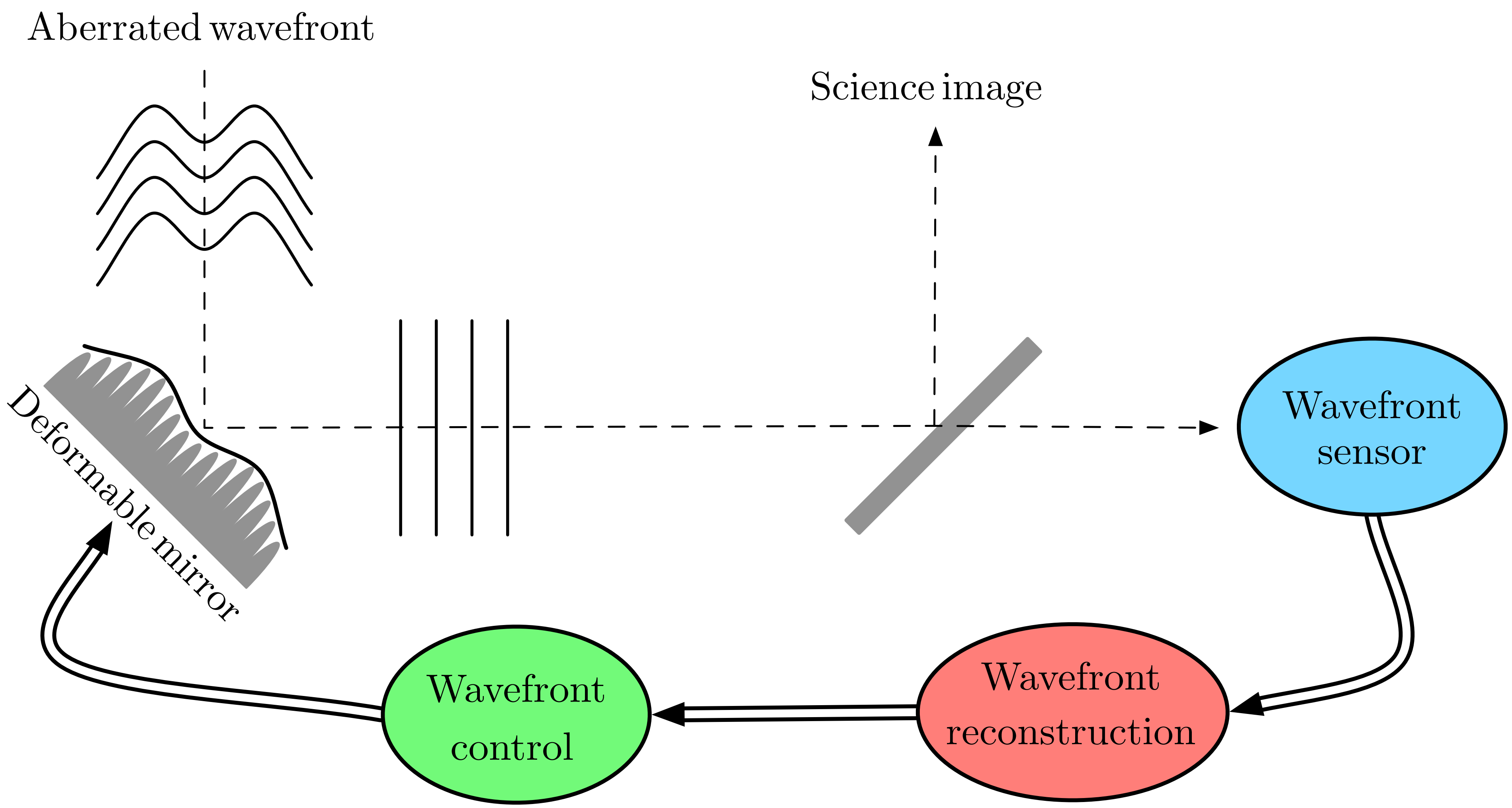


Fig. 2. Aliasing power spectrum (1/8 power-law scaling) within the LF domain; see parameters in Table 1.

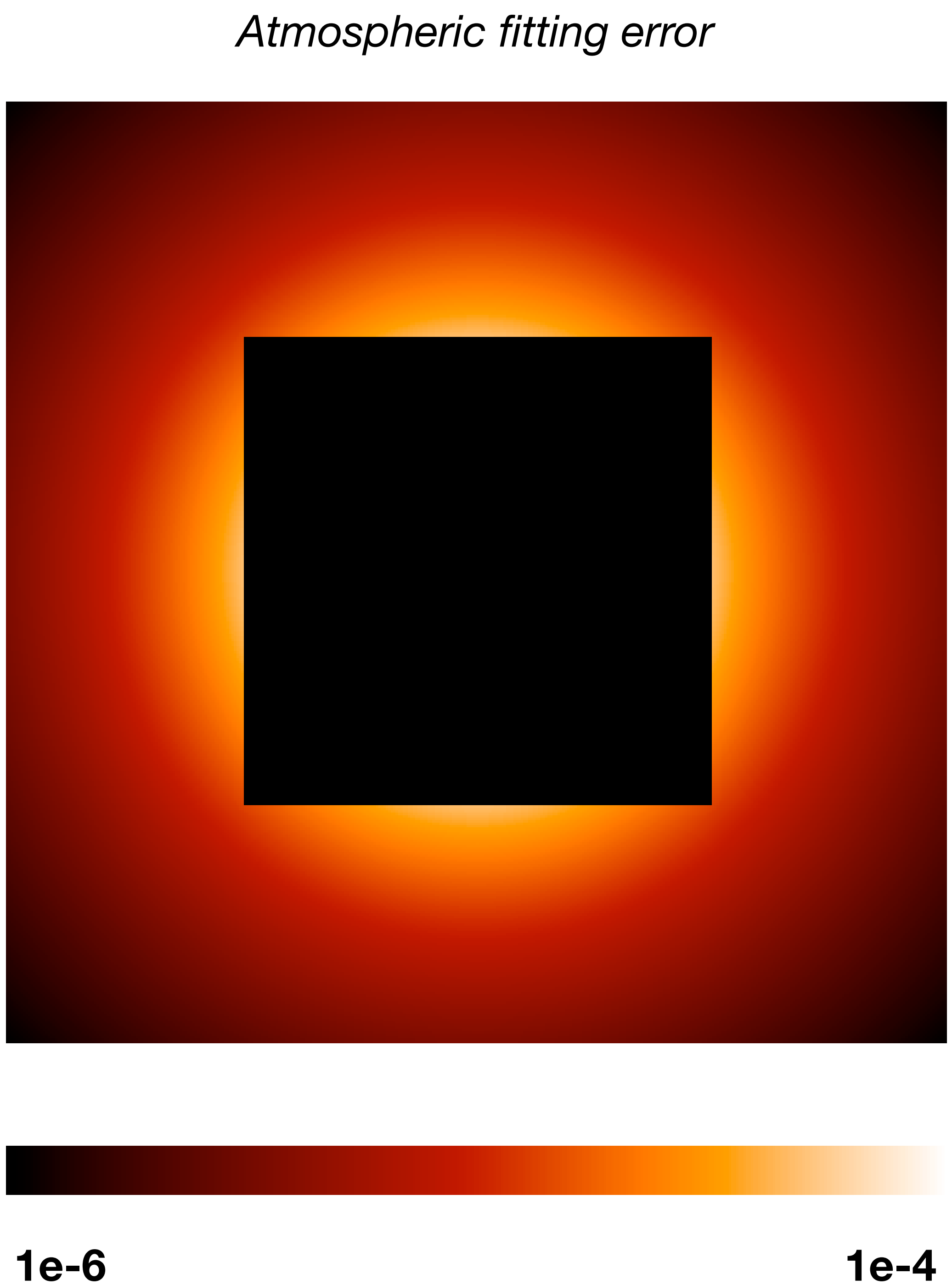
Figure taken from L. Jolissaint, J.-P. Véran, and R. Conan, "Analytical modeling of adaptive optics: foundations of the phase spatial power spectrum approach," J. Opt. Soc. Am. A **23**, 382–394 (2006).

Phase control with conjugation on DM surface

- Measure and compensate the phase



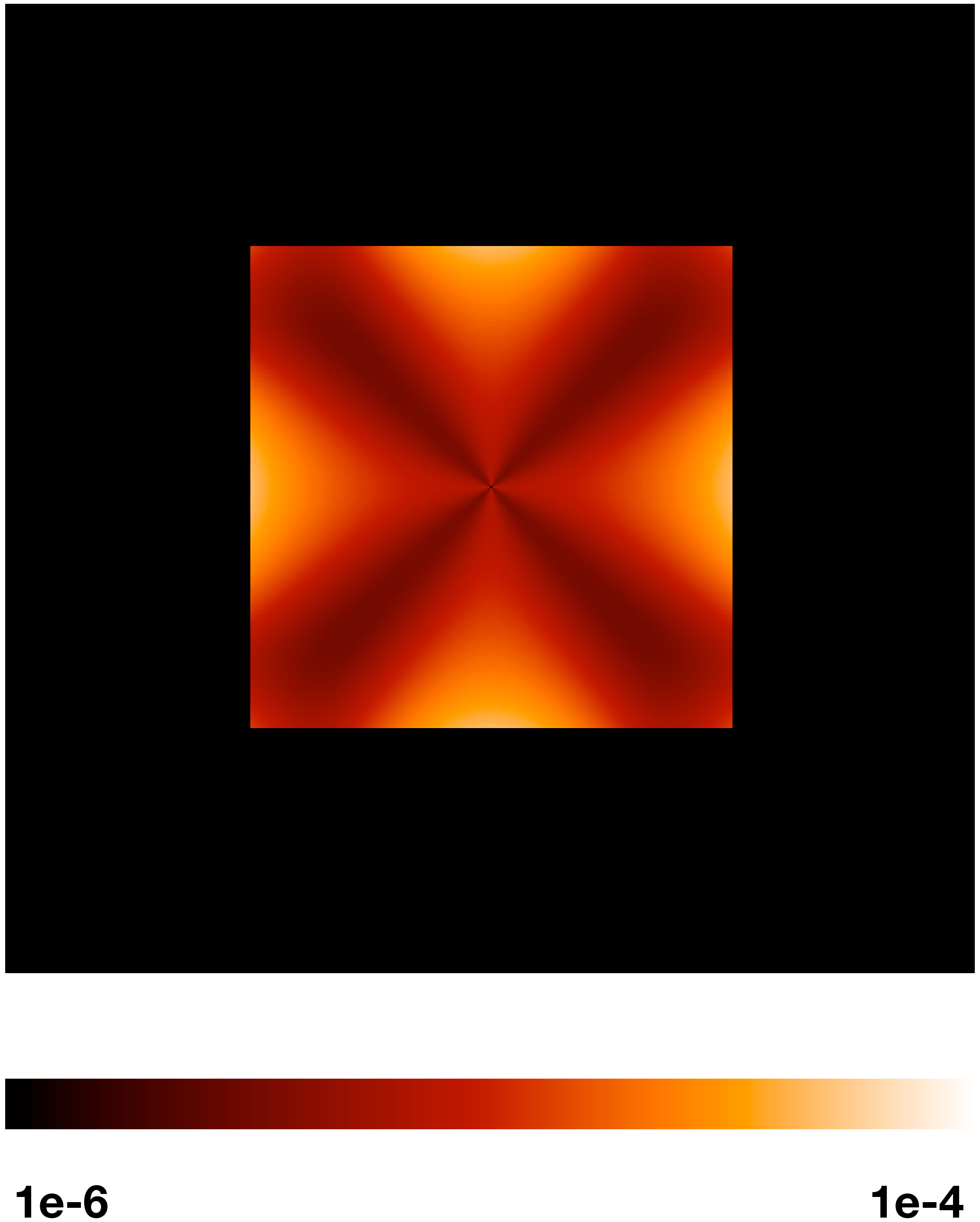
Fitting error due to uncorrected HSF phase



- Uncorrectable errors beyond spatial freq. range of DM
  - **Atmosphere**
  - **Optics**
- HSF limits contrast outside dark hole
- HSF phase may limit contrast inside dark hole due to folding term
- Ways to improve:
  - **smaller inter-actuator spacing**
  - **better site (higher r0)**
  - **better optics**

HSF phase also can cause aliasing

Atmospheric aliasing for Shack-Hartmann



- Sampling the phase produces aliasing when HSF content exists
- These incorrect measurements lead to significant error
- Ways to improve:
  - **Spatially Filtered wavefront sensor (700-900 nm shown)**
  - **Focal-plane wavefront sensor**

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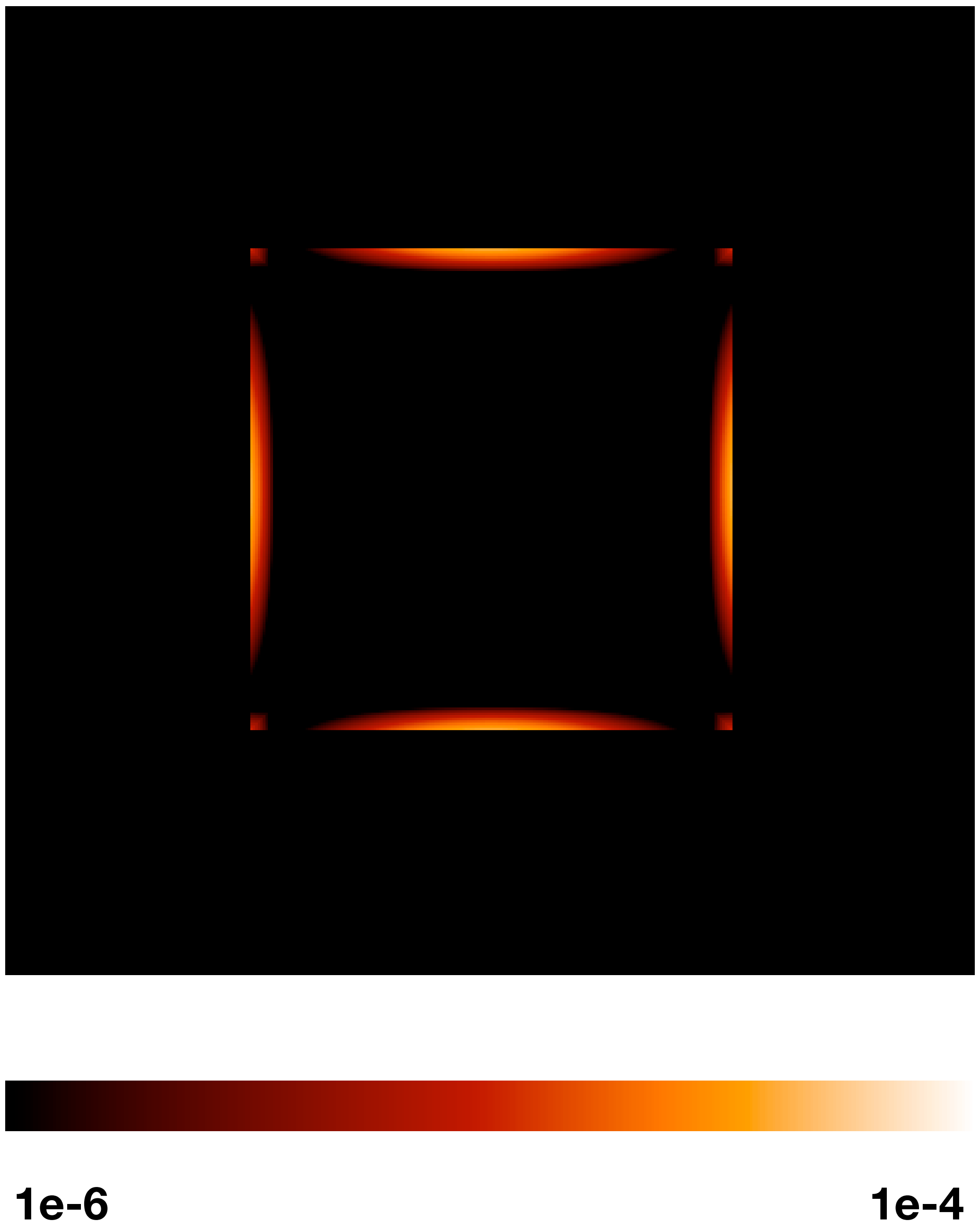
Atmospheric aliasing for Shack-Hartmann



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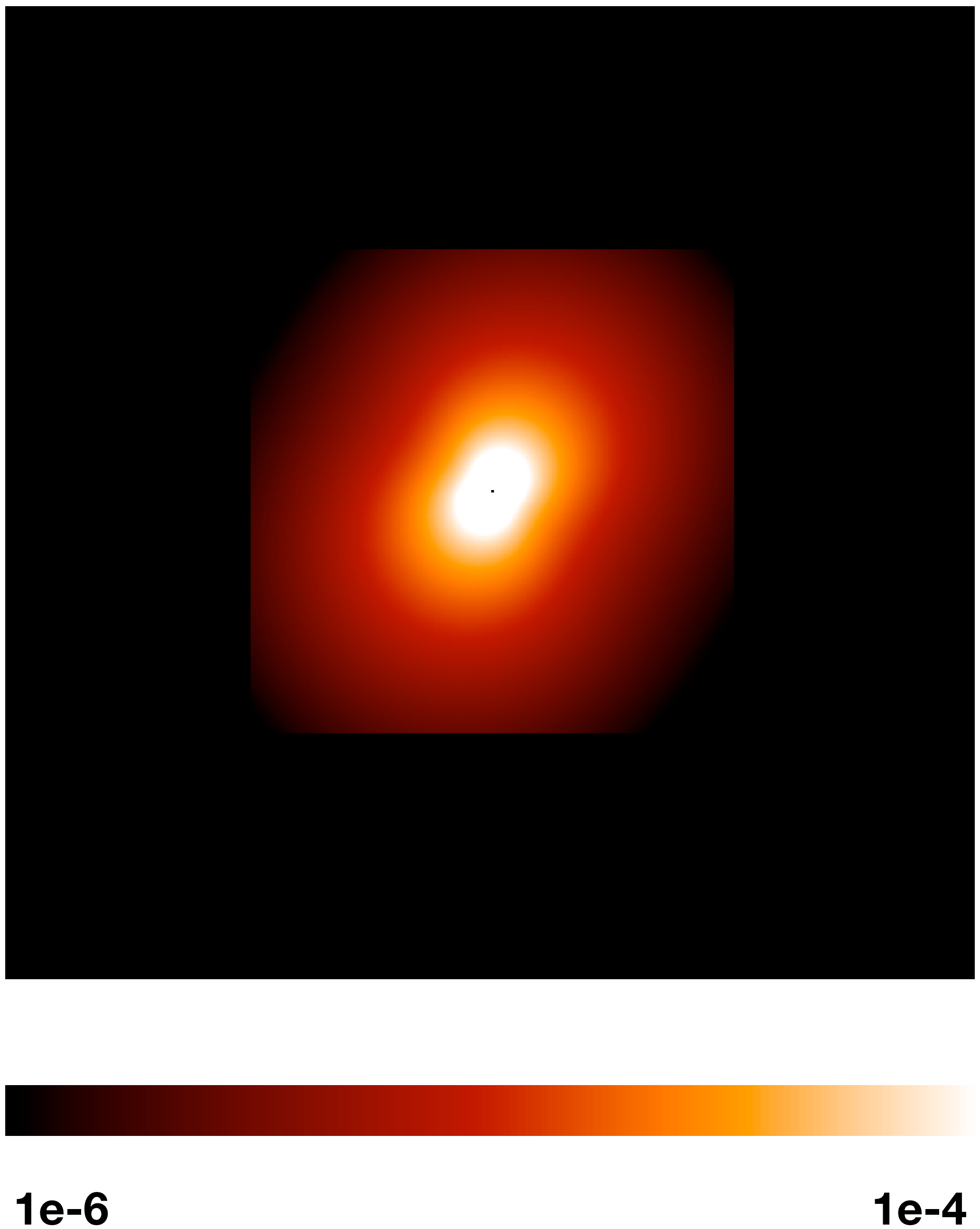
Control system delays cause temporal error

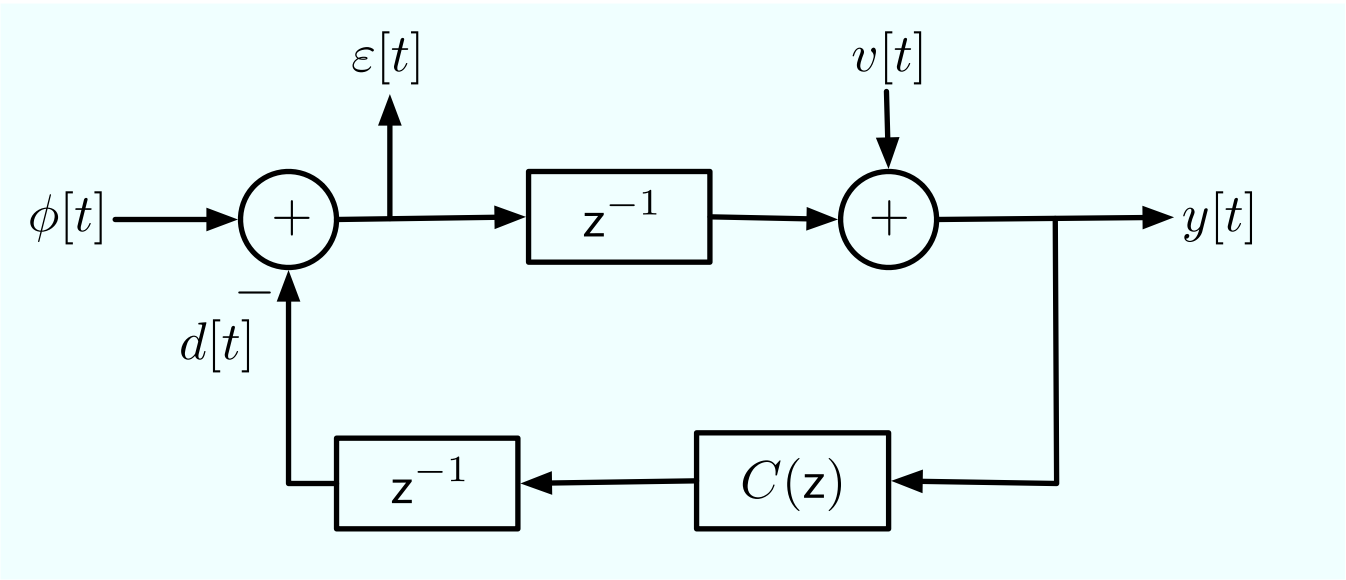
AO on five-layer frozen flow atmosphere

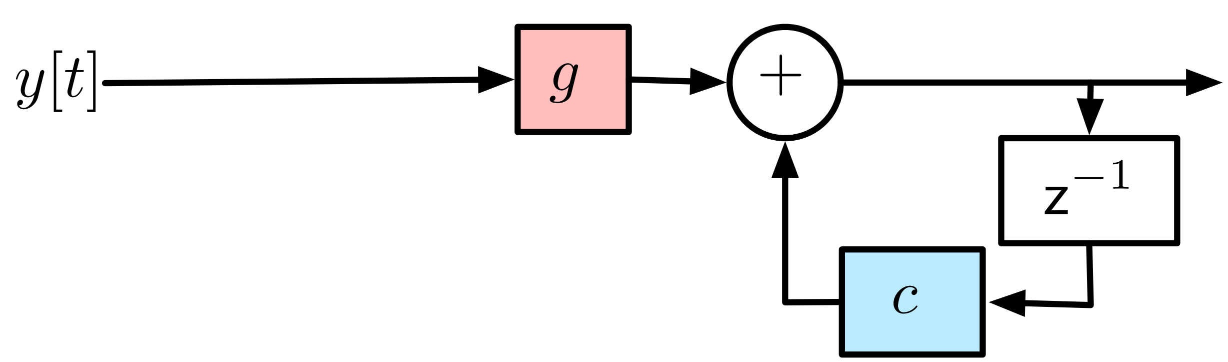


- Controller has delays which lead to error when correcting a dynamic aberration
- PSD level depends on total power and temporal characteristics of aberration
- Ways to improve:
  - **Reduce delay from measurement to application of correction**
  - **Better control algorithms**

Modal control with gain optimization

- Use closed-loop telemetry to optimize performance based on atmospheric characteristics and SNR
  - **Used currently in NAOS, Altair, and Keck AO Tip/tilt**
  - **SPHERE will use modal gain optimization**
  - **GPI will use modal gain optimization of the Fourier modes (spat. freqs)**

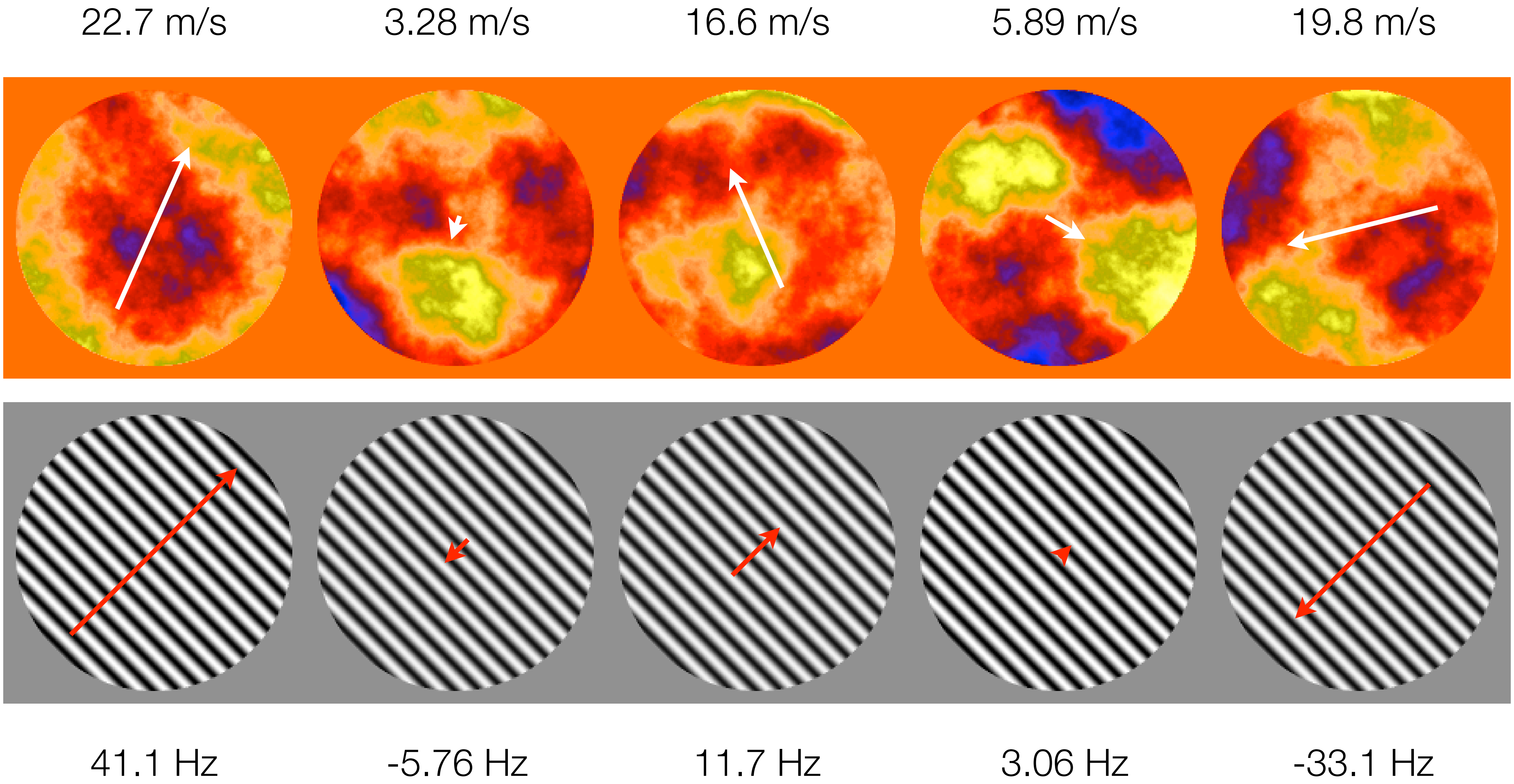




Predictive control based on Kalman filtering

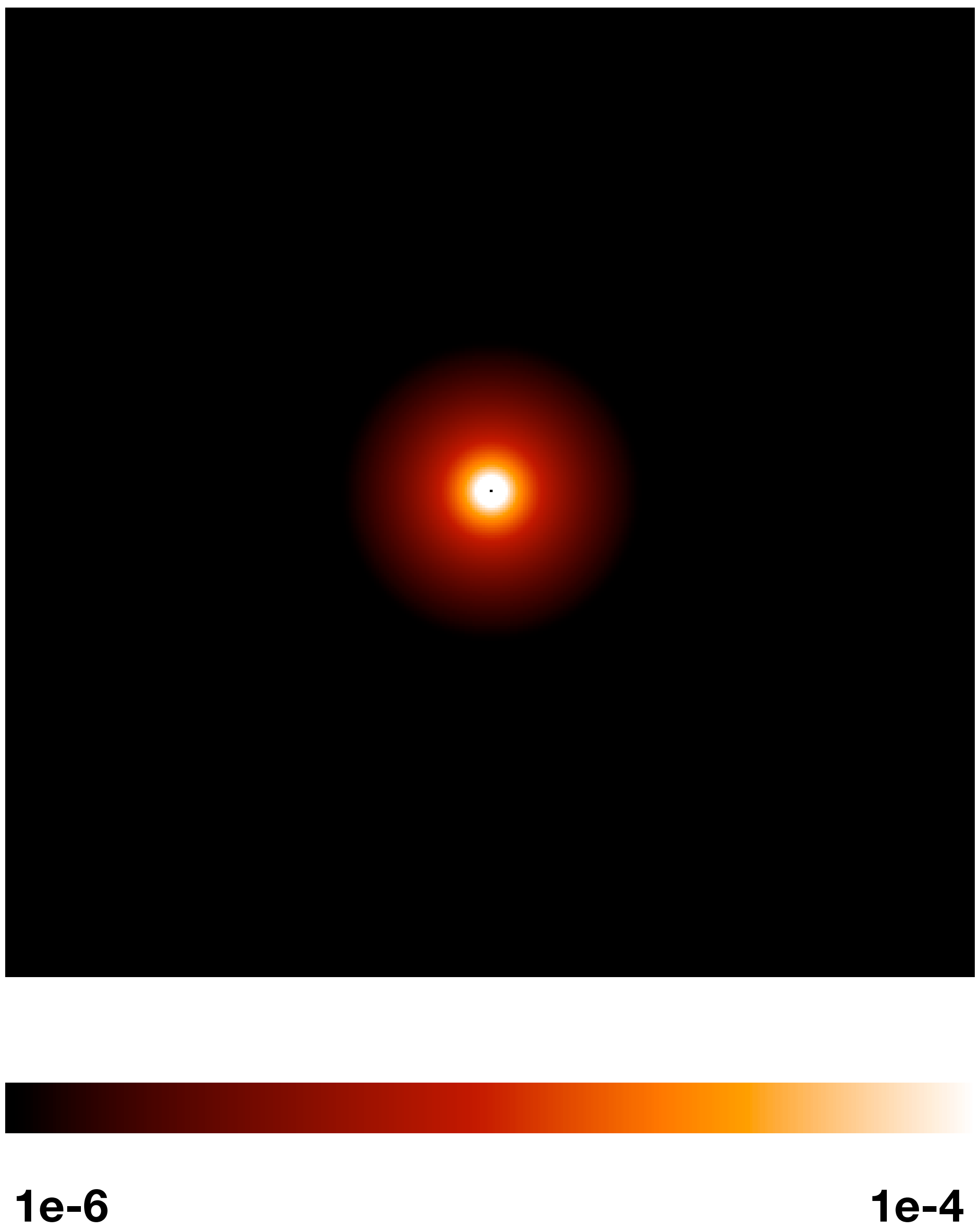
- Given a model and a framework (e.g. Kalman filtering), determine predictive control law to compensate for system lags and phase dynamics
- Vibration control for SPHERE experimentally demonstrated
- Developed for GPI: Kalman filtering for each Fourier mode, based on frozen flow assumption. Adaptive layer detection and predictive filter determination in closed-loop. Performance improvement depends on true atmospheric behavior, which is being actively researched.

Fourier mode behavior under translation



Measurement noise propagates

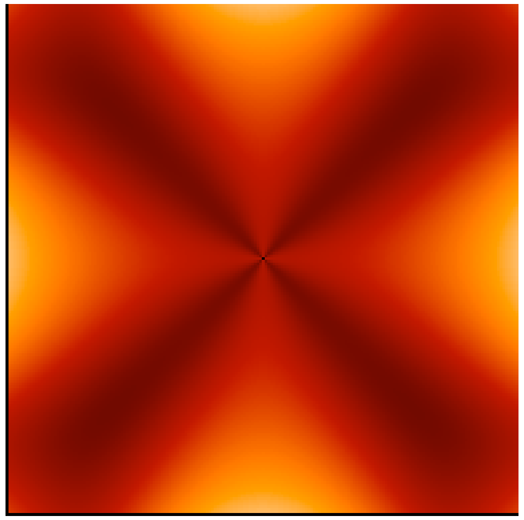
Shack-Hartmann WFS noise propagation



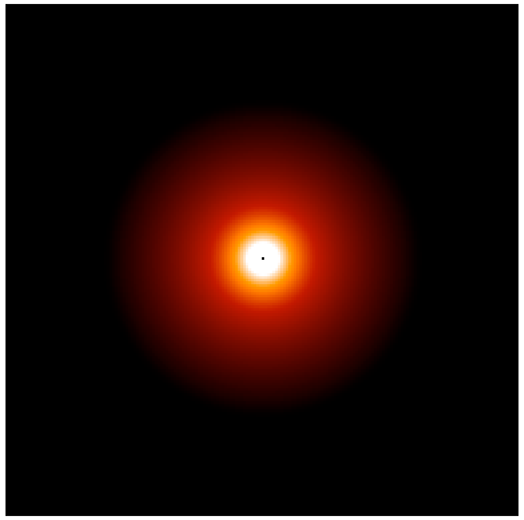
- Noise of phase/slope measurements, due to photons and detector noise
- Ways to improve:
  - **Better detectors (higher efficiency, lower read noise)**
  - **Better WFS slope estimation algorithms**
  - **Better AO control algorithms**
  - **Different wavefront sensor**

Pupil-plane slope sensor

- Implementation options:
  - **Shack-Hartmann: inexpensive, widely used (both GPI and SPHERE)**
  - **Pyramid slope sensor: starting to be implemented, requires modulation**
- Significant aliasing error, but can be fixed with Spatial Filter
- Noise propagation is non-white: f^{-2}



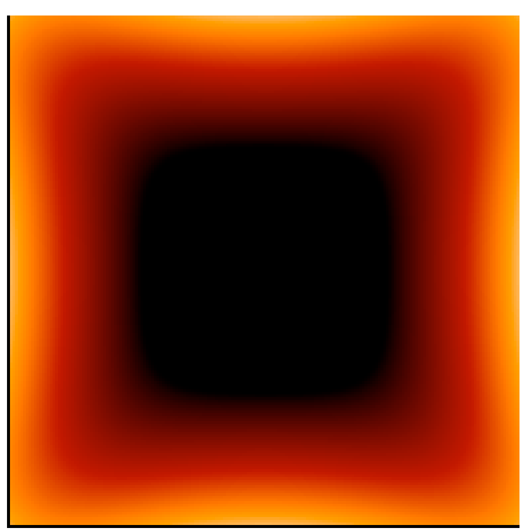
Aliasing (atmos.)



Noise halo

Pupil-plane direct phase sensor

- Multiple options (see Guyon's paper for many)
  - **Interferometer**
  - **Zernike phase contrast**
  - **Pyramid in direct phase mode**
- Less aliasing error
- White propagation: f^0



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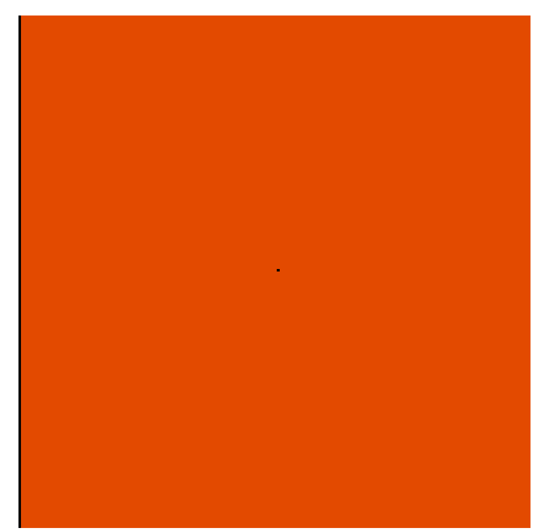

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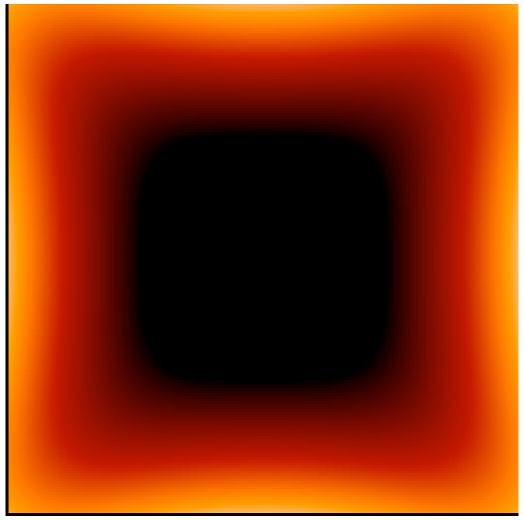
Two advantages over slope sensing:
1) less total noise as system size increases
2) flat noise profile, so better detection close in after control optimization



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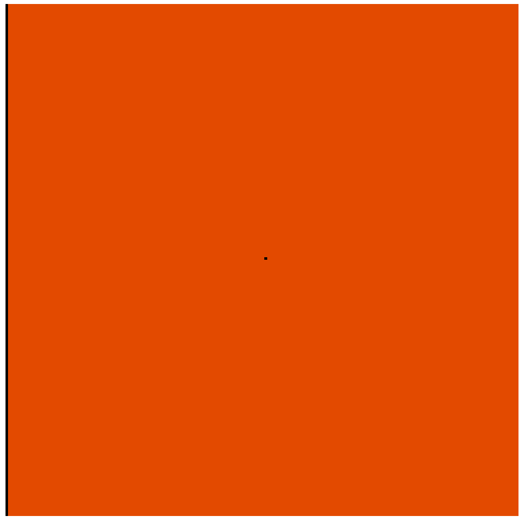
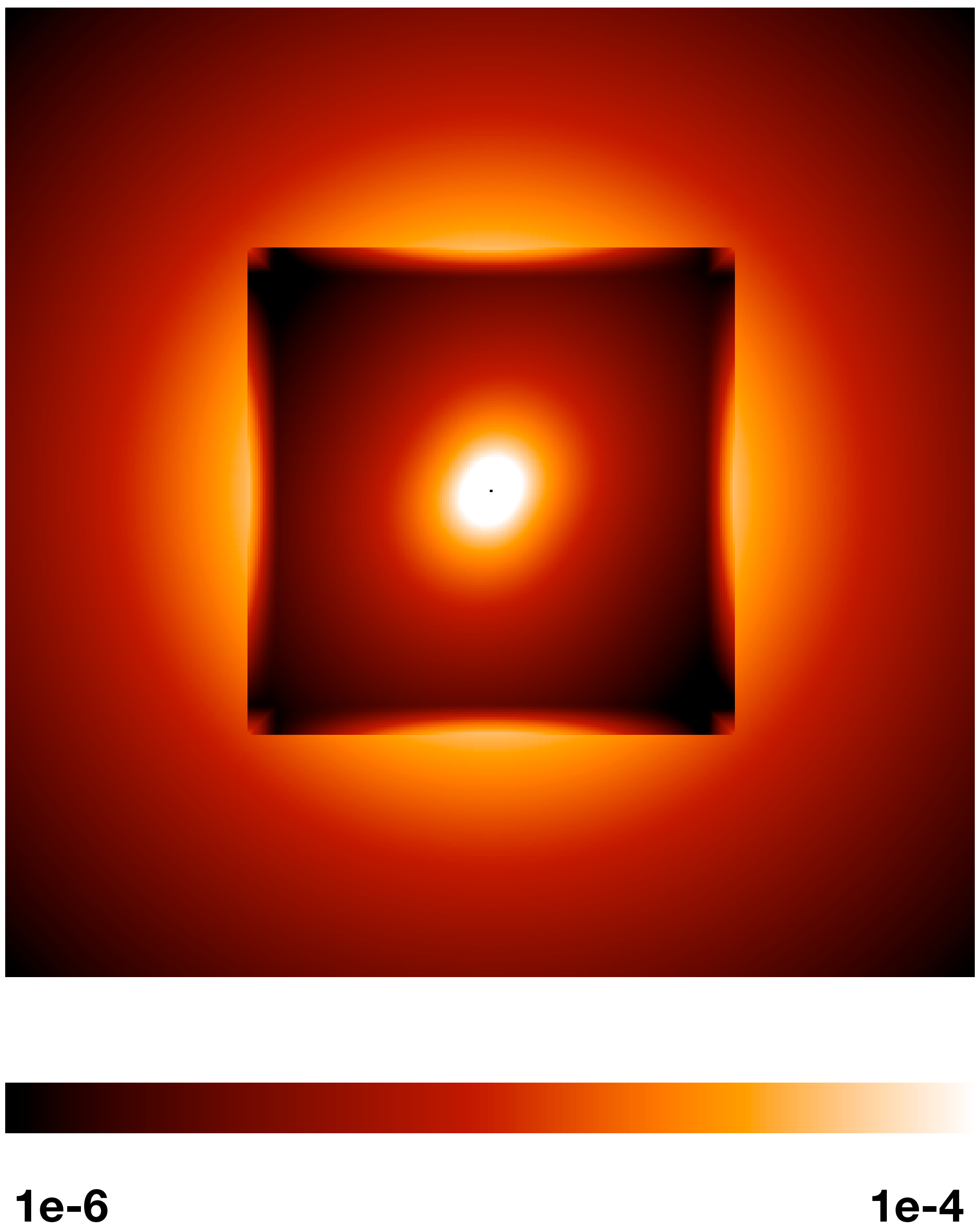


Noise halo

Long-exposure PSF halo prediction for GPI



- GPI has two different AO simulators
  - **analytic PSD code**
  - **end-to-end Fourier Optics monte carlo which simulates entire AO system**
- These two methods are in agreement
- Example shown:
  - **l=6, five-layer 14.5 cm r0 atmosphere, 2 kHz, Optimized-gain controller, 700-900 nm WFS, APLC at 1.625 microns, 5 second exposure**

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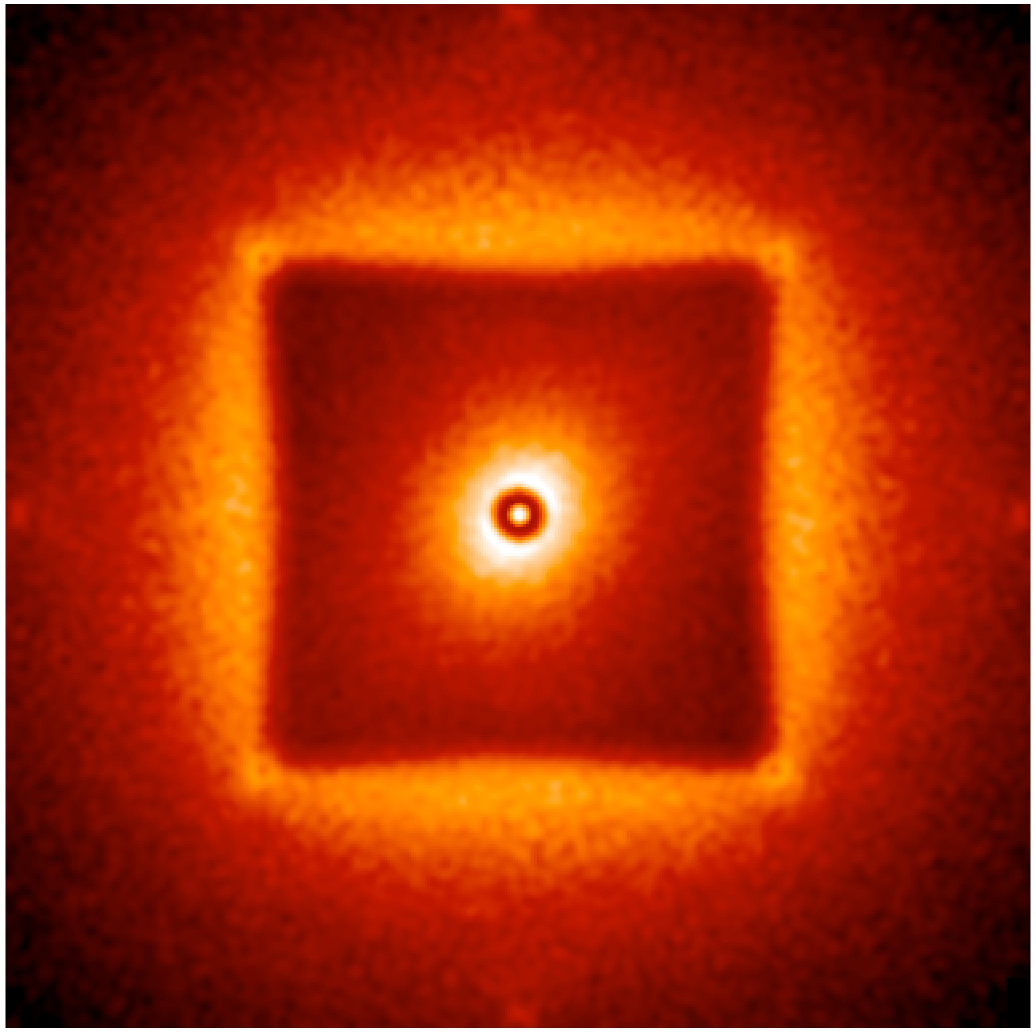

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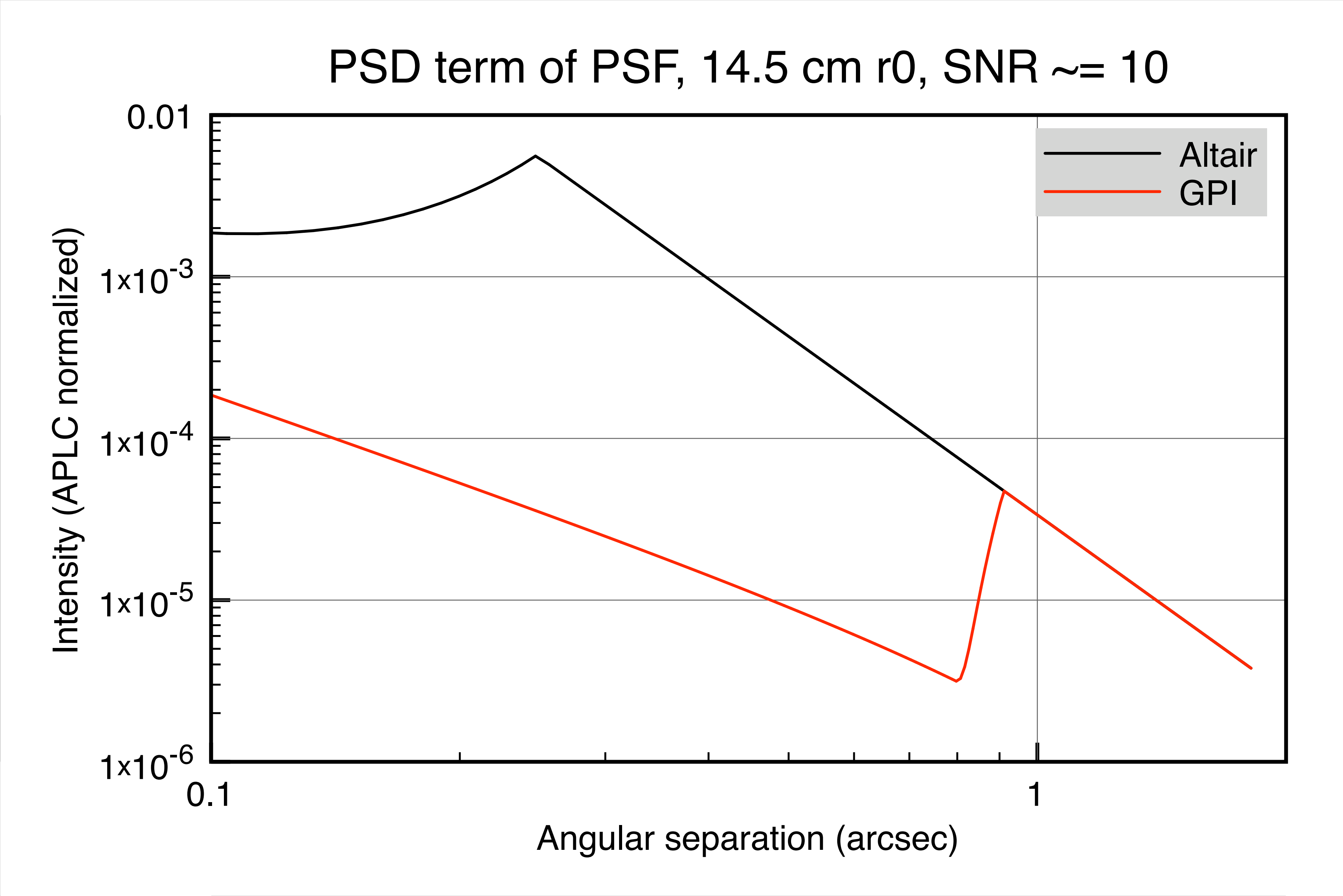


GPI should improve upon general-purpose AO

Additional error terms must be considered

- The previous four errors (along with anisoplanatism) form a set of “classic” AO errors
- For high-contrast imaging we need to assess impact of more subtle errors, as was done by Guyon.

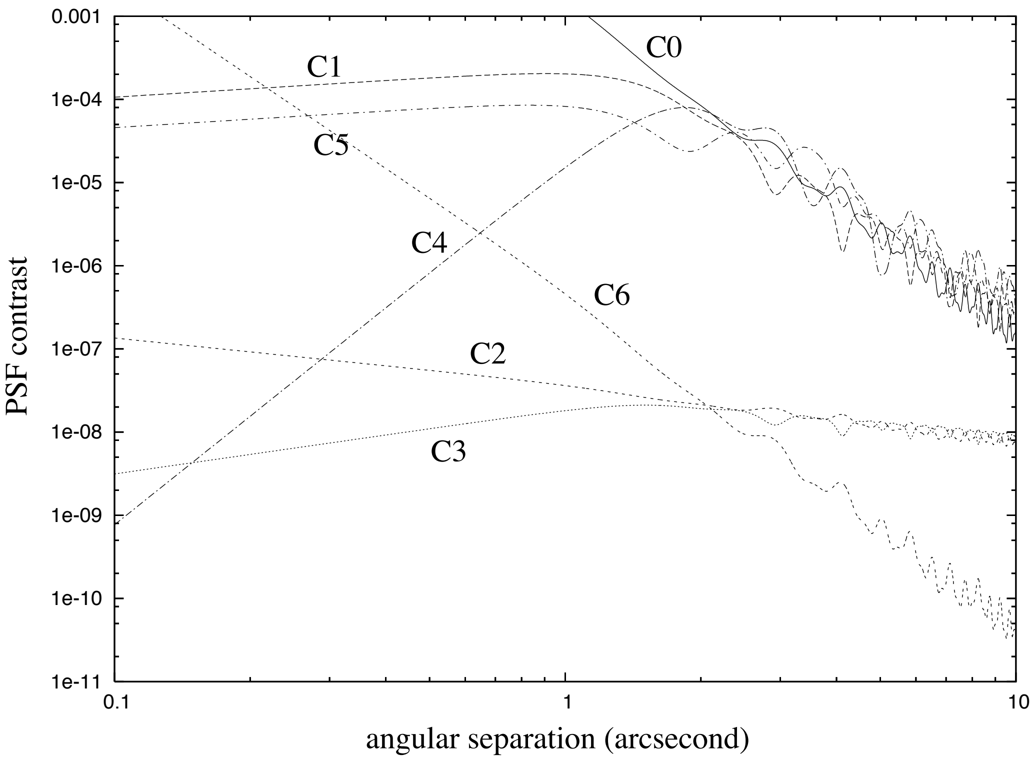
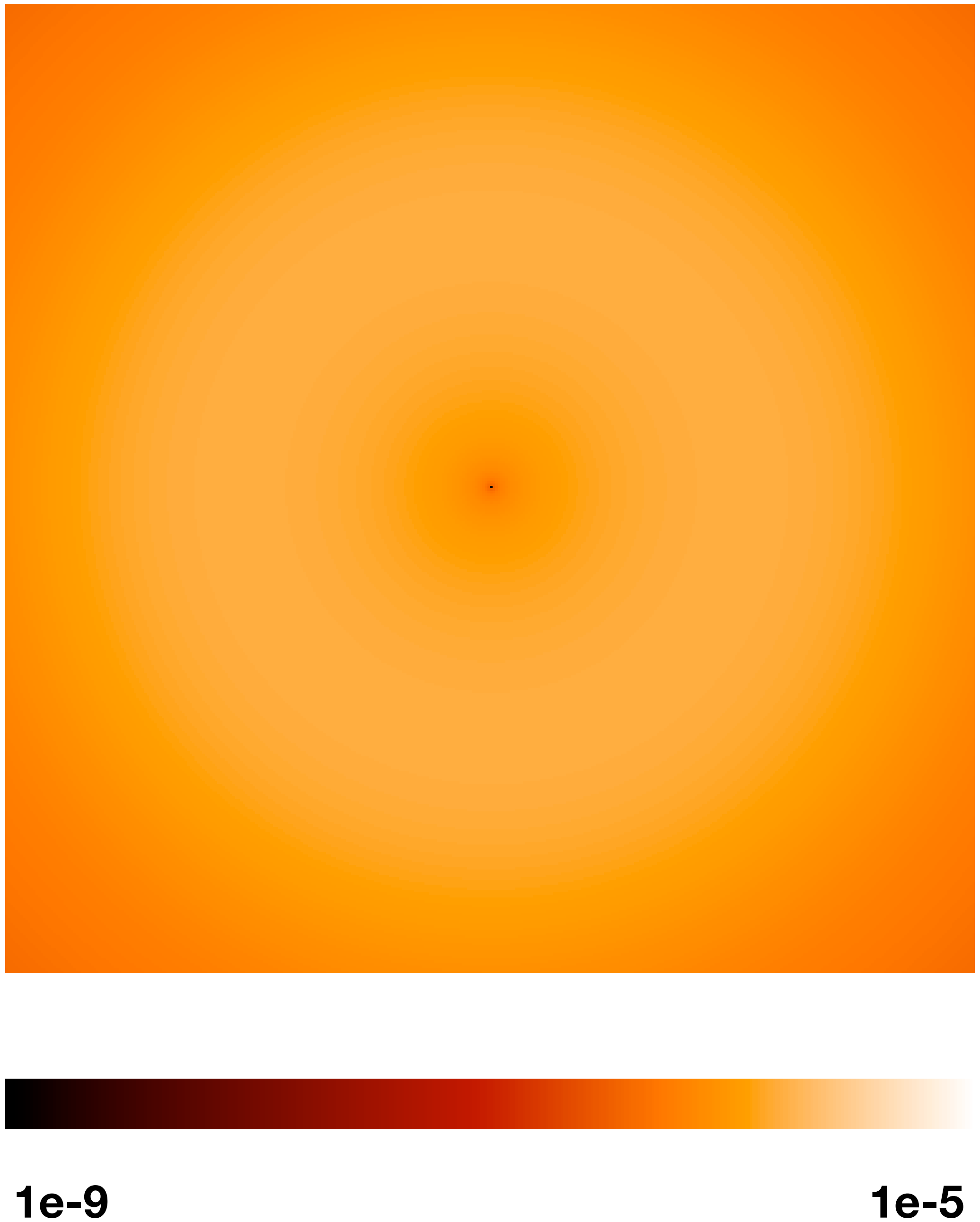


Fig. 12.— Contrast limits imposed by the uncorrected atmospheric turbulence (C0 and C1), corrected atmospheric turbulence (C2 and C3), chromatic effects (C4, C5, and C6) for a 8m telescope and a $m_v = 5$ source. See text for details.

Figure taken from O. Guyon, “Limits of adaptive optics for high-contrast imaging,” Ap. J. 629, 592–614 (2005). Revised version at http://arxiv.org/abs/astro-ph/0505086.

Amplitude errors (scintillation)

Uncorrected atmospheric scintillation



- Amplitude errors are not corrected with phase conjugation
- Possible sources
  - **Scintillation as light propagates through atmosphere**
  - **Reflectivity variations on optics**
  - **Phase errors on out-of-plane optics**
- Ways to improve:
  - **Correct amplitude with DM(s)**
  - **Improve quality of optics**

Control is not limited to phase conjugation

- Shape DM with a phase that does not conjugate
- Use of a single DM for amplitude and phase produces a half dark hole
- Use of multiple DMs for amplitude and phase produces a full dark hole
- See talks later this session

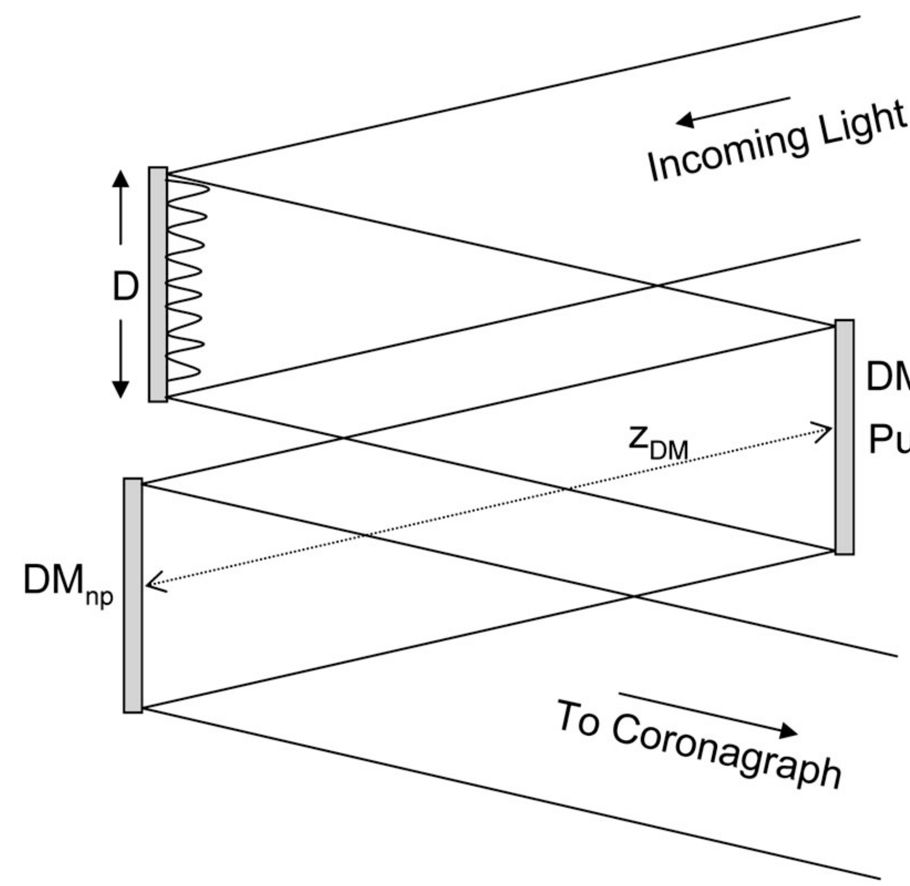


Fig. 2. Wavefront control system now consists of one DM located at a pupil image (DM_p) and a second one, DM_{np}, a distance z_{DM} downstream. DM_p controls phase, while DM_{np} controls amplitude. Both the phase-induced amplitude from the optical surface errors and the amplitude control using DM_{np} are wavelength indepen-

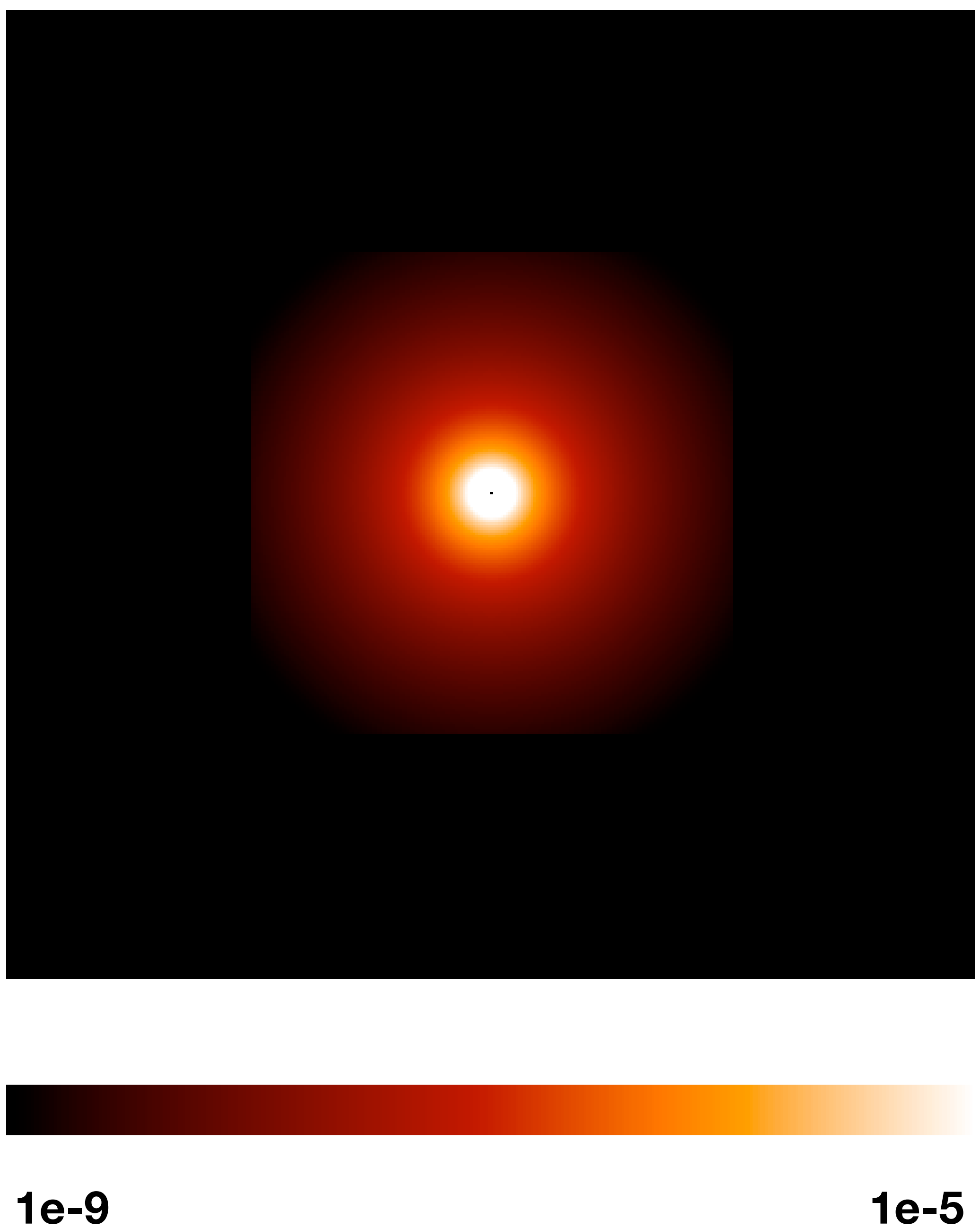
Figure taken from S. B. Shacklan and J. J. Green, "Reflectivity and optical surface height requirements in a broadband coronagraph. 1. Contrast floor due to controllable spatial frequencies", Appl. Opt. **45**, p 5143-5153 (2006)

Image plane wavefront sensing/control

- Sensing strategy usually directly tied into the control algorithm
- Advantages
  - **Everything is "common-path", same wavelength**
  - **Aperture provides anti-aliasing, provided adequate pixel size**
  - **Can be easily used in an amplitude-and-phase correction method**
- Disadvantages
  - **Requires very good correction already (e.g. Bordé & Traub's speckle nulling assumes λ/1000 aberrations)**
  - **Are detectors available which have low noise at the necessary frame rates?**
  - **Limited to narrow-band operation (sensing and correction algorithms)**

WFS not at science wavelength

Atmosphere, 700-900 nm WFS, 1600 nm science



- Chromatic terms arise when behavior is a function of wavelength
  - **Fresnel propagation**
  - **Change in index of refraction**
  - **Change in pupil position due to DAR**
- Ways to improve:
  - **Don’t use very blue light (400 nm)**
  - **Use science light for WFS**

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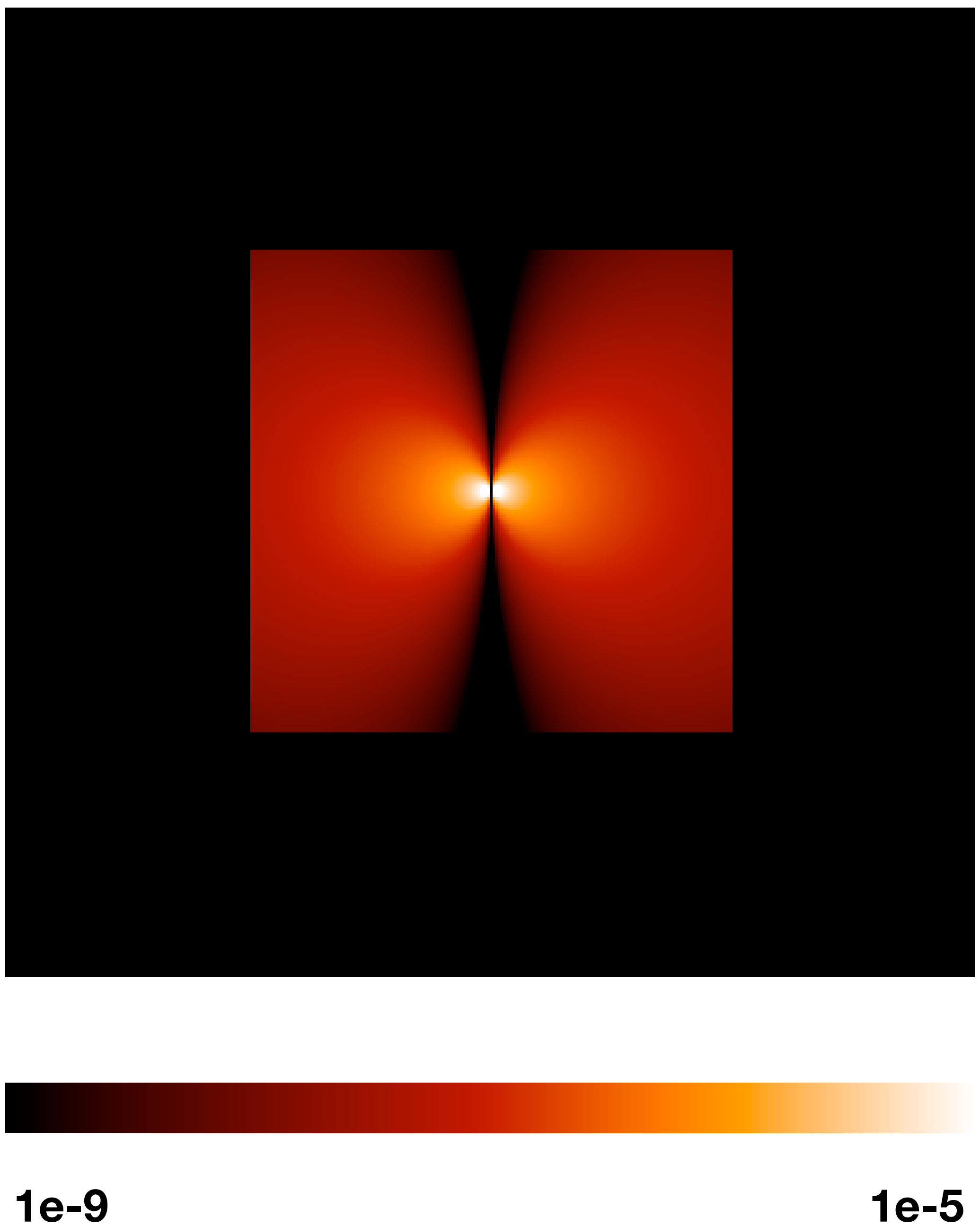

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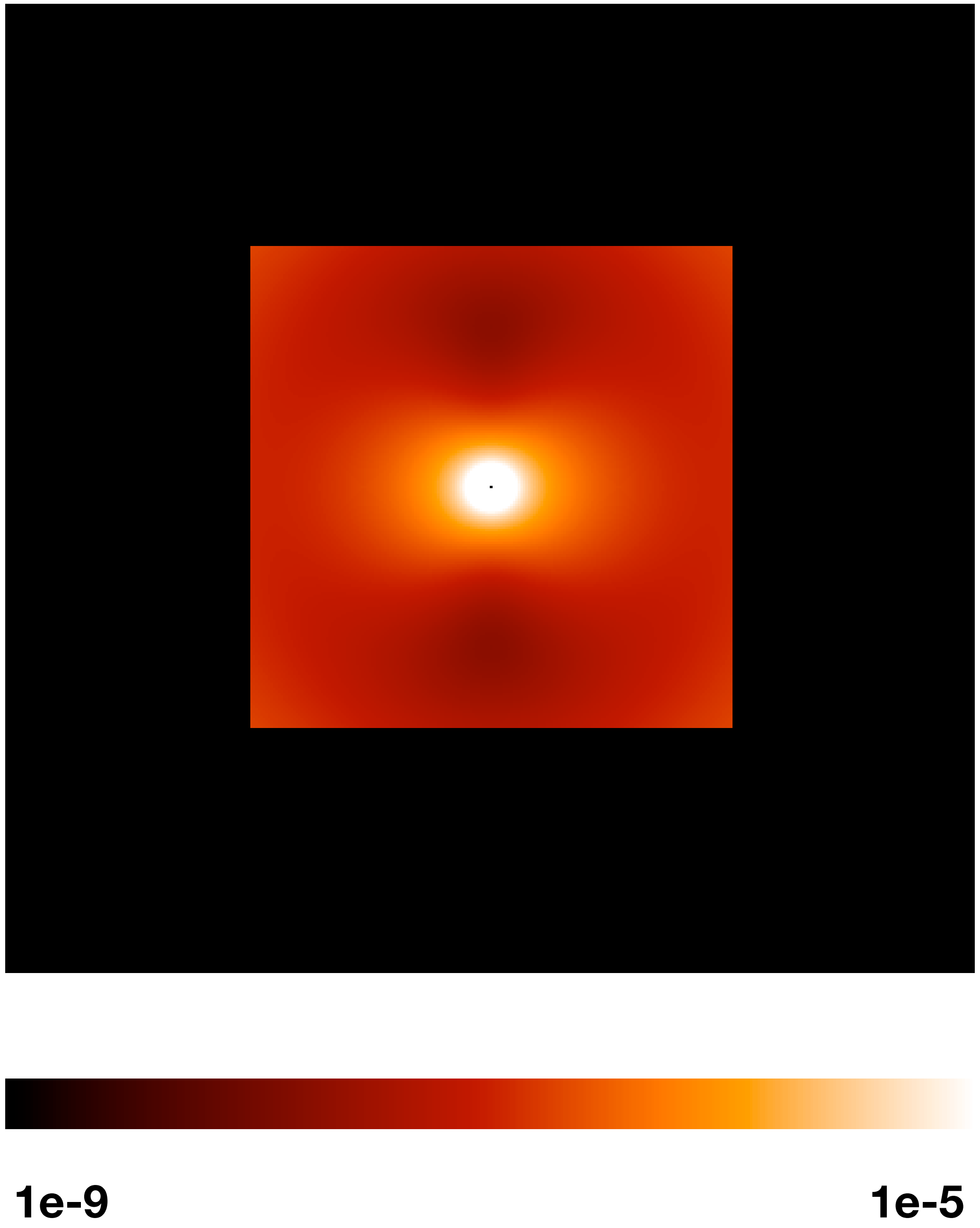

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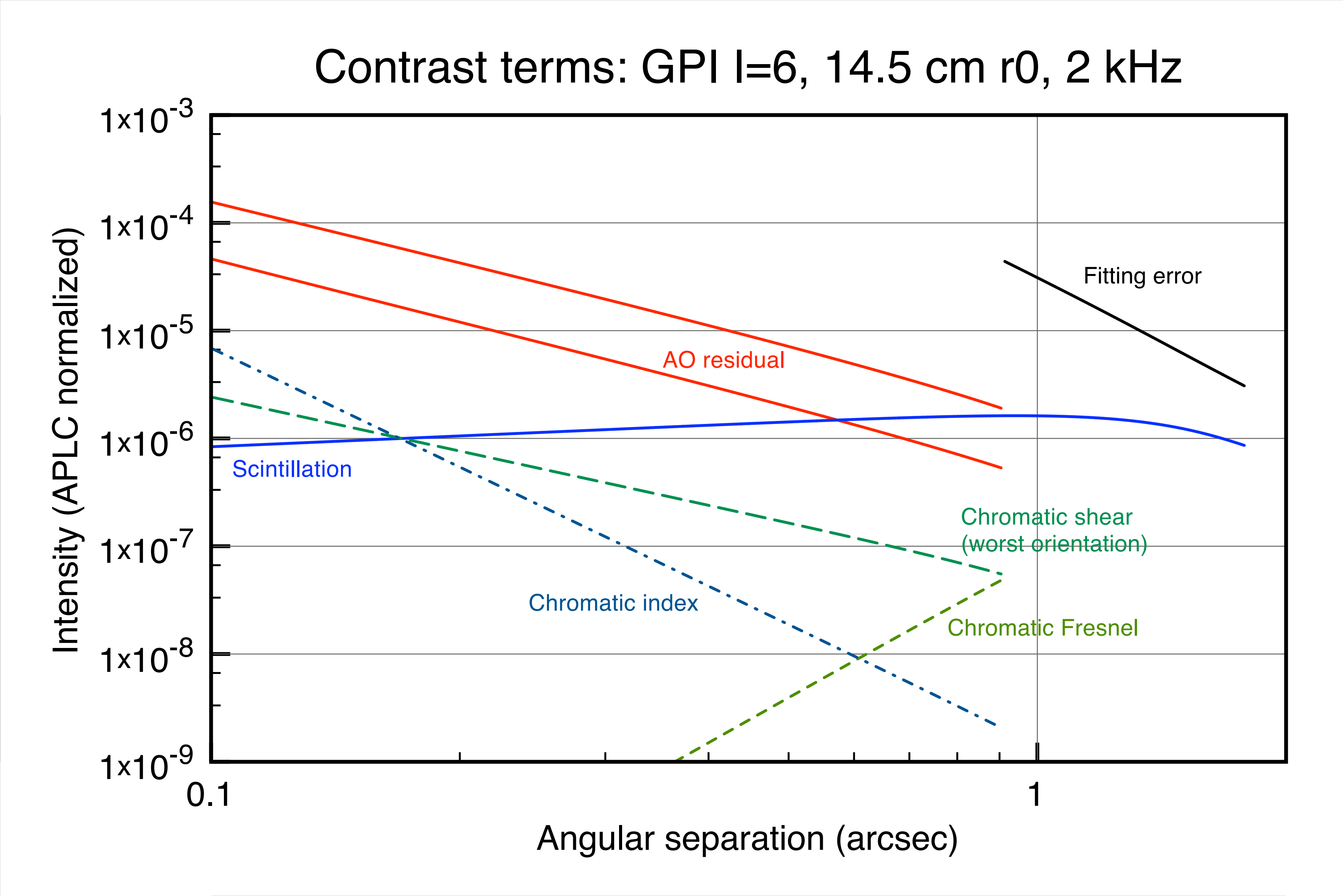


Only scintillation may matter for GPI

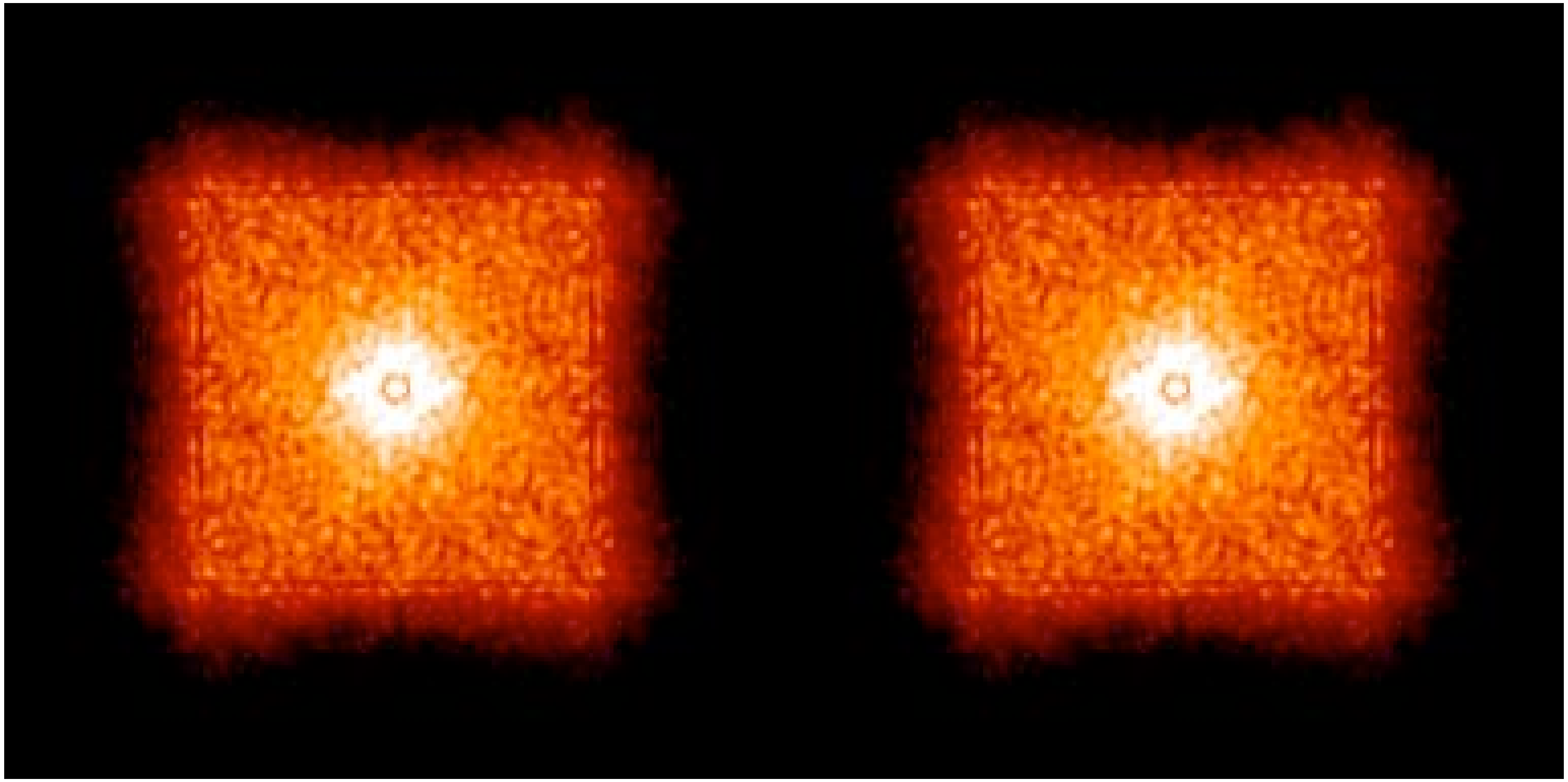
Temporal structure of PSF

- What we've shown so far has focused on the expected intensity (infinitely long exposure level)
- In reality, we have shorter exposures, and speckles from different error sources behave in different ways
  - **WFS noise**
  - **atmosphere**
  - **quasi-static error**

- 10's of nm of a rapidly decorrelating error may be better than 1's of nm of a slowly varying one

Wavefront sensor noise is nearly white

- WFS noise input is assumed to be temporally white
- WFS noise output of control system is nearly white



GPI with H-band APLC,10 msec exposures at 100 Hz

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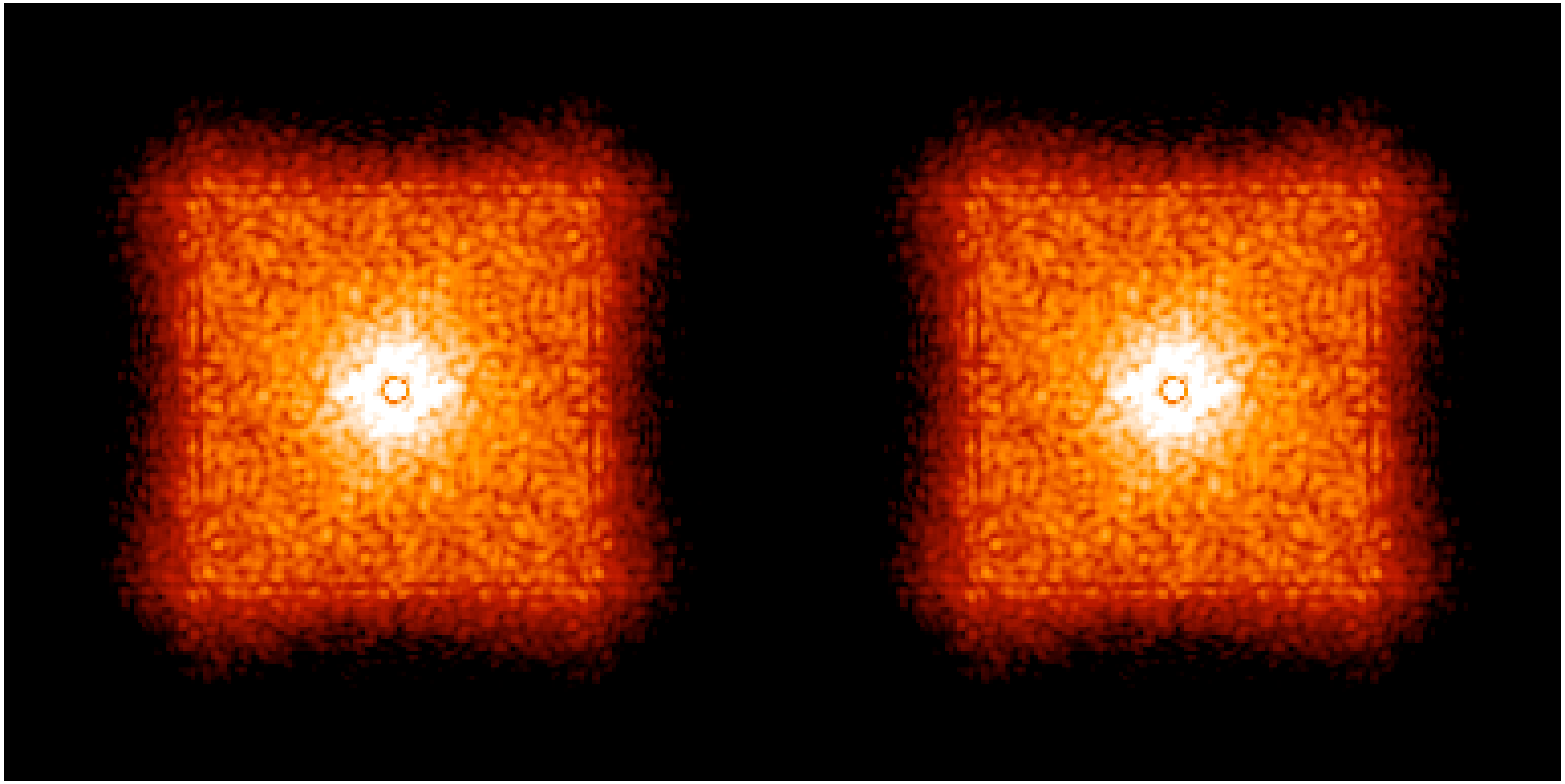

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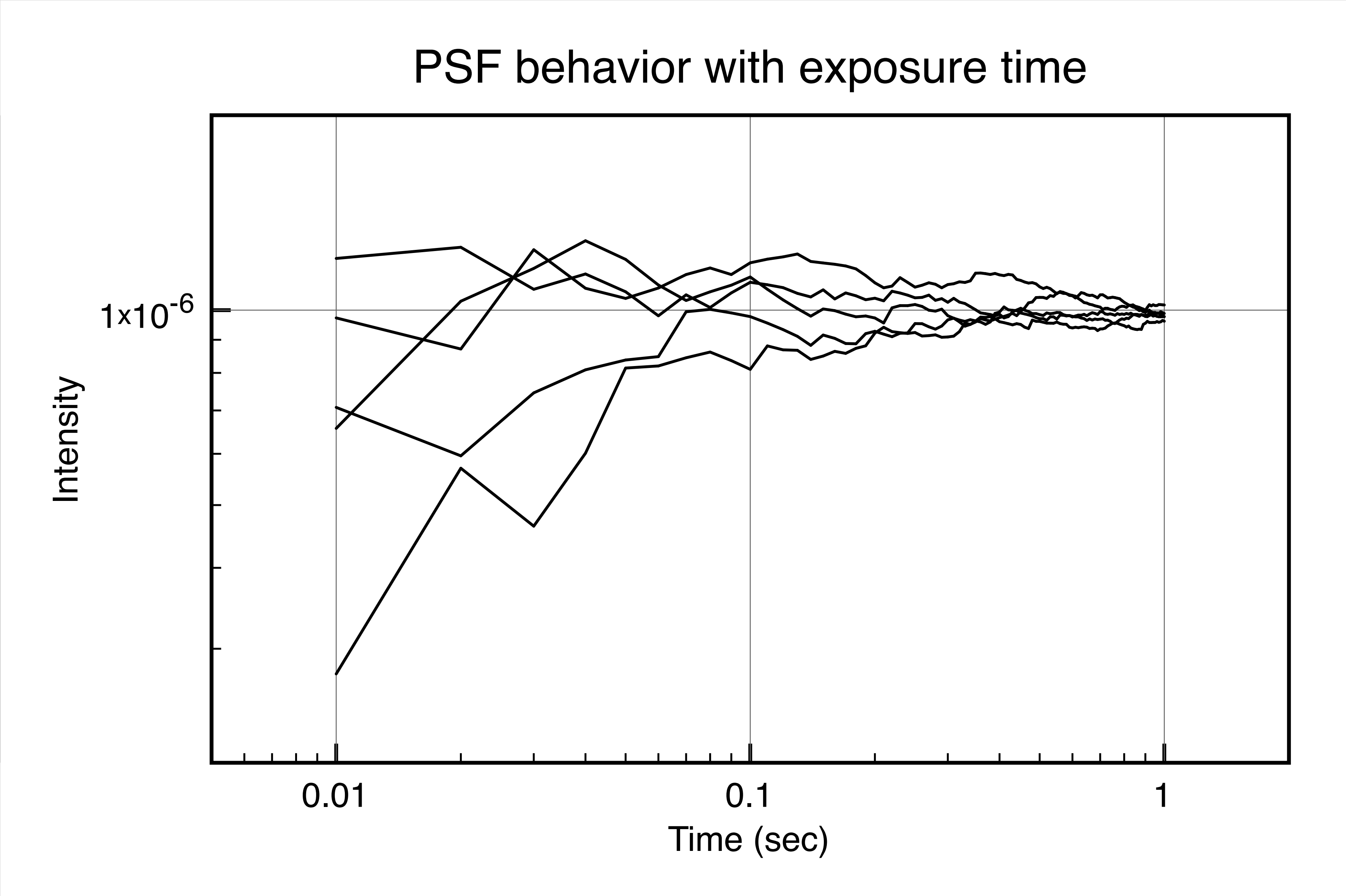
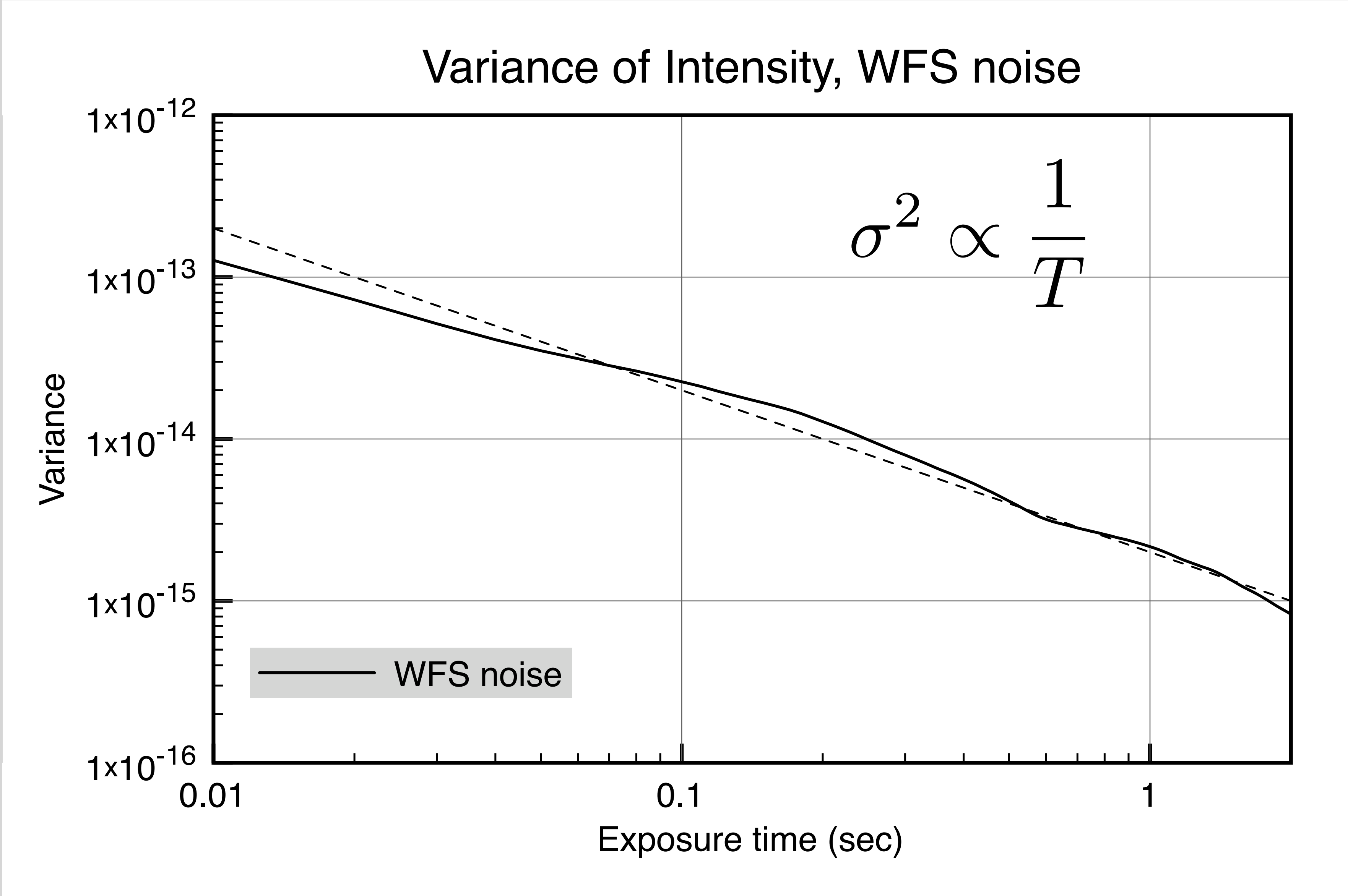


Intensity of a single speckle, tracked over five different exposures

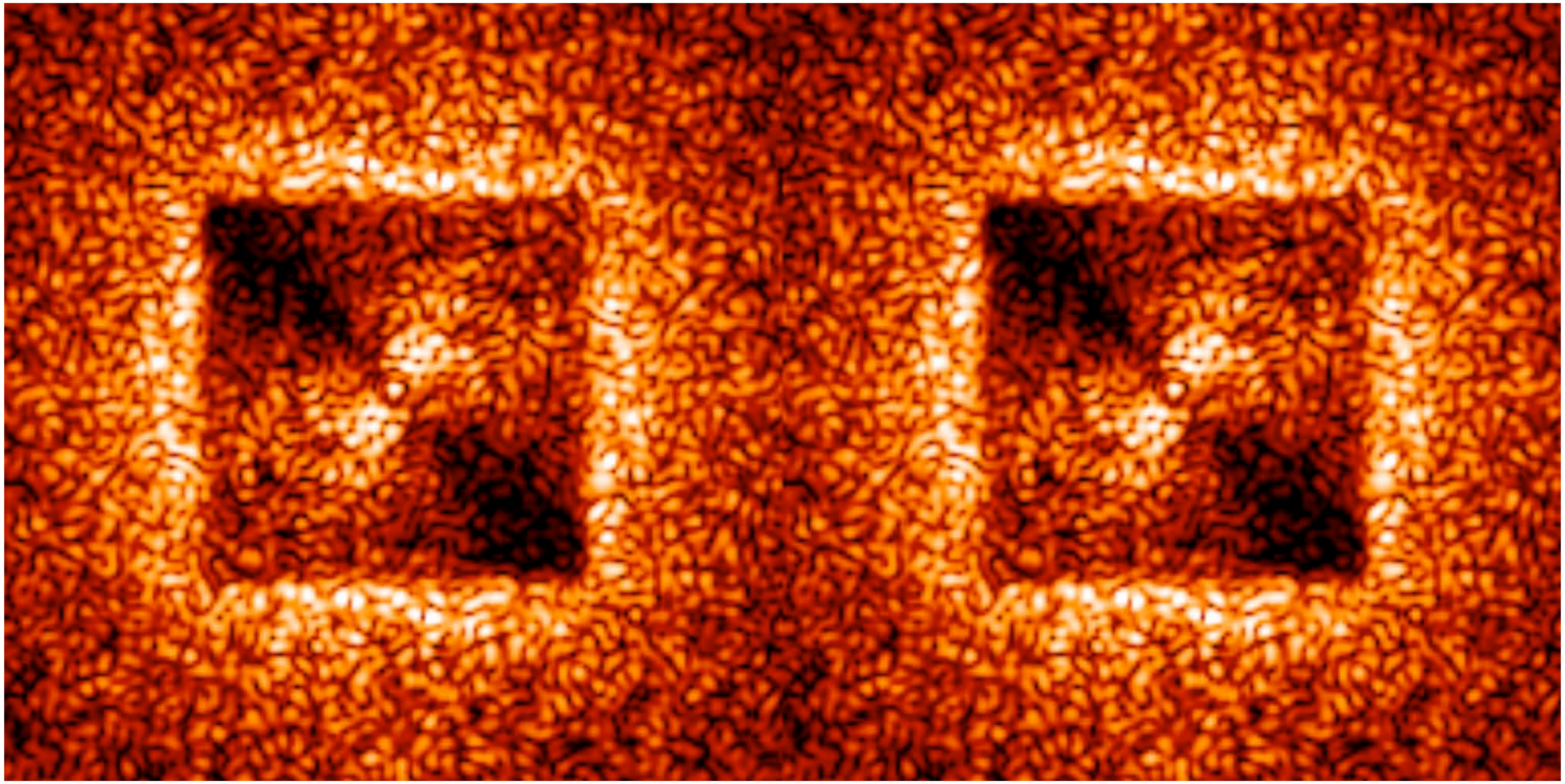
Intensity converges with longer exposures



Noise speckle variance drops rapidly

Atmospheric error is dominated by wind

- Clearing of wind over aperture $\frac{D}{v}$ sets decorrelation time



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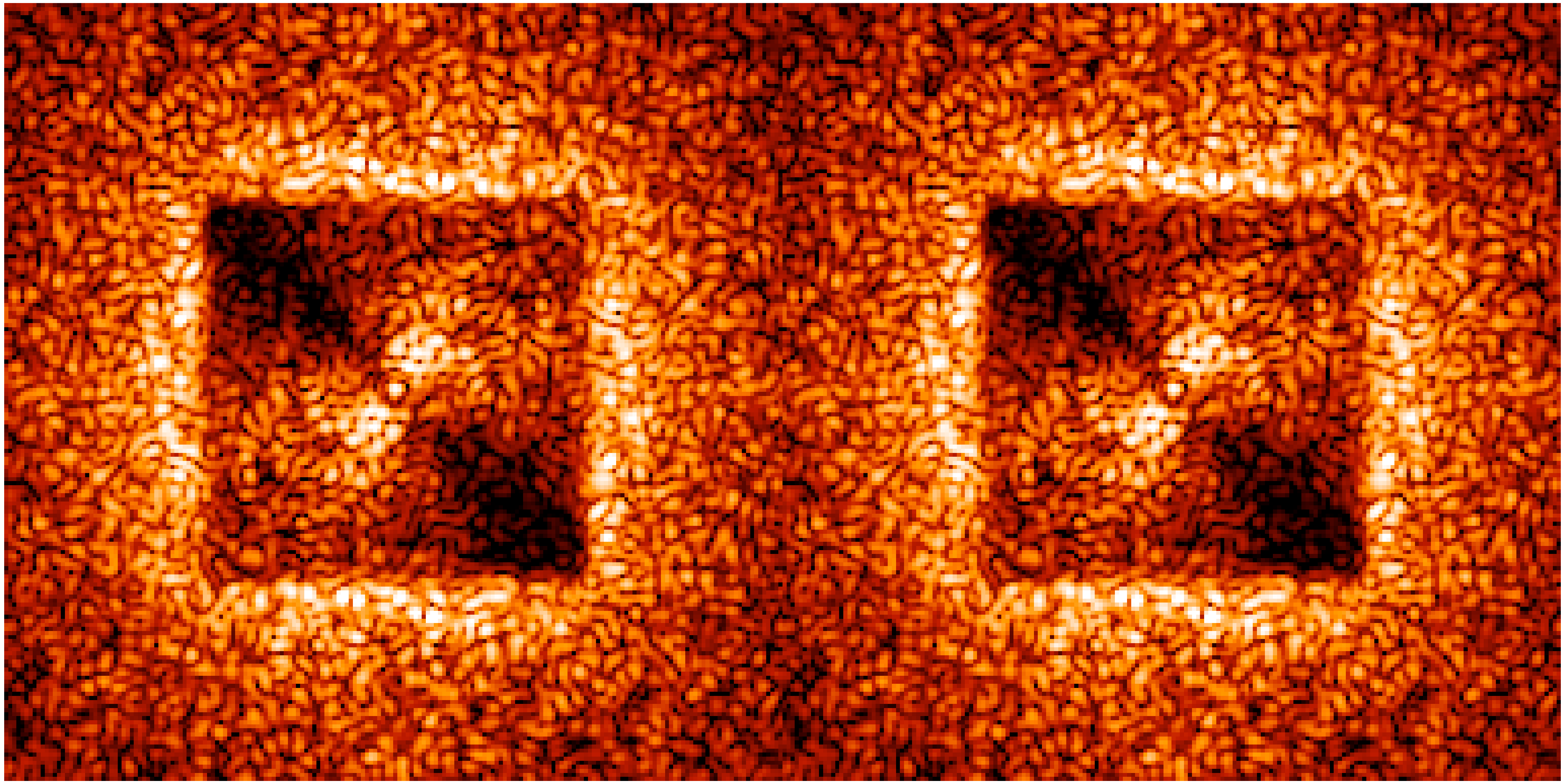

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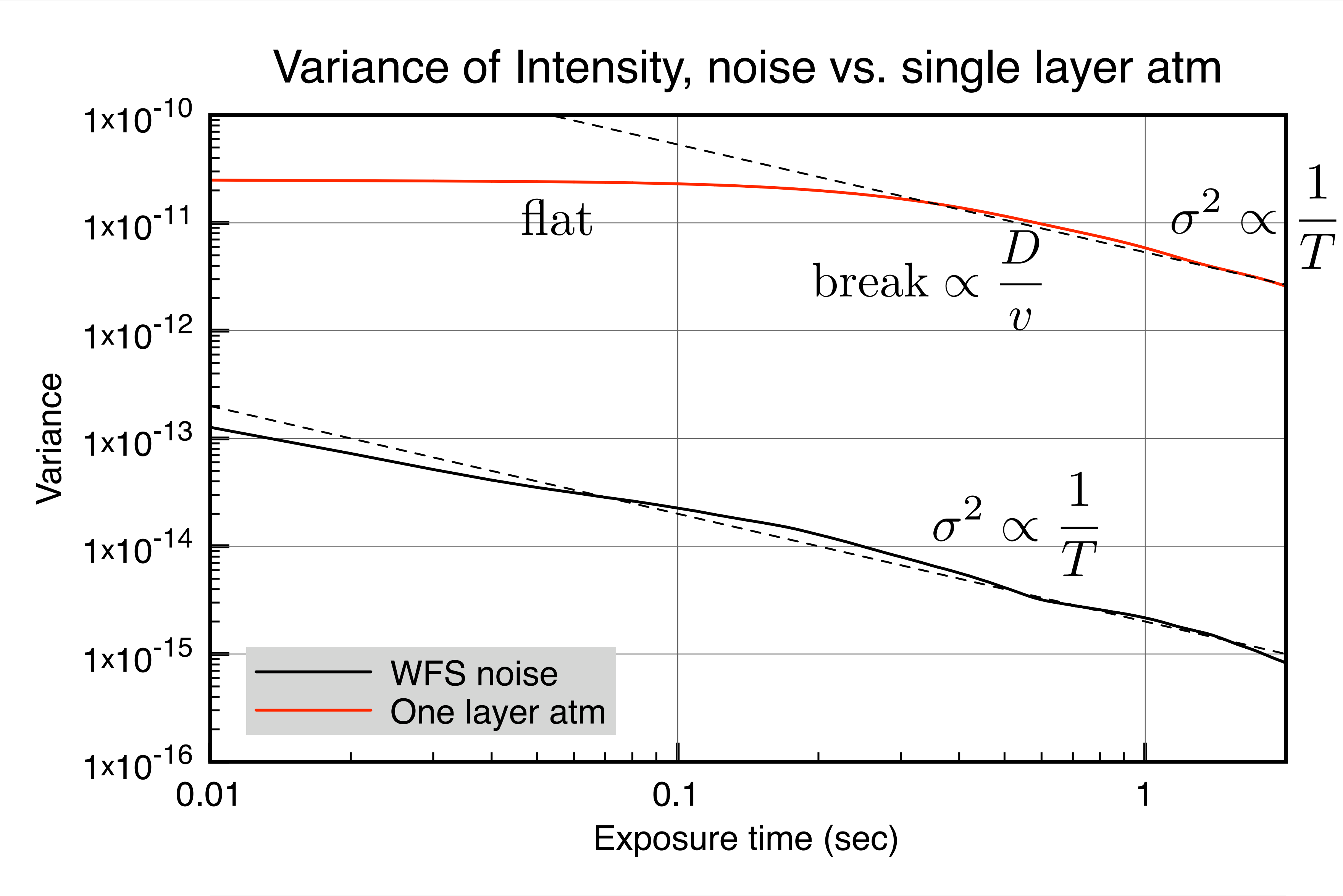
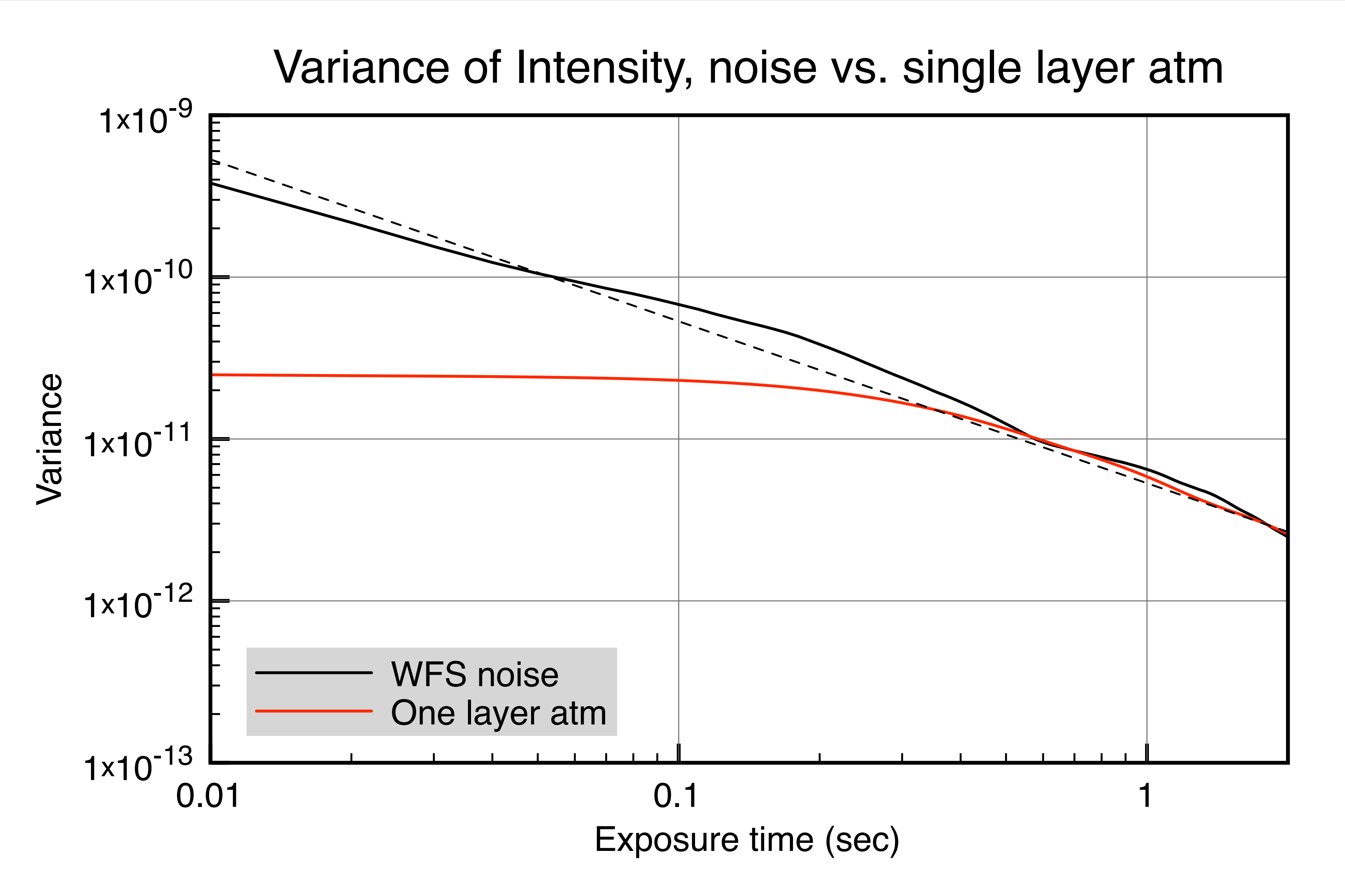
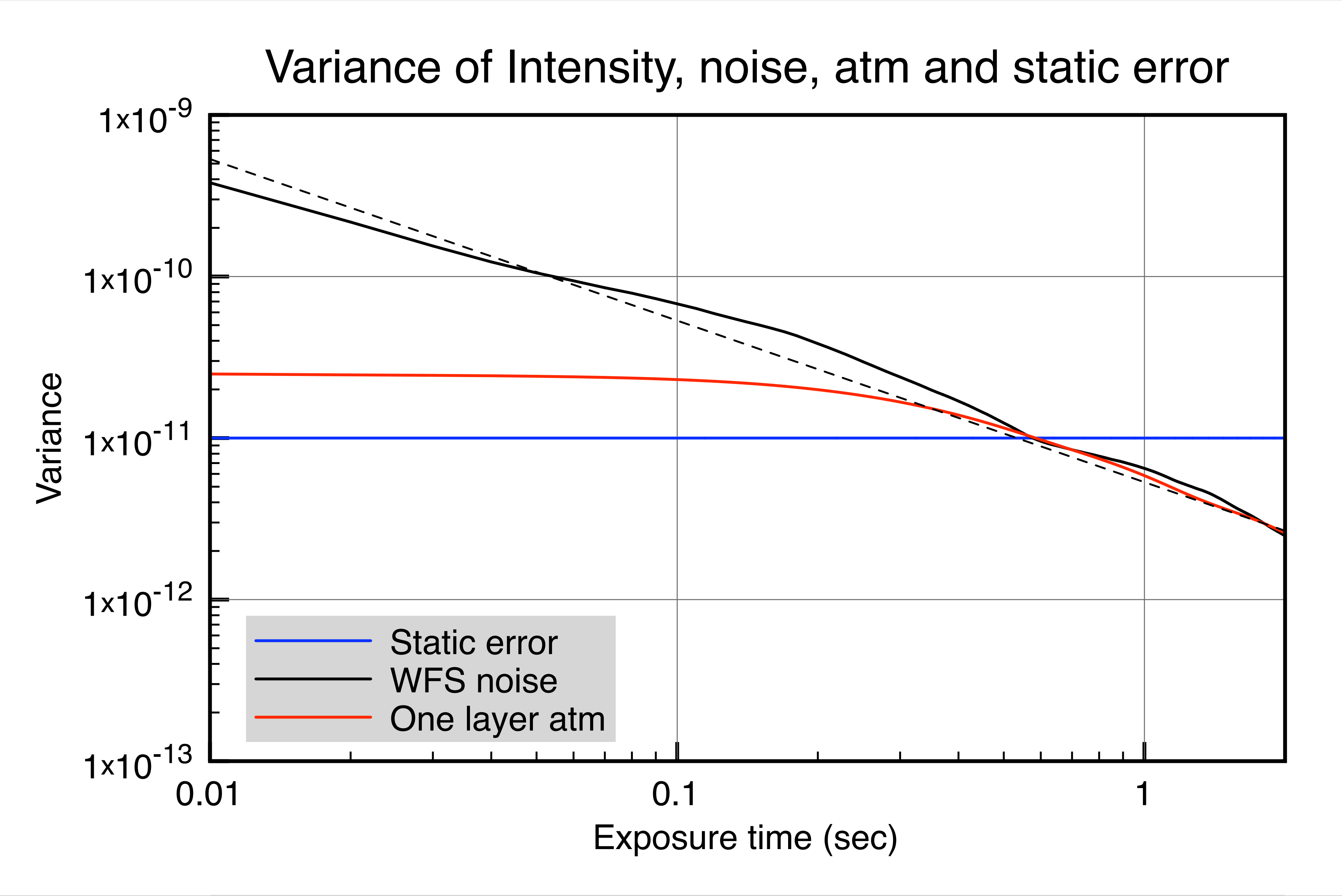


Atmospheric speckles evolve more slowly



Dominant term depends on exposure time

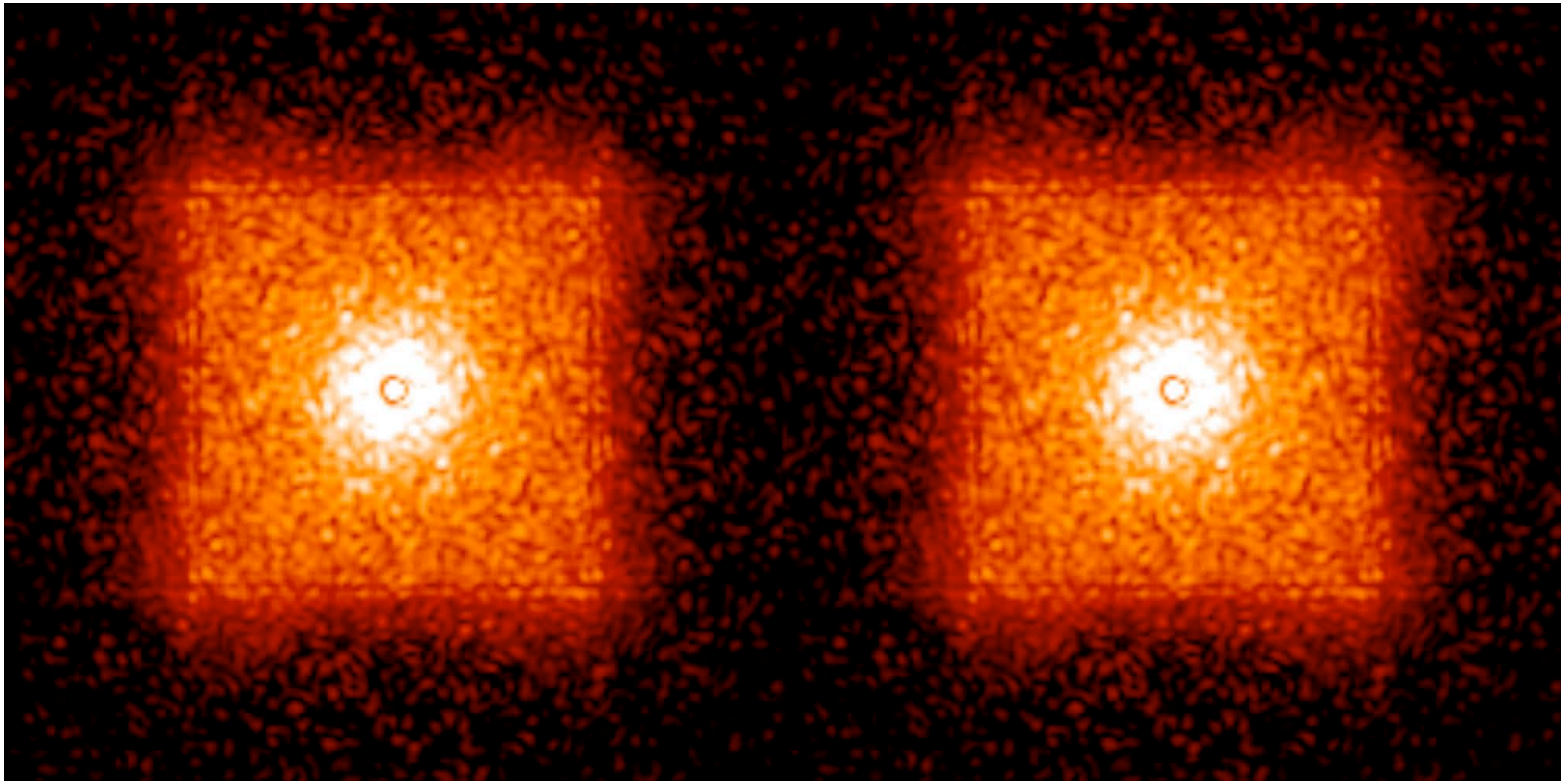


Dominant term depends on exposure time

Static errors "print through"

- 10 nm of static error appears above noise halo

GPI with H-band APLC,10 msec exposures at 100 Hz



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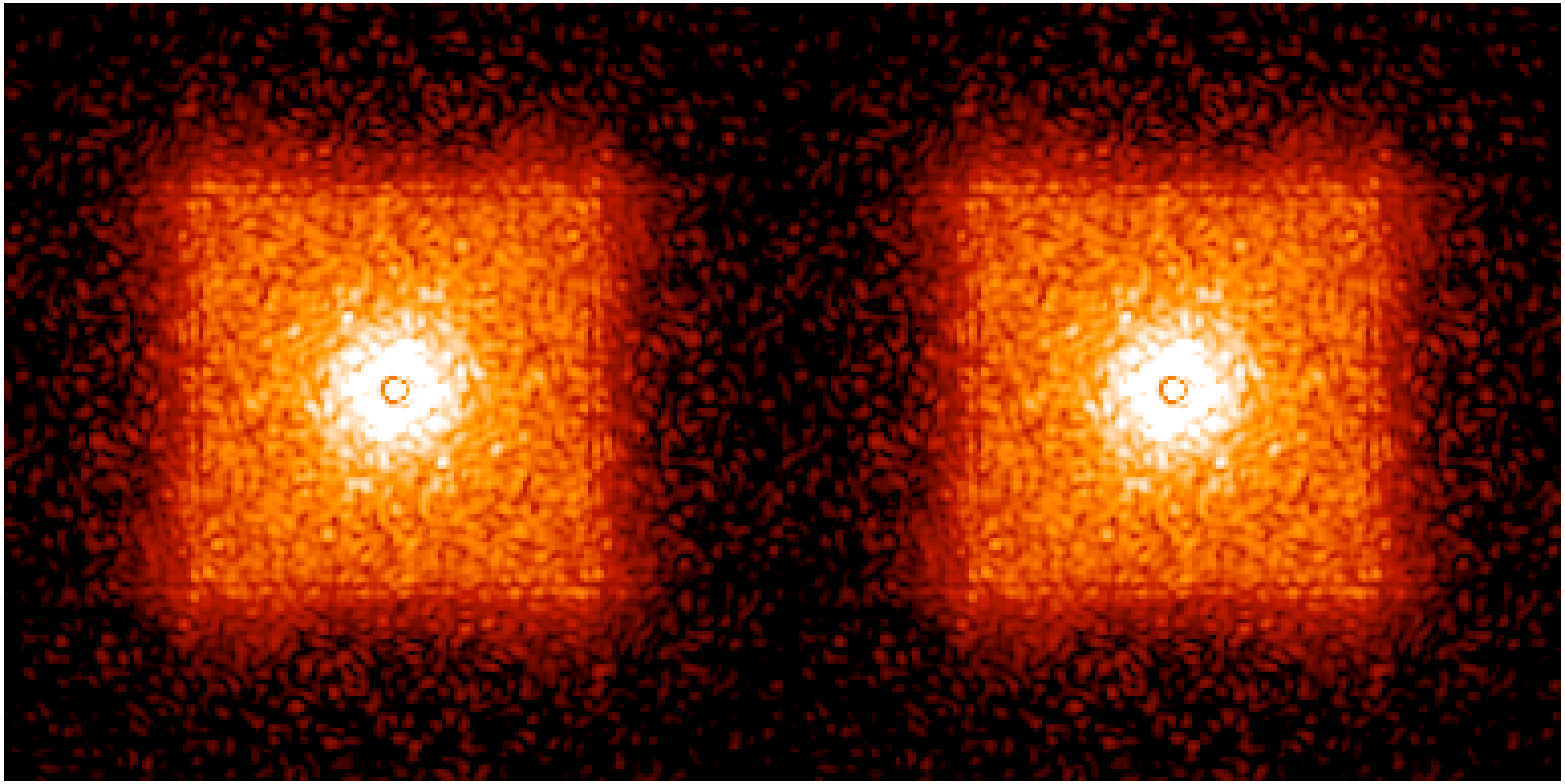
exposures at 100 Hz



Static and Atmospheric speckle noise in 2-hour GPI exposure

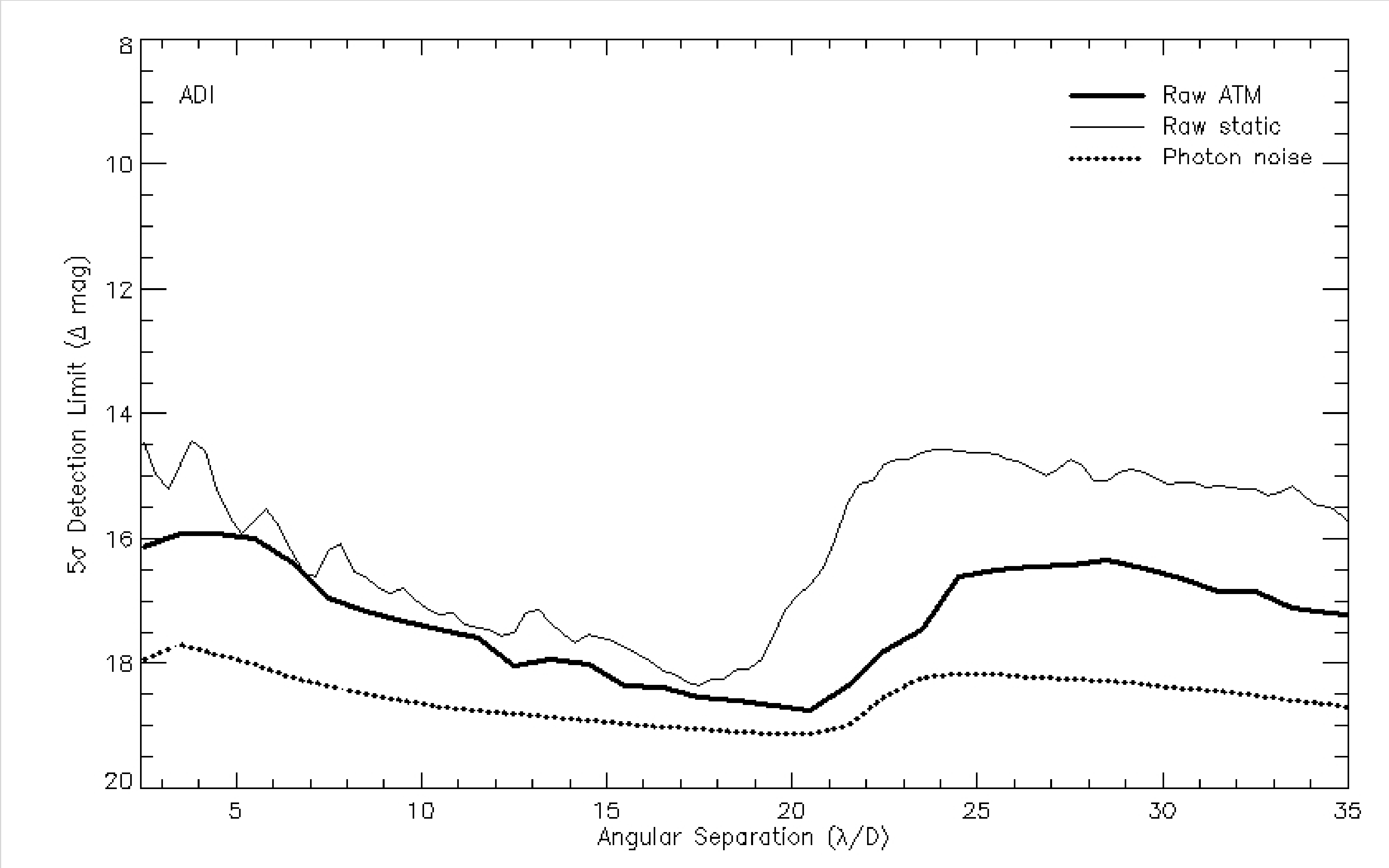


Figure courtesy of C. Marois; from the Gemini Planet Imager Preliminary Design Report (2007)

Static errors on optics important for GPI

Two scenarios with distinct characteristics

	Ground	Space
Phase errors	Rapidly varying atmospheric error dominates; also smaller and slowly varying optical errors	Slowly varying; due to optics
Amplitude errors	Much less significant; due to atmosphere and optics	Slowly varying; due to optics
WFS	Pupil-plane; slope sensor in near term, direct-phase in future	Image-plane WFS in science path
WF control	DM for phase control only	Phase and amplitude control with 1 DM (half-dark hole) or 2 DMs (full dark hole)
Time frames	> 1 kHz	> 1 milliHz
Telescope size	8-10m now, 20-30m future	1-4 m?

Need to control PSF to be dim and smooth

- Wavefront control is essential for high-contrast imaging
- Intensity (infinite-exposure case) can be addressed through analytic tools
- Planet detectability with exposure time depends on temporal character of error sources

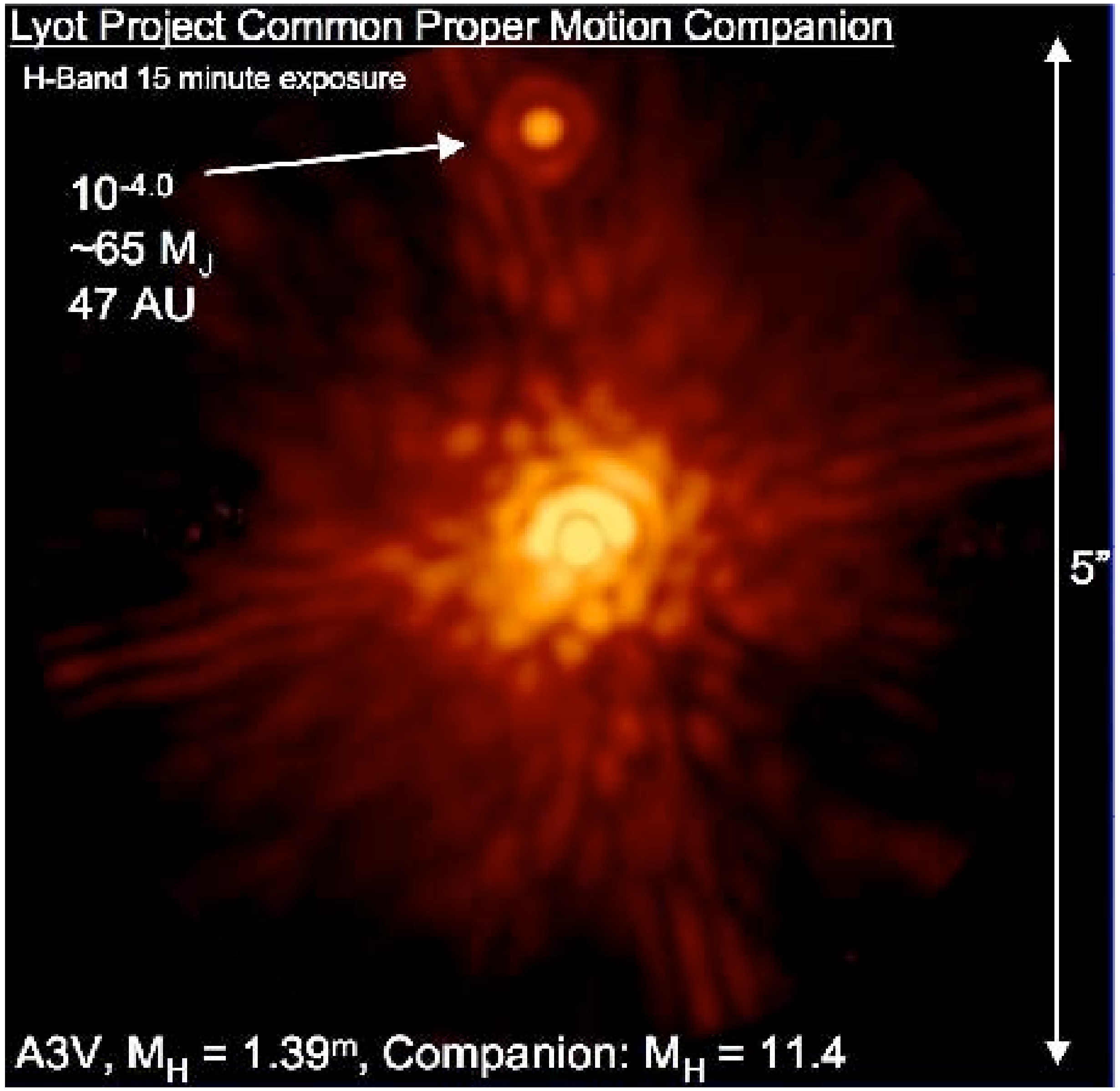


Figure courtesy of A. Sivaramakrishnan from Oppenheimer (in preparation 2007)