Advances in AO Systems (fundamental limits)

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JPL-MPIA Workshop, 2018-April-09

- Angel (1994)

Ground-based imaging of extrasolar planets using adaptive optics

J. R. P. Angel

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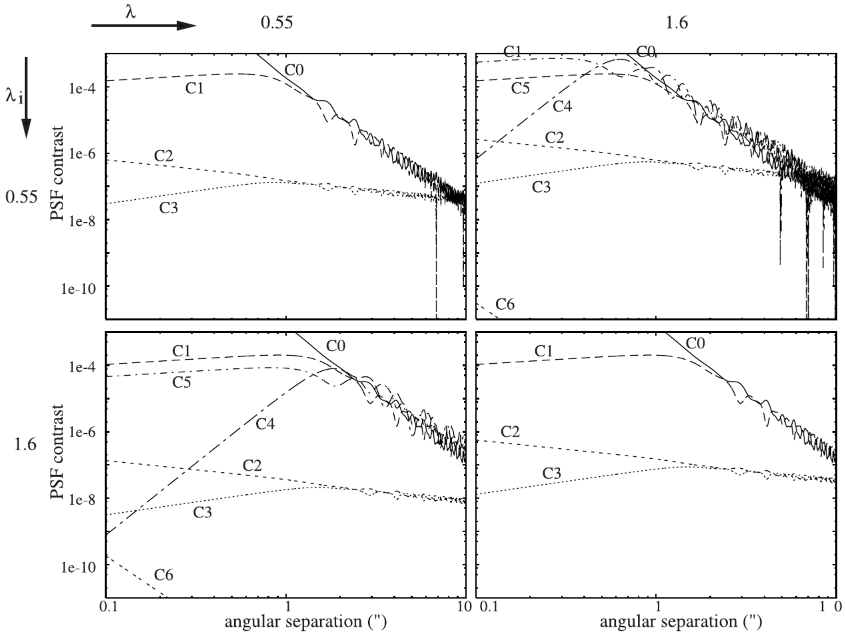
The detection of extrasolar planets by direct imaging presents an extraordinary technical challenge. They must be identified against background light scattered from a star close by and about a billion times brighter. It has been supposed that a near-perfect space telescope would be required to avoid atmospheric blurring. But by using adaptive optics operating at fundamental performance limits, the new generation of large ground-based telescopes has the potential to detect planets orbiting nearby stars.

Some History

- Angel (1994)
  - Predicted that 6.5 to 12 m ground-based telescopes would be characterizing planets orbiting nearby main-sequence stars in the coming decade.
  - Considered atmospheric speckles, which should average quickly
  - Did not yet know of the monsters called quasi-static speckles waiting just off the edge of the map…

- Guyon 2005
  - Analyzed the fundamental limits of AO
  - Primarily a spatial-PSD analysis, with simplified version of frozen-flow.



Towards the Fundamental Limit

- Goal: develop a framework for analyzing the fundamental limit of ground-based contrast
  - Closed-loop control analysis
  - Consider full multi-layer turbulent atmosphere
    - Frozen flow, but not limited to this
  - Predict post-coronagraph contrast
  - Analyze the temporal behavior of speckles.

- With apologies: this requires math . . .

AO Limits

The limit of the planet:star flux ratio that we can detect & characterize is set by the variance of intensity in the focal plane:

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

cf. Soummer et al., “Speckle Noise and Dynamic Range in Coronagraphic Images”, ApJ 669:642 (2007)

Residual Variance

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

$$\begin{aligned}
F_* &= \text{photons/sec from the star} \\
\Delta t &= \text{total integration time} \\
I_c &= \text{intensity residual from the coronagraph \& static aberrations} \\
I_{as} &= \text{intensity residual from atmospheric speckles} \\
\tau_{as} &= \text{lifetime of atmospheric speckles} \\
I_{qs} &= \text{intensity residual from quasi-static speckles} \\
\tau_{qs} &= \text{lifetime of quasi-static speckles}
\end{aligned}$$

cf. Soummer et al., "Speckle Noise and Dynamic Range in Coronagraphic Images", ApJ 669:642 (2007)

Residual Variance - Photons

$$\sigma_{tot}^2 = \underbrace{F_* \Delta t \left\{ I_c + I_{as} + I_{qs} \right.}_{\text{Photon Noise (Poisson statistics)}} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \Big\}$$

Residual Variance - Speckles

$$\sigma_{tot}^2 = F_*\Delta t \left\{ I_c + I_{as} + I_{qs} + \underbrace{F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right]}_{\text{Speckle Noise}} \right\}$$

Residual Variance - Speckles

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nasty

Residual Variance - Speckles

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + \underbrace{F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right)\right.}_{\text{Residual atmospheric speckles}} \left. + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

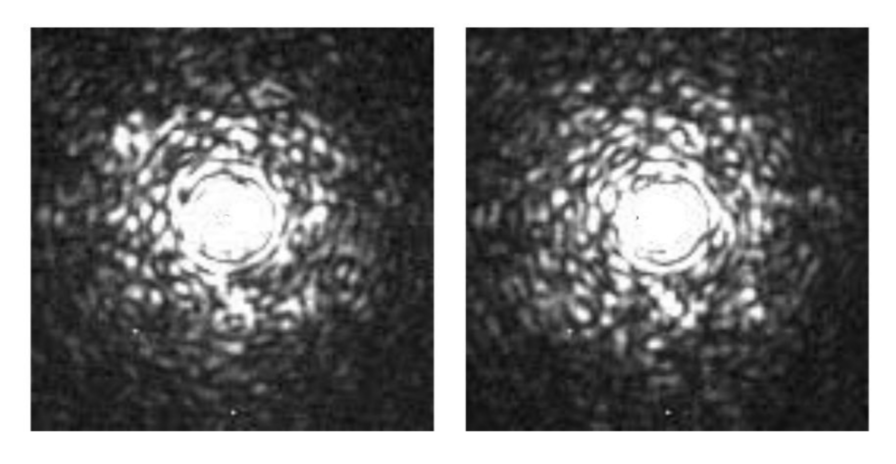
Residual atmospheric speckles

Residual Variance - Speckles

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

pinned by Airy Pattern

pinned by quasi-static

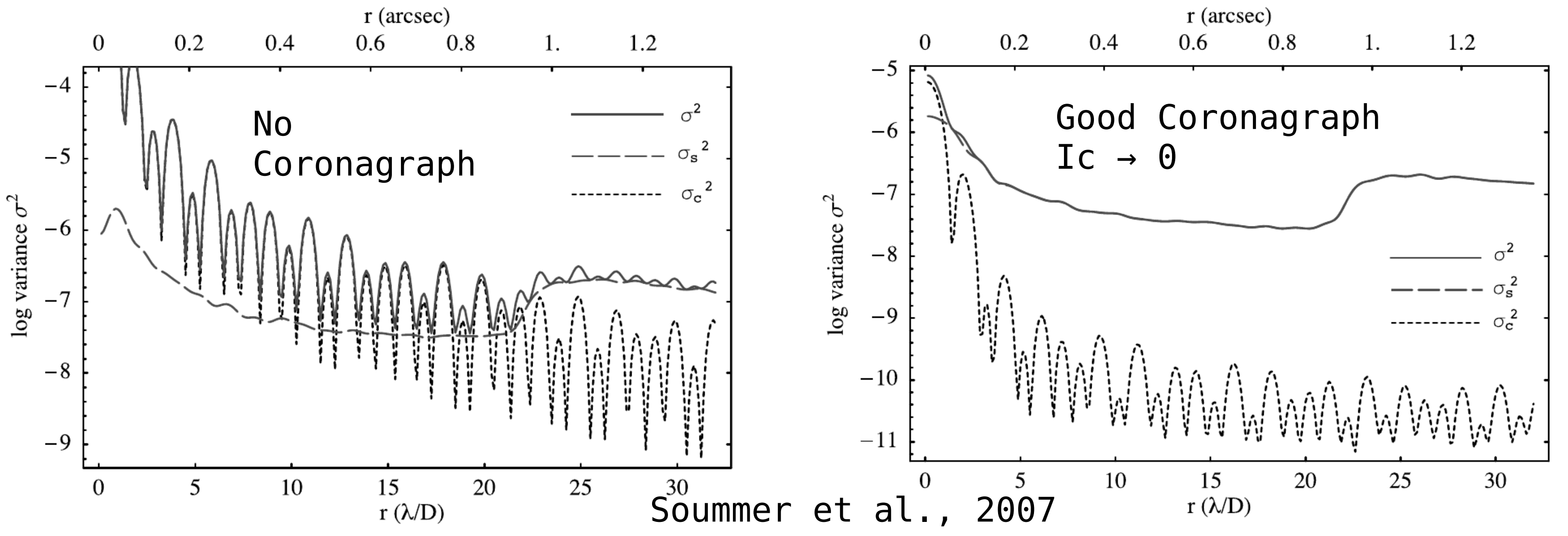


Soummer et al., 2007

Residual Variance - Speckles

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

pinned by
Airy Pattern



Soummer et al., 2007

Residual Variance - Speckles

$$\sigma_{tot}^2 = F_*\Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

- Coronagraph design is now quite advanced, (thanks WFIRST CGI!)
- It is not a wild assumption to ignore it, and that's what I'm going to do from now on.
- But: it is common to hear things like:

  "well, we'll only ever achieve 1e-5 AO residual, so that's all we need from the coronagraph"

  This is wrong. Because of pinning, coronagraph performance (I_c) must be much better than AO (I_{as}).
- Note also that I_c includes truly static aberrations, or (say) very long lived ones. So this also has implications for discussion of design and stability of ground-based instruments.

Residual Variance - Speckles

$$\sigma_{tot}^2 = F_*\Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as}\left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}]\right) + \underbrace{\tau_{qs}\left(I_{qs}^2 + 2 I_c I_{qs}\right)}_{\text{quasi-static speckles}} \right] \right\}$$

Understanding Ground-Based Contrast

- Understanding the limits of ground-based HCI requires:

1) Predict residual atmospheric speckle contrast I_{as}

2) Predict residual atmospheric speckle lifetime τ_{as}

3) Predict quasi-static speckle contrast I_{qs}

4) Predict quasi-static speckle lifetime τ_{qs}

- AO control as a time-domain control problem is described by the temporal PSD

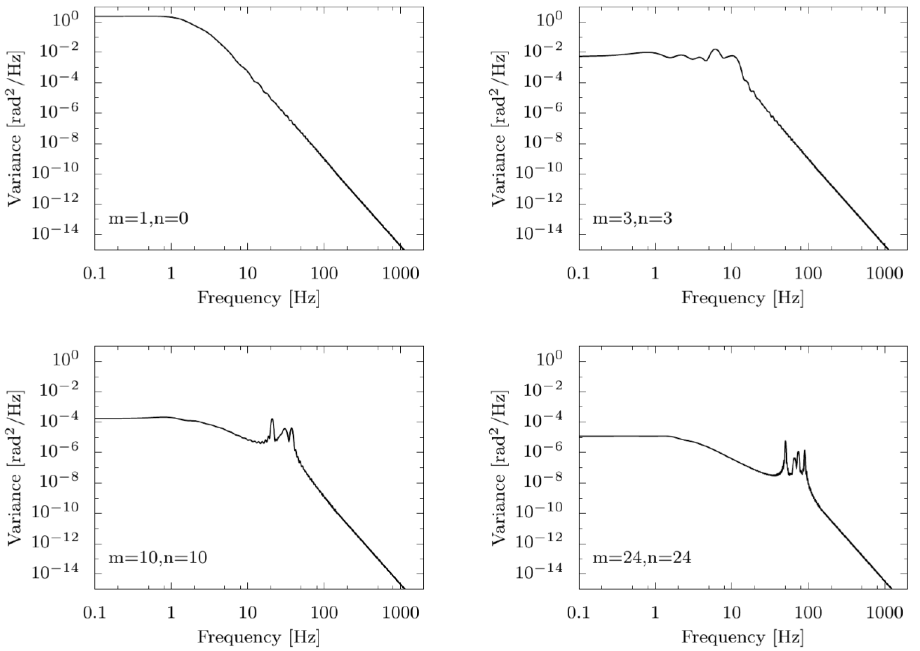


Fig 6 Calculated temporal PSDs in a 7-layer turbulence model at 4 different modes, corresponding to discrete spatial frequencies.

Males & Guyon, JATIS, 2018

These are the temporal PSDs, $\mathcal{T}_{mn}(f)$ of individual Fourier modes (or spatial frequencies) in the atmosphere.

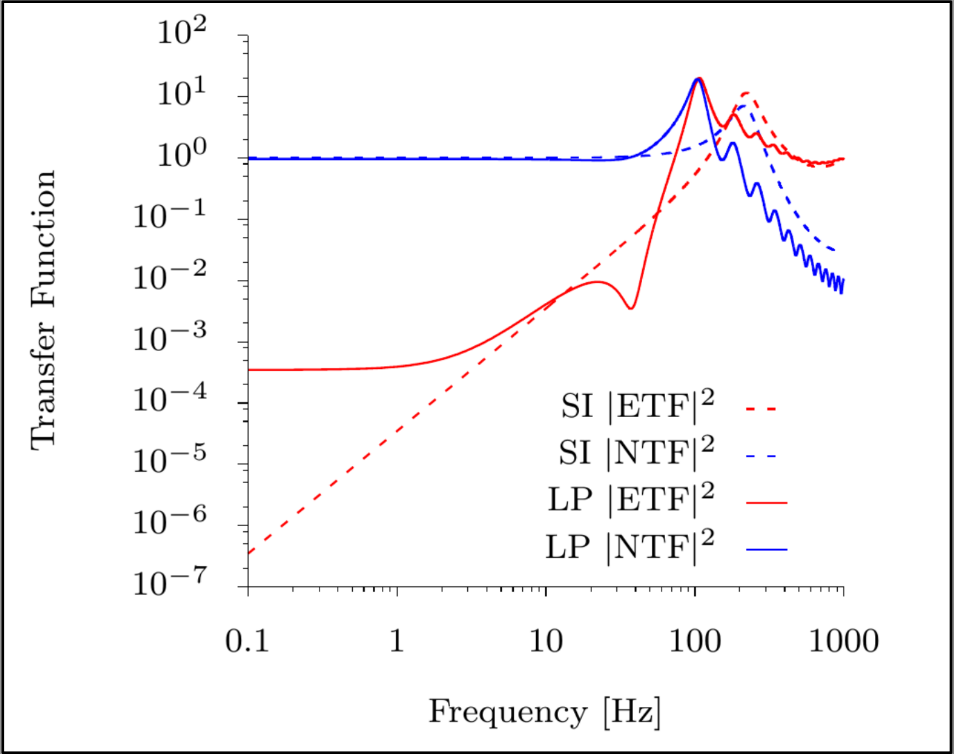
Calculations assumed frozen-flow von Karman turbulence, with LCO median conditions.

$\mathcal{T}_{mn}(f)$ describes the statistics of the modal amplitudes h_{mn}

The variance of the modal amplitudes $\langle |h_{mn}|^2 \rangle$ gives the contrast:

$$\langle I_\Phi(\vec{r}) \rangle = \left(\frac{2\pi}{\lambda} \right)^2 \langle |h_{mn}|^2 \rangle \left[\mathrm{PSF}(\vec{r} - \vec{k}_{mn}\lambda) + \mathrm{PSF}(\vec{r} + \vec{k}_{mn}\lambda) \right]$$

Transfer Functions



Males & Guyon, JATIS, 2018

- AO control acts on the input PSD.
- The output of the control system is described by its *transfer functions*

$$\mathcal{T}_{cl,mn}(f;g) = \mathcal{T}_{mn}(f)\,|\mathrm{ETF}_{cl}(s;g)|^2 + \mathcal{T}_{ph,mn}(f)\,|\mathrm{NTF}_{cl}(s;g)|^2$$

ETF = error transfer function

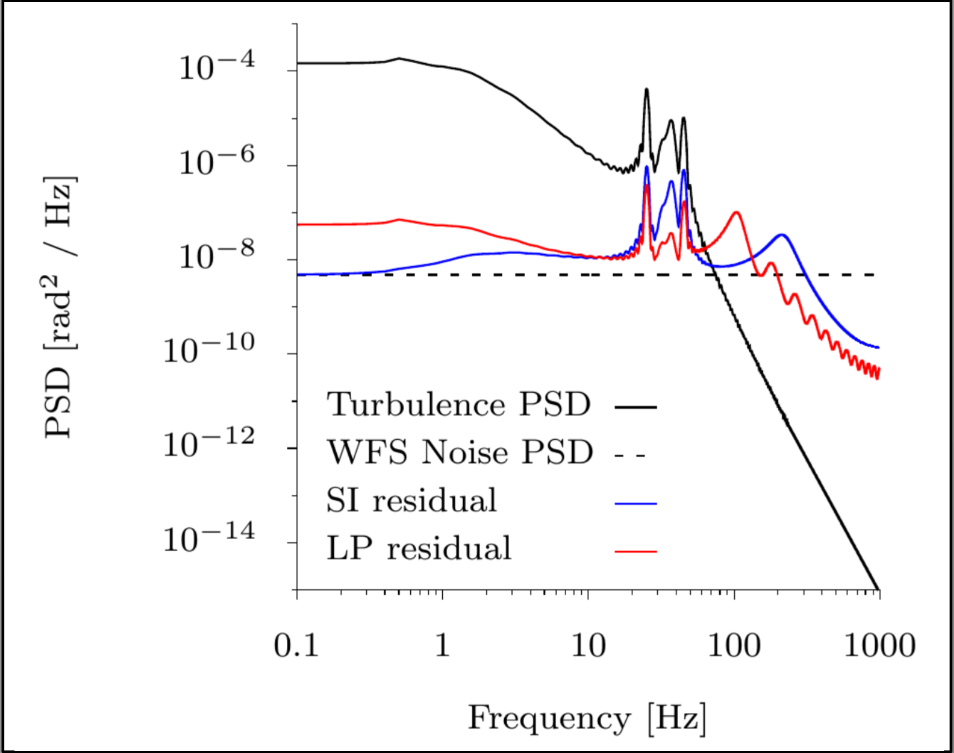
NTF = noise transfer function

- The residual variance, hence the contrast, is given by:

$$\left\langle h_{mn}^2 \right\rangle(g) = \int_0^{f_s} \mathcal{T}_{cl,mn}(f;g)\,df$$

- Goal: design system with variance minimizing ETF and NTF

Transfer Functions



Males & Guyon, JATIS, 2018

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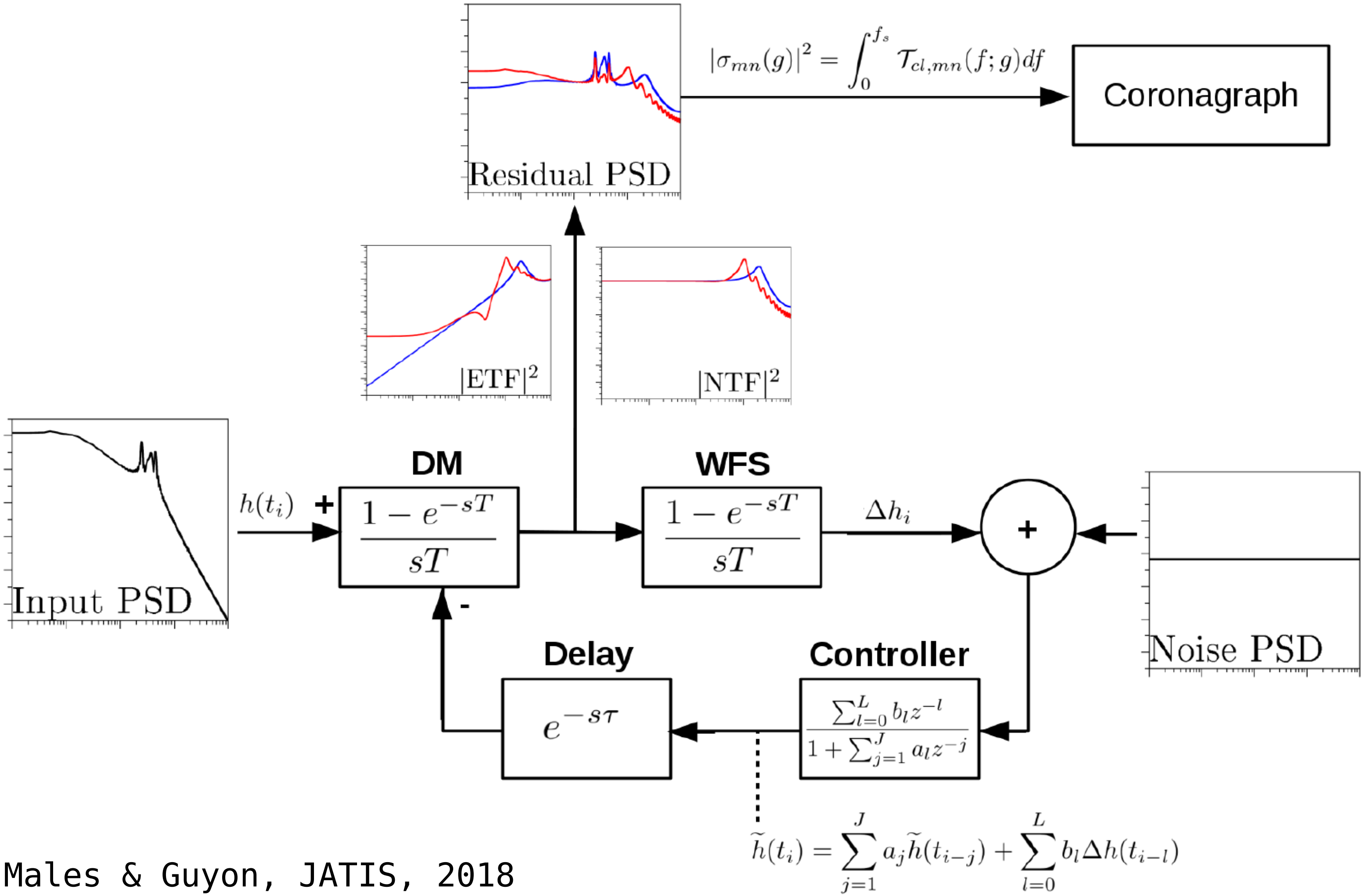
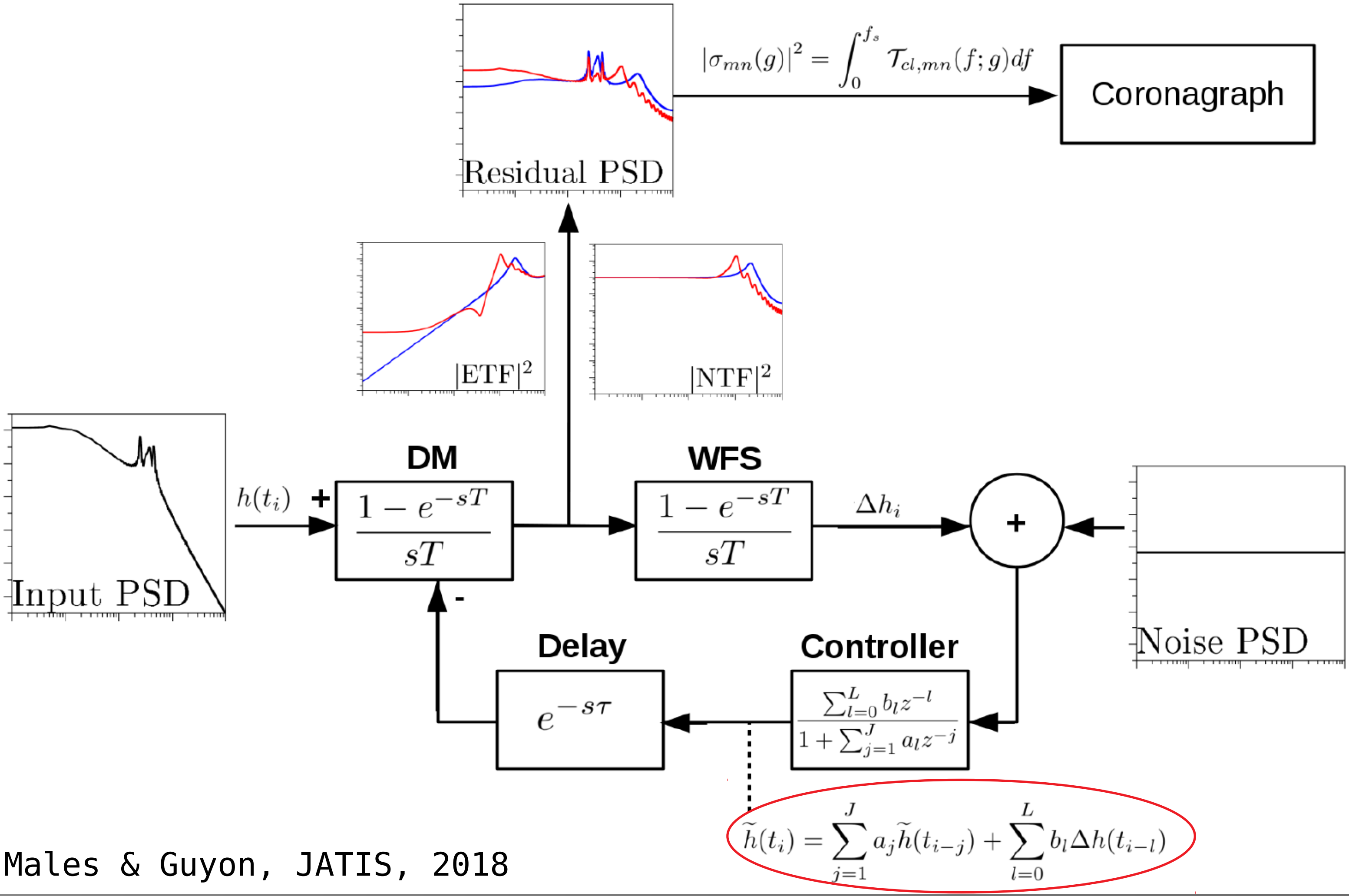
AO Control System



Males & Guyon, JATIS, 2018

AO Control System

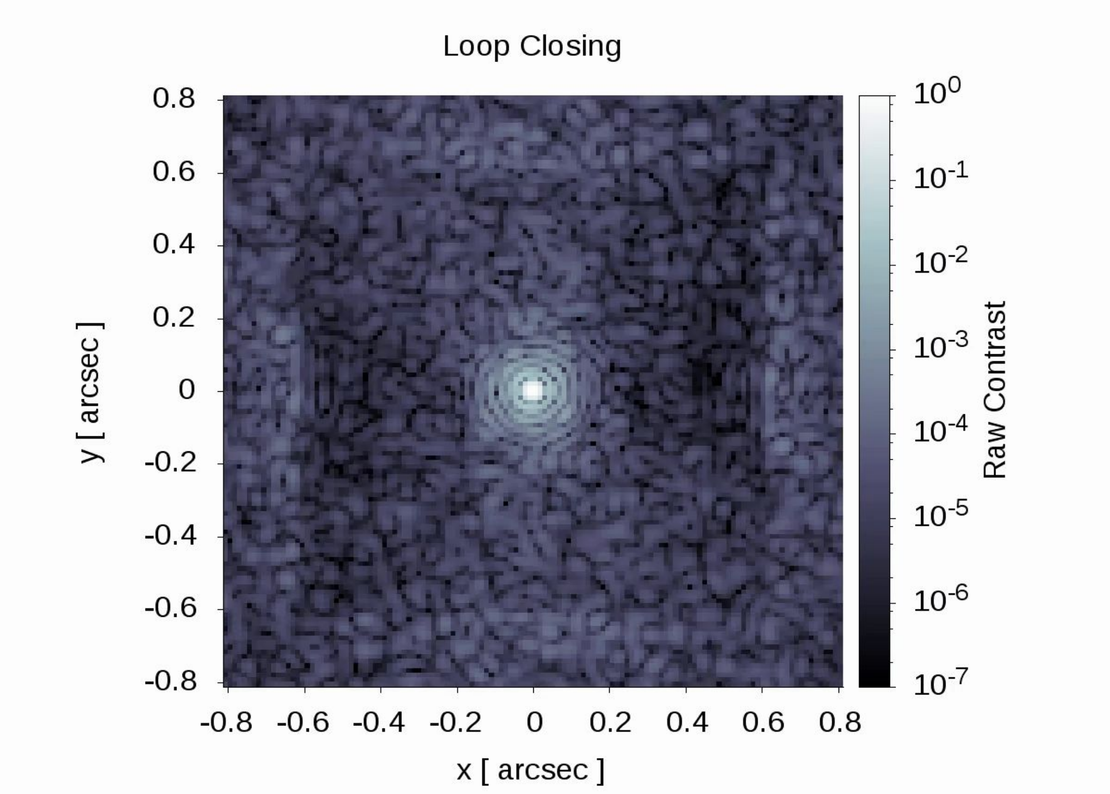


Males & Guyon, JATIS, 2018

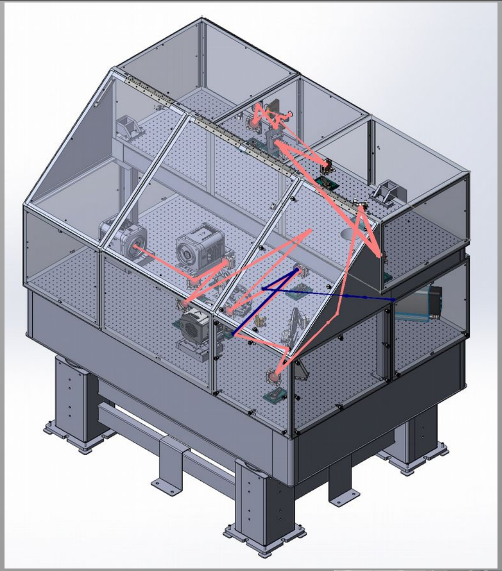
Control Law

- The control law calculates the command to apply to the DM based on the WFS measurements.
  - Simple Integrator: $\widetilde{h}_i = \widetilde{h}_{i-1} + g\Delta h_i$
  - General Integrator: $$\widetilde{h}(t_i) = \sum_{j=1}^{J} a_j \widetilde{h}(t_{i-j}) + g \sum_{l=0}^{L} b_l \Delta h(t_{i-l})$$
- Choosing an optimum set of coefficients is the subject of “predictive control”, which many studies have considered.
  - E.g. Dessenne et al. (1998), Poyneer et al. (2007) , Correia et al. (2017)
- We consider a method for determining the coefficients based on the Linear Prediction (LP) formalism using the input PSD.
  - See Males & Guyon (2018) for details . . .

Predictive Control In Action

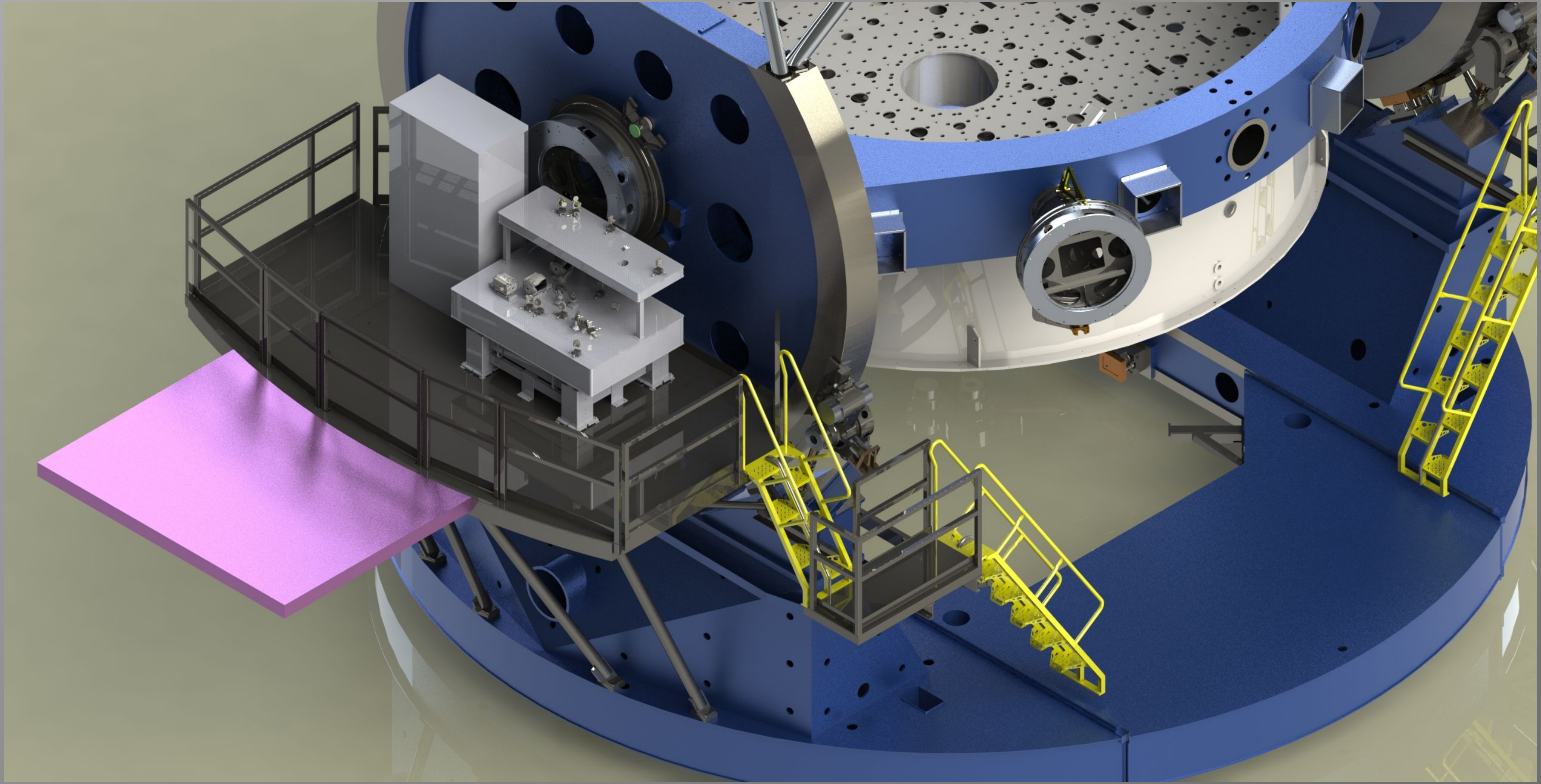


MagAO-X

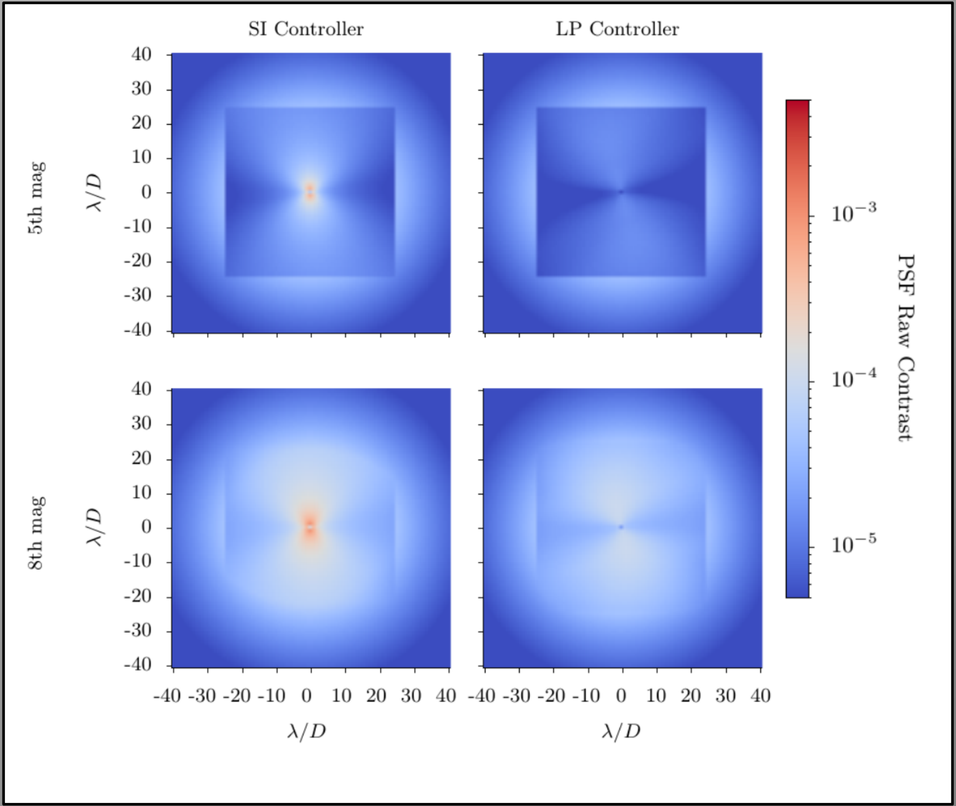


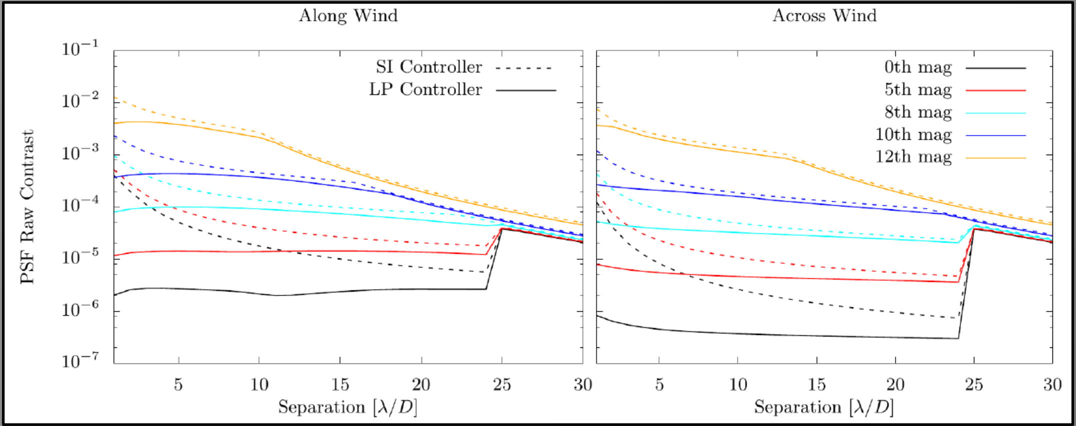
- NSF-MRI funded ExAO+Coronagraph
  - 2000 actuator BMC MEMS
  - 3.7 kHz Pyramid WFS
  - Suite of coronagraphs
    - vAPP (Leiden)
    - PIAACMC
  - Optimized for Vis-Near-IR
    - Young planets at Hα
- Integration in progress at UA
  - First-light spring 2019

MagAO-X

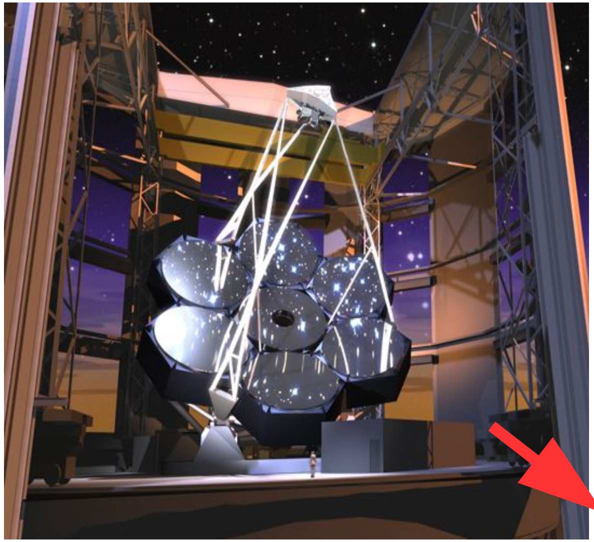


Residual Atmosphere: 6.5 m



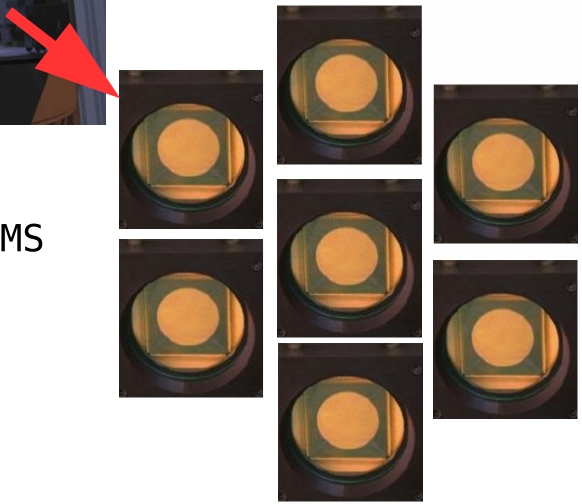


Contrast due to residual atmospheric speckles on a 6.5 m telescope.
see Males & Guyon, JATIS, 2018

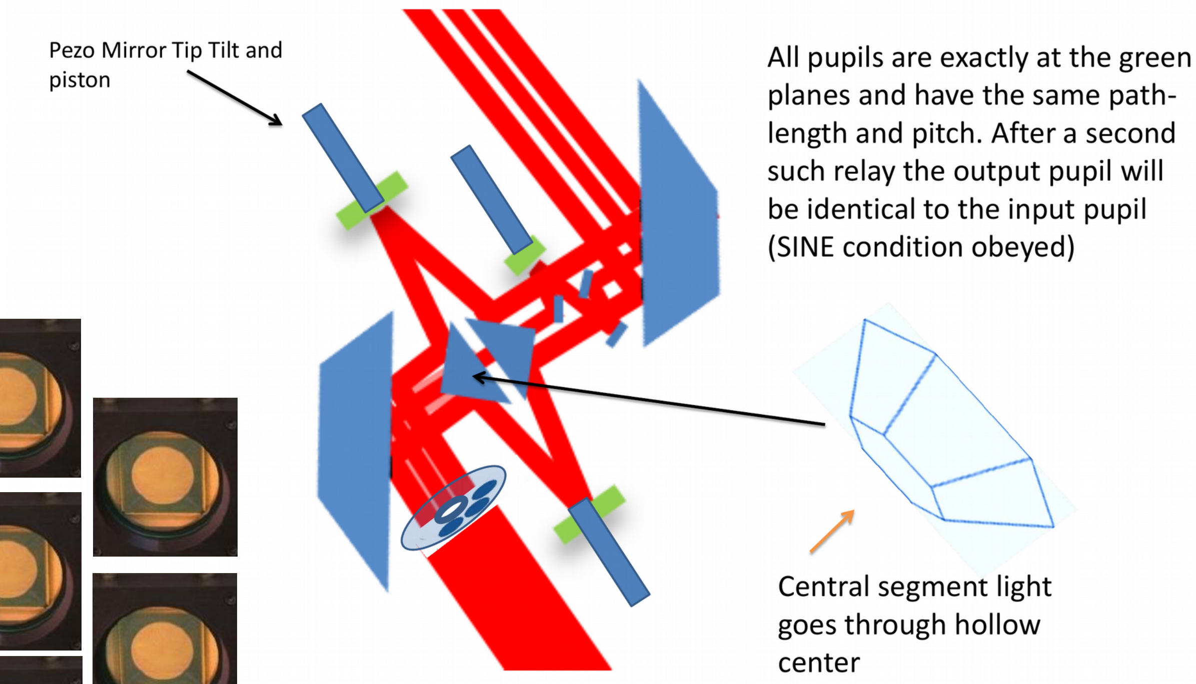


7x 3000 actuator MEMS

21,000 Actuators

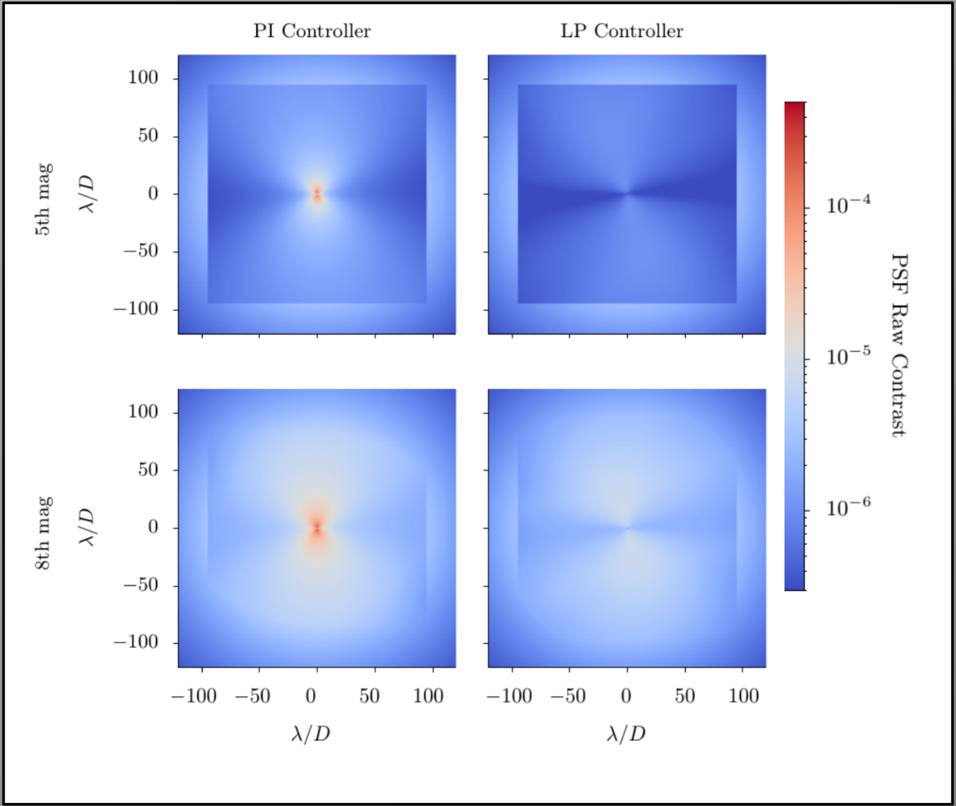


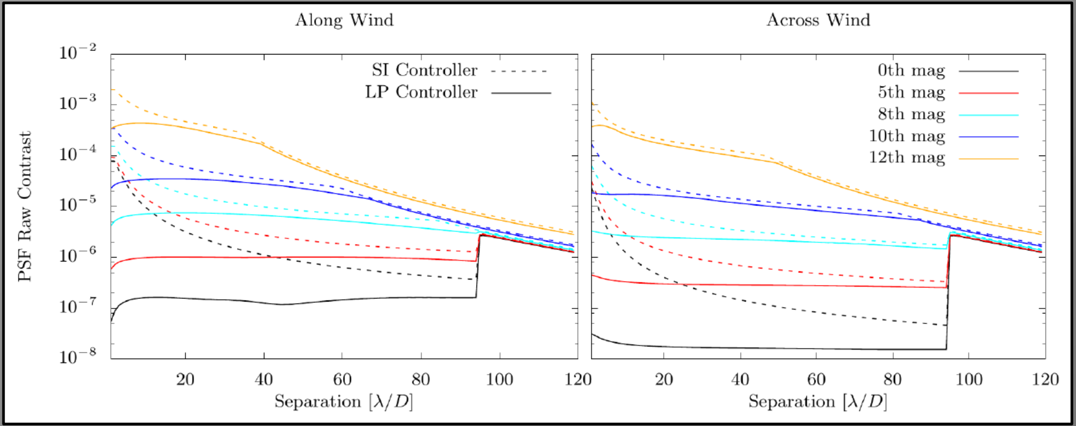
Scaling MagAO-X to the GMT



OptoMech conceptual design by L. Close

Residual Atmosphere: 25.4 m





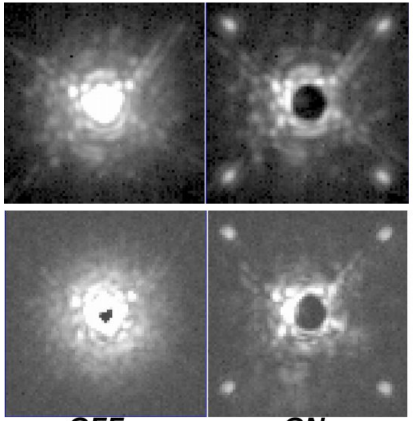
Contrast due to residual atmospheric speckles on a 25.4 m telescope.
see Males & Guyon, JATIS, 2018

How To Actually Do Predictive Control

- Make use of all available information – Sensor Fusion
  - Not just WFS
  - Accelerometers, FPWFS, etc.
- Empirical Orthogonal Functions (EOF)
  - A time-and-space PCA of all available information
  - Going back in time
  - See Guyon & Males 2017.

On sky proof of concept:
Guyon et al., in prep

On-sky results



← ***RAW***

← ***Std dev***

OFF ***ON***

Loop running at 2kHz, filter computed every 50sec

54 consecutives 0.5s images (26 sec exposure), 3 mn apart
Same star, same exposure time, same intensity scale

OFF = integrator, gain 20%

conditions: 1.5” seeing, ~35mph wind

Step 2: “Predict residual atmospheric speckle lifetime”

Speckle Lifetimes

- Now we're on step #2

- We'll define the statistical speckle lifetime by
  - Rate of increase of variance with time: $\sigma^2(t) = \sigma_o^2 \frac{t}{\tau}$
  - Or, equivalently, improvement in variance of the mean: $< |a_0|^2 >= \frac{\sigma_o^2}{t/\tau}$

- Historical note: this development started with ACESat (PIs Belikov and Bendek), trying to understand the power of post-processing over very long observations.

Variance of the Mean

- Noll (1976) calc. of statistics of a process given PSD
- Used Zernikes for 2D Kolmogorov PSD
  - Variance & co-var of amplitudes
  - Variance of process after correction of N Zernike modes.

Zernike polynomials and atmospheric turbulence*

Robert J. Noll
The Perkin-Elmer Corporation, Norwalk, Connecticut 06856
(Received 3 October 1975)

This paper discusses some general properties of Zernike polynomials, such as their Fourier transforms, integral representations, and derivatives. A Zernike representation of the Kolmogoroff spectrum of turbulence is given that provides a complete analytical description of the number of independent corrections required in a wavefront compensation system.

J. Opt. Soc. Am., Vol. 66, No. 3, March 1976

TABLE IV. Zernike-Kolmogoroff residual errors (Δ_J). (D is the aperture diameter.)

$\Delta_1 = 1.0299\ (D/r_0)^{5/3}$	$\Delta_{12} = 0.0352\ (D/r_0)^{5/3}$
$\Delta_2 = 0.582\ (D/r_0)^{5/3}$	$\Delta_{13} = 0.0328\ (D/r_0)^{5/3}$
$\Delta_3 = 0.134\ (D/r_0)^{5/3}$	$\Delta_{14} = 0.0304\ (D/r_0)^{5/3}$
$\Delta_4 = 0.111\ (D/r_0)^{5/3}$	$\Delta_{15} = 0.0279\ (D/r_0)^{5/3}$
$\Delta_5 = 0.0880\ (D/r_0)^{5/3}$	$\Delta_{16} = 0.0267\ (D/r_0)^{5/3}$
$\Delta_6 = 0.0648\ (D/r_0)^{5/3}$	$\Delta_{17} = 0.0255\ (D/r_0)^{5/3}$
$\Delta_7 = 0.0587\ (D/r_0)^{5/3}$	$\Delta_{18} = 0.0243\ (D/r_0)^{5/3}$
$\Delta_8 = 0.0525\ (D/r_0)^{5/3}$	$\Delta_{19} = 0.0232\ (D/r_0)^{5/3}$
$\Delta_9 = 0.0463\ (D/r_0)^{5/3}$	$\Delta_{20} = 0.0220\ (D/r_0)^{5/3}$
$\Delta_{10} = 0.0401\ (D/r_0)^{5/3}$	$\Delta_{21} = 0.0208\ (D/r_0)^{5/3}$
$\Delta_{11} = 0.0377\ (D/r_0)^{5/3}$	

$\Delta_J \sim 0.2944\, J^{-\sqrt{3}/2}\ (D/r_0)^{5/3}$ (For large J)

Variance of the Mean

- We can repeat Noll's analysis in 1-D with Legendre polynomials.
  - Express time-series as expansion in Legendre polynomials

$$a_n = \frac{2}{T}\int_{-T/2}^{T/2} I(t) P_n\left(\frac{2}{T}t\right) dt$$

  - Apply temporal PSD of process governing the time-series.

… bunch of math …

  - Derive covariance of coefficients:

$$< a_n^* a_{n'} >= -i^n i^{n'} \frac{\sqrt{2n+1}\sqrt{2n'+1}}{2T}\int_0^\infty \frac{J_{n+\frac{1}{2}}(2\pi k) J_{n'+\frac{1}{2}}(2\pi k)}{k} \mathcal{T}\left(\frac{2}{T}k\right) dk$$

  - Which gives variance of coefficient ***n***:

$$\boxed{< |a_n|^2 >= \frac{2n+1}{2T}\int_0^\infty \frac{J^2_{n+\frac{1}{2}}(2\pi k)}{k} \mathcal{T}\left(\frac{2}{T}k\right) dk}$$

Speckle Lifetime

- We can derive an expression for the correlation length of any process given its temporal PSD:

$$\boxed{\tau = \lim_{T\to\infty} \frac{\displaystyle\int_0^\infty \frac{J^2_{\frac{1}{2}}(2\pi k)}{k} \mathcal{T}\left(\frac{2}{T}k\right) dk}{\displaystyle 2\int_0^{f_{max}} \mathcal{T}(f) df}}$$

Males et al, in prep.

- Sanity check: if you plug in a white noise PSD, $\mathcal{T}(f) =$ constant, you get:

$$< |a_0|^2 > = \frac{\sigma_o^2 \Delta t}{T} = \frac{\sigma_o^2}{N}$$

Note: an alternative way to derive tau is to use the Wiener-Khinchin theorem to get the autocorrelation, and find tau as the integral of the A.C. (see Fitzgerald & Graham 2006). In practice, I’ve found this to be quite hard to implement with numerical PSDs.

Speckle Lifetime

- Getting to speckle intensity from Fourier amplitude

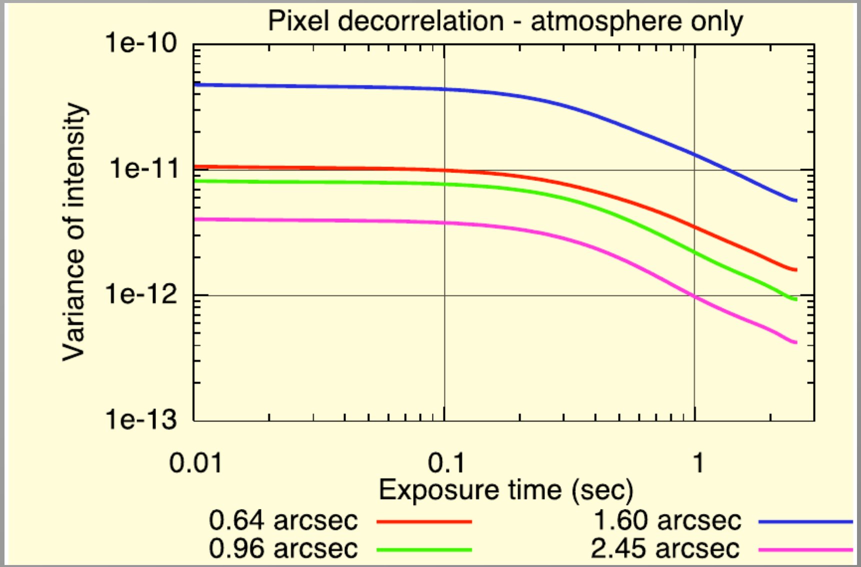
$$I_s \approx 2\left(\frac{\pi}{\lambda}\right)^2 \left(h_{mn}^{+\,2} + h_{mn}^{-\,2}\right)\left[\mathrm{PSF}(\vec{r} - \vec{k}_{mn}\lambda) + \mathrm{PSF}(\vec{r} + \vec{k}_{mn}\lambda)\right]$$

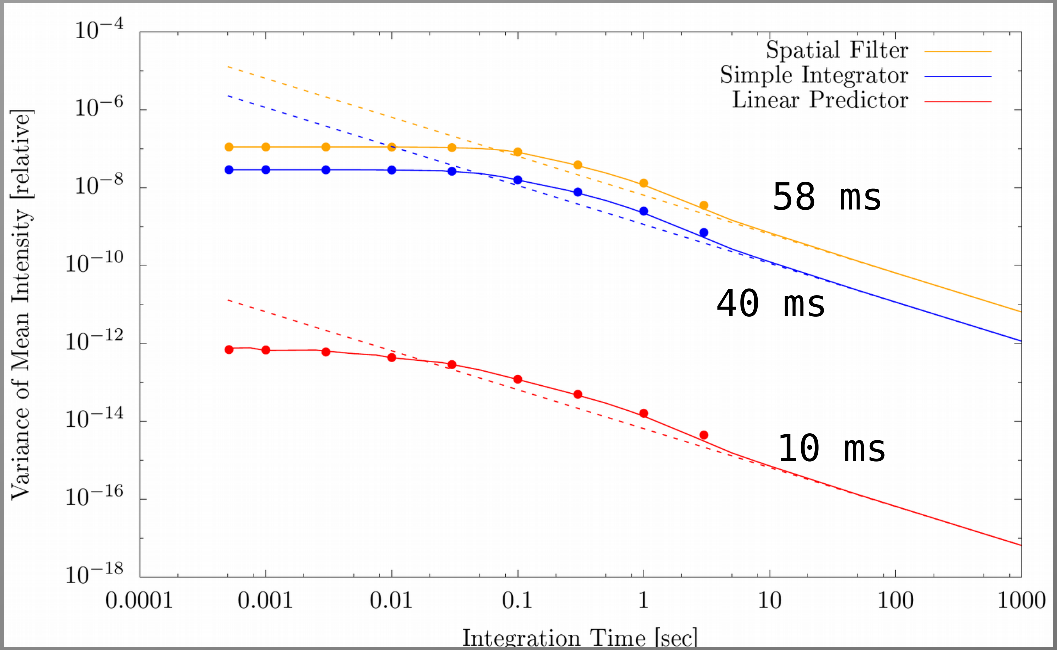
- From the closed-loop control analysis, we have the PSD of h, not h^2

- Brute force it:
  - 1) generate 2x random correlated time-series of h w/ closed-loop residual PSD of the Fourier mode amplitude
  - 2) calculate the periodogram: $\mathcal{T}_{I_s}(f) \propto \left|\mathcal{F}\left\{h_{mn}^{+\,2} + h_{mn}^{-\,2}\right\}\right|^2$
  - 3) repeat N times and average

Speckle Lifetimes

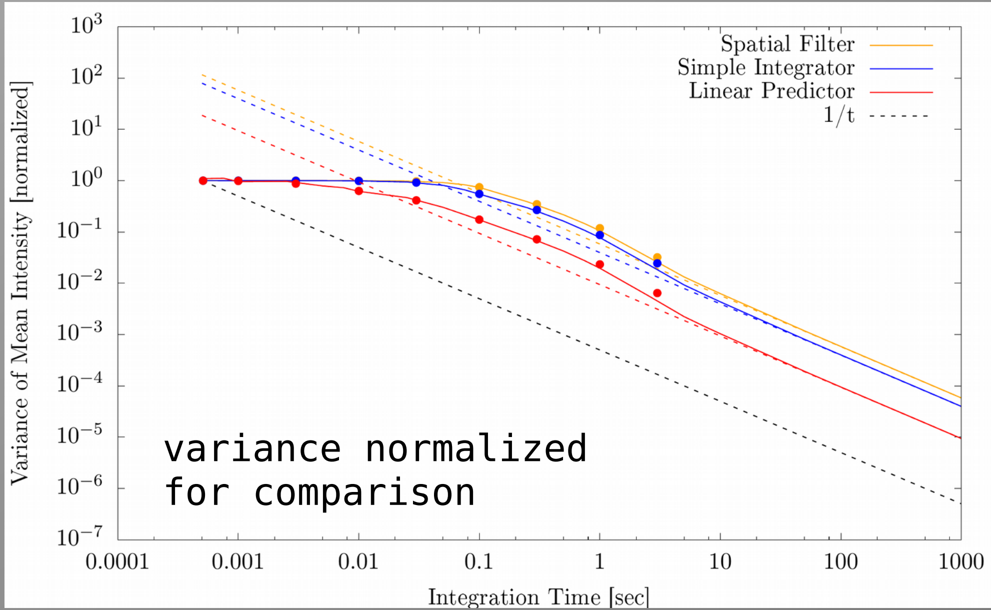
Macintosh+ 2005 (simulations):





Comparison to Macintosh et al (2005) “Crossing-Time Speckles”

Speckle Lifetimes

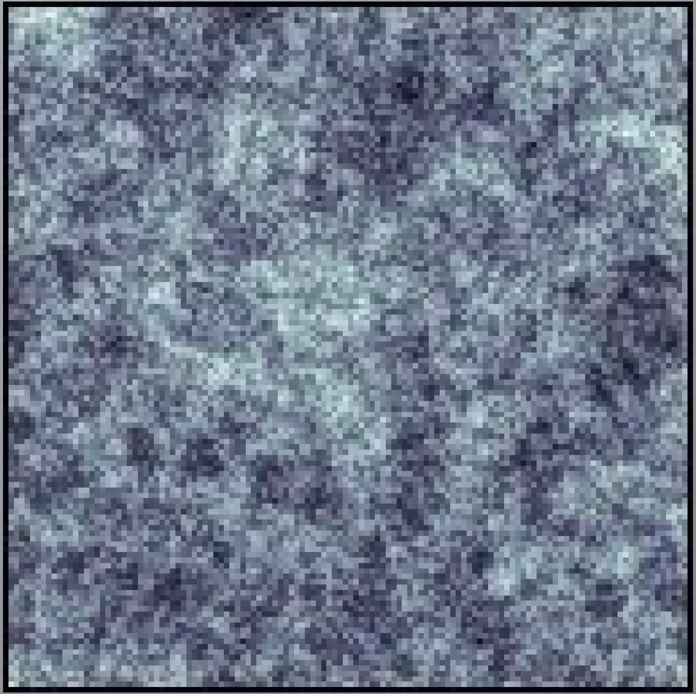


- Macintosh et al. (2005) ignored control dynamics (they acknowledged this)
- Concept of "crossing time speckle" is less useful with action of control law on PSDs
- Predictive Control significantly shortens speckle lifetime → faster averaging of noise (but still well above white noise)

Step 3: “Predict quasi-static speckle contrast”

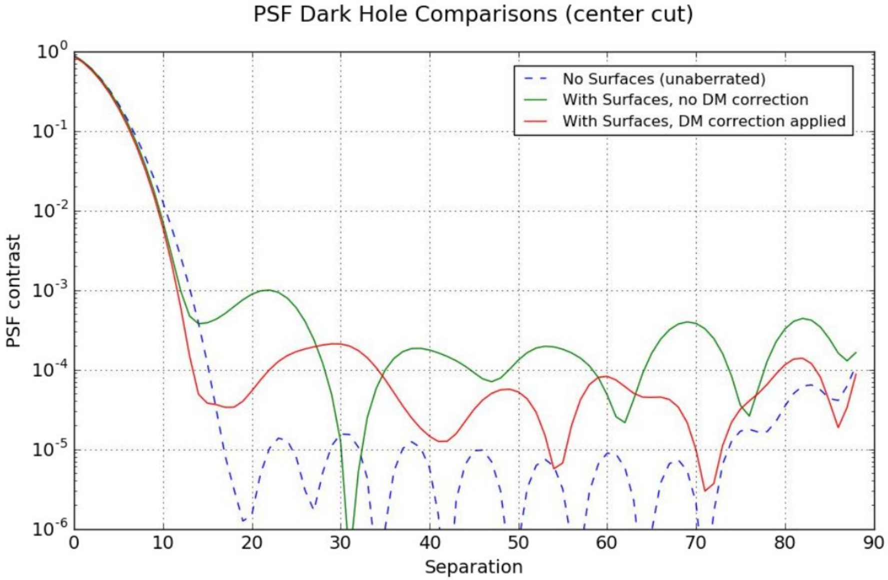
Step 4: “Predict quasi-static speckle lifetime”

Quasi-Static Speckles



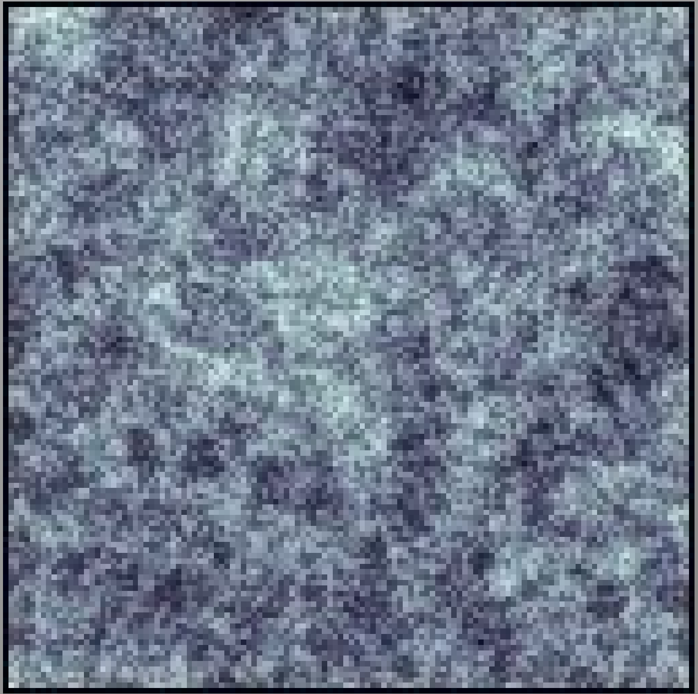
- Surface map based on MagAO-X design specs

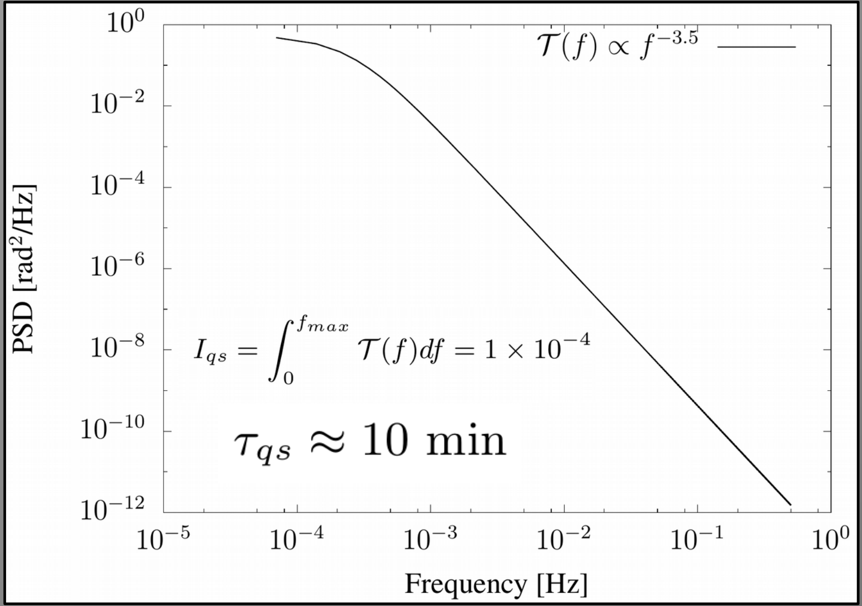
  ~1e-4 raw contrast



Fresnel analysis by J. Lumbres, UofA, for MagAO-X with vAPP coronagraph (designed by David Doelman at Leiden).

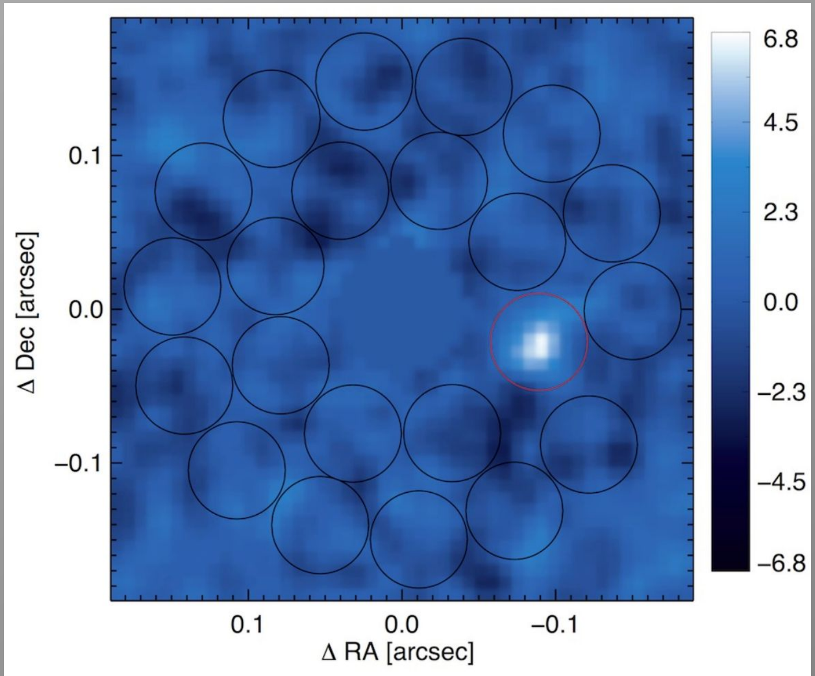
Quasi-Static Speckles





Quasi-static speckles with lifetimes of order 1 to 10 minutes commonly reported; e.g. Hinkley et al (2007), Martinez et al (2012), Milli et al (2016)

How To Take Data



LkCa 15b at Hα with MagAO+VisAO
Sallum et al, Nature, 2015

- Aperture Photometry
  - Measurement of background requires referencing a different spatial location → subject to speckle noise.
- High Dispersion Coronagraphy

  Snellen+ (2013), Mawet+ (2017), Wang+ (2017)

  - Measurement of continuum happens in-situ (across very small Δλ) → not subject to speckle noise

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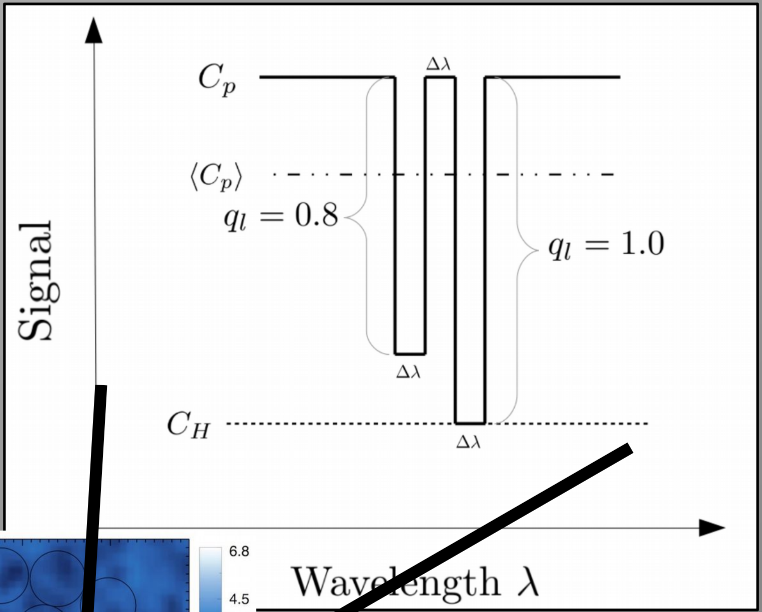

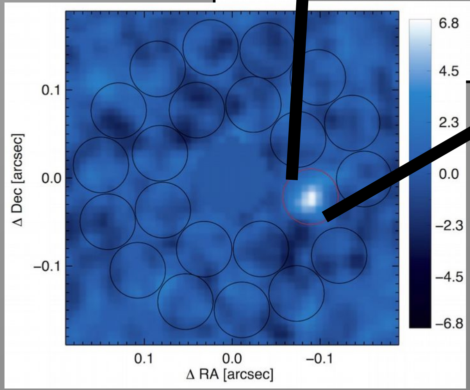

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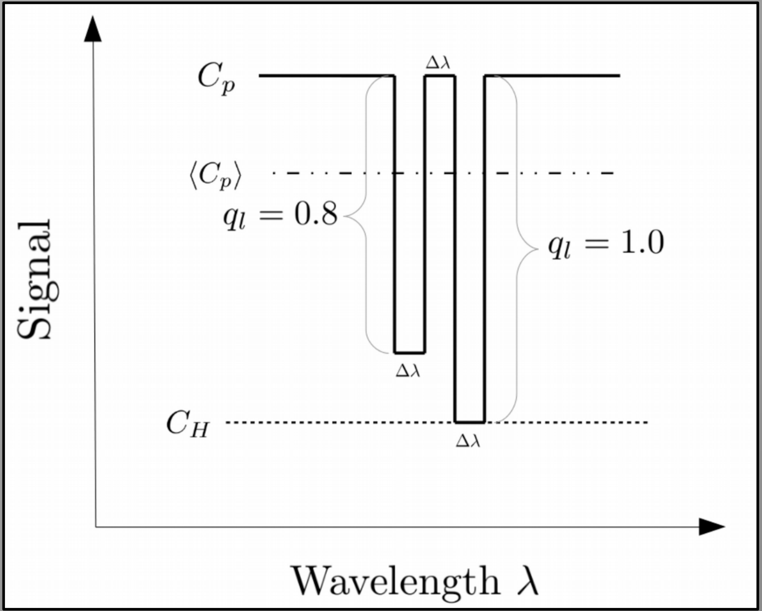


Toy model of stellar spectrum reflected by planet

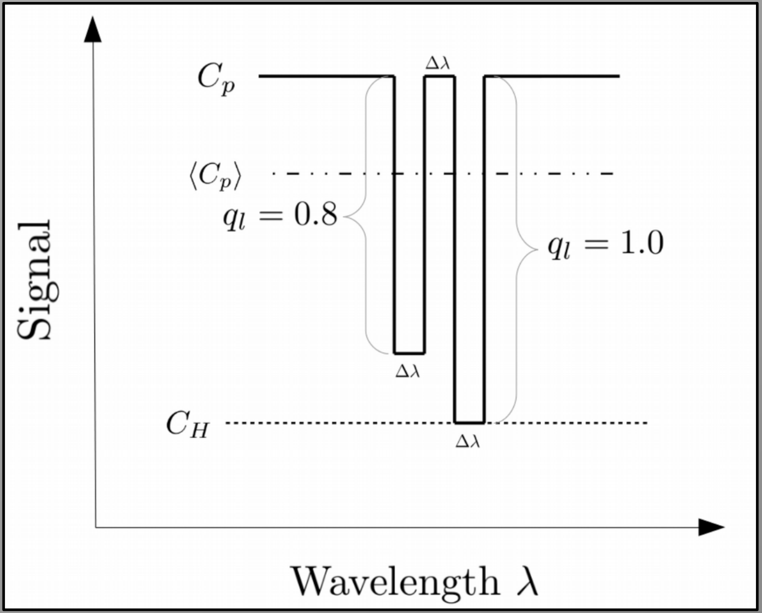
$$\frac{S/N_{HDC}}{S/N_{AP}} = \frac{\sqrt{\eta_{sp}}}{\left[1 - \frac{\Delta\lambda}{W_\lambda}\sum^{N_l} q_l\right]} \times \sqrt{\frac{\Delta\lambda N_{l,eff}}{W_\lambda}} \times \sqrt{1 + C_H F_* W_\lambda \tau_{sl}}$$

Comparison of S/N for the HDC vs AP techniques.

If this ratio is > 1 then we should do HDC.

Males et al., in prep

How To Take Data



Toy model of stellar spectrum reflected by planet

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efficiency

information content

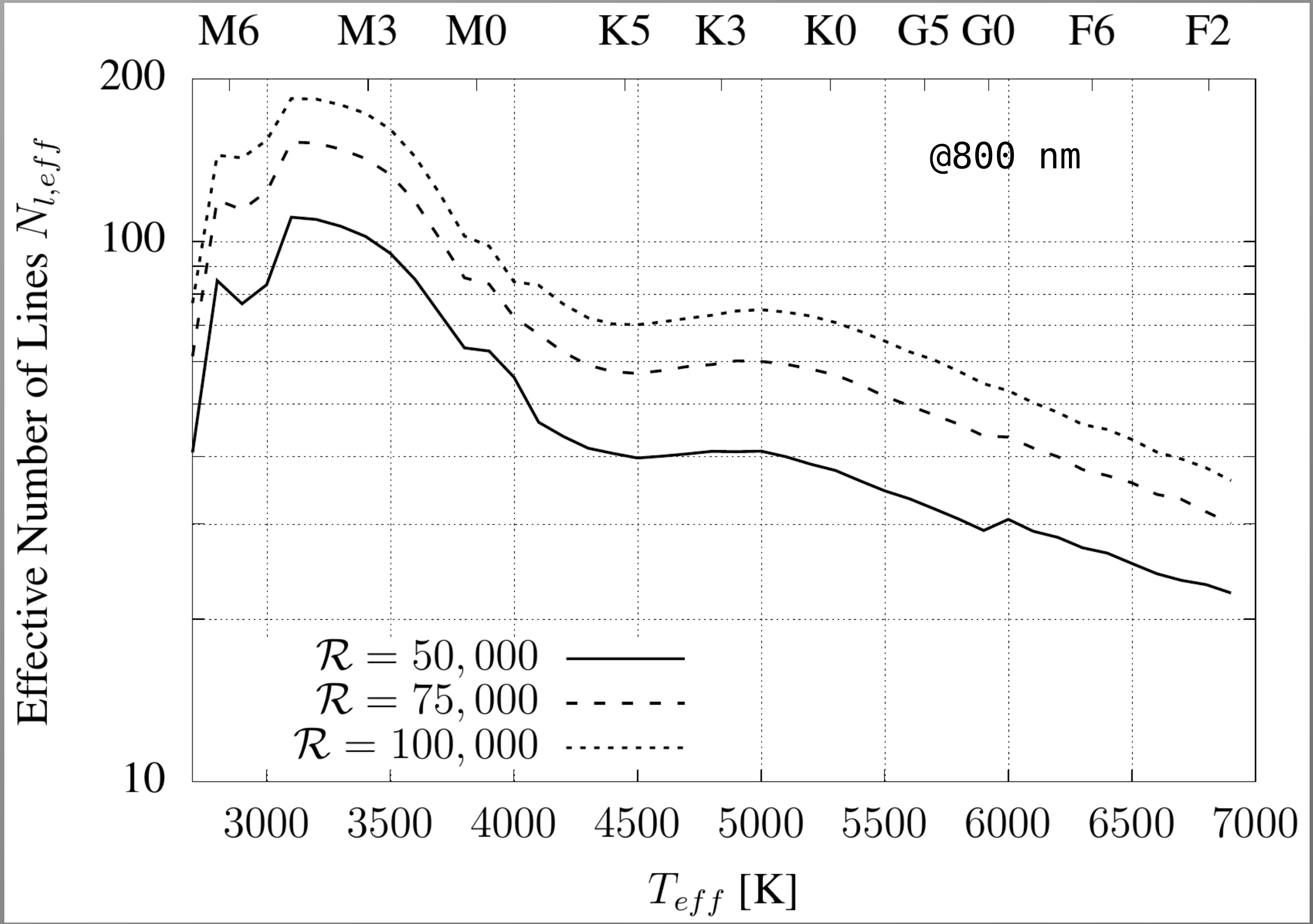
speckle noise

Males et al., in prep

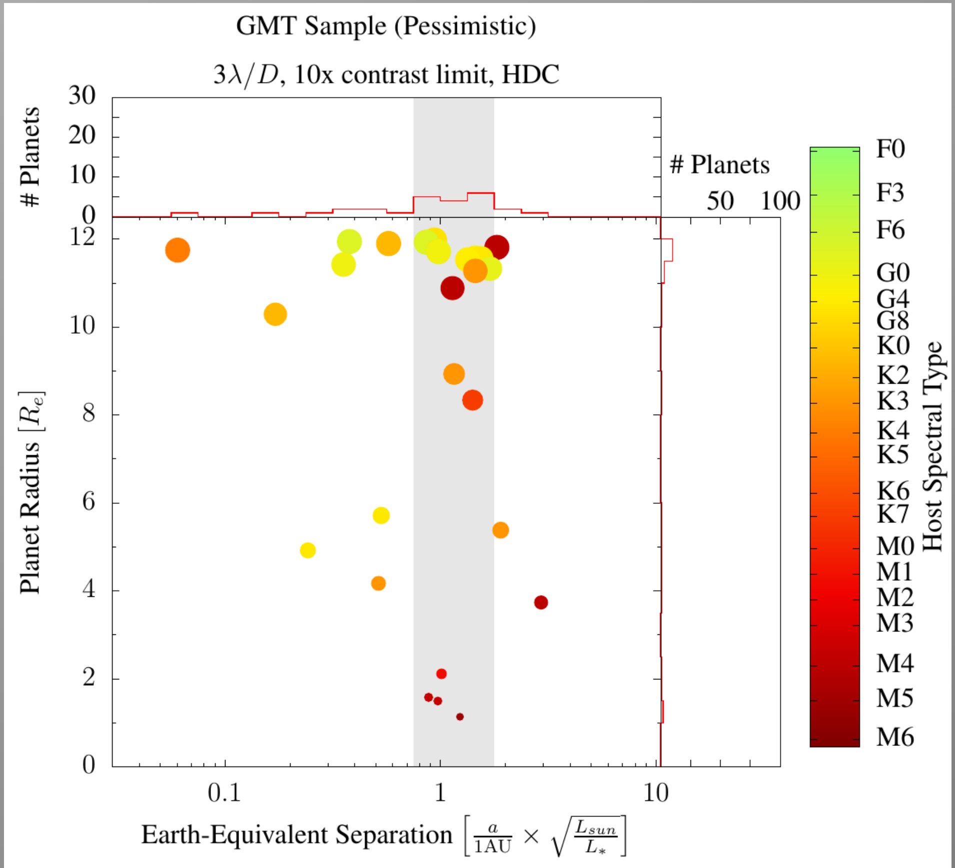
Sub-Optimal Performance ==> HDC

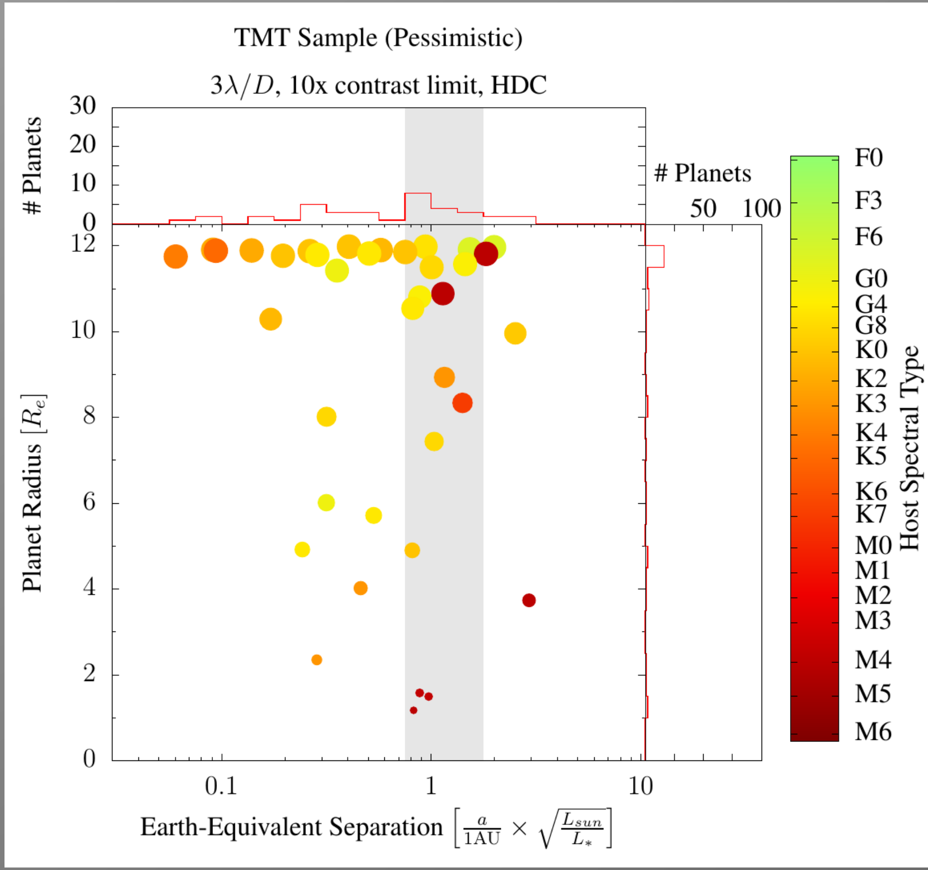
- Let's assume nothing works all that well:
  - Achieve only 10x the LP contrast
  - Residual is long lived speckles (~10 mins)
  - 3 λ/D IWA coronagraph
- And assume GMT and TMT
  - Observe known-from-RV planet hosts
  - In 25%-ile conditions for LCO and MKO
  - Science and WFS both @ 800 nm
  - 10% throughput, with noiseless detectors

HDC w/ Reflected Stellar Lines

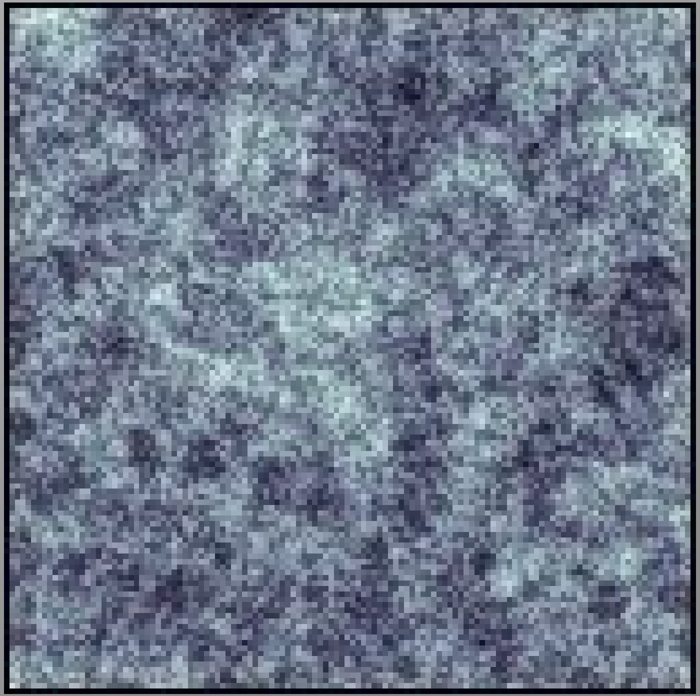


GSMT HDC Targets (reflected light albedo)





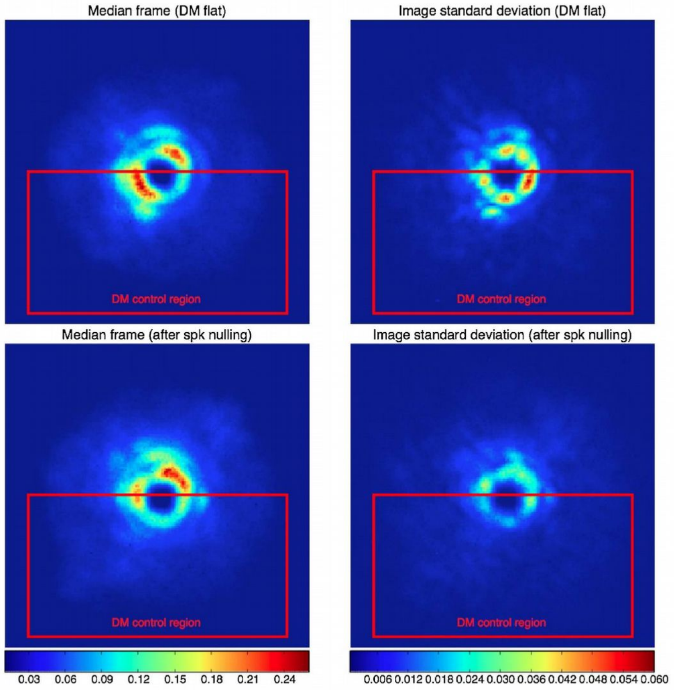
Control of Quasi-Static Speckles



- What if we implement a 1 Hz speckle control loop?
  - Analyze it with same tools we used for atmosphere

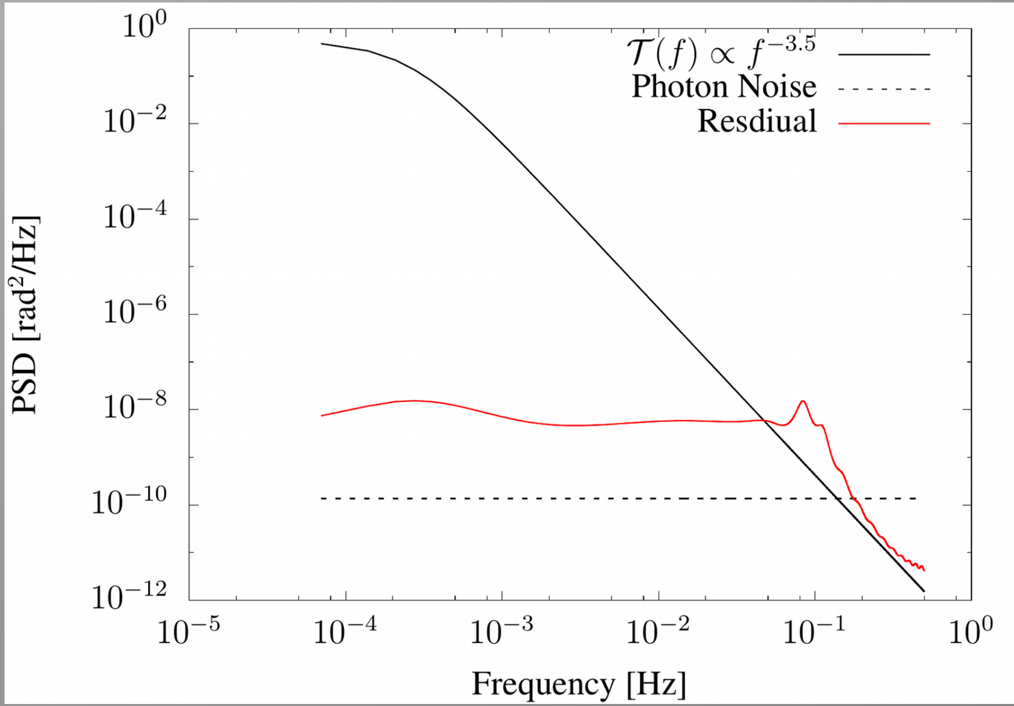
On-line Speckle Control

- On-line control of quasi-static speckles is not a new idea
- How fast can we run?
- Example: speckle nulling at SCExAO
  - Martinache et al (2014)
  - 30 Hz, using 30 probe frames
  - So getting to 1 Hz



On-sky demo of speckle nulling at ~1 Hz by Martinache et al (2014)

Control of Quasi-Static Speckles



- What if we implement a 1 Hz speckle control loop?
  - Analyze it with same tools we used for atmosphere
  - I_{qs} 1e-4 → 1e-9
  - τ_{qs} 10 min → 1 sec
- Now AP will be more efficient than HDC

Optimal Performance ==> AP

- Let's assume it all works really well:
  - Achieve the LP contrast prediction
  - Residual is short lived speckles (10 ms)
  - 1 λ/D IWA coronagraph
- And assume GMT and TMT (same as before)
  - Observe known-from-RV planet hosts
  - In 25%-ile conditions for LCO and MKO
  - Science and WFS both @ 800 nm
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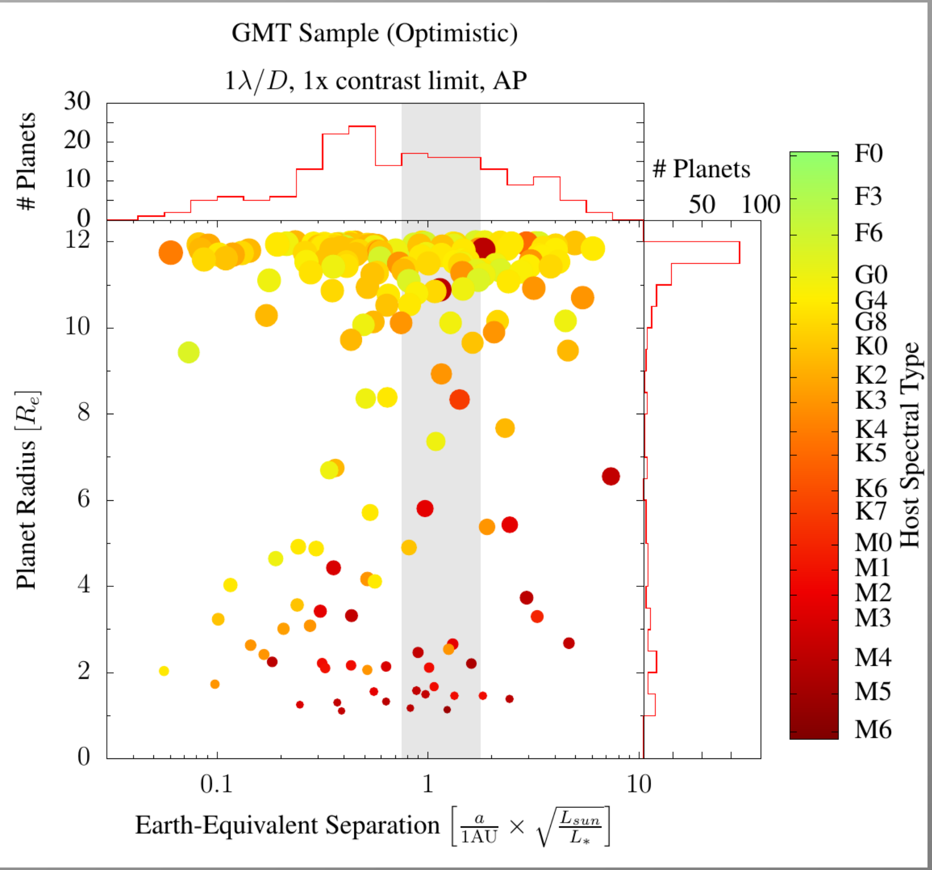
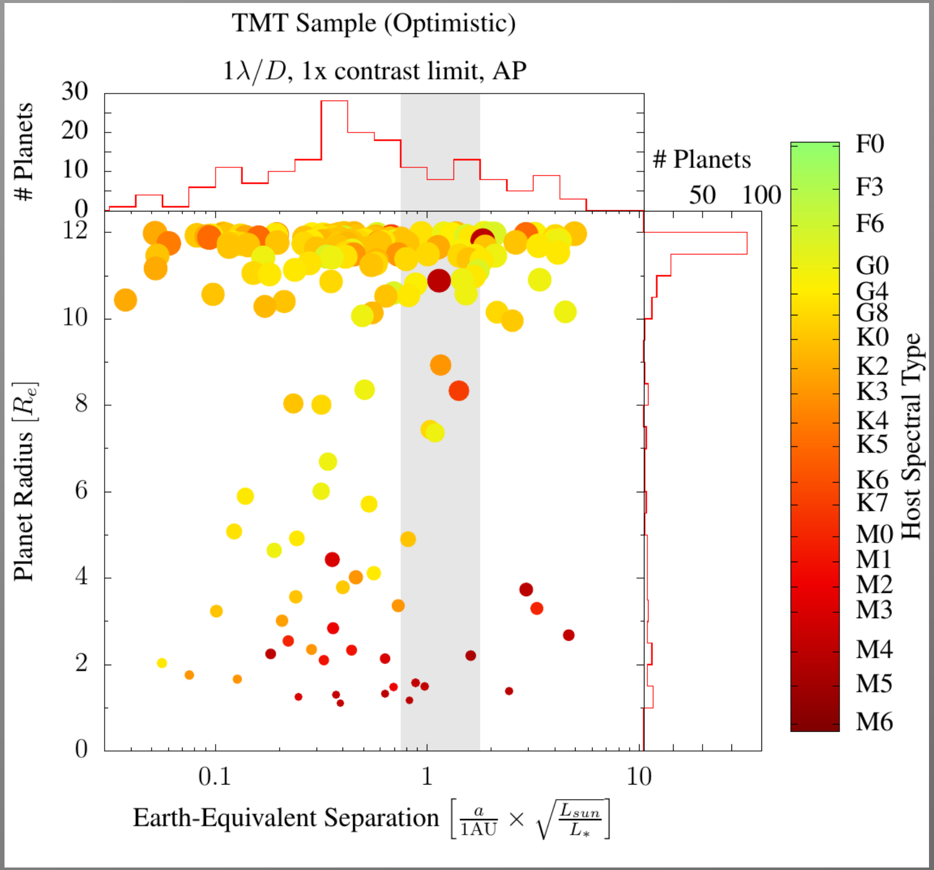
GSMT AP Targets (reflected light albedo)





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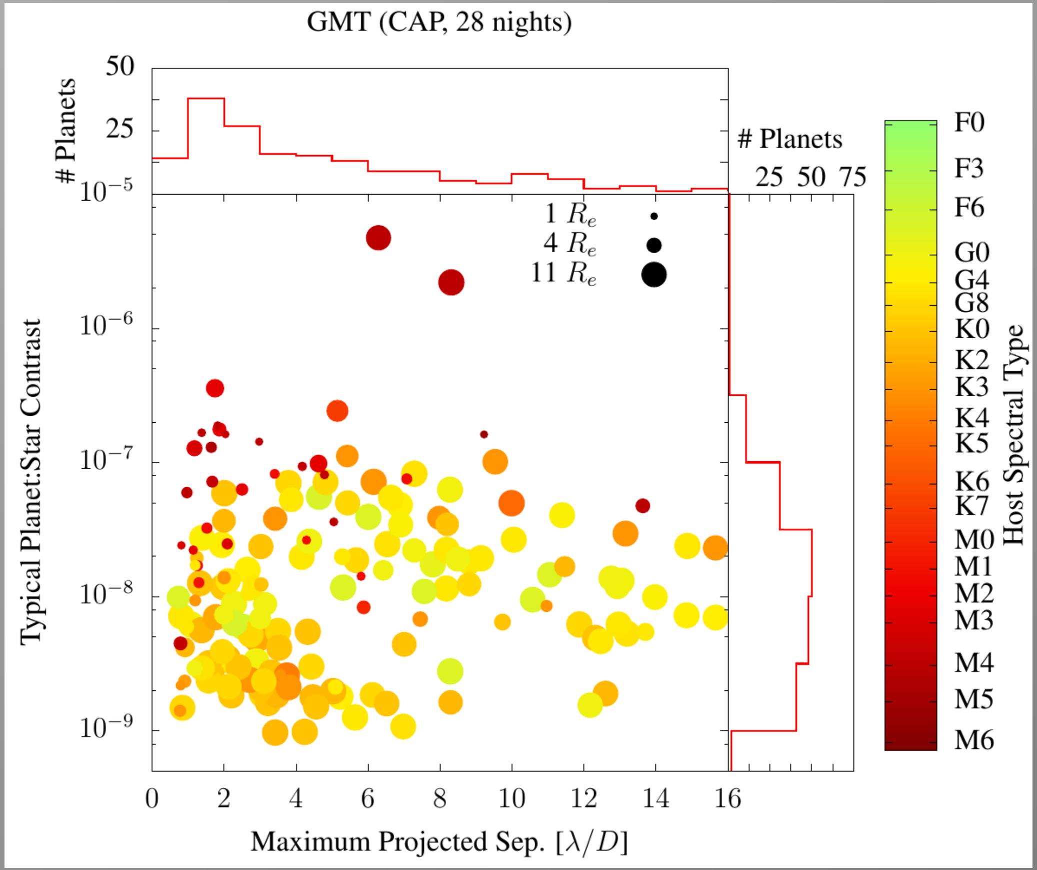
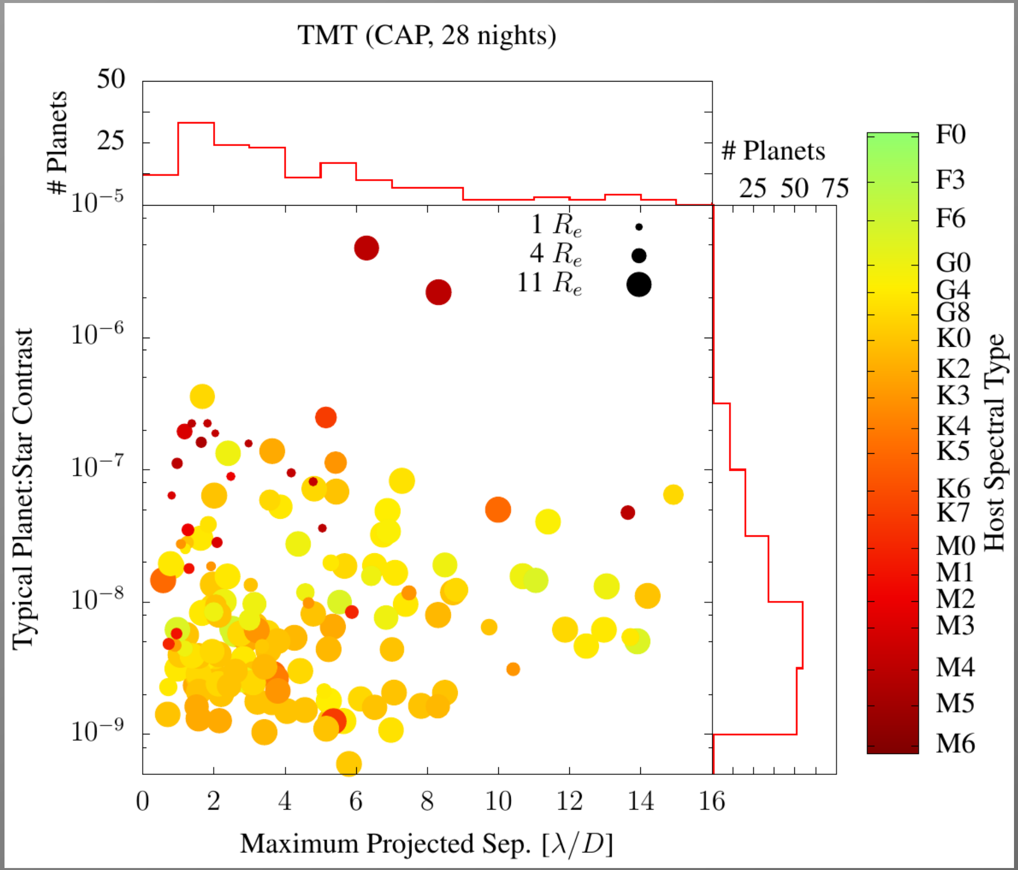
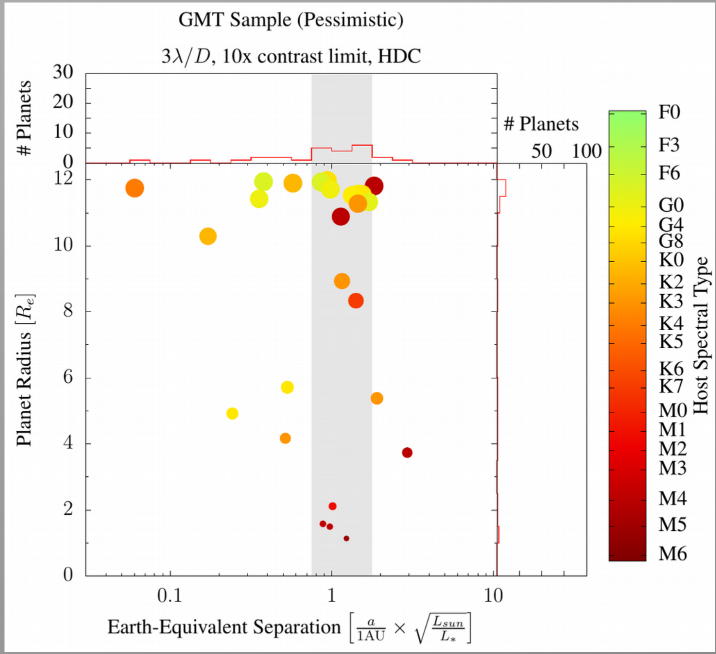




What Is Our Limit On The Ground?

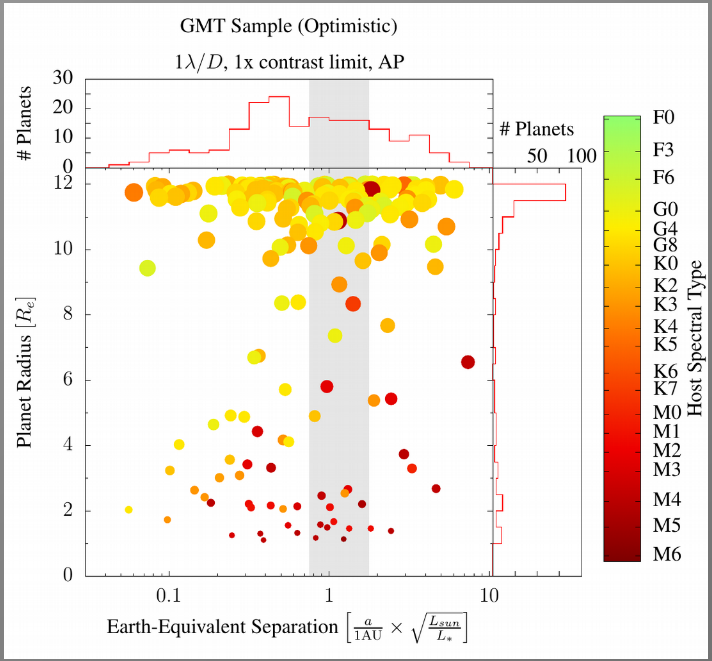


Long-lived quasi-static speckle limited → Using HDC

Ground-based telescopes will characterize something like

~40 to 300+

in reflected light



Short-lived atmospheric speckle limited → Using AP

On Post-Processing

- I have not considered Post-Processing in “fundamental” limits:

$$\sigma_{tot}^2 = F_*\Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) \cancel{+ \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right)} \right] \right\}$$

P.P. will only remove the long-lived terms – much better to remove Iqs before taking our images

- But, for long-lived speckles that we haven’t controlled, post-processing is the key to reducing their spatial variance.
- We should be able to cast the post-processing step into the temporal frequency domain as a filter.
  - See a first attempt at this in ODI (Males, Belikov, Bendek 2015).
- Any ideas on how to do this generally?

The Promise of Predictive Control

- Predictive Control offers great promise
  - Much better contrast (>10x on 8th mag star, > 1000x on bright stars)
    - See Correia 2017 for a different approach which reaches same conclusion
  - Significantly shortens speckle lifetime
  - But it’s hard…
    - Requires excellent calibration of system
    - WFS gain (which we know is variable)
    - Subtle details of system transfer functions really matter

Future Limits

- We should be able get the atmosphere out of the way
  - GMT raw contrast (@800nm and 25% conditions):
    - 1e-7 on 5th mag star
    - 1e-6 on an 8th mag star
  - 5-10 ms speckle lifetimes, will average!

- Comes down to in-instrument quasi-static speckles
- Should we be talking about moving HCIT to LCO & MKO?
  - If we can achieve optimum control of the atmosphere we will only be limited by instrumental aberrations…
  - Is that level of raw contrast motivating enough?