Direct imaging of exoplanets: signal and image processing advances

Lisa A. Poyneer (LLNL)
on behalf of the GPI Instrument and GPI Science teams

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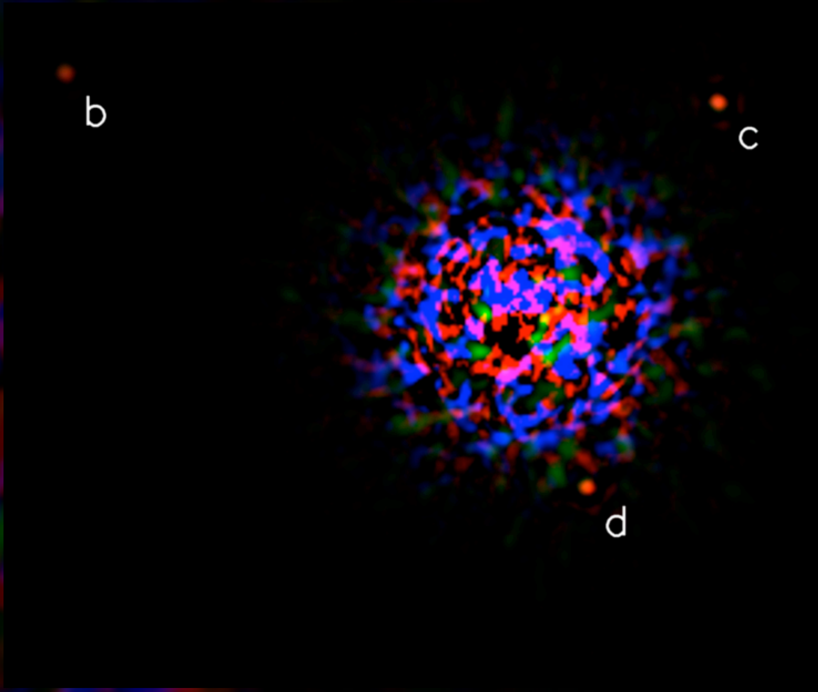
Ground-based images of planets



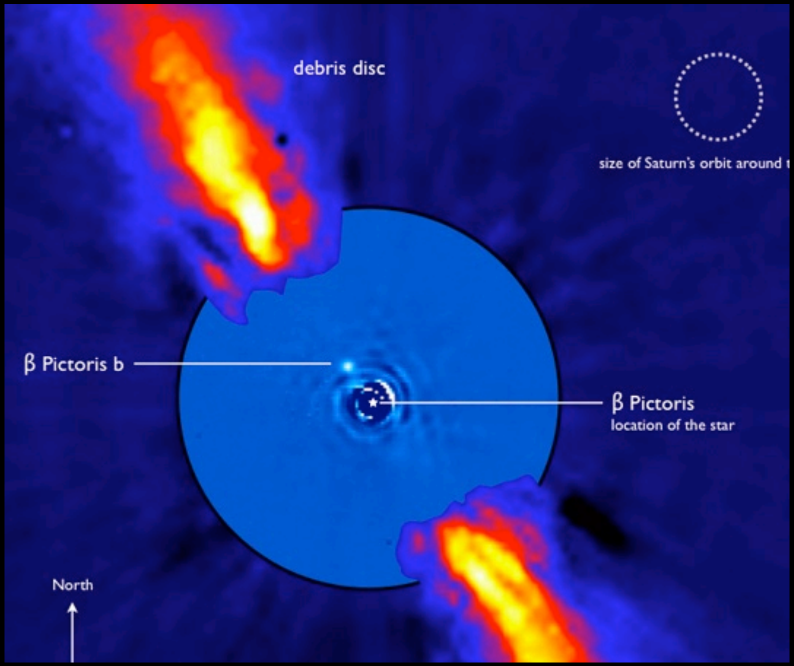
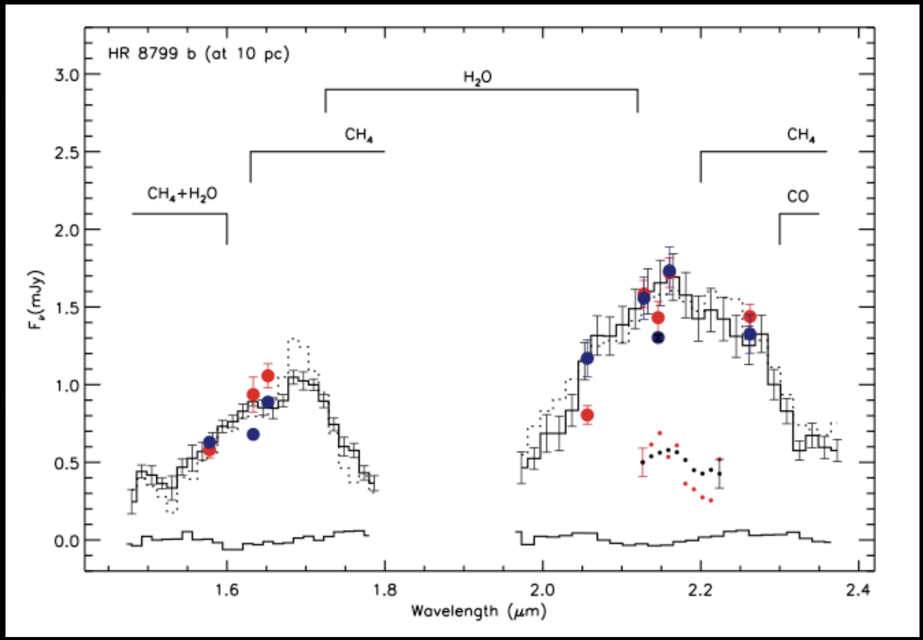


Image credits: HR 8799: C. Marois, Keck Obs.; NASA HST; Beta Pictoris: M. Lagrange, ESO

We want photons from the planet

- Indirect methods give us orbit, mass (and sometimes size)
- Claims on habitability are speculation (Earth vs Venus)
- Spectroscopic measurements of planetary light can tell us about temperature, chemistry, gravity...



Barman ApJ, (2011)

Adaptive optics removes the blur

- Corrects atmospheric turbulence in astronomy
- Corrects aberrations in the eye in vision science

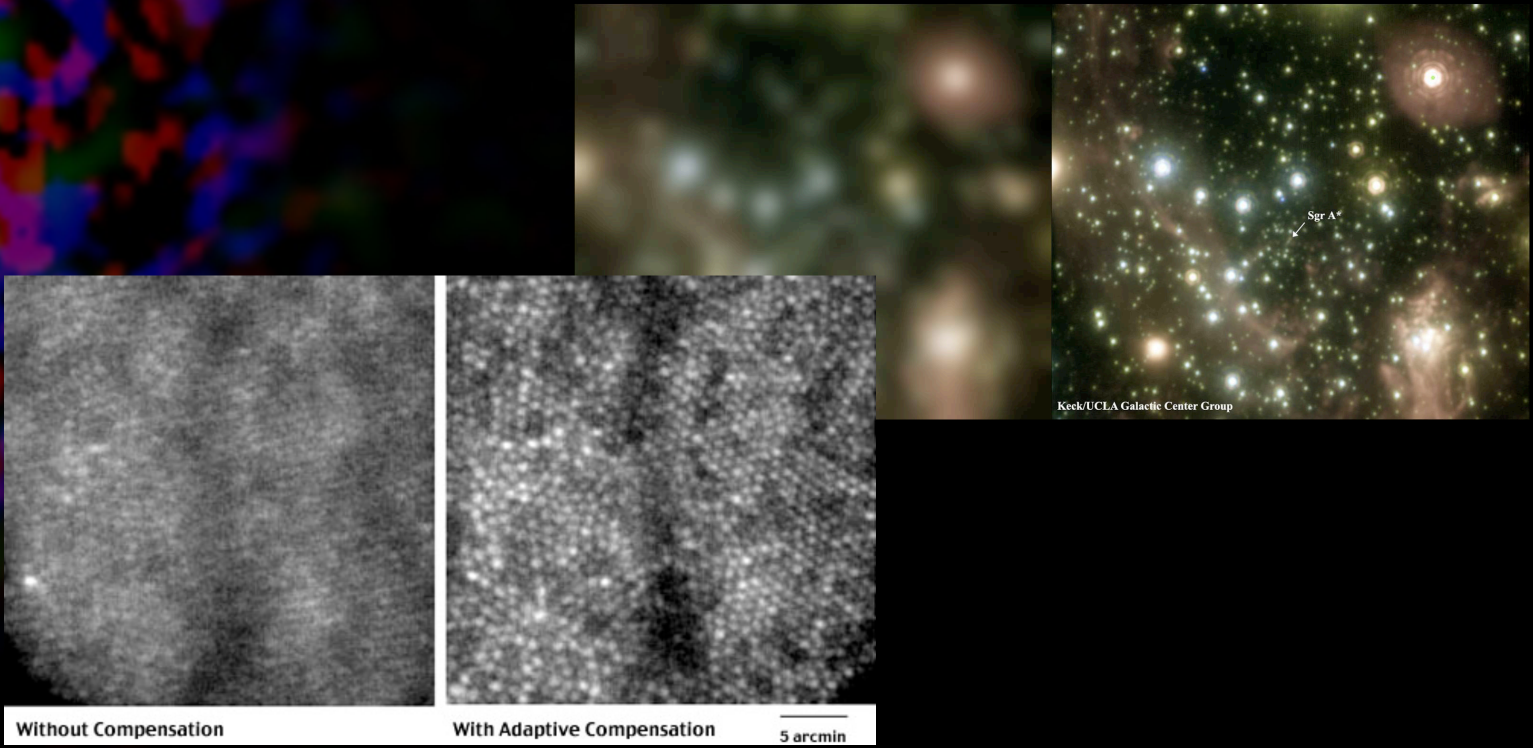
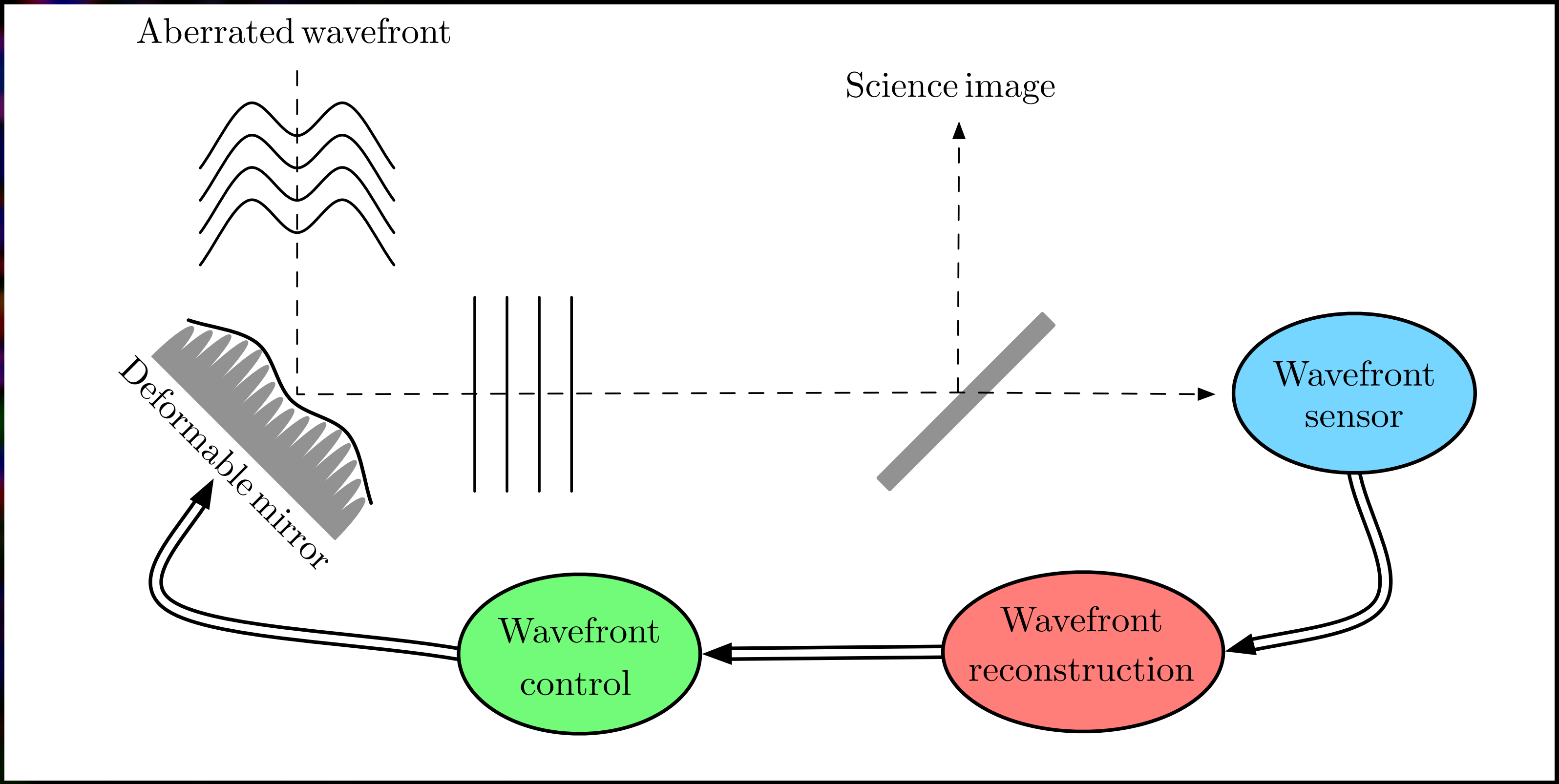


Image credits: Galactic Center: A. Ghez (UCLA), Keck Obs.; Retina: A. Roorda (UCB)

Measure and conjugate the phase



Block the star light

- Use a coronagraph to suppress diffraction
- Standard design by Lyot
- Many modifications and alternatives available (e.g. prolate spheroids) ...

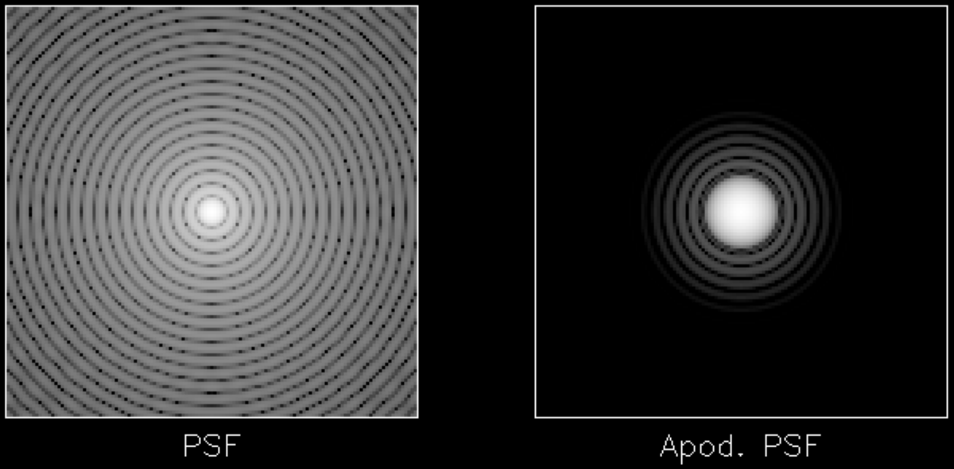
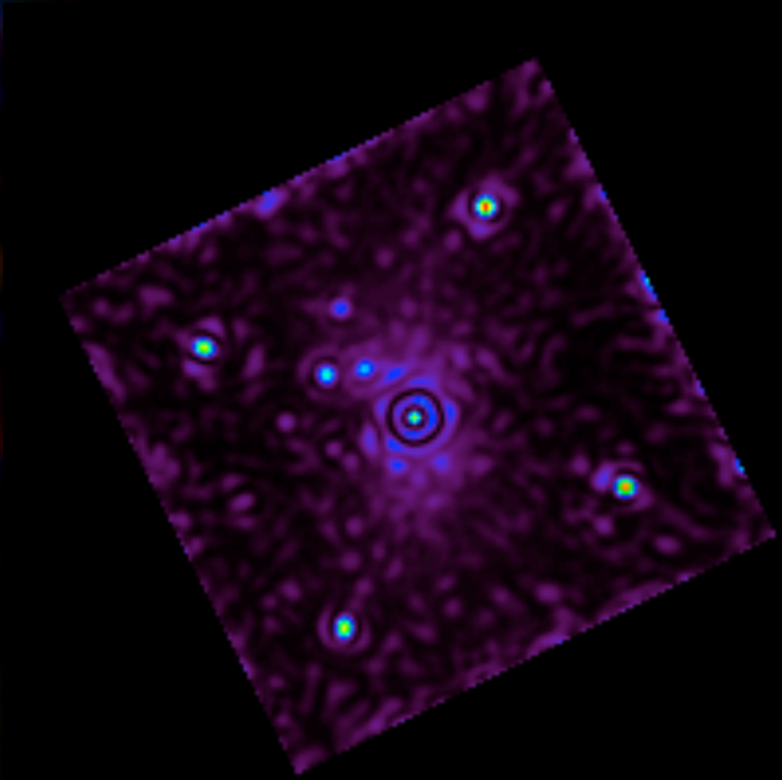


Image credits: Eclipse: DevianArt.net; PSFs: Bruce Macintosh

Diversity improves detections

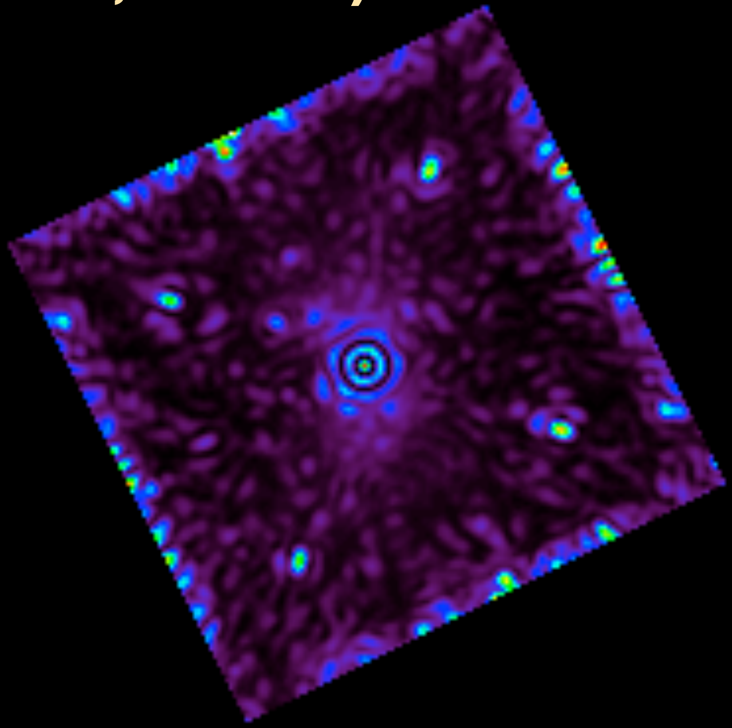
- As the telescope tracks, the planet moves ("roll deconvolution": Sparks or "ADI": Marois)



Simulation utilizes the GPI Data Simulator (thanks to J. Maire and M. Perrin)

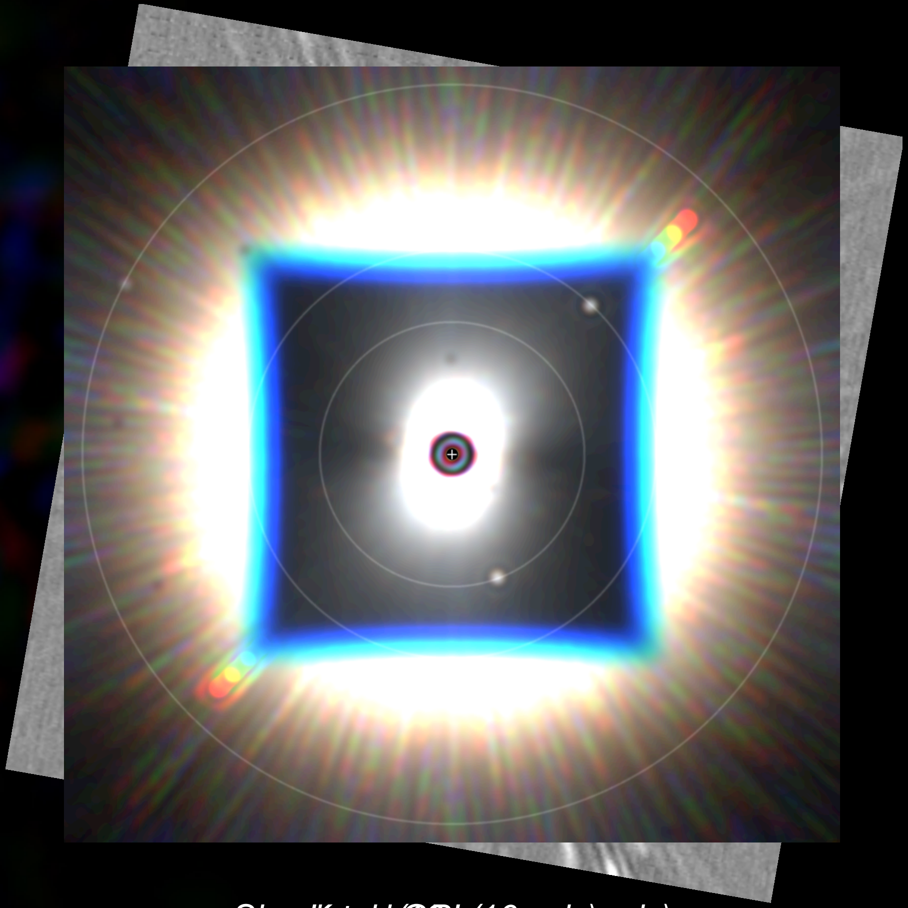
Diversity improves detections

- The position of the star and planet remain stationary with wavelength, but speckles move ("SDI": Racine, Marois)



Simulation utilizes the GPI Data Simulator (thanks to J. Maire and M. Perrin)

HR 8799... and beyond



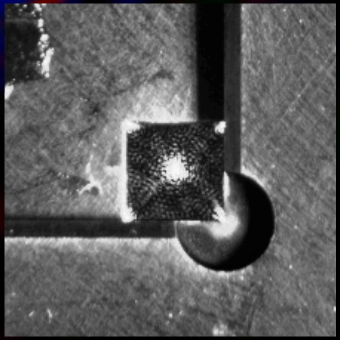
Simulated GPI (10 seconds)

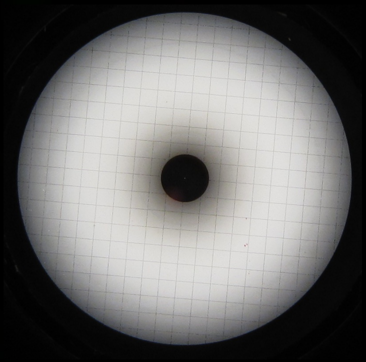
Keck (10 seconds)

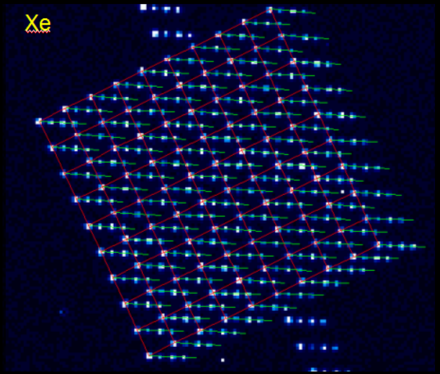
All images/simulations courtesy of Christian Marois (HIA)

Gemini Planet Imager

- GPI is a science experiment: 890 hours for a three-year survey of 600 target stars
- World’s most advanced AO system
- Improved Lyot coronagraph
- Integral field spectrograph for detection and characterization
- Calibration interferometer for low static error

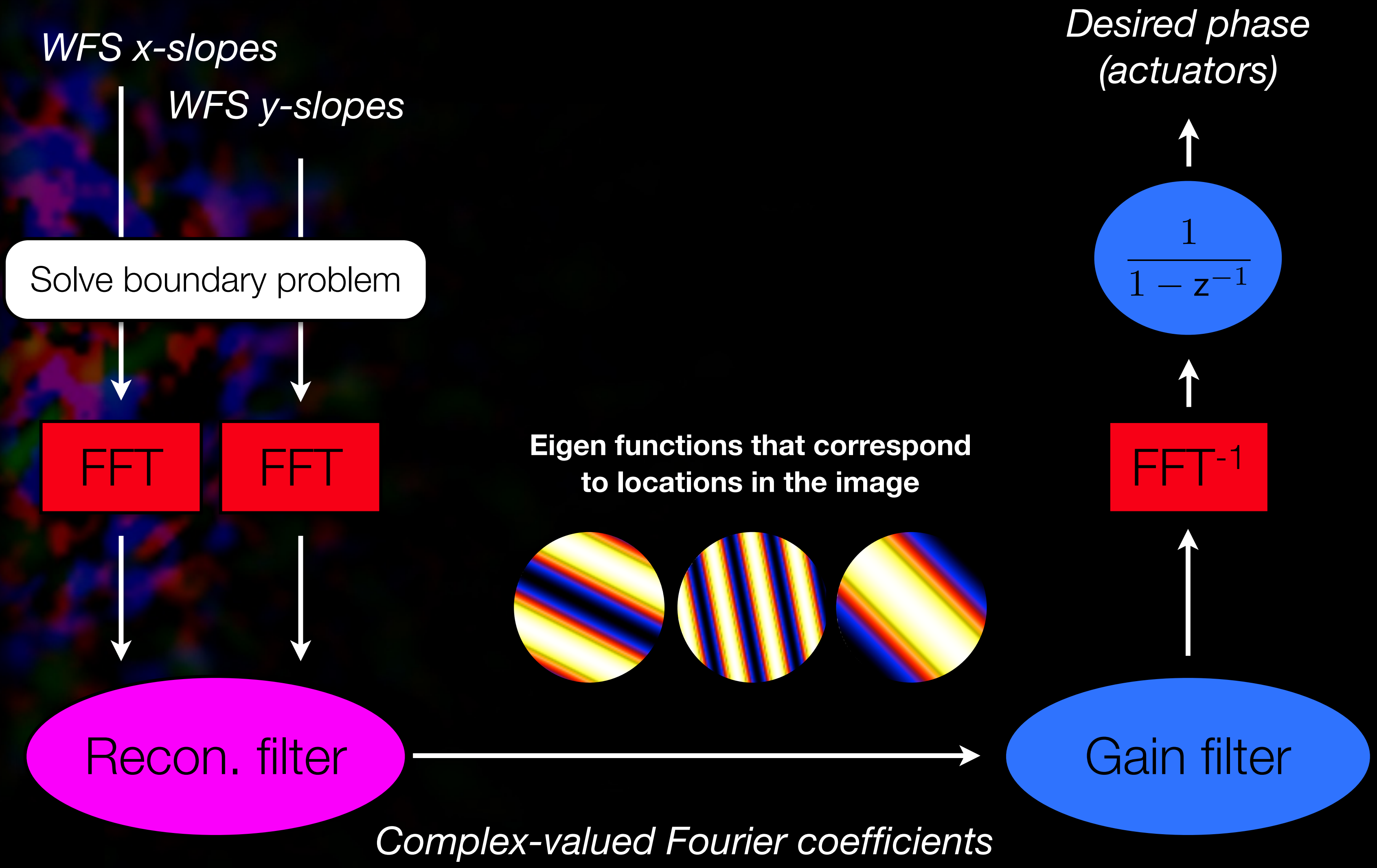






Spatial filter photo from S. Thomas and B. Macintosh; PPM image courtesy of R. Soumer; IFS optics test images from U. Montreal.

Reconstruct in Fourier space



WFS x-slopes

WFS y-slopes

Solve boundary problem

FFT

FFT

Recon. filter

Eigen functions that correspond to locations in the image

Complex-valued Fourier coefficients

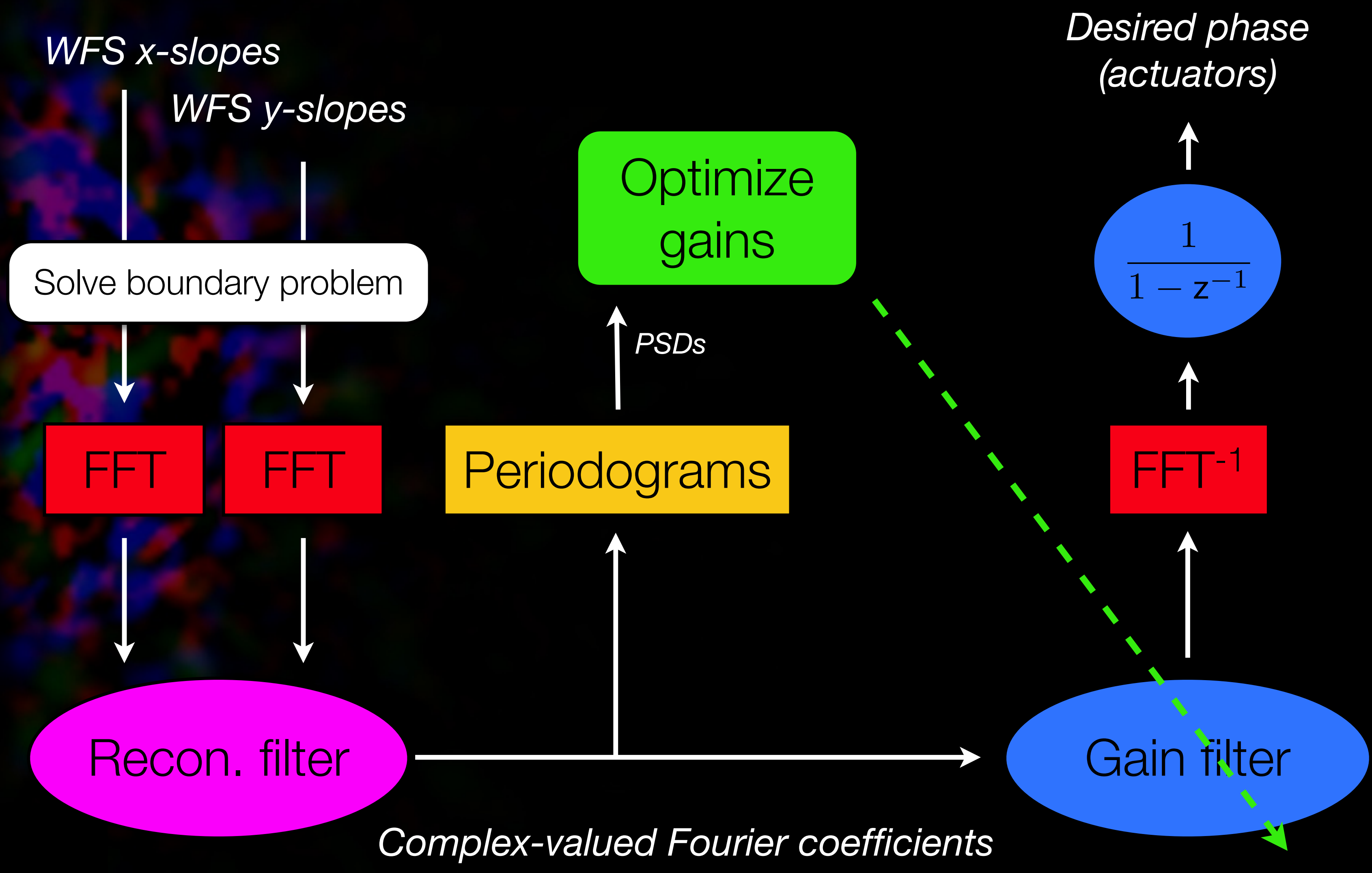
Gain filter

FFT^{-1}

$$\frac{1}{1 - z^{-1}}$$

Desired phase (actuators)

Data-driven optimization



WFS x-slopes

WFS y-slopes

Solve boundary problem

FFT

FFT

Recon. filter

Complex-valued Fourier coefficients

Periodograms

PSDs

Optimize gains

Gain filter

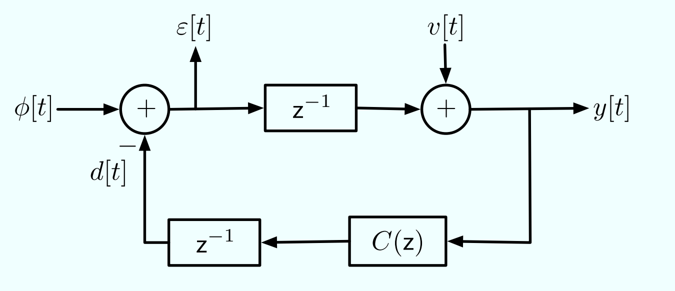
FFT^{-1}

$$\frac{1}{1-z^{-1}}$$

Desired phase (actuators)

Use a control system model

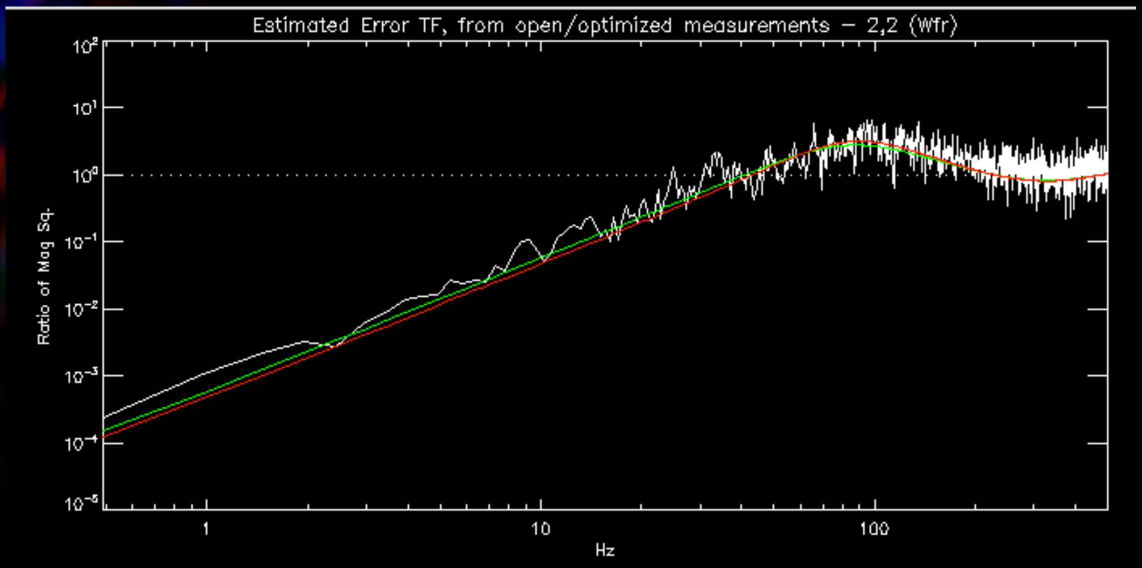
- Model and verify control system behavior using Z- or Laplace transforms
- Use wavefront residuals during operation to estimate signal and noise temporal power spectra
- Find best gain by minimizing error power



$$\underset{C(\mathrm{z})}{\operatorname{argmin}} \left\{ \int_{-\pi}^{\pi} \left| \frac{1}{1+\exp(-2j\omega)C(\omega)} \right|^2 \left|1+\exp(-j2\omega)C_0(\omega)\right|^2 \hat{P}_{y,cl}(\omega)\, d\omega \right\}$$

As-built system matches model

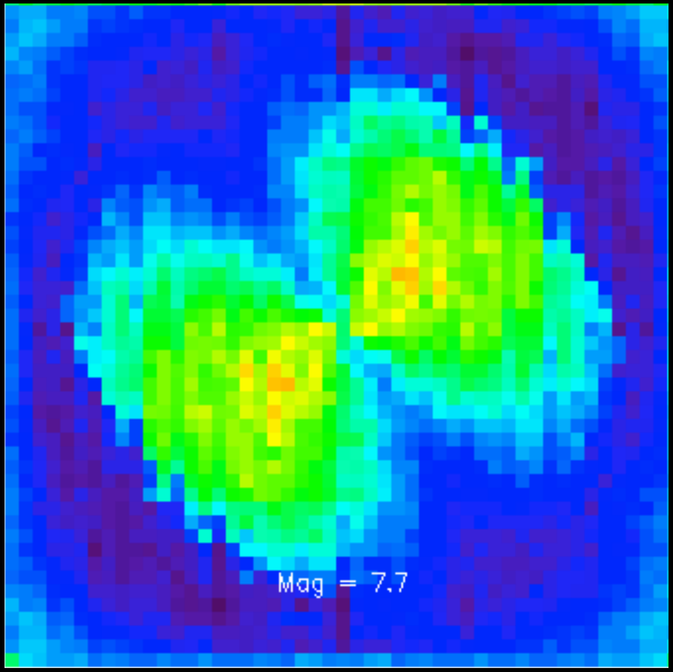
- Estimate ETF as ratio of open/closed loop measurements
- We have a detailed Laplace model of system dynamics
- Excellent agreement of model and calibration with measured data



From I=7.2 test case

Gain optimizer working correctly

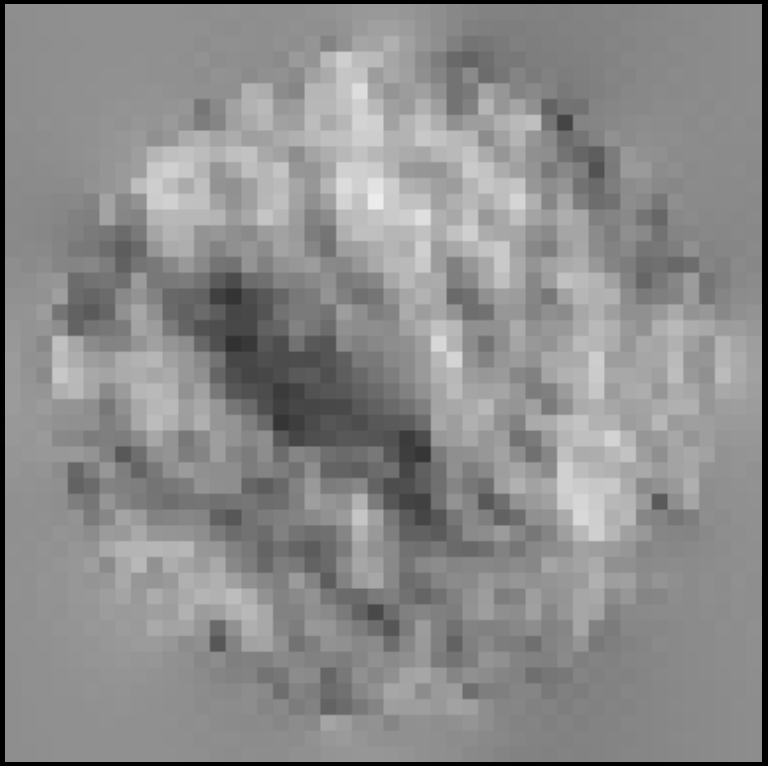
- Updates gains every 10 seconds
- Converges rapidly to correct modal gains and stays there
- Even did the right thing when we accidentally spun the phase plate to make 80 m/s wind!



Testing with same spinning phase plate

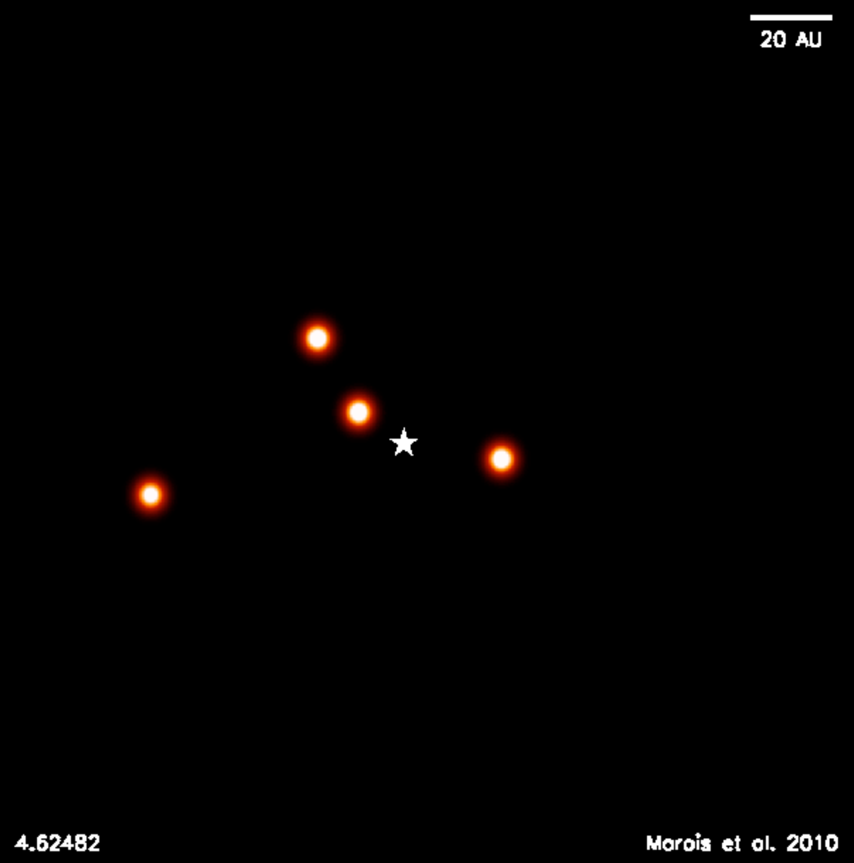
Gain optimization in action

- Bright star case
- Gains 0.1 to start
  - WFS measures 45 nm RMS
- The optimizer increases the gains to 0.3 for nearly all modes
  - WFS measures 24 nm RMS



From detection to estimation

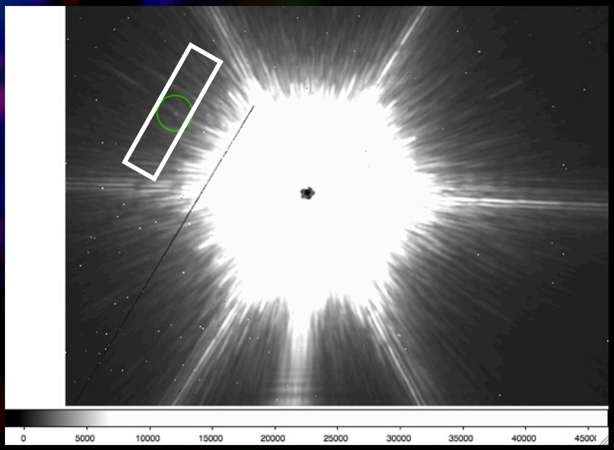
- Several key parameters we want to do science with
  - astrometry
  - photometry
  - spectral estimation

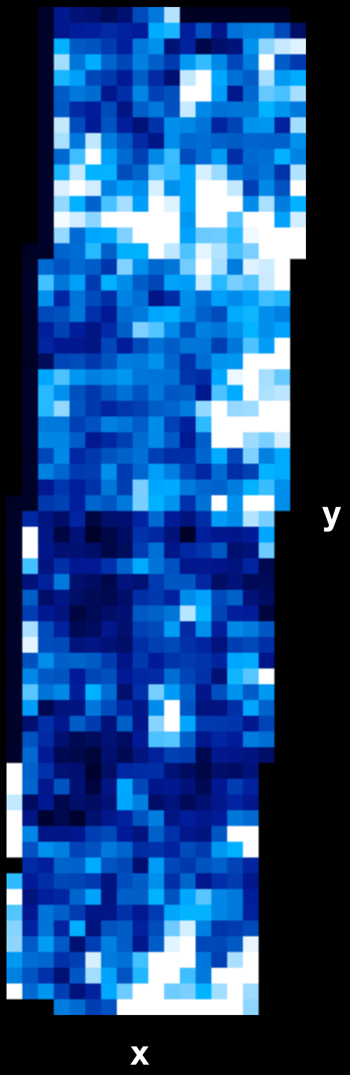


Movie courtesy Q. Konopacky (now at U. Toronto)

Separating planet from speckle

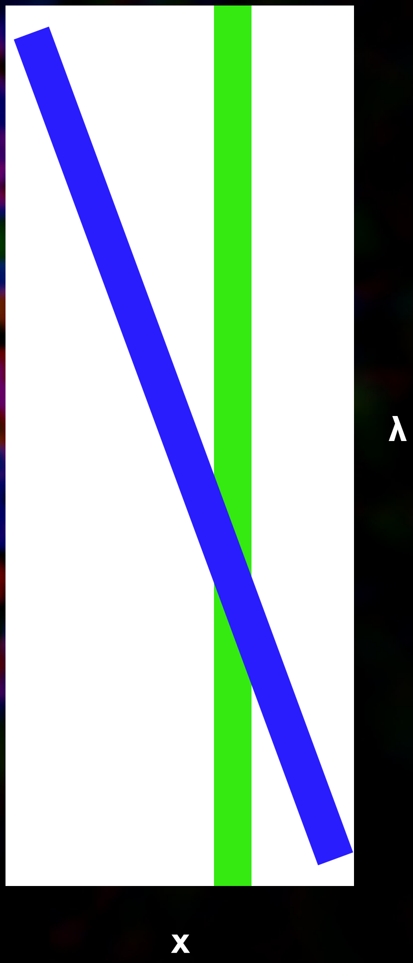
- Integral field spectrograph produces a datacube of x-y-λ
- Standard detection algorithm (LOCI) introduces artifacts



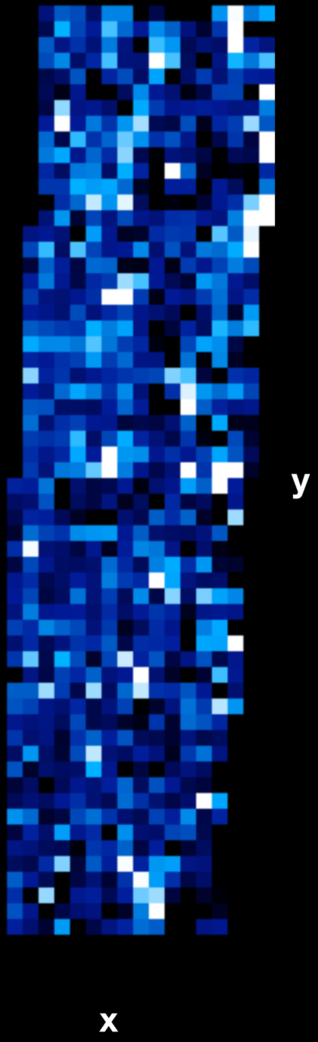


HR 8799 Keck observational data from B. Macintosh

Linear fitting algorithm



- Use a model-based linear fitting algorithm to remove speckles without biasing planet signal
- Still in progress...



GPI is nearly complete

On the horizon...

- Slowly-varying errors at the 1-5 nm level limit our performance - how to reduce these? Can we use correlations over many observations for behavior such gravity-induced beam shear?
- Laboratory and then on-sky testing of Predictive AO control (frozen flow atmosphere) to further reduce residual error