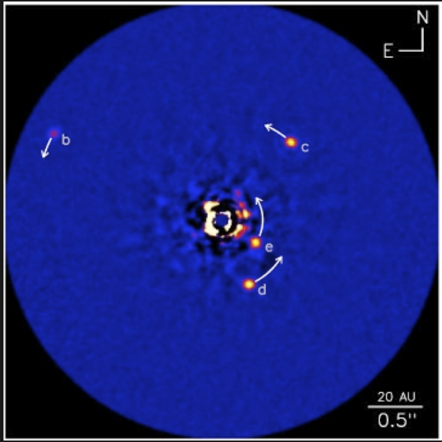
Robust High-Angular Resolution Astronomy

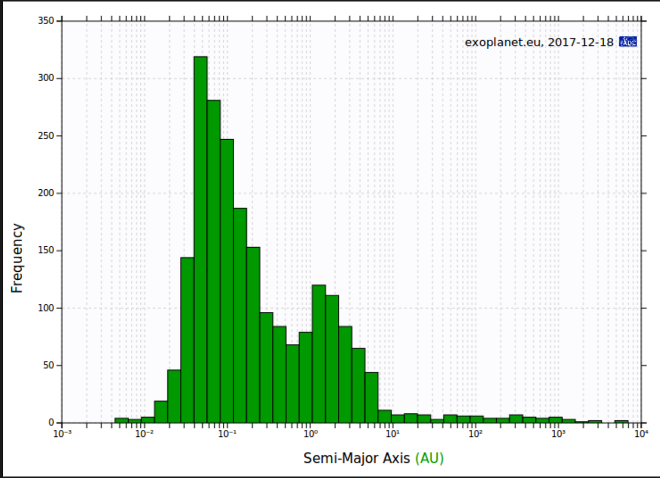
F. Martinache (+ M. Ireland)

March 8, 2018

The story of the few and the many

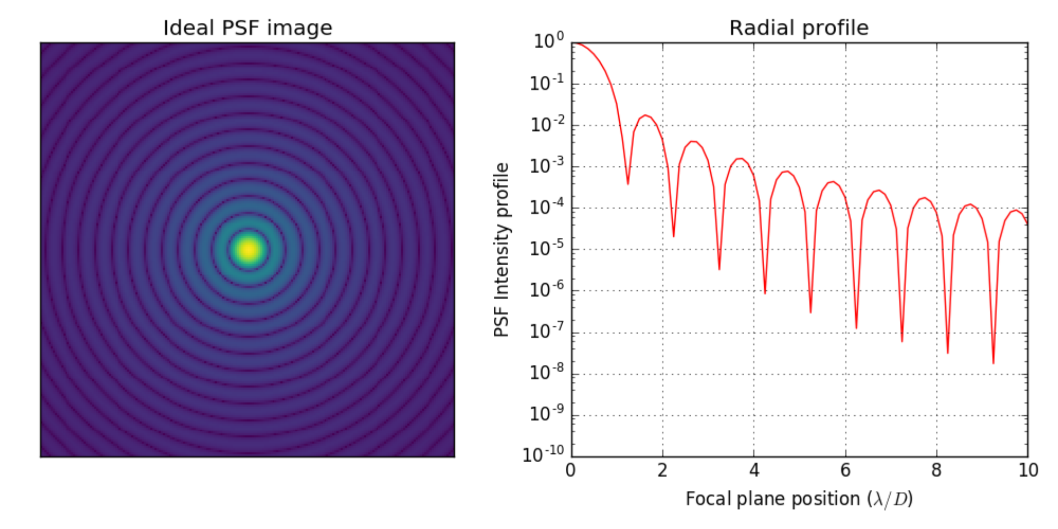


30 Myr old planetary system
HR8799



Distribution of known planets semi-major axis

The high-contrast challenge



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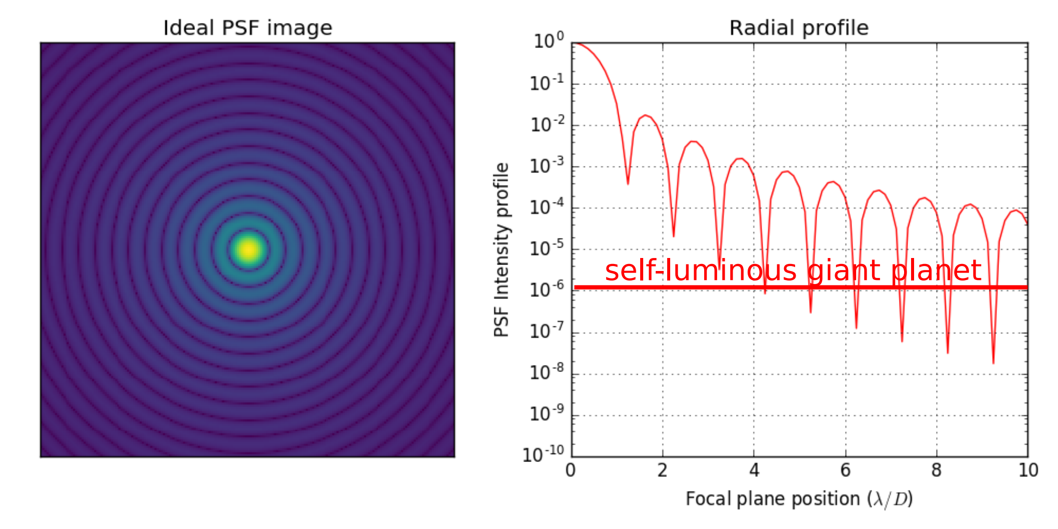

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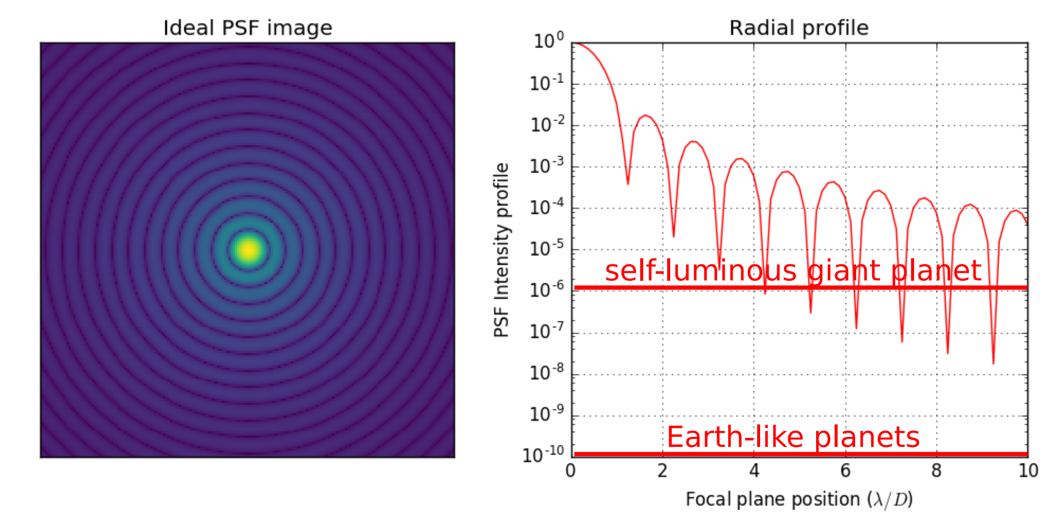
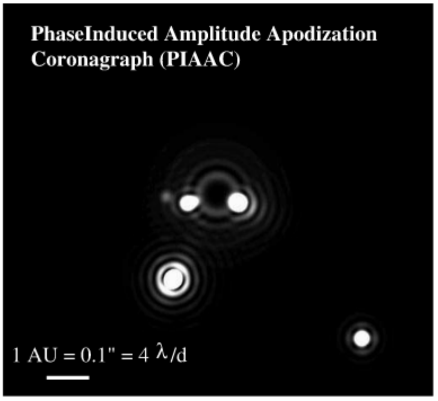


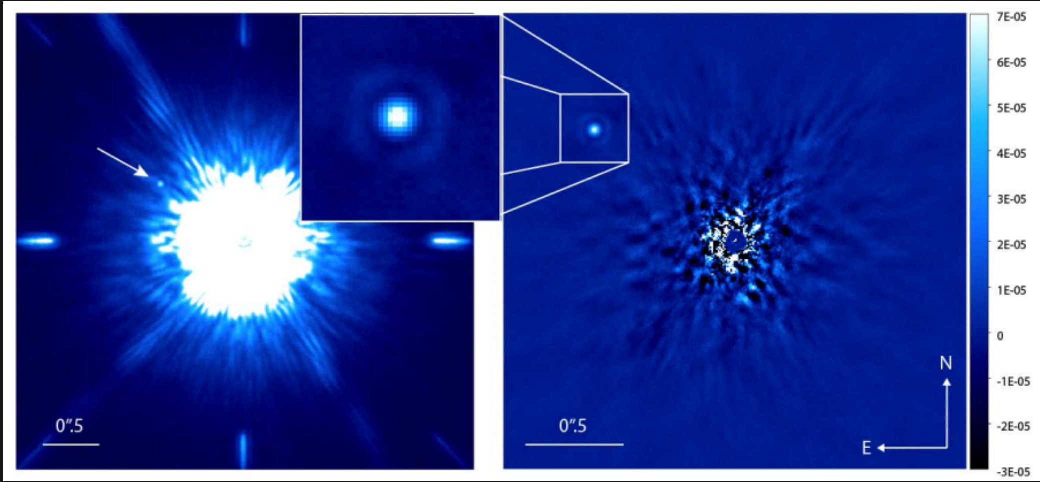
The high-contrast reality



Guyon et al, 2005, ApJ, 622, 744

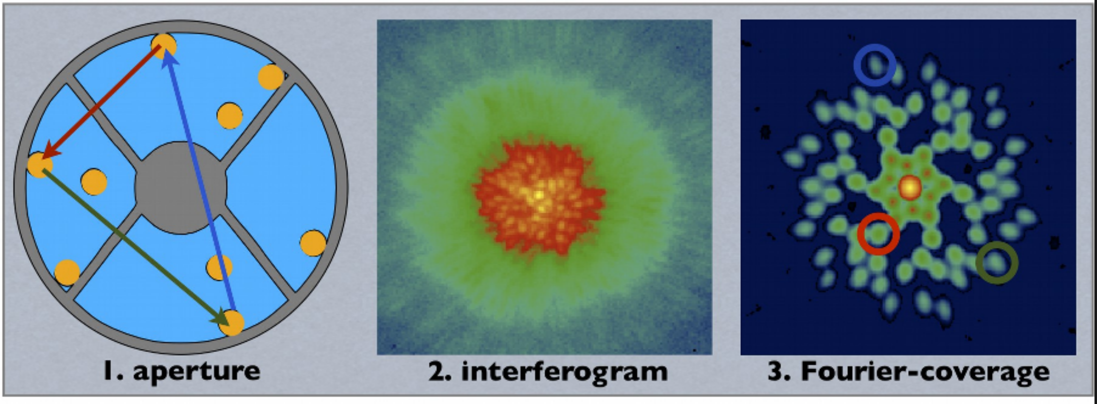
- Optical solutions are available:
  - e.g: PIAAC and Vortex coronagraphs
- In theory: very high-contrast down to the diffraction limit is possible
- In practice performance dominated by the input wavefront quality
- Stability requirement = f(raw contrast):
  - $\alpha = \lambda \times \sqrt{c}/2\pi$
  - c=$10^{-6} \rightarrow$ sub-nn wavefront quality
- State of the art: $\sim$ 50 nm ($\rightarrow$ c $\sim 4 \times 10^{-2}$)

The contribution of post-processing



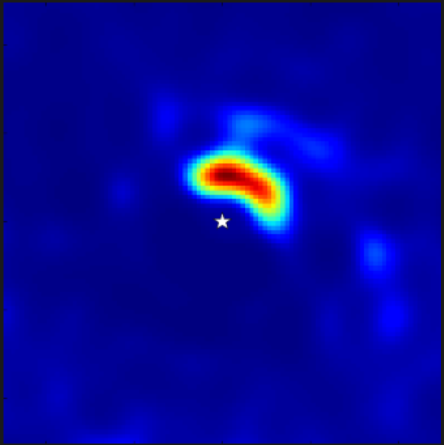
Kühn et al, 2017, PASP, in press

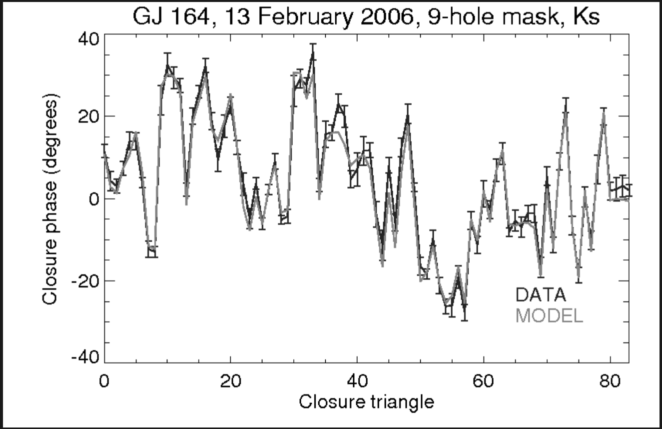
A challenger from the XIXth century?



Interferometry offers an alternative approach to this game
Trading quantity for quality, enabling calibration

Closure-phase: the self-calibrating observable!

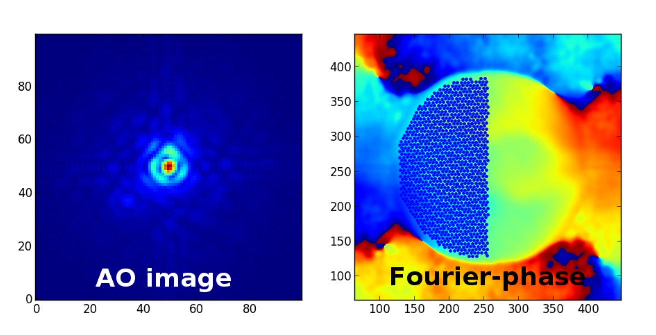




Transition Disk host LkCa 15
Ireland, 2013, MNRAS, 433, 1718

10 years ago, on-sky c-phase stability $< 1^\circ$
roughly corresponds to $\lambda/1000$

Kernel-phase: generalized closure-phase



Martinache, 2010, ApJ, 724, 464

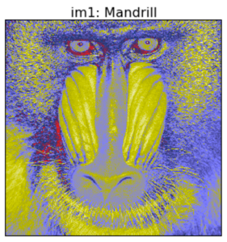
$$I = O \otimes PSF(t)$$

In the presence of time-varying aberrations, the information at each pixel is degenerate.

There is an sub-space where good observables exist that are robust against first and second order phase residuals.

These observables are called kernel-phases

Why the phase?



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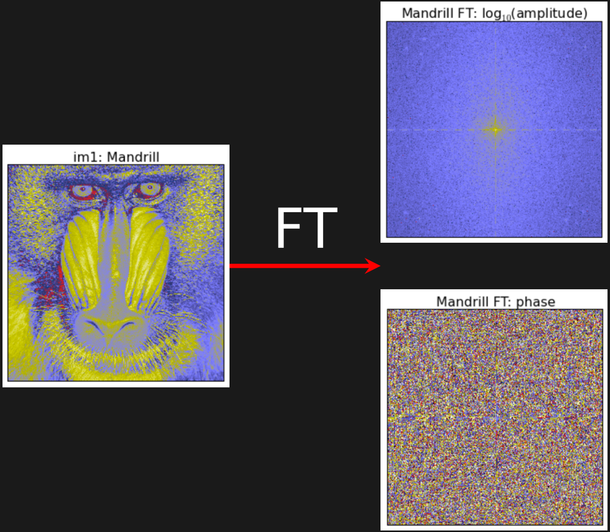

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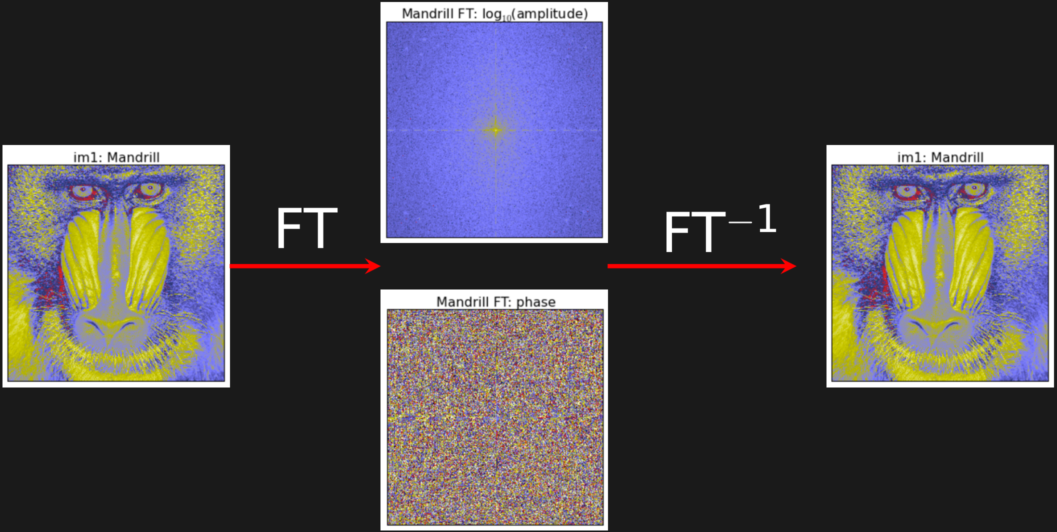

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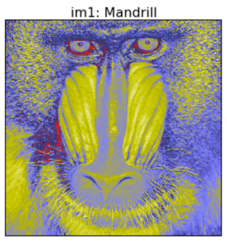
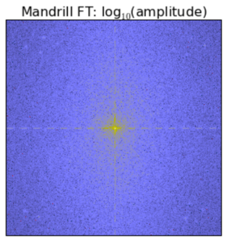


FT



FT^{-1}

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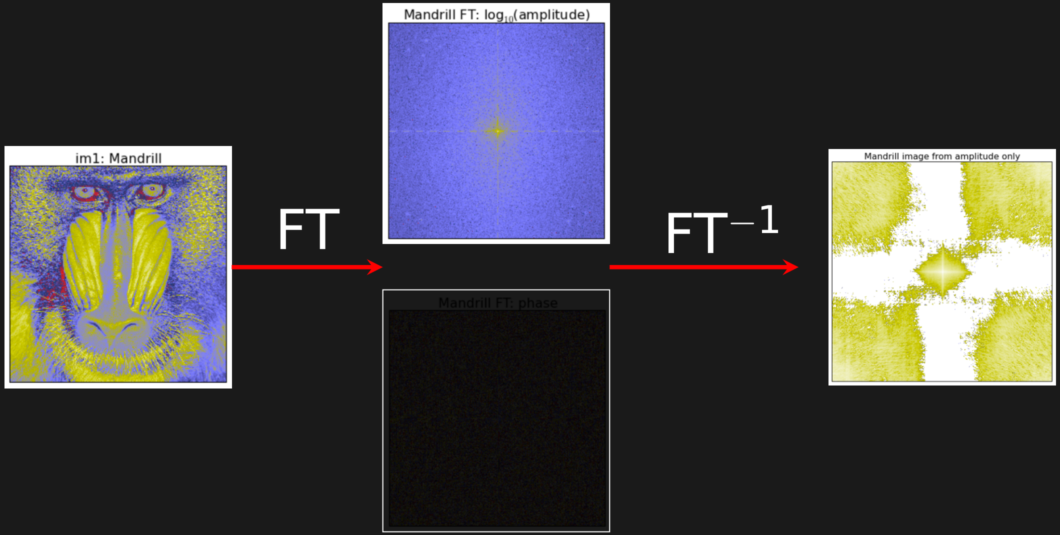

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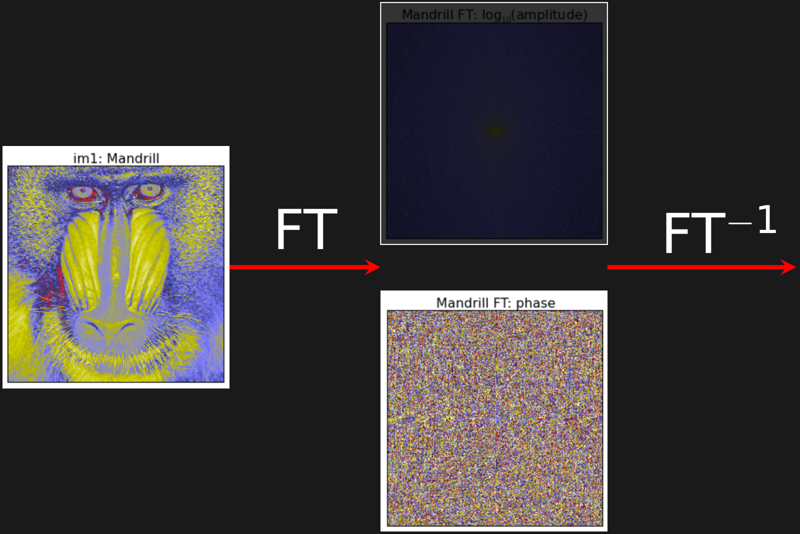

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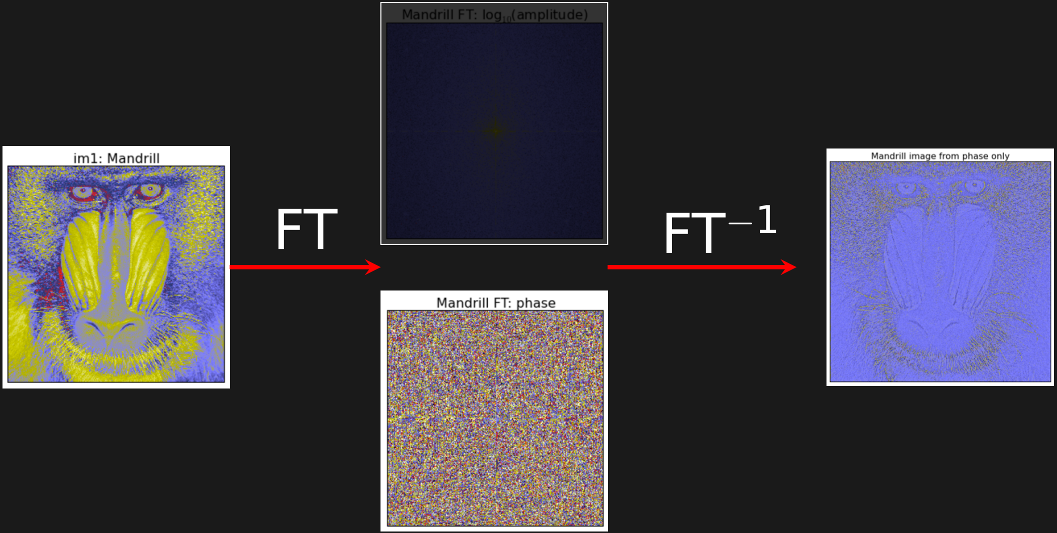
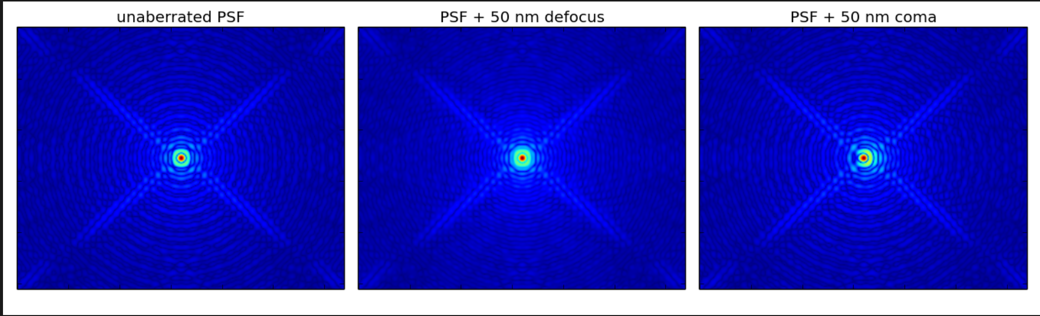


Even the odds



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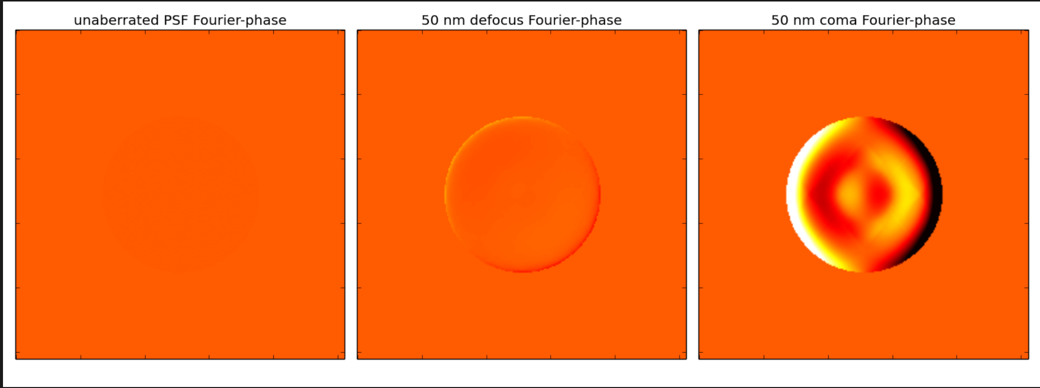
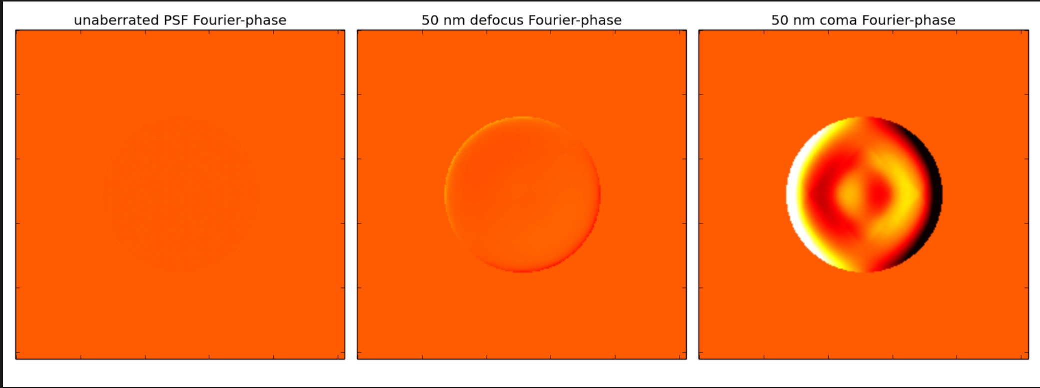


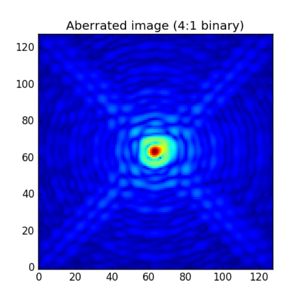
Fun fact: Most telescopes feature a symmetric pupil

Even the odds



Fun fact: Most telescopes feature a symmetric pupil
the Fourier-phase is intrinsically insensitive to all even order aberrations!

Why the kernels?



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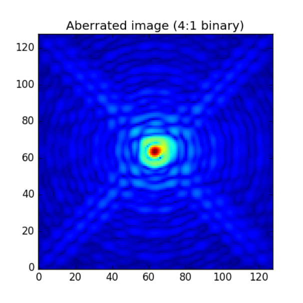

FT

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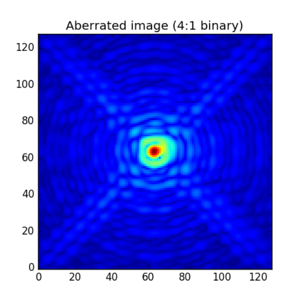
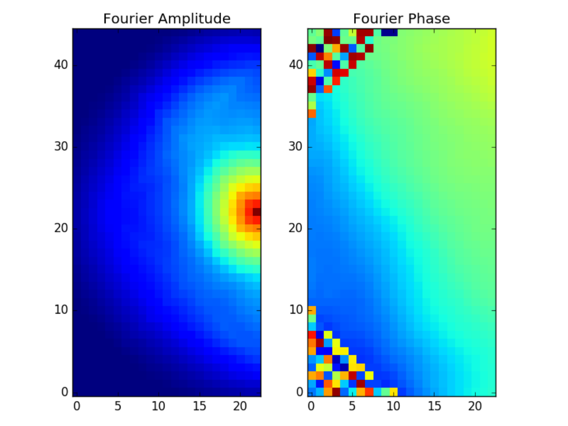
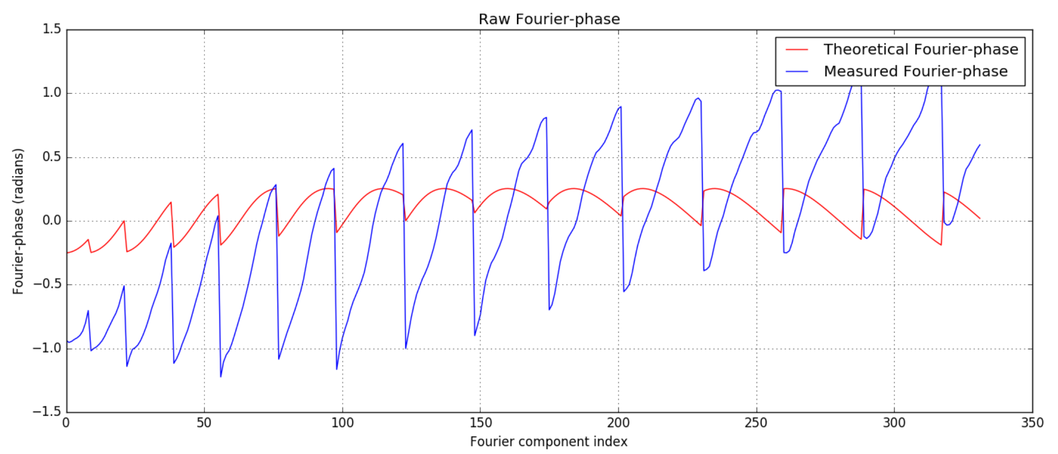




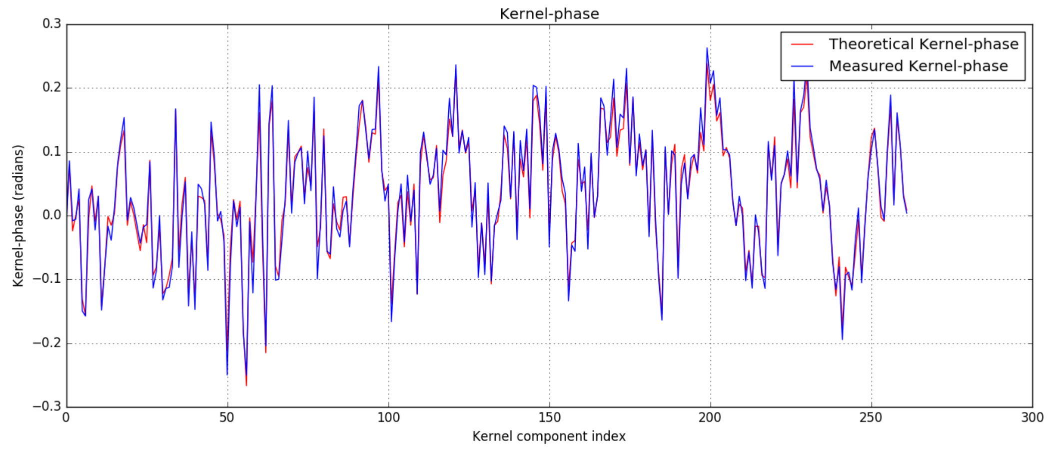
phase: remains dominated by aberrations

Why the kernels?



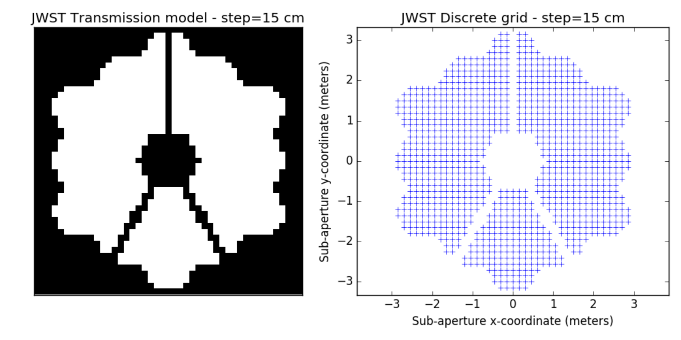
the raw phase Φ: useless information

Why the kernels?

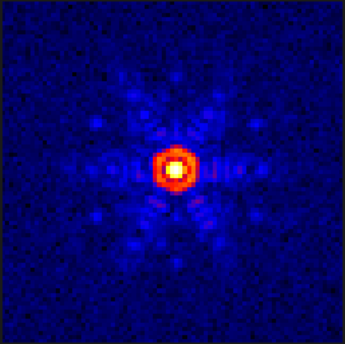


kernels K · Φ : 100 % usable information!

Preparing the Kernel-phase analysis of JWST data



JWST aperture fine grid model



NIRISS "bright" frame

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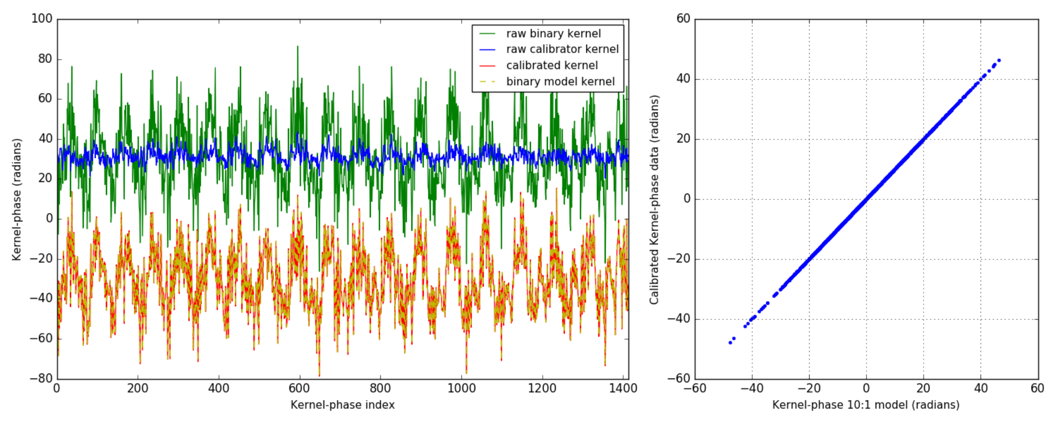

Infinite SNR simulation: perfect calibration

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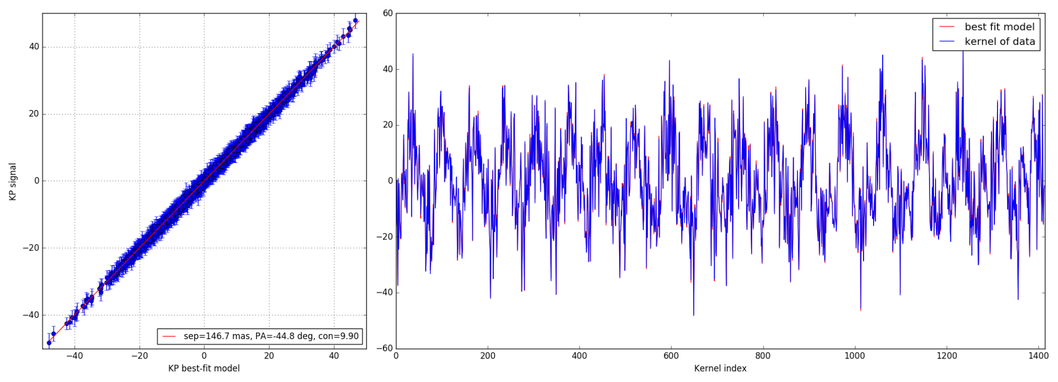

10:1 companion signature at $\sim \lambda/D$ on "bright" target

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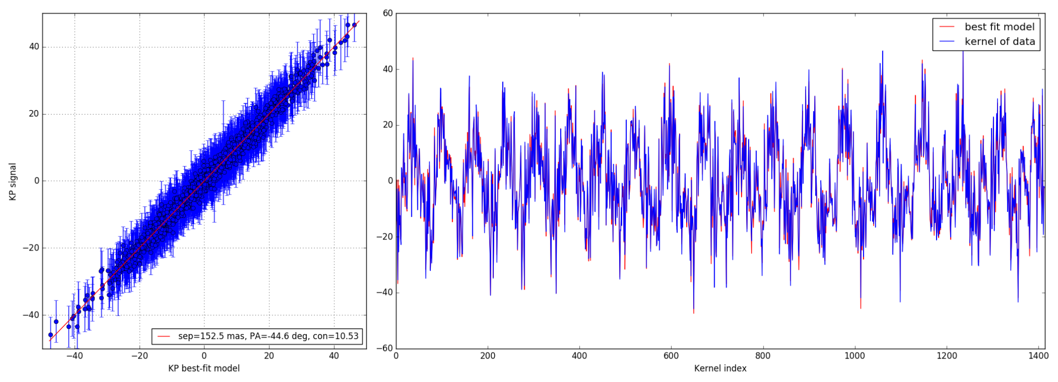

10:1 companion signature at $\sim \lambda/D$ on "faint" target

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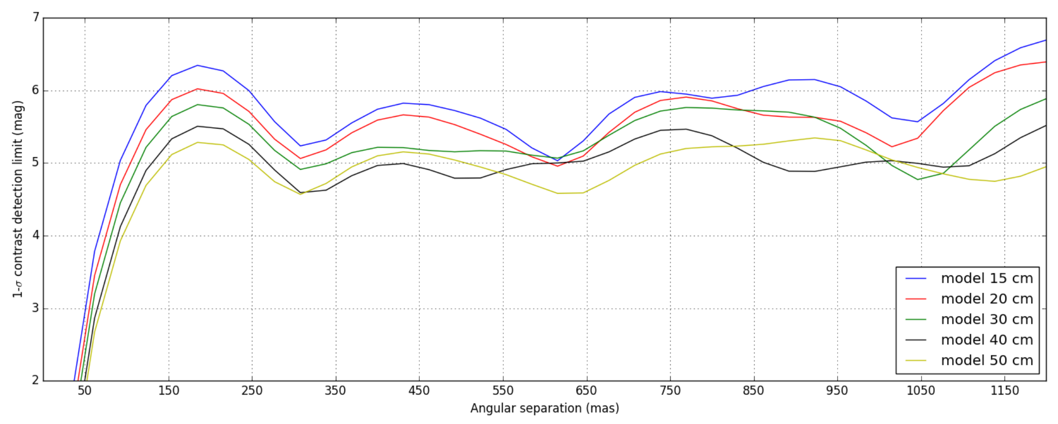
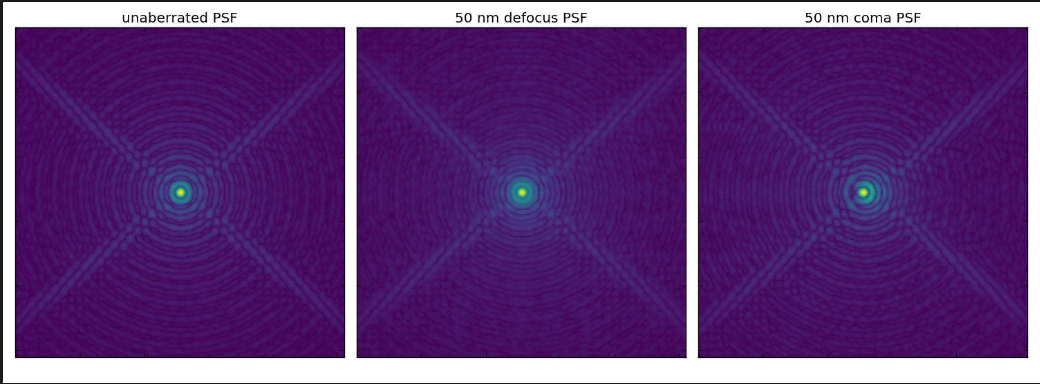


Bright contrast detection limits (Still TBD: noise decorrelation)

Focal plane metrology



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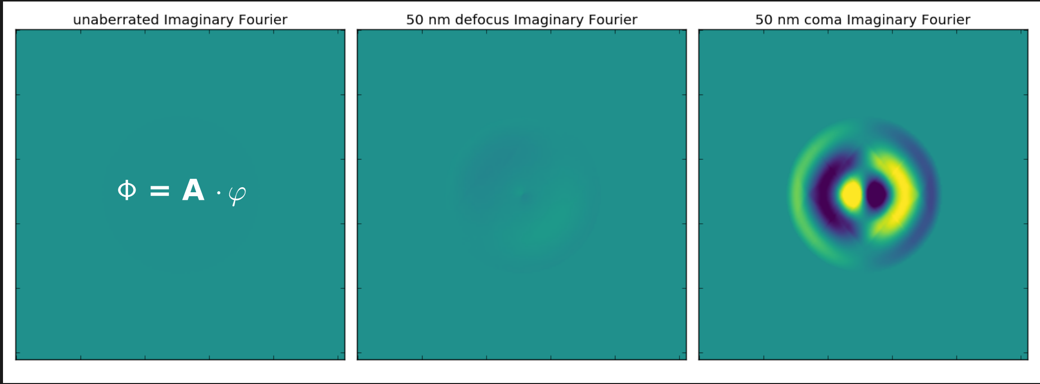

Even-order aberrations are invisible in the Fourier-phase

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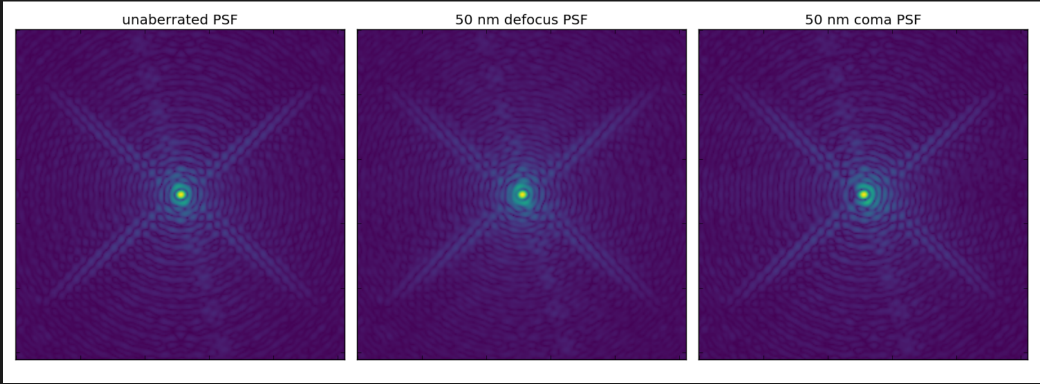
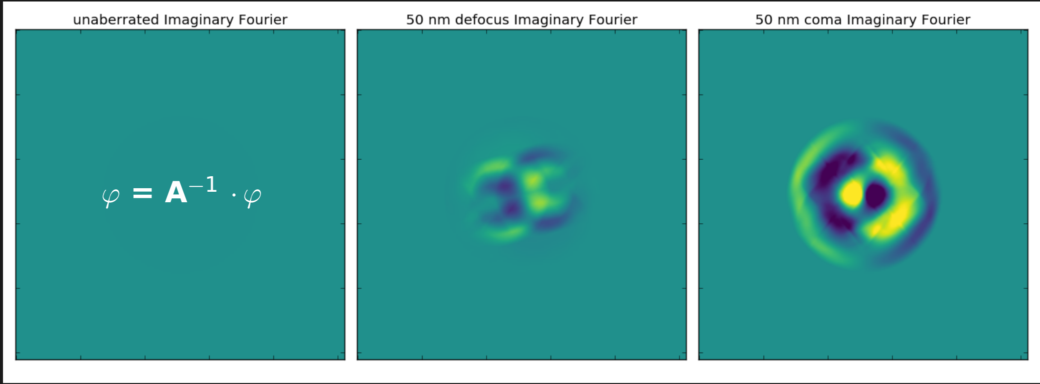


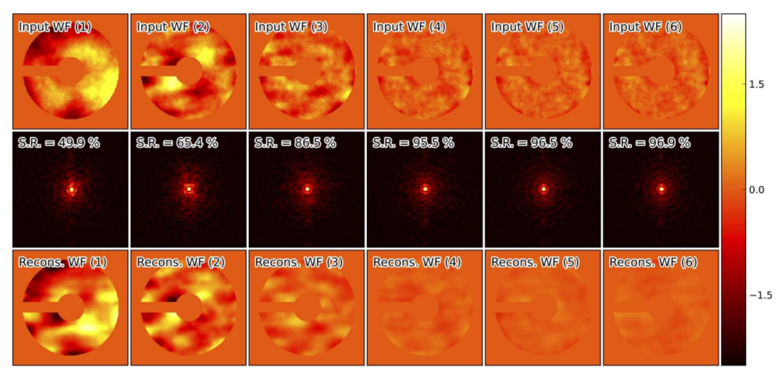
Alter the instrument pupil?

Focal plane metrology



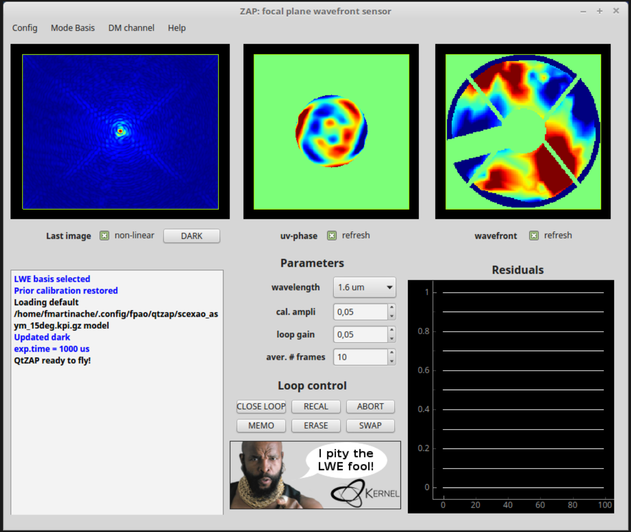
Even-order aberrations become visible if the pupil is asymmetric!

Focal plane metrology



The Asymmetric-Pupil Wavefront Sensor

Now an essential feature of SCExAO



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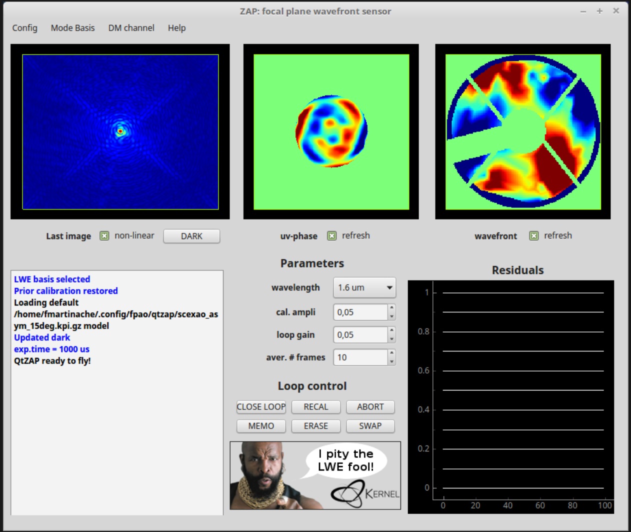
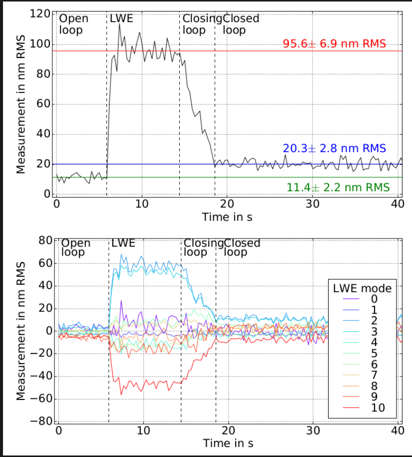
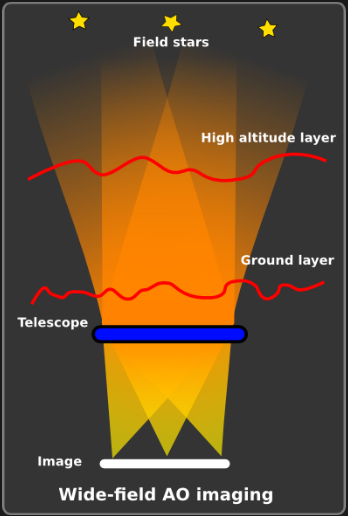




Martinache et al, 2016, A&A, 593, A33

N'Diaye et al, 2017, A&A, in press

Toward AO without a dedicated wavefront sensor?



The appeal:

- complexity hardware $\rightarrow$ software
- particulary good for low-order modes
- multi-object implementation possible

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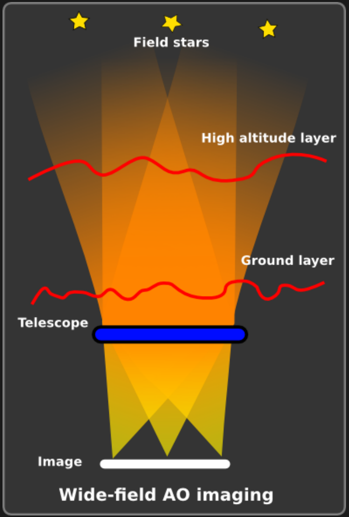

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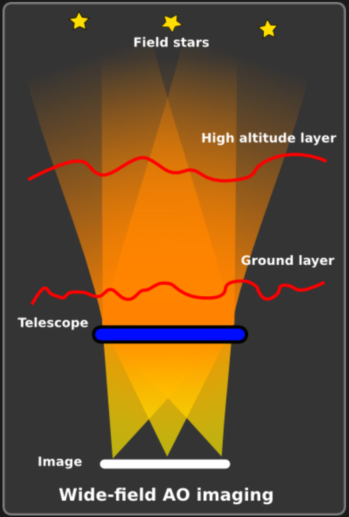

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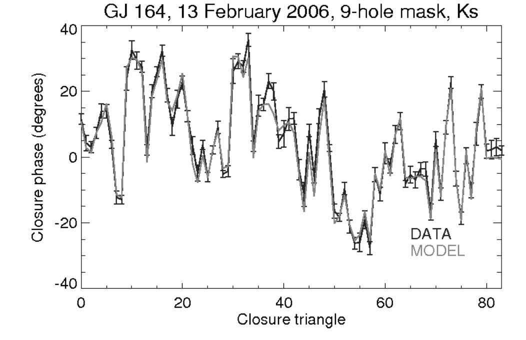
But:

- fringe tracking does it all the time
- you can adjust the sensing λ
- good detectors are available now

KERNEL: exploration program

Instrument design with robustness in mind?



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roughly corresponds to $\lambda/1000$

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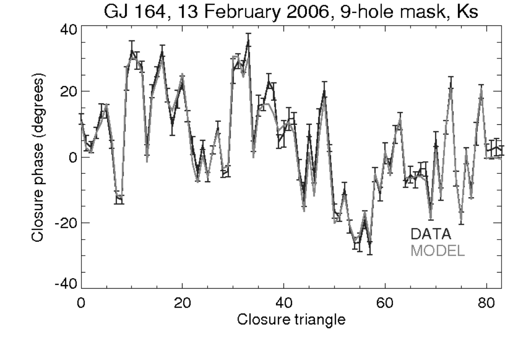

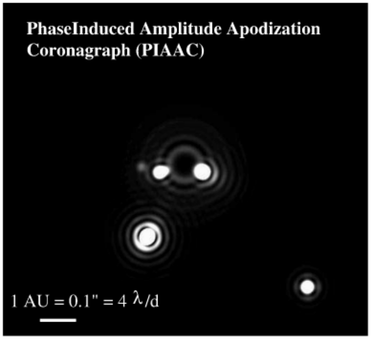

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the ideal PIAA-Coronagraph
Guyon et al, 2005, ApJ, 622, 744

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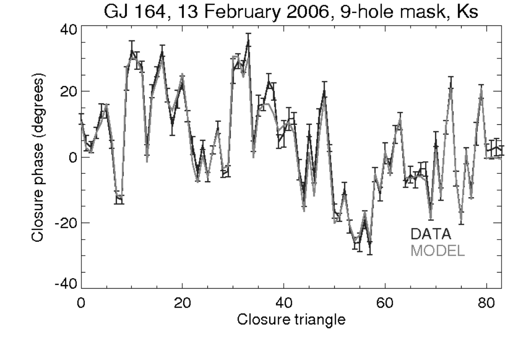

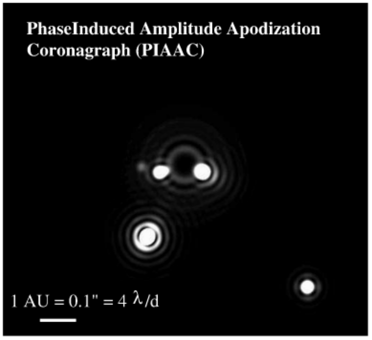

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How about self-calibrating coronagraphs and kernel-nullers?

Reconcile two approaches?

The contrast range of kernel- and closure-phase remains limited to $\sim 10^{-3}$

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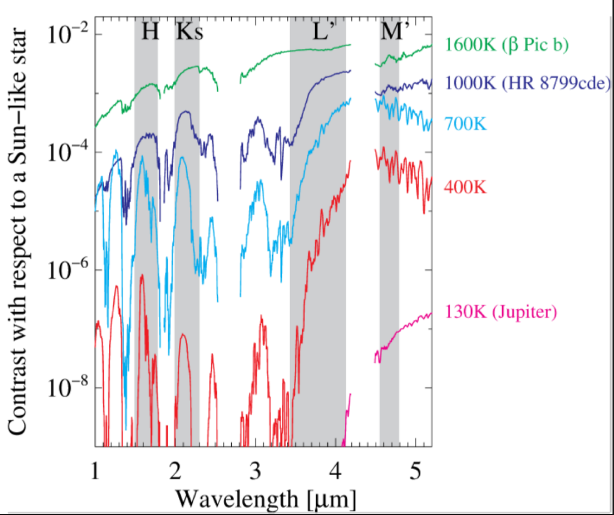
A design principle?

Can we make the ability to produce kernels a guiding principle in the instrument design?

Direct detection of what extrasolar planets?



[Credit?]

An unknown population of self-luminous giants around stars in young associations:

- the usual suspects
- L - M contrasts seem favorable
- not that many far out
- the closer, the better

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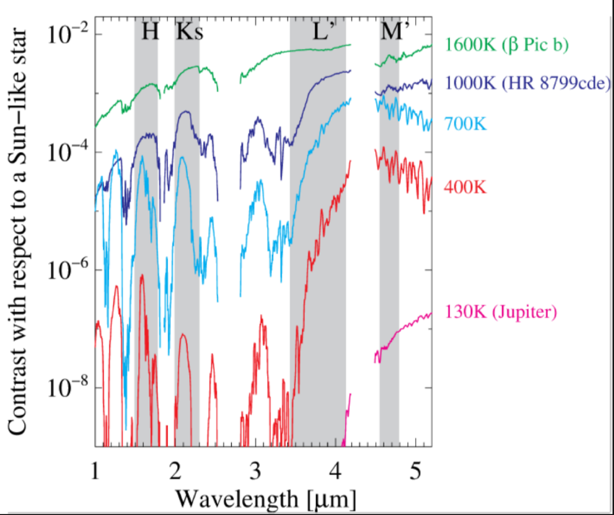

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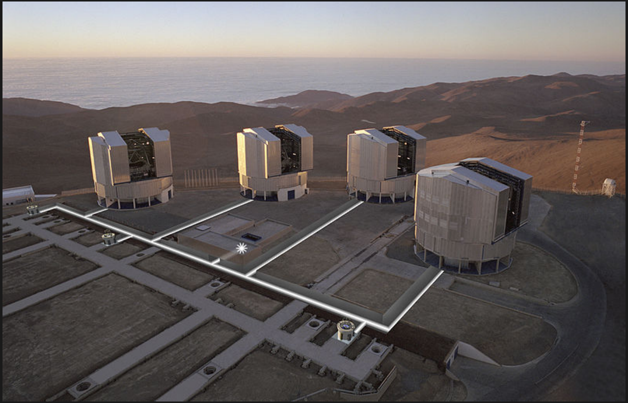
Known mature planets around nearby stars, kept warm by their host:

- planet luminosity $\propto 1/a^2$
- milli-arcsecond resolution

Nulling interferometry



[VLTI (ESO)]

Favorable contrast → L-band

Milliarcsec resolution → VLTI

- four 1.8-m ATs for blind search for young planets
- four 8-m UTs for targeted survey of known planets

High-contrast → Nulling

Design a Kernel-nuller?

Nulling interferometry:

- Cancel on-axis light source (Bracewell, 1978):
- Solutions exist for N-aperture interferometers (Guyon et al, 2013)
- Design emphasis: produce dark (nulled) outputs
- Like a coronagraph, rejection is sensitive to environment
- Post-processing required (e.g. Null Self-calibration, Hanot et al, 2011)

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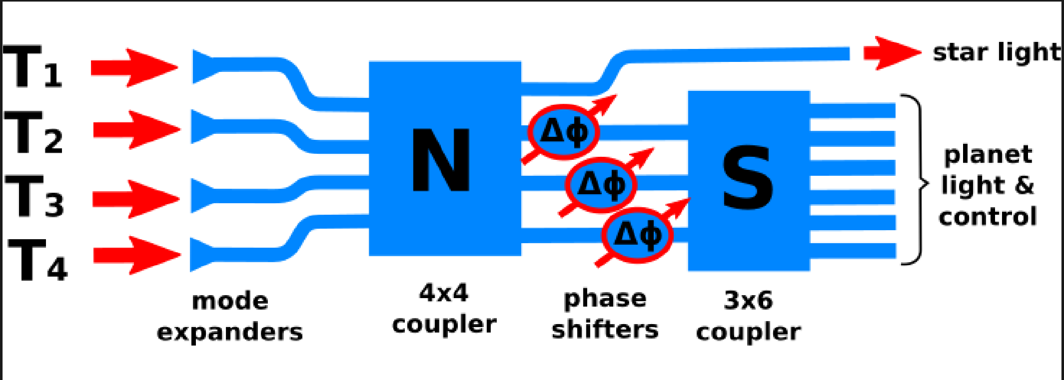
Kernel-nuller:

- 4T $\rightarrow$ 4 outputs (3 nulled)
- nulled outputs $\rightarrow$ mixing stage
- produce 6 non-symmetrical outputs
- build Kernels: combinations of outputs robust against phase errors
- use Kernel-outputs for science

Two-stage architecture

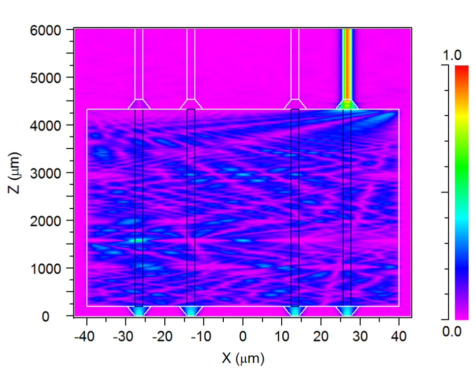


4T-Nuller: the principle

$$N = 0.5 \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

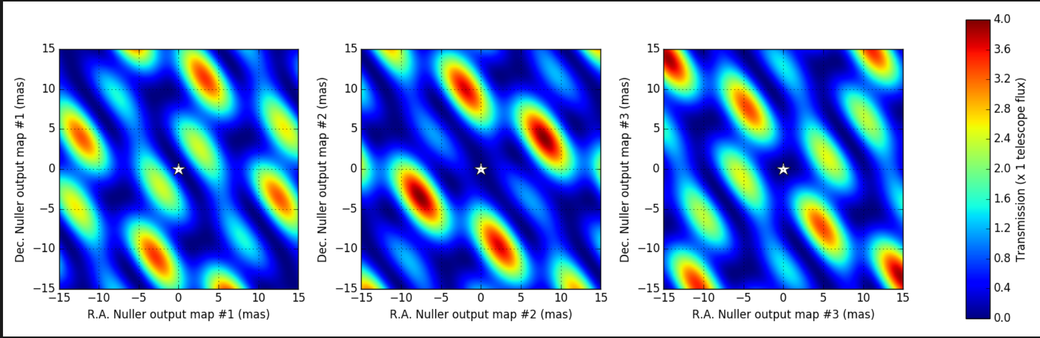
- Four telescope inputs
- One bright output
- Three dark outputs

4x4 nuller



(MMI design by Harry-Dean Kenchington Goldsmith, ANU PhD candidate)

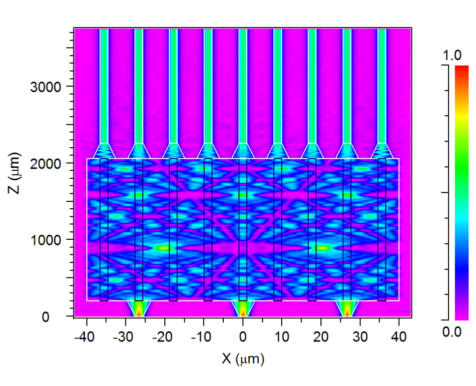
4T-Nuller: On-sky response for VLTI



Only at zenith!

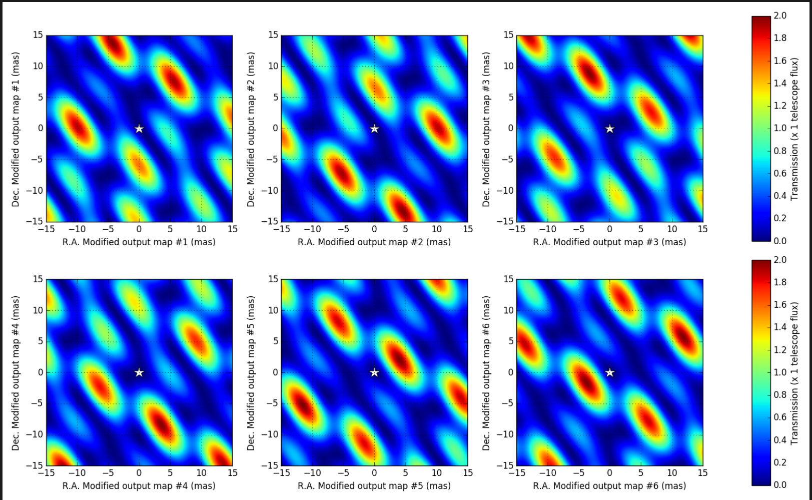
Modified 4T-Nuller: principle

$$\mathbf{S} = \frac{1}{\sqrt{4}} \times \begin{bmatrix} 1 & e^{i\theta} & 0 \\ -e^{-i\theta} & 1 & 0 \\ 1 & 0 & e^{i\theta} \\ -e^{-i\theta} & 0 & 1 \\ 0 & 1 & e^{i\theta} \\ 0 & -e^{-i\theta} & 1 \end{bmatrix}$$



(MMI design by Harry-Dean Kenchington Goldsmith, ANU PhD candidate)

Modified 4T-Nuller: on-sky response for VLTI



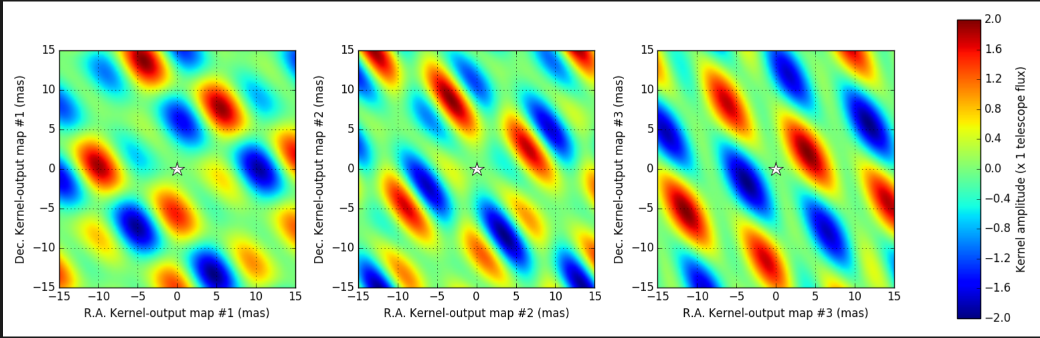
Kernel-nulled outputs

- Unlike kernel-phase, no first order dependance on piston errors
- Nuller error dominated by second order errors

$$\delta \mathbf{I} = \mathbf{A} \times \left[\frac{\partial^2 \mathbf{I}}{\partial \varphi_1^2}, \frac{\partial^2 \mathbf{I}}{\partial \varphi_2^2}, \frac{\partial^2 \mathbf{I}}{\partial \varphi_3^2}, \frac{\partial^2 \mathbf{I}}{\partial \varphi_1 \partial \varphi_2}, \frac{\partial^2 \mathbf{I}}{\partial \varphi_1 \partial \varphi_3}, \frac{\partial^2 \mathbf{I}}{\partial \varphi_2 \partial \varphi_3} \right]^T . \tag{1}$$

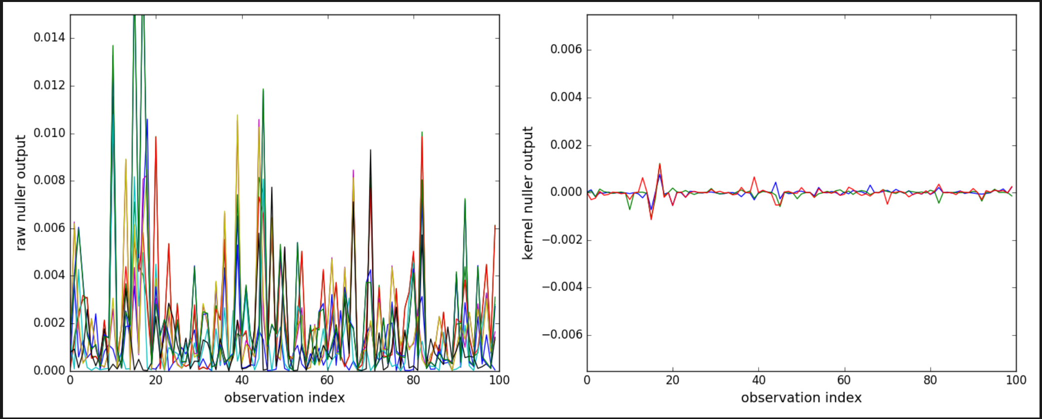
- record a new 2^{nd} order perturbation response matrix **A**
- and find a kernel for this matrix

Kernel-Nulled outputs: on-sky response for VLTI



Maps are anti-symmetric! A single snapshot observation can constrain a companion's position.

Kernel-Nulled outputs: enhanced stability

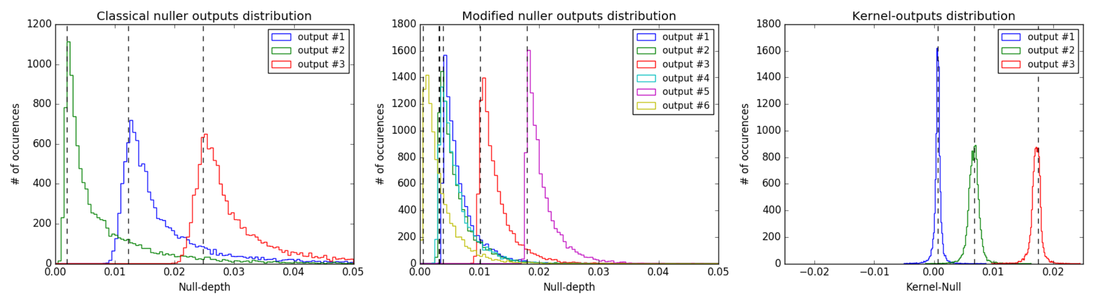


50 nm RMS random piston error for the array

Same vertical scale for raw (left) and kernel (right) outputs.

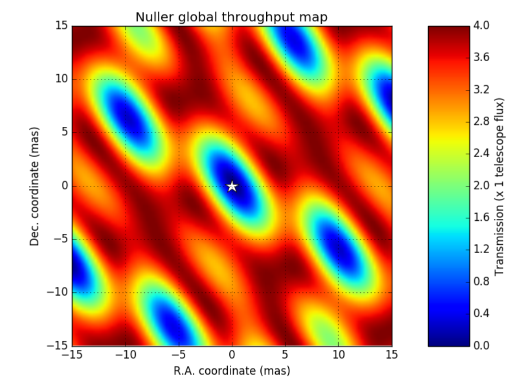
The kernel-outputs indeed provide additional filtering

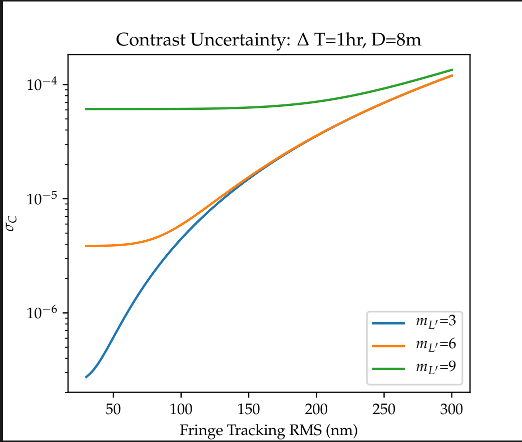
Kernel-nulled outputs: more robust against piston



And incidentally, also robust against photometric fluctuations!

L-band VLTI 4UT





Non-uniform response over the field of view

Median contrast uncertainty

VIKiNG: the VLTI Infrared Kernel NullinG

Two VIKiNG raids:

- Blind survey of potential young hosts using 4 ATs
- Targeted survey of known planets at thermal equilibrium with their host using the 4 UTs for max sensitivity

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Using exoplanet.eu database and assuming Neptune-like density planet at thermal equilibrium:

- semi-major + distance $\rightarrow$ angular separation + T
- mass + density + T $\rightarrow$ planet radius $\rightarrow$ luminosity
- contrast cut-off > 10^{-5}: 14 targets make the cut
- angular separation range from 5 to 12 mas
- 14 planets detectable in < 2 hours (SNR=5) with UTs

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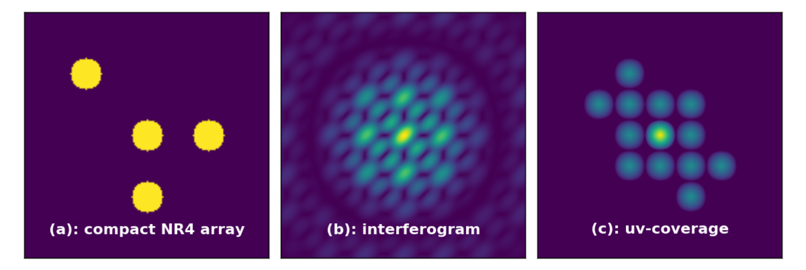
Catalogue
GJ 86 A b
BD+20 2457 b
HD 110014 c
11 Com b
ksi Aql b
61 Vir b
HIP 105854 b
HIP 107773 b
mu Ara c
nu Oph b
HD 168443 b
HIP 67851 b
HD 69830 b
HD 16417 b

The High-Efficiency Infrared Does-it-All Recombiner

Bring VLTI fringe tracking capability down to 50 nm RMS!



- Multi-λ recombiner to simultaneously track pistons, tip-tilt and alignment.
- Can be used for science?
- Prototyped by the KERNEL bench
- ARC Proposal led by M. Ireland

Thank you

Kernel-nulling

The power of Thor's hammer (the nuller) now driven with surgical precision and accuracy (the kernel): the weapon of choice for any VIKiNG aiming to discover new lands!

Please check out our paper:
https://arxiv.org/abs/1802.06252

[Image Credit: http://www.kungfury.com/]