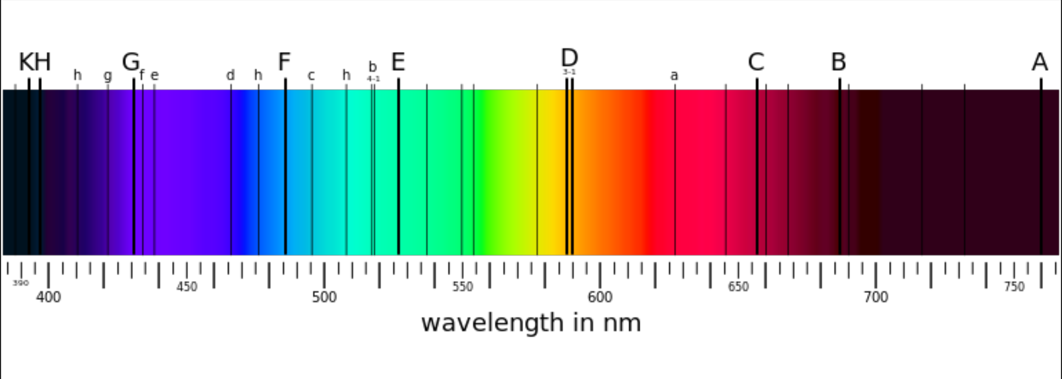
Robust High-Angular Resolution Astronomy

F. Martinache (+ M.J. Ireland)

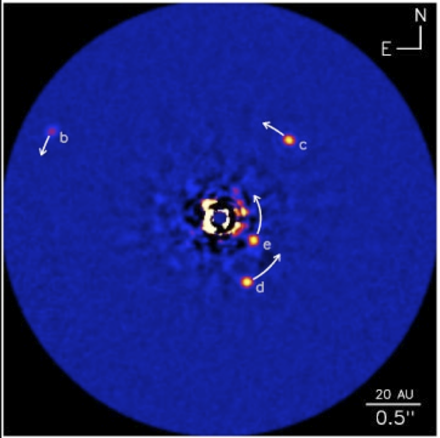
May 14, 2018

Stellar Spectroscopy

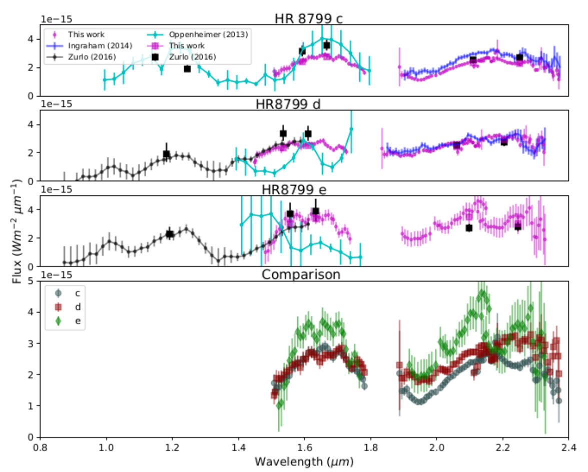


Fraunhofer lines [credit: Wikipedia]

Extrasolar planets

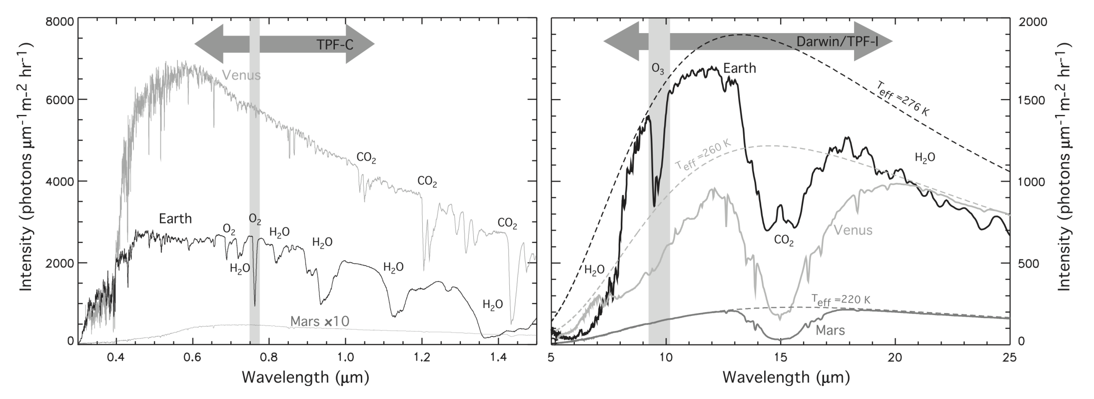


30 Myr old planetary system
HR8799



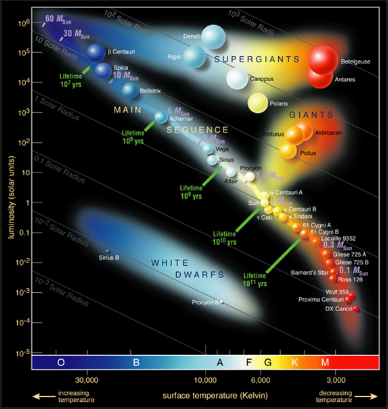
Greenbaum et al, 2018.

The ambition: bio-markers!



Selsis et al, 2008.

A global story of the life of extrasolar planets



[credit: ESO]

- Build a planet equivalent of the HR diagram?
- To tell a story of planet formation and evolution
- Core-accretion and/or gravitational instability start
- Migration tracks?
- Need many unambiguous spectroscopic observations

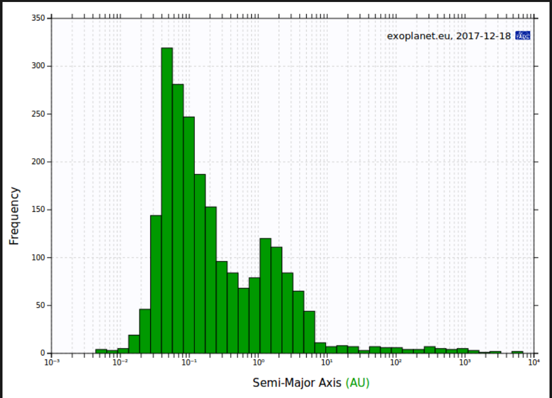
Earth-Sun equivalent

A Solar system equivalent at 10 pc:

- Earth: 1 AU $\rightarrow$ 100 mas
- Jupiter: 5 AU $\rightarrow$ 500 mas

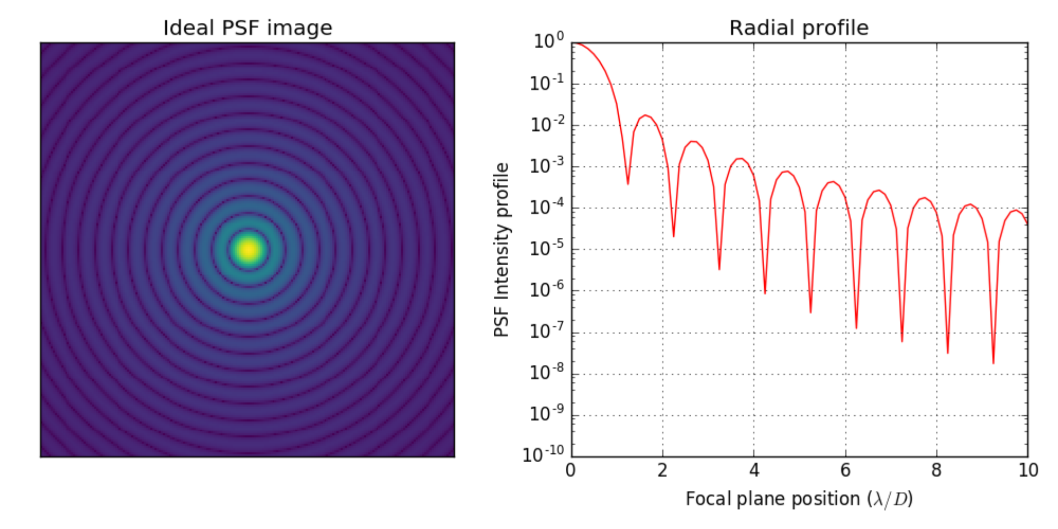
To be compared to:

- the diffraction limit
- given by the ratio λ/D
- 8-meter (1.6 μ m): 40 mas
- 100 meter (3.6 μ m): 5 mas

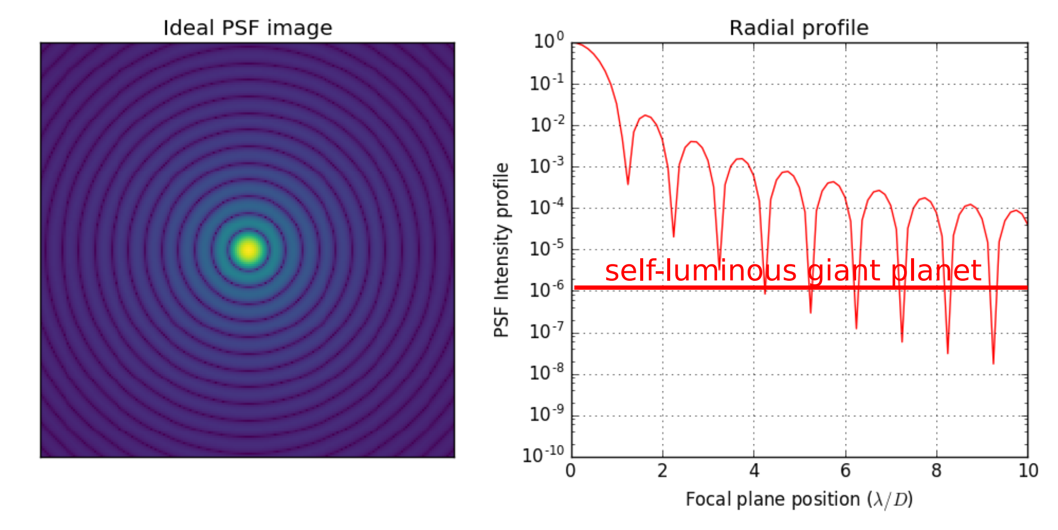


Distribution of known planets semi-major axis

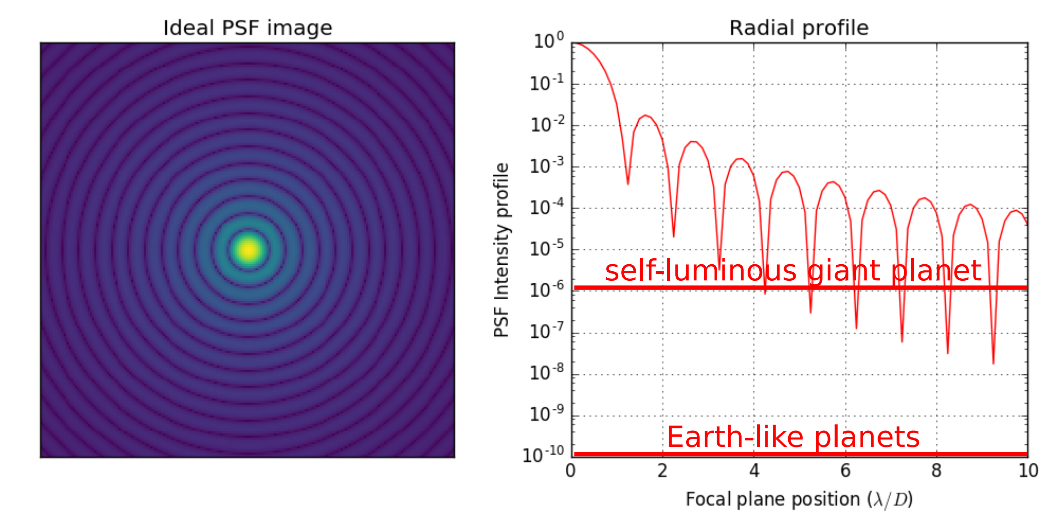
Physics says OK but hard



Physics says OK but hard

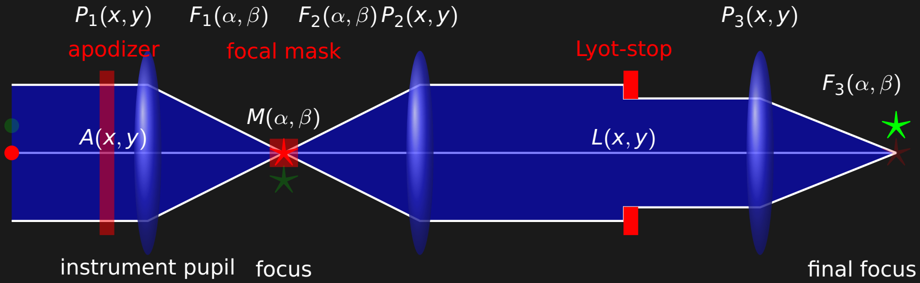


Physics says OK but hard



High-contrast imaging

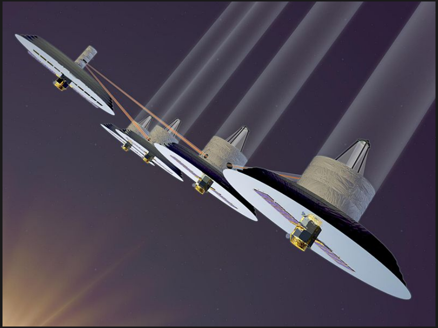
- Reduce the photon noise of the bright source to reveal the faint structures
- Two solutions: coronagraphy and interferometric nulling
- Example: coronagraphy



In both cases, the device suppresses the static on-axis diffraction pattern

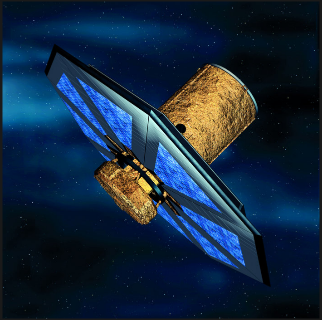
From incredibly daring to very prudent

[credit: NASA]



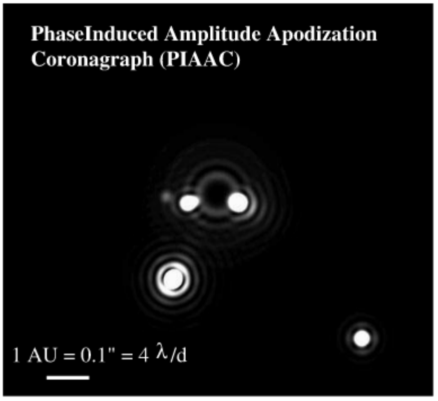
- in 2004: coronagraph and interferometer!
- in 2011: project canceled

[credit: ESA]



- 2004: ESA examines Darwin
- In 2007: concept study closed
- There is no Darwin project today

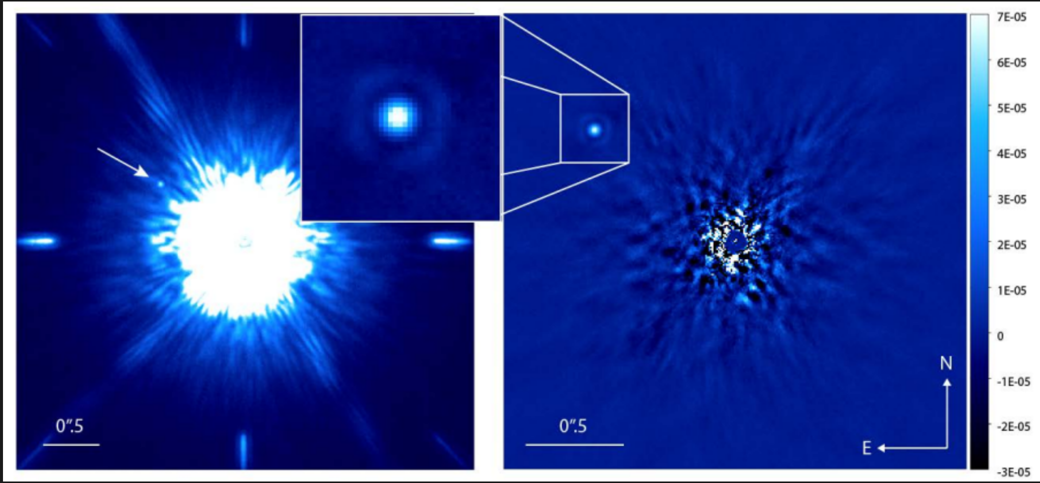
Ideal solutions in a non-ideal world



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 $\sim 4 \times 10^{-2}$)

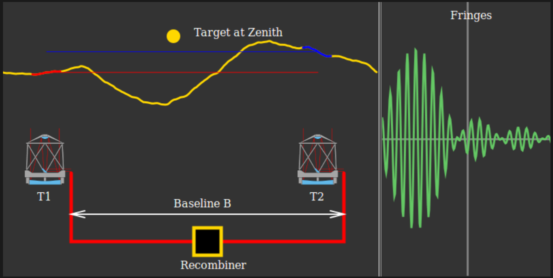
Operating in an imperfect world



Kühn et al, 2017, PASP, 2018

Coronagraphy saved by post-processing

Interferometry: measuring one thing well

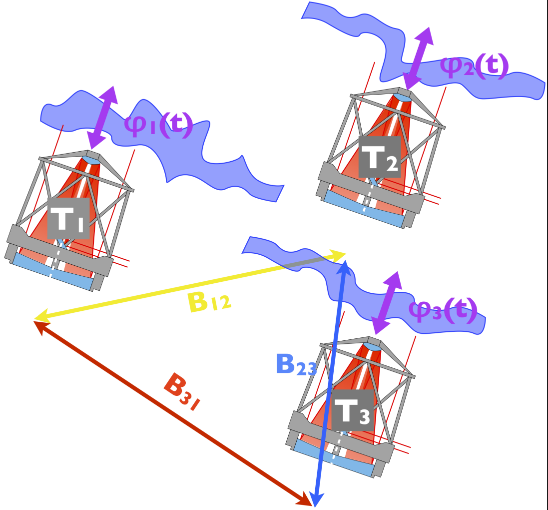


web-link

Measuring the complex visibility

- one single complex number
- understand biases and noises
- goes beyond the resolution limit

Take the environment into account



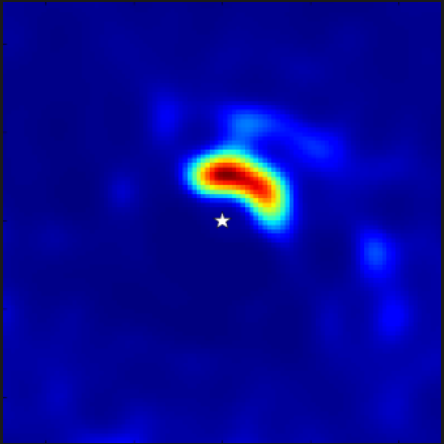
A special treatement for the phase:

$$\begin{aligned}\Phi(1-2) &= \Phi_O(1-2) + (\varphi_1 - \varphi_2)\\ \Phi(2-3) &= \Phi_O(2-3) + (\varphi_2 - \varphi_3)\\ \Phi(3-1) &= \Phi_O(3-1) + (\varphi_3 - \varphi_1).\end{aligned}$$

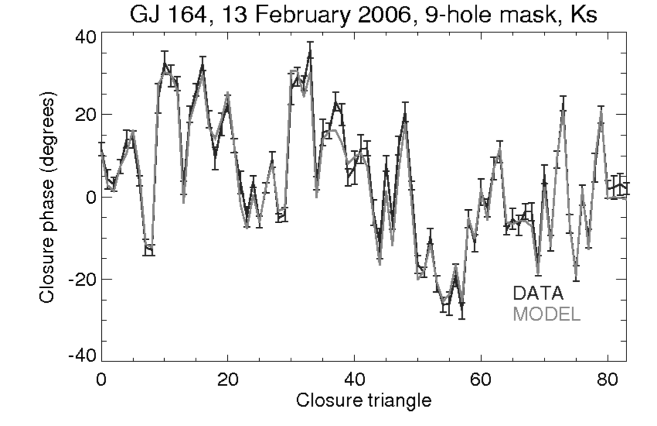
- linear perturbation term
- coupling of the perturbation along multiple baselines
- can find linear combinations that cancel the perturbation

Jennison R.C., 1958.

Closure-phase

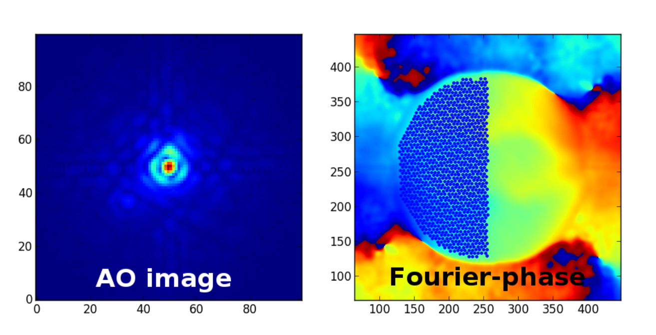


Transition Disk host LkCa 15
Ireland, 2013, MNRAS, 433, 1718



2009: AO-residuals $\sim$ 150 nm RMS
closure-phase stability $< 1^\circ$
roughly corresponds to $\lambda/1000$

Kernel-phase: beyond the triangle



Martinache, 2010, ApJ, 724, 464

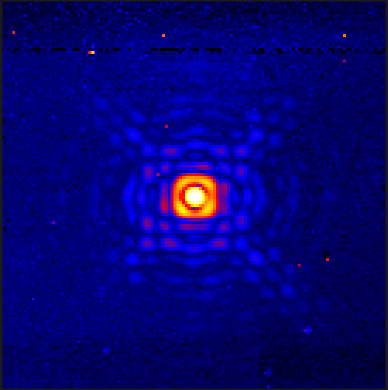
$I = O \otimes PSF(t)$

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

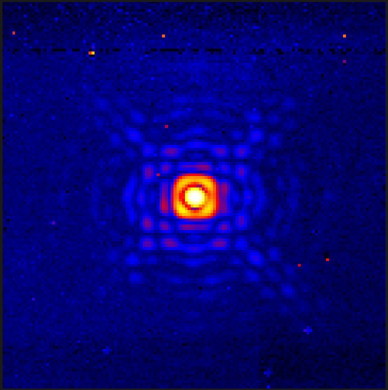
Use case 1



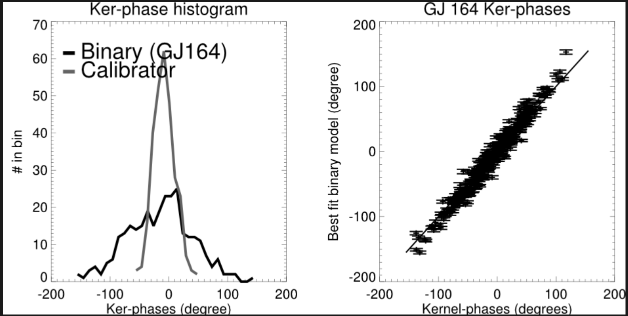
GJ 164 (HST/NICMOS1)

Use case 1

super-resolution detection is possible



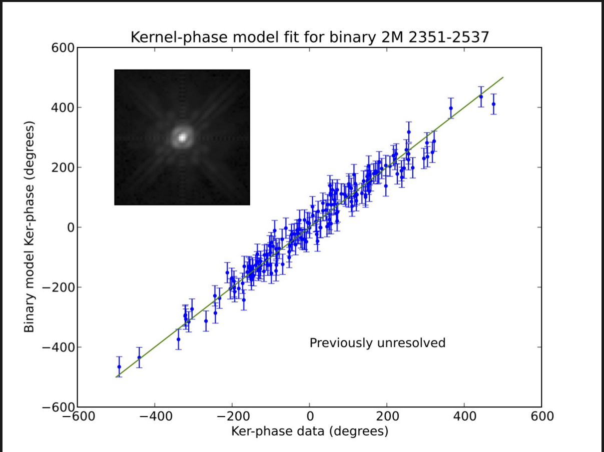
GJ 164 (HST/NICMOS1)



Histogram and kernel model of GJ 164

- companion c~ 10 : 1 at 0.5λ/D detected
- relative astrometry and phot. constraints

Use case 2



- snapshot survey of $\sim$ 80 L-Dwarfs
- two filters: F110W and F170M
- 10 known visual binaries
- 5 clear new detections
- 4 marginal detections
- separations down to $\sim$ 1 AU

Pope et al, 2013, ApJ, 767, 110

Phase noise is dead: long live photon noise!

- An instant phase-noise canceling filter: powerful tool
- The photon noise of the bright source remains
- Reported detections are in the $\sim 10^{-3}$ contrast range

Phase noise is dead: long live photon noise!

- An instant phase-noise canceling filter: powerful tool
- The photon noise of the bright source remains
- Reported detections are in the $\sim 10^{-3}$ contrast range

High-contrast imagers:

- designed for greatness
- highly sensitive to their operating conditions

Phase noise is dead: long live photon noise!

- An instant phase-noise canceling filter: powerful tool
- The photon noise of the bright source remains
- Reported detections are in the $\sim 10^{-3}$ contrast range

High-contrast imagers:

- designed for greatness
- highly sensitive to their operating conditions

Kernel-phase:

- characterized by its robustness
- limited by its intrinsic dynamic range

Phase noise is dead: long live photon noise!

- An instant phase-noise canceling filter: powerful tool
- The photon noise of the bright source remains
- Reported detections are in the $\sim 10^{-3}$ contrast range

High-contrast imagers:

- designed for greatness
- highly sensitive to their operating conditions

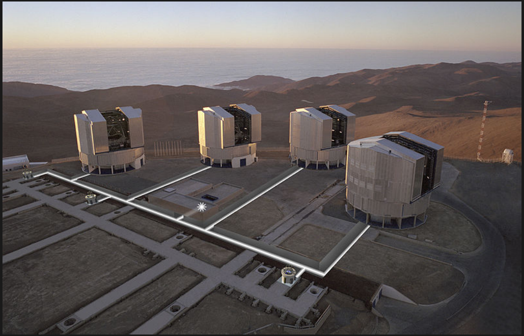
Kernel-phase:

- characterized by its robustness
- limited by its intrinsic dynamic range

A design principle?

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

A simple problem: a 4-telescope interferometer



[VLTI [Credit: ESO]]

Favorable contrast → L-band

Milliarcsec resolution → VLTI

High-contrast → Nulling

- Four telescopes: 75 % efficiency
- A finite number of degrees of freedom
- A finite number of covariated quantities
- → The problem can be well posed

Nulling interferometry

State of the Art:

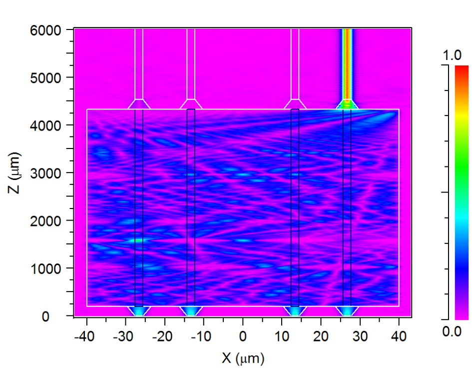
- Cancel on-axis light source (Bracewell, 1978):
- Solutions exist for N-aperture interferometers (Guyon et al, 2013)
- Design emphasis: produce dark (nulled) outputs
- Like a coronagraph, rejection is sensitive to environment
- Post-processing required (e.g. Null Self-calibration, Hanot et al, 2011)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

4T nuller for VLTI!

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

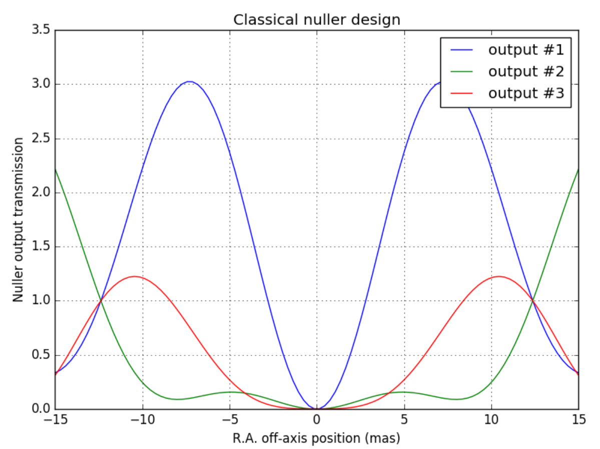
- Four telescope inputs
- One bright output
- Three dark outputs

4x4 nuller



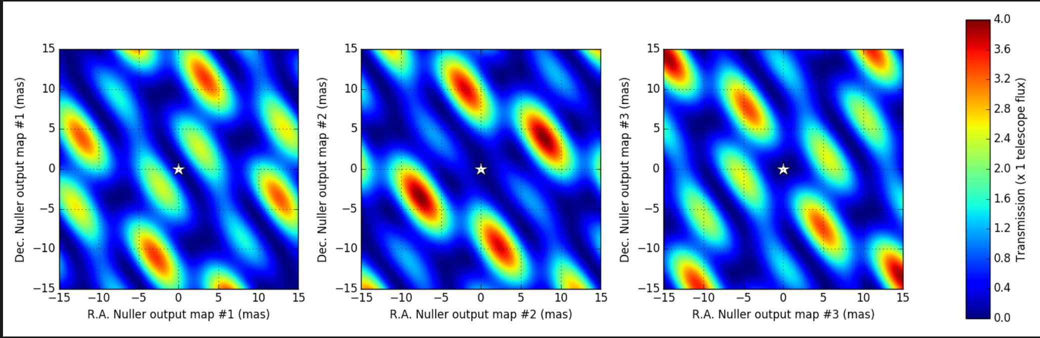
(MMI design by Harry-Dean Kenchington Goldsmith, ANU PhD candidate)

Quadratic output (for an inline interferometer)



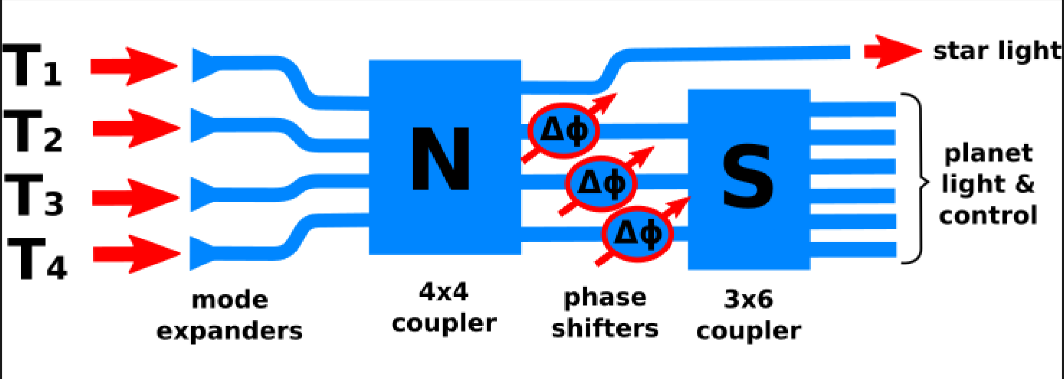
The effect of the perturbation is degenerate
The behavior is the same for photometric perturbations

4T-Nuller: On-sky response for VLTI



Only at zenith!

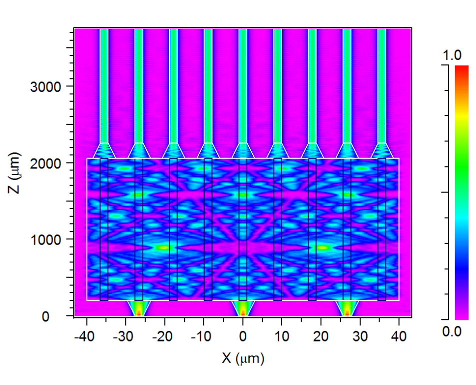
Modify the nuller



To asymmetrize the perturbation dependance of the nuller!

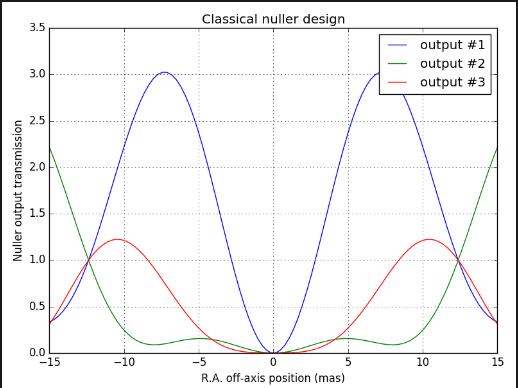
Modified 4T-Nuller: principle

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

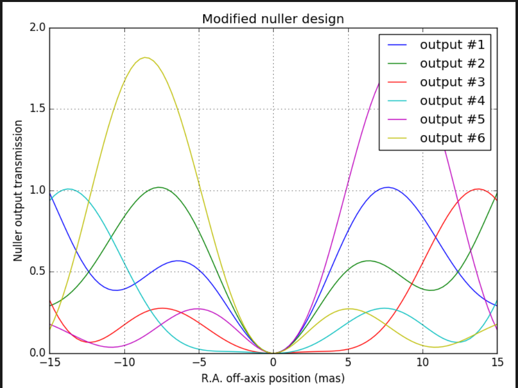


(MMI design by Harry-Dean Kenchington Goldsmith, ANU PhD candidate)

Break the symmetry

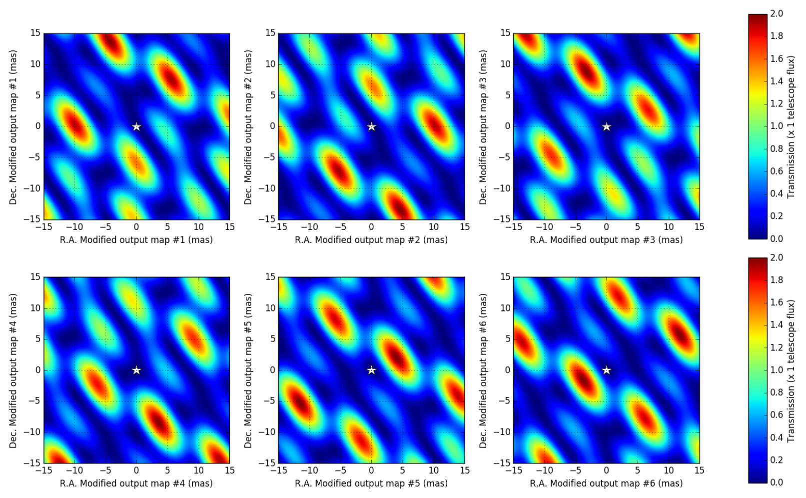


Classical design



Modified design

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



From 3 to 6 outputs

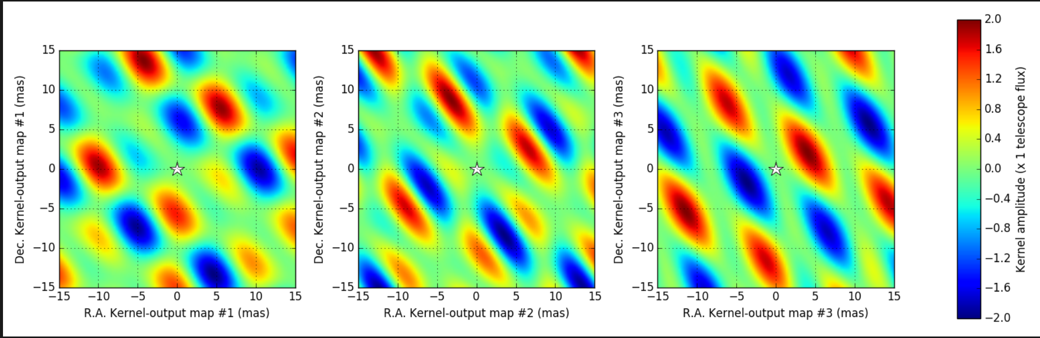
Kernel-nulled outputs

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

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

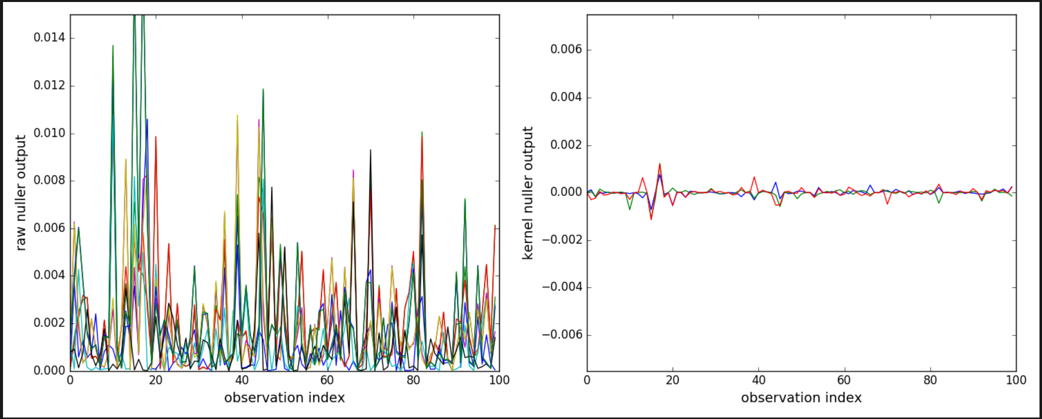
- record a new 2^{nd} order perturbation response matrix **A**
- and find a kernel for this matrix

Kernel-Nulled outputs: on-sky response for VLTI



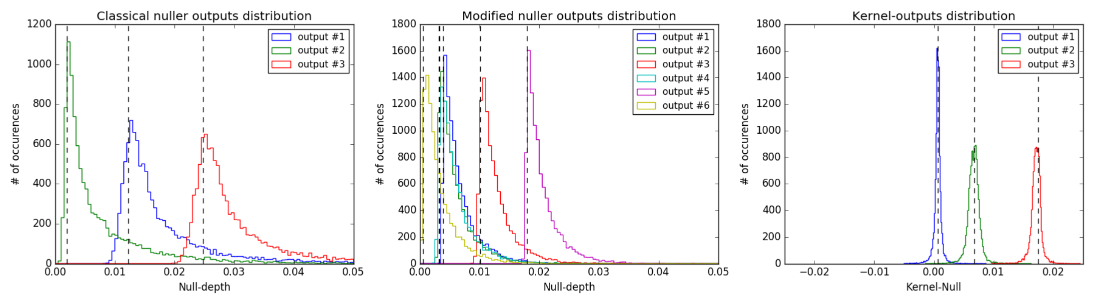
Maps are anti-symmetric! A single snapshot observation can constrain a companion's position.

Kernel-Nulled outputs: enhanced stability



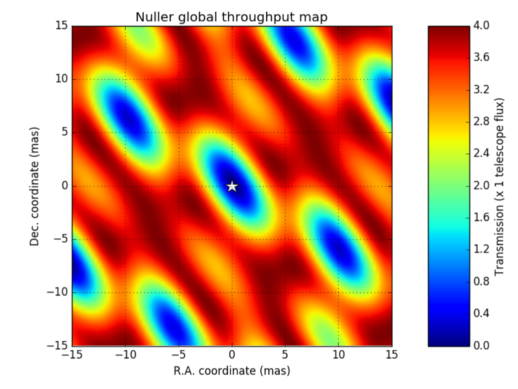
50 nm RMS random piston error for the array
Same vertical scale for raw (left) and kernel (right) outputs.
The kernel-outputs indeed provide additional filtering

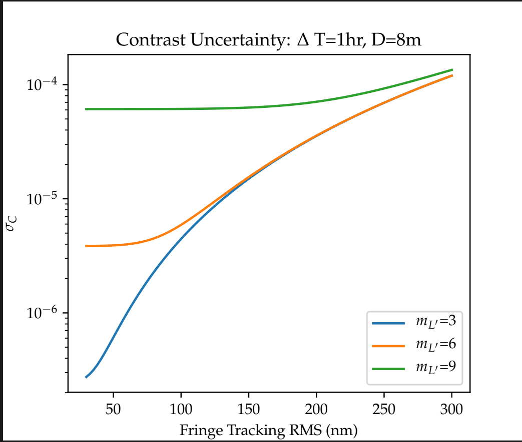
Kernel-nulled outputs: more robust against piston



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

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

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

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

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

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

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/]