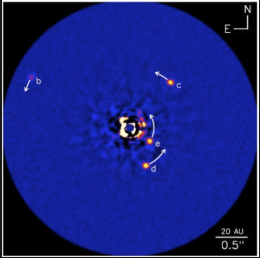
The ASGARD visitor instrument suite

Martinache, Ireland, Kraus & Defrere

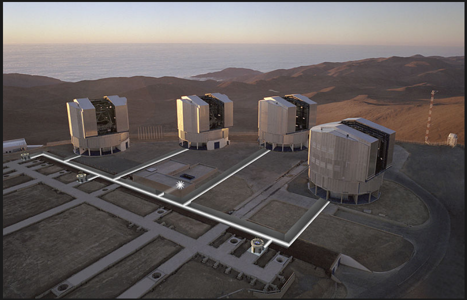
June 20, 2019

The high-contrast imaging ambition

- High-contrast observations like those delivered by **SPHERE**
- At the spatial resolution of **VLTI**
- $c < 10^{-5}$ @ a few mas



High-contrast image of HR 8799

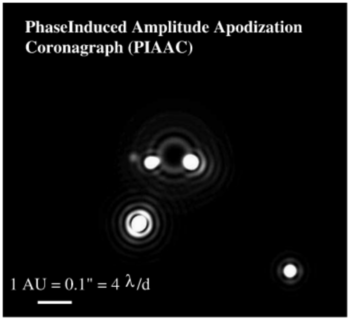


Hi-5
High-contrast Interferometry up to 5 microns

[Defrere et al, 2018]

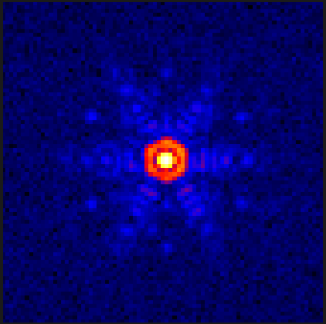
The high-contrast imaging dual challenge

CORONAGRAPHY



Photon noise ✓
Phase noise ✗

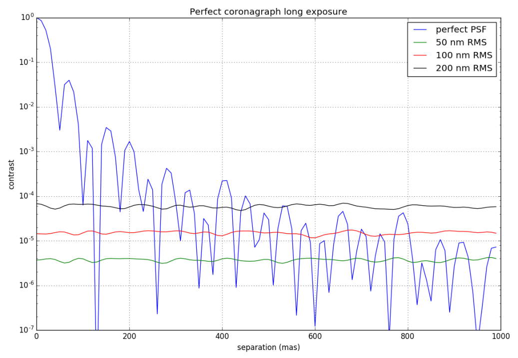
KERNEL



Photon noise ✗
Phase noise ✓

Can we combine the two approaches?

The trick is. . .



The ideal coronagraph

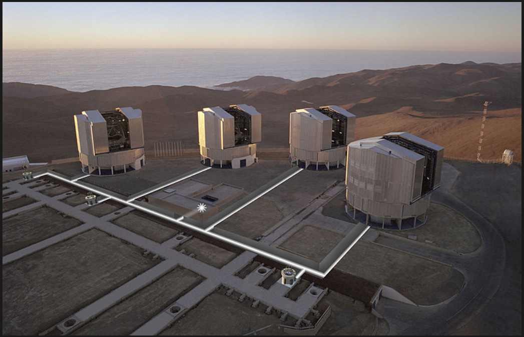
In the presence of a high-contrast device, errors are quadratic: $c \sim (2\pi\sigma/\lambda)^2$

- the problem is non-linear
- the problem is degenerate
- lots of covariance

kernel-coronagraphy is a high-dimension problem that is just hard to write

VLTI: a chance to do things right

One telescope is hard. Four is easy??



[VLTI [Credit: ESO]]

Science cases require:

- High angular resolution → **VLTI**
- High-contrast → **Nulling**

- Four telescopes: efficiency 75 %
- Finite number of degrees of freedom
- Finite number of covariances
- → A well-posed problem

Nulling... in theory

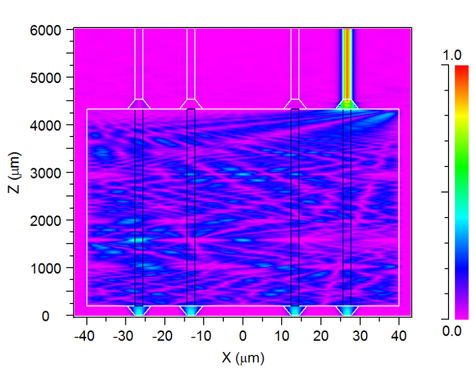
$$\mathbf{N} = 0.5 \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

- Four input beams
- One bright output
- Three **dark** outputs

Photons of off-axis sources coupled in the dark outputs

Still sensitive to perturbations.

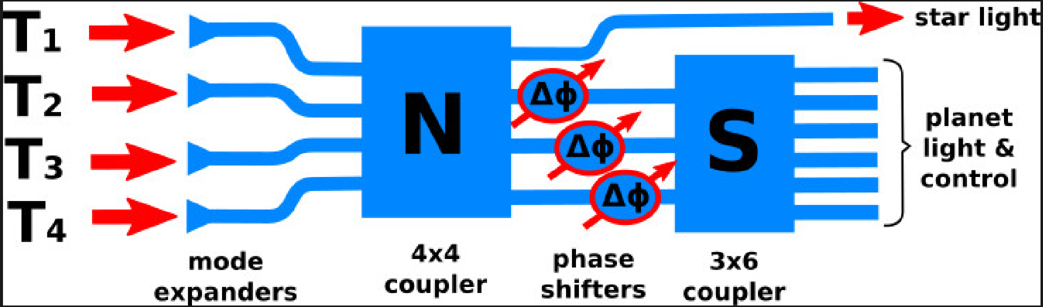
4x4 nuller



Integrated optics technology option

MMI design by Harry-Dean Kenchington Goldsmith, ANU

Nuller → Kernel-nuller

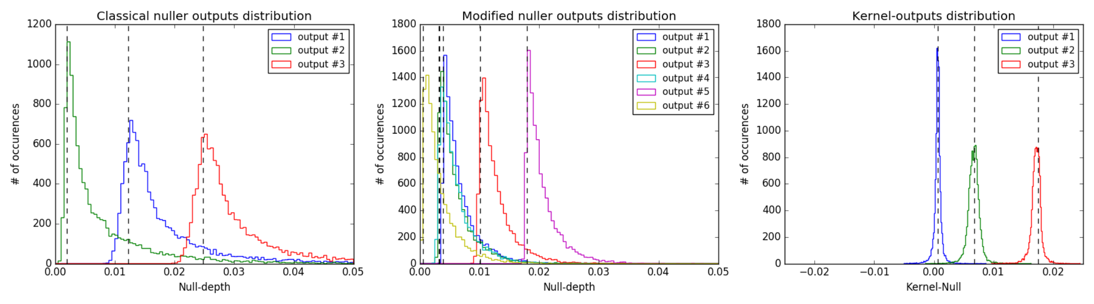


The innovation: a 2^{nd} stage, a **scrambling** unit that:

- makes the outputs respond to perturbation in an asymmetric manner
- builds kernels: observables **robust against second order piston errors**

Kernel-nulled outputs: robustness is possible

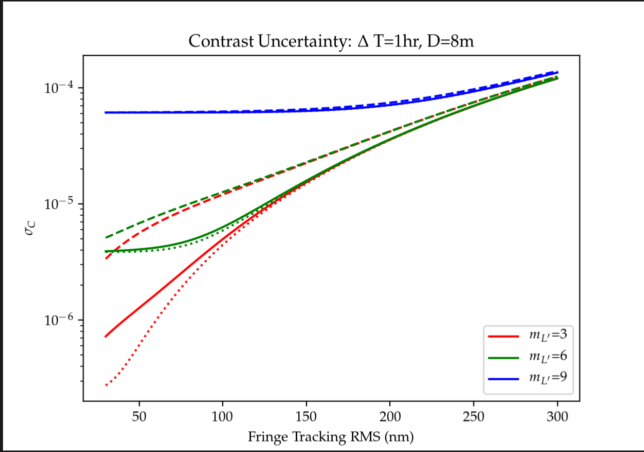
In the presence of piston residual errors



kernels filter out second order errors

[Martinache & Ireland, **619**, 87 (2018)]

VIKiNG contrast detection limits



5-σ L-band (4-UTs) contrast detection limits.

Performance depends on:

- cophasing stability
- star magnitude (compete with sky background)
- injection stability (AO correction)

Characterization of thermal emission of known RV planets is possible

Top-level requirements

cophasing:

- targets are on the bright side
- **low-RMS** is the focus, not extreme sensitivity

photometric stability:

- benefit from improved VLTI AO systems or...
- include internal DM tweeter

additionally:

- simplicity of design (**high throughput**)
- chromatic OPD control (from the Y to the L band)

ASGARD in a nutshell

HEIMDALLR

- Fringe-tracker
- closure-phase
- H+K bands
- Galactic Archeology

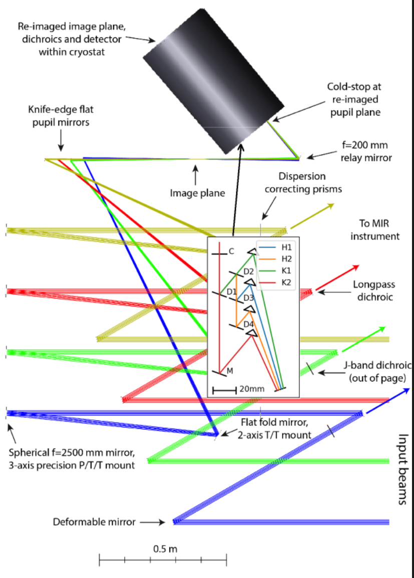
BIFROST

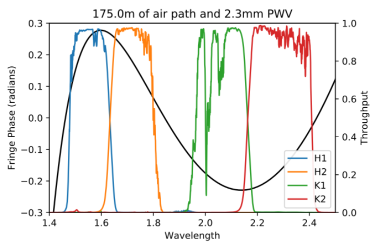
- R = 1000 $\rightarrow$ 25000
- Y+J bands
- 3D characterization
- Accretion lines

VIKiNG

- Kernel-nuller
- L-band
- planet atmospheres
- Hi-5 alternative

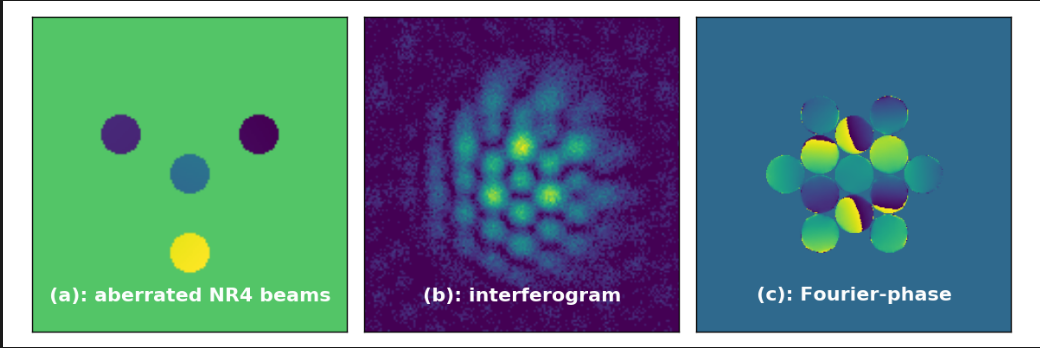
HEIMDALLR





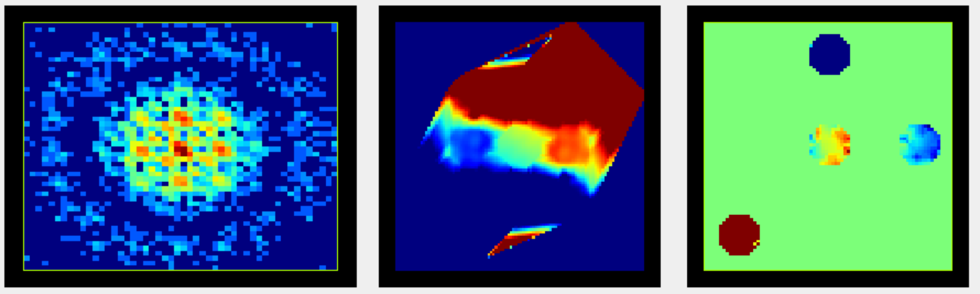
- broad bandwidth (active dispersion compensation)
- dichroic based design (high throughput)
- 2D multi-axial recombiner (SAM interferometry)
- measures visibility and closure-phase
- serves as a fringe-tracker (and more!)
- **proposal submitted to ARC (PI Ireland)**

HEIMDALLR as a fringe-tracker



- Single mode of operation
- Non-redundant compact configuration
- The 2D interferogram provides high-sensitivity wavefront sensing
- Multiple-λ avoids the 2π phase ambiguity problem

HEIMDALLR as a wavefront sensor?



In the low-aberration regime:

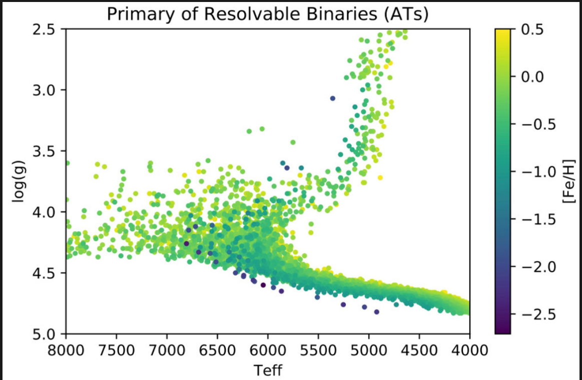
- The 2D fringe pattern can be used for intra-beam WF metrology
- Can feedback embedded deformable mirrors
- Concept of the **APF-WFS**, validated on-sky at Subaru/SCExAO

[Martinache et al, A&A, 2016, N'Diaye et al, A&A, 2018]

HEIMDALLR as an instrument

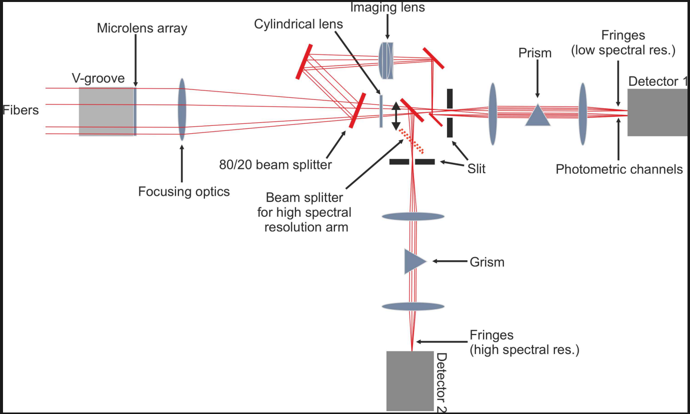
Galactic Archeology:

- High-throughput instrument
- Resolved observations of many tight binaries is possible
- Accurate (2%) dynamical masses can be determined
- one binary per 15-minute observing sequence (with ATs)
- $\sim$5000 Gaia binaries observables



ASGARD/Gaia sample with enough diversity to also constrain the ages of many objects.

BIFROST: Y+J band spectroscopy



- fringe-tracking by HEIMDALLR
- fiber injection optimization
- birefringence compensation

two-arm design:

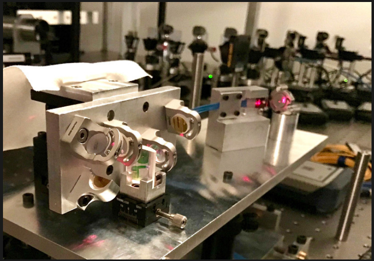
low-res arm:

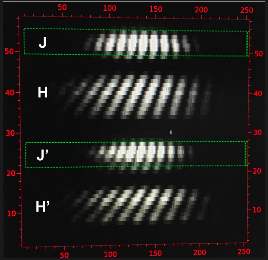
- R=40
- short integration
- continuum visibility
- chromatic dispersion tracking

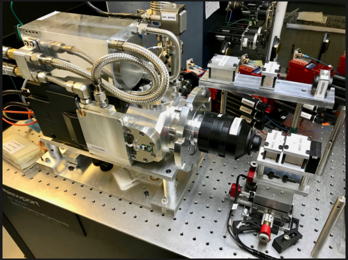
high-res arm:

- R=1000, 6000, 25000
- long integration
- spectral lines visibility

BIFROST: Y+J band spectroscopy

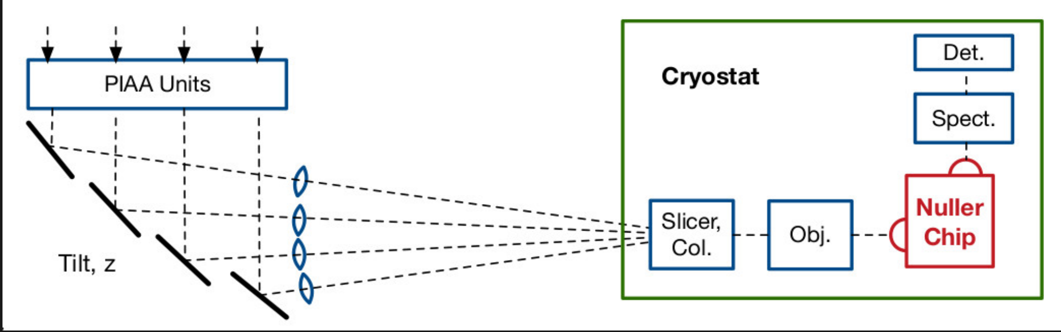






- Inspired by the work done on MIRCX at CHARA in the H and J-bands
- Enabled by the superior performance of the existing VLTI infrastructure
- High-resolution spectroscopy on milliarcsecond scale: kinematic studies & velocity-resolved imaging in Pa-β, Pa-γ, He I, [FeII]
- $\rightarrow$ Presentation by S. Kraus

VIKiNG: system level



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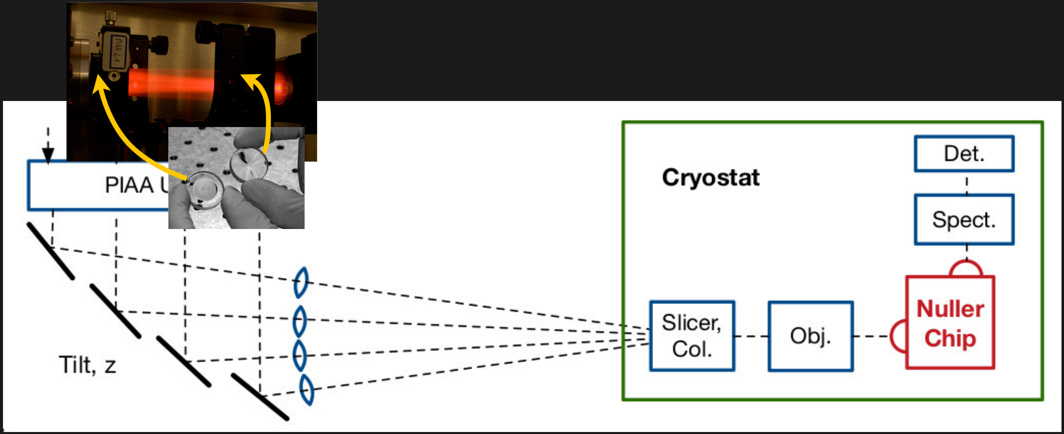
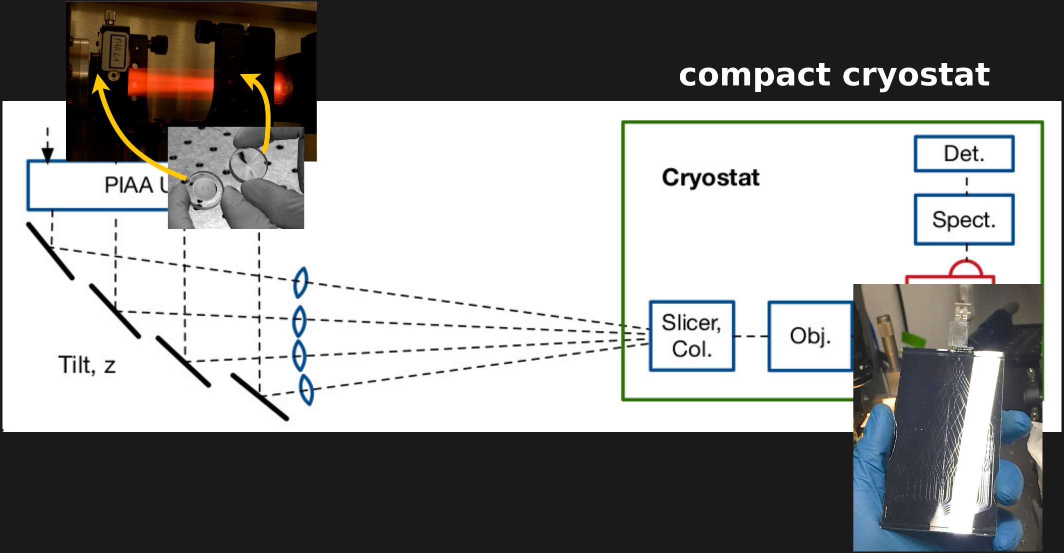


VIKiNG: system level

compact cryostat



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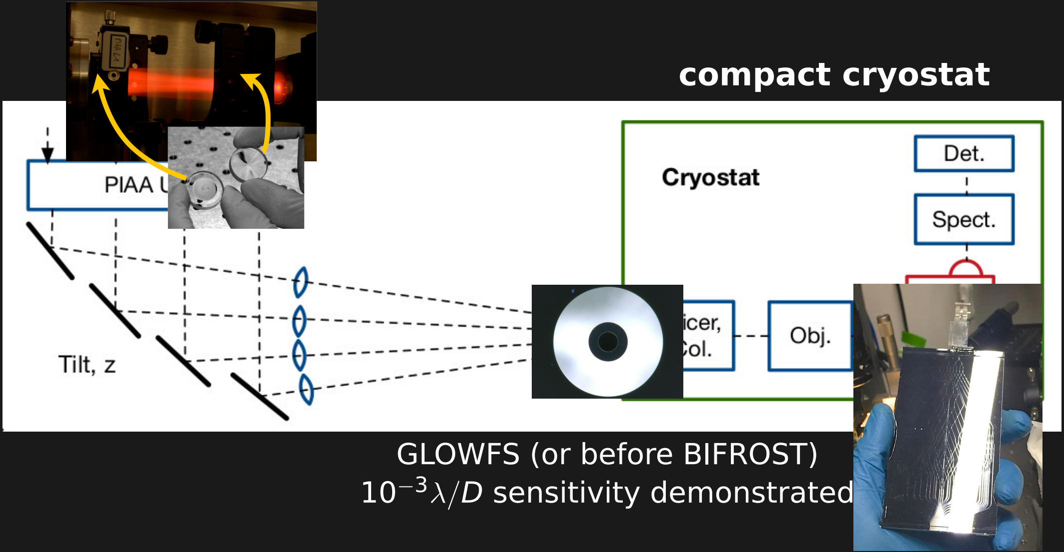
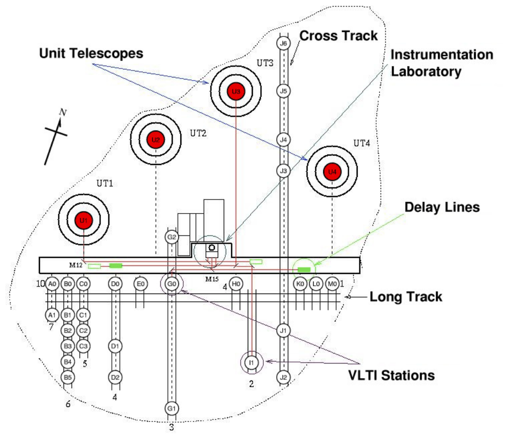
compact cryostat



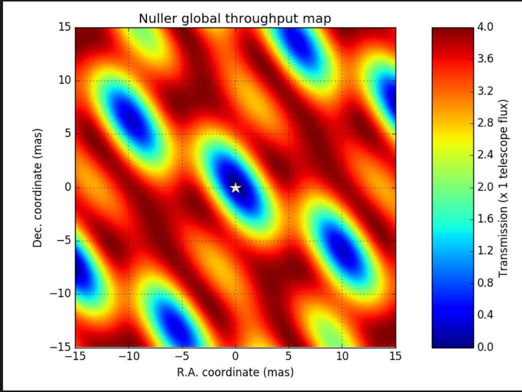
GLOWFS (or before BIFROST)

$10^{-3}\lambda/D$ sensitivity demonstrated

VIKiNG: efficiency

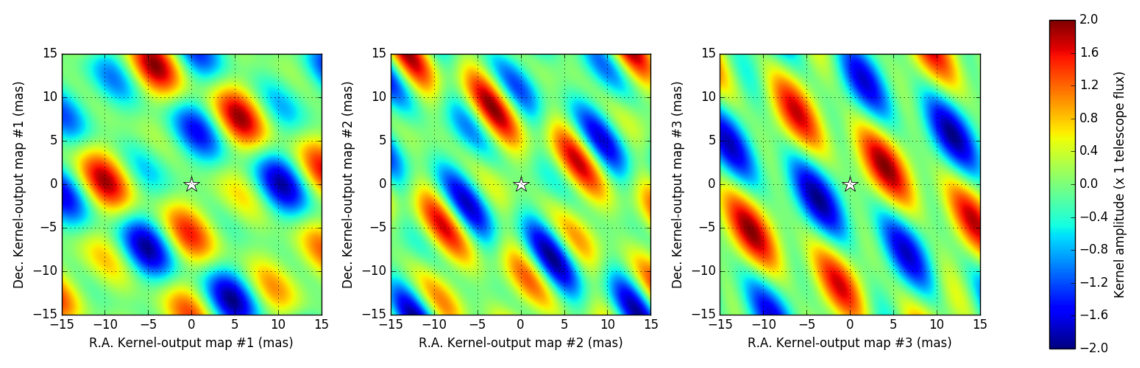


VLTI array (UTs)



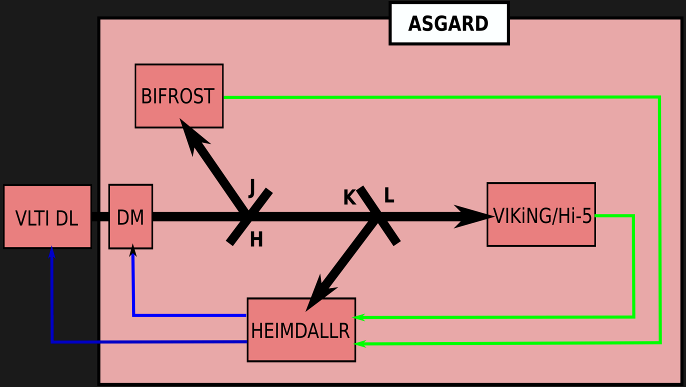
Overall nuller efficiency

VIKiNG: kernel-maps



- Kernel sensitivity maps in the Zenith 4-UT VLTI field of view.
- High-contrast observations with the properties of closure-phase
- $\rightarrow$ Presentations by D. Defrere & M. Ireland

ASGARD: a self-contained ecosystem



- wavefront control strategy inspired from XAO
- shared memory data structure
- modules feedback HEIMDALLR who drives

Thank you - to Valhallah!

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