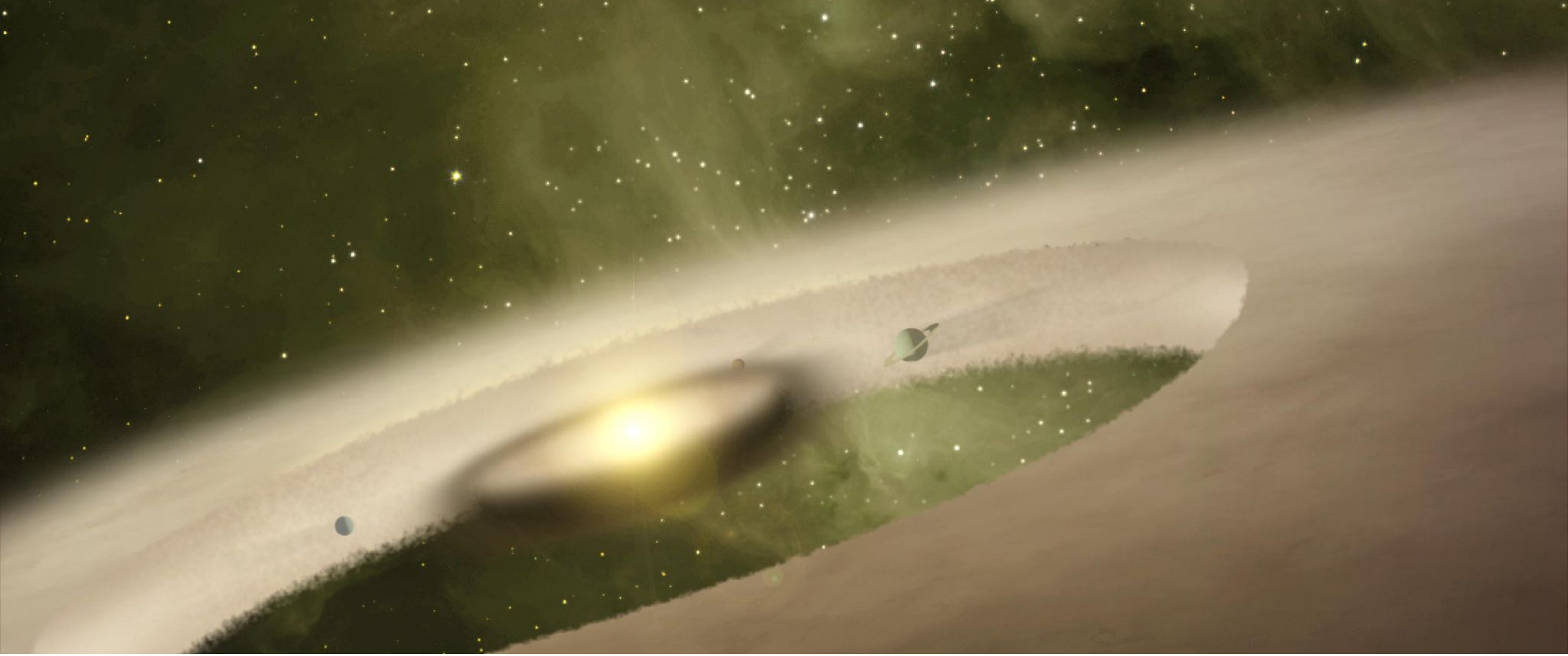


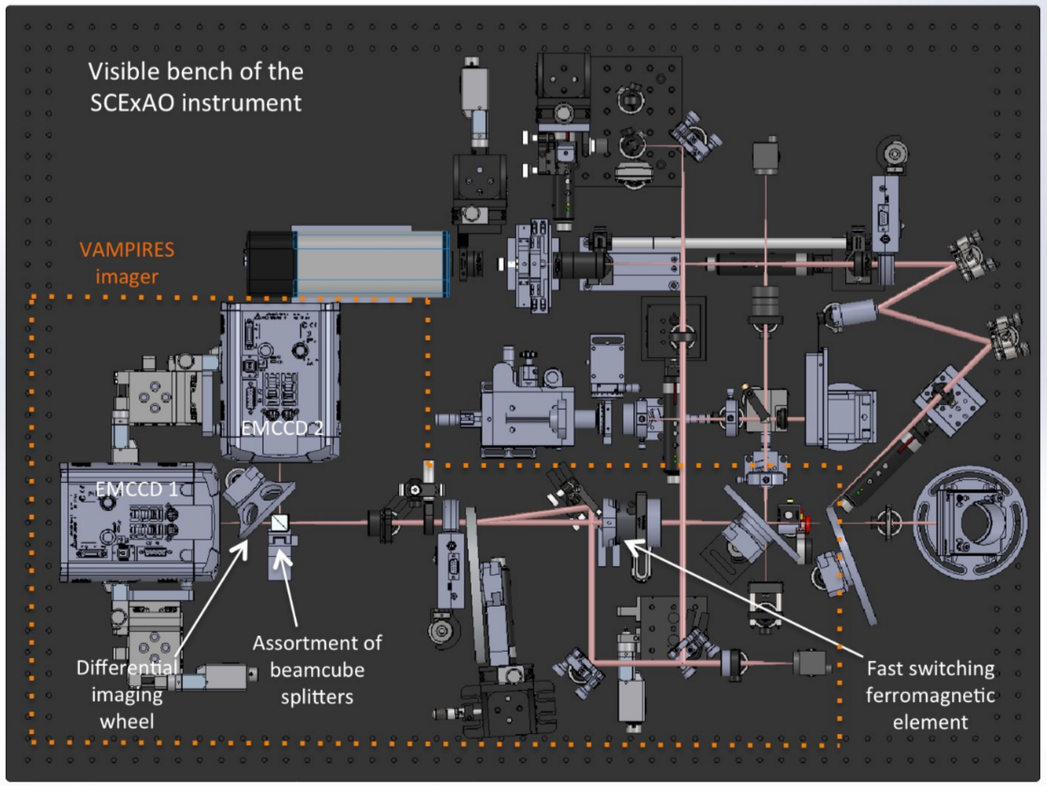
DIFFRACTION-LIMITED POLARIMETRIC IMAGING OF PROTOPLANETARY DISKS AND MASS-LOSS SHELLS WITH VAMPIRES

Sydney Institute for Astronomy, University of Sydney
Subaru Telescope, National Astronomical Observatory of Japan
The Australian Astronomical Observatory (AAO)
MQ Photonics Research Centre, Macquarie University

Image: NASA/JPL-Caltech

BACKGROUND – THE VAMPIRES INSTRUMENT

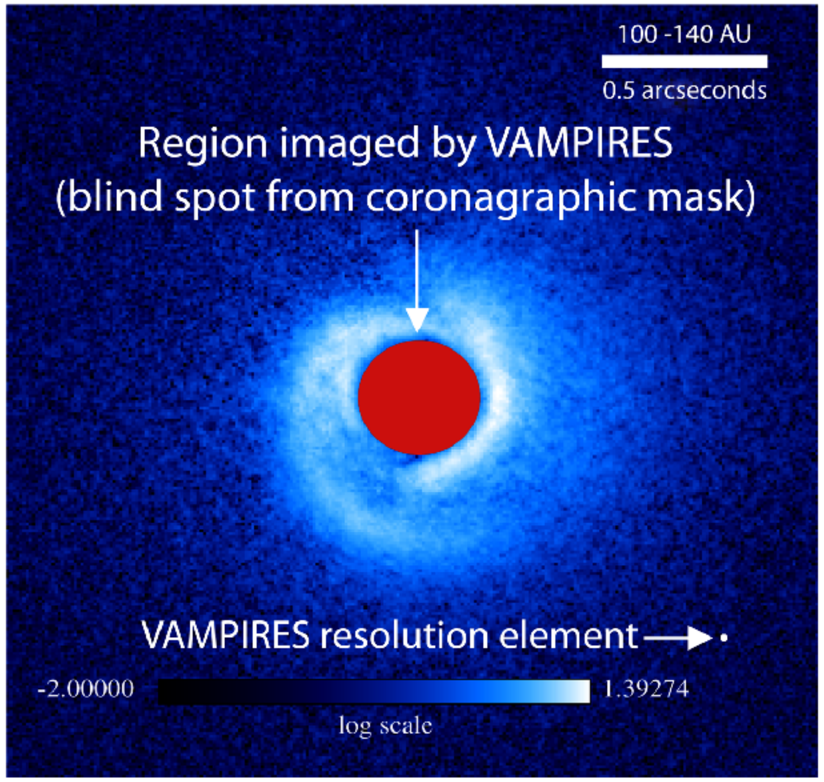
- Polarimetric aperture masking and imaging in the visible
  - **Aperture masking**
    - Diffraction limited imaging through the atmosphere…
    …resolution of 10s mas
  - **Differential polarimetry**
    - imaging scattered starlight
    - Precision differential calibration beats the contrast problem (triple-differential)
    - Measurement of dust grain type, size
- 'Hitch-hiker instrument' - operates on visible channel of SCExAO on Subaru telescope, simultaneous with IR observations (e.g. CHARIS)



SCIENCE CASE: IMAGING THE INNER REGION OF PROTO-PLANETARY DISKS AT SOLAR-SYSTEM SCALES

Inner region (10's of AU) critical for understanding planet formation and disk structure

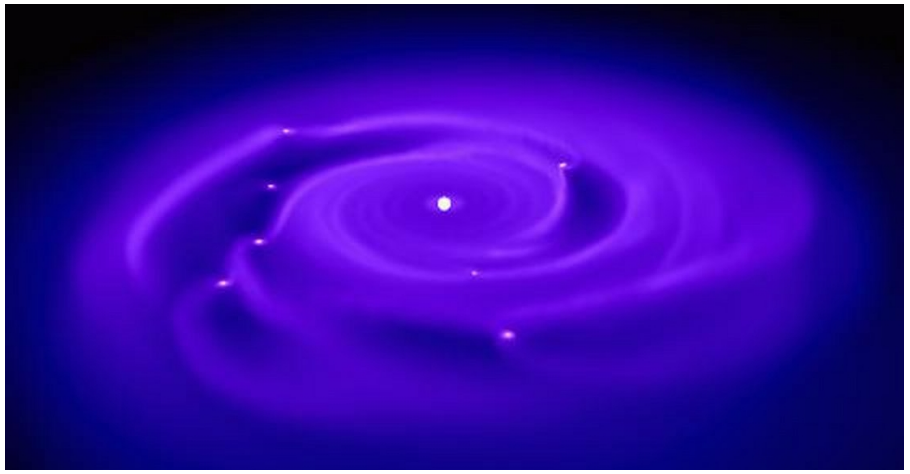
- Precise measurement of transition disk gaps and inner disk
- Density perturbations from massive bodies within disk (e.g. warps, spirals)
- Gravitationally bound clumping dust immediately surrounding forming planets
- Dust grain species and size determination



MWC758 - Base image: **Grady et al., ApJ, 2013**

Complementary to coronagraphy

- Resolution ~10 mas; 0.5λ/D
  - ~1 AU at 100 pc
- NRM F.O.V. ~500 mas, PDI ~3 arcsec
- Scattered starlight, not thermal

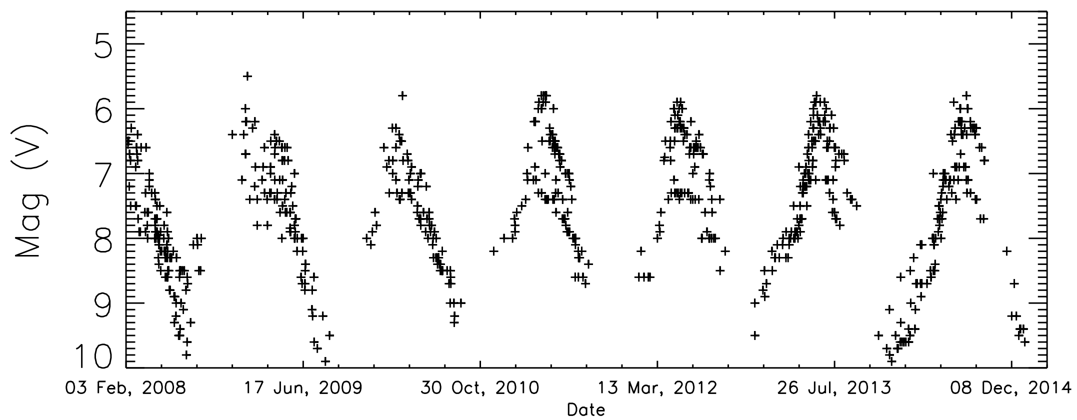


Hydrodynamical modelling of gravitational collapse of protoplanetary disk, with resulting fragmentation causing gravitationally bound clumps
Mayer L., et al., 2007, ApJ 661 77

SCIENCE CASE: IMAGING THE INNER MASS-LOSS REGION OF EVOLVED STARS

Mass-loss process poorly understood

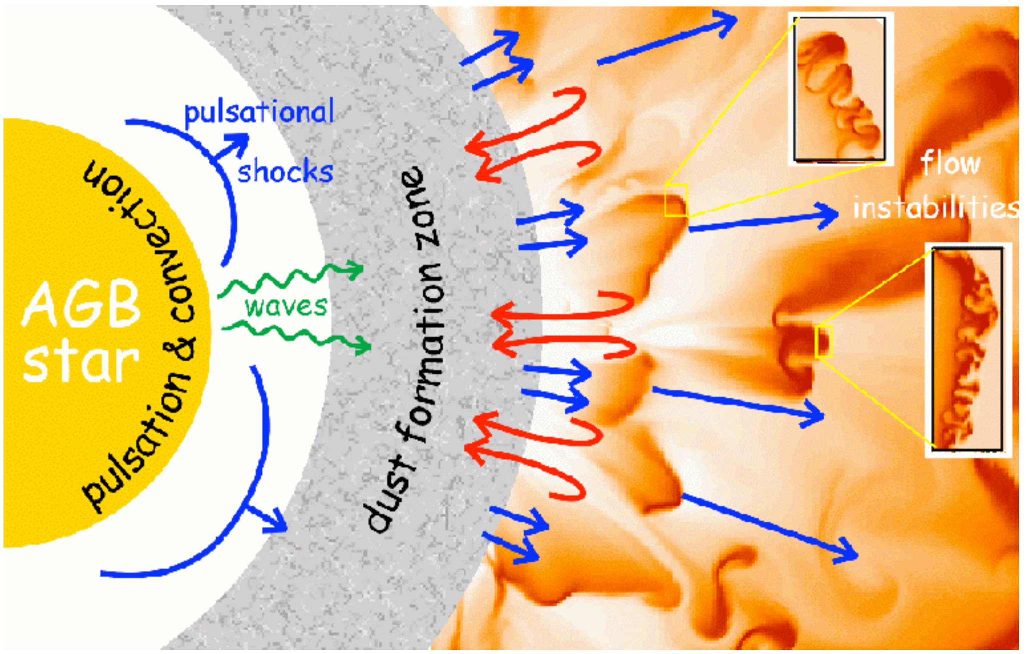
- Ejected material comprises next generation of stars & planets
- What drives this wind?
- *Directly image inner dust condensation region, explore grain size and composition (polarimetry)*



W Hya light curve (AAVSO)

Origin of asymmetries

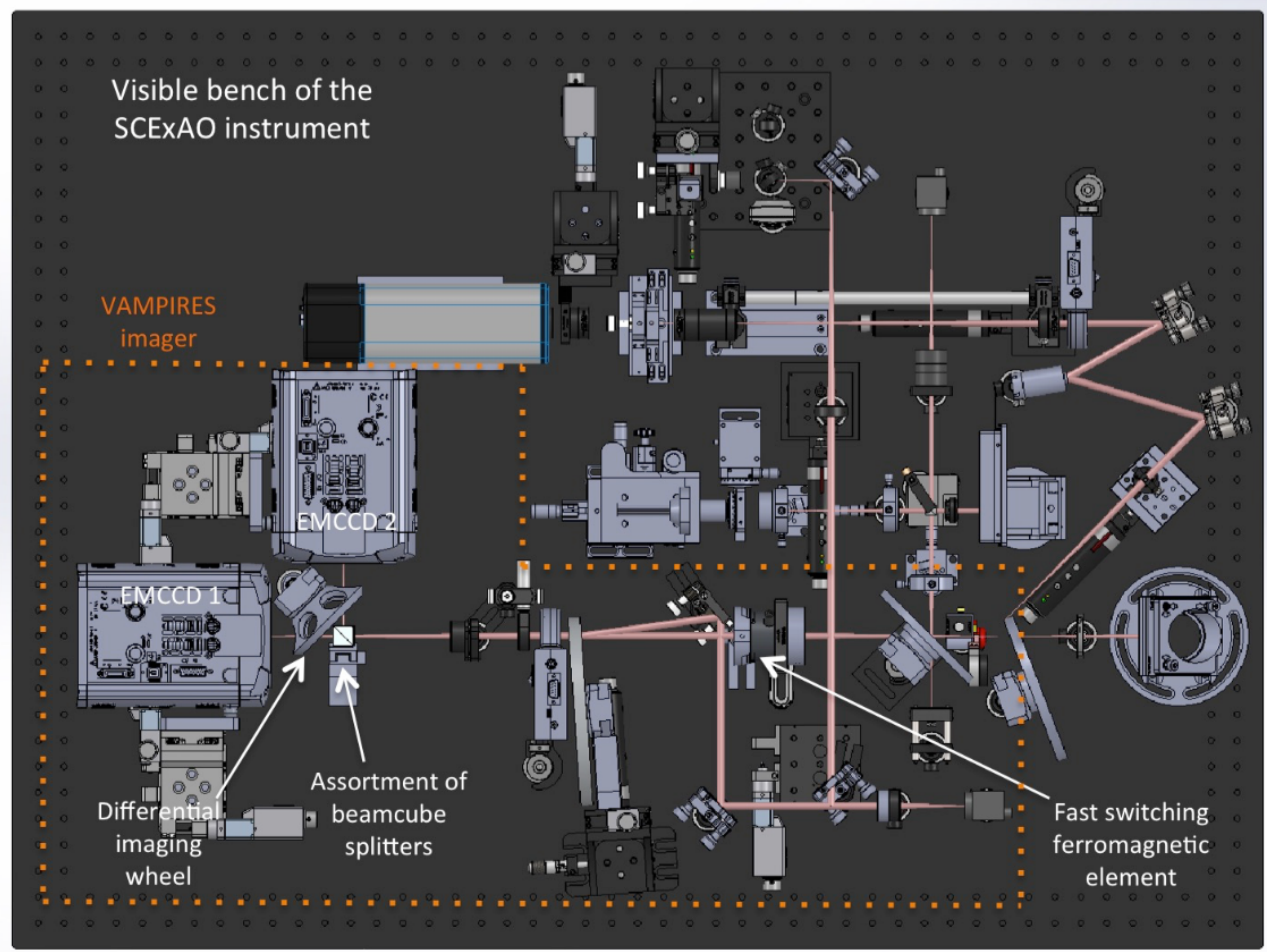
- Asymmetries observed at wide scales - where do they originate?
- At star (effect of stellar atmosphere) or interstellar medium?



Peter Woitke: http://www.strw.leidenuniv.nl/~woitke/AGB_popular.html

Extension of red giant atmospheres

- Does radiative pressure on dust in atmosphere contribute to extension?


Visible bench of the SCExAO instrument
VAMPIRES imager
EMCCD 2
EMCCD 1
Differential imaging wheel
Assortment of beamcube splitters
Fast switching ferromagnetic element

New mode -
Differential spectral line imaging - Hα, SII
Operates double-differential to calibrate NCP

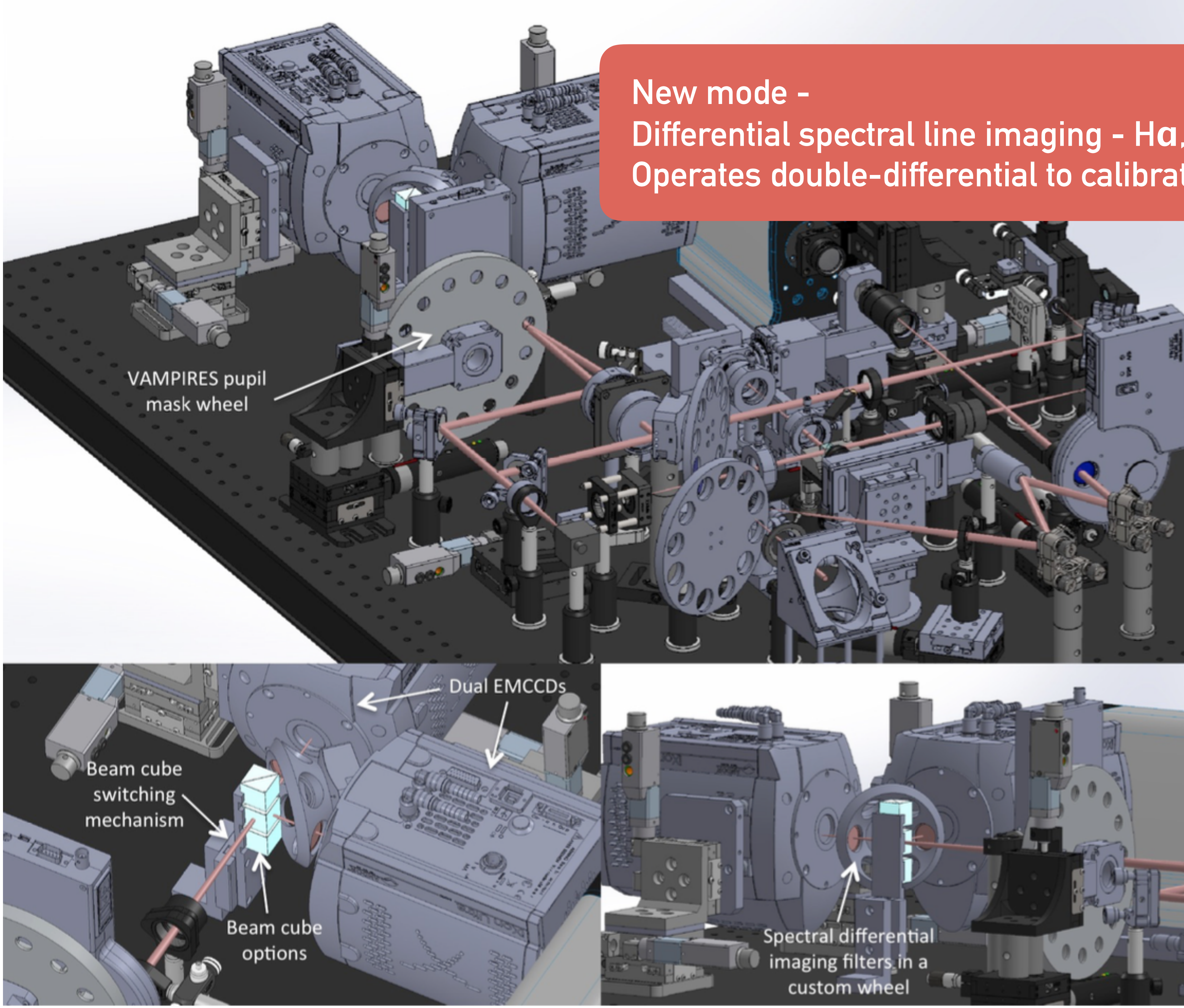
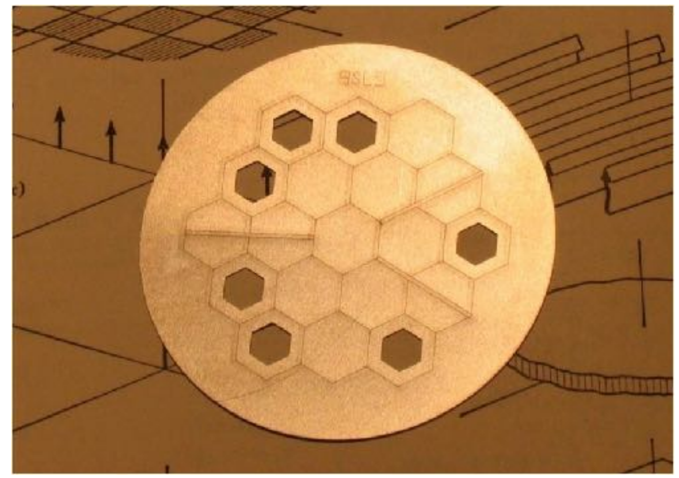


Figure 4: (Top) A view of the entire visible bench of SCExAO. (Bottom left) A zoomed in view of the beam cube switching mechanism. (Bottom right) A zoomed in view of the wheel to switch the filters for differential imaging mode.

Diffraction limited imaging through atmosphere: One method: Non-Redundant Masking

State of the art 10m telescope:
- Diffraction limit ~ 10 mas
- Seeing limited ~ 1000 mas

The goal: mitigate the effect of the turbulent atmosphere to allow diffraction limited, high contrast imaging.

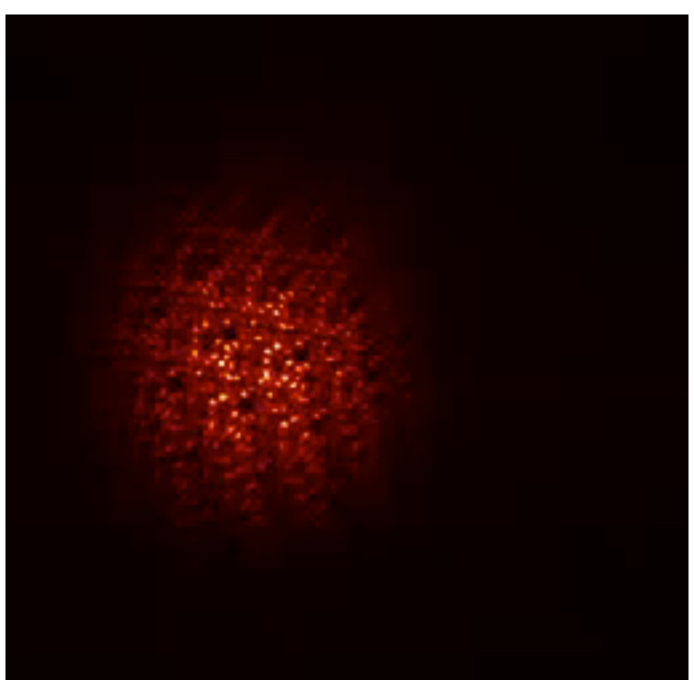


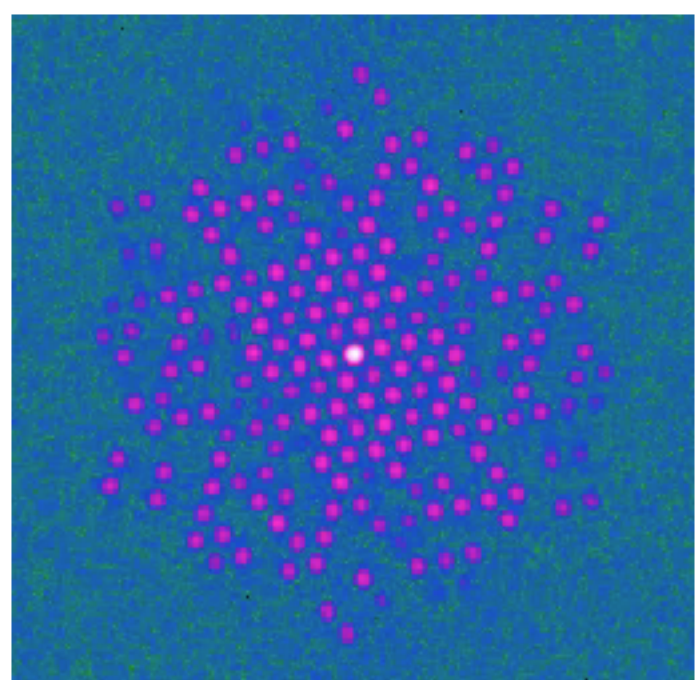
Aperture masking interferometry present state of art

—> Each and every hole-pair is baseline of interferometer

—> Recover diffraction limited performance

Visibilities - a power spectrum, independent of phase





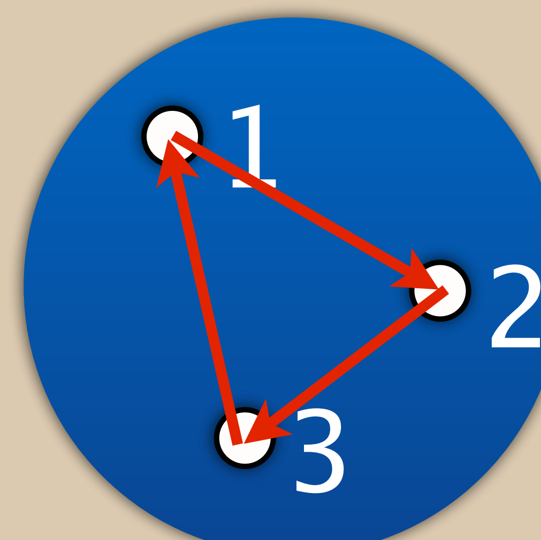
Closure phase

independent of phase

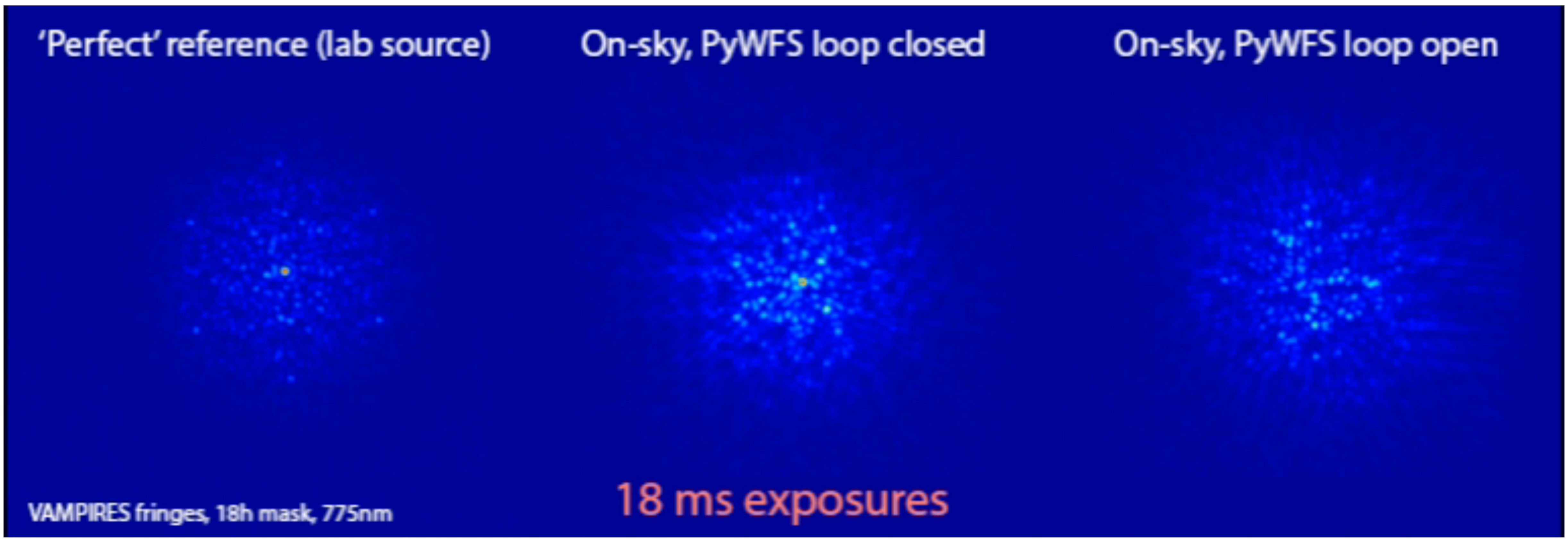
ψ – Measured baseline phase
ϕ – Actual baseline phase
e – error from atmosphere

$$\psi_{12} = \phi_{12} + e_2$$
$$\psi_{23} = \phi_{23} + e_3 - e_2$$
$$\psi_{31} = \phi_{31} - e_3$$

$$\text{C.P.} = \psi_{12} + \psi_{23} + \psi_{31} = \phi_{12} + \phi_{23} + \phi_{31}$$



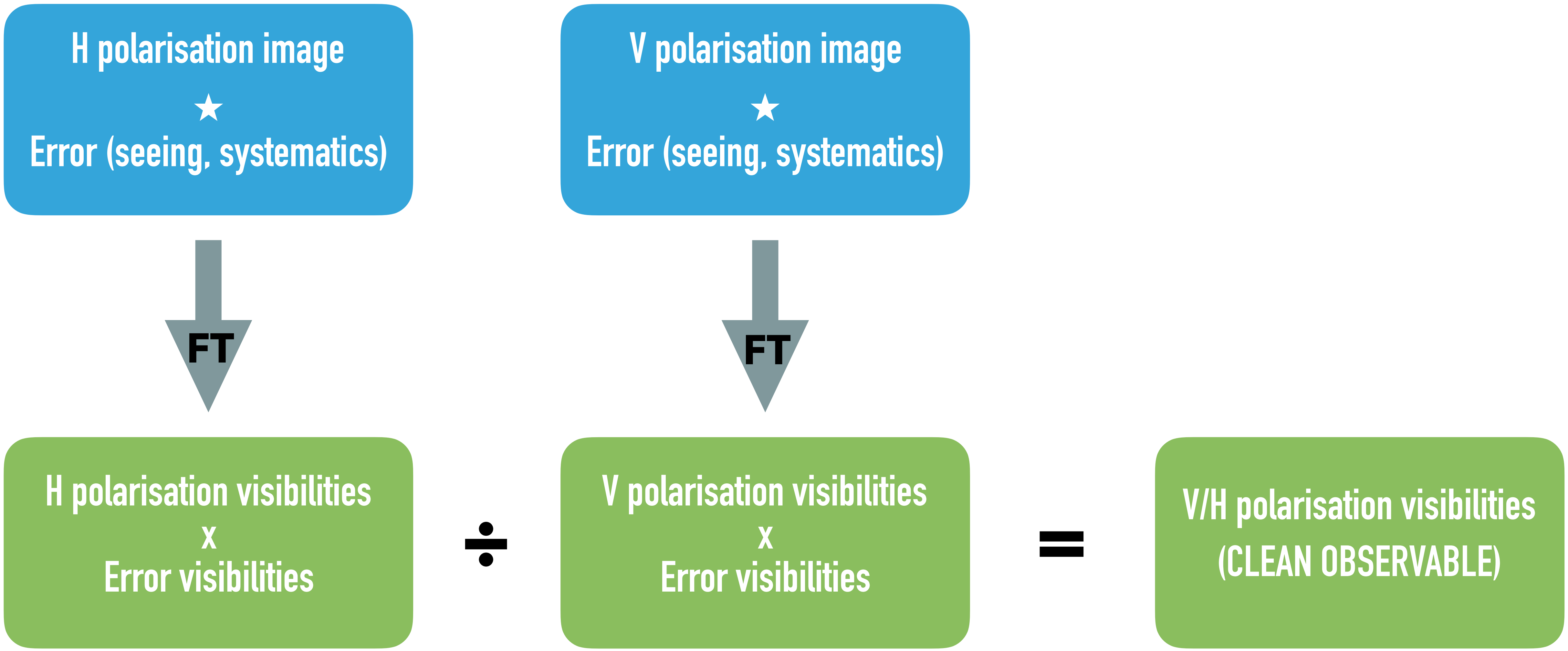
WHY AO & ADVANTAGE OF HIGH TIME-CADENCE



Poor seeing / large residual WF error

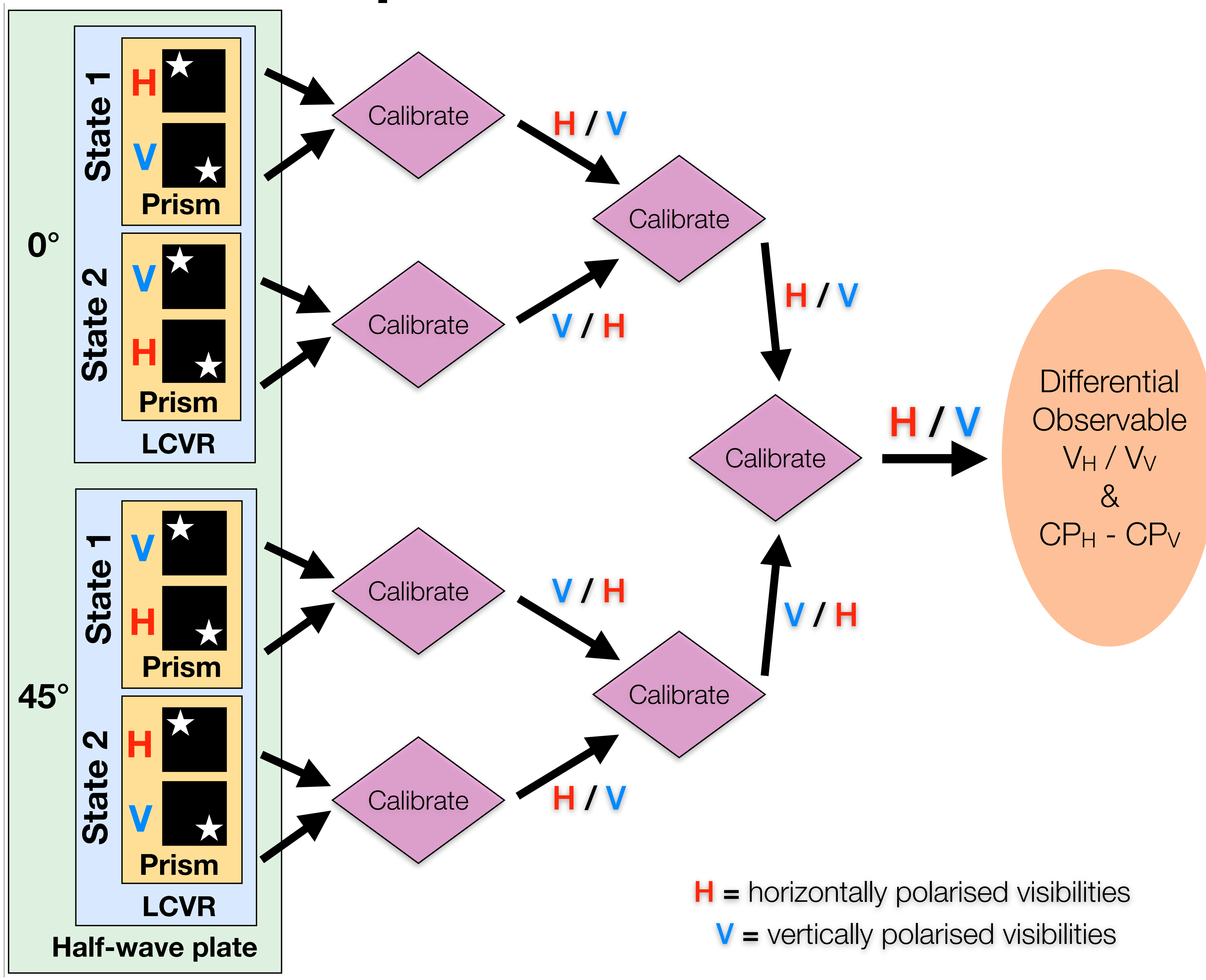
High time cadence = high fringe visibilities (and S/N)

DIFFERENTIAL CALIBRATION – IN AN IDEAL WORLD…



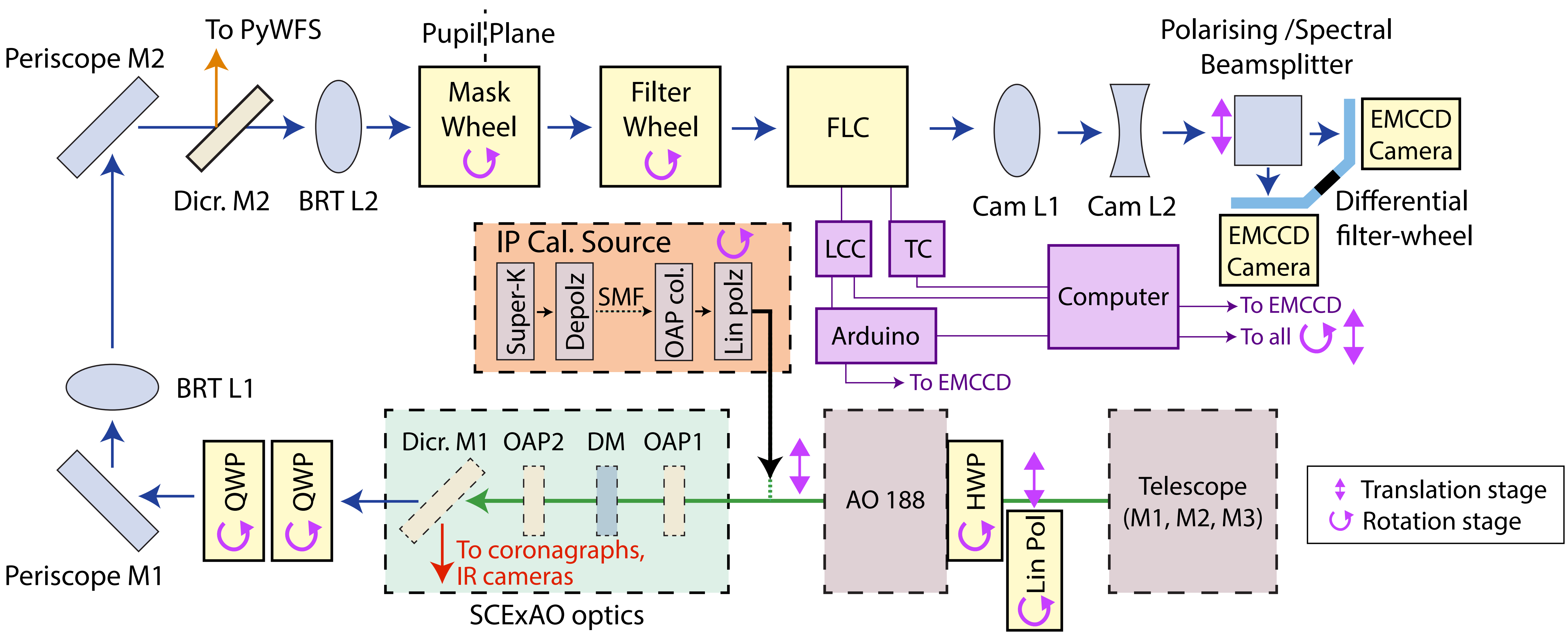
DIFFERENTIAL CALIBRATION – TRIPLE LAYER SWITCHING!

Address non-common-path & non-simultaneous errors



DIFFERENTIAL CALIBRATION – TRIPLE LAYER SWITCHING!

Address non-common-path & non-simultaneous errors



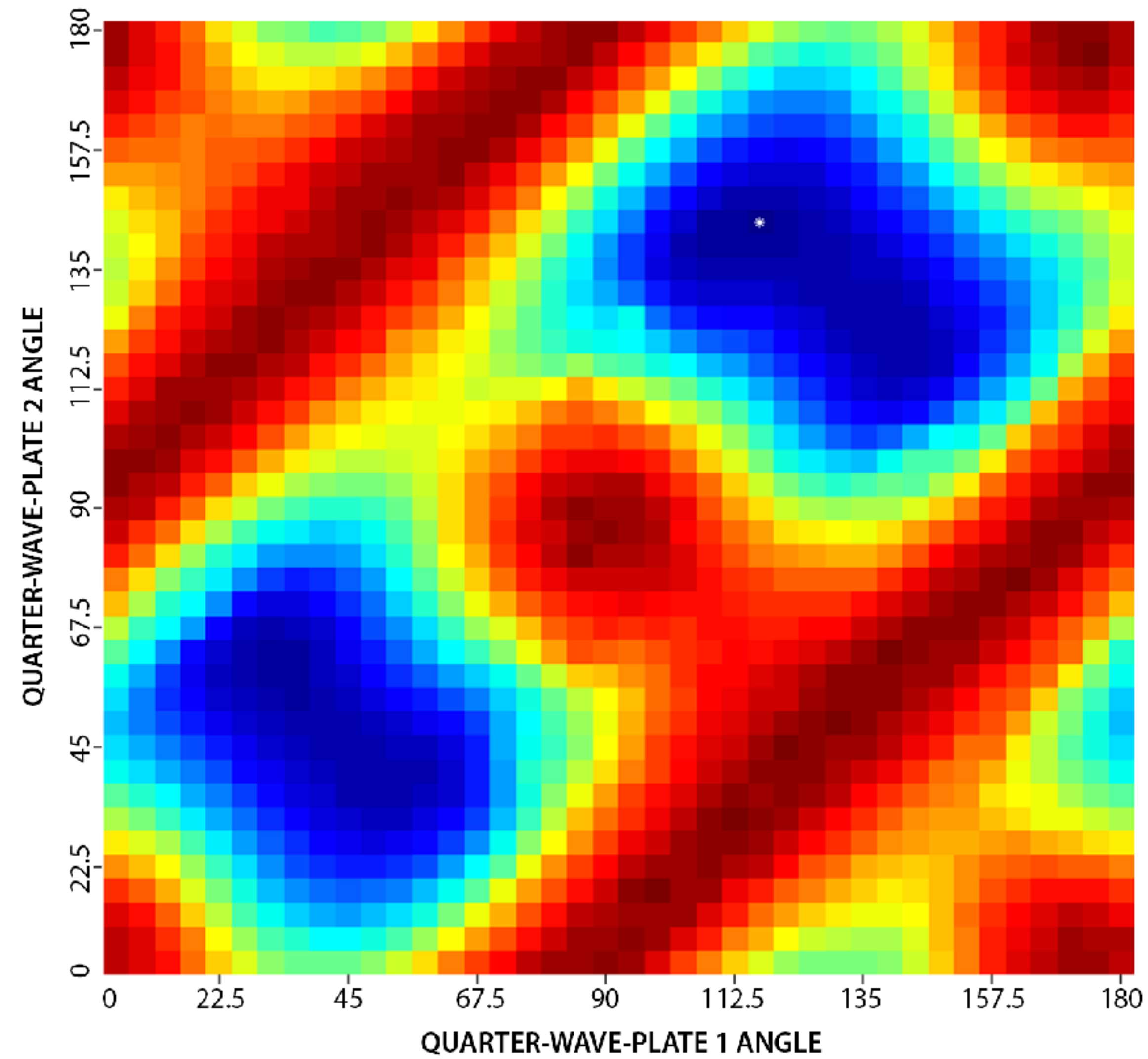
Instrumental Polarisation Calibration + Compensation

- Measurement of instrumental polarisation is important especially due to k-mirror (image rotator) in AO188, periscope within SCExAO
  - Calibration sets using AO188 cal lamp + SCExAO + VAMPIRES have been measured, to constrain instrumental Mueller matrix (then multiply model by M^{-1})
- But don't measure V - lose signal, can't correct by calibration
  - Use Eigenpolarisation approach

Corrects for most of instrumental polarisation using two quarter-wave plates

On the right is a measured chi-squared map showing the accuracy of Stokes Q transmission through AO188+SCExAO+VAMPIRES as a function of QWP angles. The minimum (blue) corresponds to the setting with optimally corrected transmission.

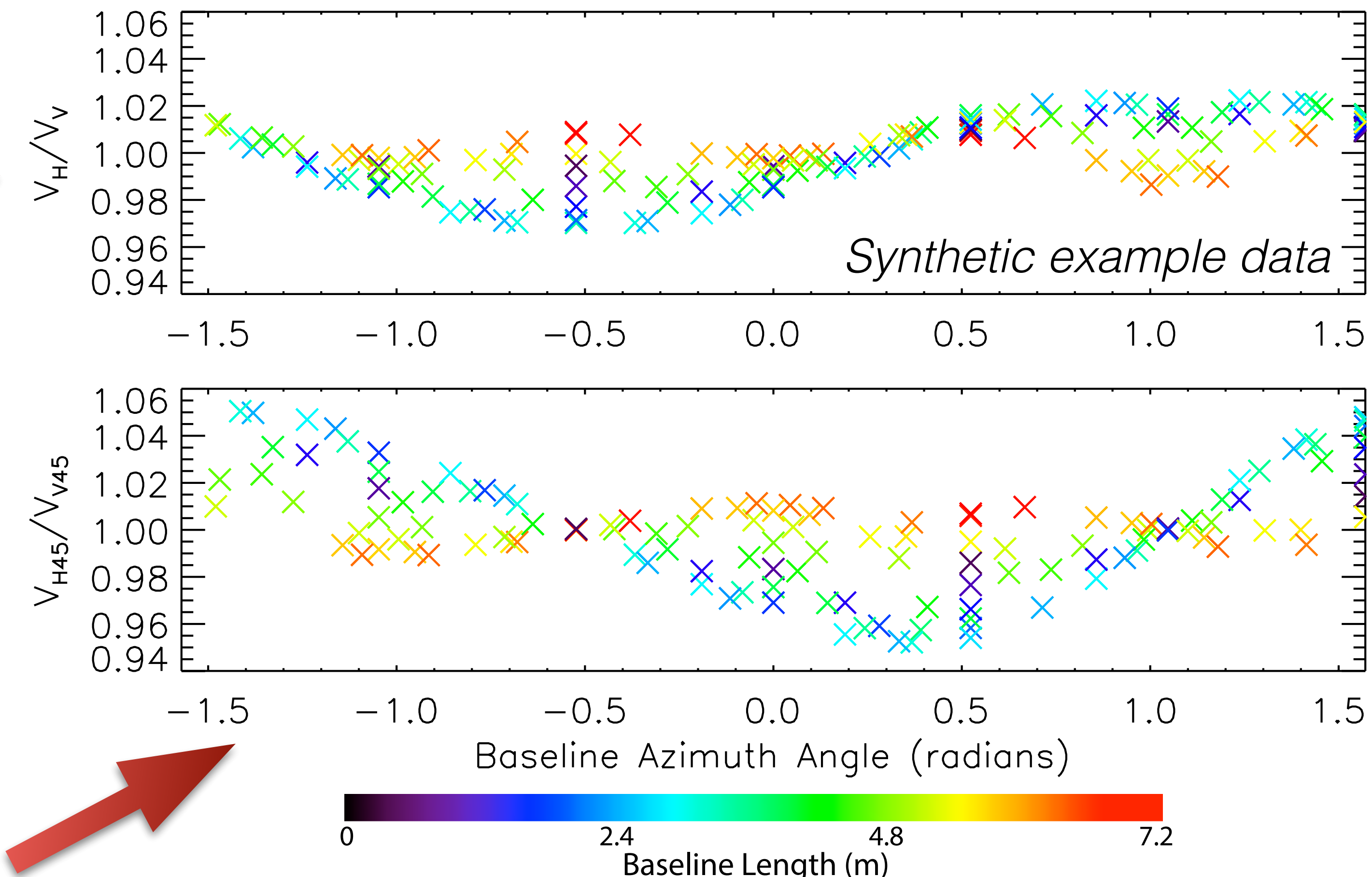
Final calibration should be confirmed each observing period by polarised standard star observations.



NECESSARY TECHNICAL NOTE…

Effective way of plotting calibrated VAMPIRES data is with a polarised visibility ratio plot:

Y Axis:
Ratio of horizontally-polarised to vertically-polarised interferometric visibilities (Fourier power)



2 plots:
Correspond to Stokes Q and U coordinates

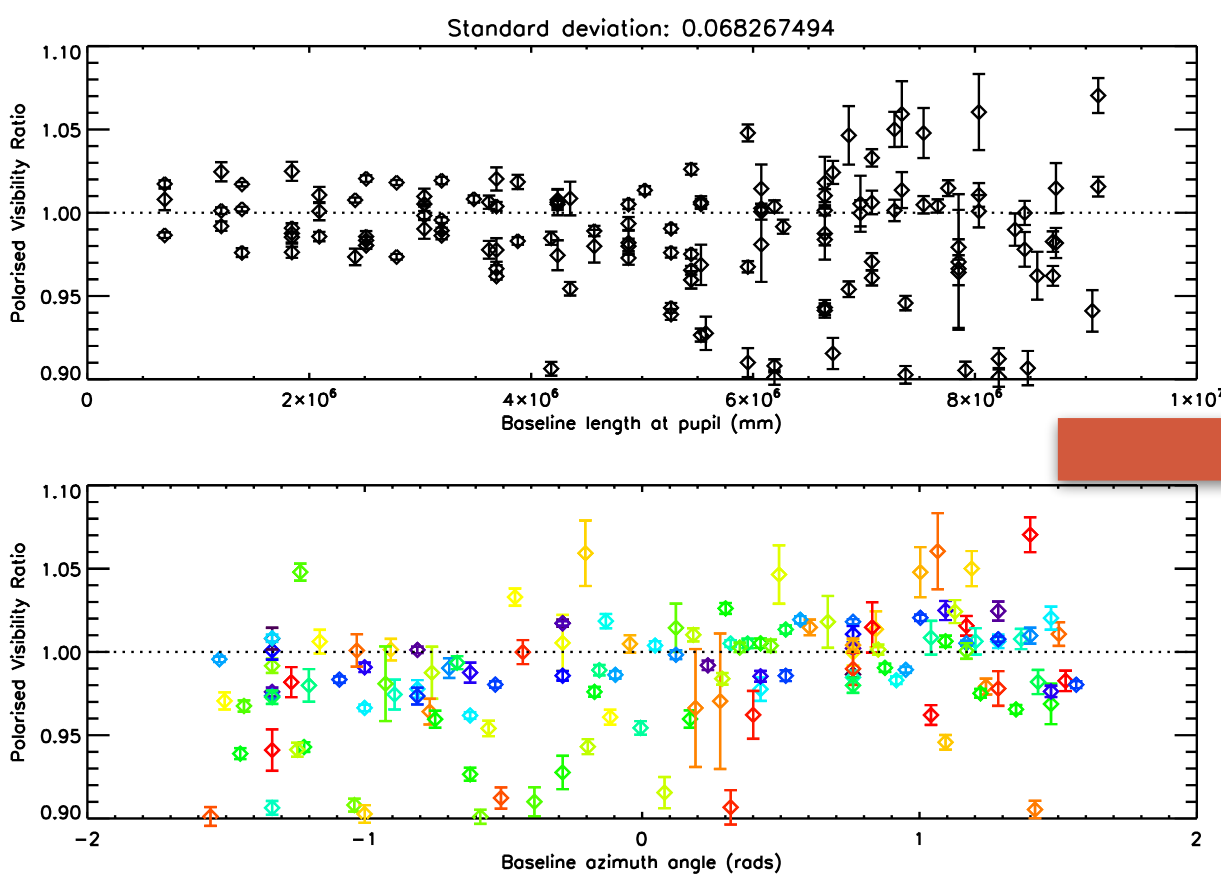
X Axis:
Azimuthal angle (on-sky) of the baseline (spatial frequency coordinate)

Color scale:
Baseline length (on-sky) (abs value value of spatial frequency coordinate)

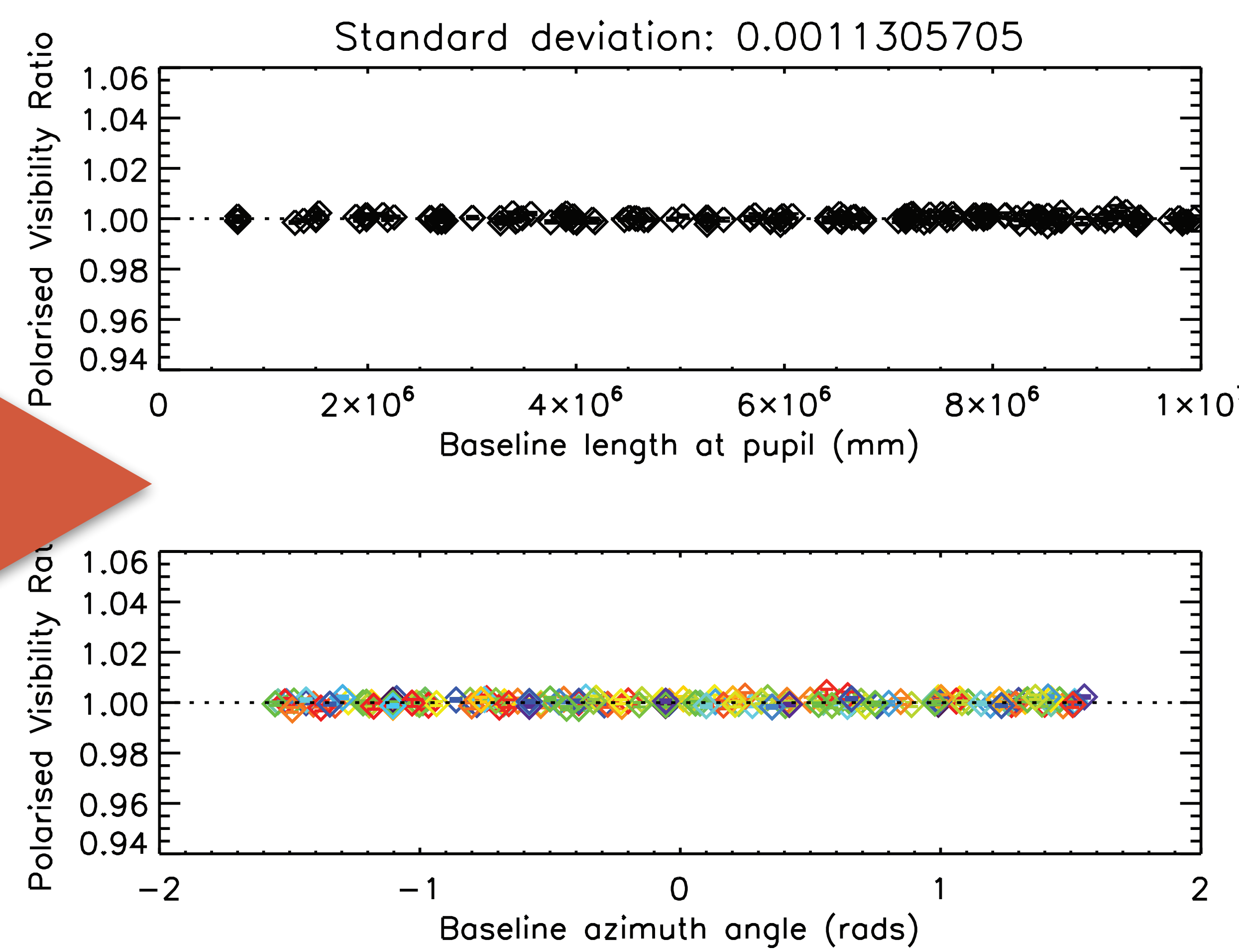
Should = 1 for all unpolarised targets…
Demonstrates calibration precision

NRM MODE CALIBRATION PERFORMANCE

- Demonstrated polarised-differential NRM visibility calibration to 1 part in 10 ^ 3 *per baseline*.
  - Roughly speaking, achievable contrast at 0.5λ/D (10 mas) goes as $\sqrt{}_{\mathrm{nBaselines}}$ - DOF



Conventional 2-beam polarimetry

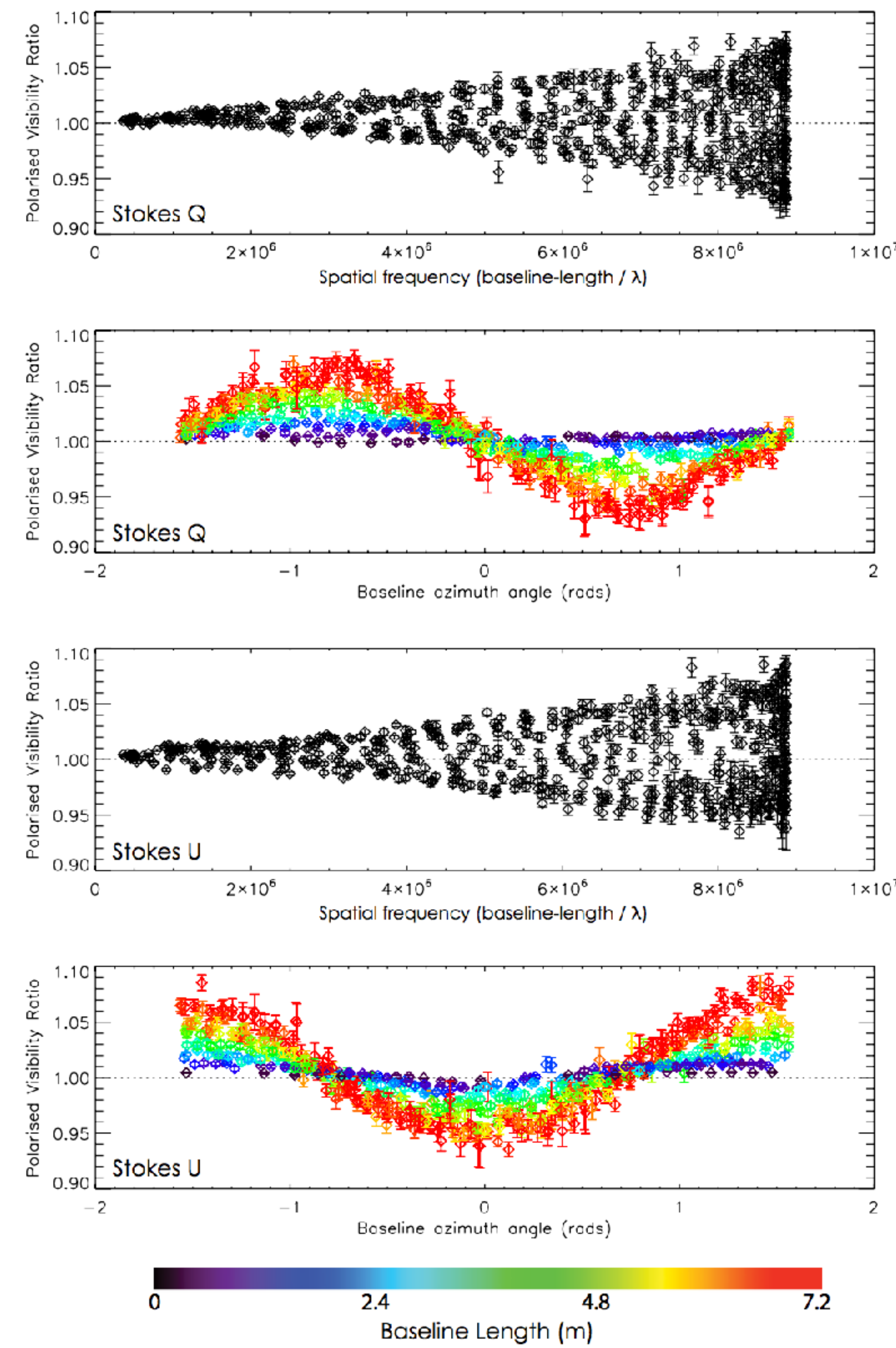


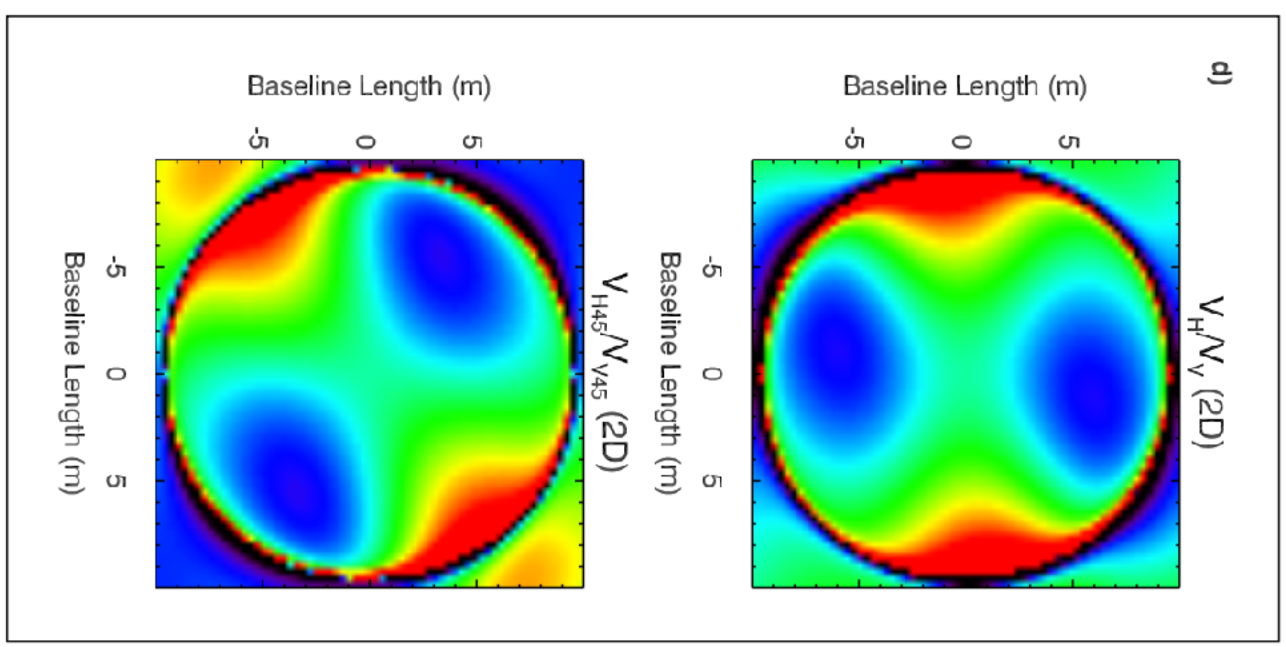
Triple-differential calibration

NRM-MODE EXAMPLE SCIENCE-RESULT

Investigation of supergiant mass-loss via direct imaging of Circumstellar dust around Red Supergiant μ Cephei

- Observed with annulus mask at 775 nm
- Raw differential polarized visibilities show distinctive sinusoidal signature of circumstellar dust shell, with clear asymmetry **(right)**
- Dust scattering model fitted via synthetic differential visibilities **(below)**



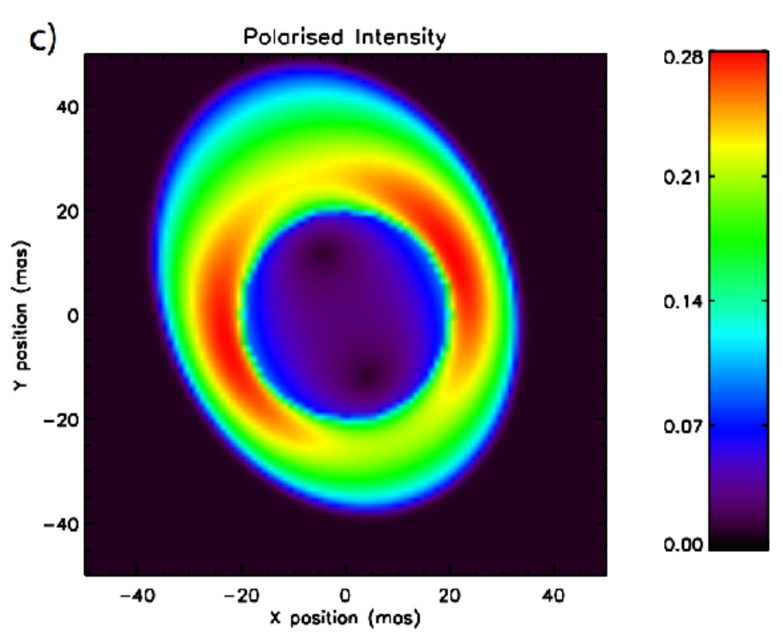


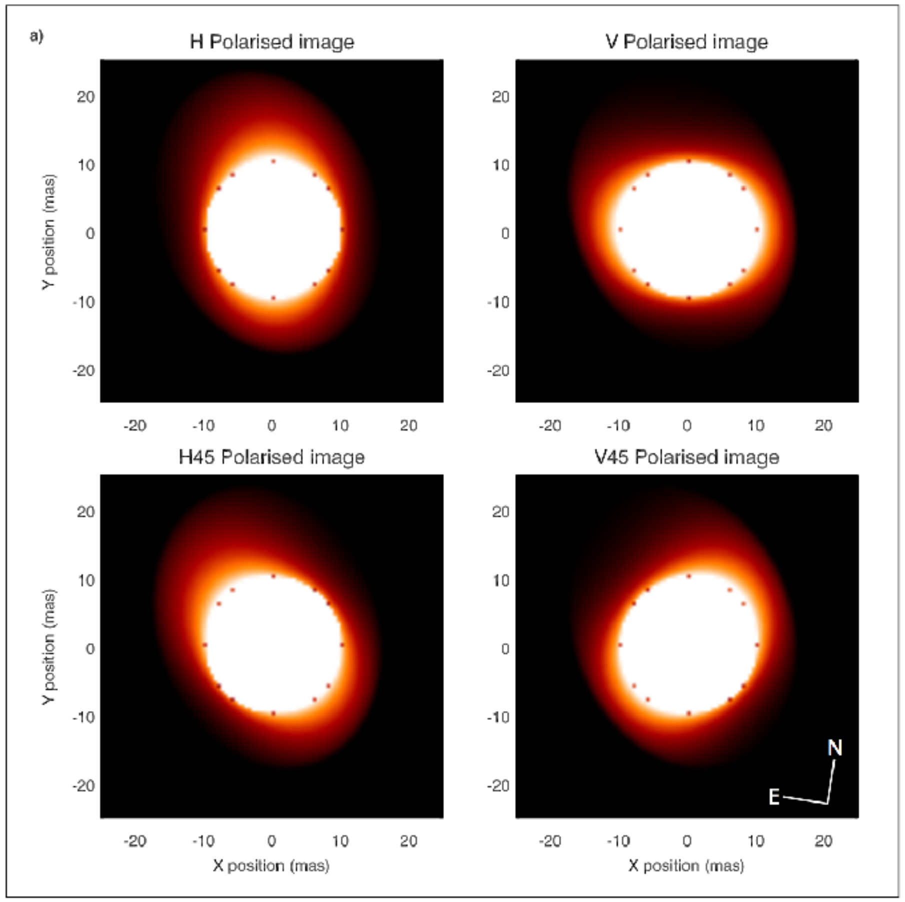
NRM-MODE EXAMPLE SCIENCE-RESULT

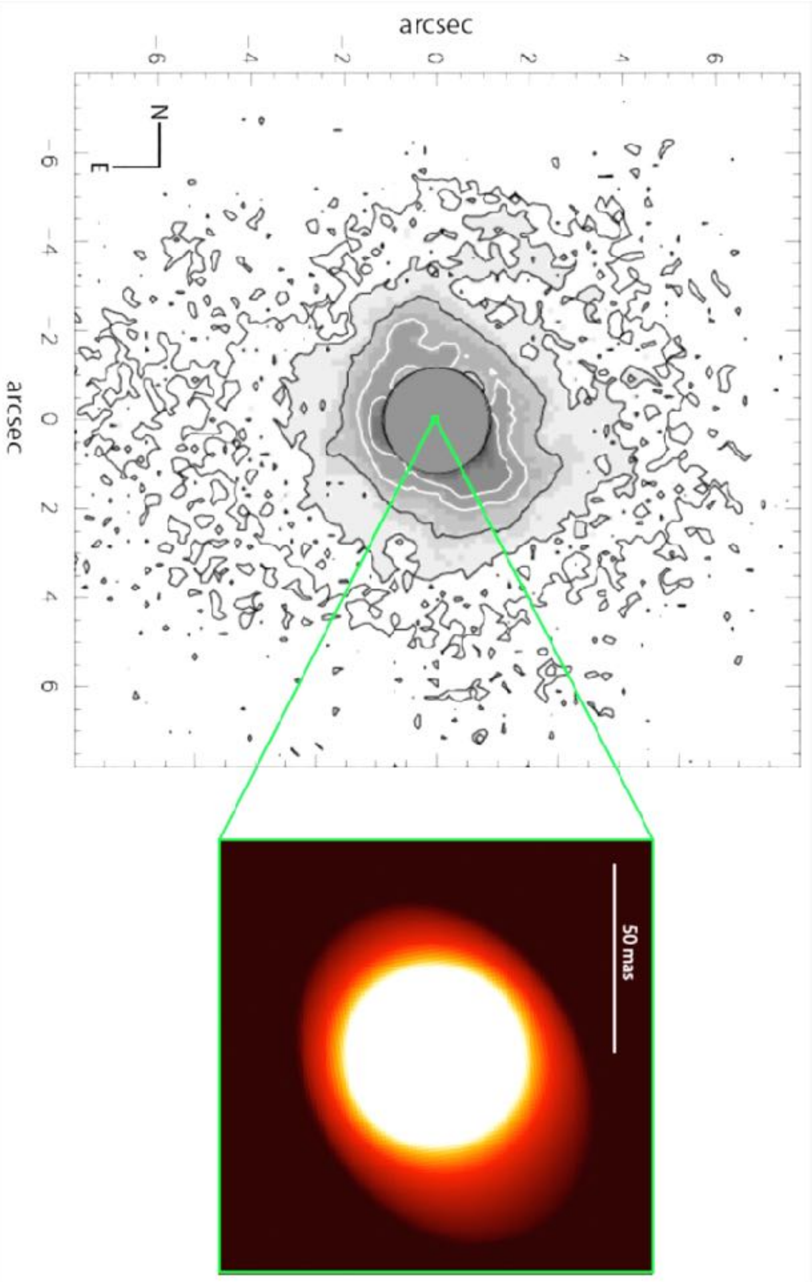
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al_2O_3) important for unexplained extension of RSG atmospheres.

Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})
Scattered-light fraction: 0.081 ± 0.002
PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03

Left: model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.

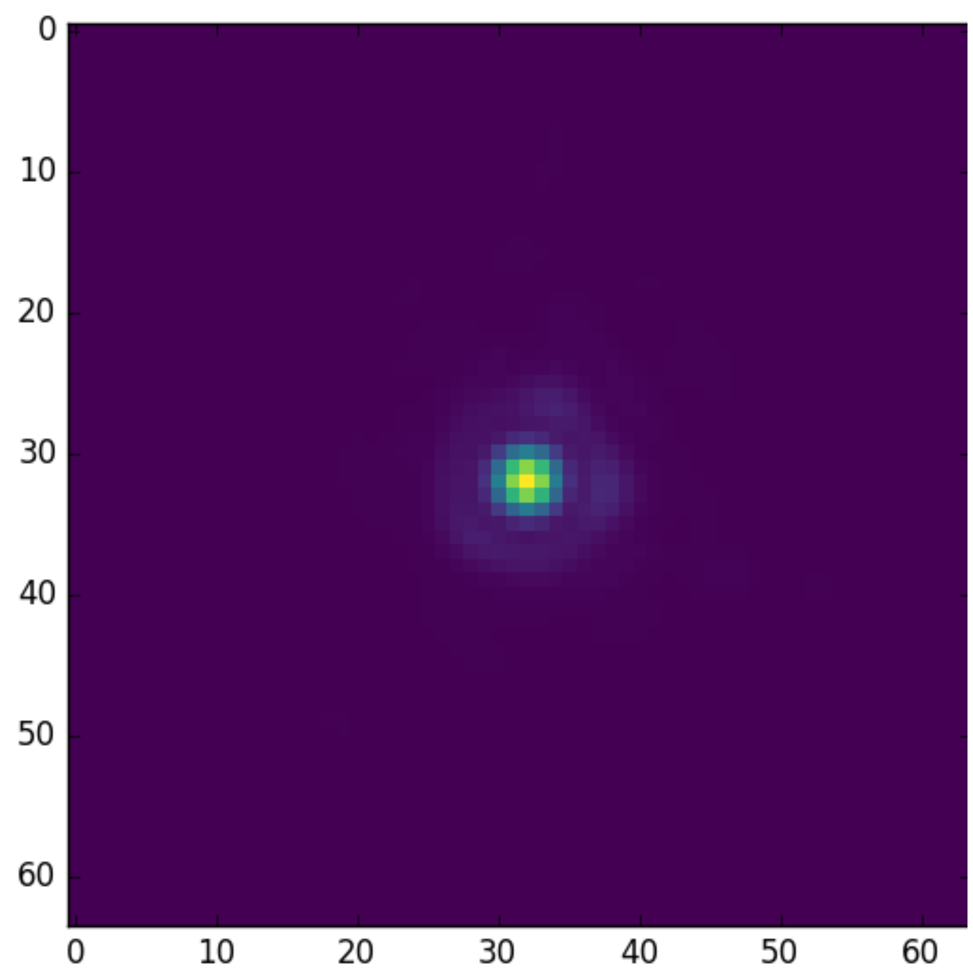


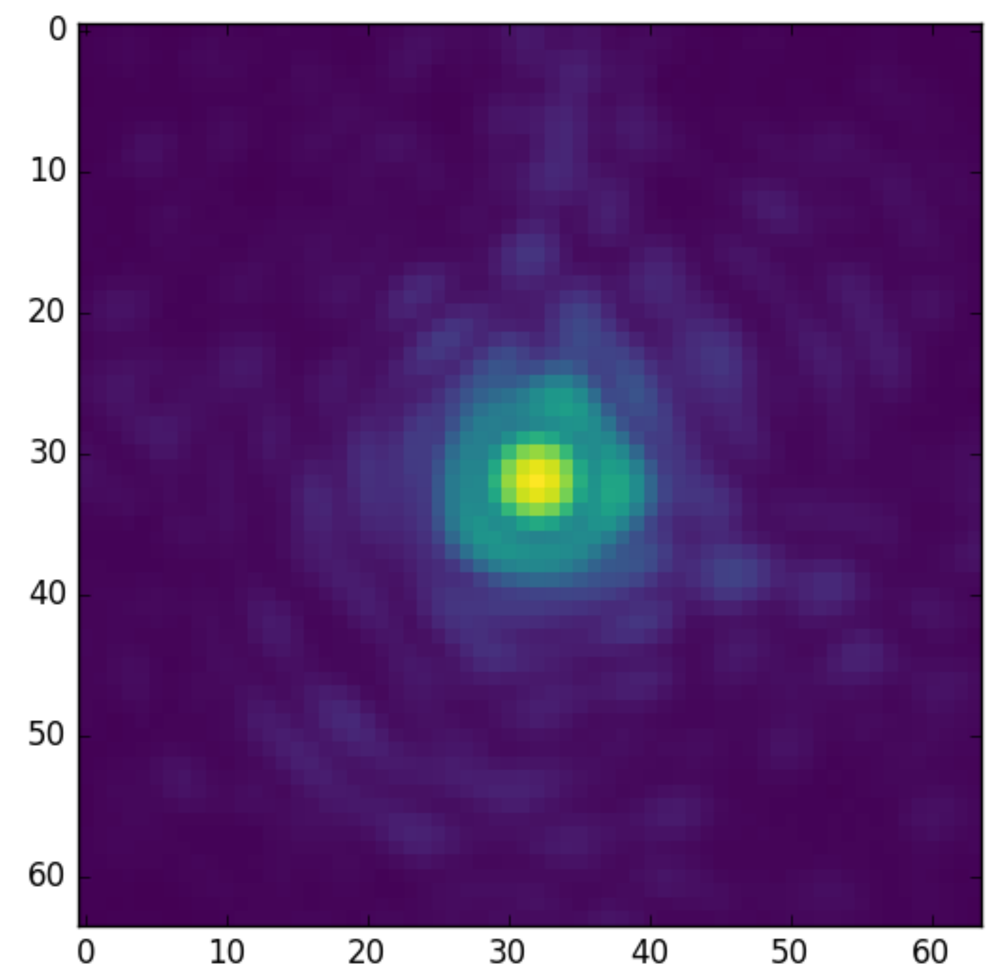




IMAGING/PDI MODE

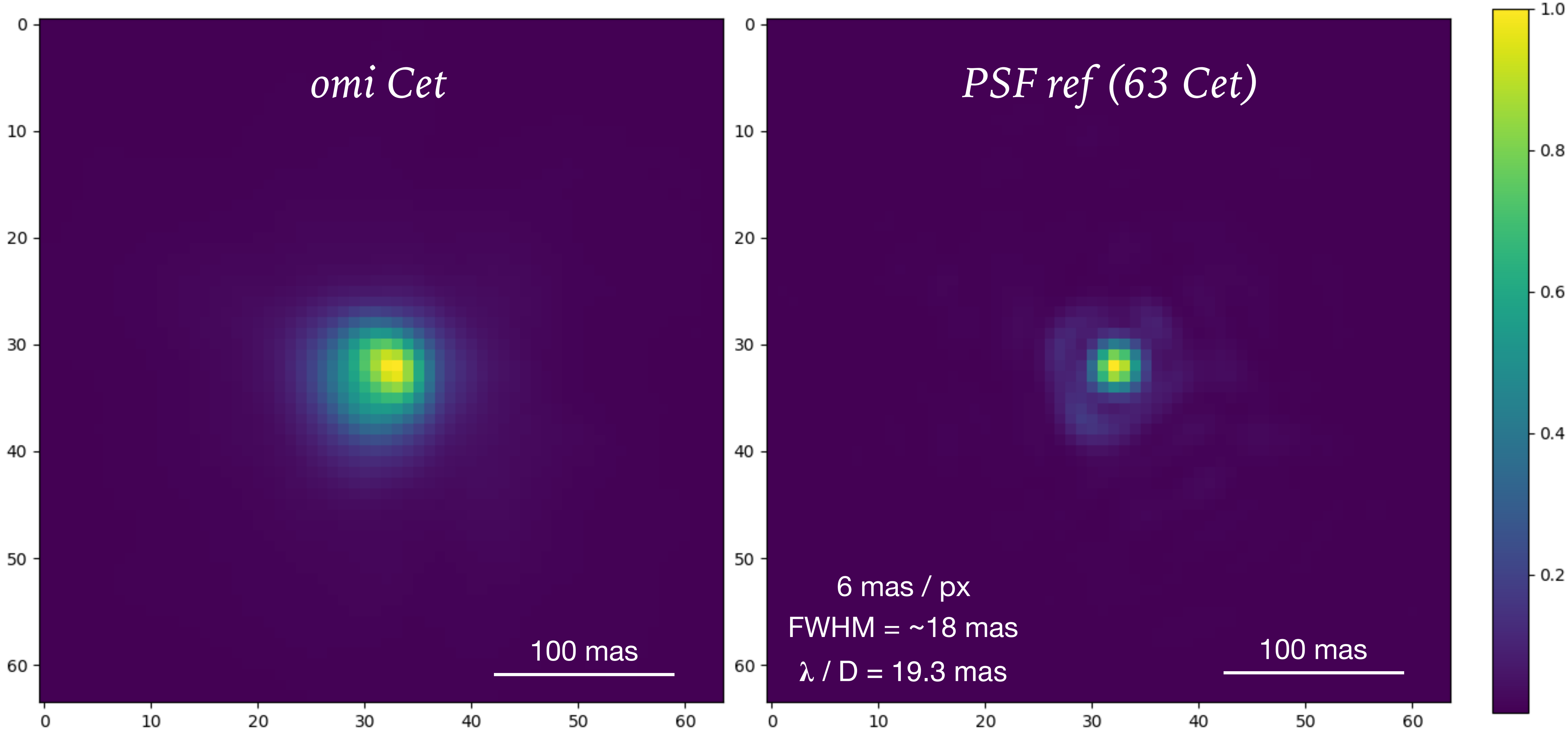
- High-speed acquisition and polarisation switching rate (up to 500 Hz) - allows offline tip/tilt correction and ‘lucky imaging’ approach, unlike CCD-shuffle based systems
  - Example: 750 nm PSF, 100 frames/sec, discard 80% lowest-Strehl frames, align and sum (~30 secs of data)





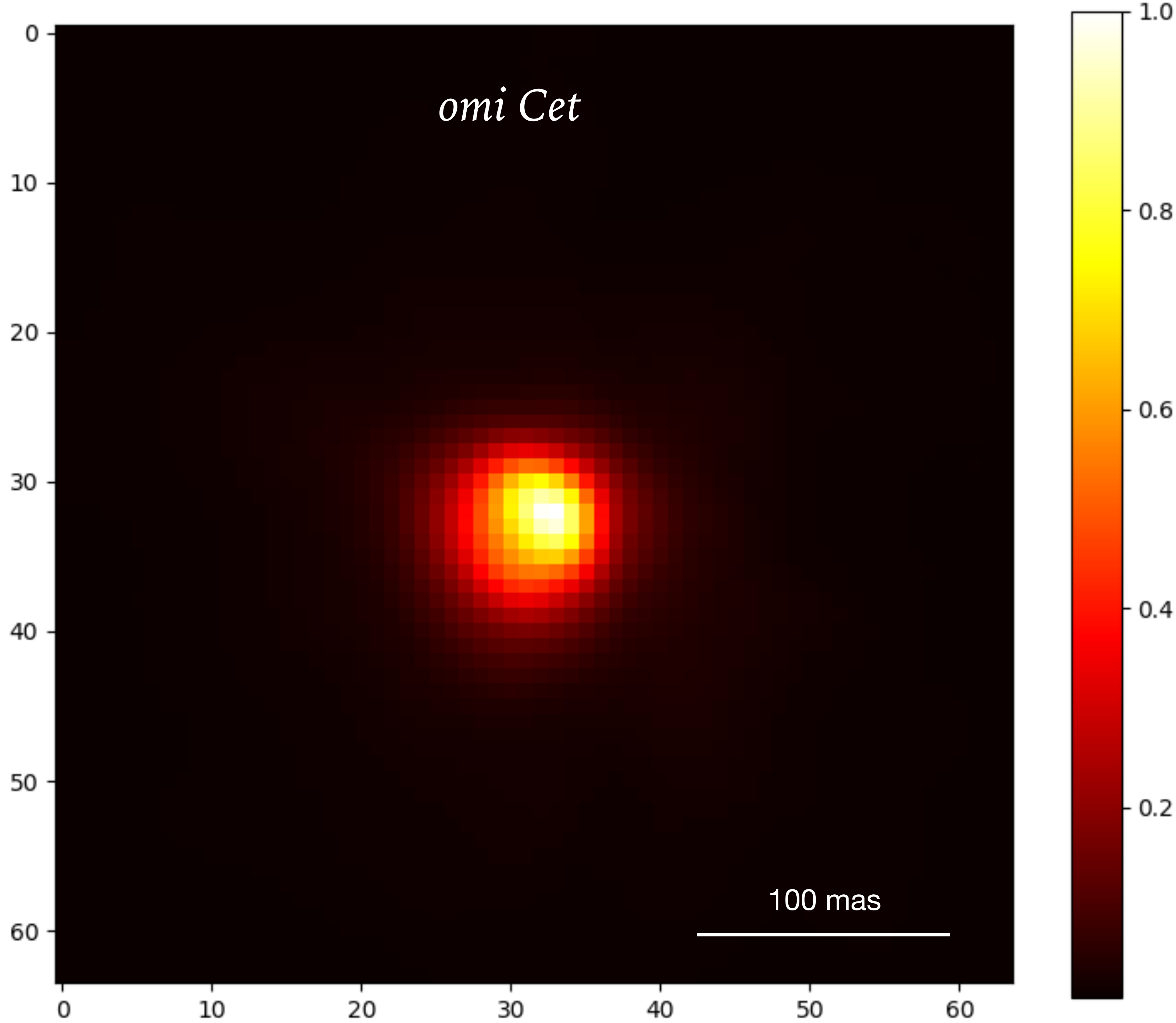
IMAGING-MODE EXAMPLE SCIENCE-RESULT

- Direct imaging of omi Cet - clear asymmetry seen.
    - Speckle imaging - diffraction-limited



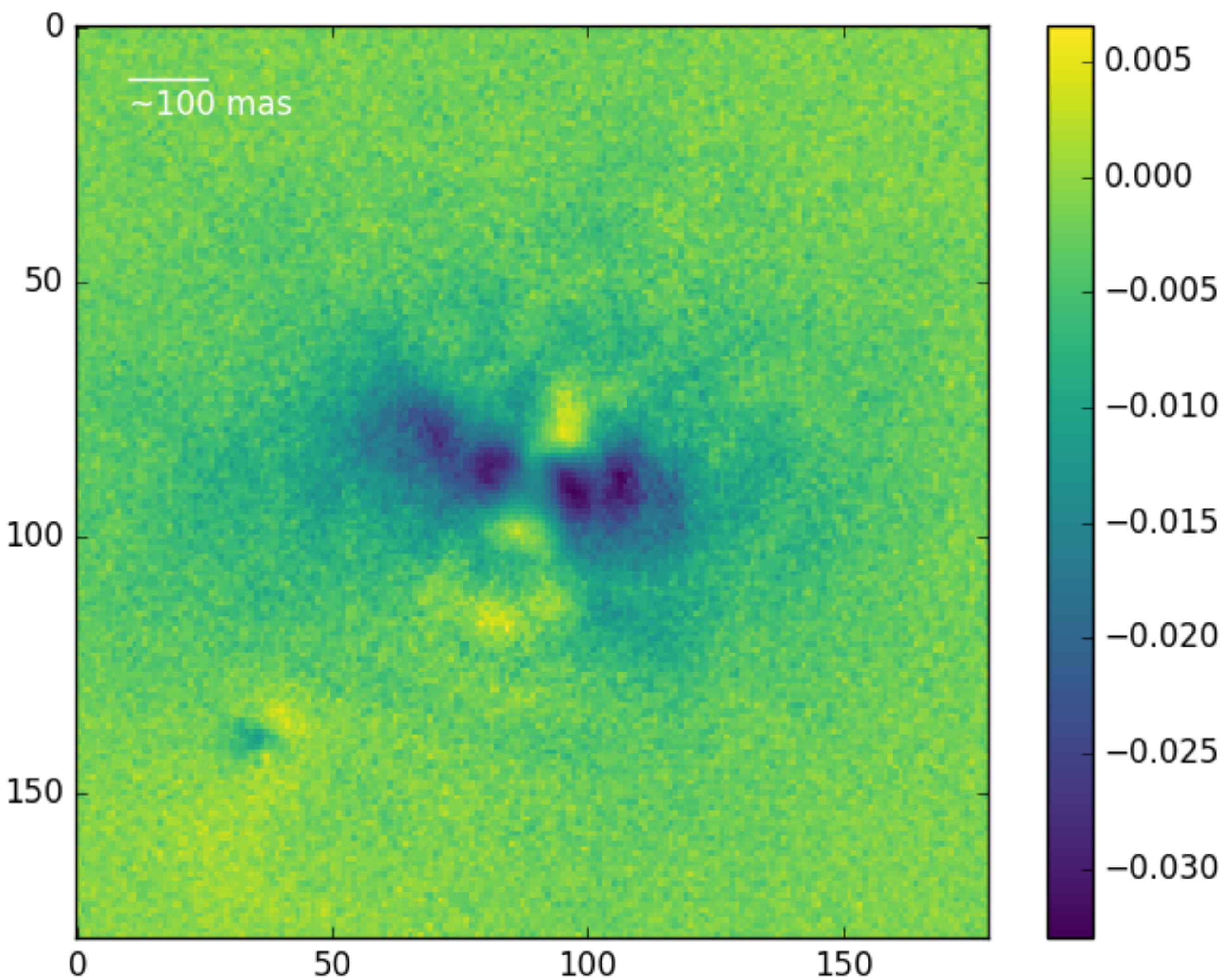
Observed 12/09/2017

IMAGING-MODE EXAMPLE SCIENCE-RESULT

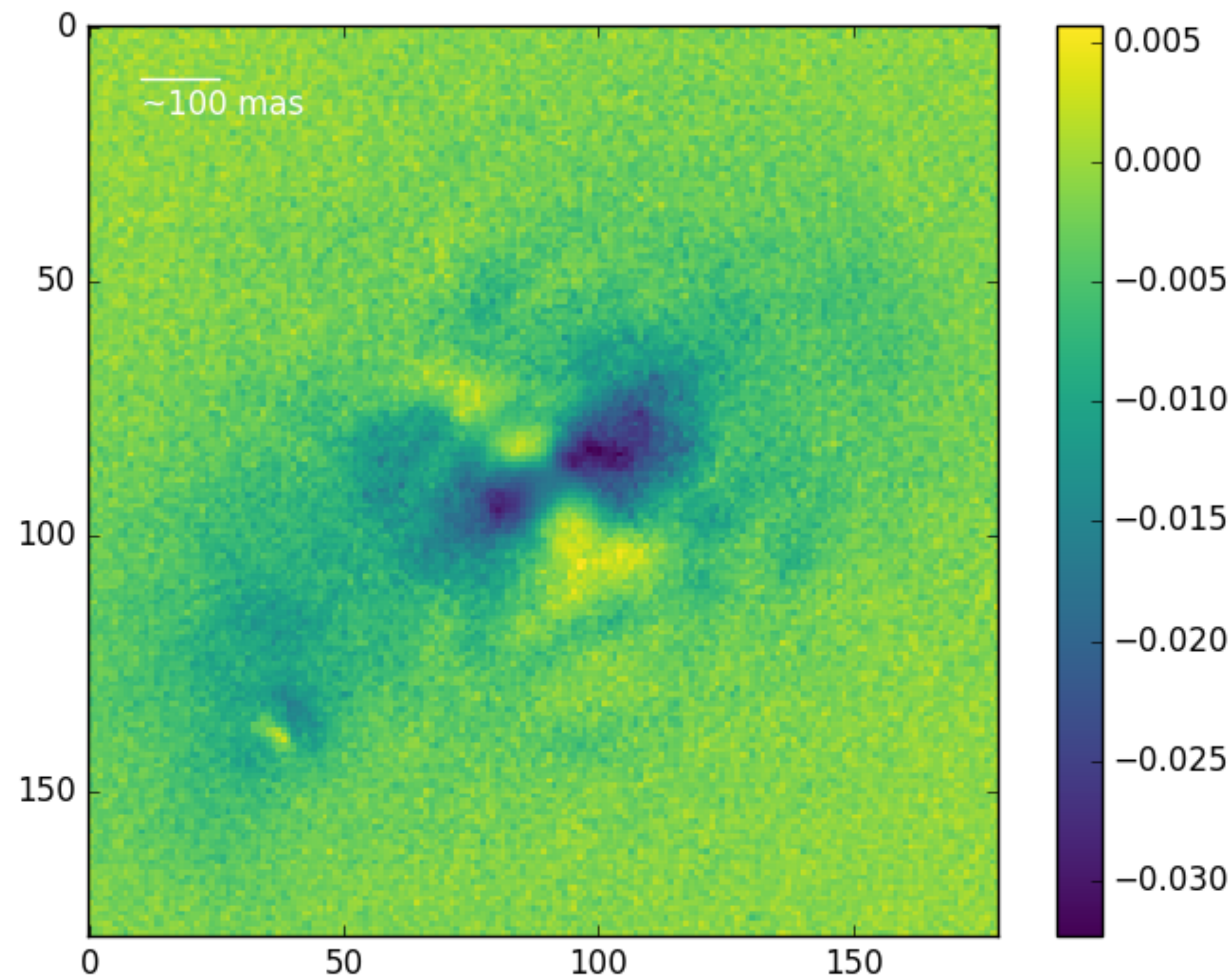


IMAGING-MODE EXAMPLE SCIENCE-RESULT

- Observation of omi Cet - dust shells and disk around omi Cet b observed
  - Very preliminary reduction



Stokes Q

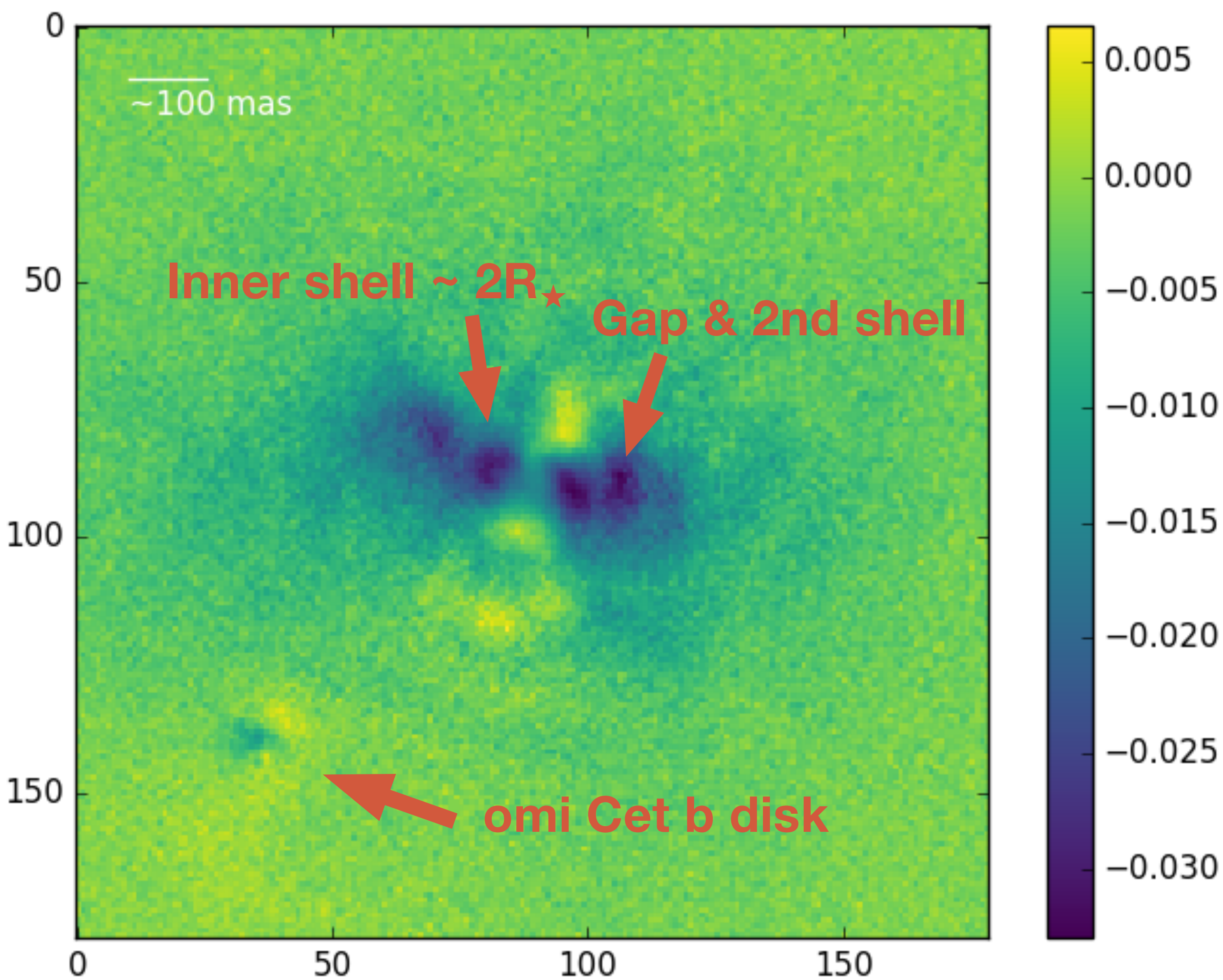


Stokes U

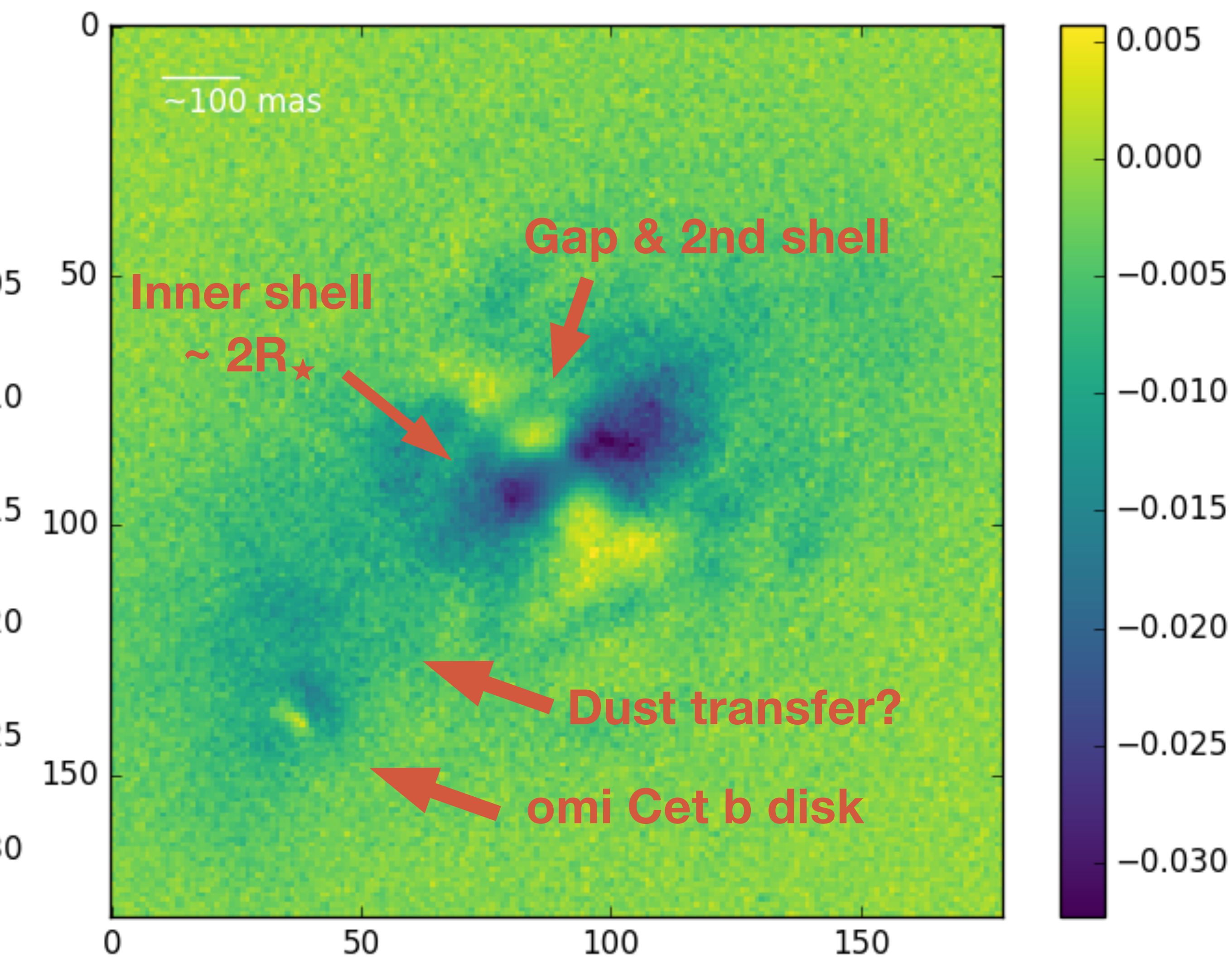
Observed 12/09/2017

IMAGING-MODE EXAMPLE SCIENCE-RESULT

- Observation of omi Cet - dust shells and disk around omi Cet b observed
  - Very preliminary reduction



Stokes Q

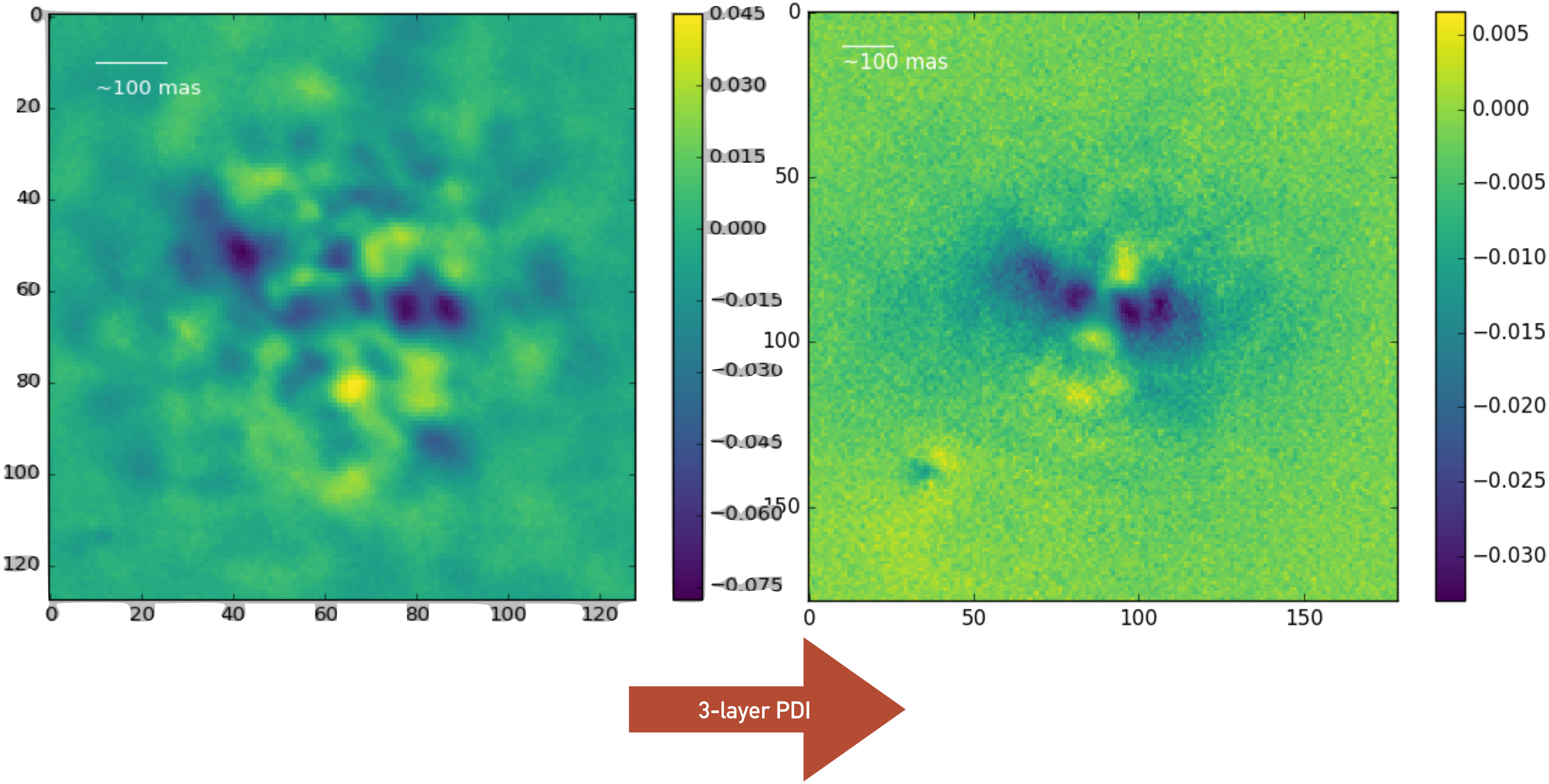


Stokes U

Observed 12/09/2017

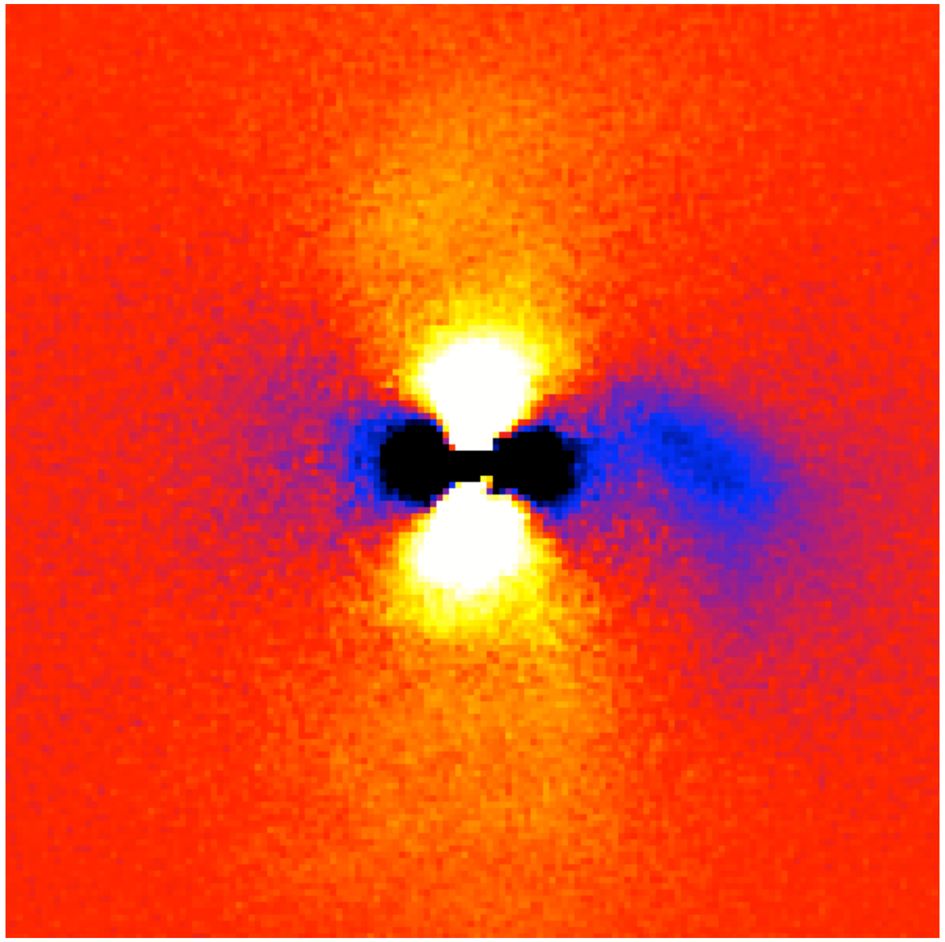
IMAGING-MODE EXAMPLE SCIENCE-RESULT

- Effect of single vs triple polarisation calibration



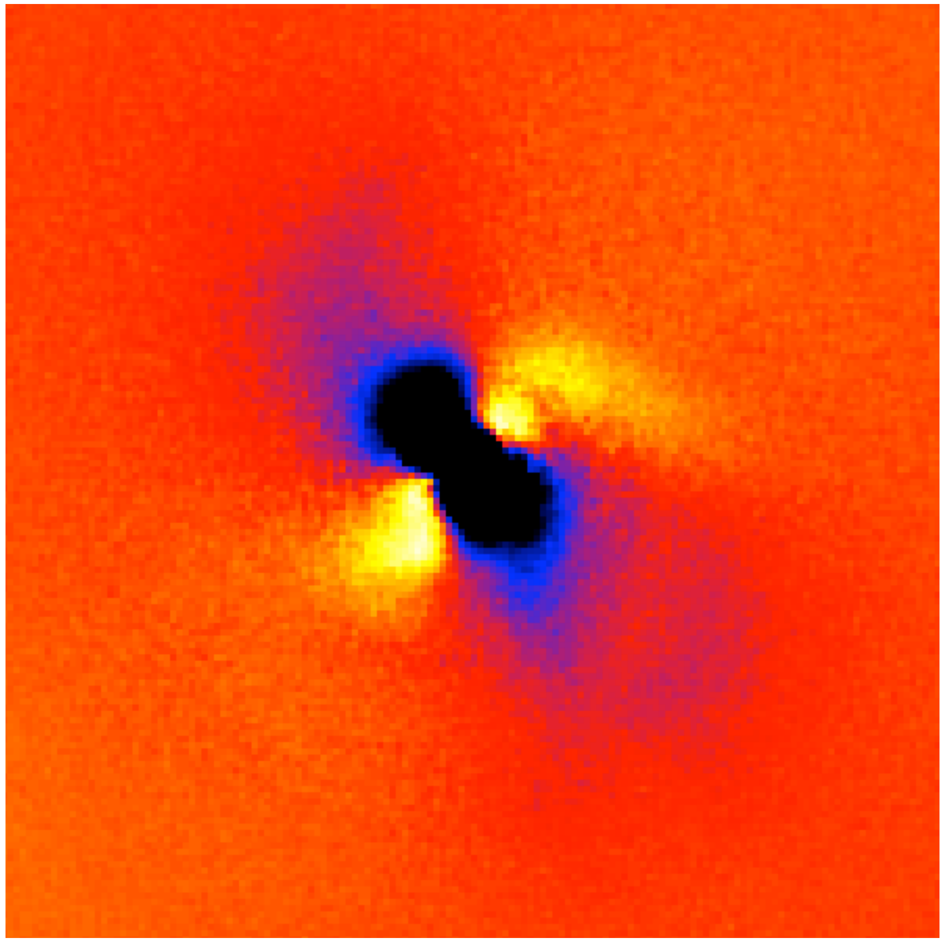
Stokes Q

IMAGING-MODE EXAMPLE SCIENCE-RESULT



Stokes Q

Disk around AB Aur



Stokes U

100 mas

Conclusion

VAMPIRES
Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures

VAMPIRES uses aperture masking & differential polarimetry: Directly image dusty inner circumstellar regions (protoplanetary disks, evolved star mass-loss) in scattered light

- Protoplanetary disks, evolved star mass-loss
- Resolution ~10 mas, 600 - 800 nm

Incorporated into SCExAO extreme AO system at the Subaru 8m telescope

- Simultaneously conducts R,I band observations at same time as IR instruments (CHARIS, …)
- Extreme AO correction, access to telemetry
- Differential line imaging - Hα, OI, SII
- Can operate double-differential to calibrate some NCP
- Non-redundant masking and full pupil (inc. speckle, PDI) modes

On-sky results

- Differential visibilities to 0.1% and closure phases to ~0.5 deg
- Evolved star and protoplanetary disk science results in prep for publication

Recent upgrades

- Fast FLC polarisation switching and dual cameras (up to ~500 fps)
- Spectral differential as well as polarisation modes
- Time-resolved differential polarimetry (suitable for PDI-speckle and NRM)

Available for use!

- Apply via usual Subaru proposals… or talk to me!