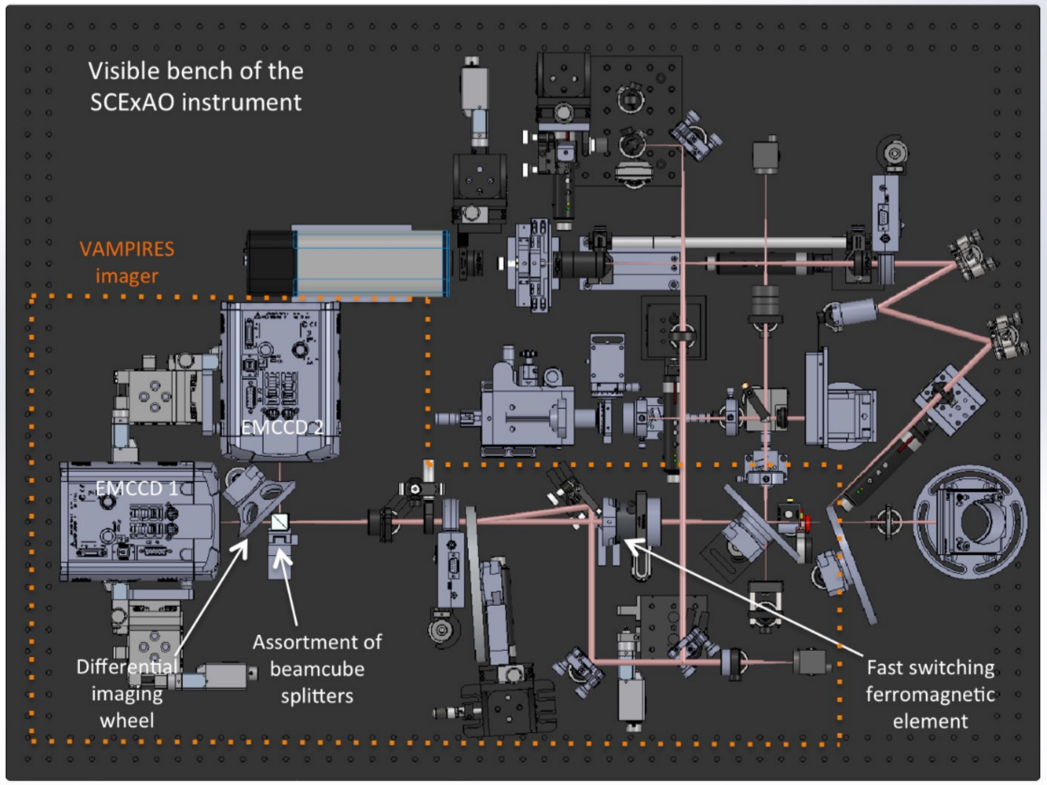
# BACKGROUND - THE VAMPIRES INSTRUMENT

- Polarimetric aperture masking and imaging in the
  - Aperture masking
    - Diffraction limited imaging through the atmo
    …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)



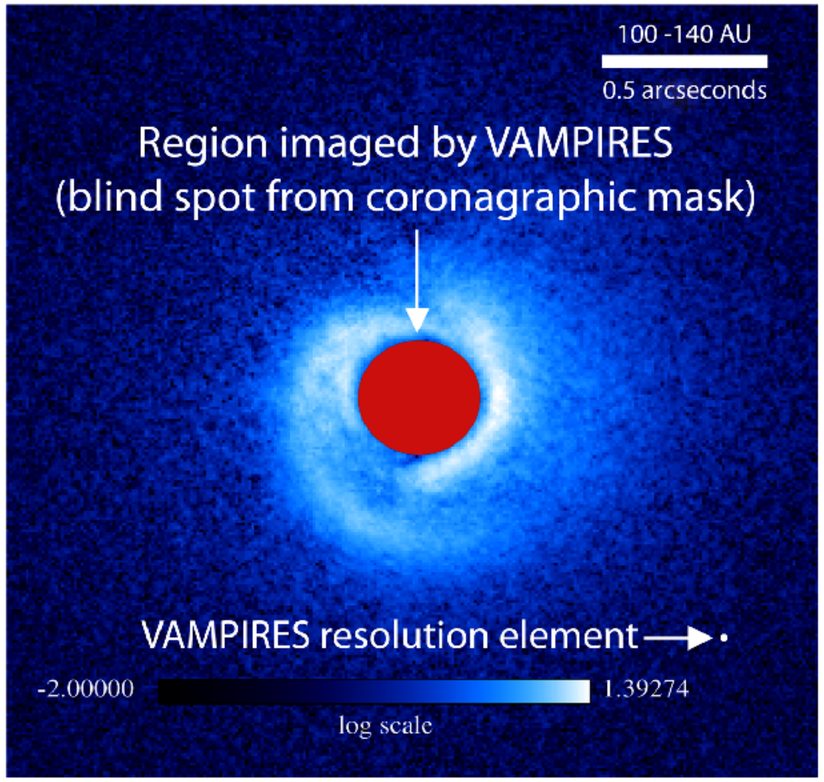
# SCIENCE CASE: IMAGING THE INNER REGION OF PROTO-PLANETARY DISKS AT SOLAR-SYSTEM SCALES

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

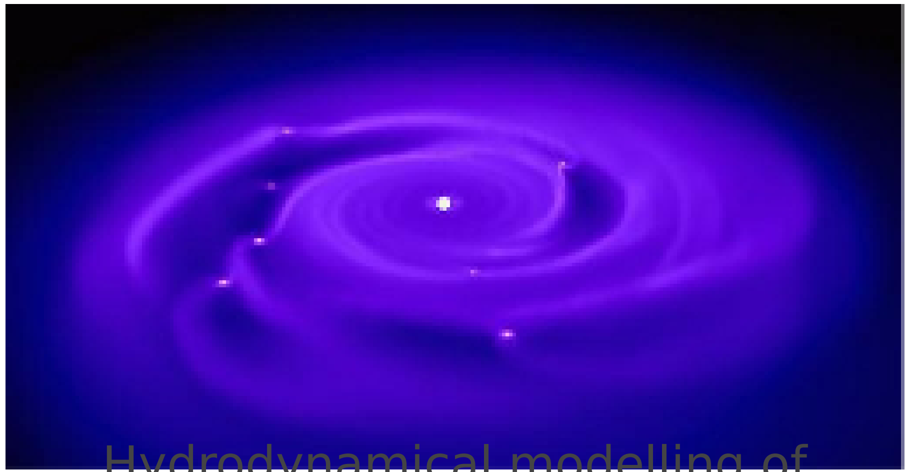
- Precise measurement of transition disk gaps and inner disk
- Density perturbations from massive bodies within disk (e.g. warps, spirals)
- Gravitationally bound clumping dust immediately surrounding forming planets
- Dust grain species and size determination

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




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

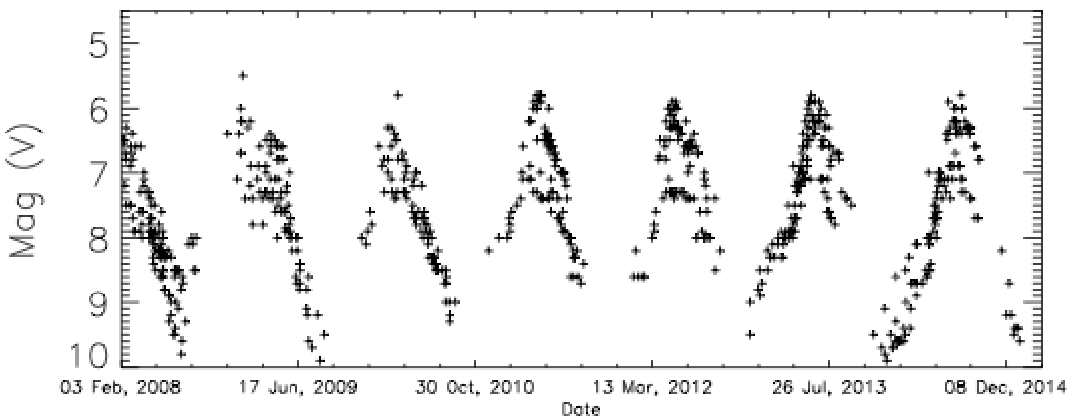


Hydrodynamical modelling of gravitational collapse of protoplanetary disk, with resulting fragmentation causing gravitationally bound clumps **Mayer L., et al., 2007, ApJ 661 77**

# 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)*



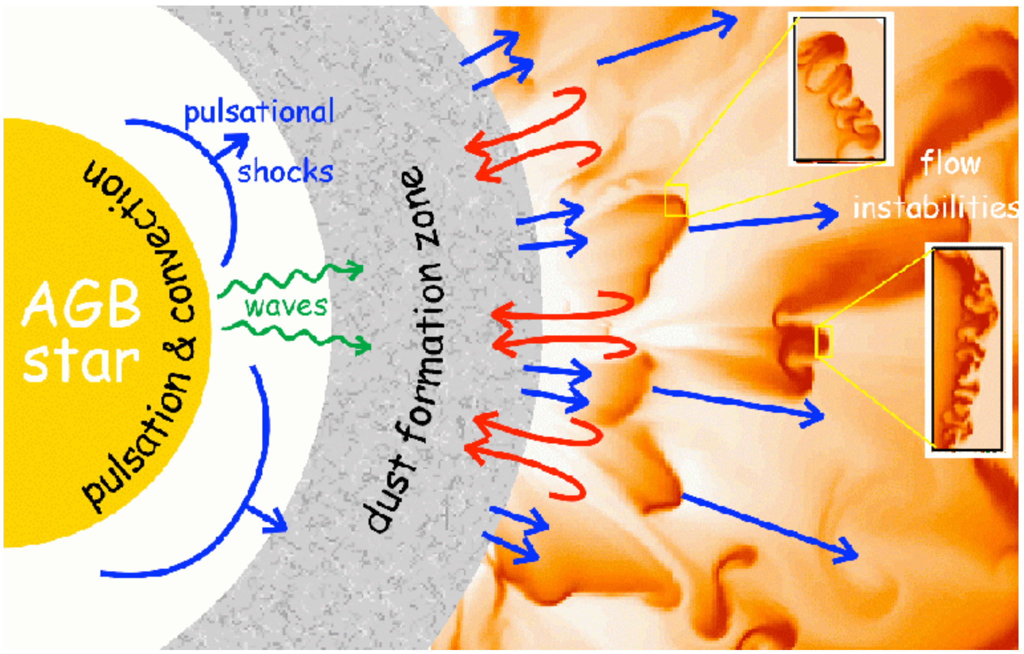

*W Hya light curve (AAVSO)*

Origin of asymmetries

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

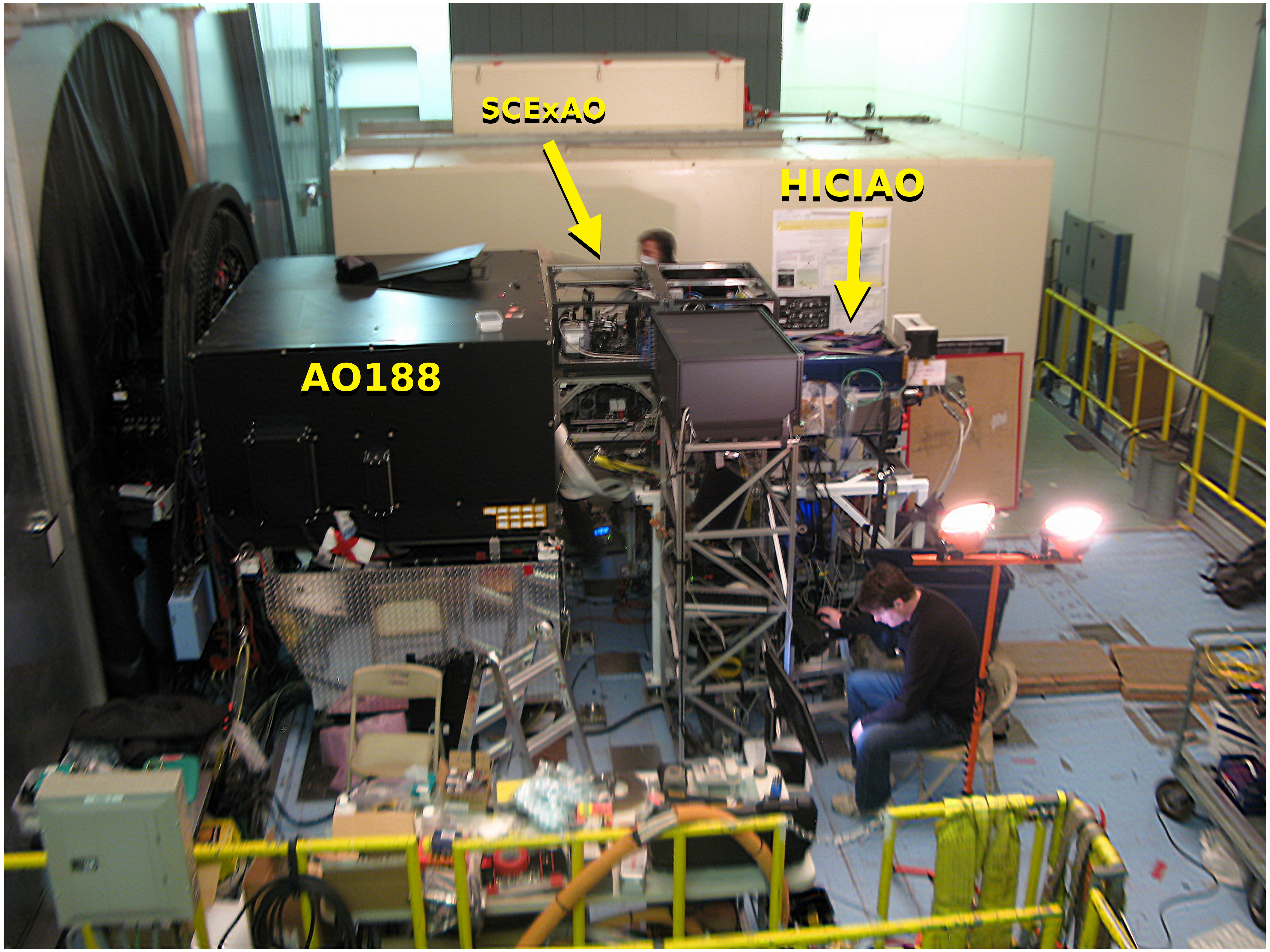
Extension of red giant atmospheres

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

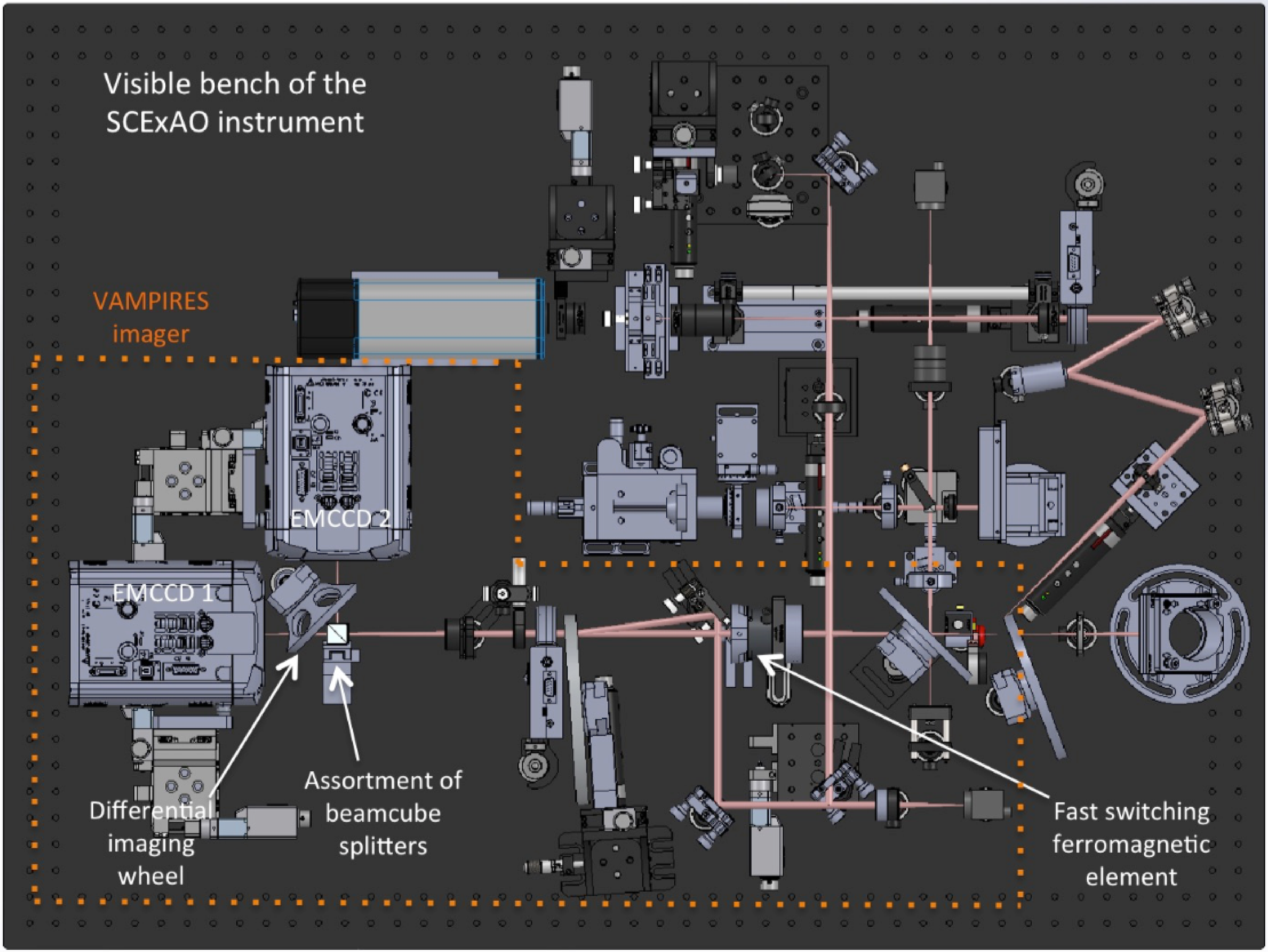



*Peter Woitke: [http://www.strw.leidenuniv.nl/~woitke/AGB_popular.html](http://www.strw.leidenuniv.nl/~woitke/AGB_popular.html)*

# Nuts and bolts: VAMPIRES within SCExAO




Subaru IR Nasmyth platform



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

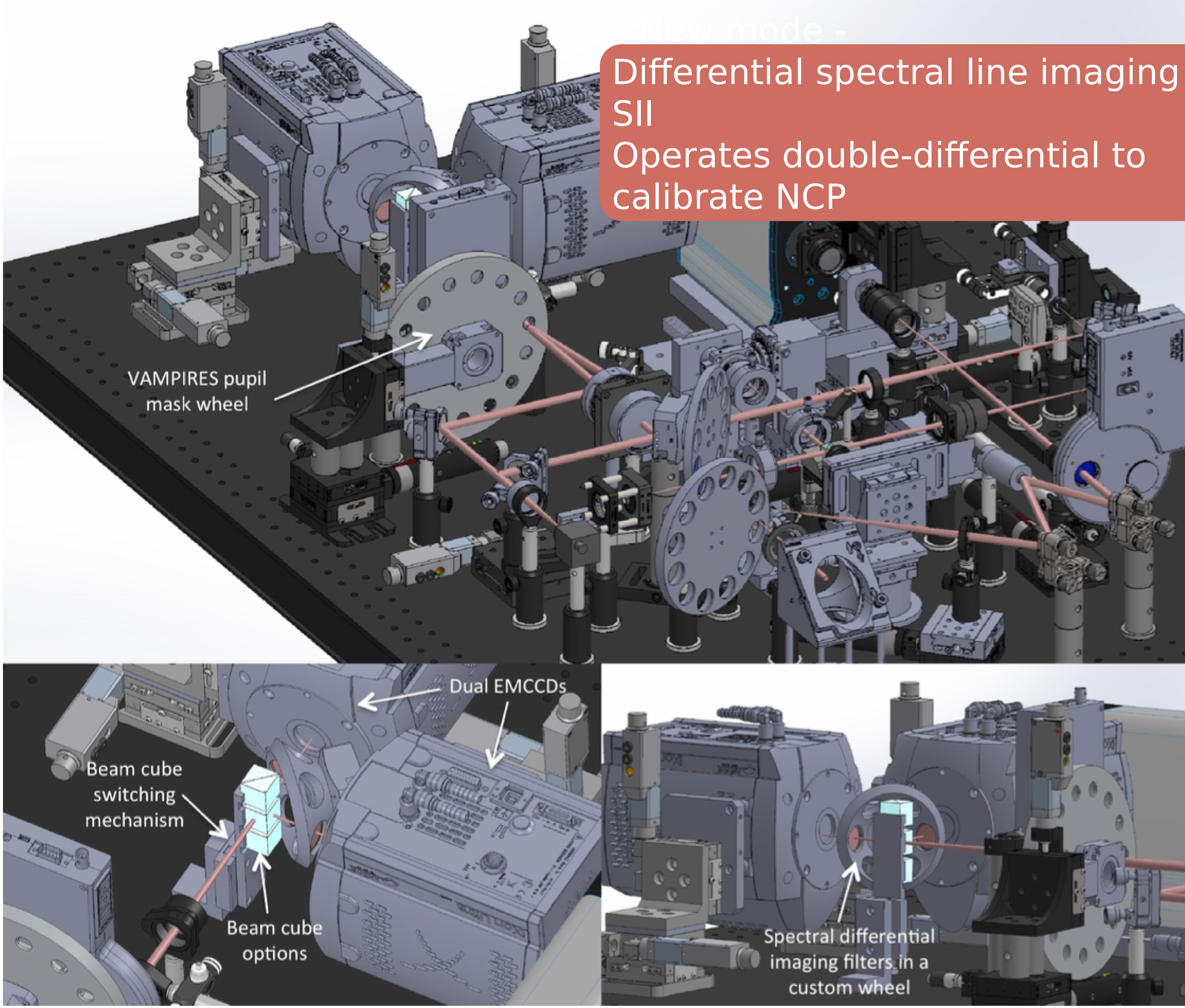
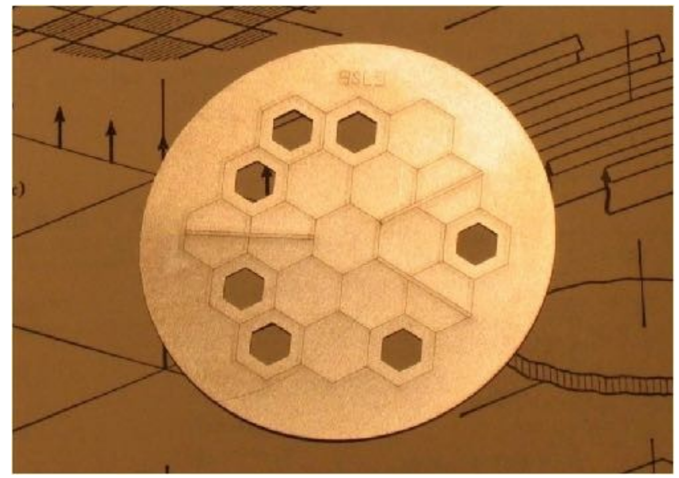



Figure 4: (Top) A view of the entire visible bench of SCExAO. (Bottom left) A zoomed in view of the beam cube switching mechanism. (Bottom right) A zoomed in view of the wheel to switch the filters for differential imaging mode.

# 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

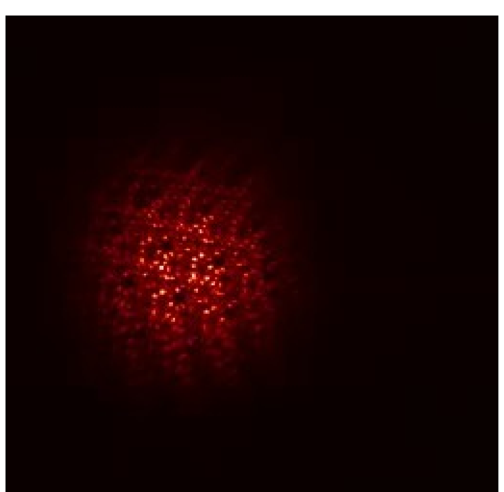
## Closure phase
independent of phase

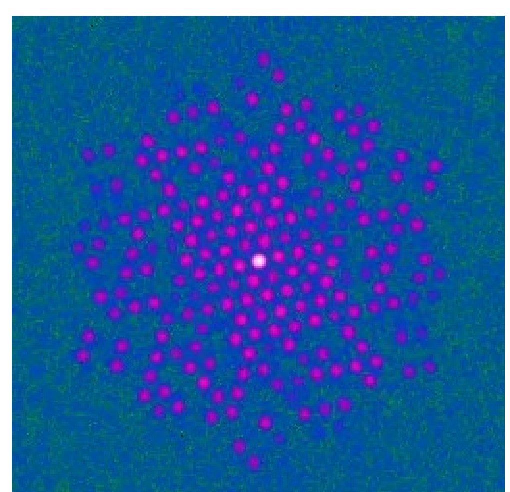
ψ – Μεασυρεδ βασελινε πηασε
φ – Αχτυαλ βασελινε πηασε
ε – ερρορ φρομ ατμοσπηερε

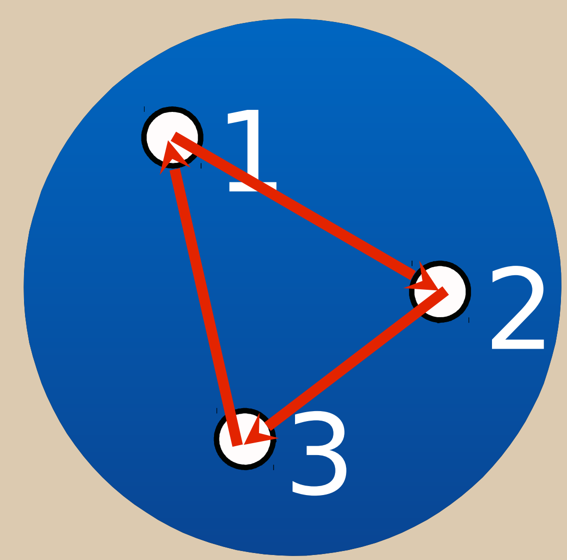
$$\psi_{12} = \phi_{12} + \varepsilon_2$$
$$\psi_{23} = \phi_{23} + \varepsilon_3 - \varepsilon_2$$
$$\psi_{31} = \phi_{31} - \varepsilon_3$$

$$\mathrm{Χ.Π.} = \psi_{12} + \psi_{23} + \psi_{31} = \phi_{12} + \phi_{23} + \phi_{31}$$

## Visibilities - a power spectrum, independent of phase



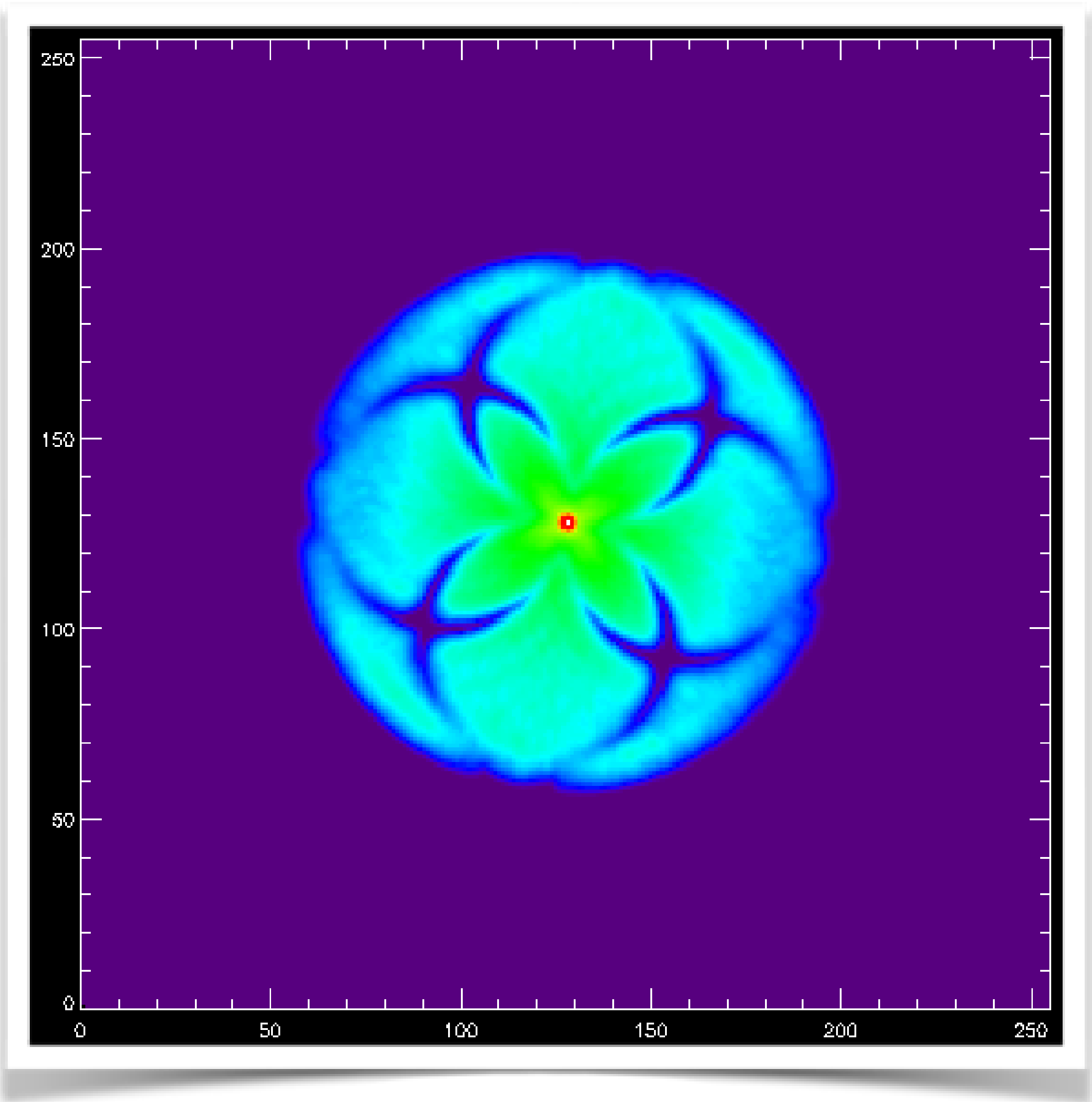


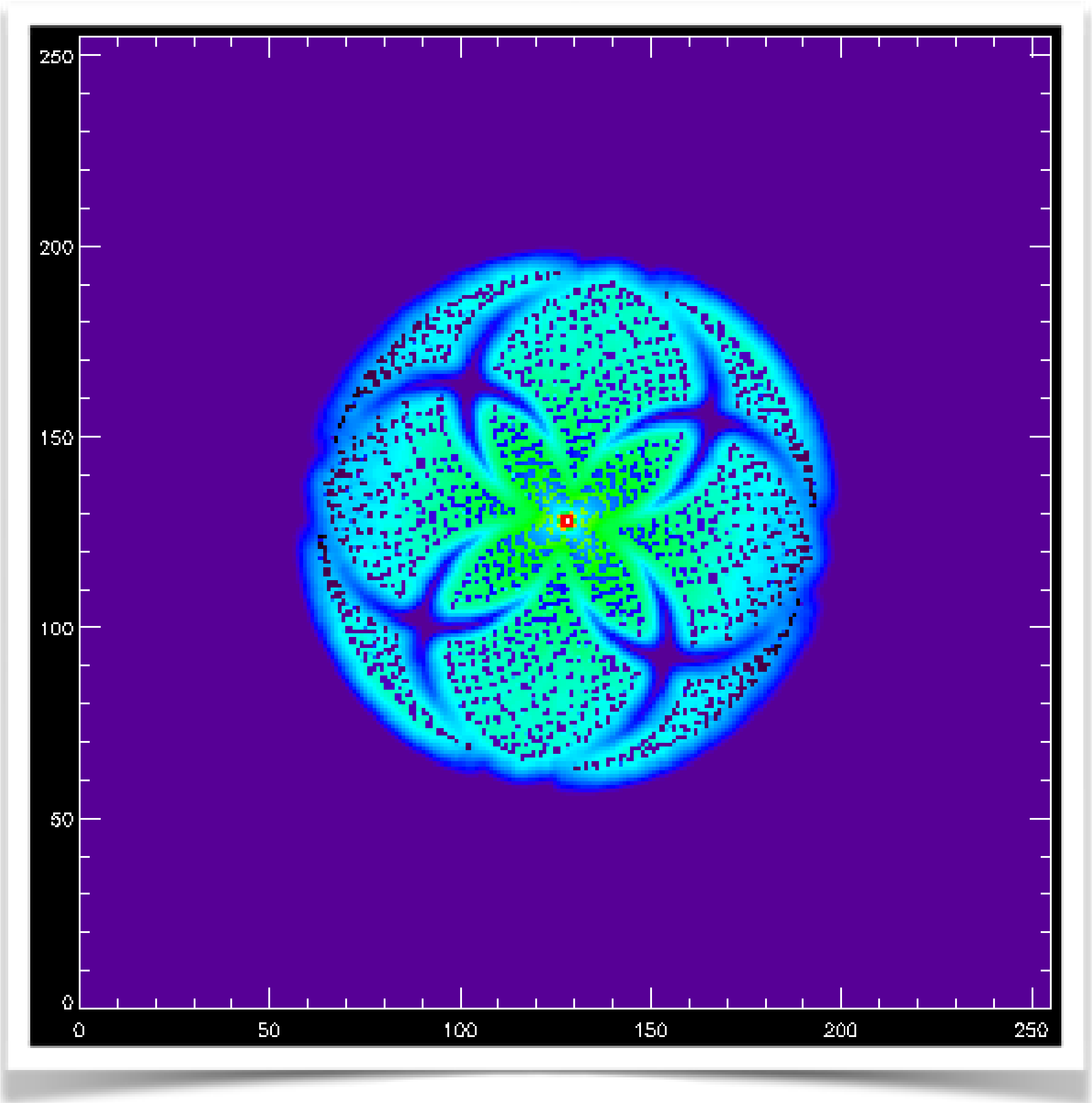


# Power spectrum example: annulus

Discrete sampling of Annulus PS

Excellent Fourier coverage, arbitrarily short baselines.




Vega, 4s integration

# DIFFERENTIAL CALIBRATION - IN AN IDEAL WORLD...

H polarisation image
$\star$
Error (seeing, systematics)

FT

H polarisation visibilities
x
Error visibilities

÷

V polarisation image
$\star$
Error (seeing, systematics)

FT

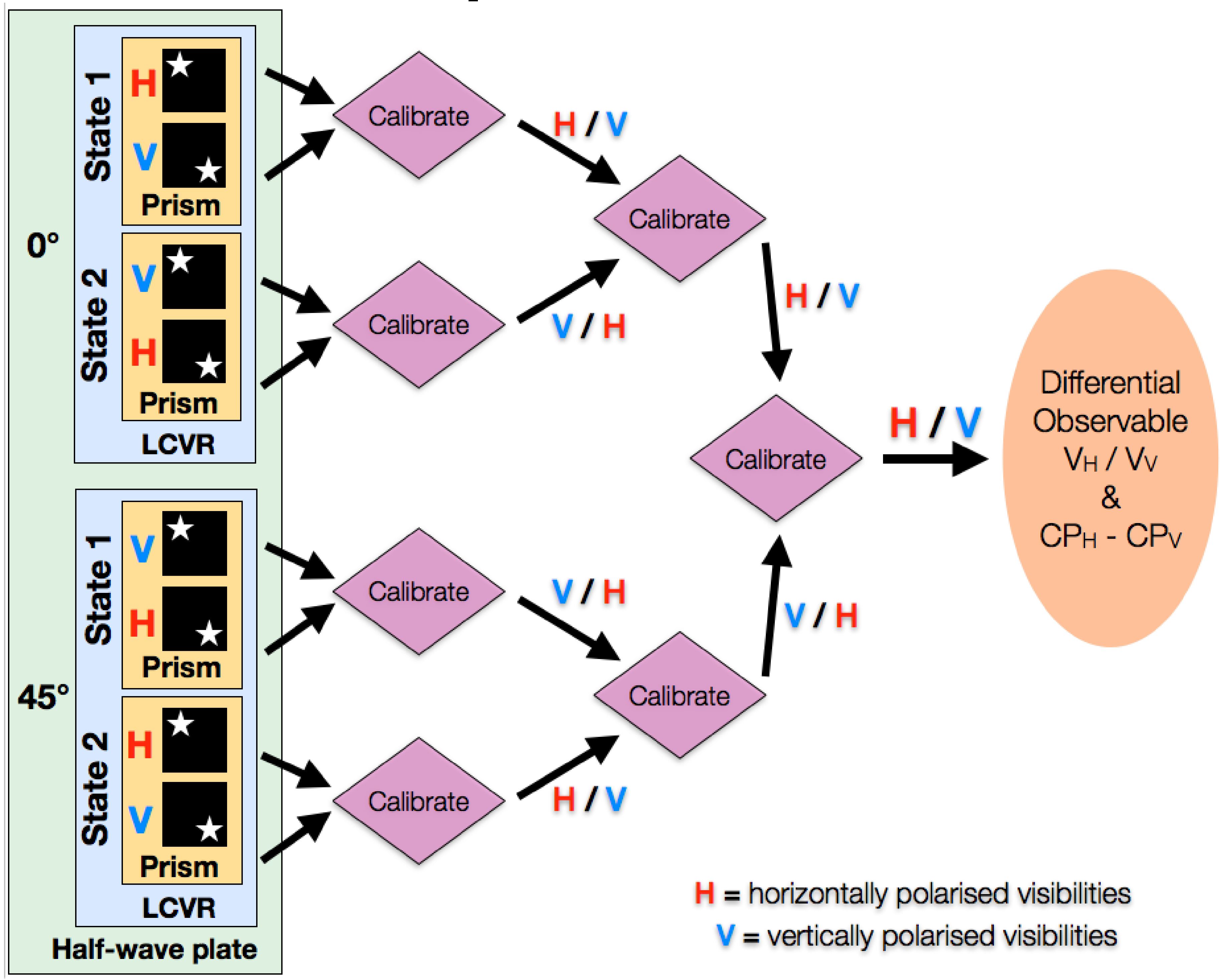
V polarisation visibilities
x
Error visibilities

=

V/H polarisation visibilities
(CLEAN OBSERVABLE)

# DIFFERENTIAL CALIBRATION - TRIPLE LAYER SWITCHING!

**Address non-common-path & non-simultaneous errors**



# DIFFERENTIAL CALIBRATION - TRIPLE LAYER SWITCHING!

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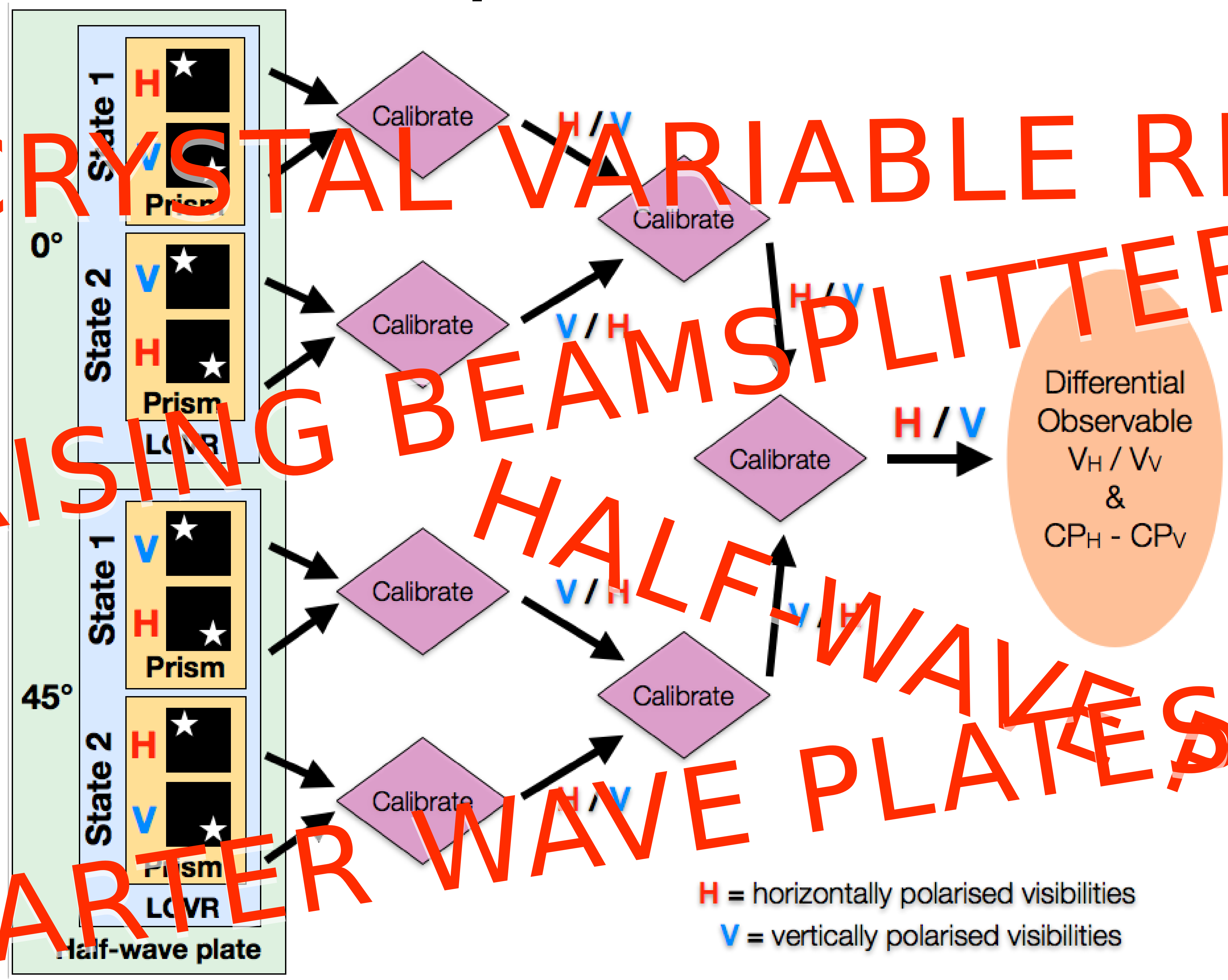



UID CRYSTAL VARIABLE RETAR

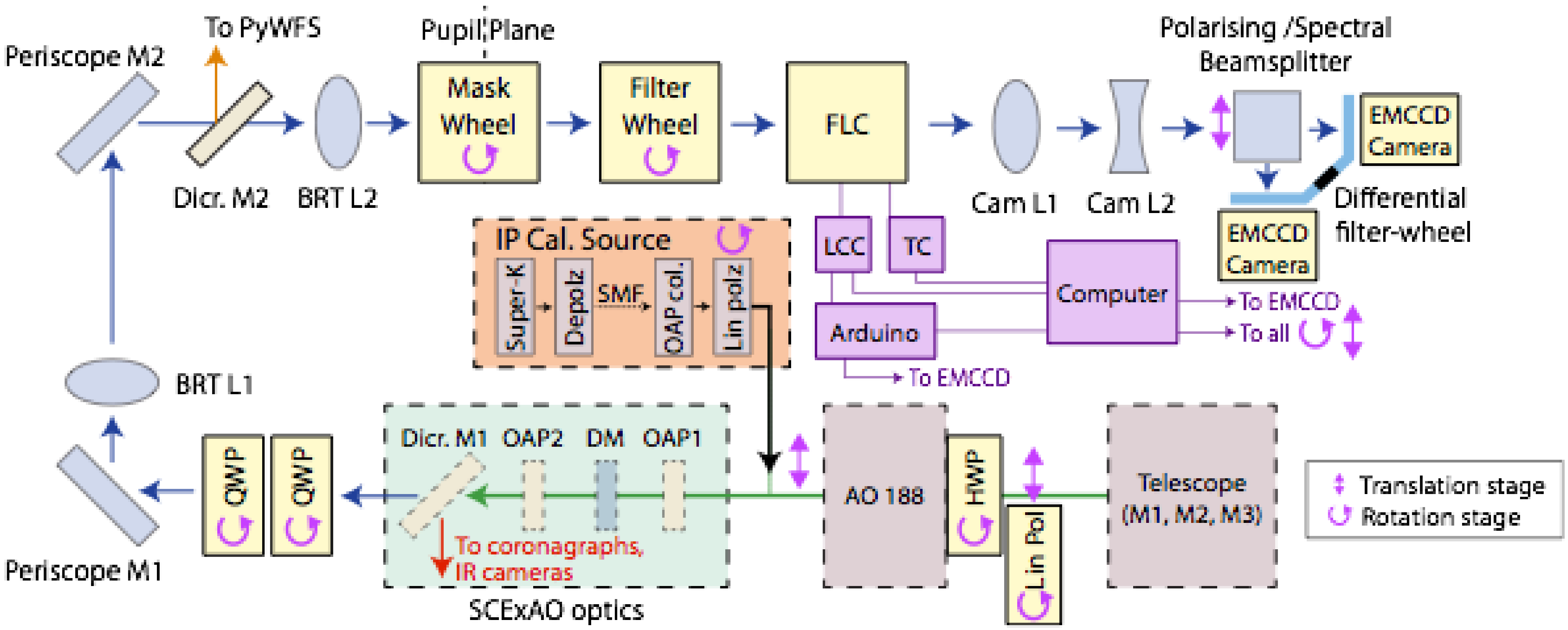
OLARISING BEAMSPLITTER!

HALF-WAVE PLATE!

2 QUARTER WAVE PLATES!

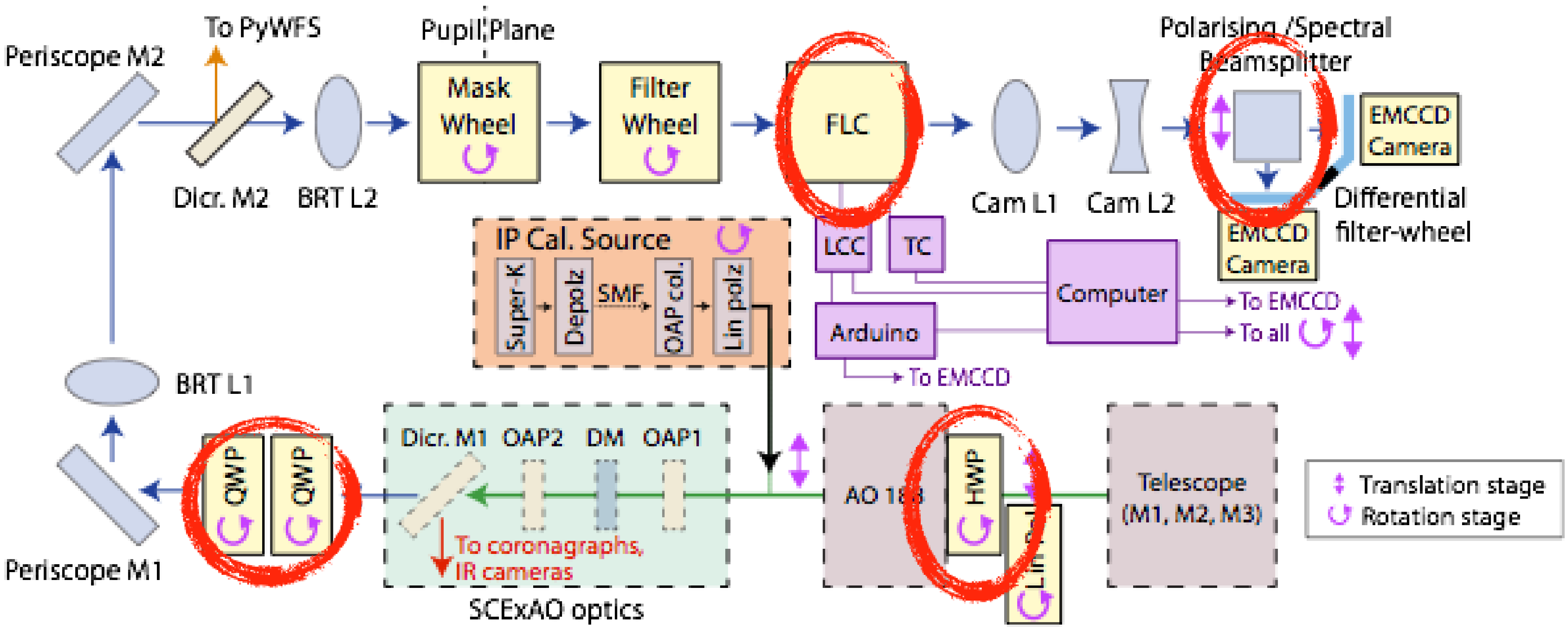
# DIFFERENTIAL CALIBRATION - TRIPLE LAYER SWITCHING!

**Address non-common-path & non-simultaneous errors**



# DIFFERENTIAL CALIBRATION - TRIPLE LAYER SWITCHING!

**Address non-common-path & non-simultaneous errors**

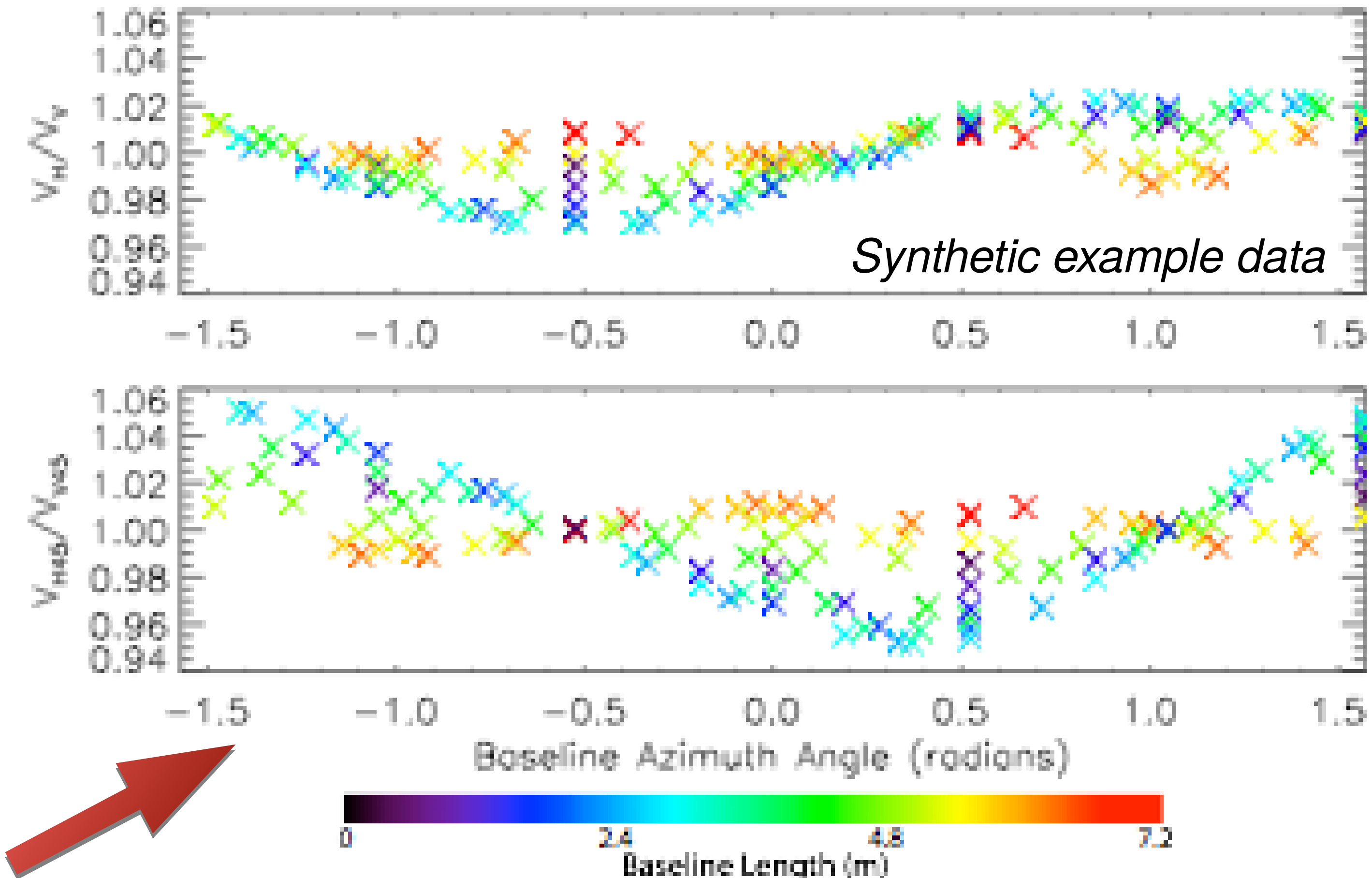


# NECESSARY TECHNICAL NOTE…

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



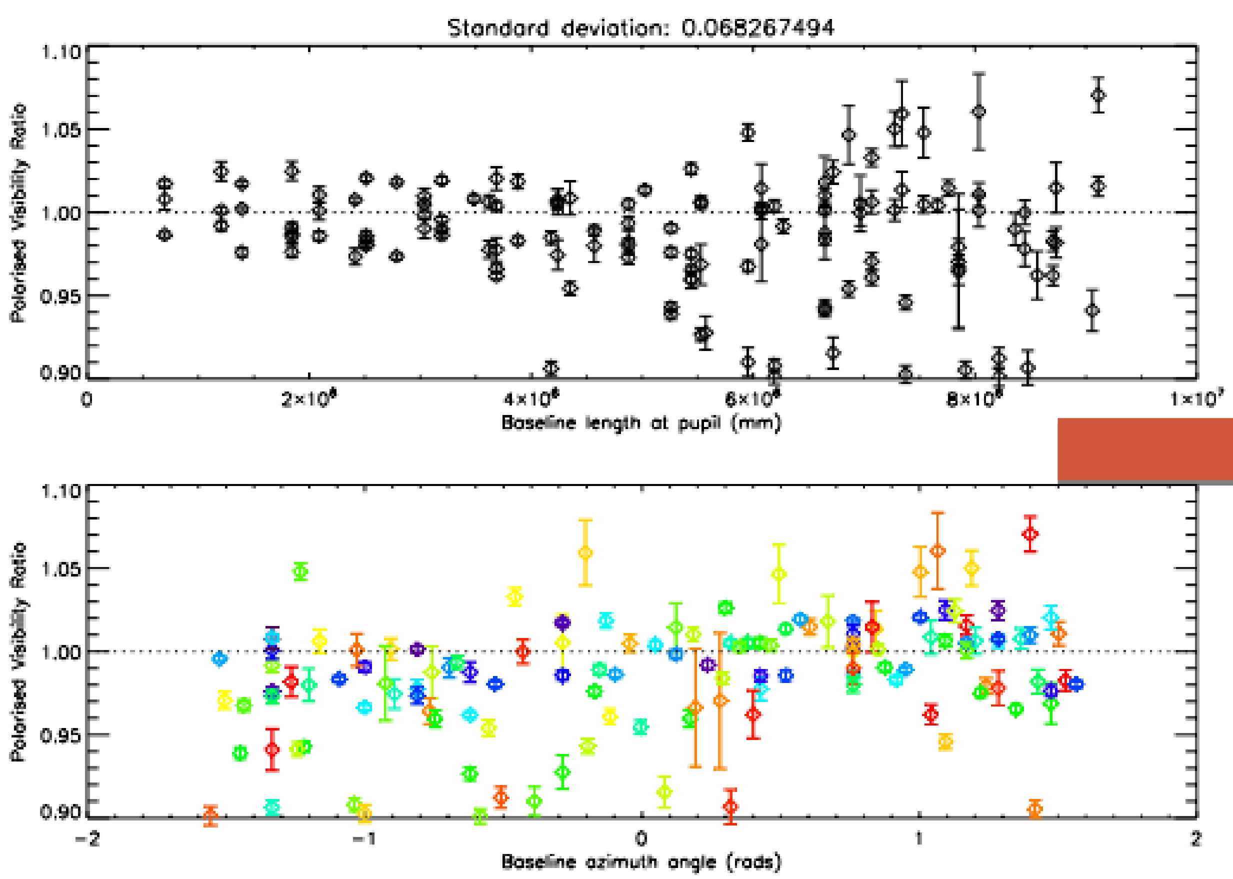

X Axis:
Azimuthal angle (on-sky) of the baseline (spatial frequency coordinate)

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

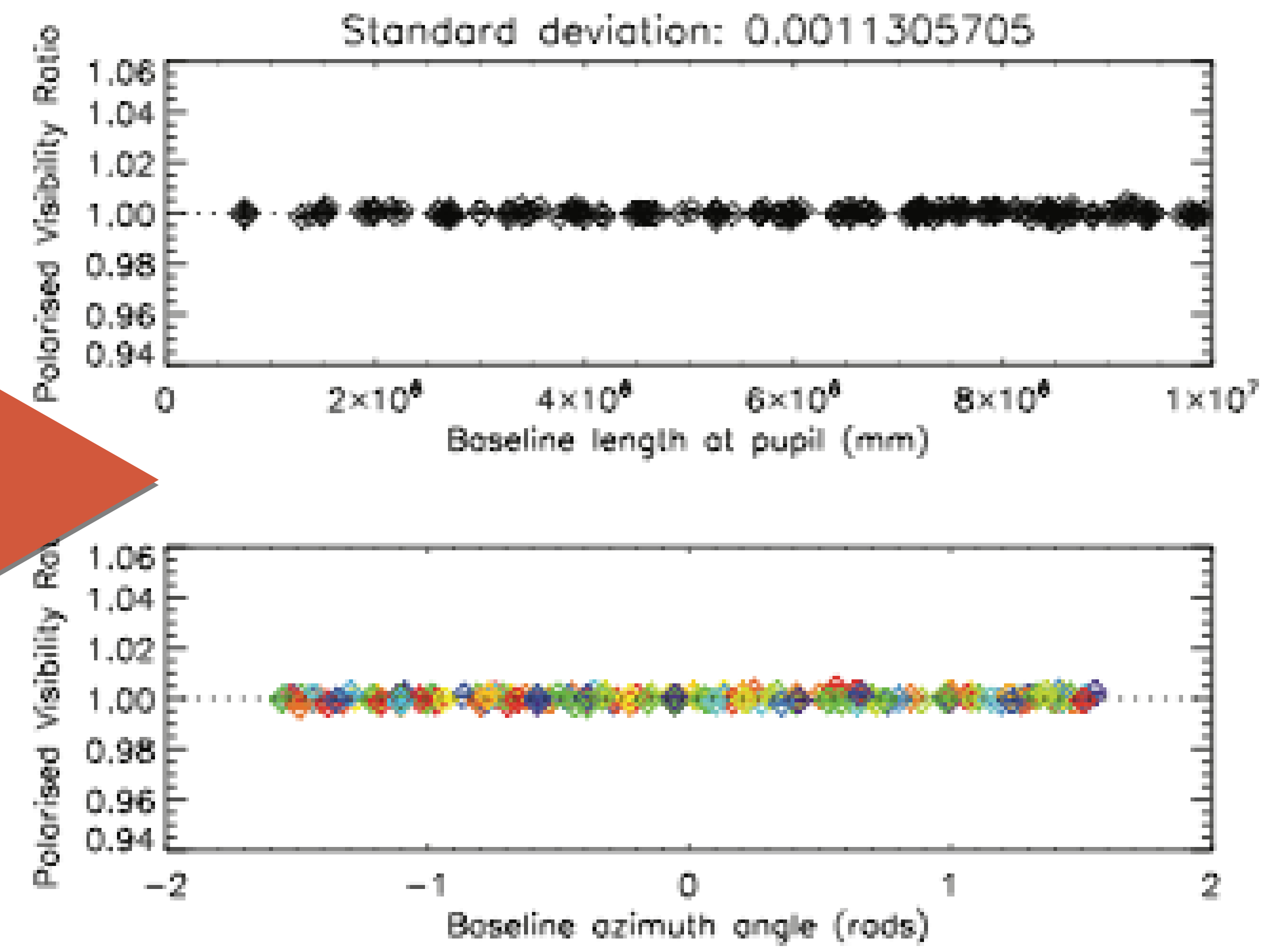
*Should = 1 for all unpolarised targets…*
*Demonstrates calibration precision*

# NRM MODE CALIBRATION PERFORMANCE

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




*Conventional 2-beam polarimetry*

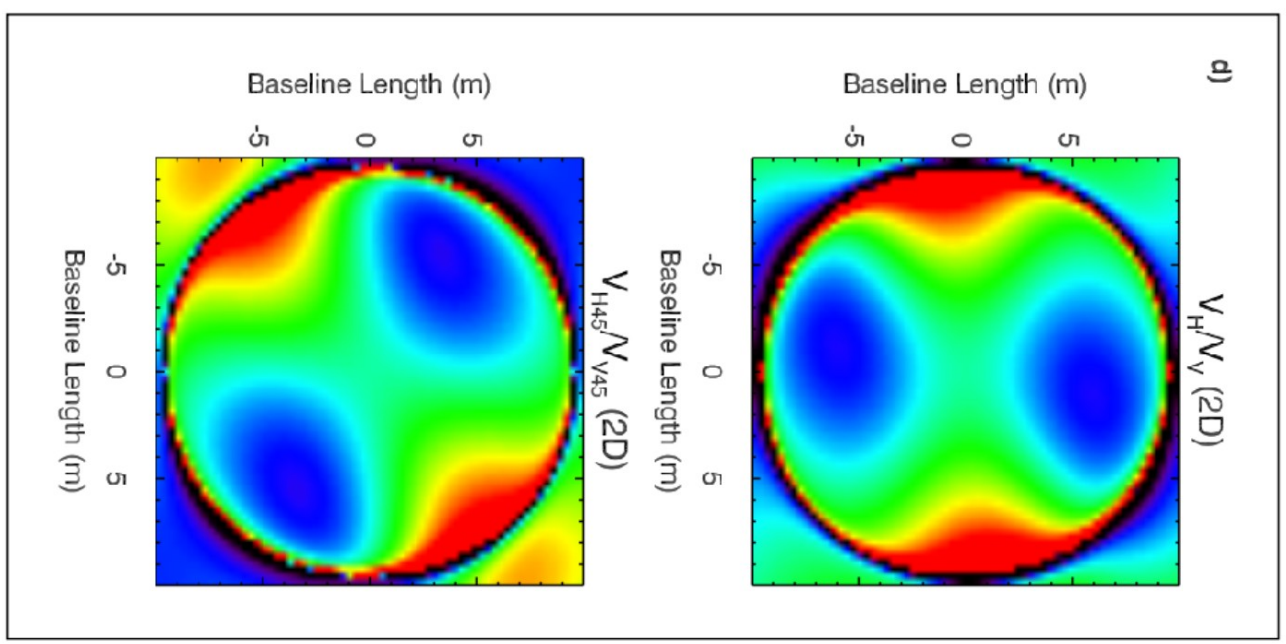


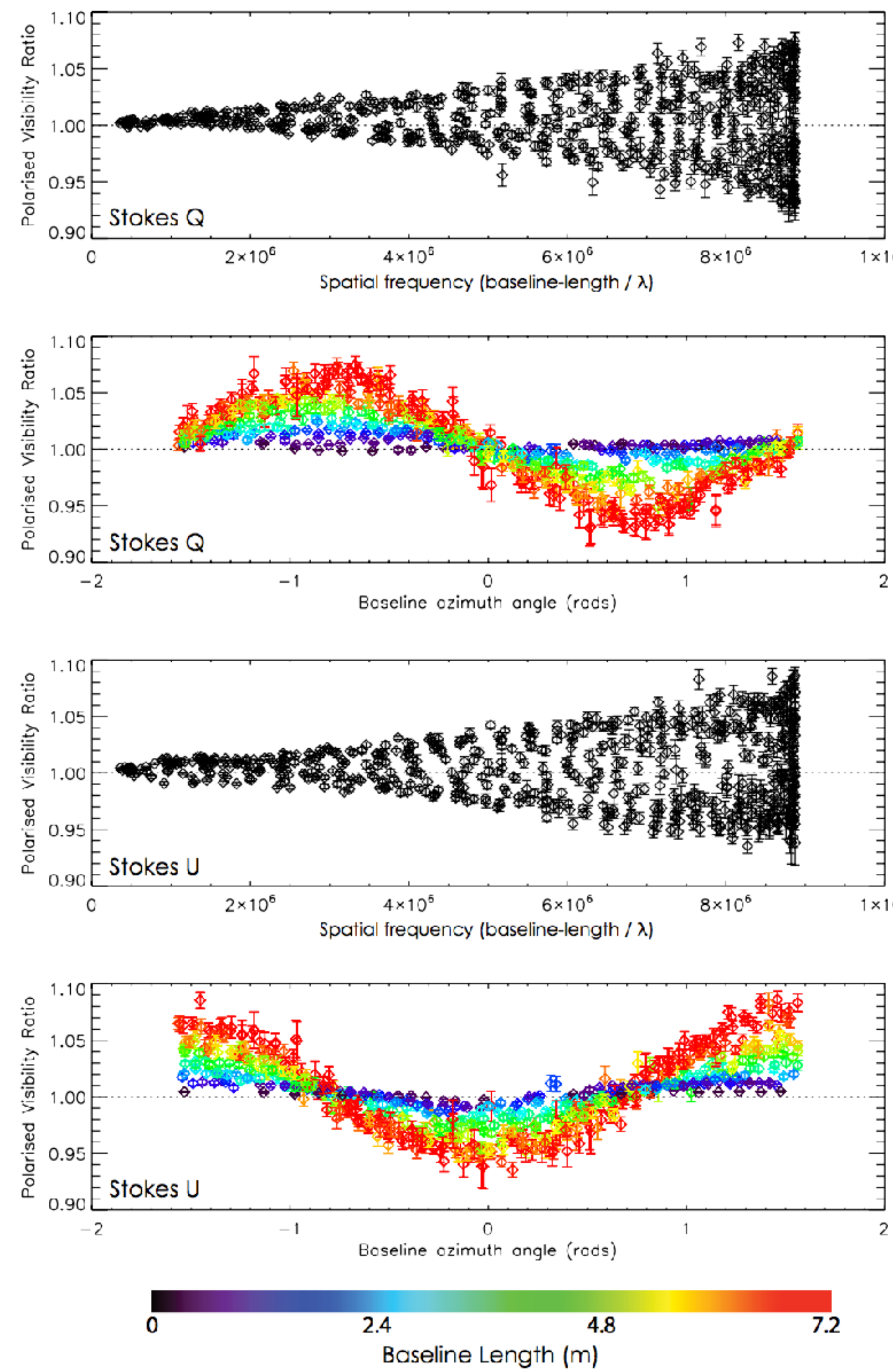

*Triple-differential calibration*

# 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)**



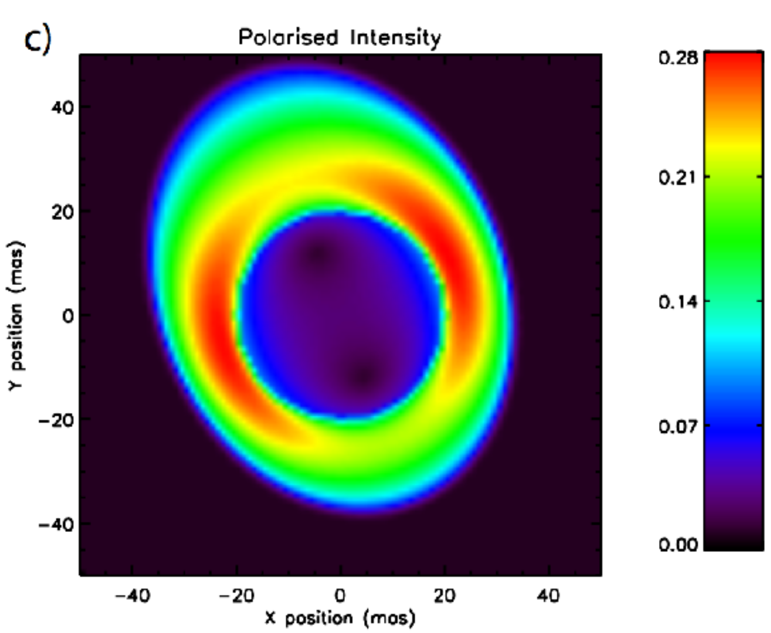



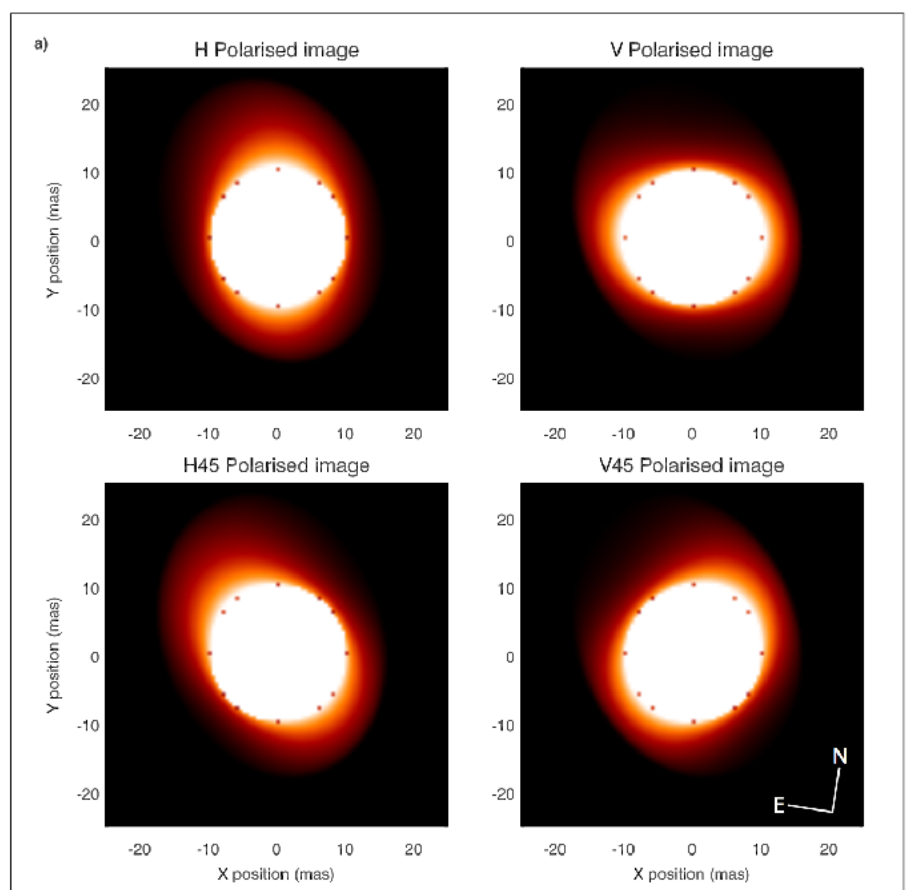
# NRM-MODE EXAMPLE SCIENCE-RESULT

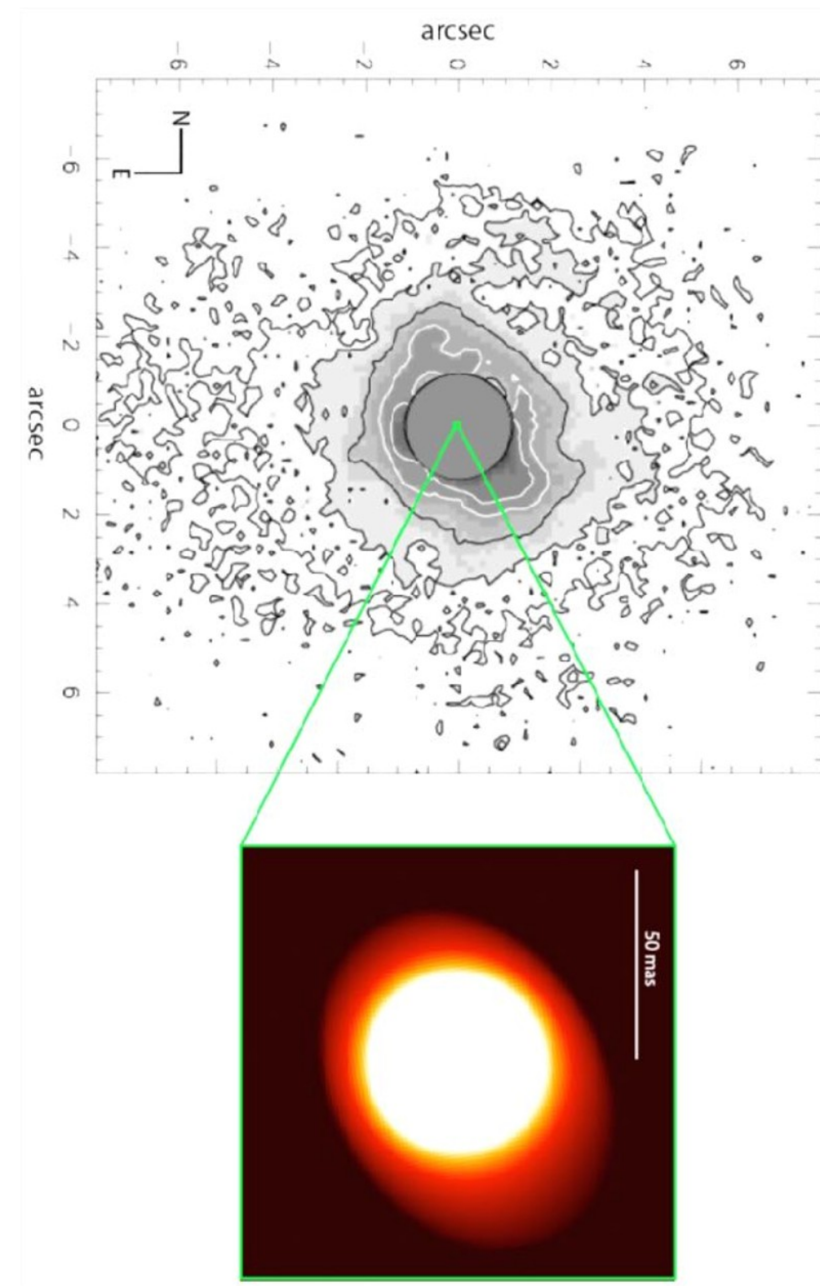
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely $Al_2O_3$) important for unexplained extension of RSG atmospheres.

*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.

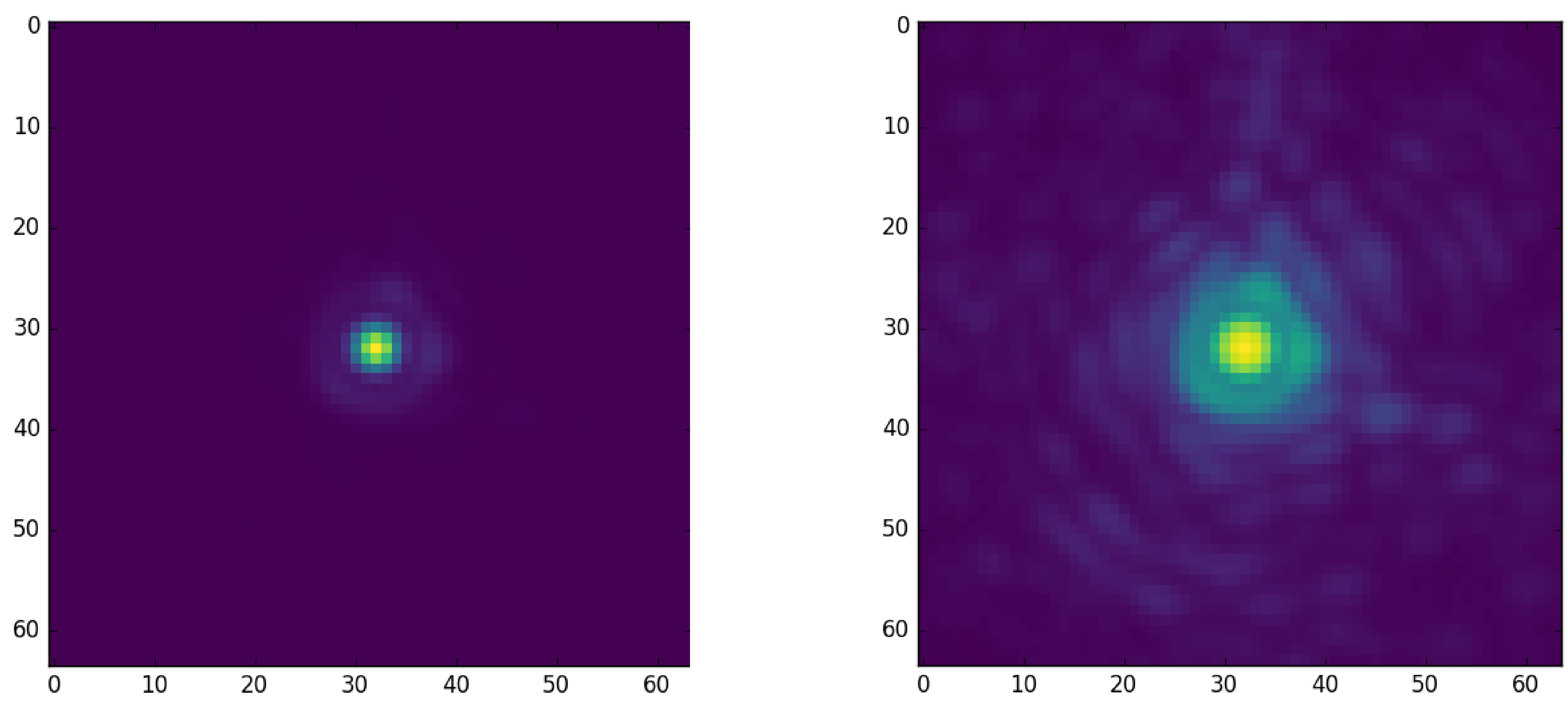


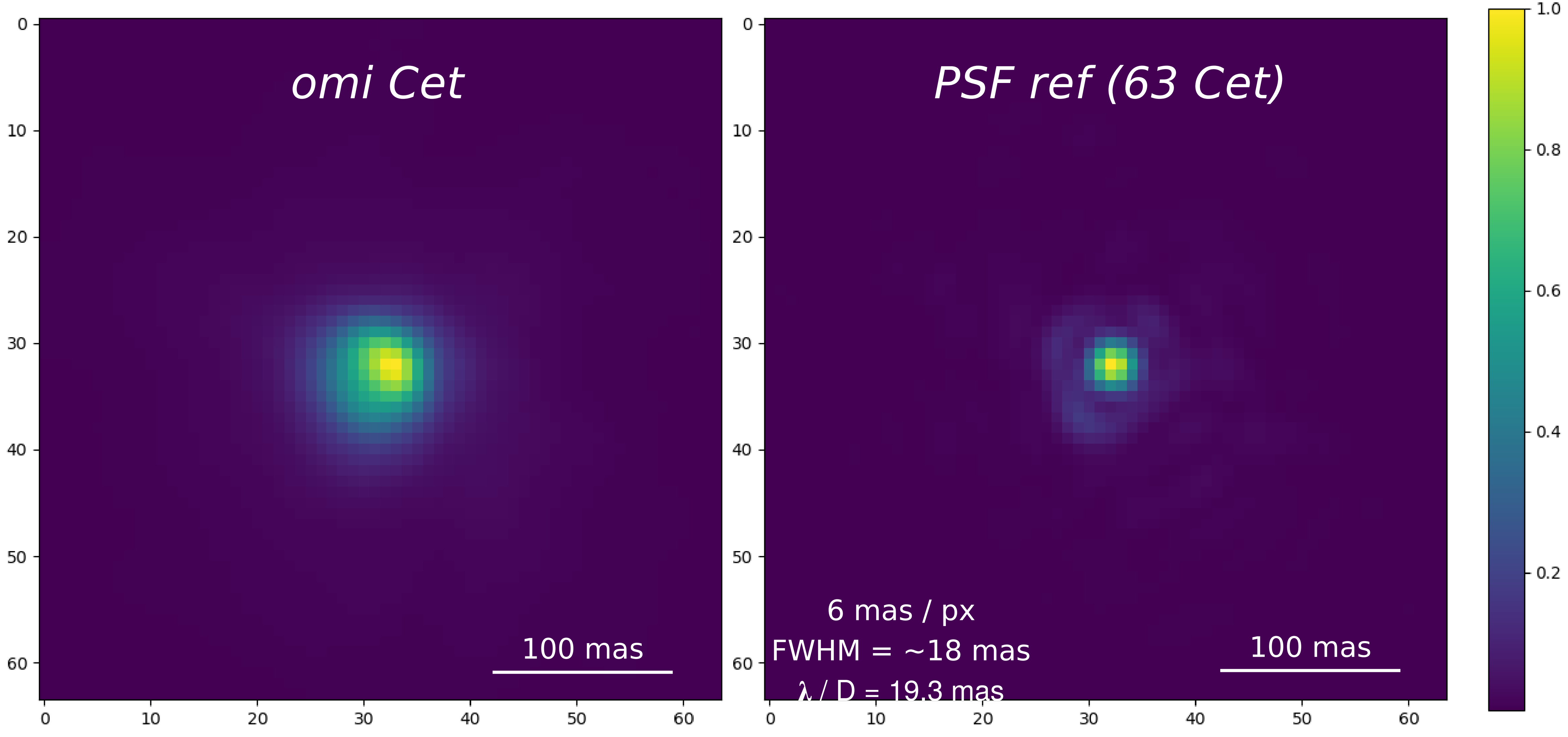
# IMAGING/PDI MODE

- 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

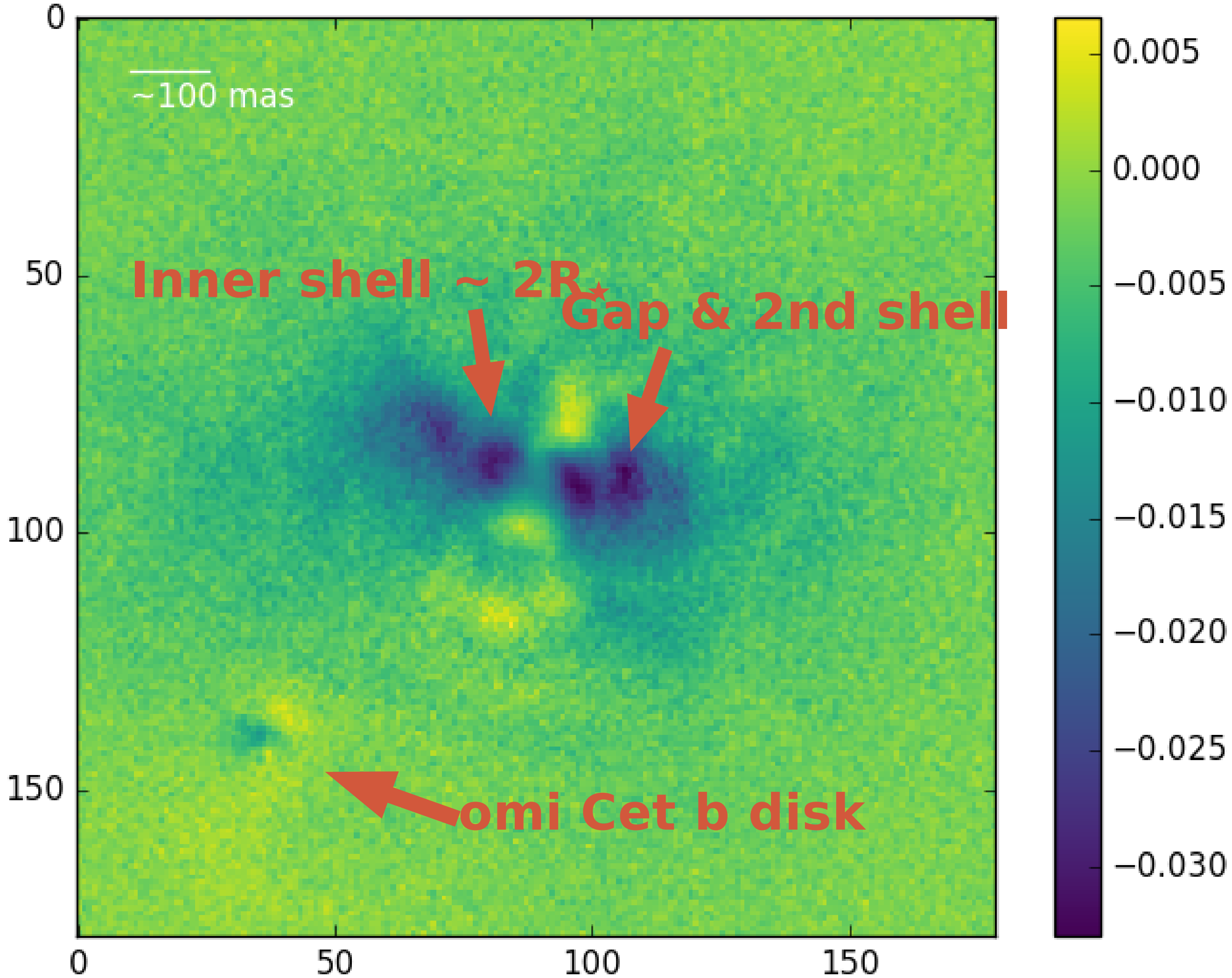
- Direct imaging of omi Cet - clear asymmetry seen.
  - Speckle imaging - diffraction-limited



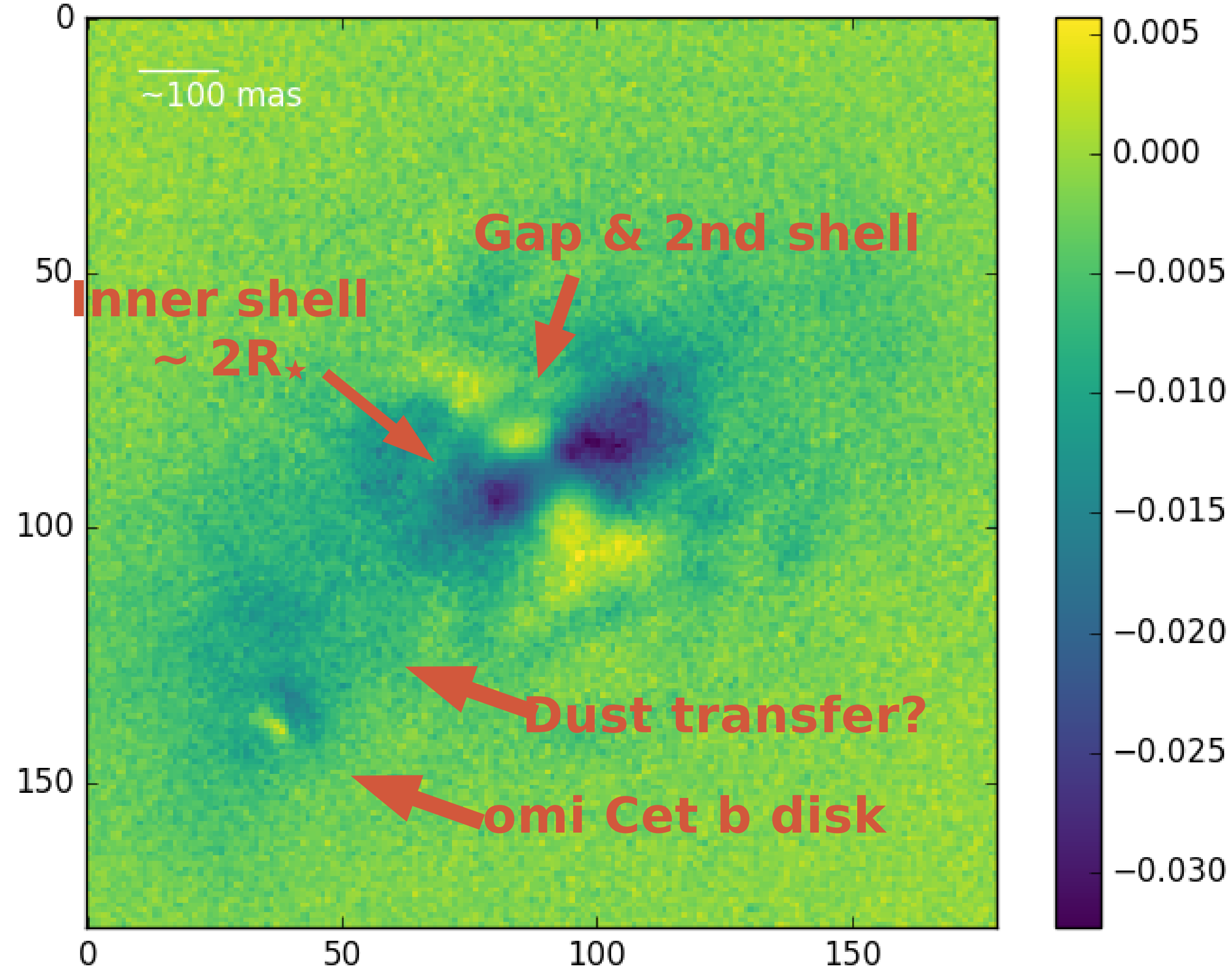

*Observed 12/09/2017*

# IMAGING-MODE EXAMPLE SCIENCE-RESULT

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




*Stokes Q*

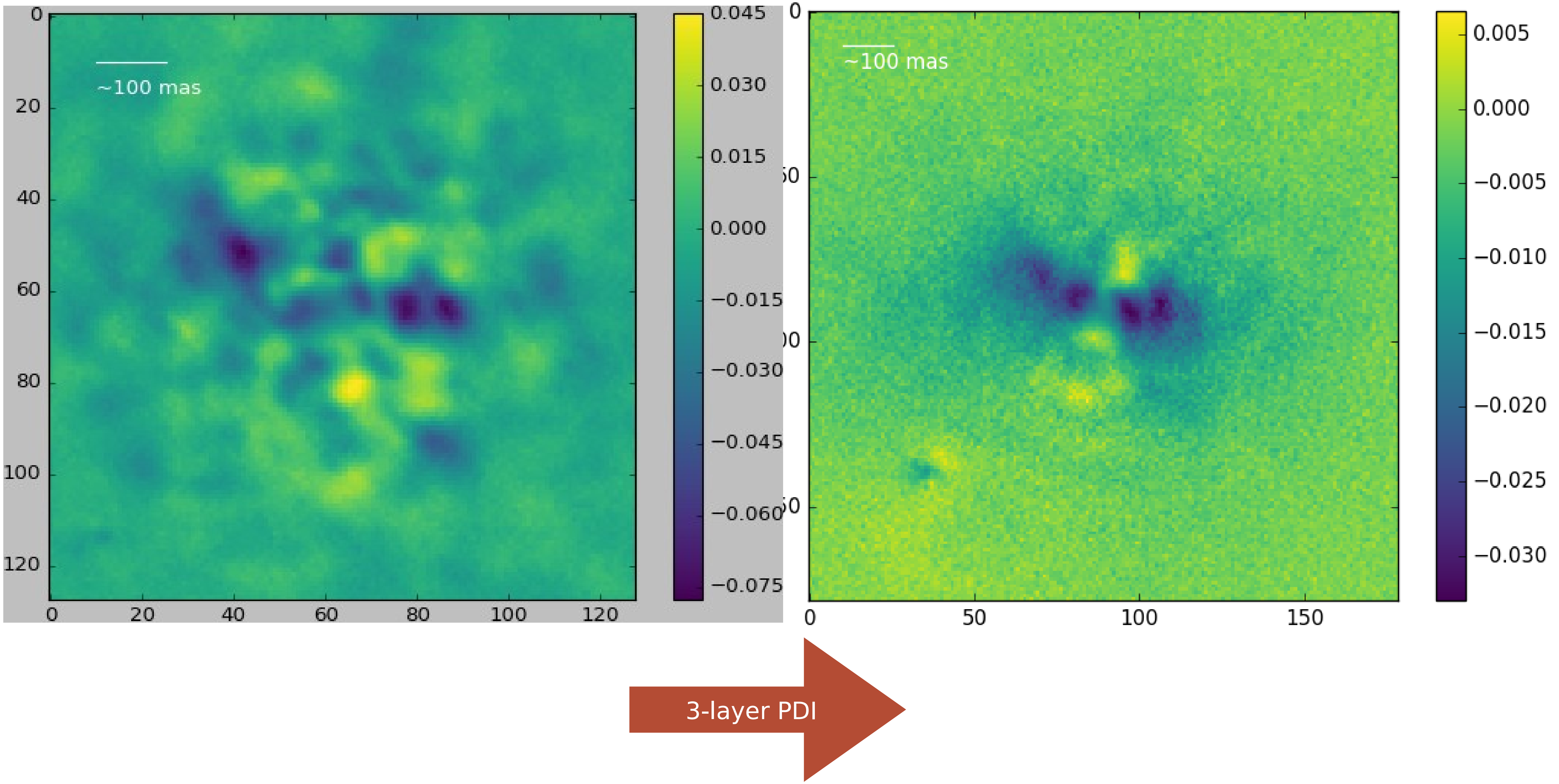



*Stokes U*

*Observed 12/09/2017*

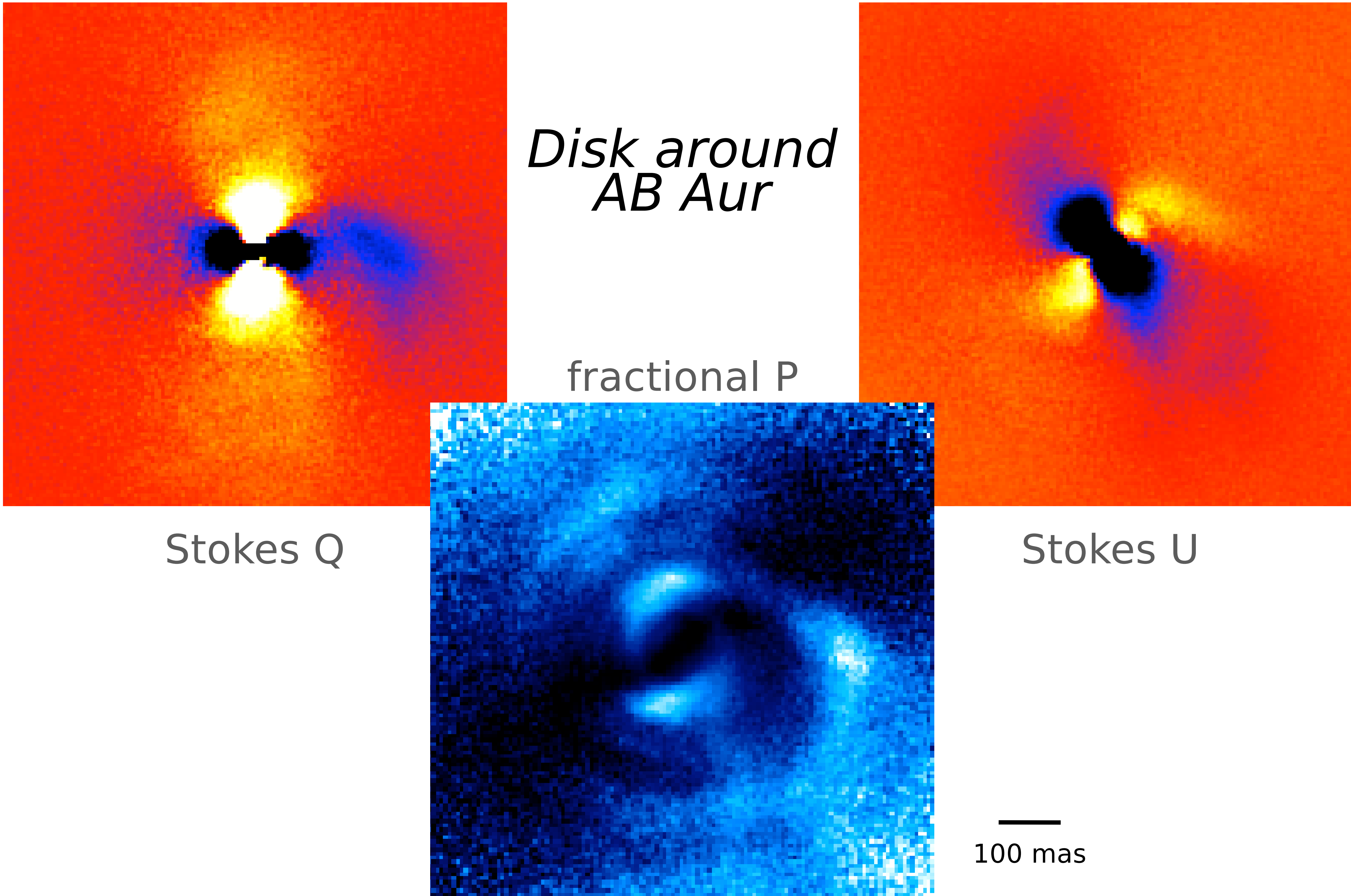
# IMAGING-MODE EXAMPLE SCIENCE-RESULT

- Effect of single vs triple polarisation calibration



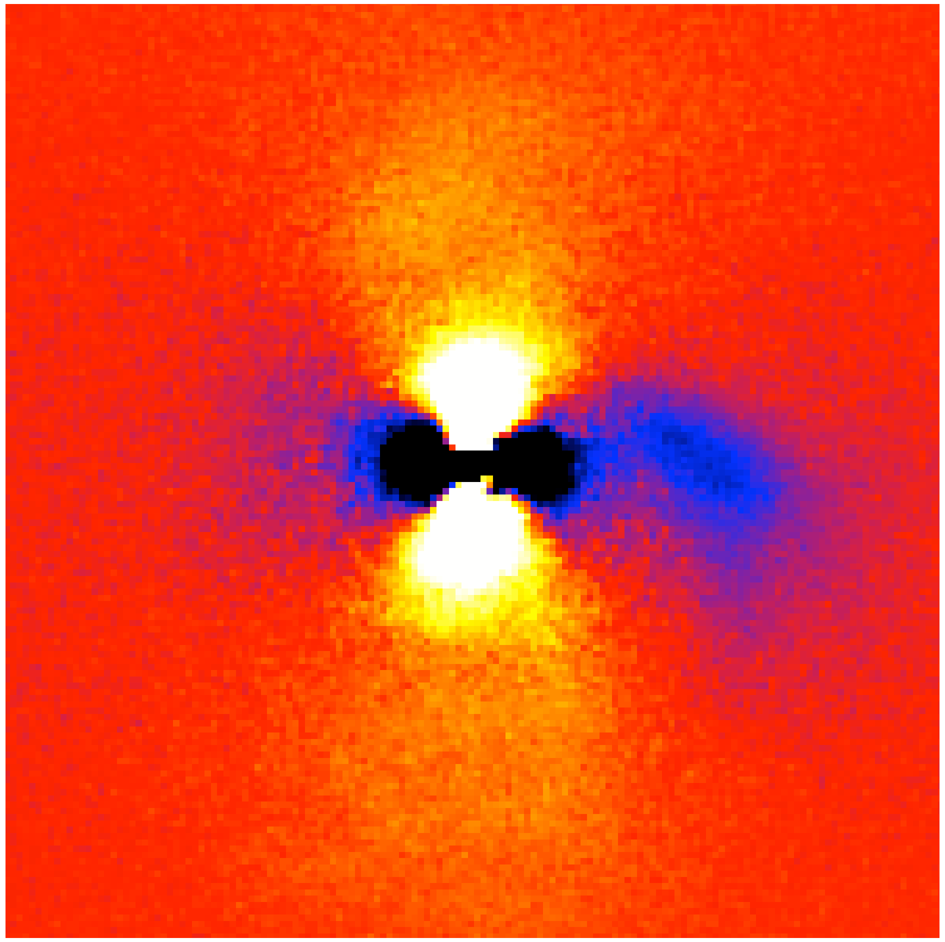

*Stokes Q*

# IMAGING-MODE EXAMPLE SCIENCE-RESULT

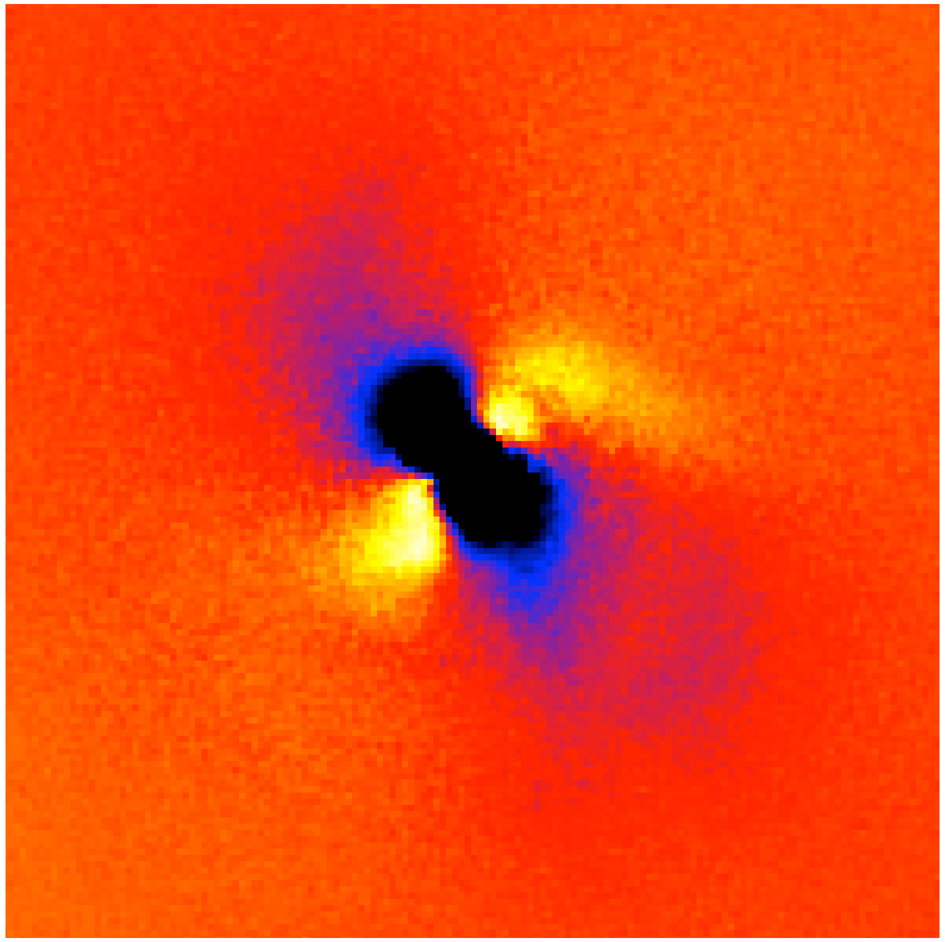


# IMAGING-MODE EXAMPLE SCIENCE-RESULT

*Disk around AB Aur*



Stokes Q

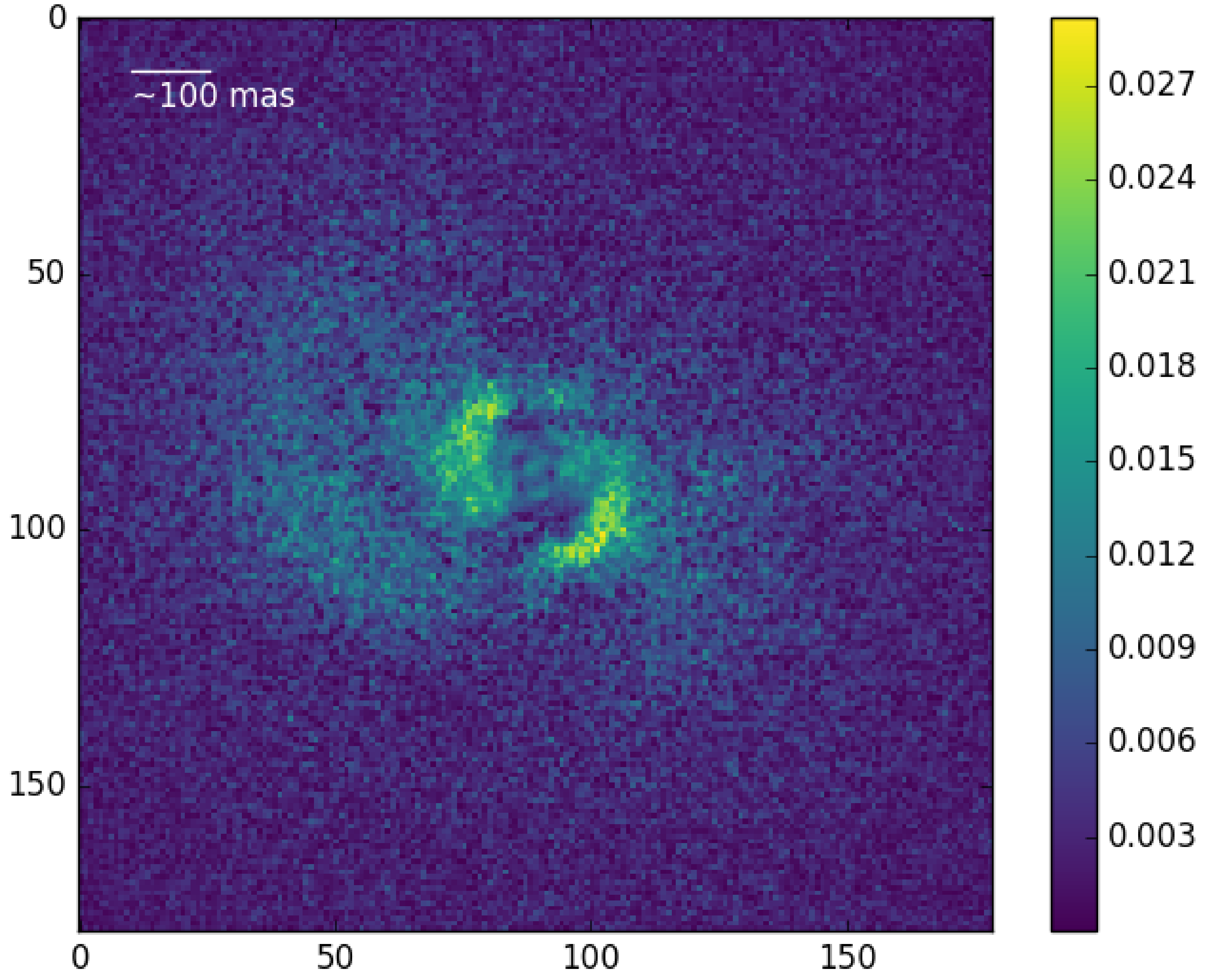


Stokes U

100 mas

# IMAGING-MODE EXAMPLE SCIENCE-RESULT

*Disk around AB Aur - poorer seeing*



# IMAGING-MODE EXAMPLE SCIENCE-RESULT

- Observation of AB Aur - new inner-regions of disk identified
  - Preliminary reduction, optimal pipeline in development