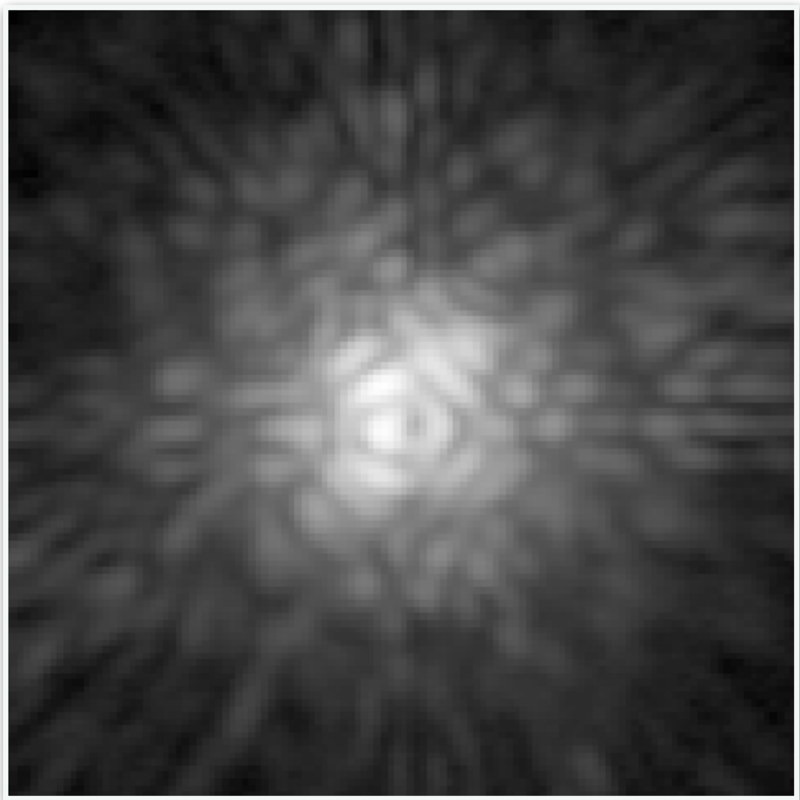
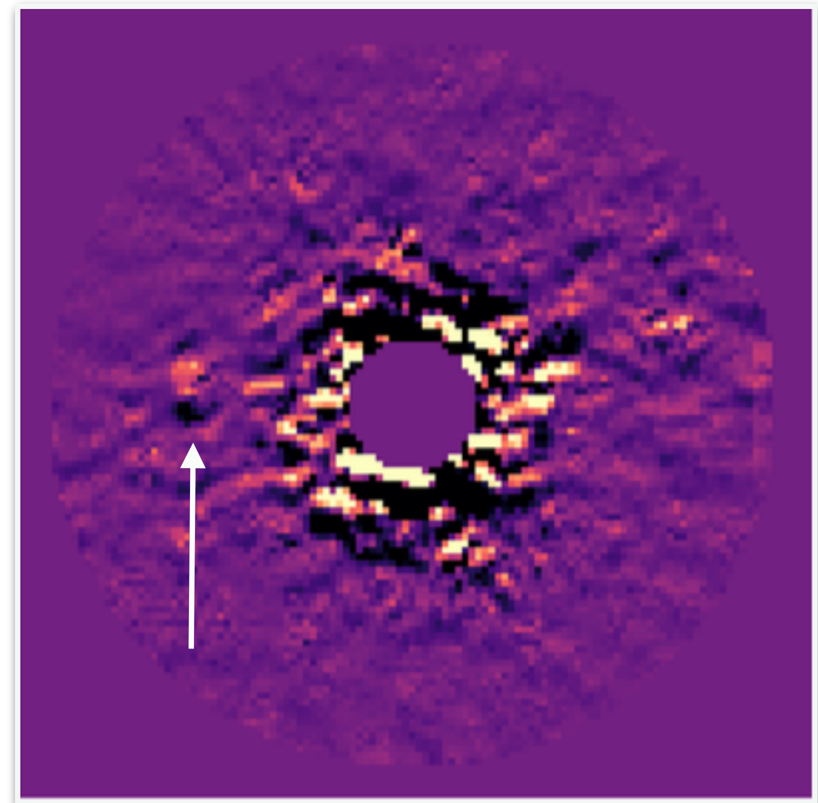
Focal plane wavefront sensing and companion detection using phase-shifting interferometry

HD 49197 b



Coherent + incoherent intensity



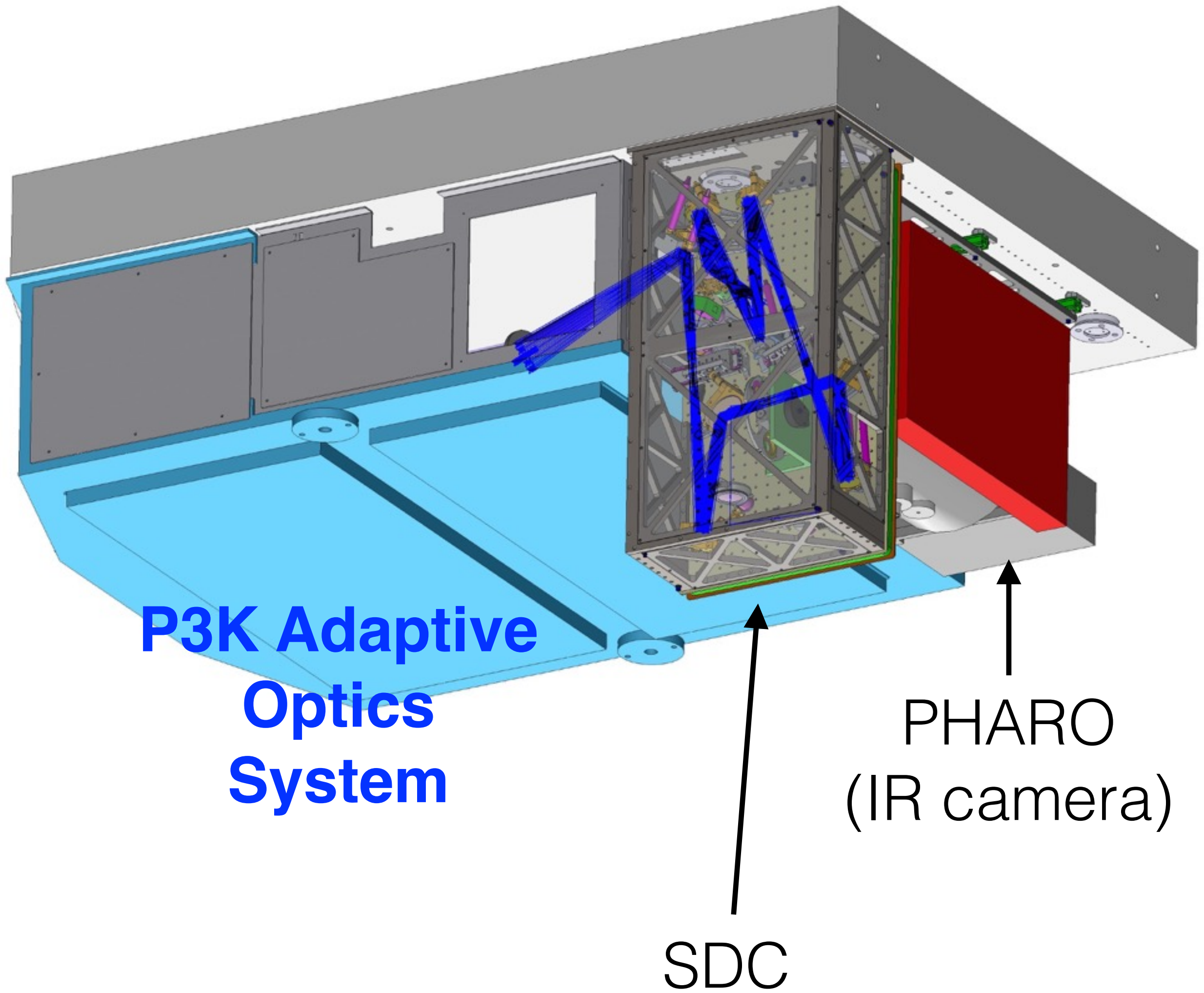
Incoherent intensity only

Michael Bottom (JPL, Caltech)
KISS workshop
California Institute of Technology
23 August 2016

with JPL collaborators
J. Kent Wallace
Randall Bartos
J. Chris Shelton
Eugene Serabyn (PI)

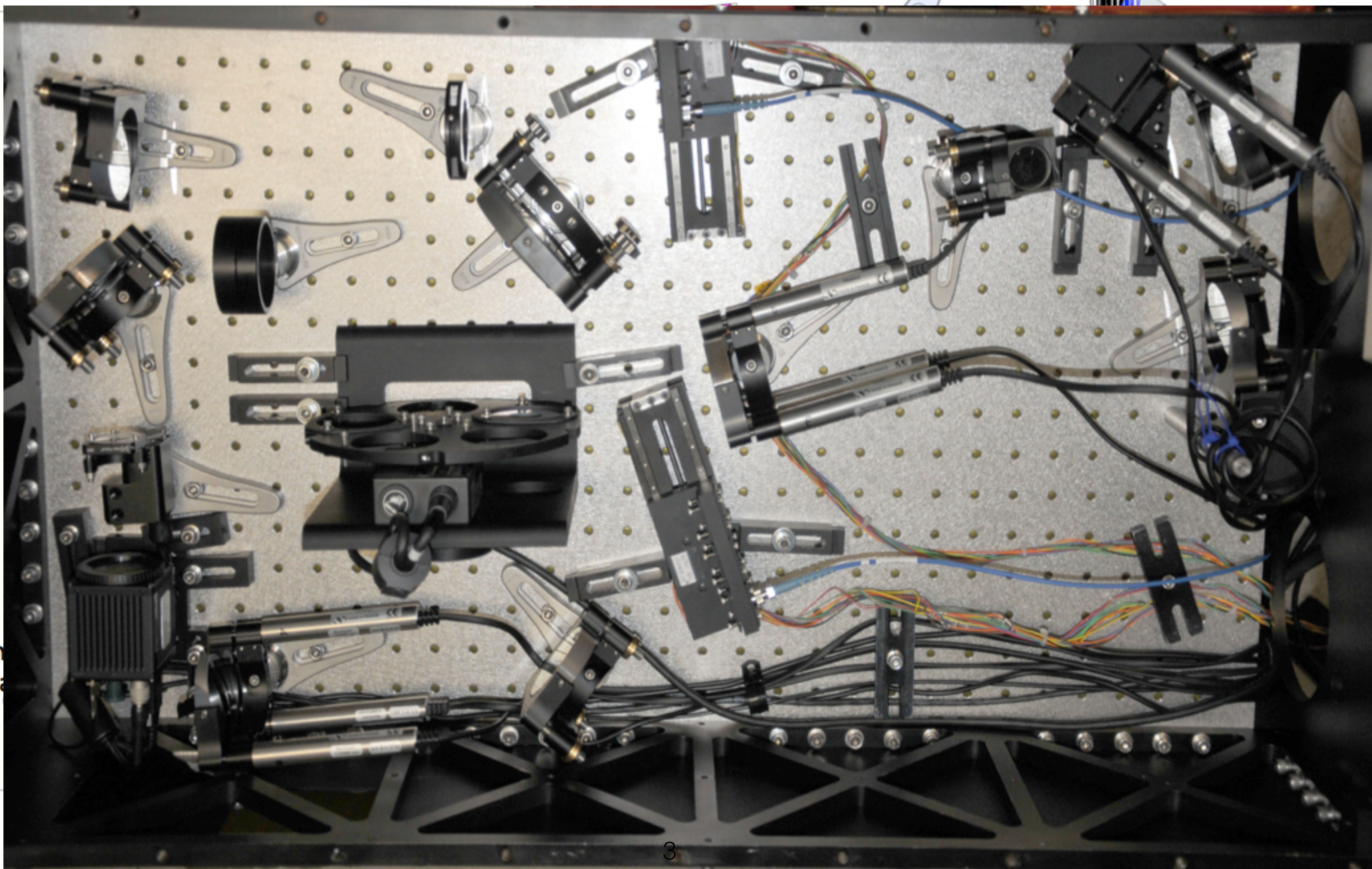
Background: Stellar Double Coronagraph (SDC)

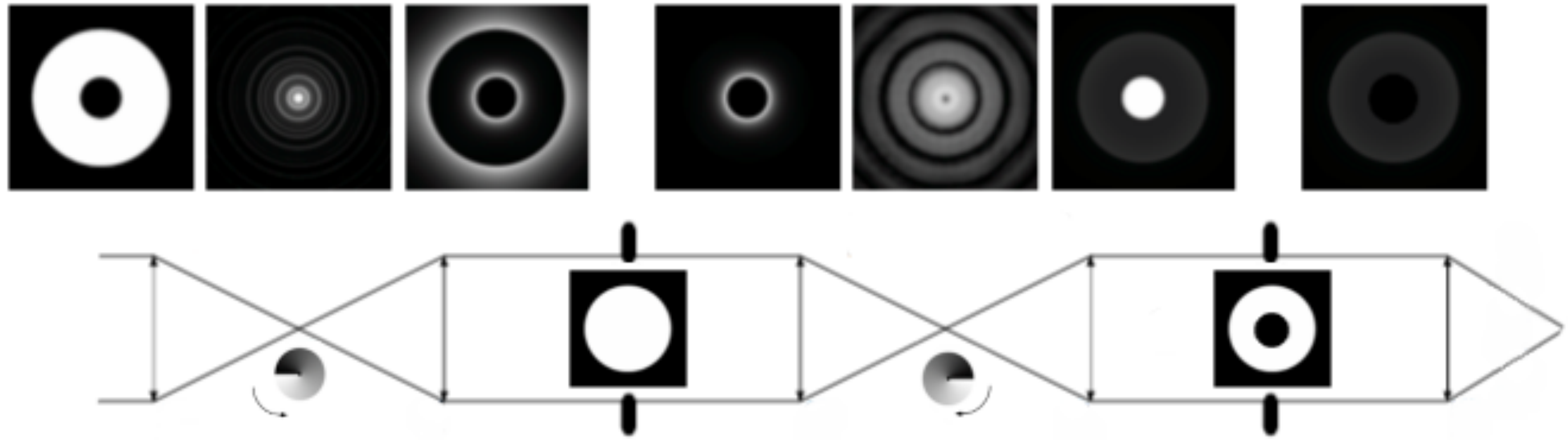
- **Scientific motivation—**Imaging of planets and disks
- **Technical motivation—**develop new coronagraphic and wavefront sensing techniques.
- **Philosophy: flexible design—** accommodates multiple observing configurations that can be rapidly interchanged without opening the instrument. Minimally invasive to install new elements or try new things.

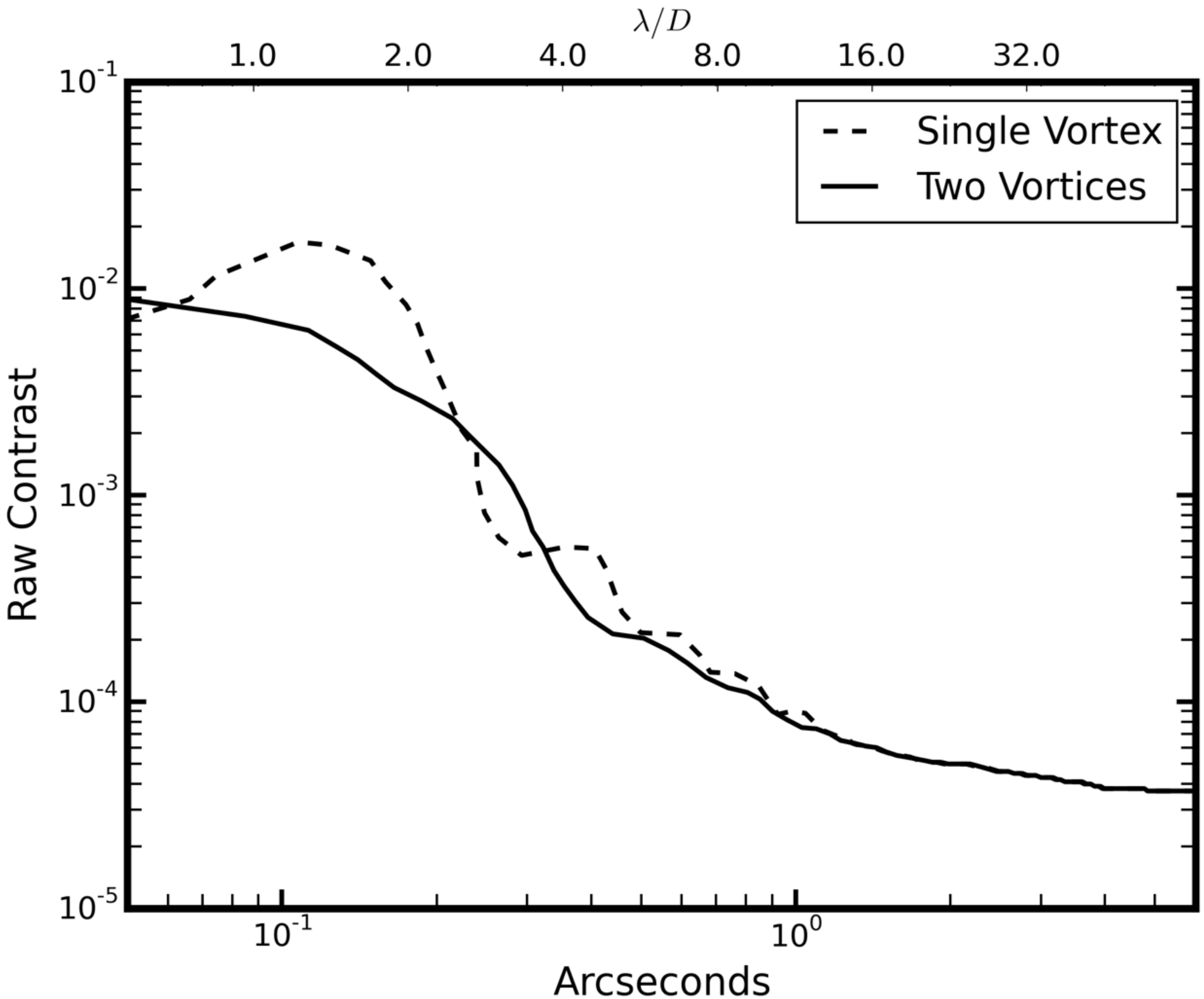


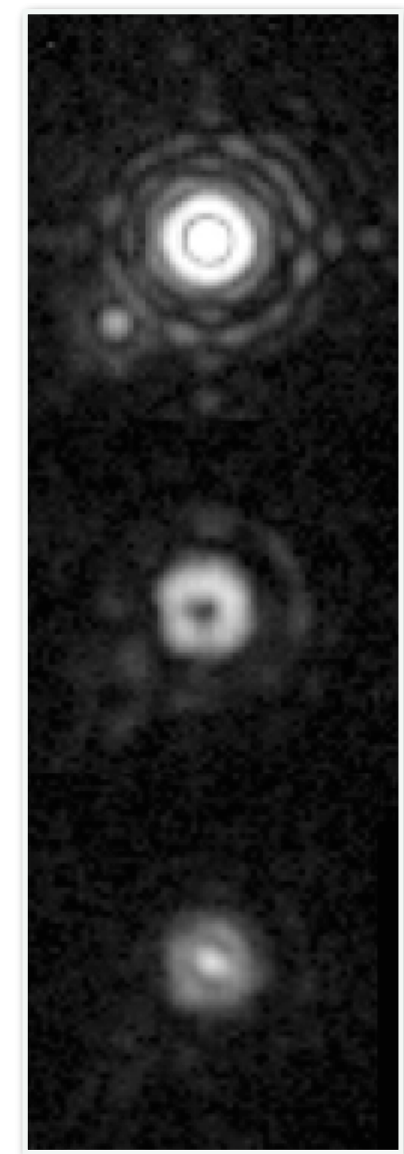
Bottom et al. 2016

In
Ca



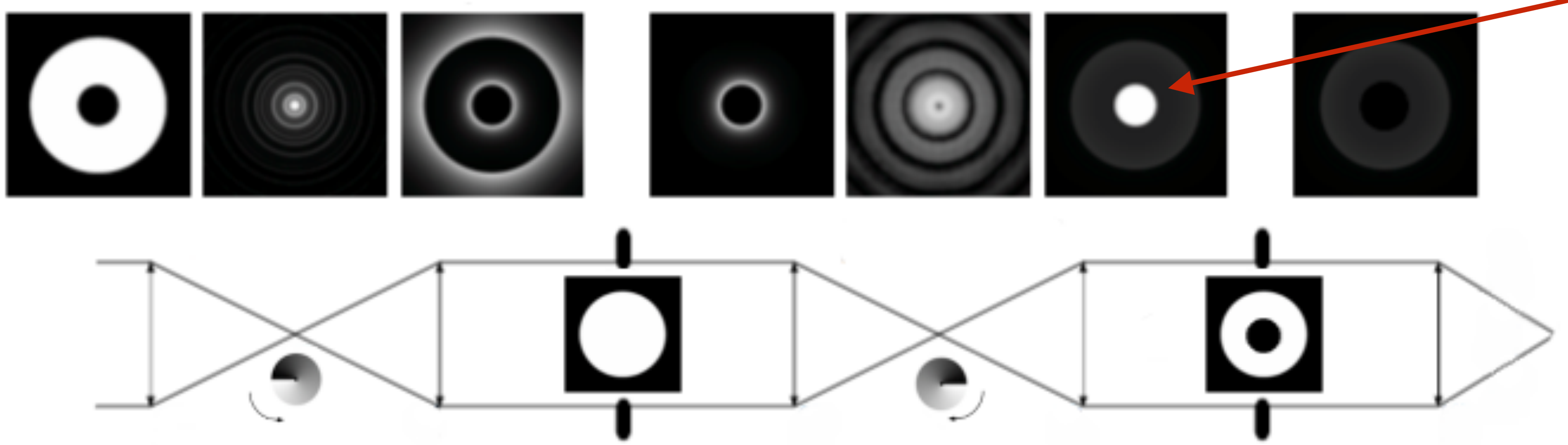


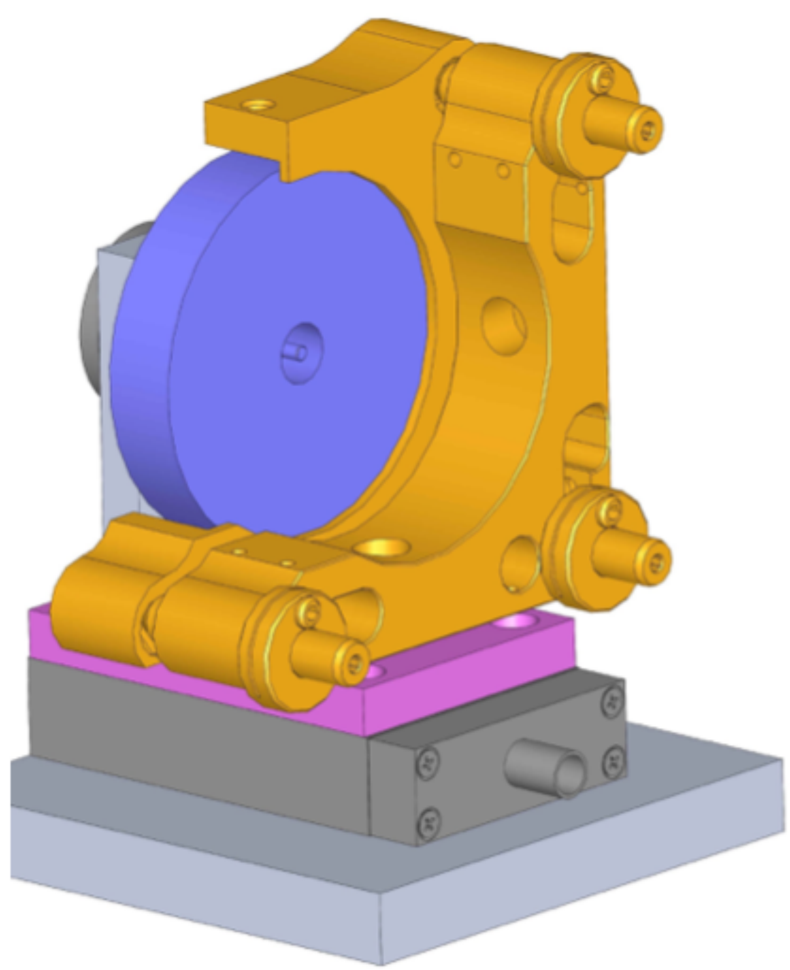


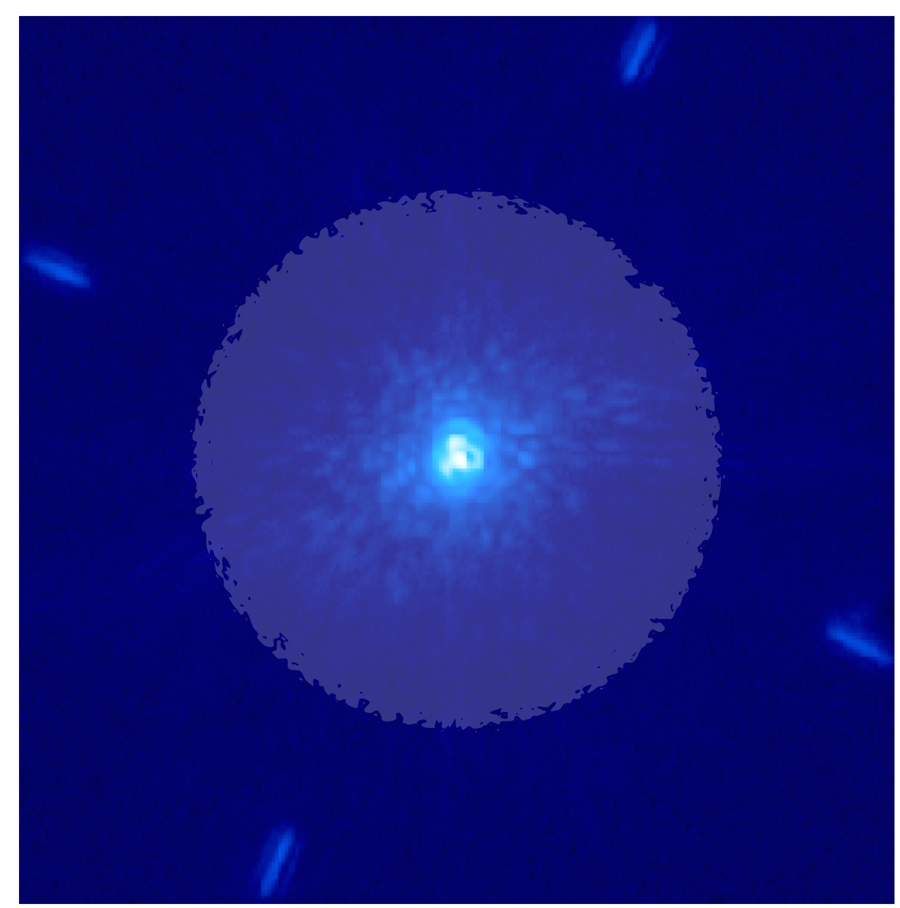


Bottom et al. 2016, Mawet et al. 2013 Optics Letters 36, 8

Why let nice coherent light go to waste??
Can interfere it with speckles!!



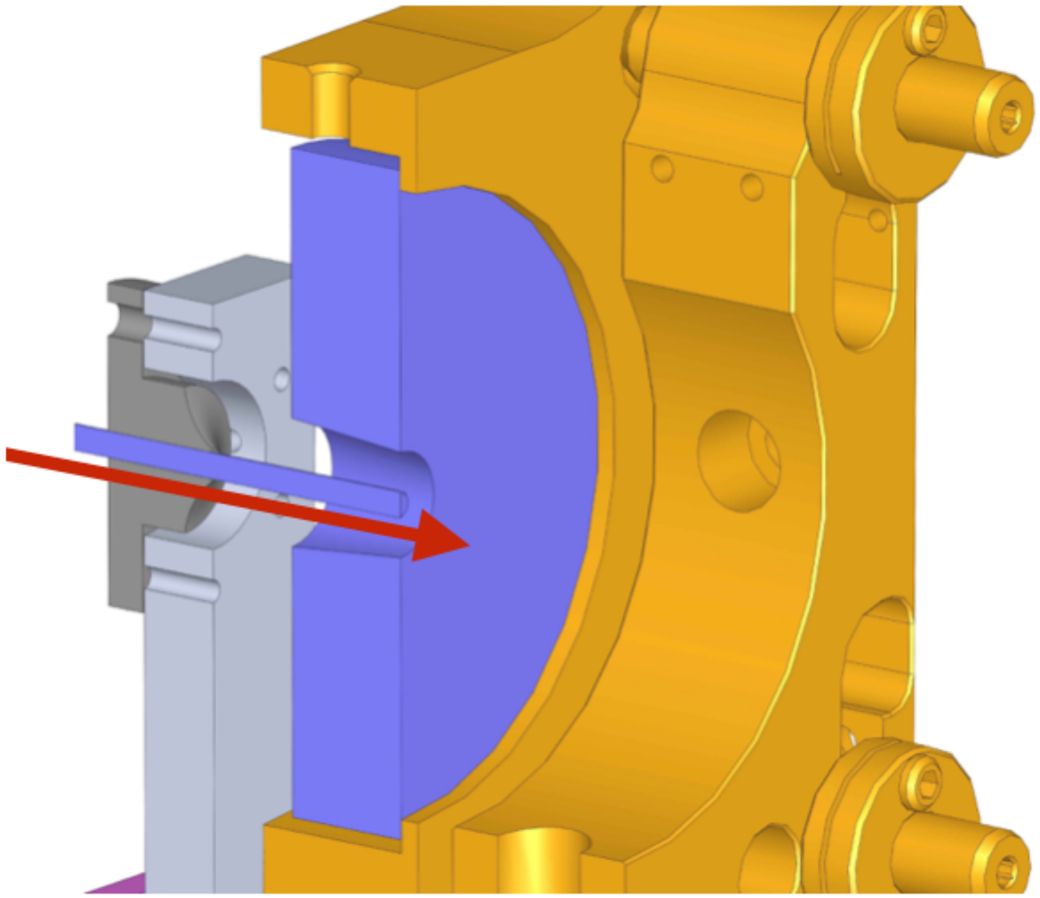


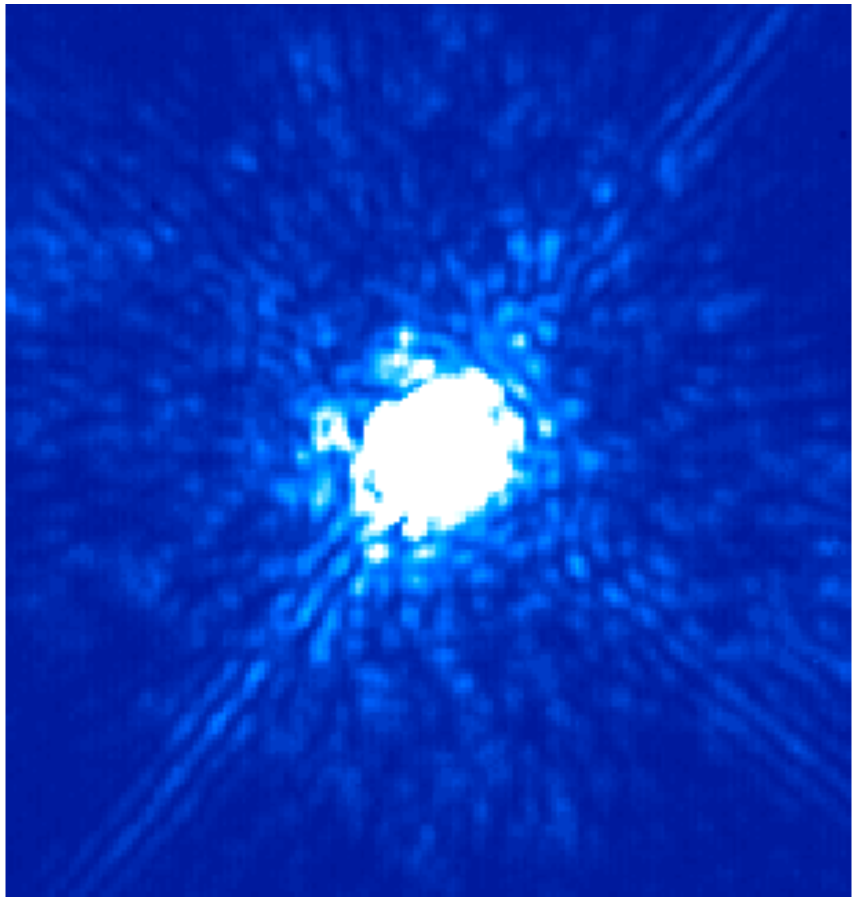


Serabyn et al. 2011 Applied Optics, 50, 5453.

As the inner mirror pistons, the speckles interfere with its broad diffraction pattern

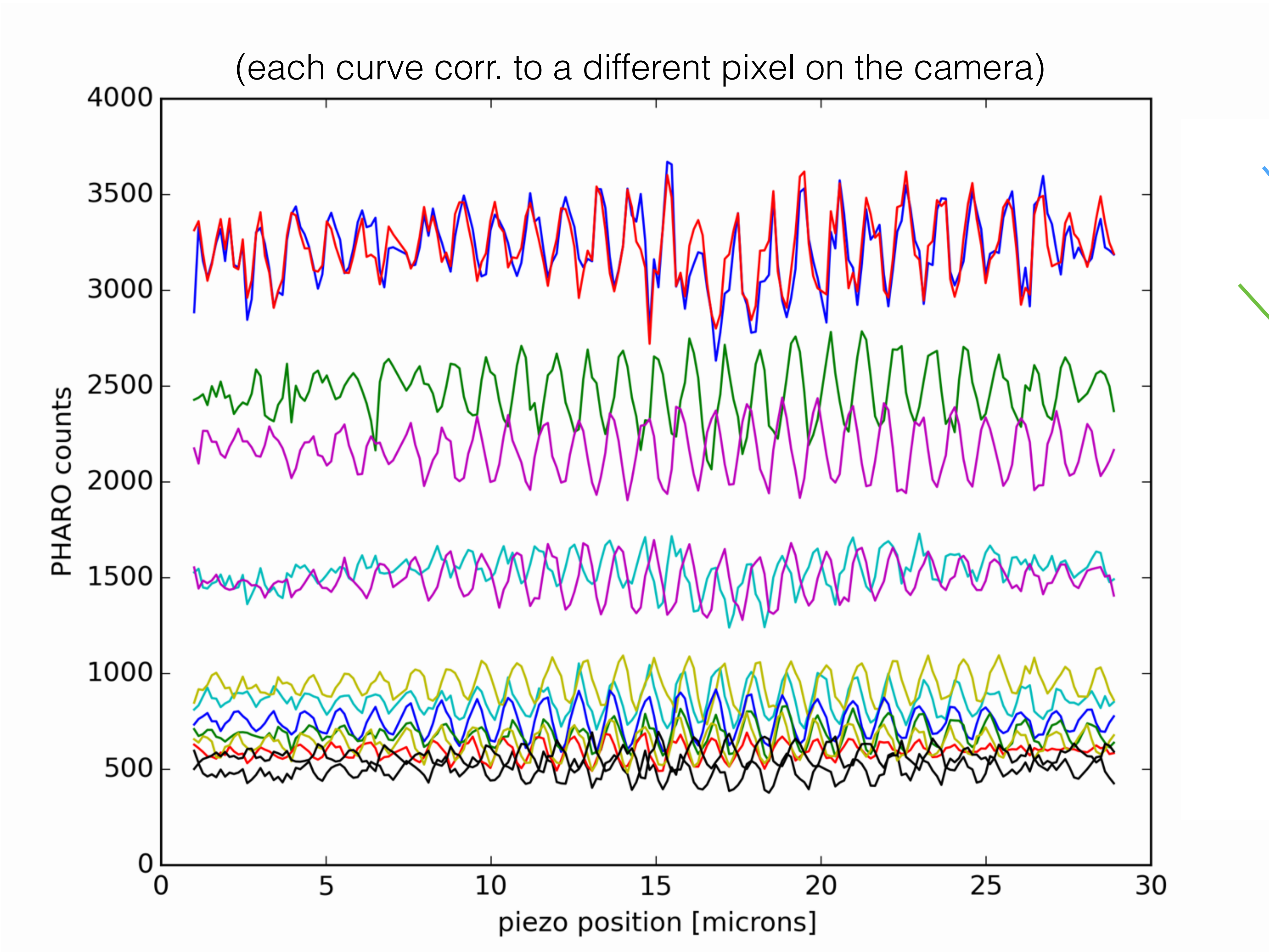
The intensity modulates in sinusoidal way

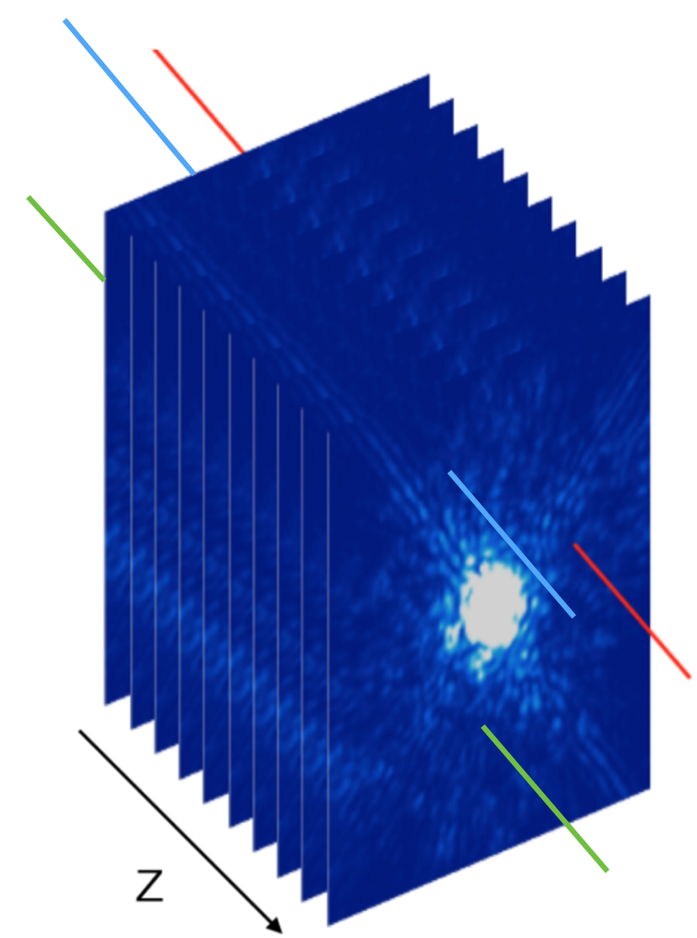




The *relative phase* between each sine wave corresponds to the *relative phases* of the speckles

Can use this to build a map of the *electric field* of the focal plane



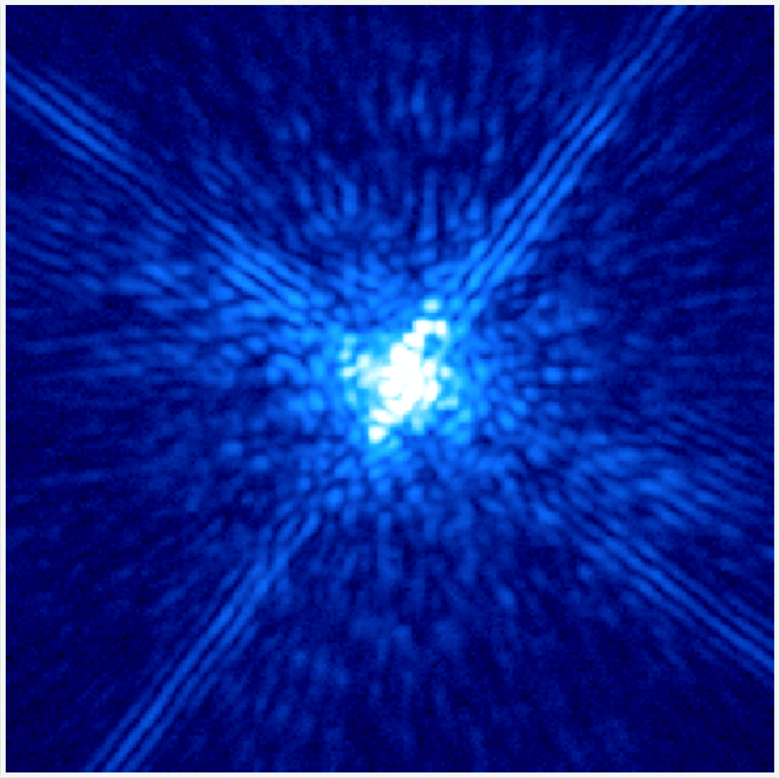


Bottom et al. submitted

Phase and visibility

Electric field of speckles

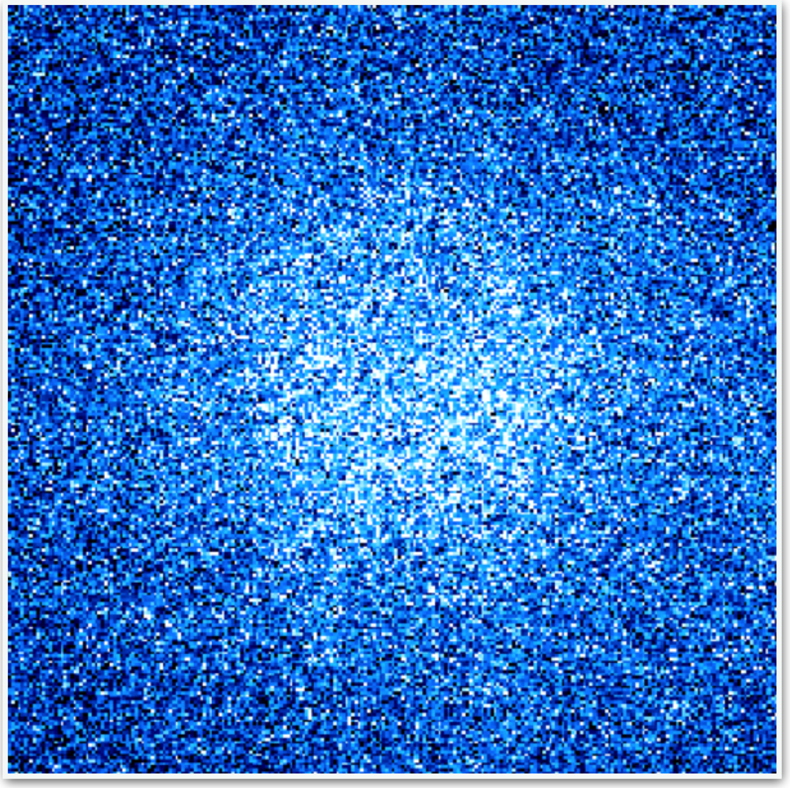
$$E_s(x,y) = a_s(x,y)e^{i\phi_s(x,y)}$$



Speckle Intensity = E_s^2

Electric field of inner mirror

$$E_r(x,y) = a_r(x,y)e^{i[\phi_r(x,y)-\delta(t)]}$$



Reference Intensity = E_r^2

$$I(x,y,t) = |E_s(x,y) + E_r(x,y)|^2$$

$$= a_s(x,y)^2 + a_r(x,y)^2 + 2a_s(x,y)a_r(x,y)\cos[\phi_s(x,y) - \phi_r(x,y) + \delta(t)]$$

$$= \boxed{I_s + I_r + 2\sqrt{I_s I_r}\cos[\phi_s(x,y) - \phi_r(x,y) + \delta(t)]}$$

Phase and visibility

$$I_s + I_r + 2\sqrt{I_s I_r}\cos[\phi_s(x,y) - \cancelto{0}{\phi_r}(x,y) + \delta(t)]$$

Letting ϕ_r =0, if the pistoning mirror phase is δ_j **= 0, λ/4, λ/2, 3λ/4**, you get:

$$I_1 = I_s + I_r + 2\sqrt{I_s I_r}\cos[\phi_s(x,y)]$$

$$I_2 = I_s + I_r - 2\sqrt{I_s I_r}\sin[\phi_s(x,y)]$$

$$I_3 = I_s + I_r - 2\sqrt{I_s I_r}\cos[\phi_s(x,y)]$$

$$I_4 = I_s + I_r + 2\sqrt{I_s I_r}\sin[\phi_s(x,y)]$$

Then you can solve for the ***phase*** and ***visibility***

$$\boxed{\phi_s(x,y) = \tan^{-1}\left[\frac{I_4 - I_2}{I_1 - I_3}\right]}$$

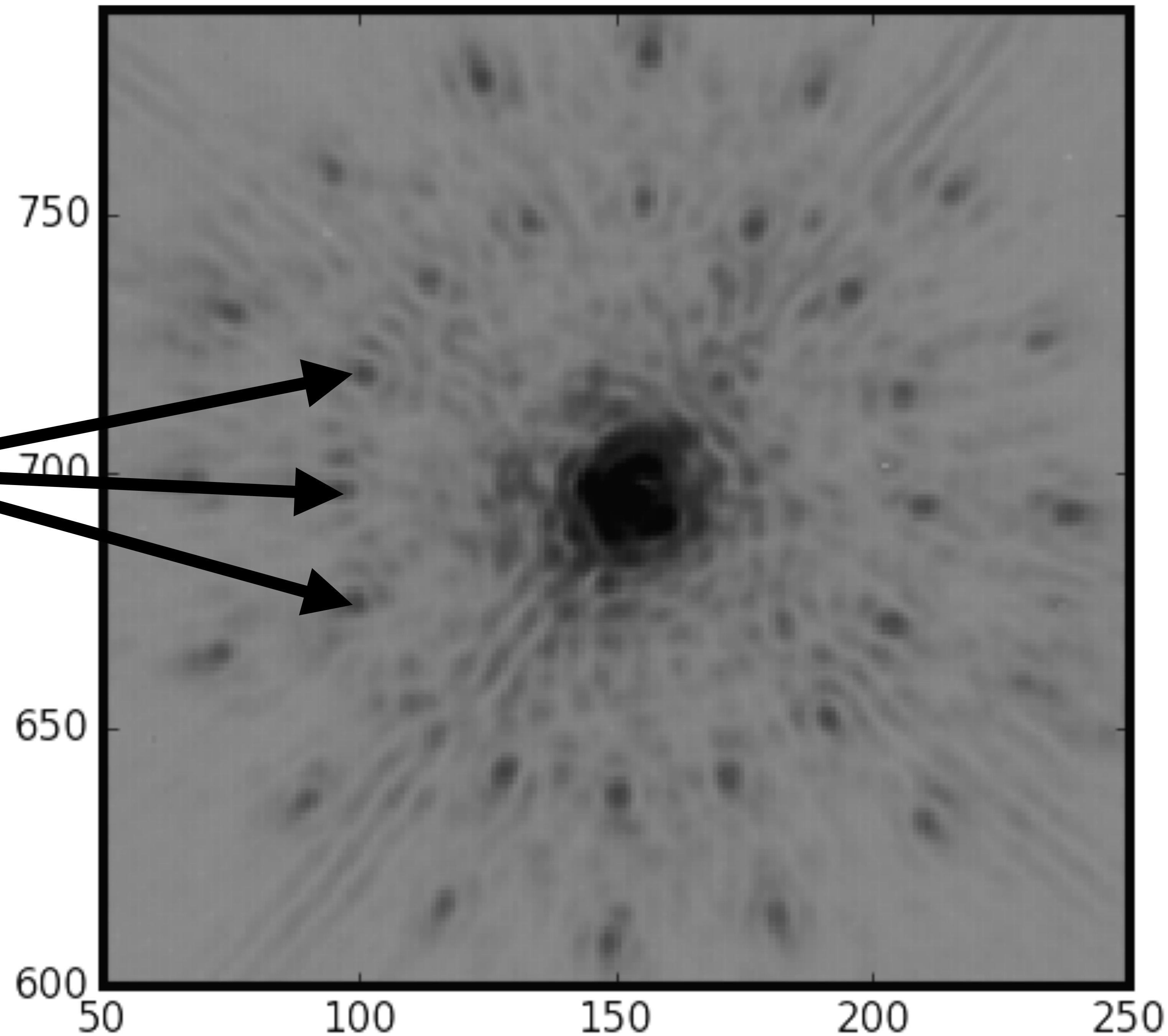
$$\boxed{\gamma(x,y) = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{(I_4 - I_2)^2 + (I_1 - I_3)^2}}{I_1 + I_2 + I_3 + I_4} = \frac{2\sqrt{I_s I_r}}{I_s + I_r}}$$

Bottom et al. submitted

Phase recovery

$$I \propto |E|^2 = |Ae^{\imath\phi}|^2$$

Spots are supposed to be zero phase

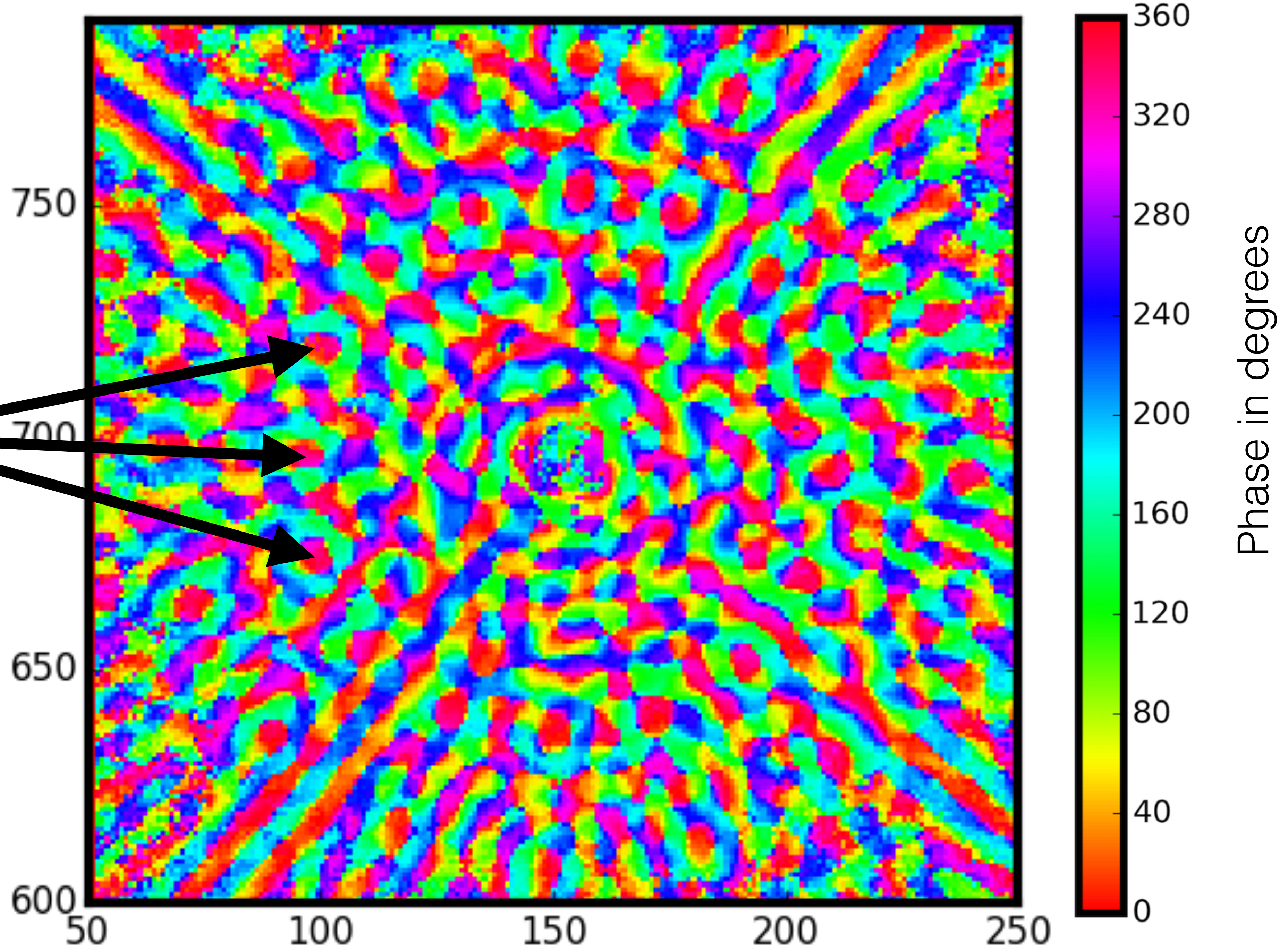


Bottom et al. submitted

Phase recovery!

$$I \propto |E|^2 = |Ae^{\imath\phi}|^2$$

Spots are supposed to be zero phase

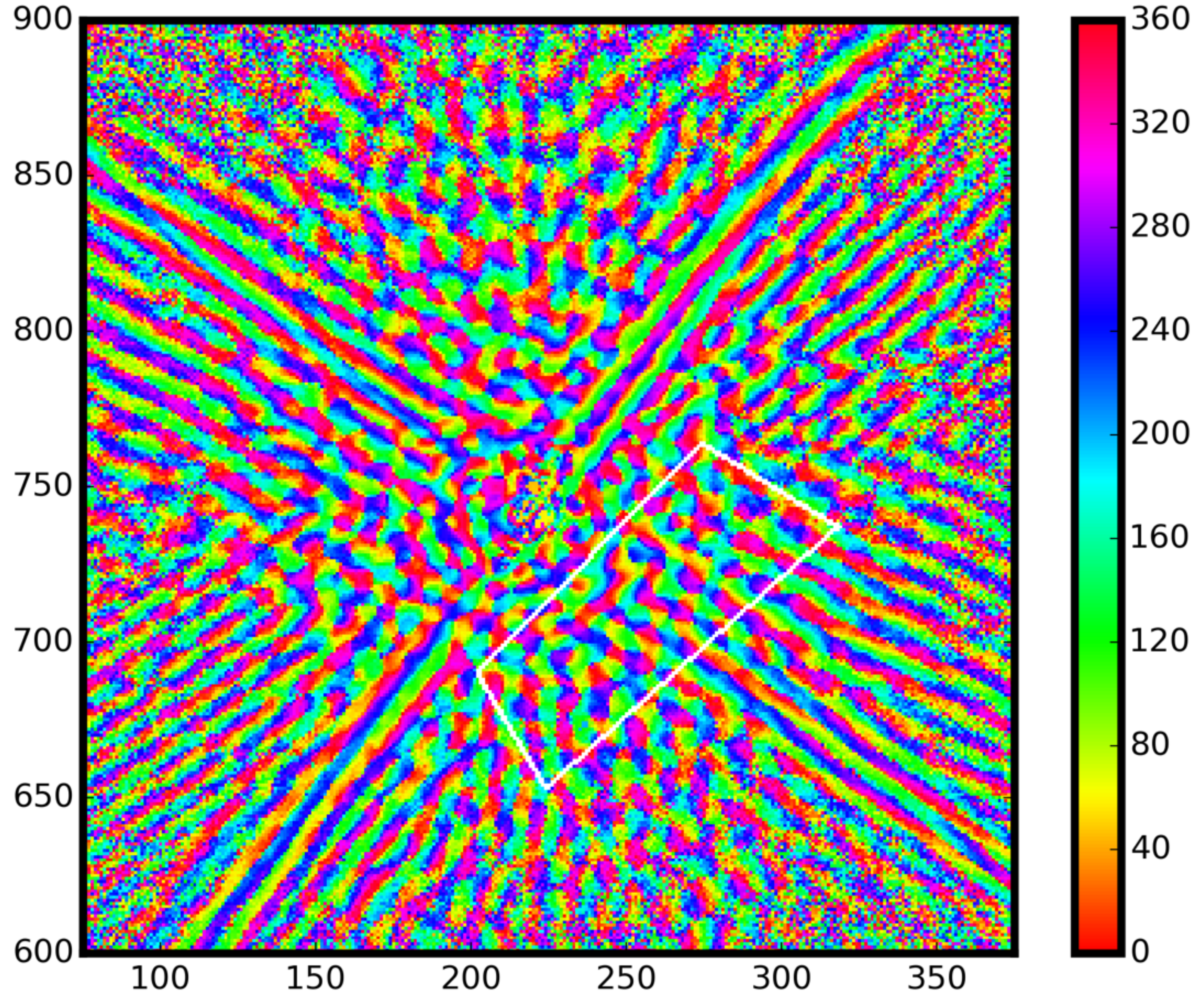


Bottom et al. submitted

Speckle electric field phase knowledge

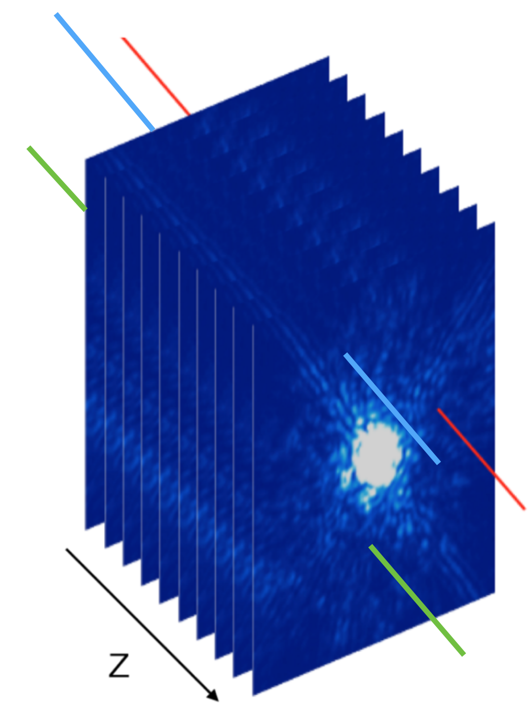
- With knowledge of phase, can put *opposite* phase on deformable mirror— this removes speckles!

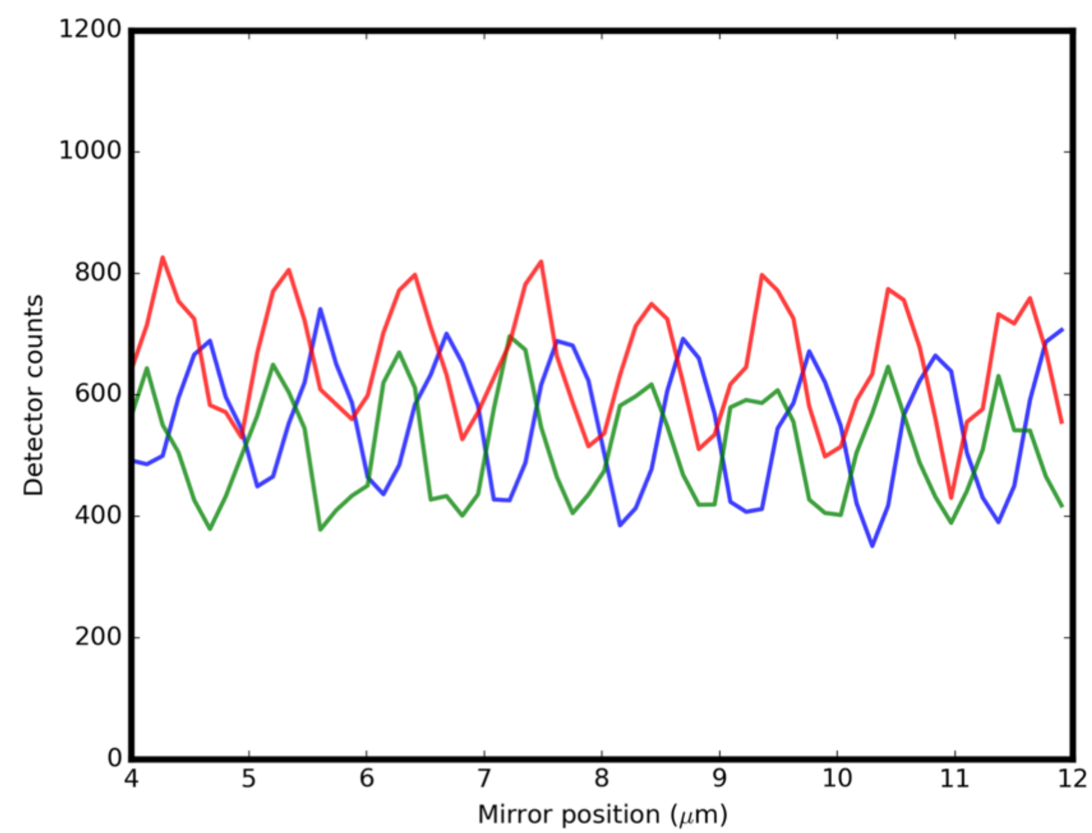
- (Note—slightly more complicated, must solve for phase gradient in image plane)



Coronagraphic phase-shifting interferometry

- New way of measuring and removing speckles in the focal plane
- Non-invasive during on-sky observing, can work passively
- **Planets will not modulate. A way of discriminating planets from speckles based on coherence properties of light**

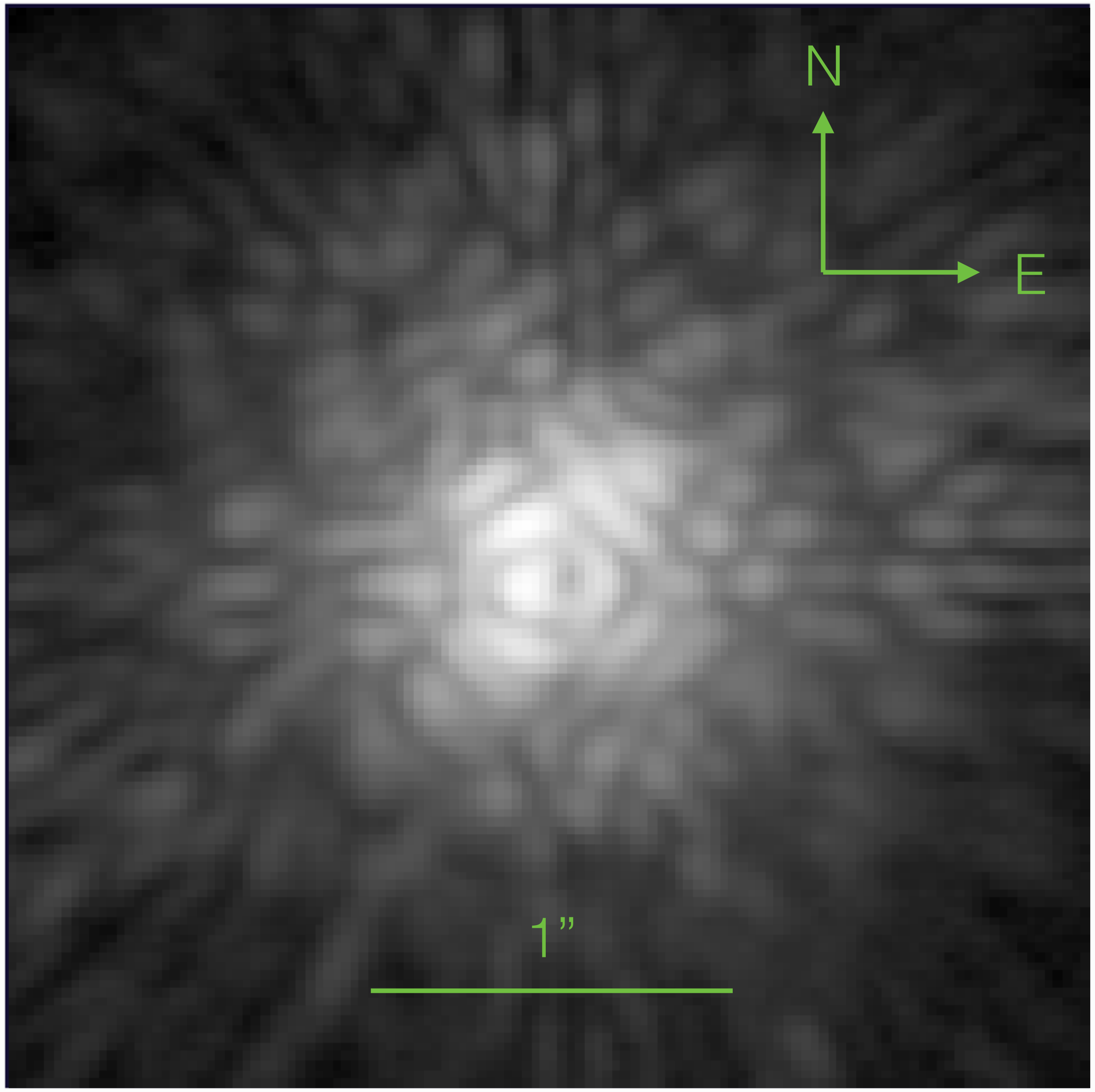




Bottom et al. in revision

Companion detection example: HD49197b

- Brown dwarf companion
- ~2000 times as faint as the central star
- 0.95” separation

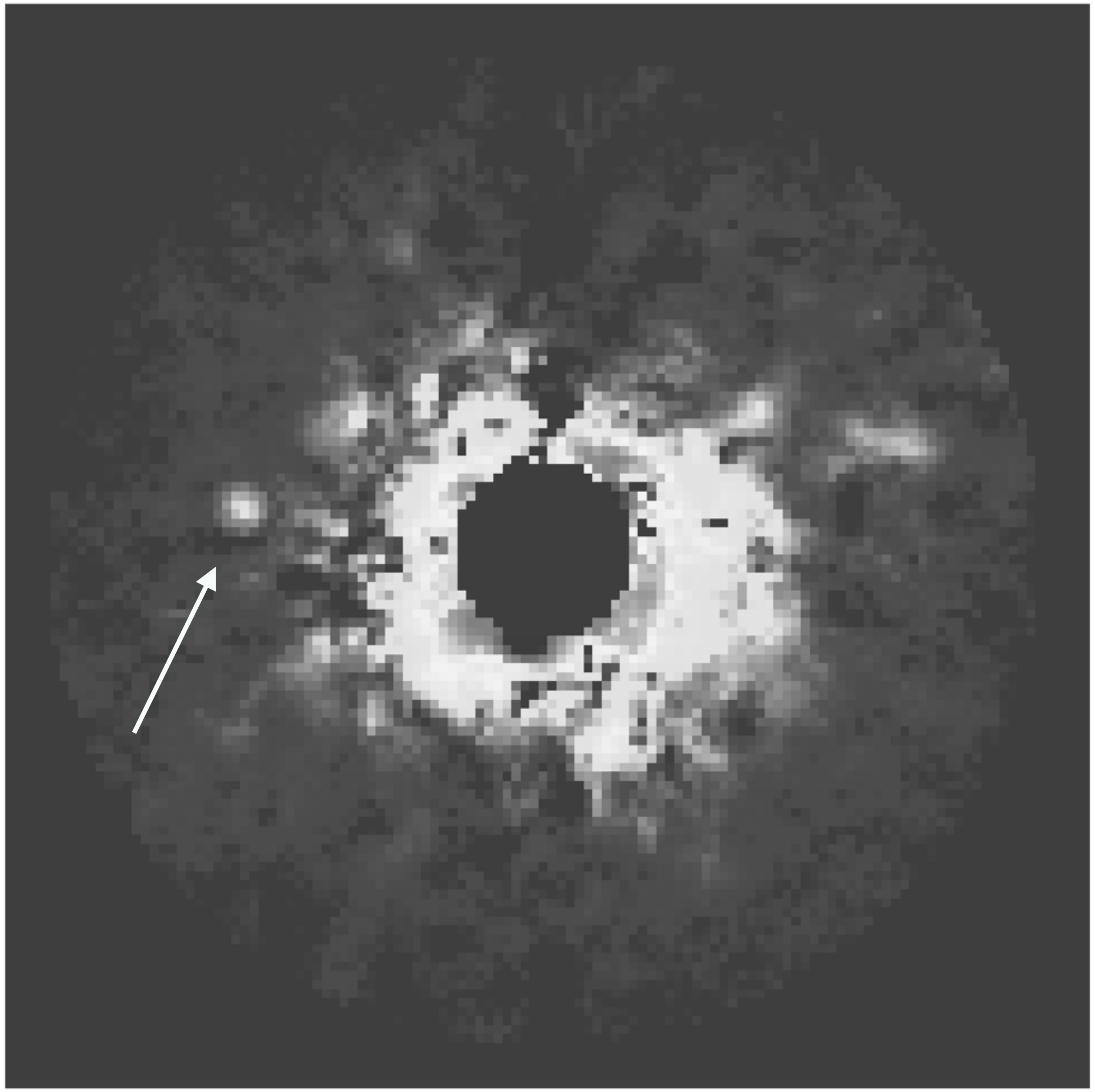


Mean of image frames

Bottom et al. in revision

Coronagraphic phase-shifting interferometry

- Uses *same data frames* as previous image combined with pistoning mirror position information
- Clean detection, SNR improvement
- *No need for reference star*
- **First detection of a substellar companion using coherence** (as far as I know)

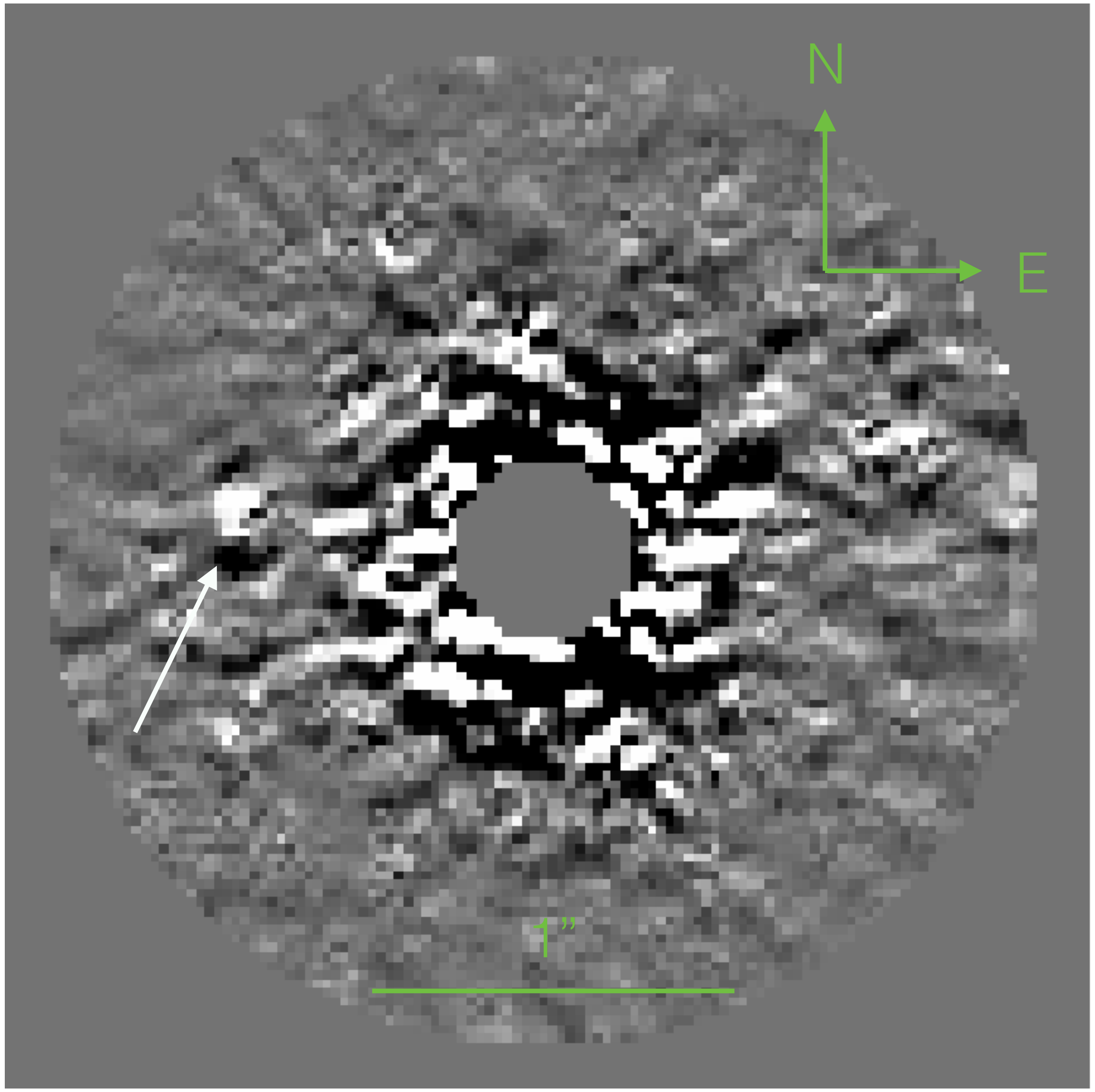


Using coherence

Bottom et al. in revision

Coronagraphic phase-shifting interferometry

- Uses *same data frames* as previous image combined with pistoning mirror position information
- Clean detection, SNR improvement
- *No need for reference star*
- **First detection of a substellar companion using coherence** (as far as I know)



Using coherent PCA

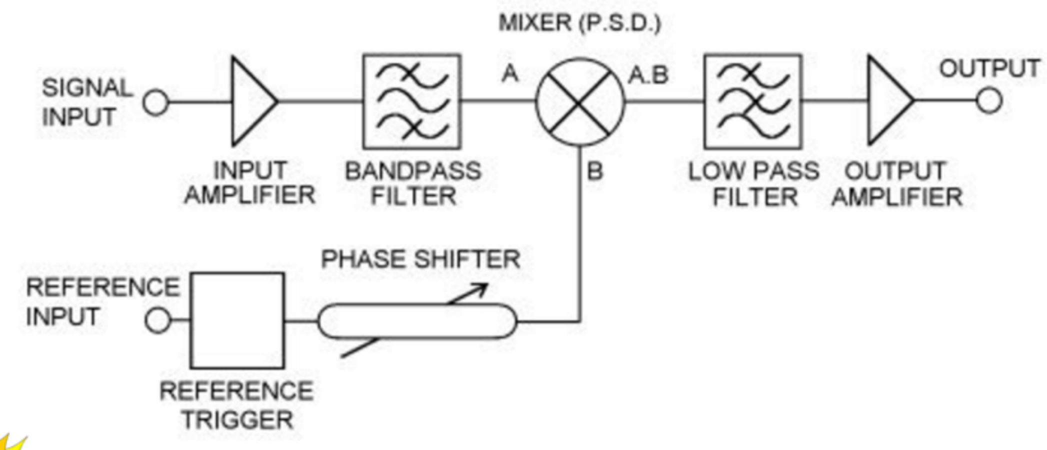
Bottom et al. in revision (MNRAS)

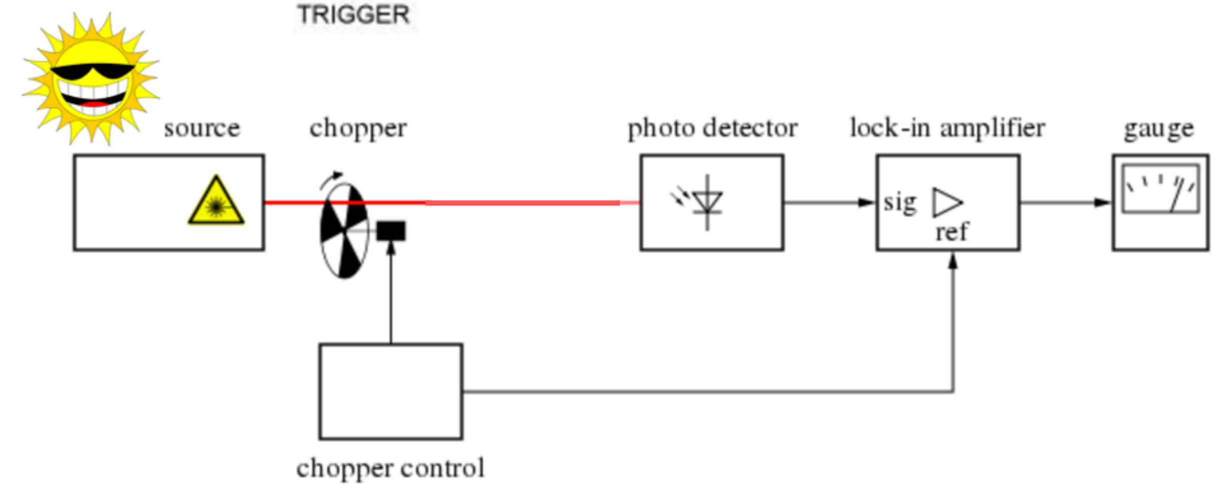
Summary

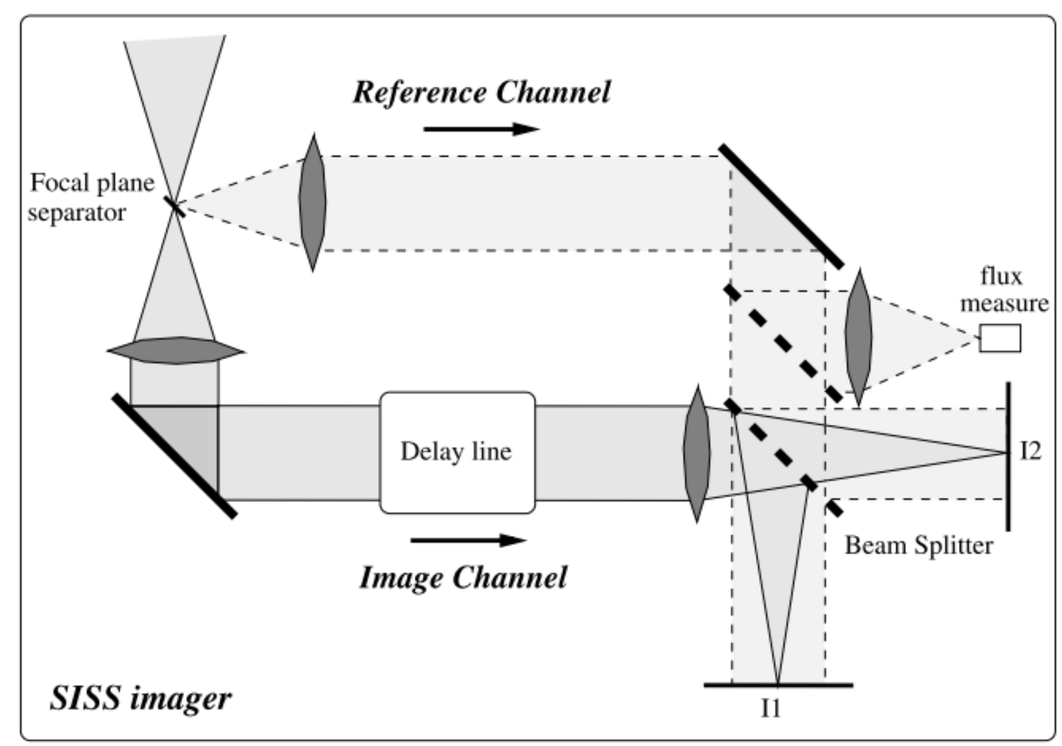
- Advantages
  - Huge strokes on interferometer easy to get. No issues of crosstalk, stroke limits, linearity approximations, etc. Leads to easy phases and visibilities.
  - Uses “waste” light to get meaningful information.
  - Simple analytic formulation for getting speckle phases and visibilities—minimal system model.
  - Robust companion detection, worked the first time.
- Disadvantages
  - Need to measure and remove phase gradients in focal plane for efficient speckle suppression
  - Two focal plane coronagraphs and an interferometer in series? Really??

Discussion ideas

- The best methods of low signal, high background signal detection involve actively modulating the signal (lock-in amplification, Dicke switches, etc)—>phase sensitive detection
    - In exoplanet imaging, the only way it seems you can do this is using ADI/roll deconvolution or polarization modulation. In the latter case, you lose a factor of ~100 or more since the planet is (usually) not polarized (see S. Wiktorowicz's work)
    - Is there another way?
- Alternatively, you can actively modulate the noise (not as good)
    - Synchronous interferometric speckle subtraction (SISS) (Guyon)
    - "spectral deconvolution"—sort of
    - EFC-type/active DM implementations
    - this work



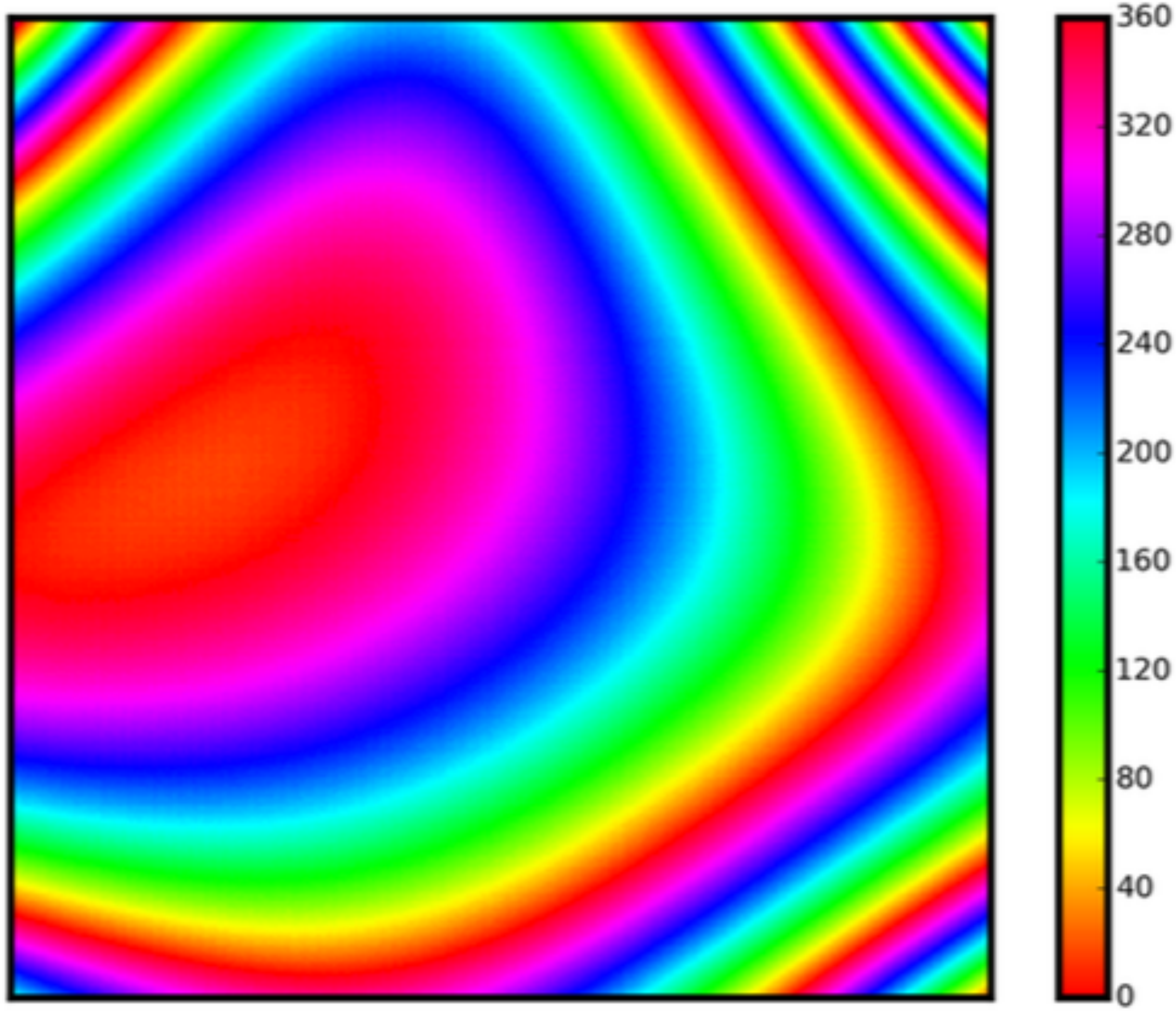




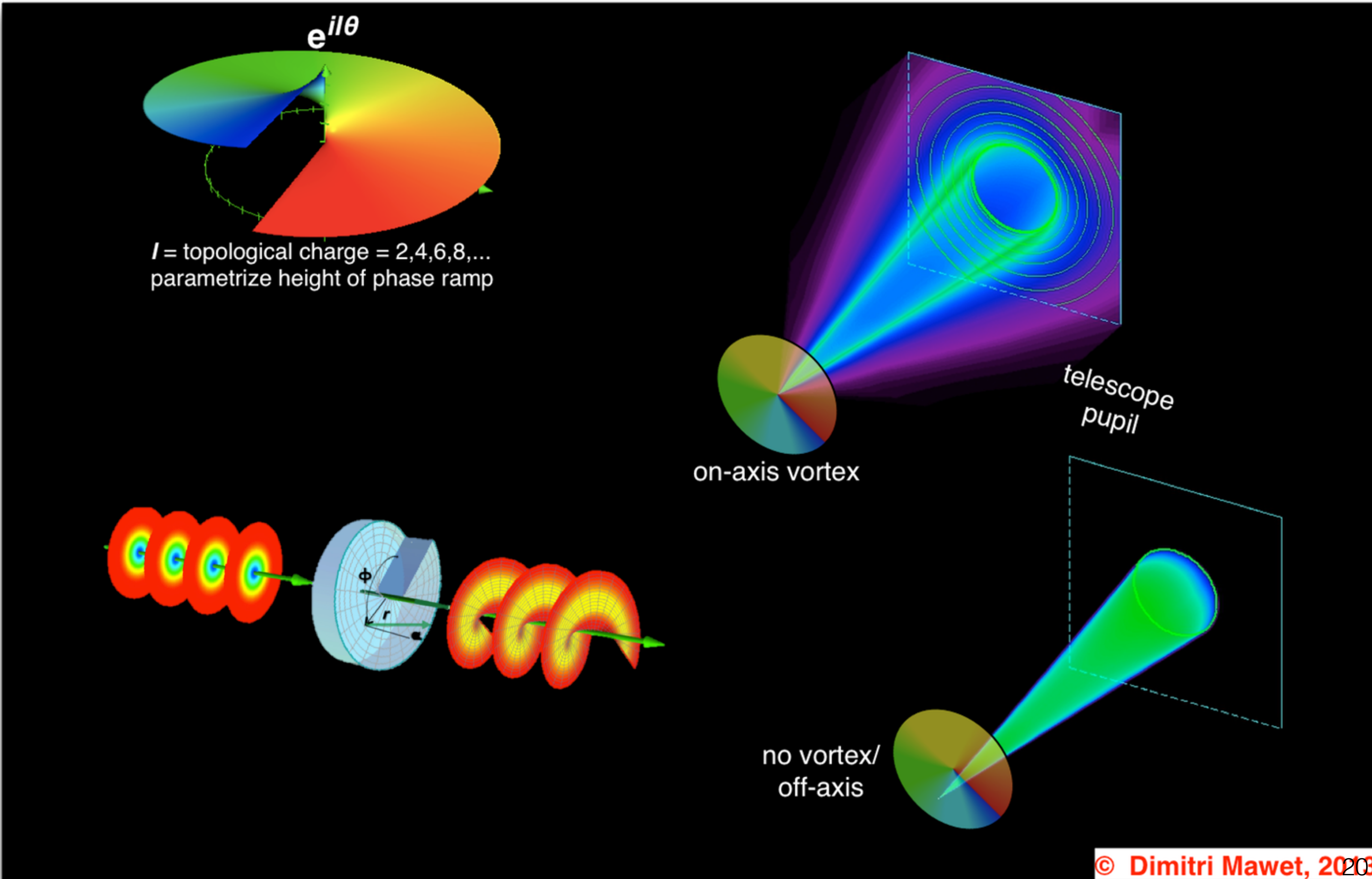
Guyon et al. 2004

Guyon et al. 2004

The phase gradient I was talking about



The Vortex Coronagraph



$$\gamma = \frac{2\sqrt{(I_4 - I_2)^2 + (I_3 - I_1)^2}}{I_1 + I_2 + I_3 + I_4}$$

$$\langle I \rangle = \frac{I_1 + I_2 + I_3 + I_4}{4}$$

$$\langle I \rangle = I_s + cI_{rn} + I_p$$

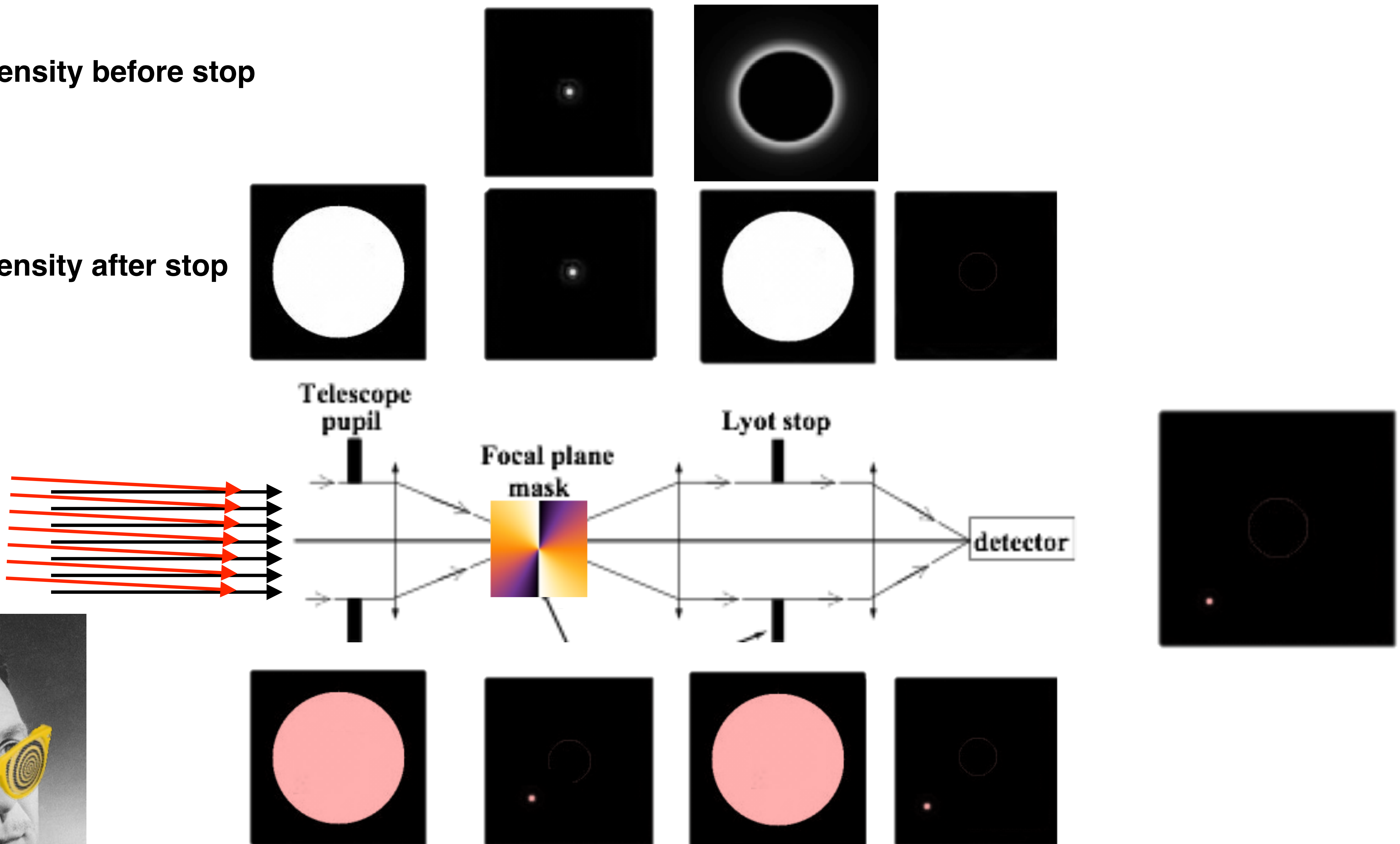
$$\gamma = \frac{2\sqrt{cI_{rn}I_s}}{cI_{rn} + I_s + I_p}$$

$$\Rightarrow I_p = \langle I \rangle - cI_{rn} - \frac{\gamma^2 \langle I \rangle^2}{4cI_{rn}}$$

The Vortex Coronagraph

Starlight intensity before stop

Starlight intensity after stop



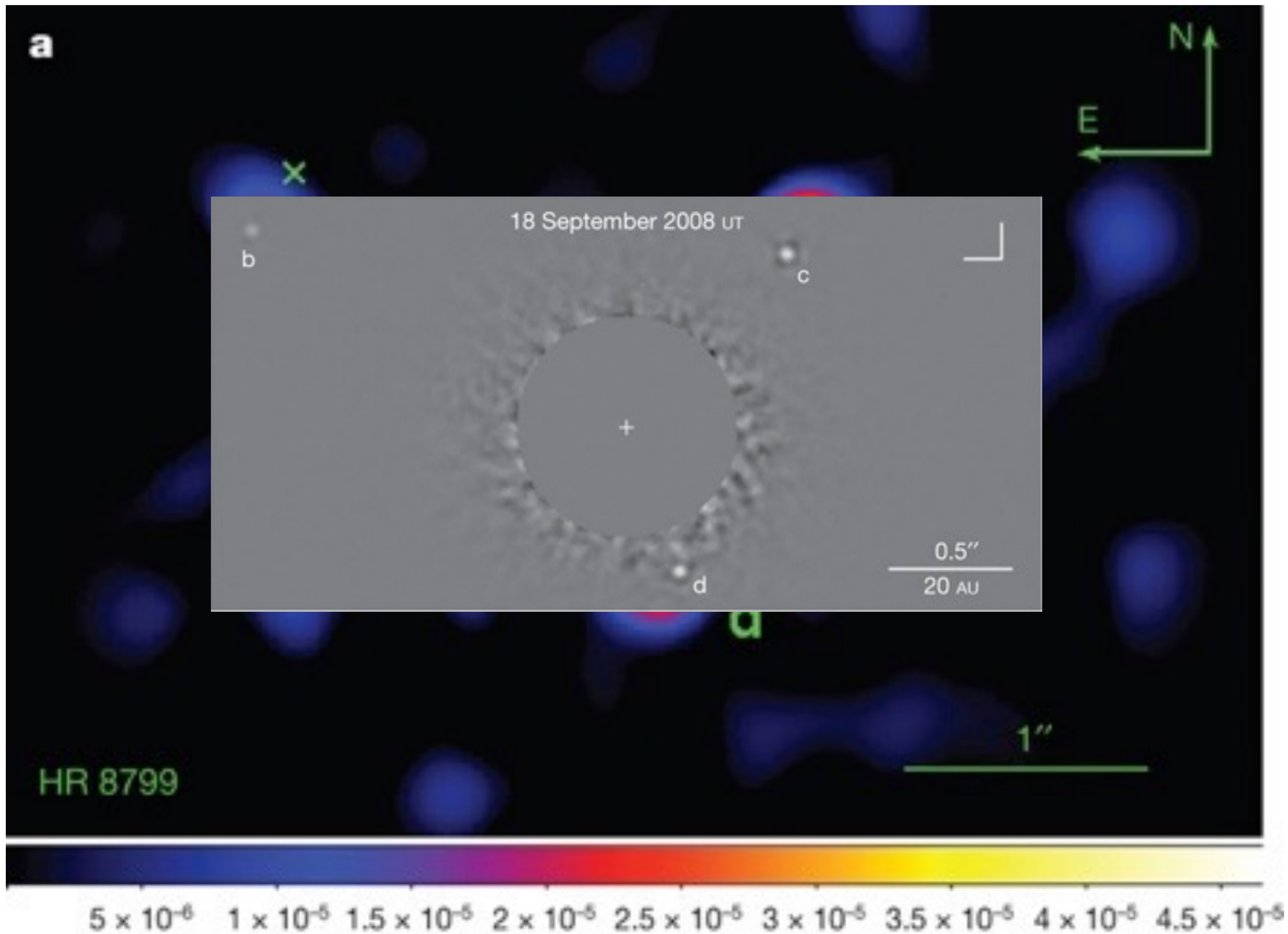
Planetlight intensity

www.lyot.org

Mawet et al. 2005

Planet imaging example

1.5 M aperture!!!!!

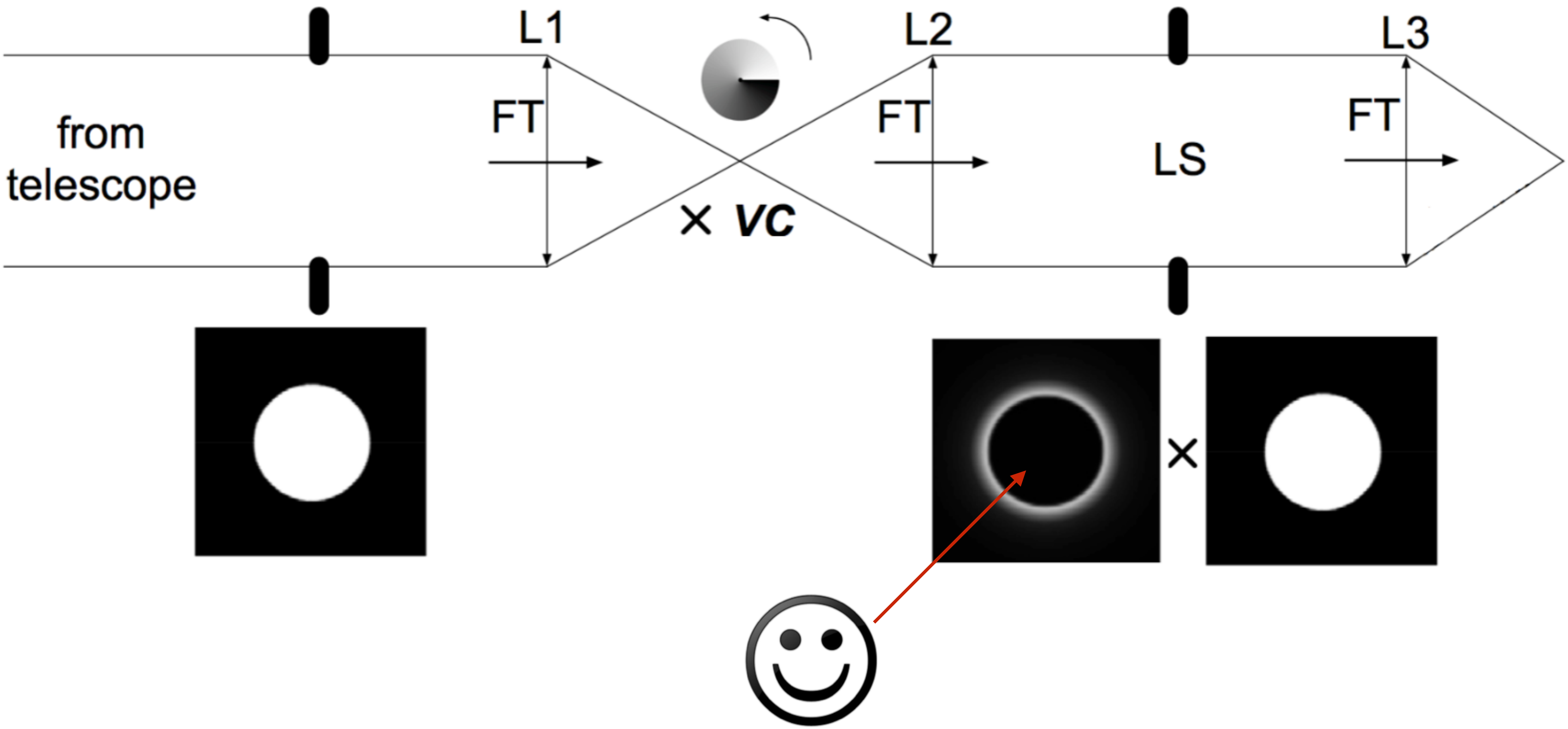


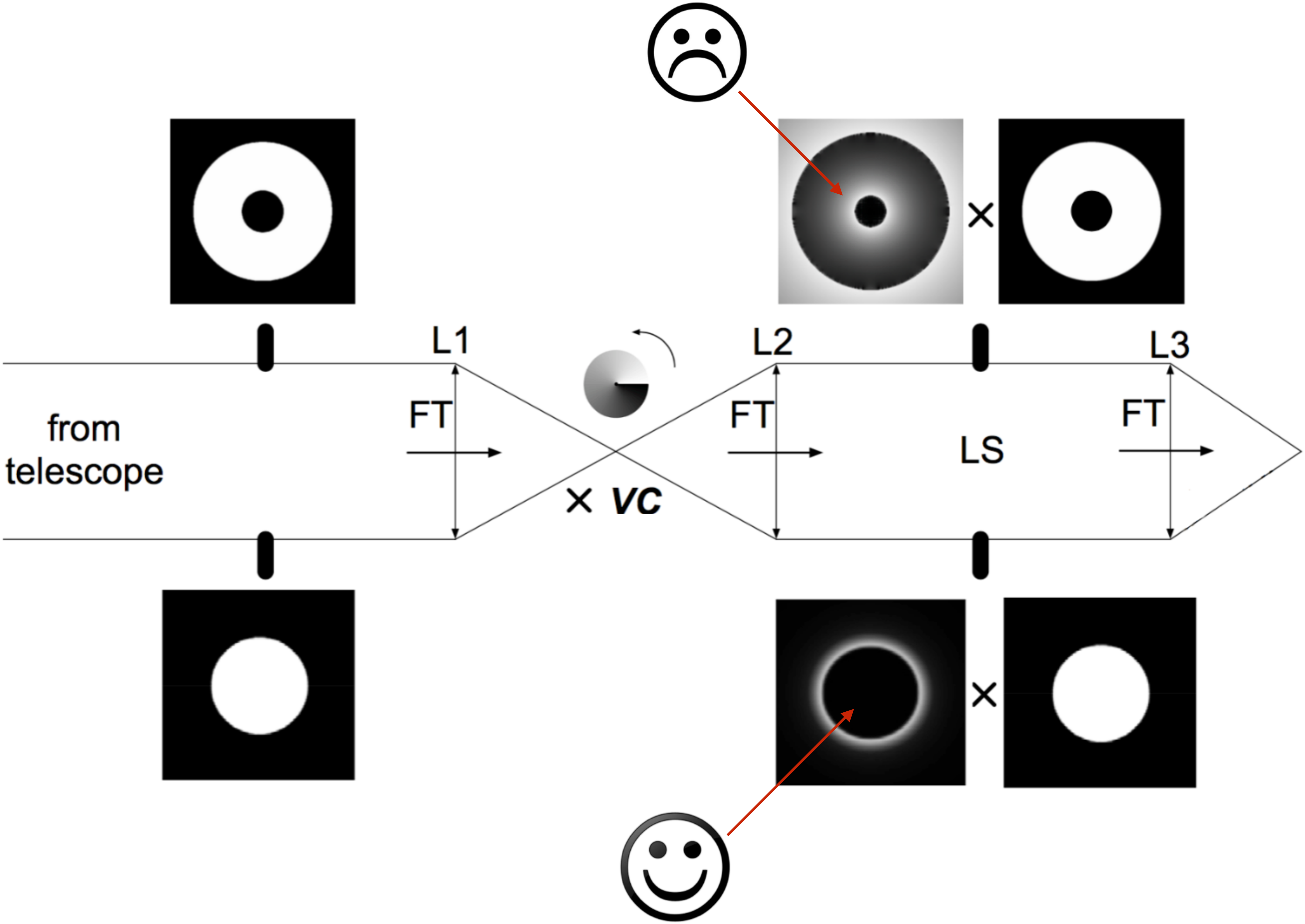
Direct imaging of multiple planets orbiting the star HR 8799

C. Marois, et al. *Science*, 21 November 2008

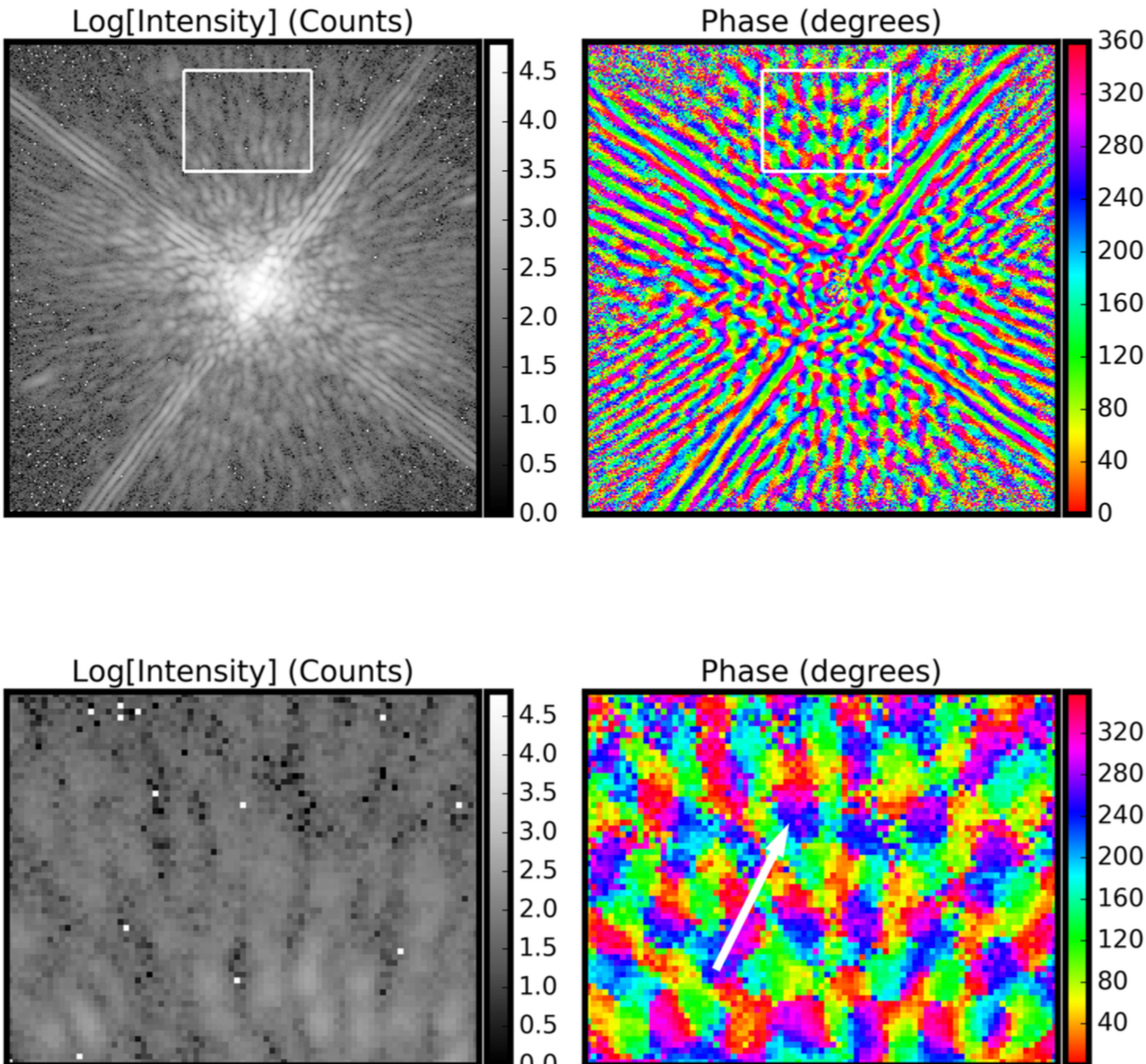
An image of an exoplanet separated by two diffraction beamwidths from the star

E. Serabyn, D. Mawet, R Burruss. *Nature* **464**, 1018–1020 (15 April 2010)


L1
L2
L3
from
telescope
FT
FT
FT
LS
× VC
×



×
L1
L2
L3
from
telescope
FT
FT
FT
LS
× VC
×


Log[Intensity] (Counts)
Phase (degrees)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
360
320
280
240
200
160
120
80
40
0
Log[Intensity] (Counts)
Phase (degrees)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
320
280
240
200
160
120
80
40