Large Synoptic Survey Telescope

Primer on Wavefronts & Aberrations: the LSST optical PSF

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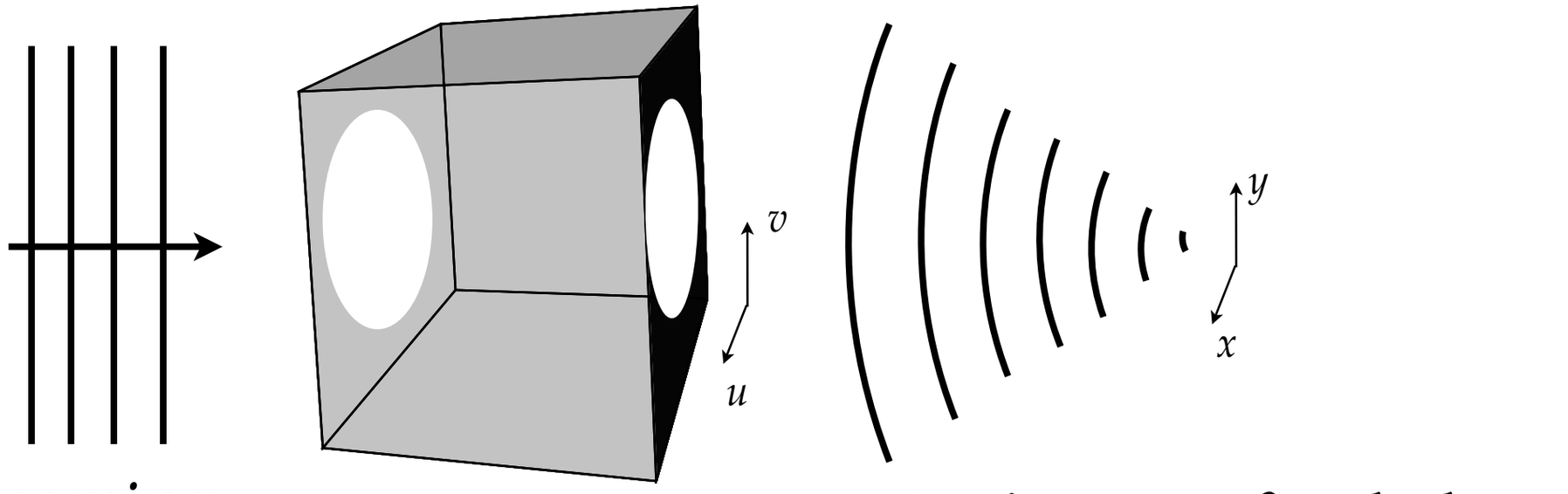
Primer on Fourier Optics

a Telescope:

converts Angle on the Sky to Position on the Focal Plane

Idealized Telescope



incoming plane wave

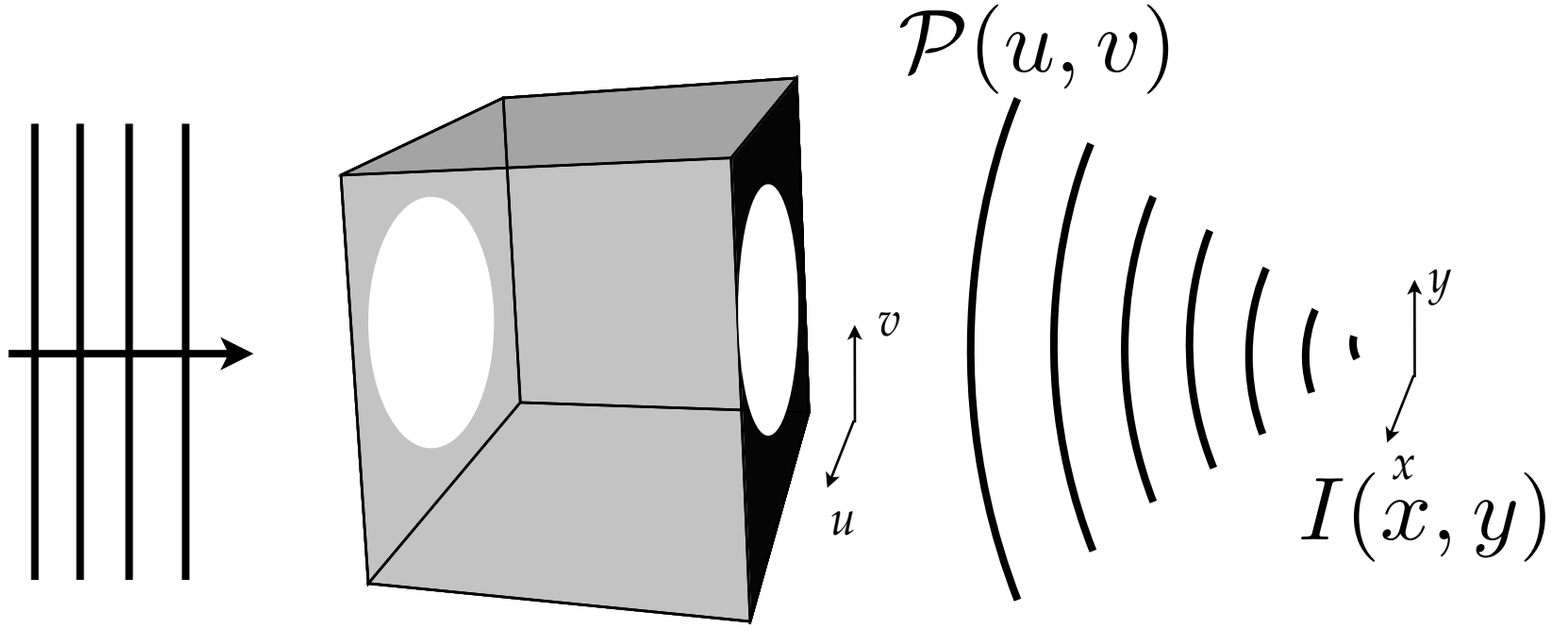
entrance, exit pupils

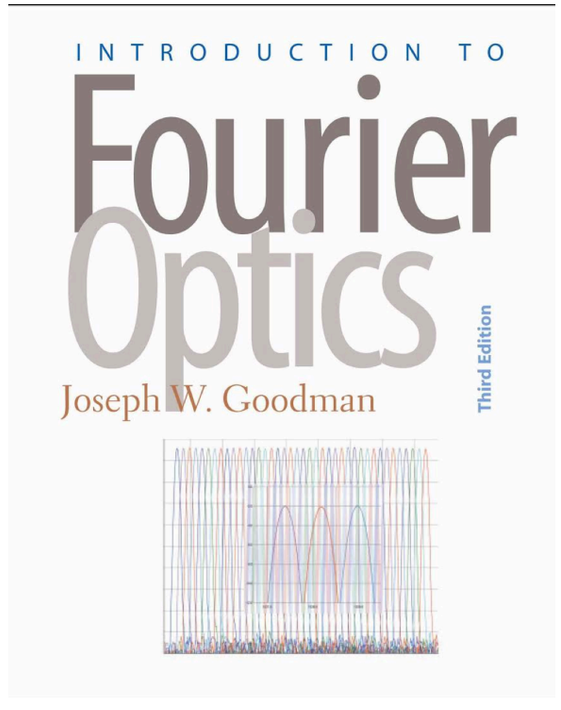
outgoing converging spherical wave

focal plane

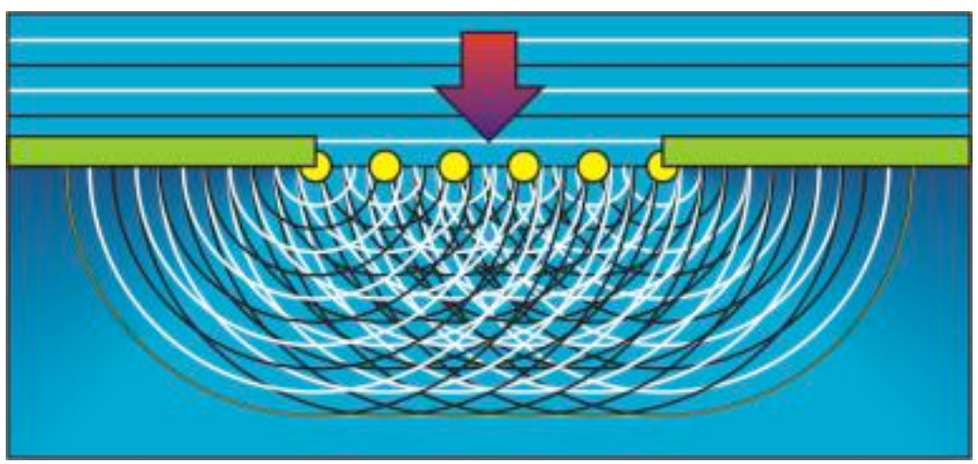
Angle & Position are Conjugate Variables

Fresnel Diffraction





$$I(x,y) = \left| \frac{1}{\lambda z} \int \left\{ \mathcal{P}(u,v) e^{i\frac{k}{2z}(u^2+v^2)} \right\} e^{-i\frac{2\pi}{\lambda z}(xu+yv)} du dv \right|^2$$



Huygens Principle

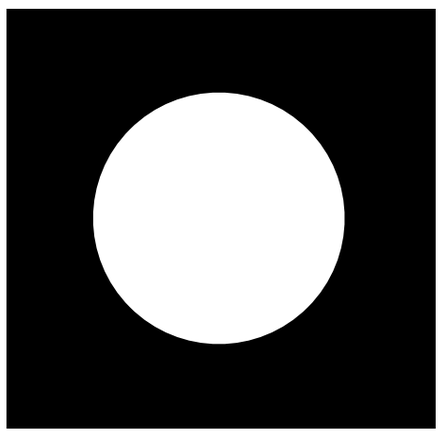
Fraunhofer Diffraction

Fresnel ⇨ Fraunhofer

- far field
- spherically converging beam

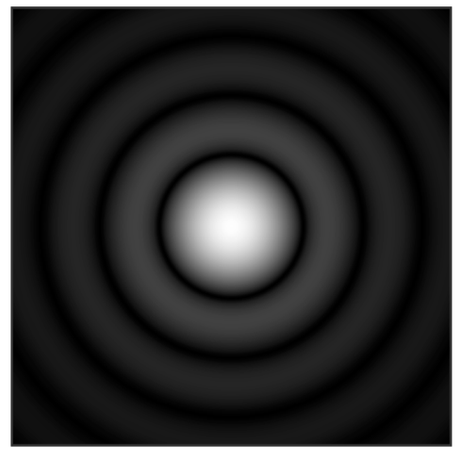
$$I(x,y) = \left| \frac{1}{\lambda z} \int \mathcal{P}(u,v) e^{-i\frac{2\pi}{\lambda z}(xu+yv)} du dv \right|^2$$

note that this is a Fourier Transform



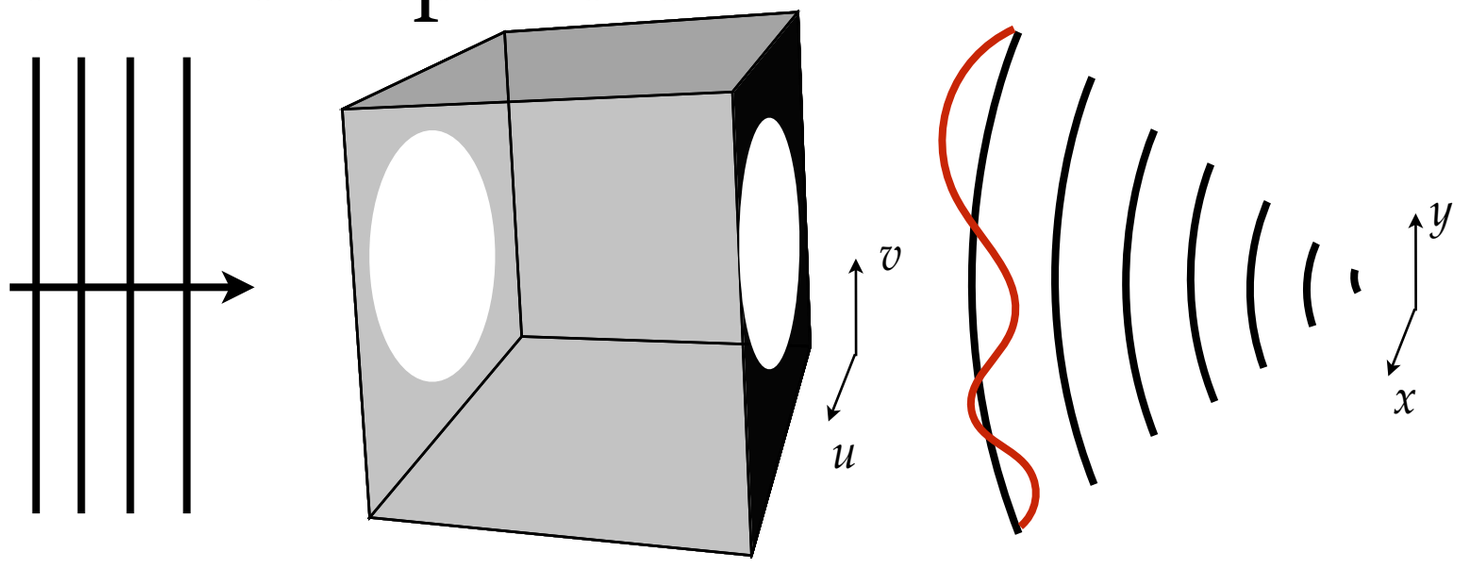
$\mathcal{P}(u,v)$ is the Pupil Function

Circular pupil and perfectly converging beam gives the Airy pattern

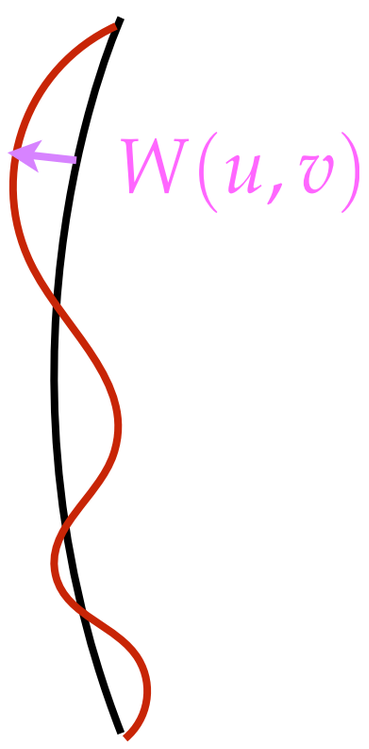


Wavefront & Zernike expansion

Imperfect optical system?



$$I(x,y) = \left| \frac{1}{\lambda z} \int P(u,v) e^{i2\pi W(u,v)/\lambda} e^{-i\frac{2\pi}{\lambda z}(xu+yv)} du dv \right|^2$$



Wavefront or Aberration Function

$$W(u,v) = \sum a_i Z_i(\rho,\theta)$$

Zernike expansion

Index	Name	Zernike Polynomial
2	Tilt X	$2\rho\cos\theta$
3	Tilt Y	$2\rho\sin\theta$
4	Focus	$\sqrt{3}(2\rho^2-1)$
5	Astigmatism Y	$\sqrt{6}\rho^2\sin 2\theta$
6	Astigmatism X	$\sqrt{6}\rho^2\cos 2\theta$
7	Coma Y	$\sqrt{8}(3\rho^3-2\rho)\sin\theta$
8	Coma X	$\sqrt{8}(3\rho^3-2\rho)\cos\theta$
9	Trefoil Y	$\sqrt{8}\rho^3\sin 3\theta$
10	Trefoil X	$\sqrt{8}\rho^3\cos 3\theta$
11	Spherical	$\sqrt{5}(6\rho^4-6\rho^2+1)$

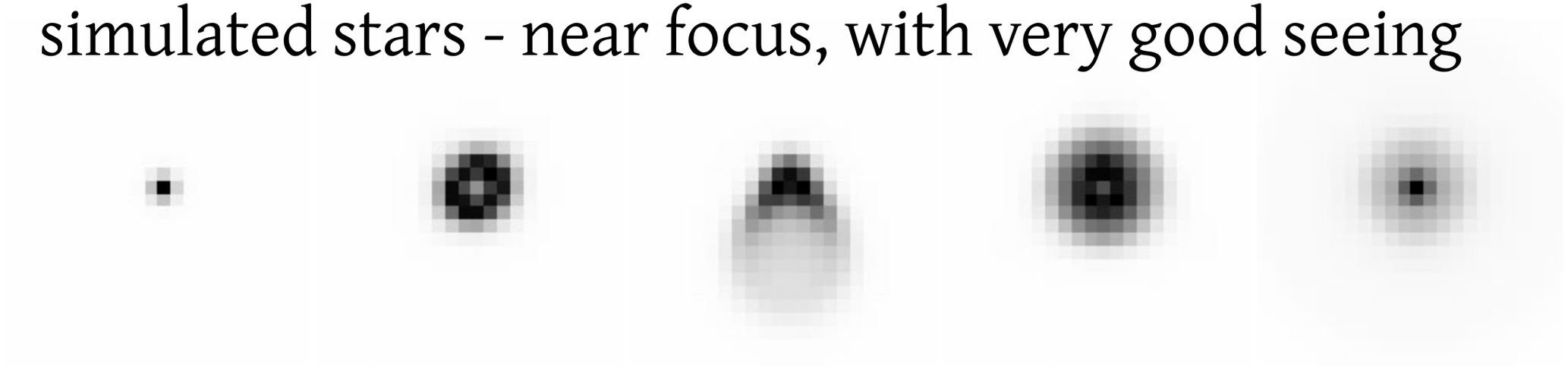
Gallery of Aberrations

simulated stars - near focus, with very good seeing

Q1: Identify Astigmatism, Coma, Trefoil, Spherical

Gallery of Aberrations

simulated stars - near focus, with very good seeing



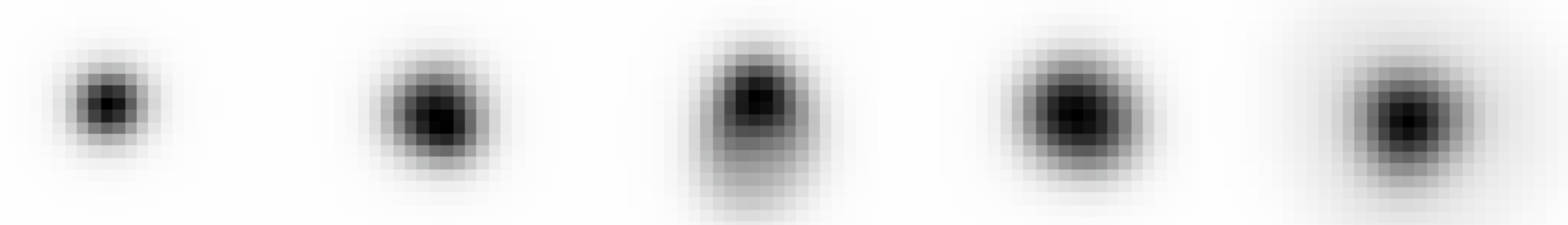
nominal | 2λ Astigmatism | 2λ Coma | 2λ Trefoil | 2λ Spherical

simulated stars - 1.5mm out of focus, with very good seeing

nominal | 2λ Astigmatism | 2λ Coma | 2λ Trefoil | 2λ Spherical

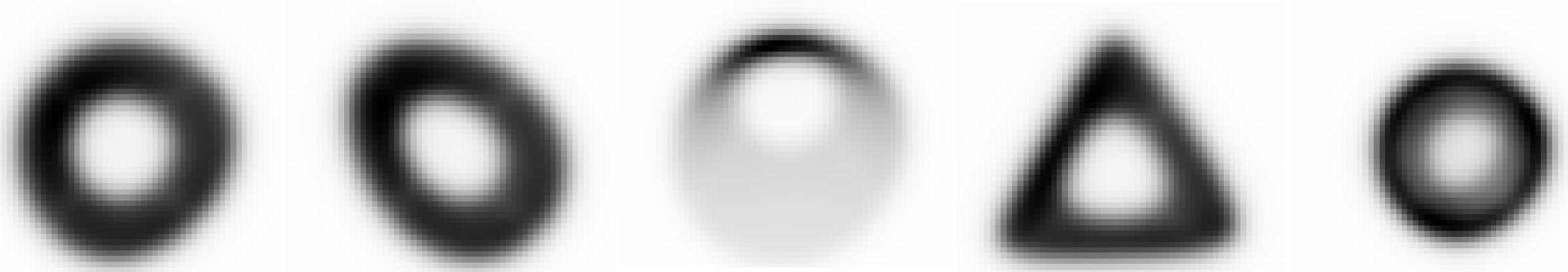
Gallery of Aberrations

simulated stars - near focus, with typical seeing



nominal | 2λ Astigmatism | 2λ Coma | 2λ Trefoil | 2λ Spherical

simulated stars - 1.5mm out of focus, with typical seeing



nominal | 2λ Astigmatism | 2λ Coma | 2λ Trefoil | 2λ Spherical

Donuts

PSF Contributions

$$I(x,y) = \sum_{t_i} \left| \mathcal{F}\left\{ P(u,v) e^{i2\pi W_i(u,v)/\lambda} \right\} \right|^2 \otimes \mathrm{CCD}(x,y|x',y')$$

$$W(u,v) = W_{\mathrm{optics}(u,v)} + W_{\mathrm{atmos.}(u,v)}$$

approximate as:

$$I(x,y) = \left| \mathcal{F}\left\{ P(u,v) e^{i2\pi W_{\mathrm{optics}}(u,v)/\lambda} \right\} \right|^2 \otimes \mathrm{Seeing} \otimes \mathrm{CCD}$$

LSST FWHM Requirements: 0.25” 0.6” 0.3”

Sources of Ellipticity: may be roughly equal parts optics & seeing

Q2: Can you identify any violations of the assumptions for PSF made here? List as many as you can.

Exercises: (pick one)

E1) Use the WaveToImage code to explore the functional dependence of PSF ellipticity on Wavefront aberrations. Can you find: $e = F(z_i)$?

E2) Use the Zemax Wavefront pickles to calculate the PSF ellipticity vs. Focal Plane position for LSST.

E3) Derive the functional dependence of PSF moments on aberrations.

E4)

Wavefront Research Topics

PSF Estimation from Optical Wavefronts

PSF usually measured in Stars
and *interpolated* to location of Galaxies

instead Estimate PSF from knowledge of Optical system
advantages:

- requires far fewer free parameters
- uses knowledge of system behavior
- potential to improve quality of PSF estimates

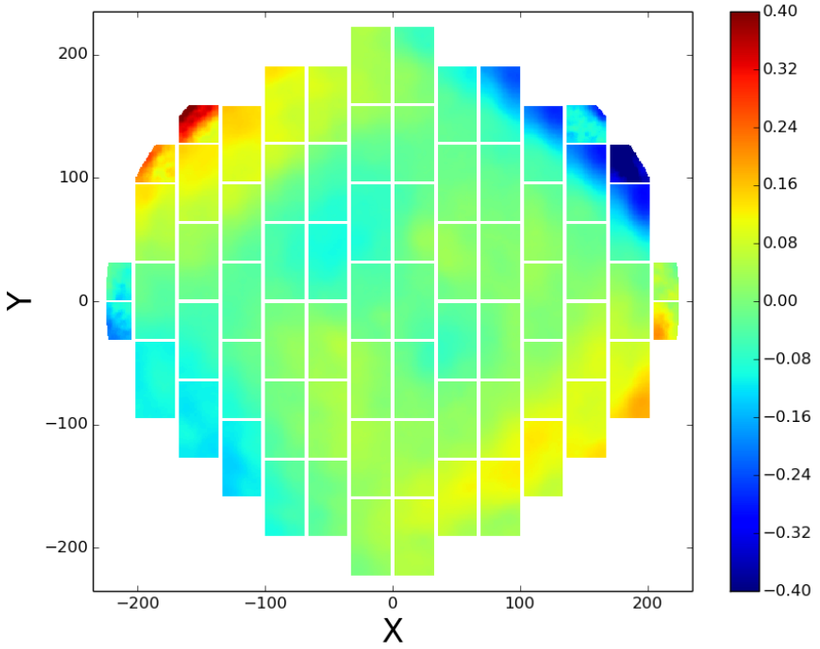
Wavefront PSF model:

- measure optical wavefront at all Focal Plane locations
- parametrize image to image changes in wavefront in terms of a few physically motivated parameters
- fit Star's FWHM and Ellipticity to Wavefront PSF model

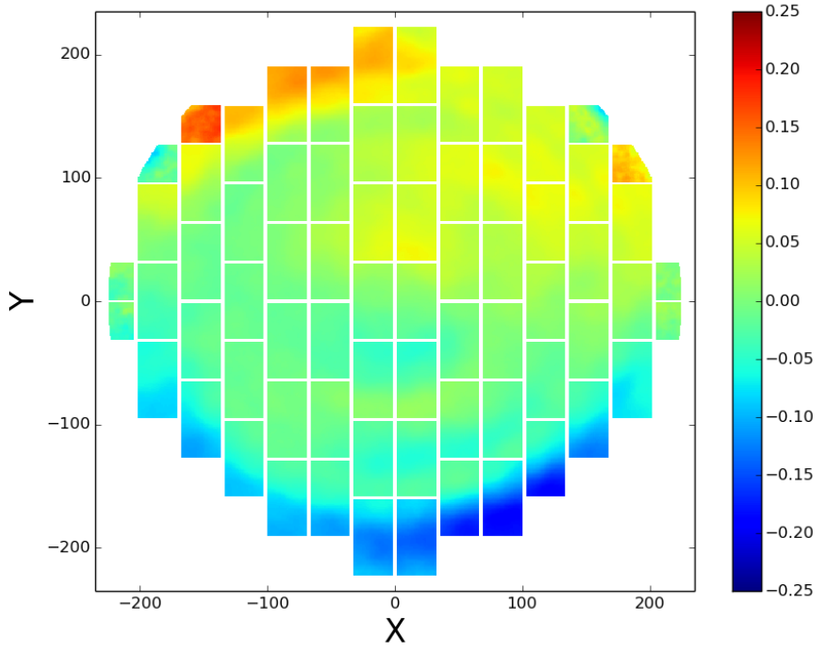
work by Chris Davis

Reference Wavefront - DECam

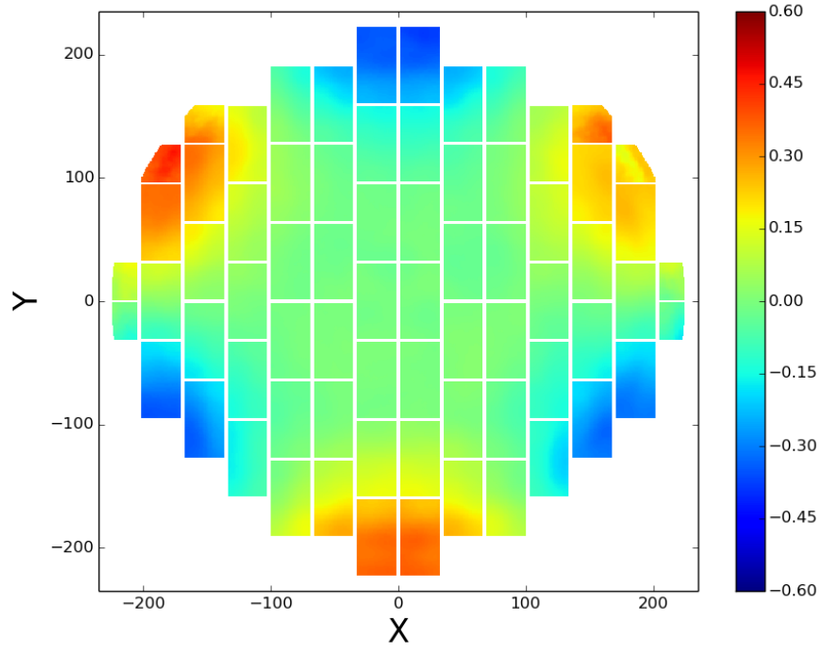
Z5 AstigmatismY



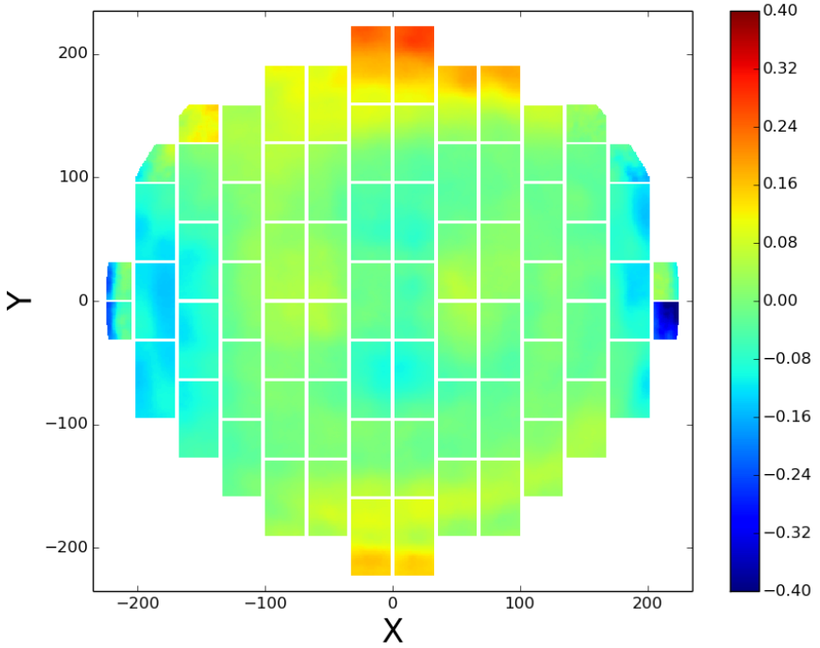
Z7 ComaY



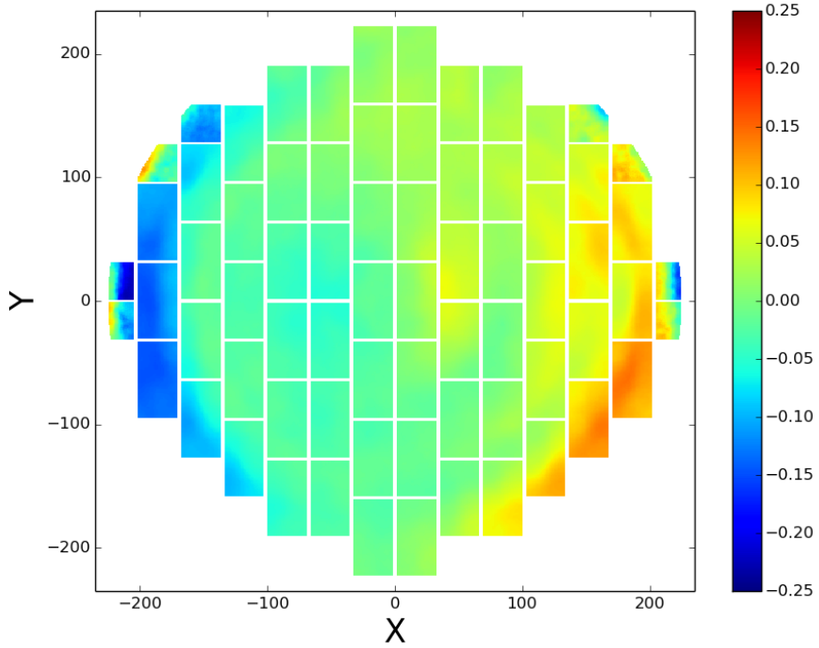
Z9 Trefoil Y



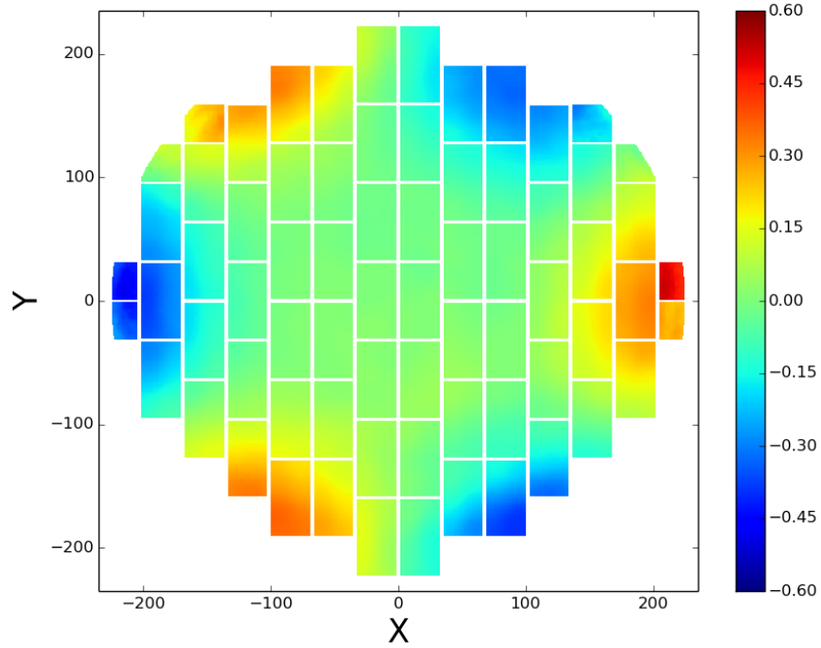
Z6 AstigmatismX



Z8 ComaX



Z9 Trefoil X



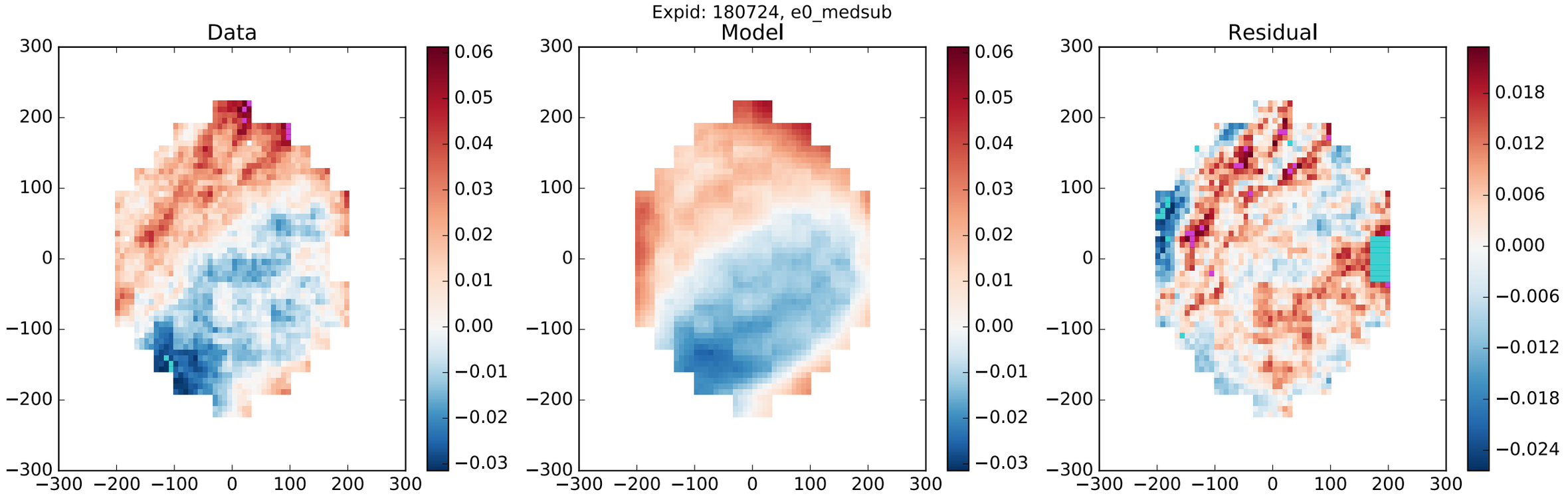
units are λ @(700nm)

Wavefront PSF Model Results

Fit DES SV images to Wavefront PSF Model
from Chris Davis

compare e0 Data, Model, and Data-Model

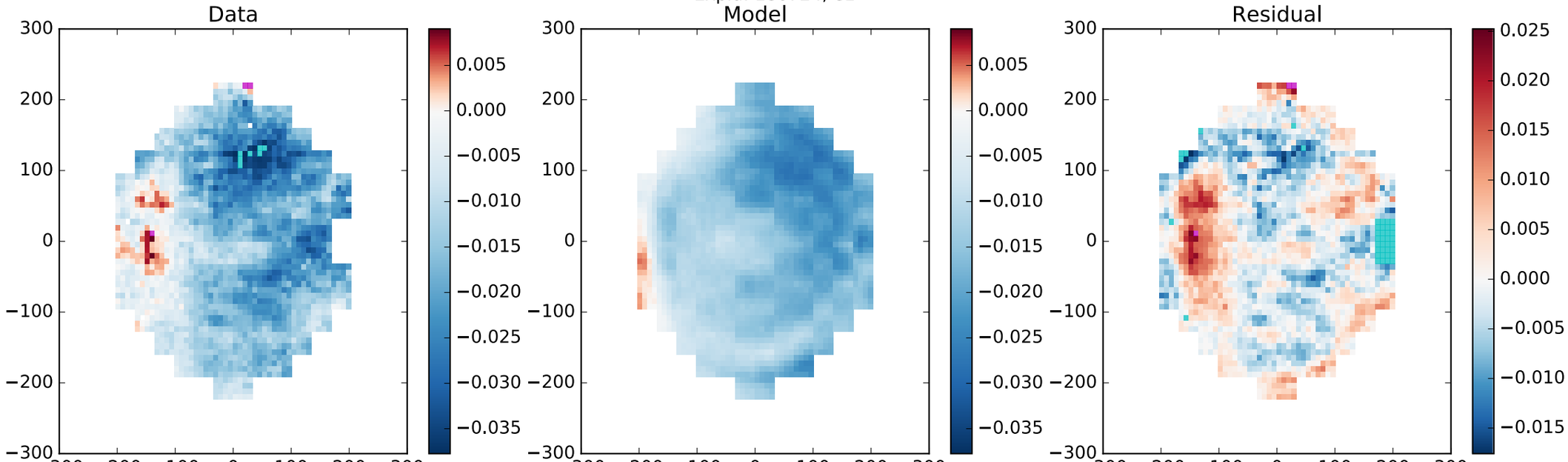
$$e0 = I_{xx} + I_{yy}$$



Wavefront PSF Model Results

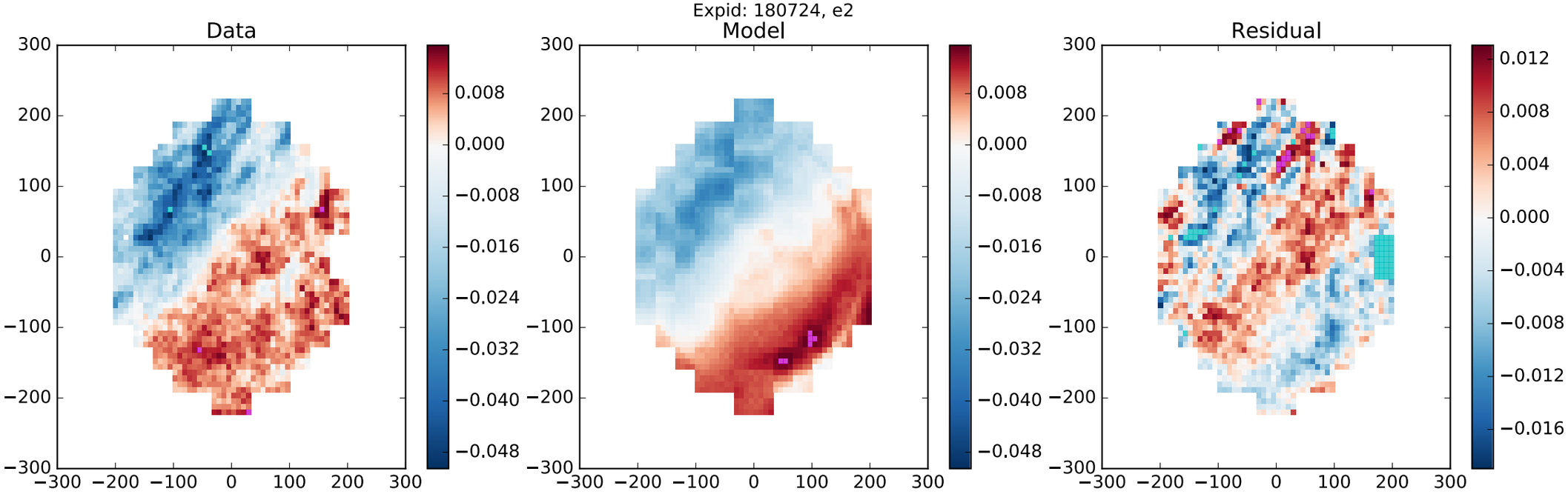
$$e1 = I_{xx} - I_{yy}$$

Expid: 180724, e1



$$e2 = 2I_{xy}$$

Expid: 180724, e2



Changes in Focus Zernike