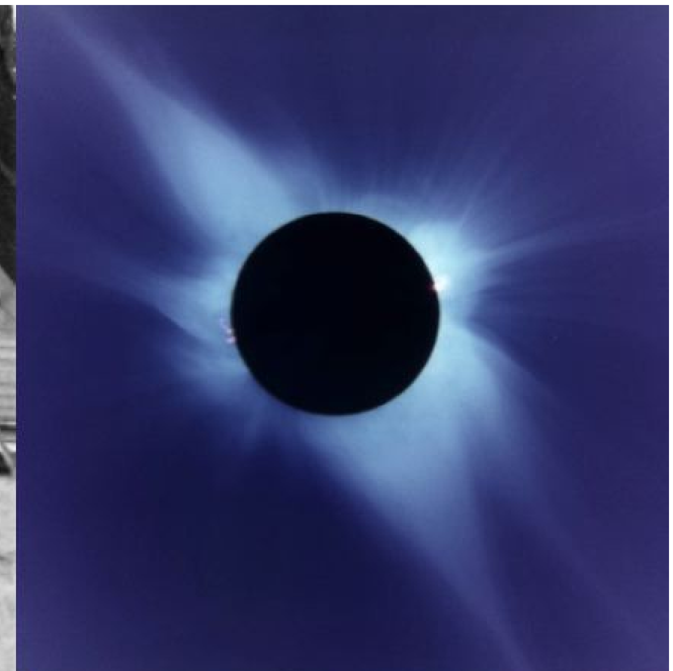
High contrast imaging

Lyot Coronagraph

Stellar coronagraphy is a diffractive problem
(not geometrical optics)

Lyot Coronagraph was first developed to observe the solar corona



Bernard Lyot, 1939, at Pic du Midi
French Astronomer
Inventor of the Coronagraph

Lyot Coronagraph architecture

Relies on focal plane mask AND pupil mask (Lyot stop) to augment contrast

Why a Lyot pupil mask ?

- Focal plane occulter blocks central part of the image = low spatial frequencies in pupil plane
- What is left after focal plane mask are high spatial frequencies in pupil plane = light around edges
- This light can be masked by an undersized pupil plane stop

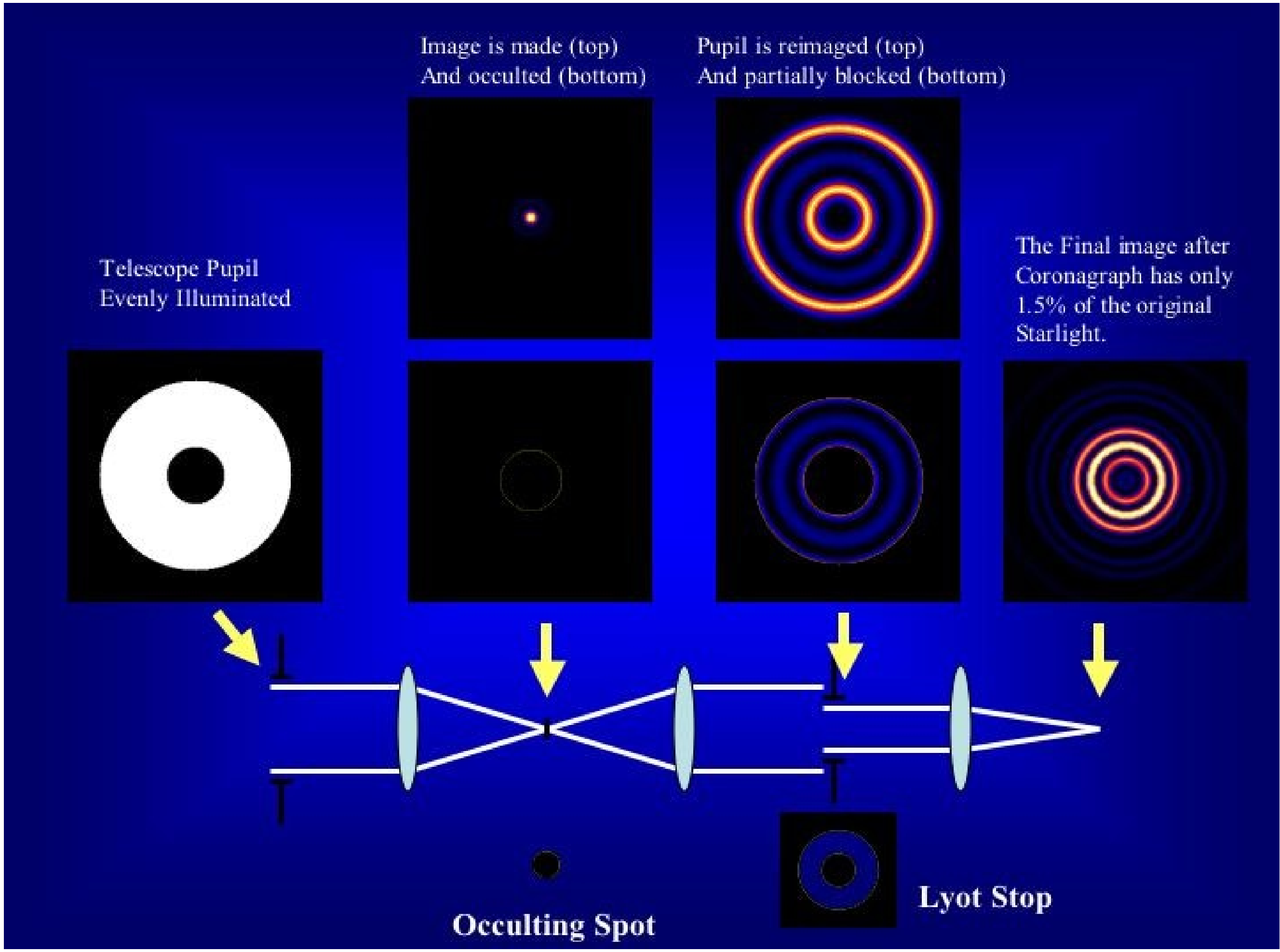


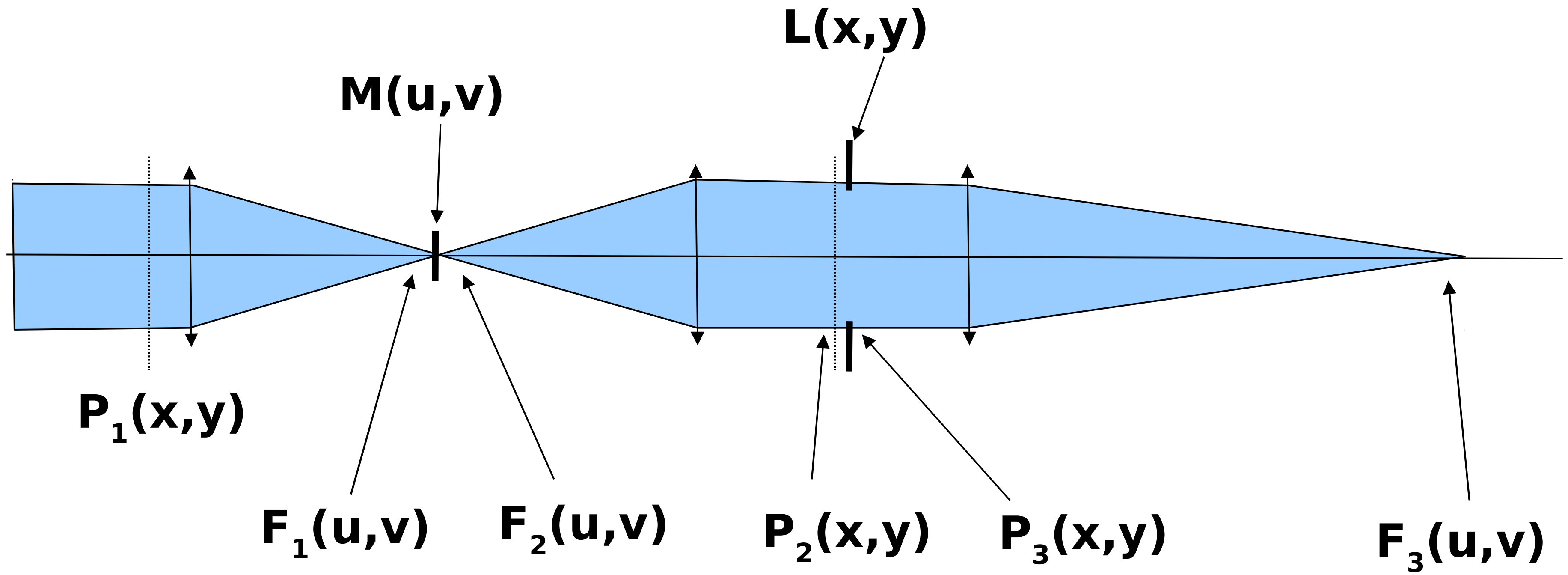
figure from Lyot project website

Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
Coordinates in focal plane : u,v
 * denoting convolution (product = convolution in Fourier transform)



Lyot Coronagraph explained by Fourier transforms

Entrance pupil of telescope: $P_1(x,y)$

Focal plane complex amplitude (before focal plane mask): $F_1(u,v)$

$F_1(u,v) = FT (P_1(x,y))$

Focal plane mask complex amplitude transmission: $M(u,v)$

Focal plane complex amplifude (after focal plane mask): $F_2(u,v)$

$F_2(u,v) = F_1(u,v) x M(u,v) = FT(P_1(x,y)) x M(u,v)$

Exit pupil plane:

$P_2(x,y) = FT^{-1}(F_2(u,v)) = FT^{-1} (FT(P_1(x,y) x M(u,v)) = P_1(x,y) * FT^{-1}(M(u,v))$

With * denoting convolution

$P_3(x,y) = L(x,y) x P_2(x,y)$

$\mathbf{P_3(x,y) = L(x,y) x (P_1(x,y) * FT^{-1}(M(u,v)))}$

$F_3(u,v) = FT(L(x,y)) * (F_1(u,v) x M(u,v))$

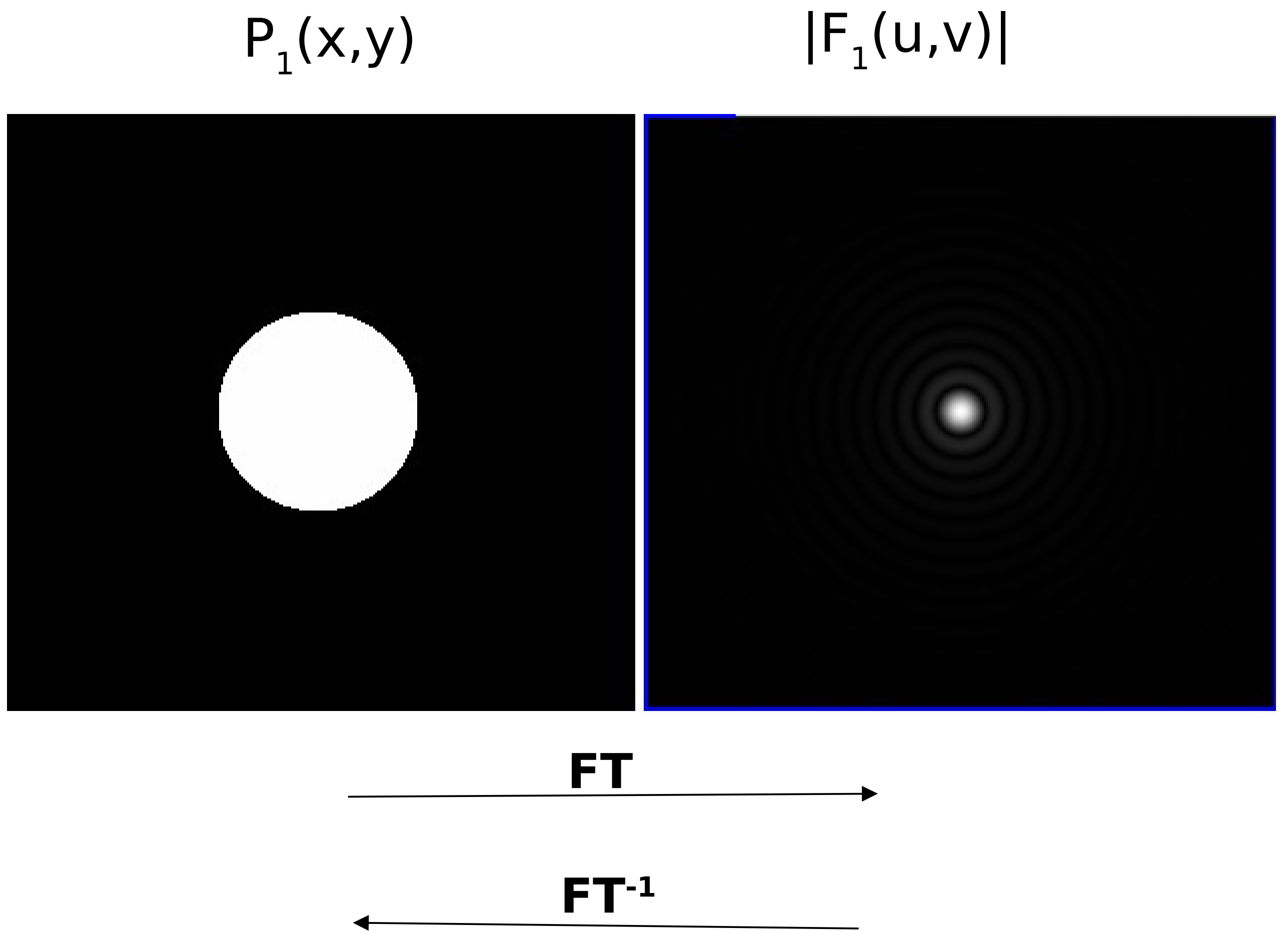
Coronagraphy problem: minimize $P_3(x,y)$ for on-axis point source

Lyot Coronagraph explained by Fourier transforms

Entrance pupil of telescope: $P_1(x,y)$

Focal plane complex amplitude (before focal plane mask): $F_1(u,v)$

$F_1(u,v) = FT\ (\ P_1(x,y)\ )$

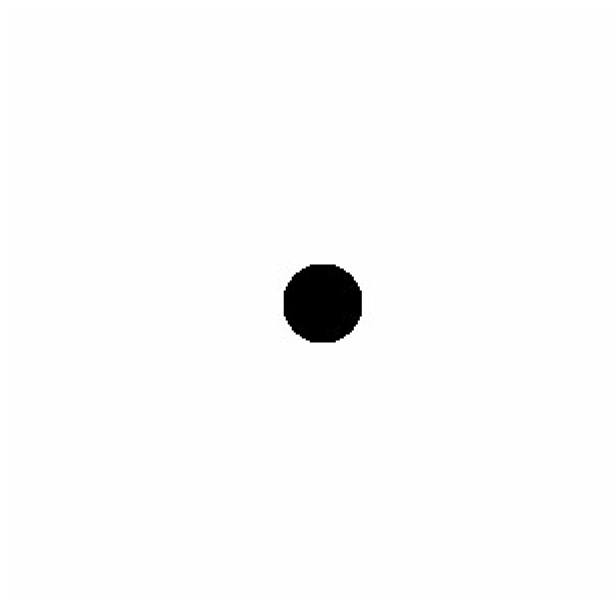


Lyot Coronagraph explained by Fourier transforms

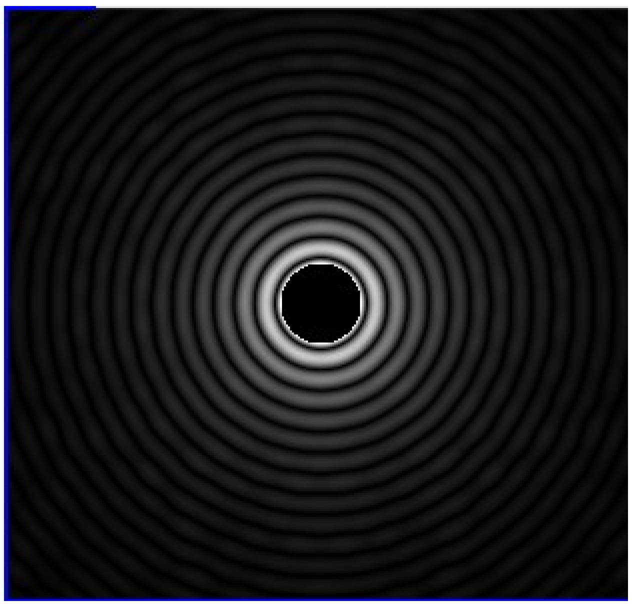
Focal plane mask complex amplitude transmission: M(u,v)
Focal plane complex amplifude (after focal plane mask): $F_2(u,v)$

$F_2(u,v) = F_1(u,v) \times M(u,v) = FT(P_1(x,y)) \times M(u,v)$

M(u,v)



|$F_2(u,v)$|



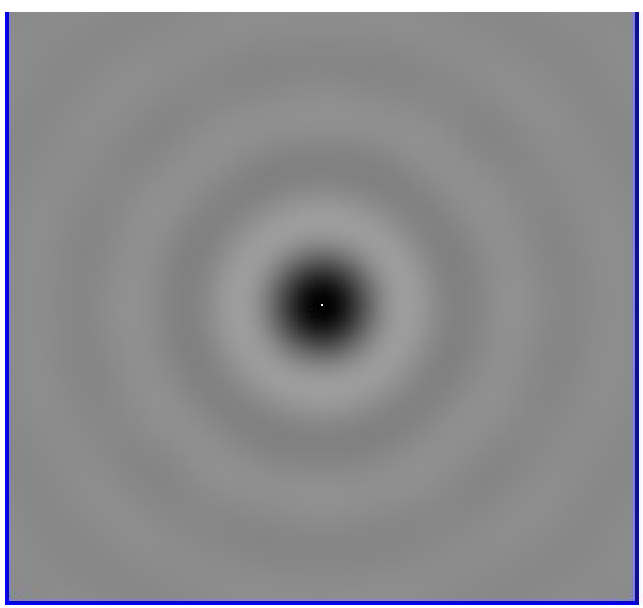
Lyot Coronagraph explained by Fourier transforms

Exit pupil plane:

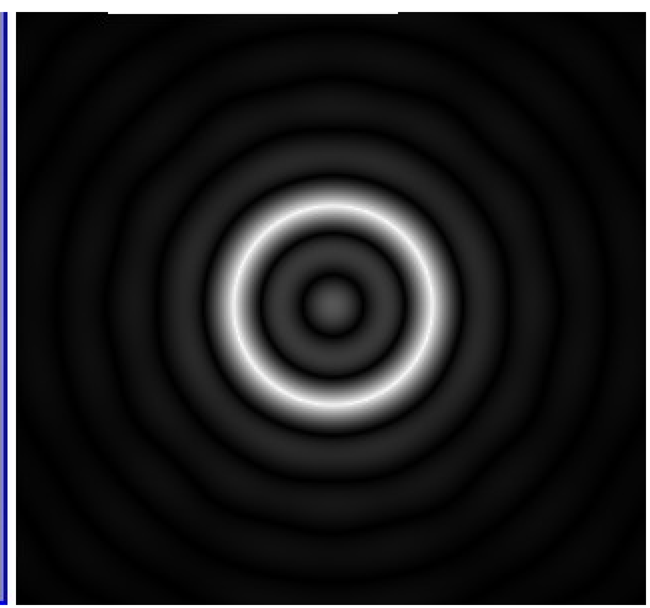
$P_2(x,y) = FT^{-1}(F_2(u,v))$

$= FT^{-1} (FT(P_1(x,y) \times M(u,v)) = P_1(x,y) * FT^{-1}(M(u,v))$

$FT^{-1}(M(u,v))$



$|P_2(x,y)|$



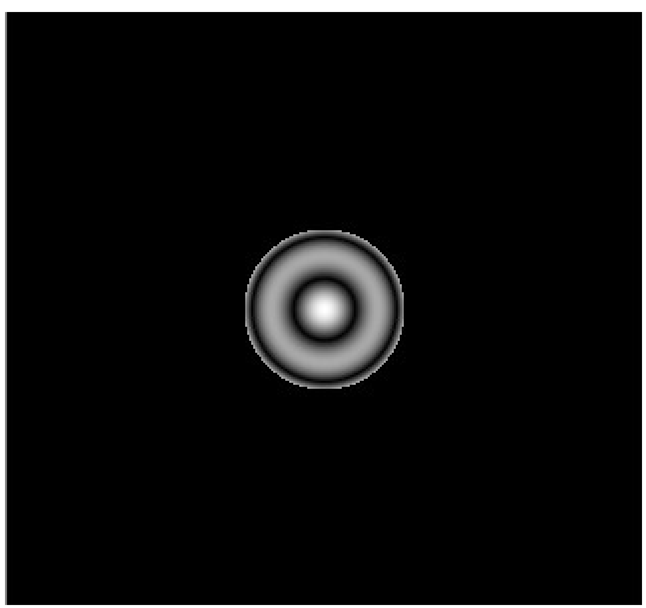
Lyot Coronagraph explained by Fourier transforms

$P_3(x,y) = L(x,y) \times P_2(x,y)$

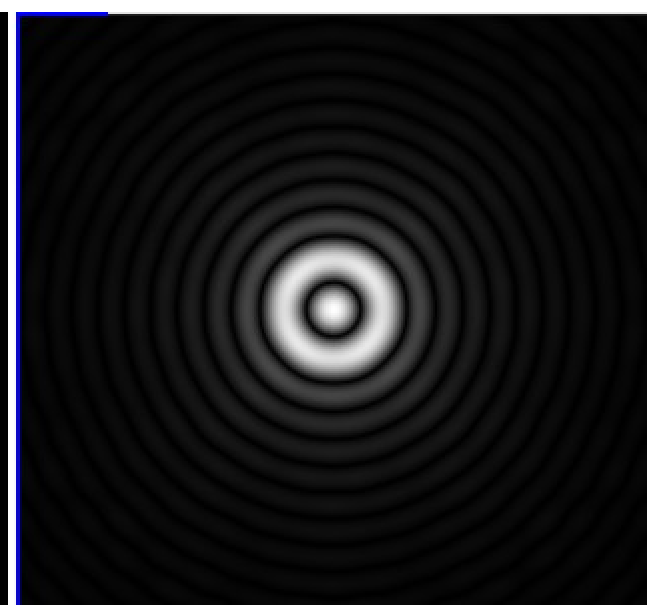
$\mathbf{P_3(x,y) = L(x,y) \times (P_1(x,y) * FT^{-1}(M(u,v)))}$

$F_3(u,v) = FT(L(x,y)) * (F_1(u,v) \times M(u,v))$

$|P_3(x,y)|$

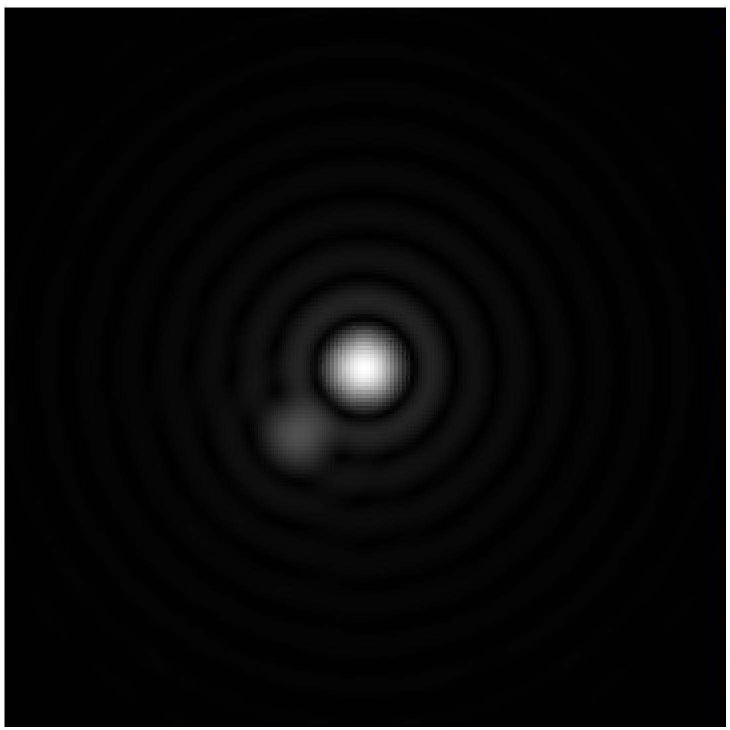


$|F_3(u,v)|$

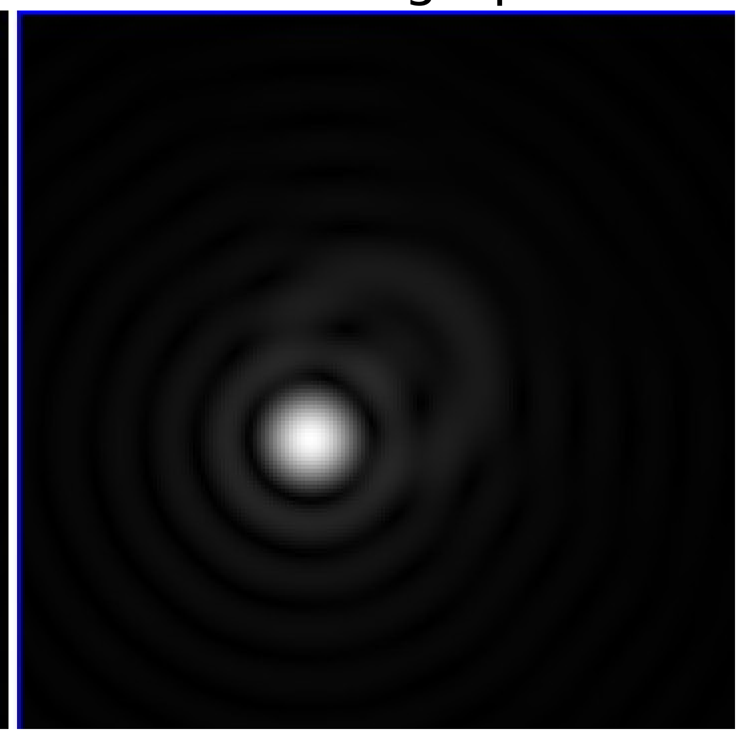


Numerical simulation of final image for 10:1 contrast

No coronagraph



With Lyot Coronagraph



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Exit pupil plane:

$P_2(x,y) = FT^{-1}(\ F_2(u,v)\ ) = FT^{-1}\ (\ FT(P_1(x,y) \times M(u,v)\ ) = P_1(x,y) * FT^{-1}(M(u,v))$

With * denoting convolution

$P_3(x,y) = L(x,y) \times P_2(x,y)$

$\mathbf{P_3(x,y) = L(x,y) \times (P_1(x,y) * FT^{-1}(M(u,v)))}$

$F_3(u,v) = FT(L(x,y)) * (F_1(u,v) \times M(u,v))$

Coronagraphy problem: minimize $P_3(x,y)$ for on-axis point source