Design of Coronagraph for the observation of beam halo at HLC

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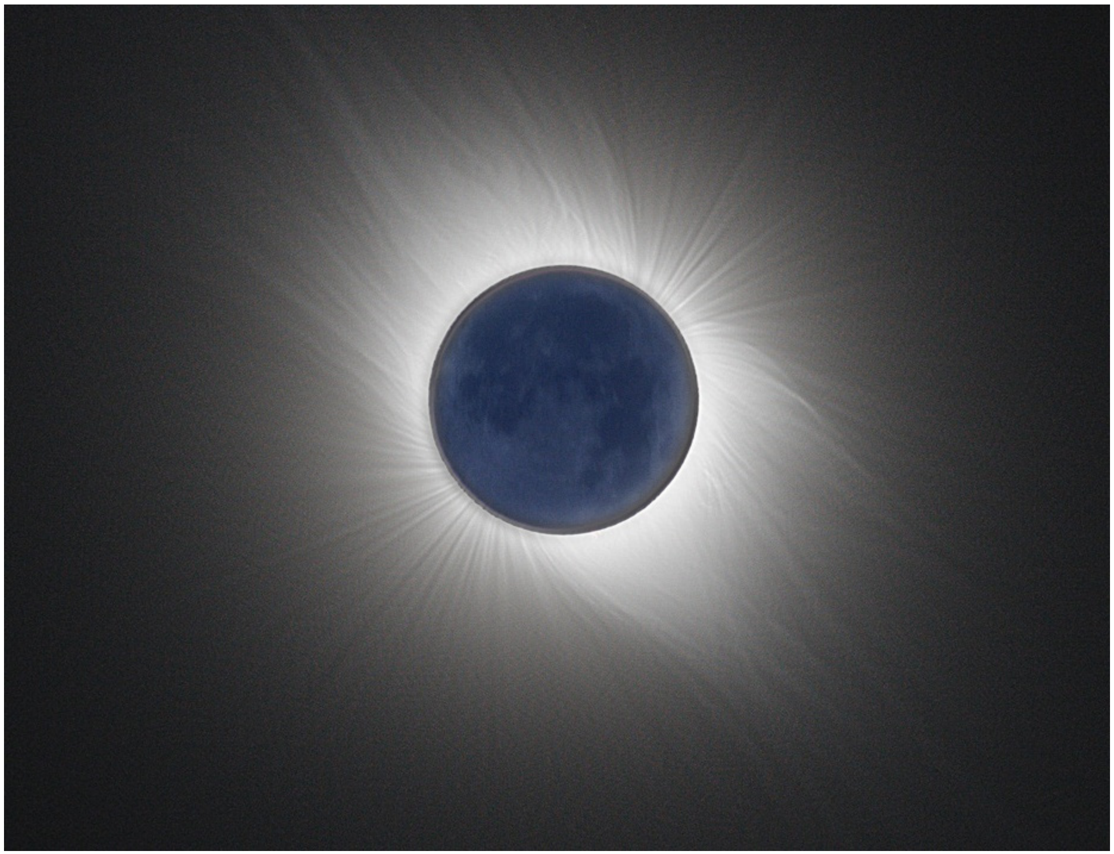
Agenda for my talk

1. What is the coronagraph
2. Plan of observation of beam halo with coronagraph in the LHC
3. Diffraction analysis for phase 1 coronagraph
4. Mie-scattering noise from optical component surface
5. Arrangement of phase 1 coronagraph on B2 optical table
6. Phase 2 coronagraph

1. What is the coronagraph?
an introduction

Everything was start with astronomer's dream……



Eclipse is rare phenomena, and only few second is available for observation of sun corona, prominence etc.

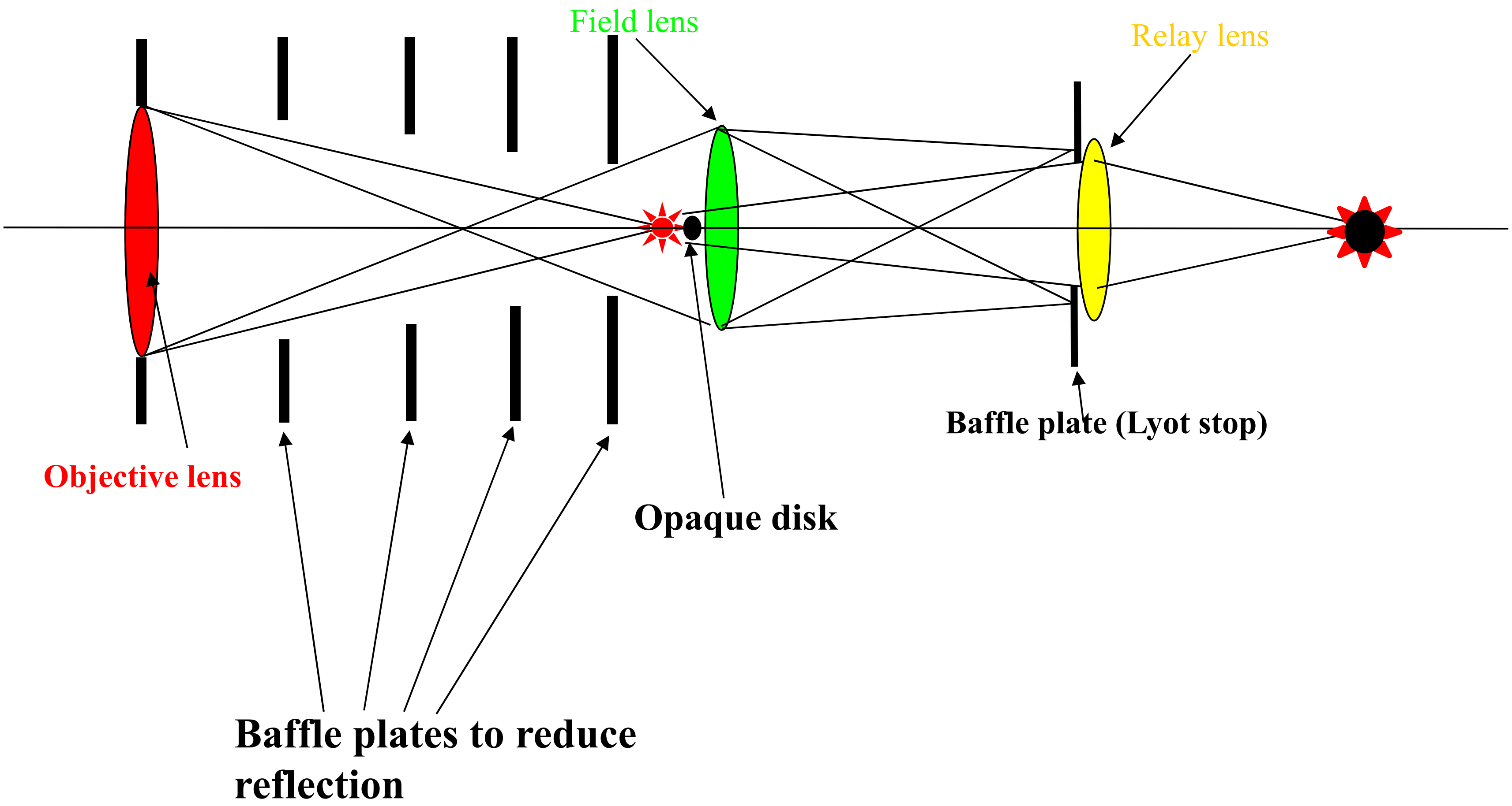
Artificial eclipse was dream of astronomers, but……..

The coronagraph to observe sun corona

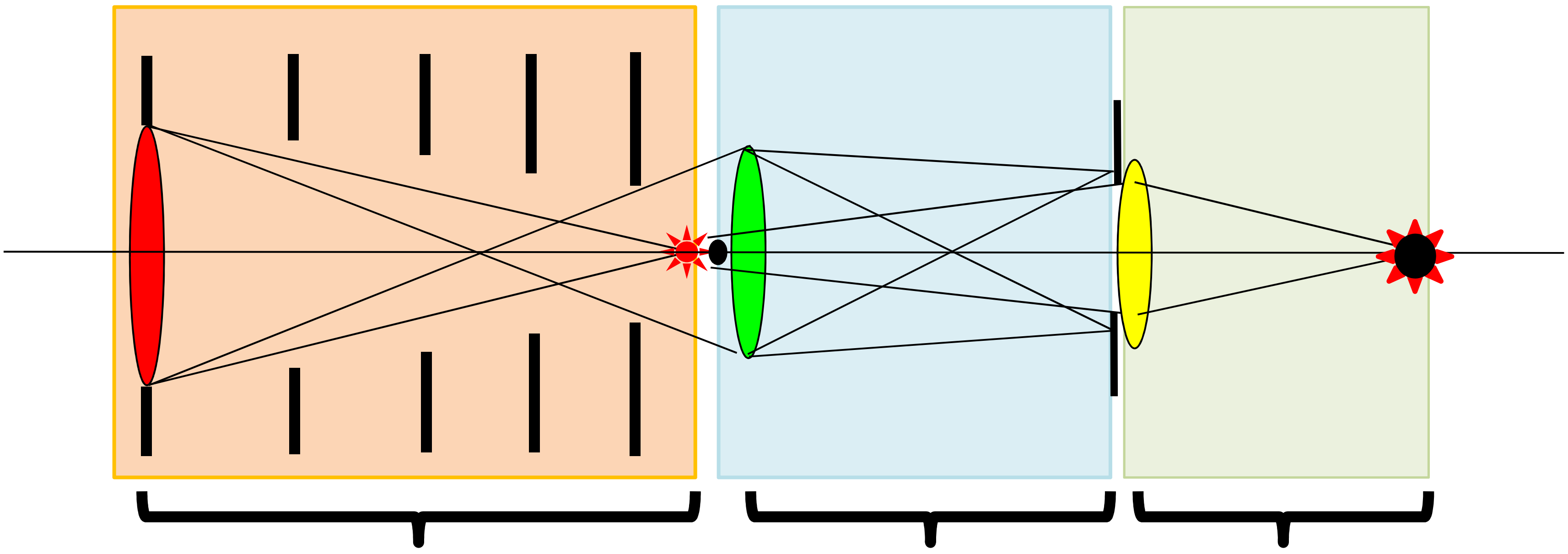
Developed by B.F.Lyot in 1934 for a observation of sun corona by artificial eclipse.

Special telescope having a "*re-diffraction system*" to eliminate the diffraction fringe.

Optical system of Lyot's corona graph



3 stages-optical system in the Lyot's coronagraph

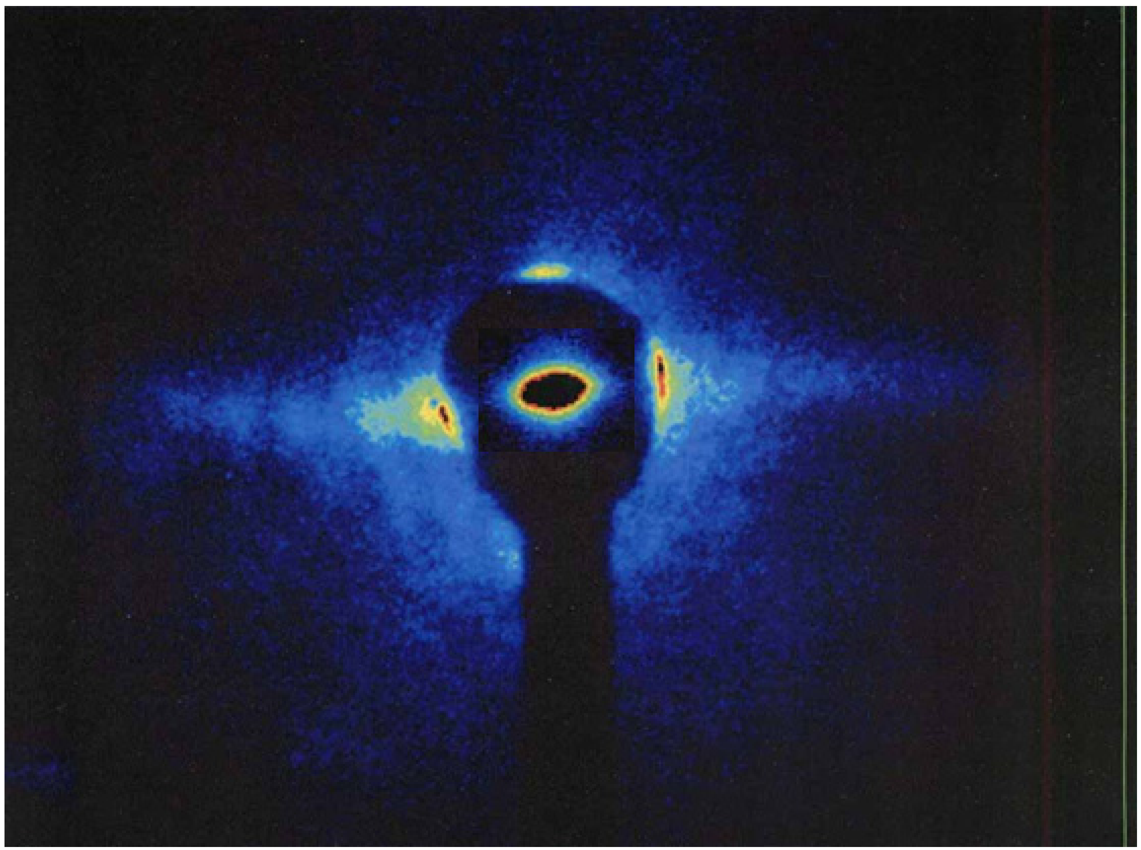


1st stage : Objective lens system

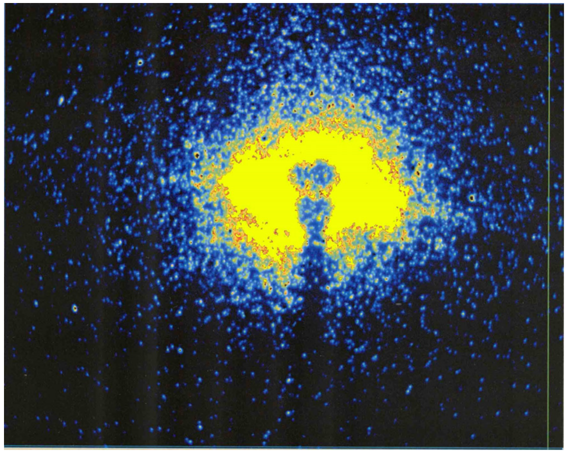
2ed stage : re-diffraction system

3ed stage : Relay lens

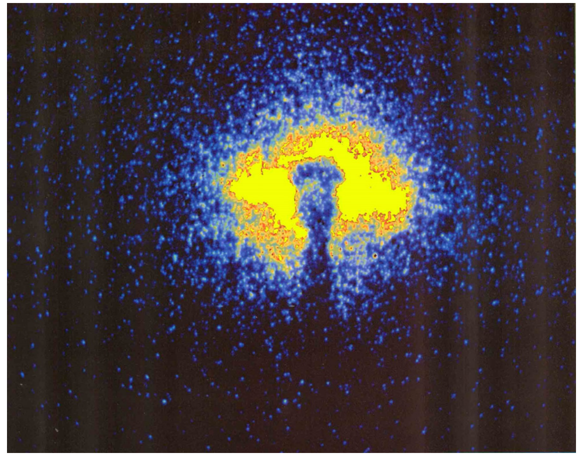
Observation inPF,KEK 2005
Beam core + halo (superimposed)



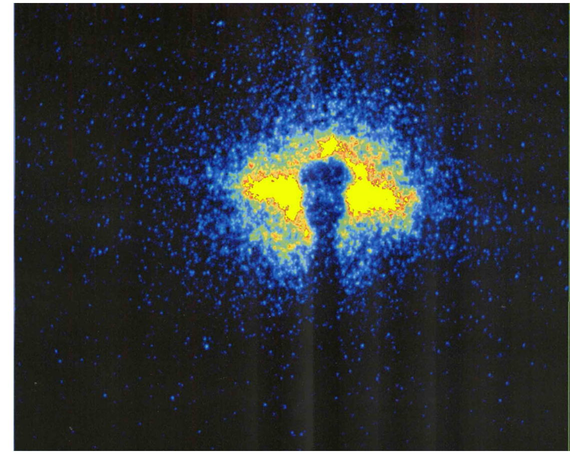
Beam halo images in the single bunch operation at the KEK PF measured at different current 2005.



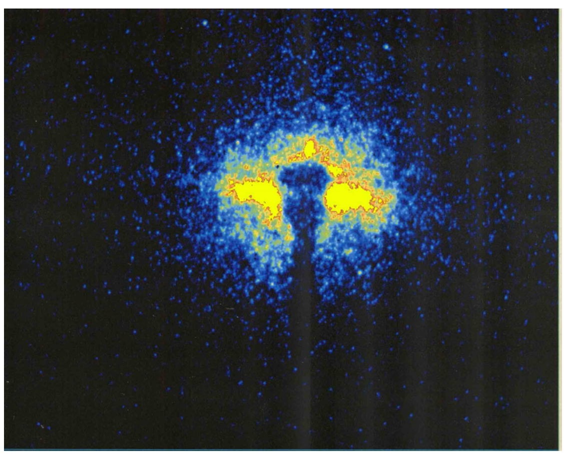
65.8mA



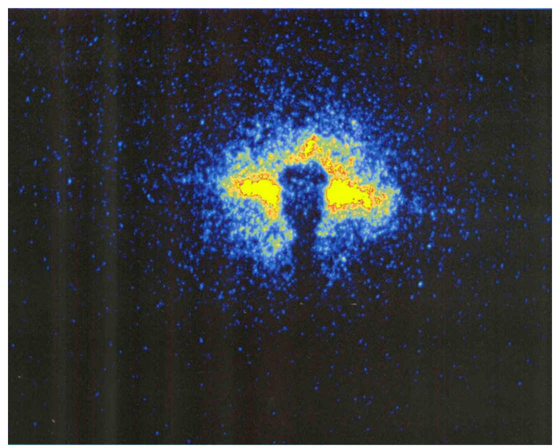
61.4mA



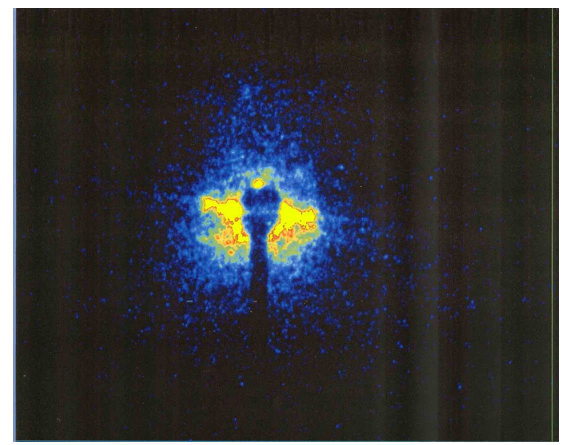
54.3mA



45.5mA



35.5mA



396.8mA

Multi-bunch

bunch current 1.42mA

2. Plan of halo observation by using the coronagraph in LHC

The coronagraph is planned to apply for an observation of beam halo image in the LHC. This project will perform by two phases.

Phase1: Test observation,

Designed and constructing a coronagraph by modifying the optical design of coronagraph constructed in 2005 in the KEK.
Aiming a halo observation with 10^3 to 10^4 contrast to the beam core, and it will set in B2 SR monitor line.

Phase2: Design and construct an optimum coronagraph for the LHC,

aiming 10^5 to 10^6 contrast.

Table1: Key conditions for design the coronagraph at PF (2005) and LHC (2015).

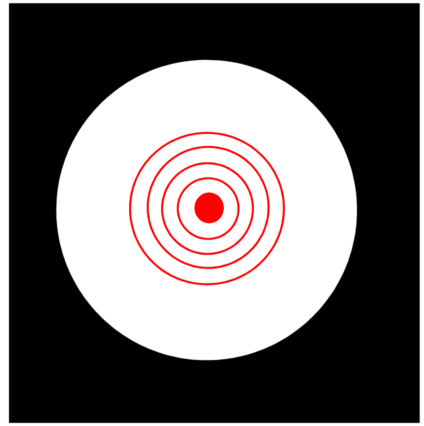
	PF (BL28)	LHC(B2)
Distance between source point and objective lens	8.0m	28.5m
Beam size in horizontal (1σ of beam core)	263μm	330μm/3.75μmrad 270μm/2.5μmrad
Beam size in vertical (1σ of beam core)	80μm	430μm/3.75μmrad 350μm/2.5μmrad
Minimum size of opaque disk against beam core	6σ of beam core	5 σ of beam core

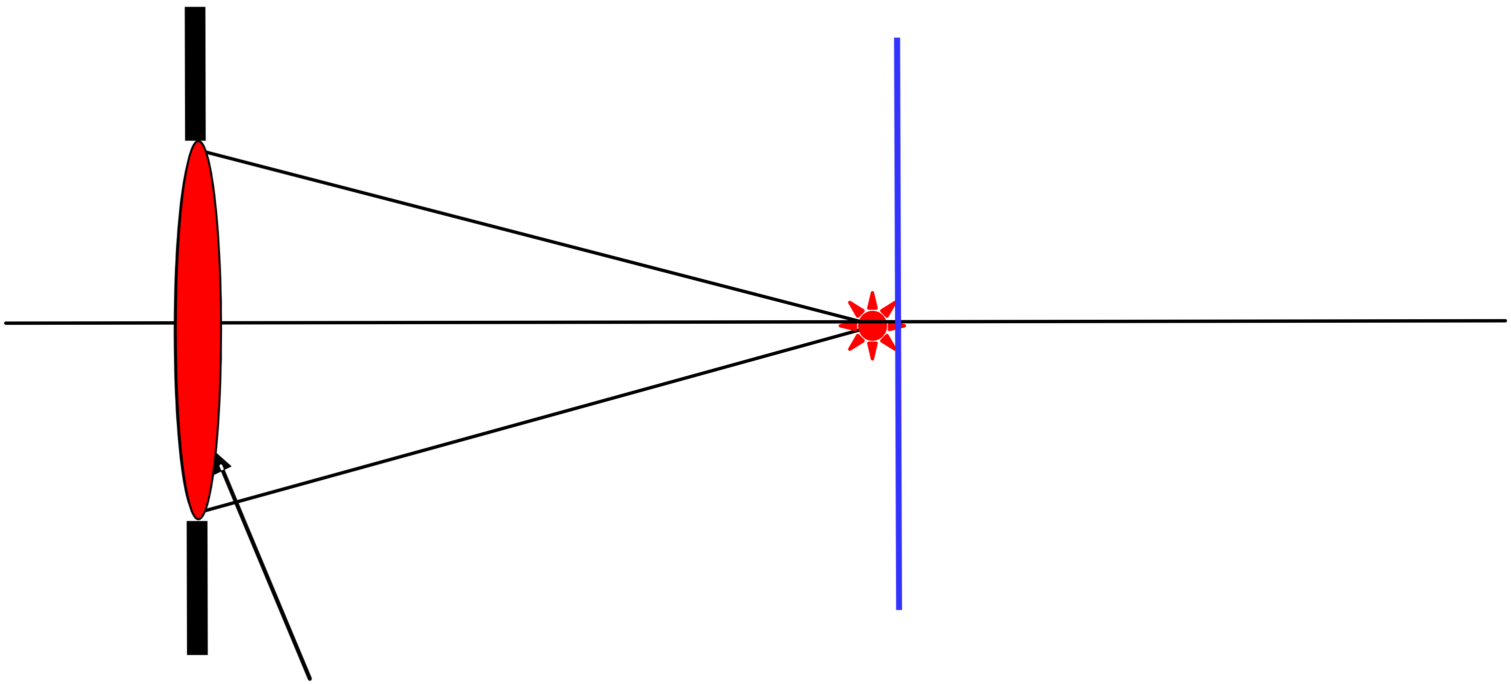
Table2: The optical design of previous and phase 1 coronagraph.

	PF (BL28)	LHC(B2)
Focal length of objective lens	2000mm	2000mm
Objective lens aperture	50 x 50mm	25 x 25 mm
Transverse magnification	0.333	0.0754
Opaque disk size in radius	0.5mm	0.110-0.162mm
Focal length of field lens	500mm	800mm
Movable range of Lyot stop	2 x 2mm to 20 x 20 mm	2 x 2mm to 20 x 20 mm
Focal length of relay lens	36mm	500mm

3. Diffraction analysis for Phase 1 Coronagraph

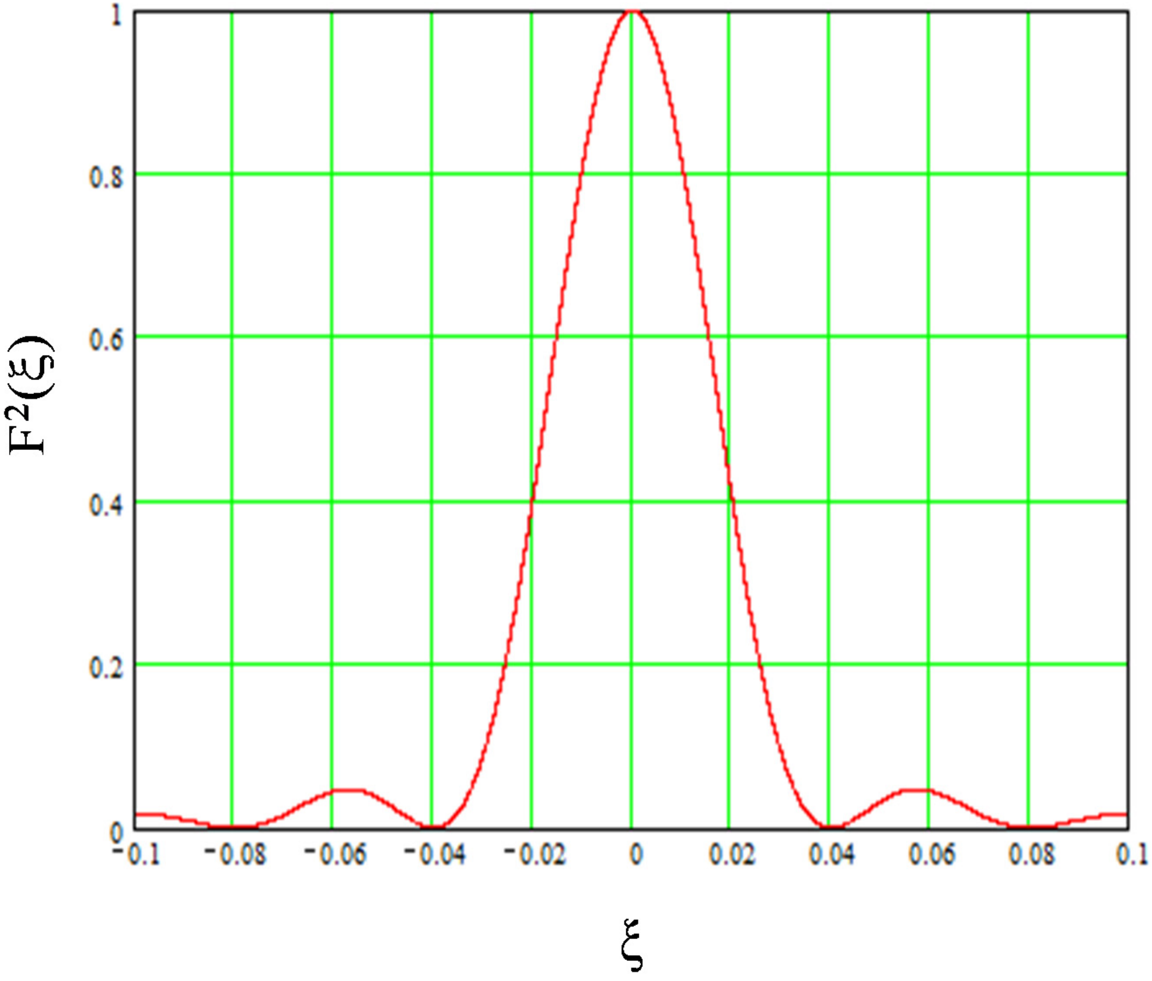
Diffraction from first objective system

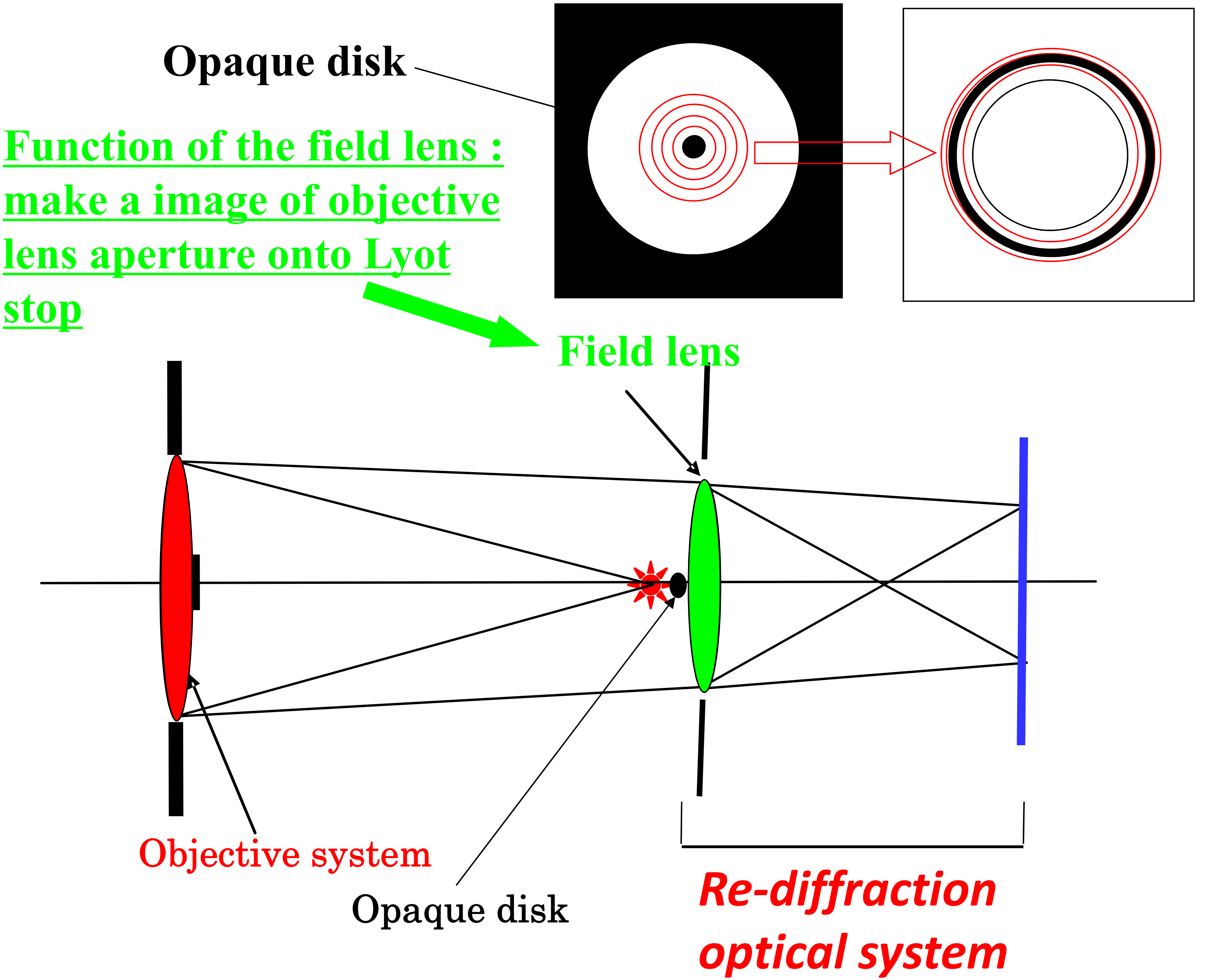




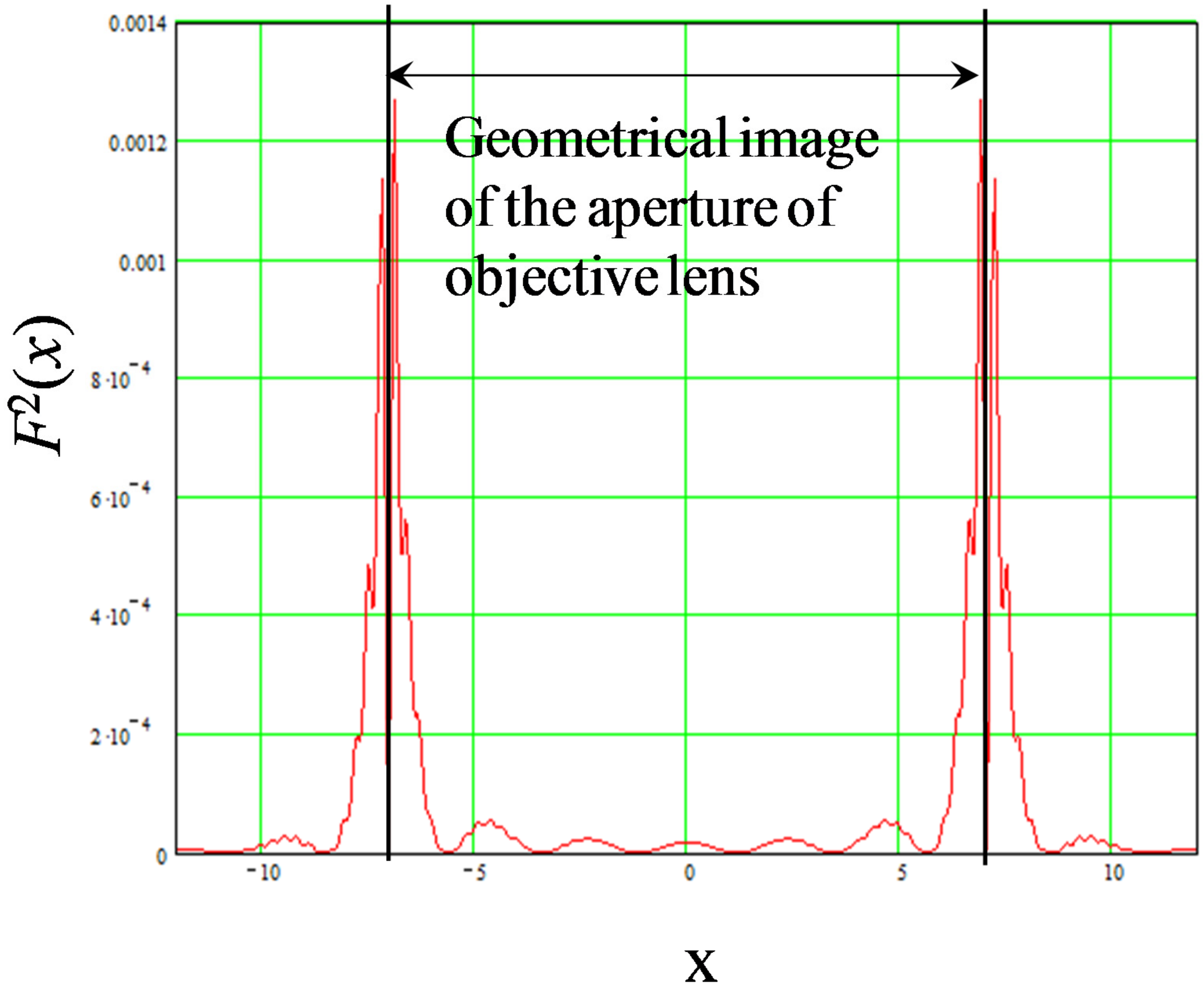
The entrance pupil of the objective lens

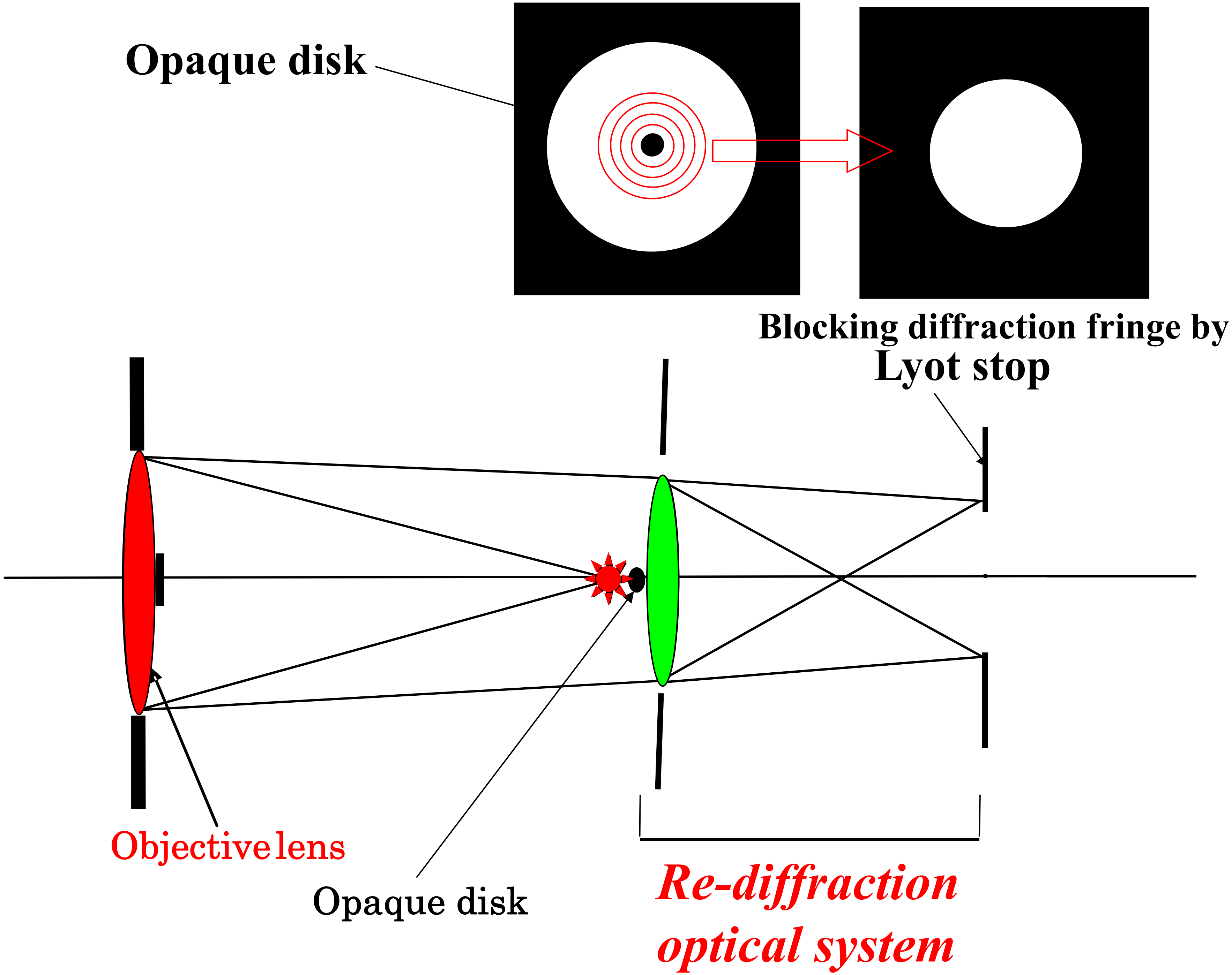
Diffraction in first stage λ=500nm Magnification of objective system=0.0754




Opaque disk
Function of the field lens : make a image of objective lens aperture onto Lyot stop
Field lens
Objective system
Opaque disk
Re-diffraction optical system

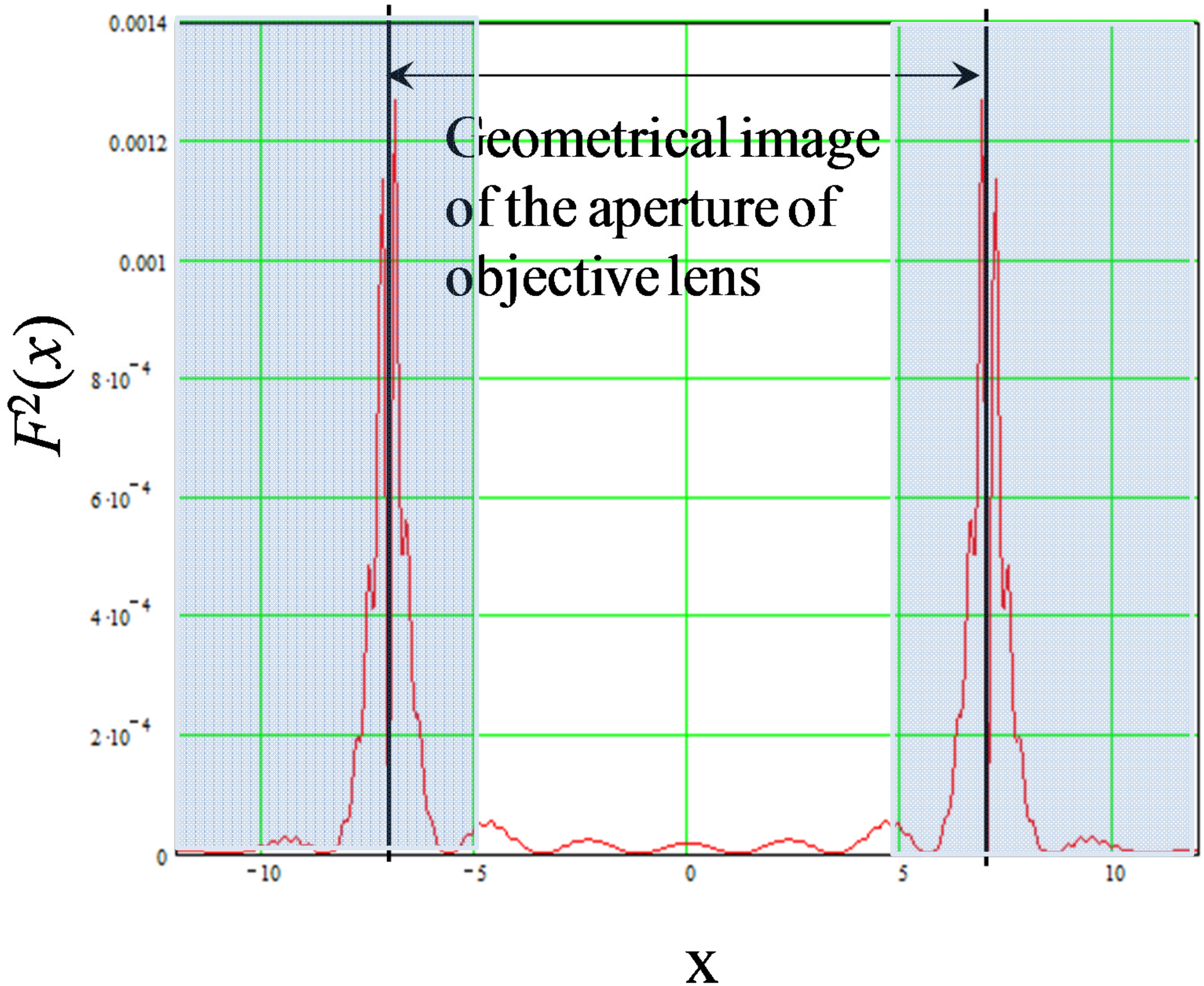
Diffraction in re-diffraction system





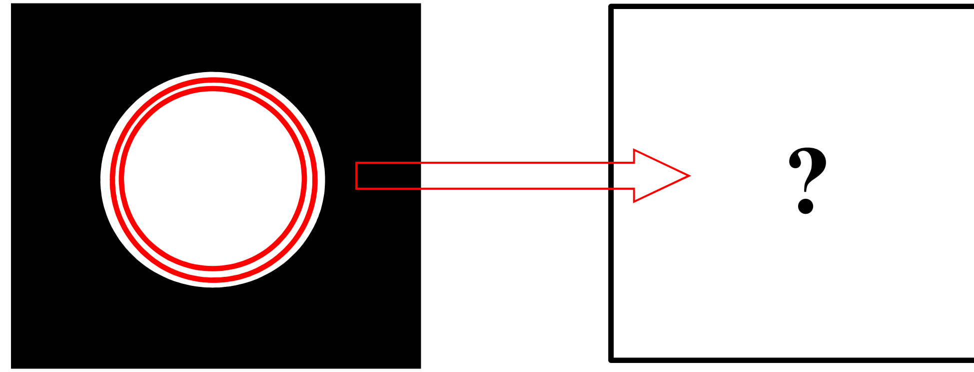
Opaque disk
Blocking diffraction fringe by
Lyot stop
Objective lens
Opaque disk
Re-diffraction
optical system

Lyot stop at +/-5mm

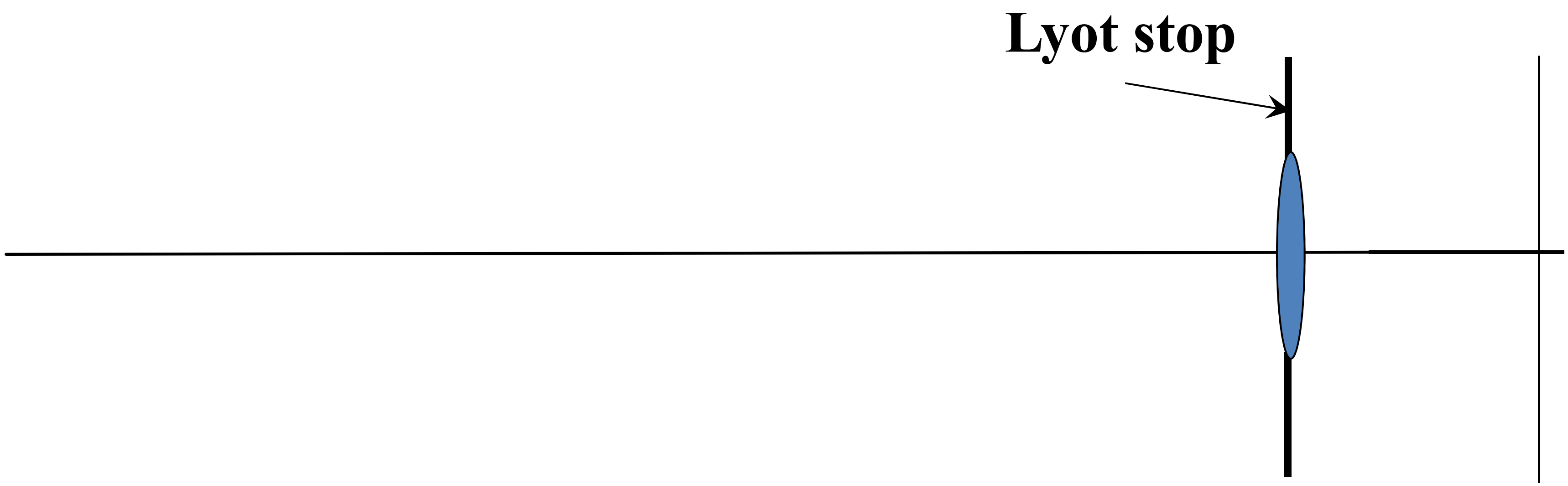


Diffraction background in final image plane

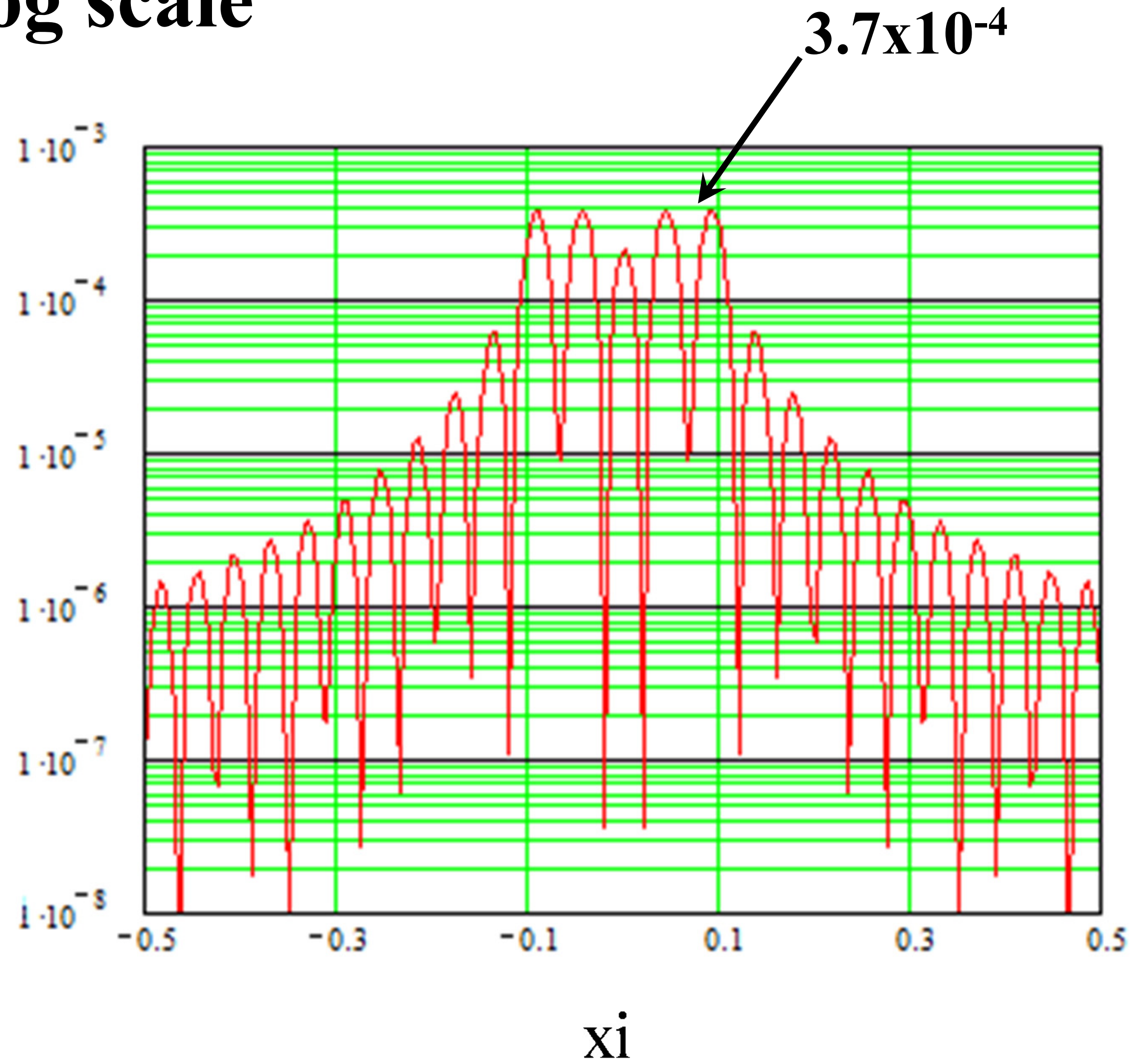
Overflowed fringe inside of Lyot stop

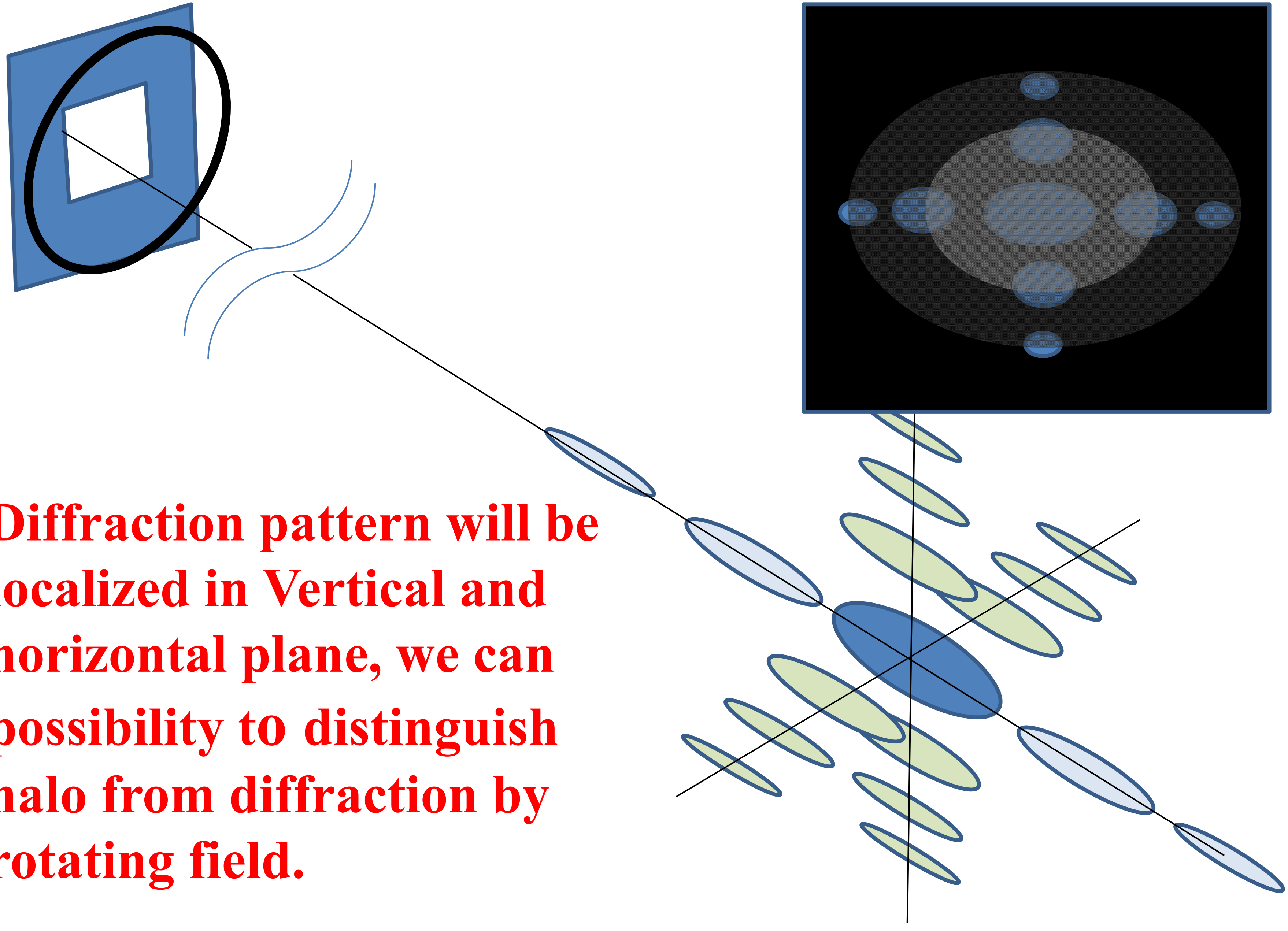


Blocking diffraction fringe by

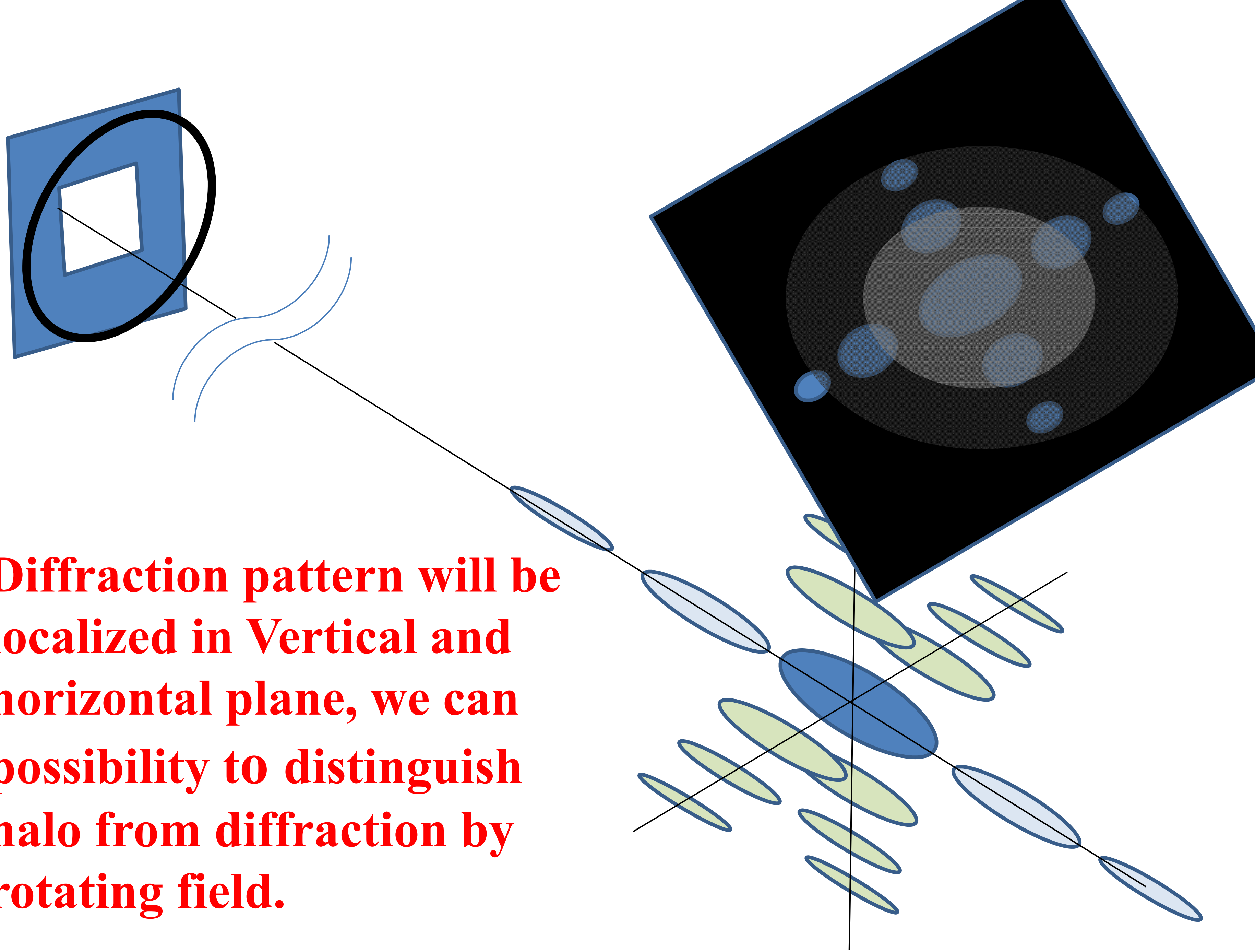


Diffraction background at 3ed stage in log scale





Diffraction pattern will be localized in Vertical and horizontal plane, we can possibility to distinguish halo from diffraction by rotating field.



Diffraction pattern will be localized in Vertical and horizontal plane, we can possibility to distinguish halo from diffraction by rotating field.

4. Mie-scattering noise from optical component surface

Background source in coronagraph

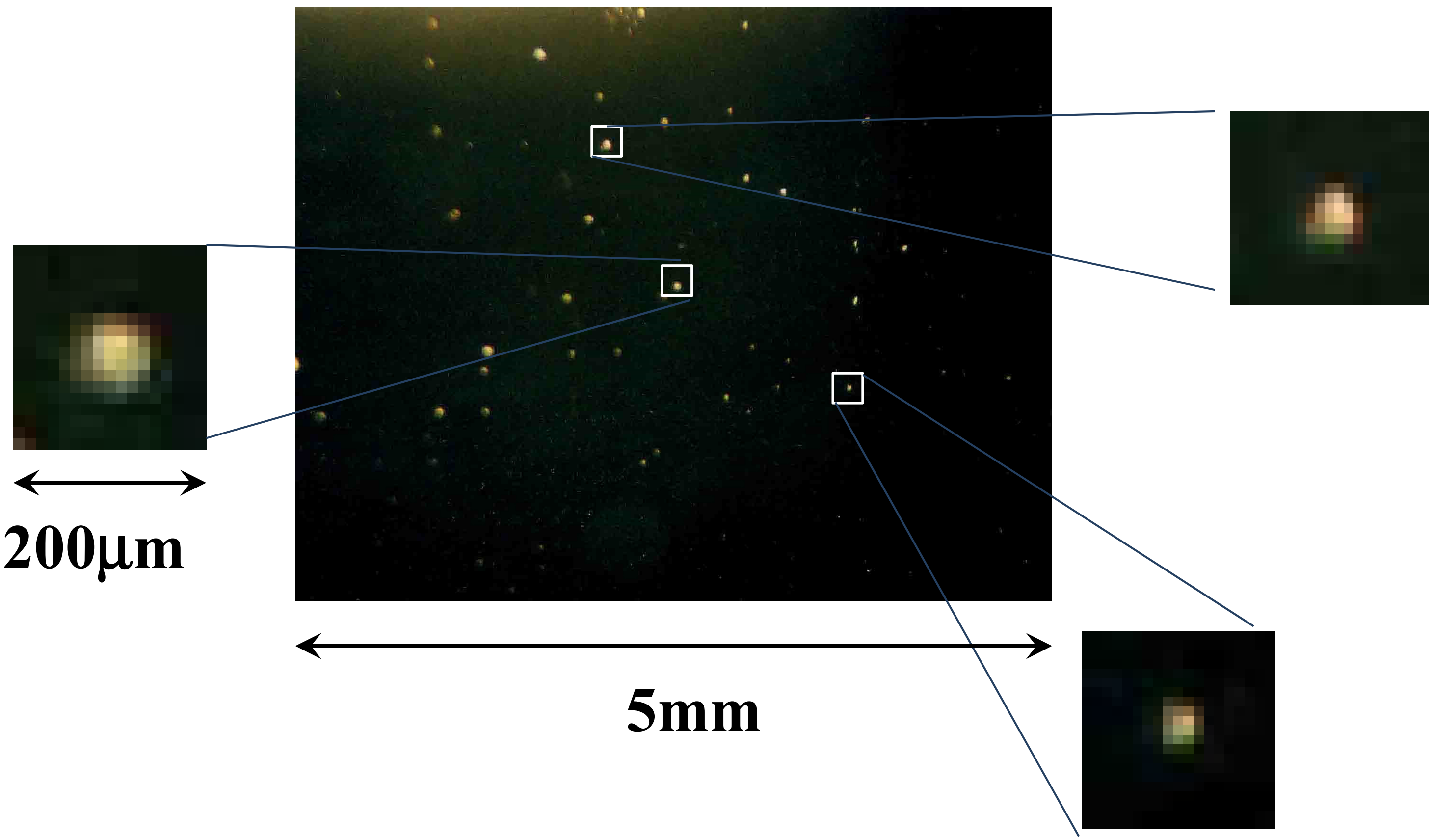
1. **Noise from defects on the lens surface (inside) such as scratches and digs.**
2. **Noise from the optical components (mirrors) in front of the coronagraph.**
3. **Reflections in inside wall of the coronagraph.**
4. **Noise from dust in air.**
5. **Rayleigh scattering from air molecule.**

Background source in coronagraph

1. **Noise from defects on the lens surface (inside) such as scratches and digs.**
2. **Noise from the optical components (mirrors) in front of the coronagraph.**
3. **Reflections in inside wall of the coronagraph.**
   Apply baffles
4. **Noise from dust in air. Apply dust filter**
5. **Rayleigh scattering from air molecule.**
   Not significant in few ten meter optical path

Digs on glass surface of scratch & dig 60/40

The optical surface quality 60/40 guarantees no larger scratches than 6μm width, and no larger dig than 400μm.



Noise source in the pupil has two effects,

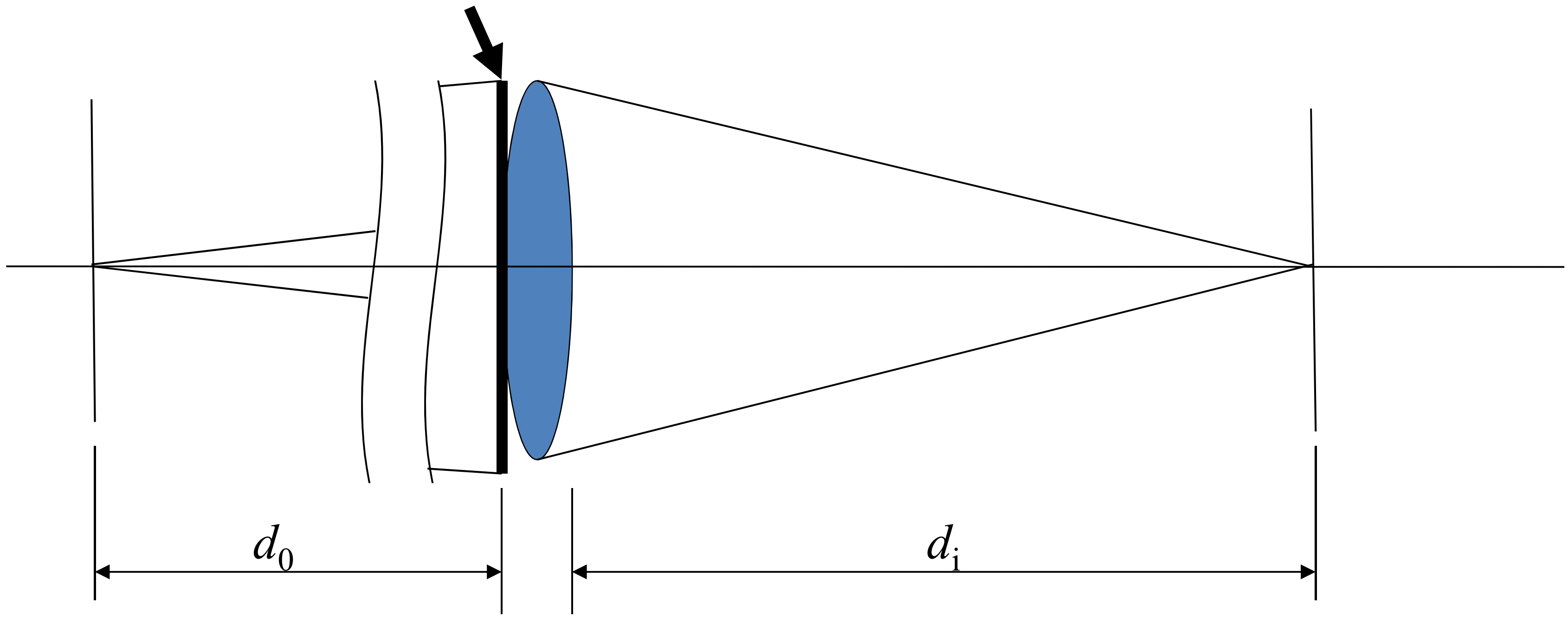
1. **Refraction in noise source**
   phenomena in sun or moon halo is produced by this effect.

2. **Mie scattering by noise source**
   opaque dust or dig on lens or on any optical components are classified this effect. Dust in air also has same effect.

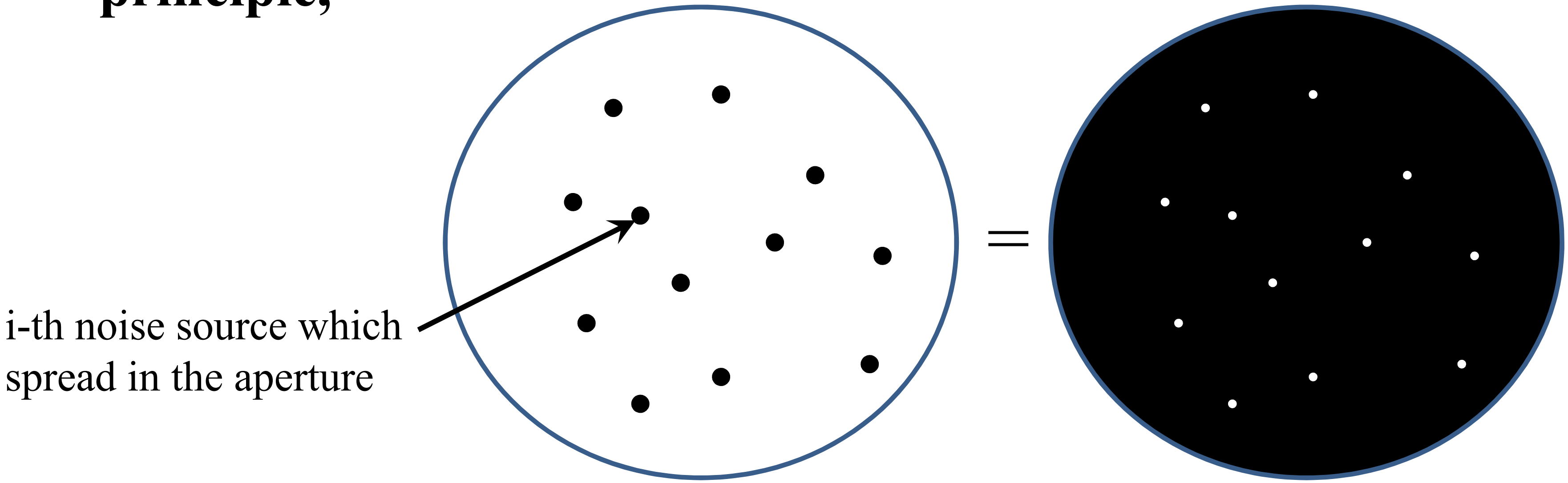
Mie scattering,
it's diffraction treatment

Case 1. Noise source in the entrance pupil of objective lens

***P*(x, y): pupil function with assembly of diffraction noise sources on the lens**



Let us approximate i-th noise source in the pupil as a opaque disk having a diameter of r_0 , Using the Babinet's principle,



$$P_i(r_0, x, y) = circ(r_0, x_i, y_i)$$

Then pupil function having many noise source is given by,

$$P(\bar{r}, x, y) = \sum_i P_i(r_{0,} x, y) \cdot \exp(-ik(x_i + y_i))$$

When the mean distance of noise source is longer than 1st order transverse coherent length , pupil function with noise sources is simply given by,

$$P(\bar{r},x,y)=\sum_i P_i(r_0,x,y)$$

Then the impulsive response $h(x_i,y_i;x_0,y_0)$ **on the image plane is given by,**

$$h(x_i,y_i;x_0,y_0)=\frac{1}{\lambda d_0 d_i}\iint P(\bar{r},x,y)\exp\left\{-i\frac{2\pi}{\lambda d_i}\left[(x_i+Mx_0)x+(y_i+My_0)y\right]\right\}dxdy$$

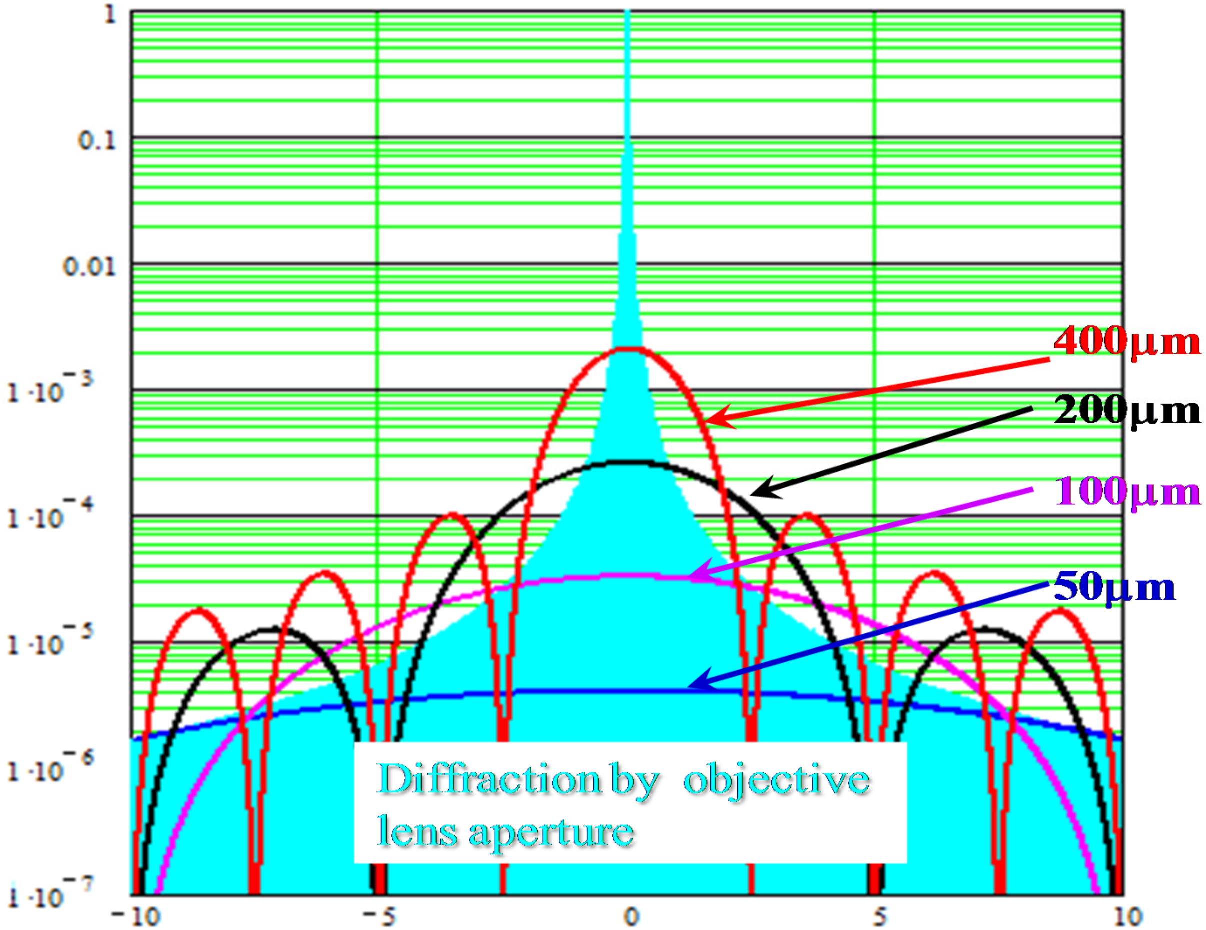
in here, $M=d_i/d_0$ **denotes geometrical magnification.**

The intensity of diffraction from noise sources is inverse-proportional to extinction rate,

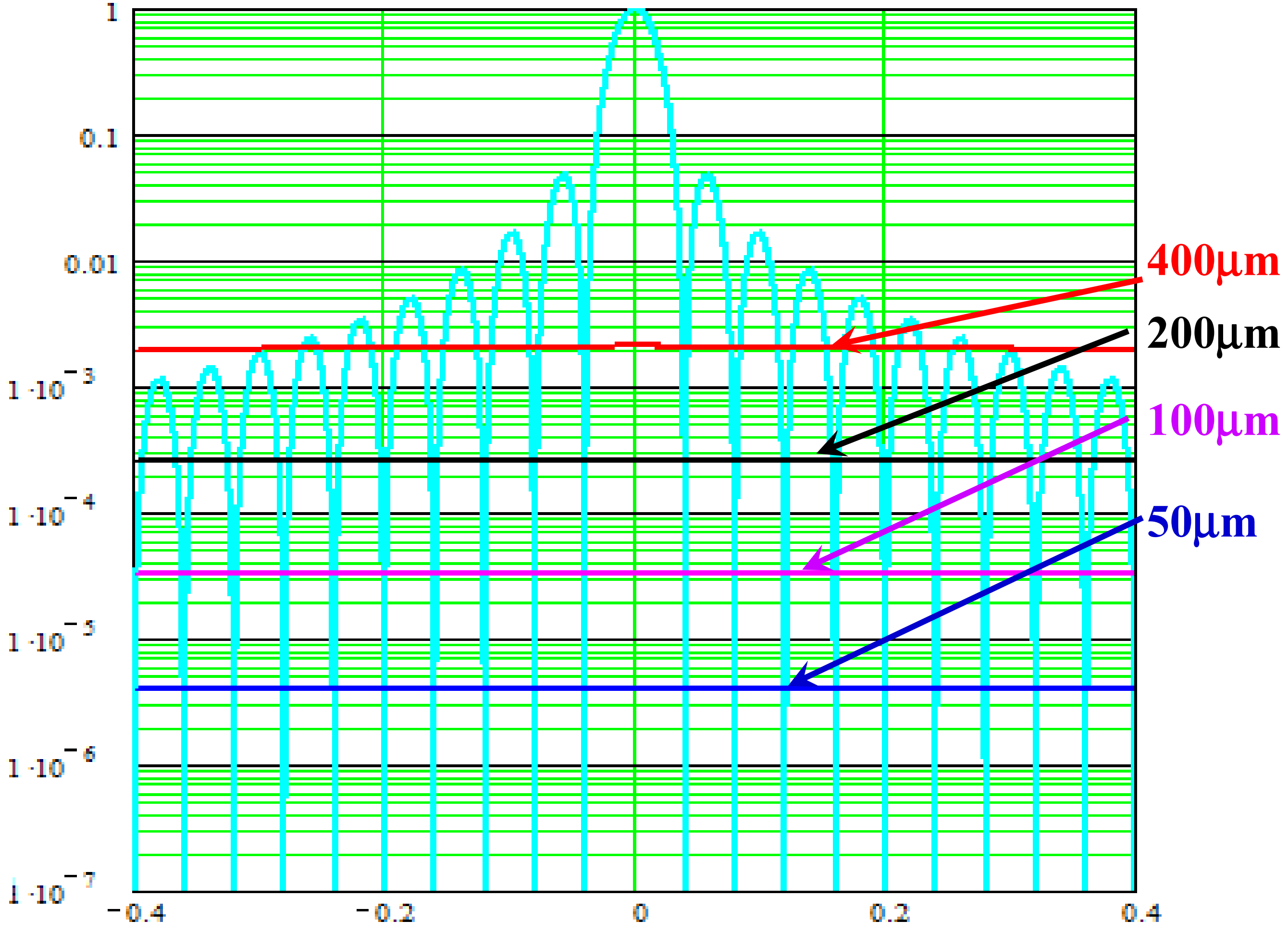
Extinction rate = entrance pupil aperture area / total area of noise source

To escape from noise produced by the objective lens is most important issue in the coronagraph!!

Simulation result of background produced by dig on objective surface



A zoom up plot near Airy disk



How to eliminate Mie scattering??

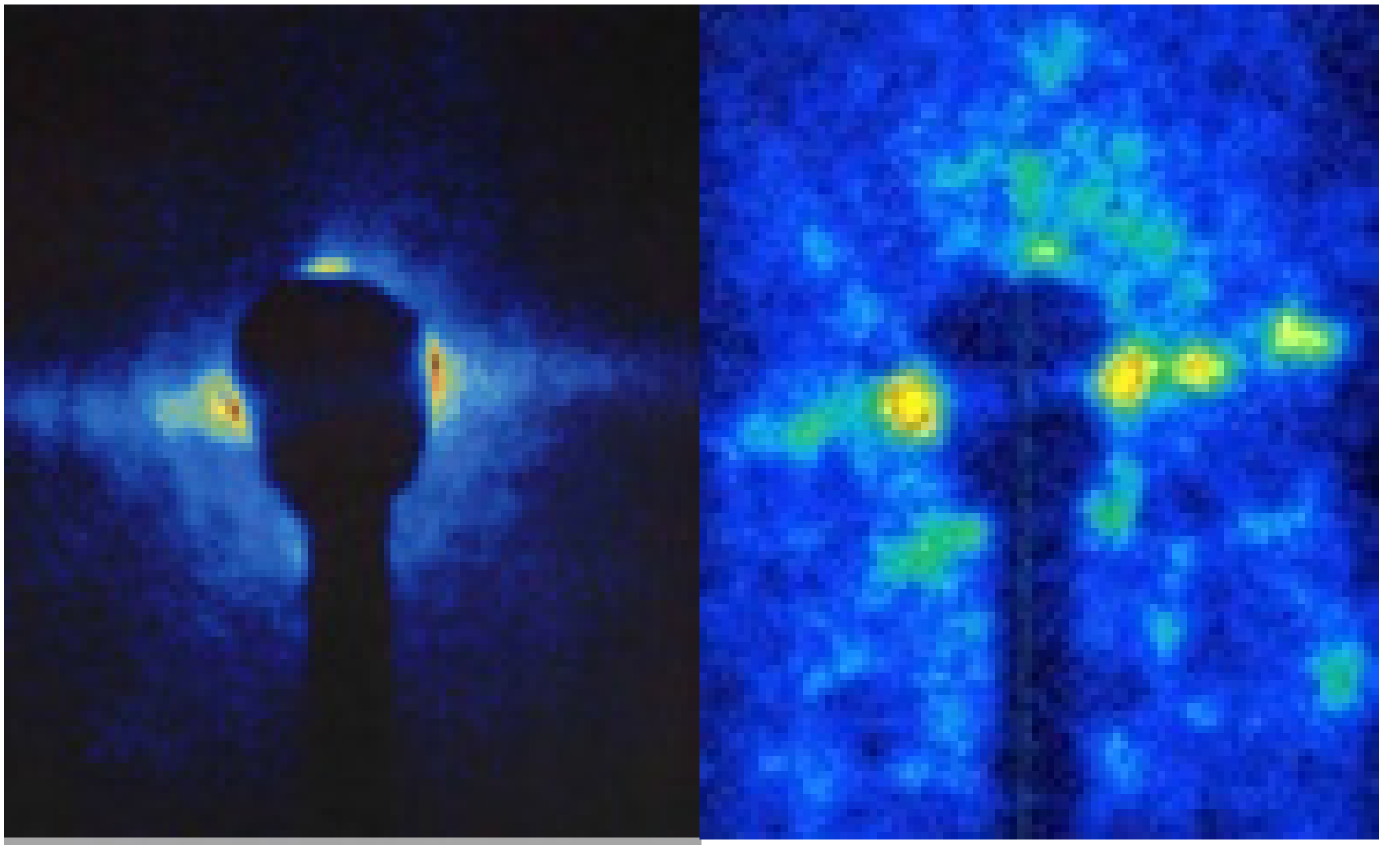
1. A careful optical polishing for the objective lens.
2. Reduce number of glass surface. use a singlet lens for the objective lens.
3. No coating (Anti-reflection, Neutral density etc.) for objective lens.

Comparison between normal optical polish and careful optical polish for coronagraph

S&D 60/40 surface of the lens

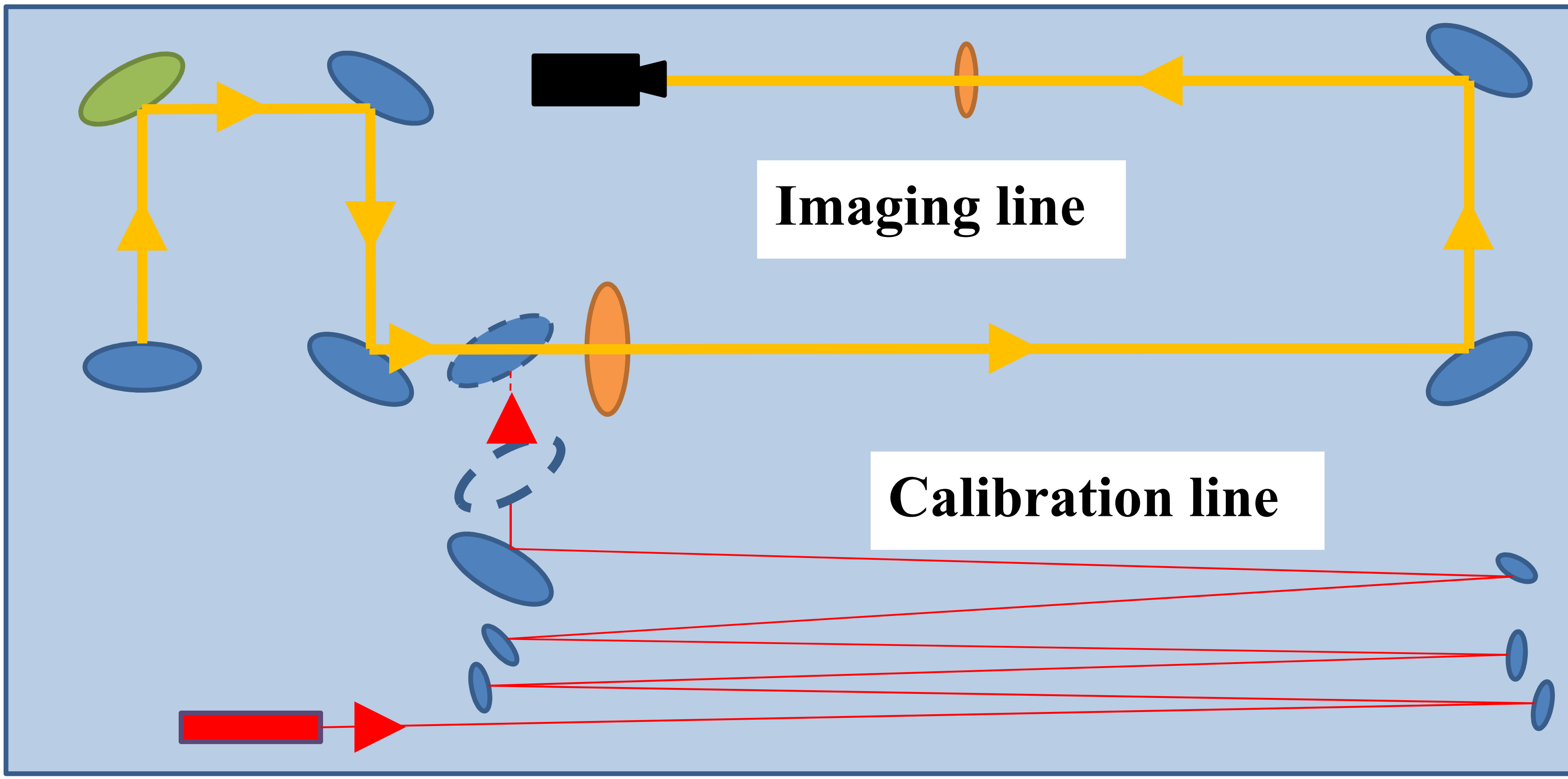
Surface of the coronagraph lens

Example of Mie-Scattering noise

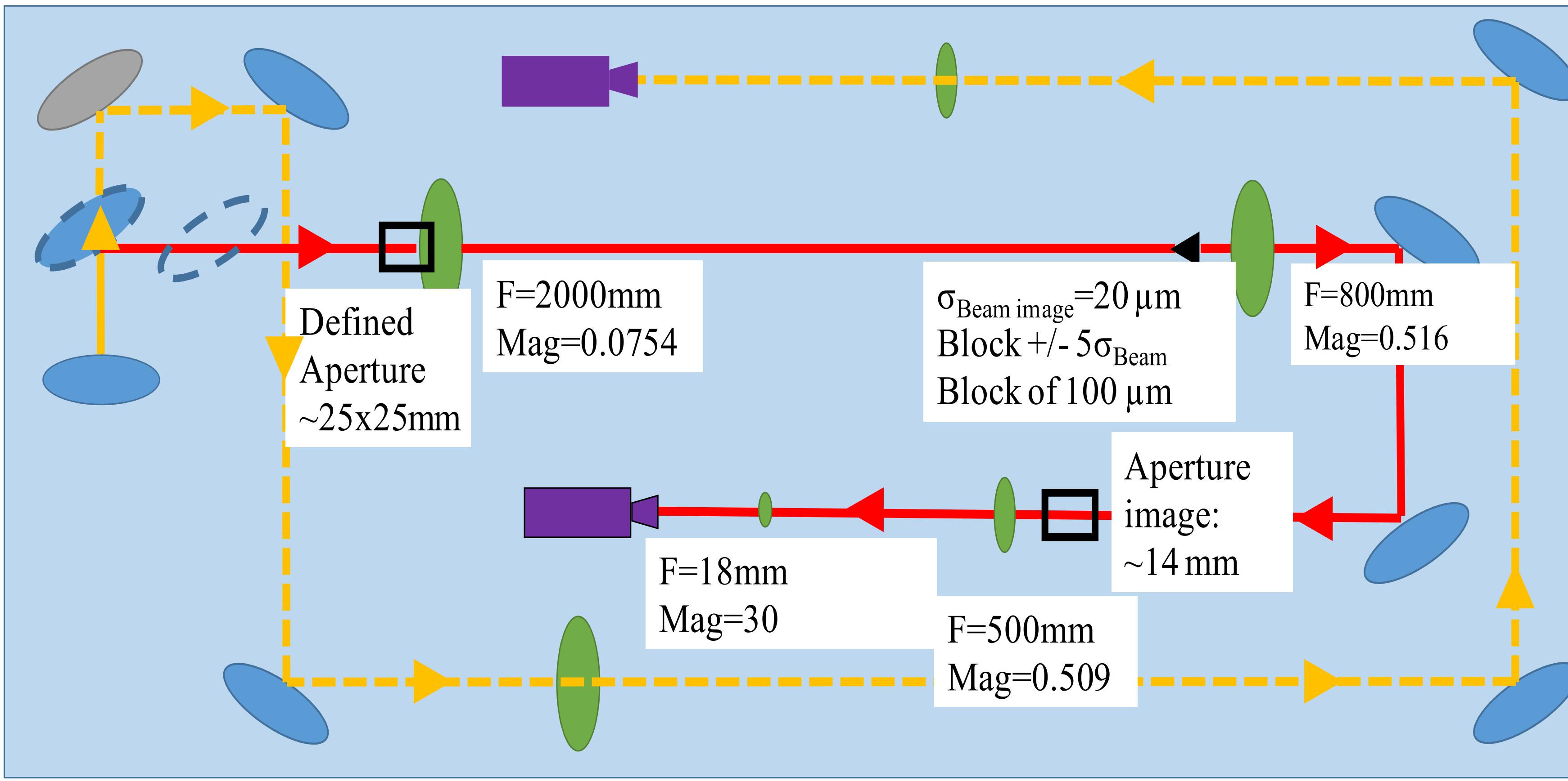


5. Arrangement of phase 1 coronagraph on B2 optical table

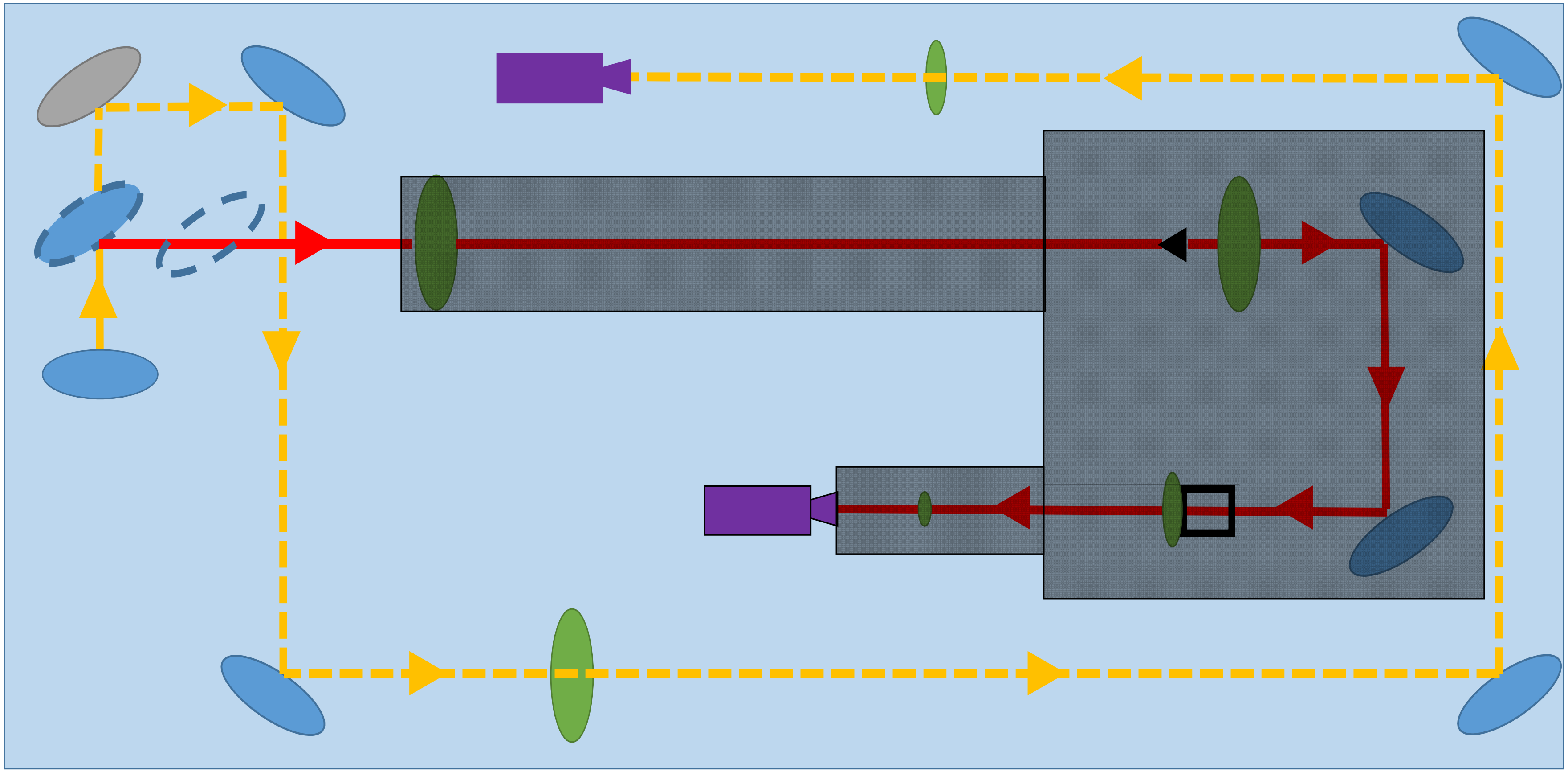
Present Layout B2



Arrangement of the Phase 1 coronagraph



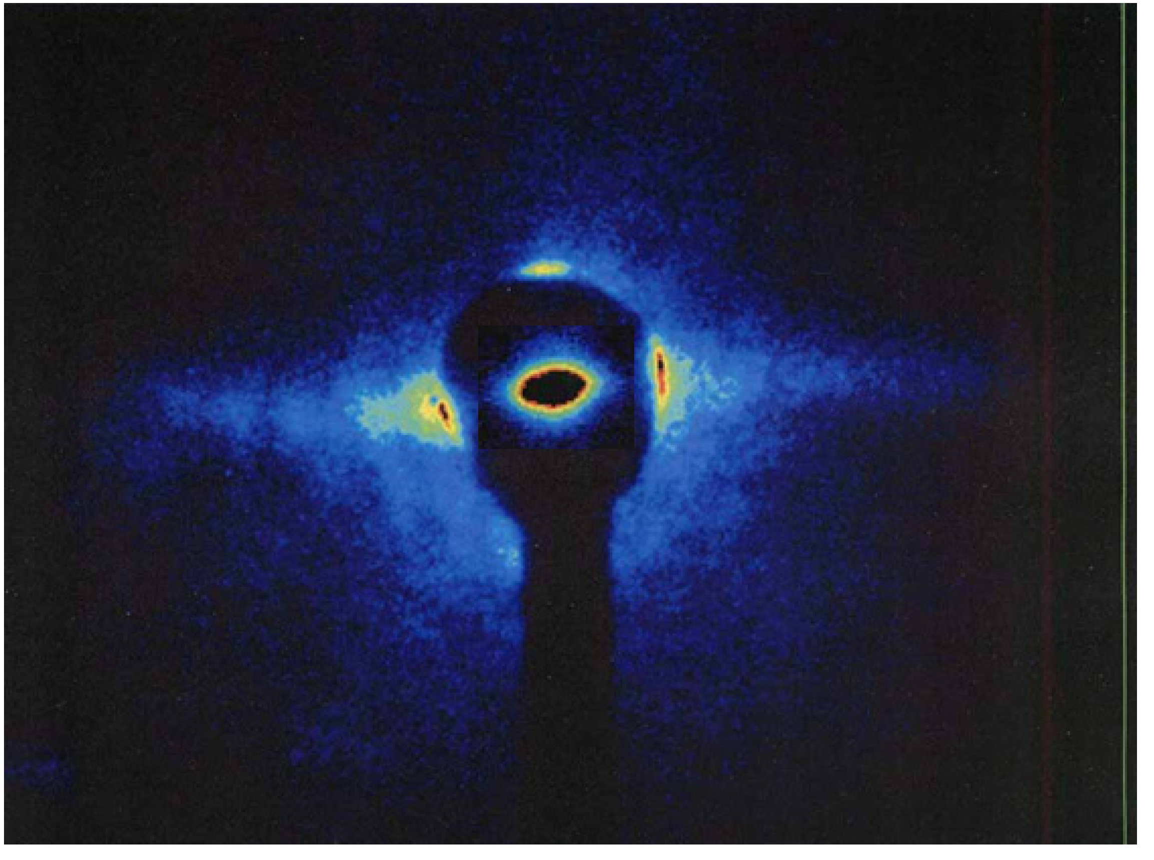
Surrounding dark box and tubes



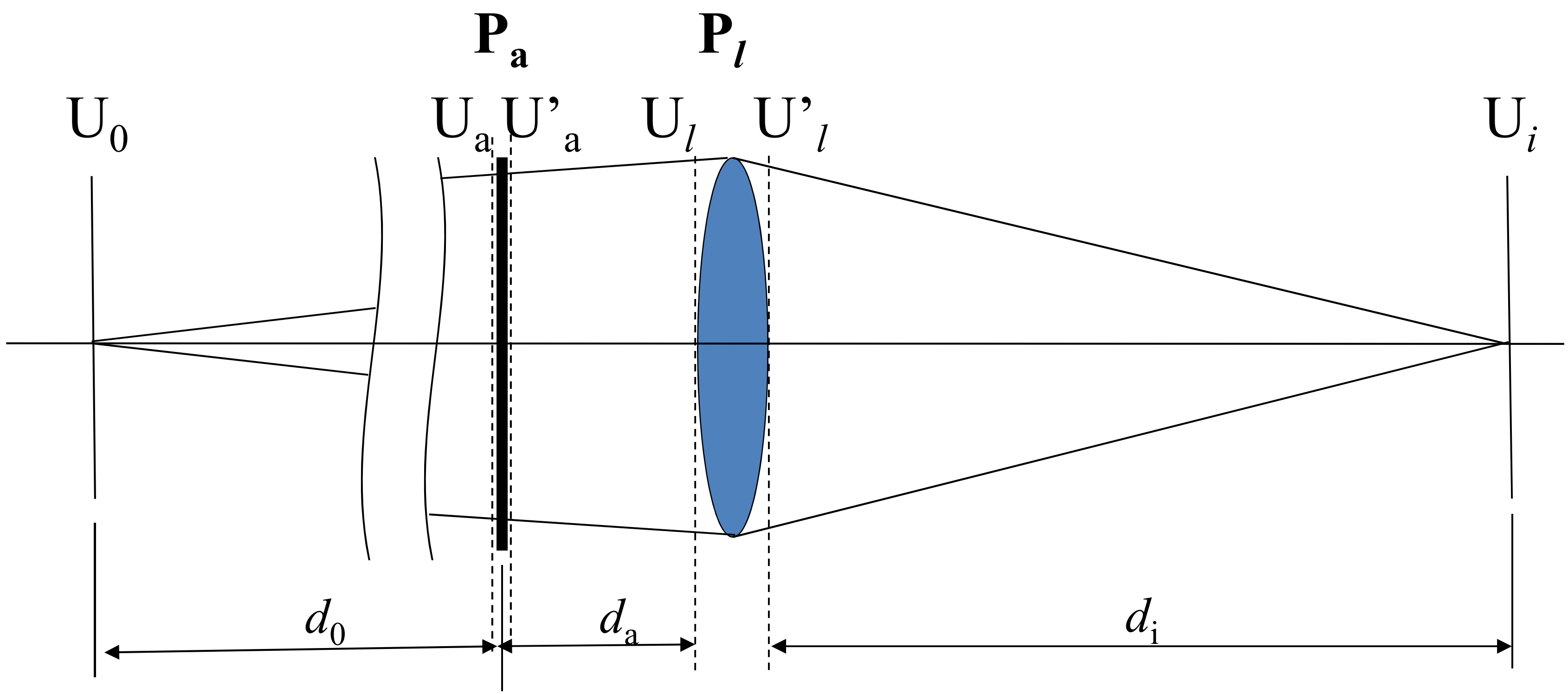
Summary for phase 1 coronagraph design

1. Coronagraph optics for phase 1 observation of beam halo is designed for B2 SR monitor beam line at LHC.
2. From diffraction analysis the background in phase1 coronagraph from leakage of diffraction fringe is estimated to $3.7x10^{-4}$. Other of 2 fringes in the centre, most of diffraction fringes have intensities of 10^{-5} to 10^{-6} range.
3. The digs having a diameter smaller than 100mm are the majority. An order of 10^{-4} to 10^{-5} background can be appeared phase 1 using the B2 SR monitor line.

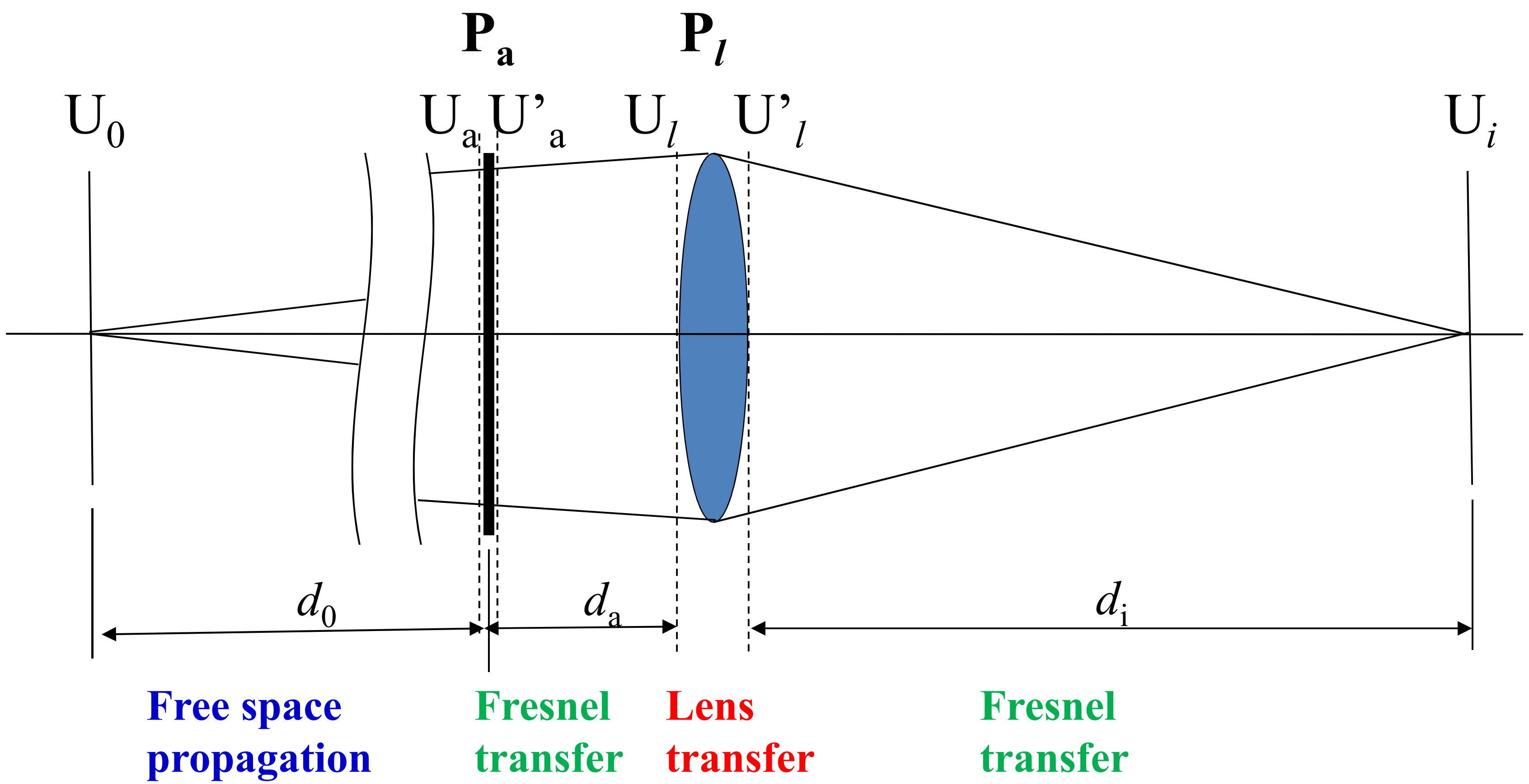
Thank very much for your attention!



Case 2. Noise source in front of the objective lens



Noise source in front of the lens



After tired calculations,

$$U_i(x_i, y_i) = \iint \left[\iint P_a(x_a, y_a) \, exp\left\{ i \frac{k}{2} \left(\frac{1}{d_0 - d_a} - \frac{1}{d_a} \right) \left(x_a{}^2 + y_a{}^2 \right) \right\} \right.$$

$$\left. \cdot \, exp\left\{ -ik \left(\left(\frac{x_0}{d_0 - d_a} + \frac{x_l}{d_a} \right) x_a + \left(\frac{y_0}{d_0 - d_a} + \frac{y_l}{d_a} \right) y_a \right) \right\} dx_a dy_a \right]$$

$$\cdot \, P_l(x_l, y_l) \, exp\left\{ i \frac{k}{2} \left(\frac{1}{d_l} + \frac{1}{d_i} - \frac{1}{f} \right) \left(x_l{}^2 + y_l{}^2 \right) \right\}$$

$$\cdot \, exp\left\{ -i \frac{k}{d_i} \left(x_i \, x_l + y_i \, y_l \right) \right\} dx_l dy_l$$

$$in\ here,\ d_l = d_a + d_0$$

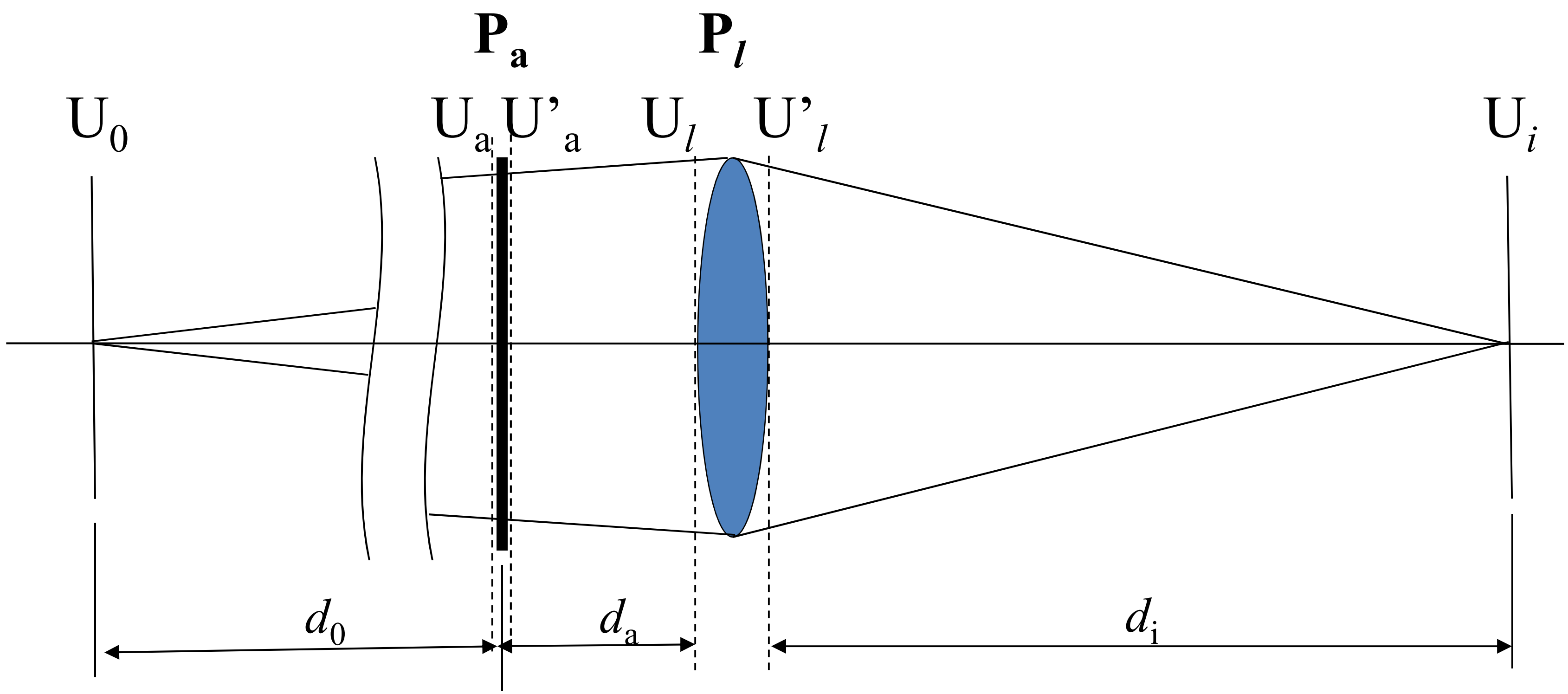
After tired calculations,

Diffraction by noise source

$$U_i(x_i, y_i) = \iint \left[\iint P_a(x_a, y_a) \exp\left\{ i\frac{k}{2}\left(\frac{1}{d_0 - d_a} - \frac{1}{d_a} \right)\left(x_a^2 + y_a^2\right) \right\} \cdot \exp\left\{ -ik\left(\left(\frac{x_0}{d_0 - d_a} + \frac{x_l}{d_a} \right) x_a + \left(\frac{y_0}{d_0 - d_a} + \frac{y_l}{d_a} \right) y_a \right) \right\} dx_a dy_a \right]$$

$$\cdot P_l(x_l, y_l) \exp\left\{ i\frac{k}{2}\left(\frac{1}{d_l} + \frac{1}{d_i} - \frac{1}{f} \right)\left(x_l^2 + y_l^2\right) \right\} \cdot \exp\left\{ -i\frac{k}{d_i}\left(x_i x_l + y_i y_l\right) \right\} dx_l dy_l$$

Diffraction by lens pupil



Noise source to objective lens ➡ Fresnel like diffraction

Then this input is re-diffracted by objective lens pupil

d_a is shorter : out of focus image of noise source +Fresnel like diffraction

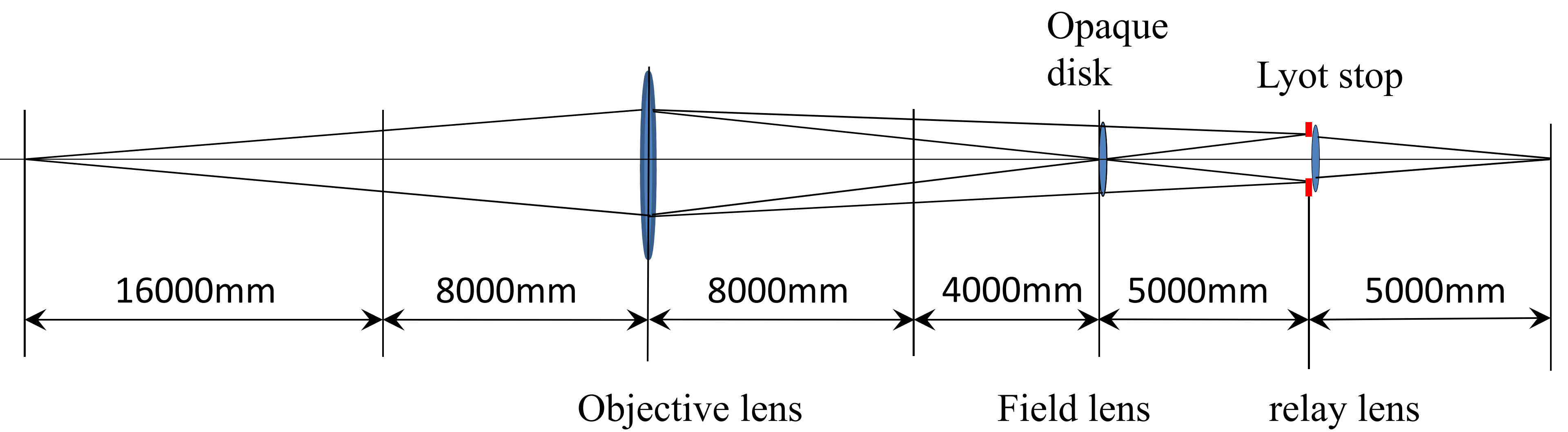
d_a is longer : quasi-focused image of noise source +Fraunhofer like diffraction

Phase 2 coronagraph

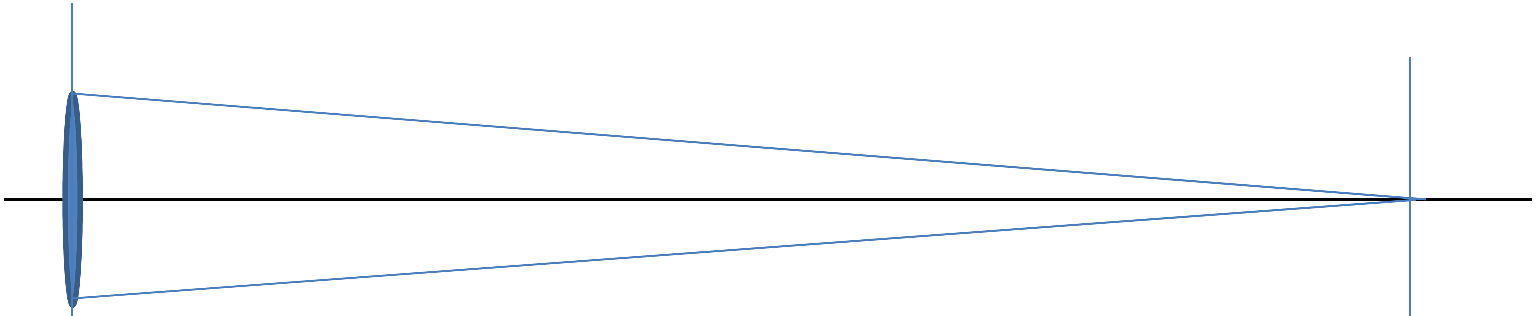
1. The leakage of diffraction fringe reduces by increase of opaque disk diameter.
We can realize better contrast with bigger image size of the beam core.
We should design the focal length of objective lens longer.

2. Chromatic shift on optical axis is given by focal length divided by the Abbe number, designing long focal length means increase of chromatic foal shift.
We should apply reflector focusing system for the objective instead of the objective lens system in phase 2.

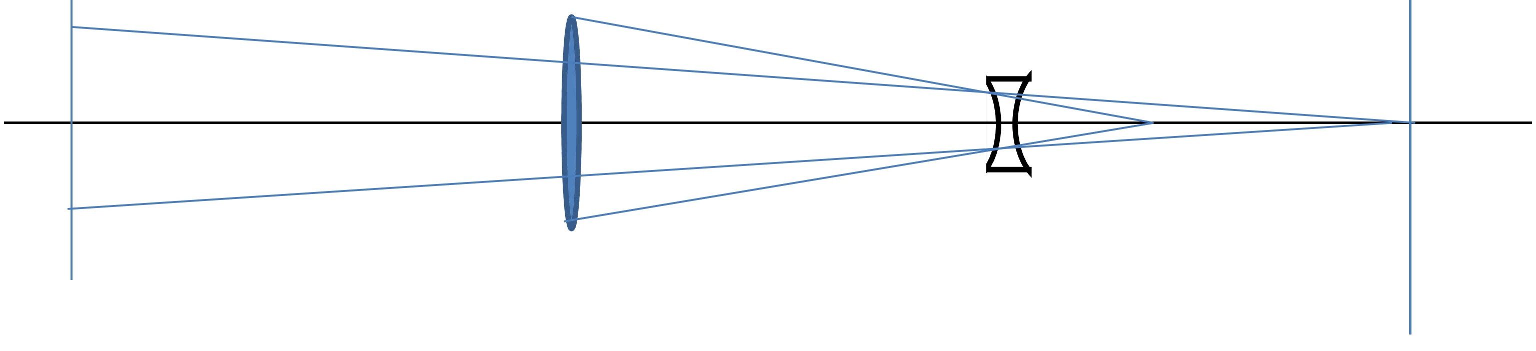
Coronagraph having a magnification of 0.5



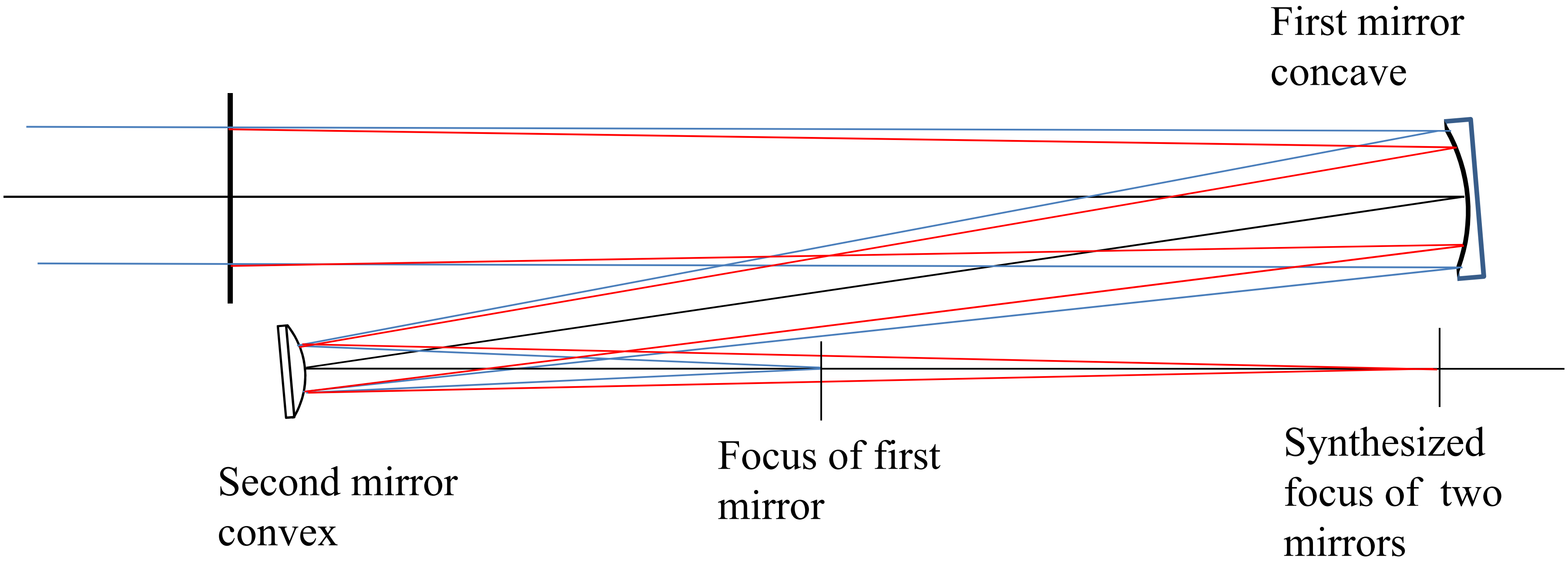
Reduction the actual length of long focus of the simple objective lens with a combination of focus and defocus lenses.



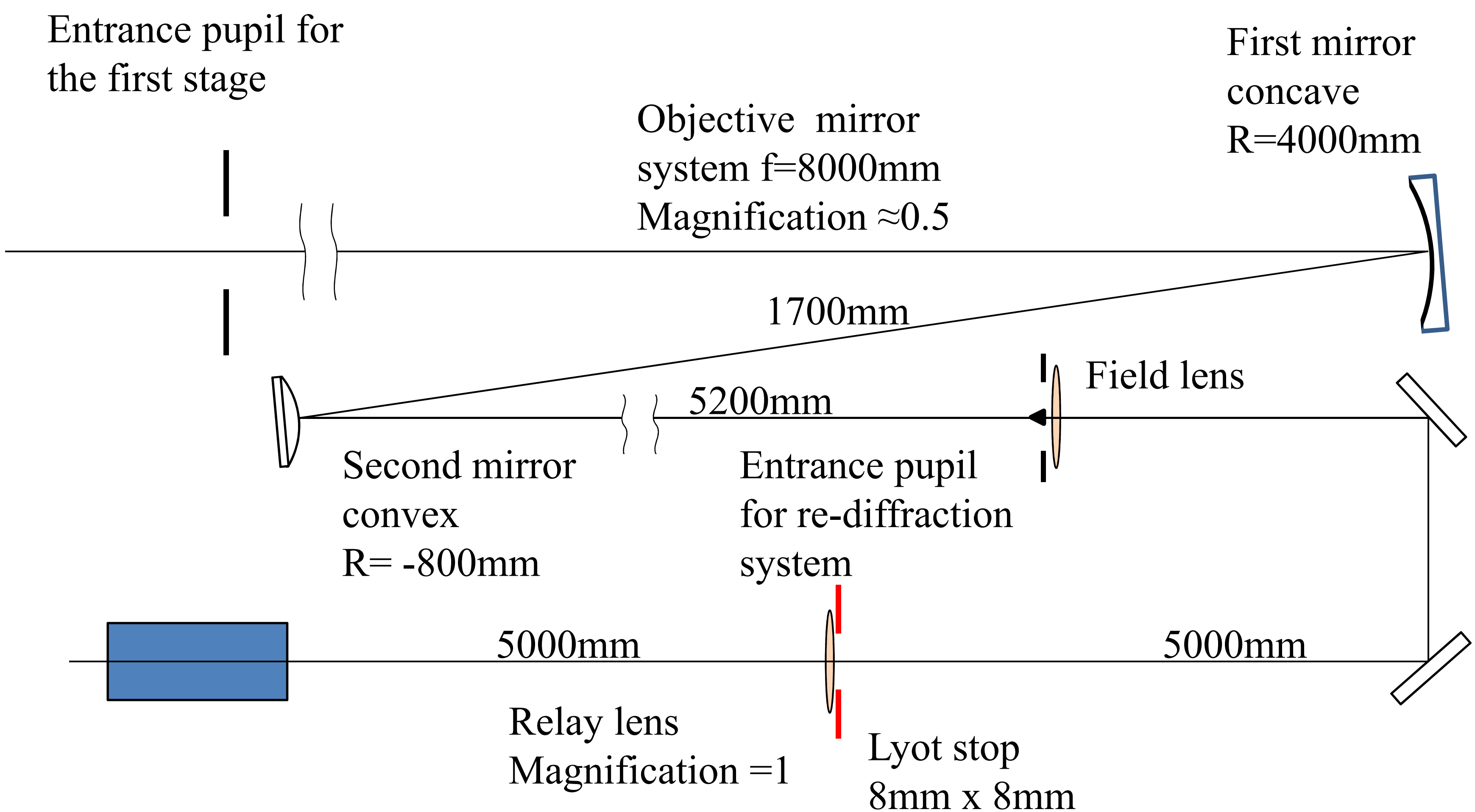
Telephoto type lens



Telephoto type with reflectors

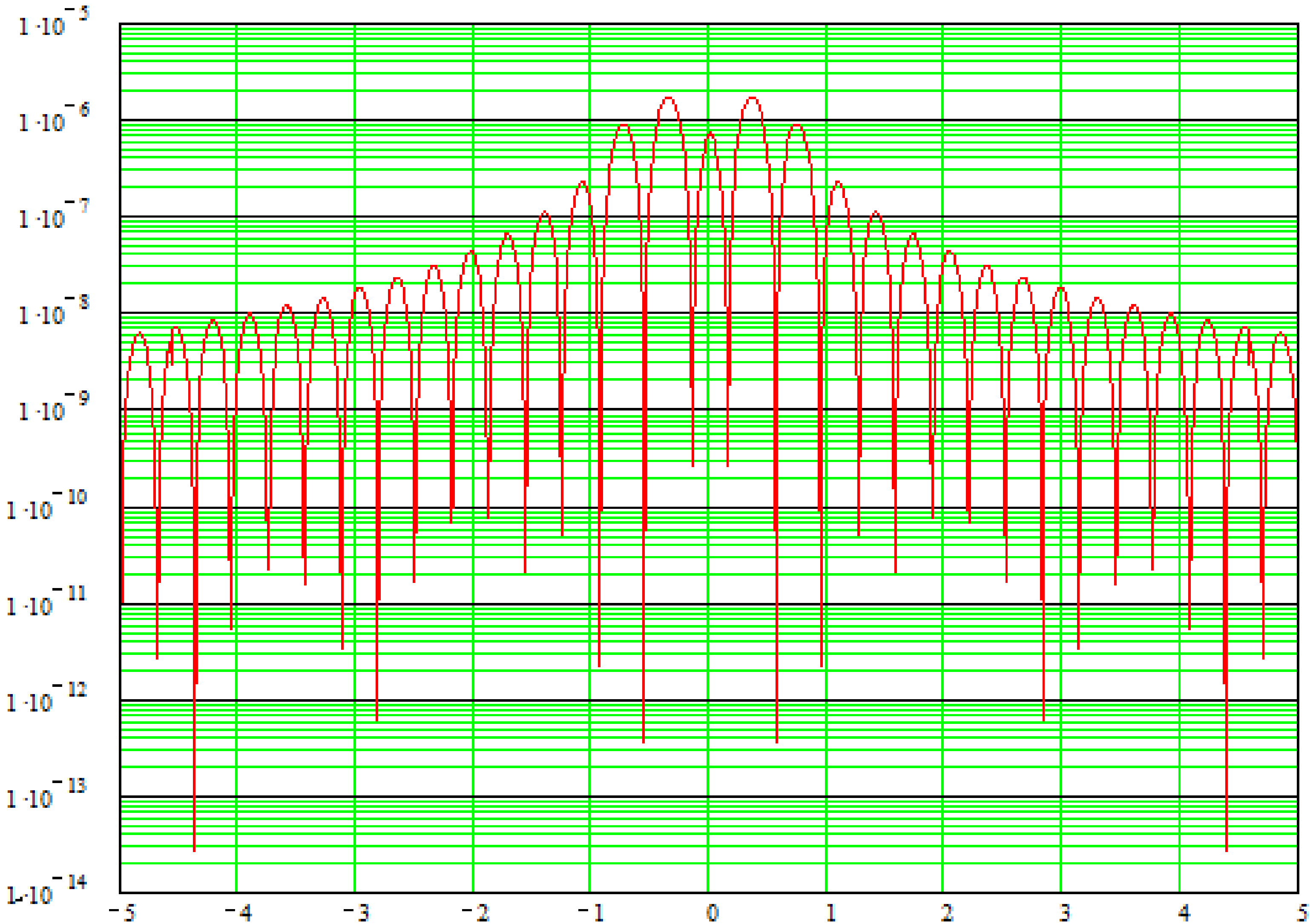


Optical design



Diffraction background at 3ed stage

In Log scale 2x10^{-6} to 10^{-7}



Possibility of appodization at aperture of relay lens (may be new idea for coronagraph)

Since normal appodization at objective lens aperture is not applicable because it's Mie scattering noise.

We can apply an appodization at relay lens aperture which is conjugated point to objective lens aperture.

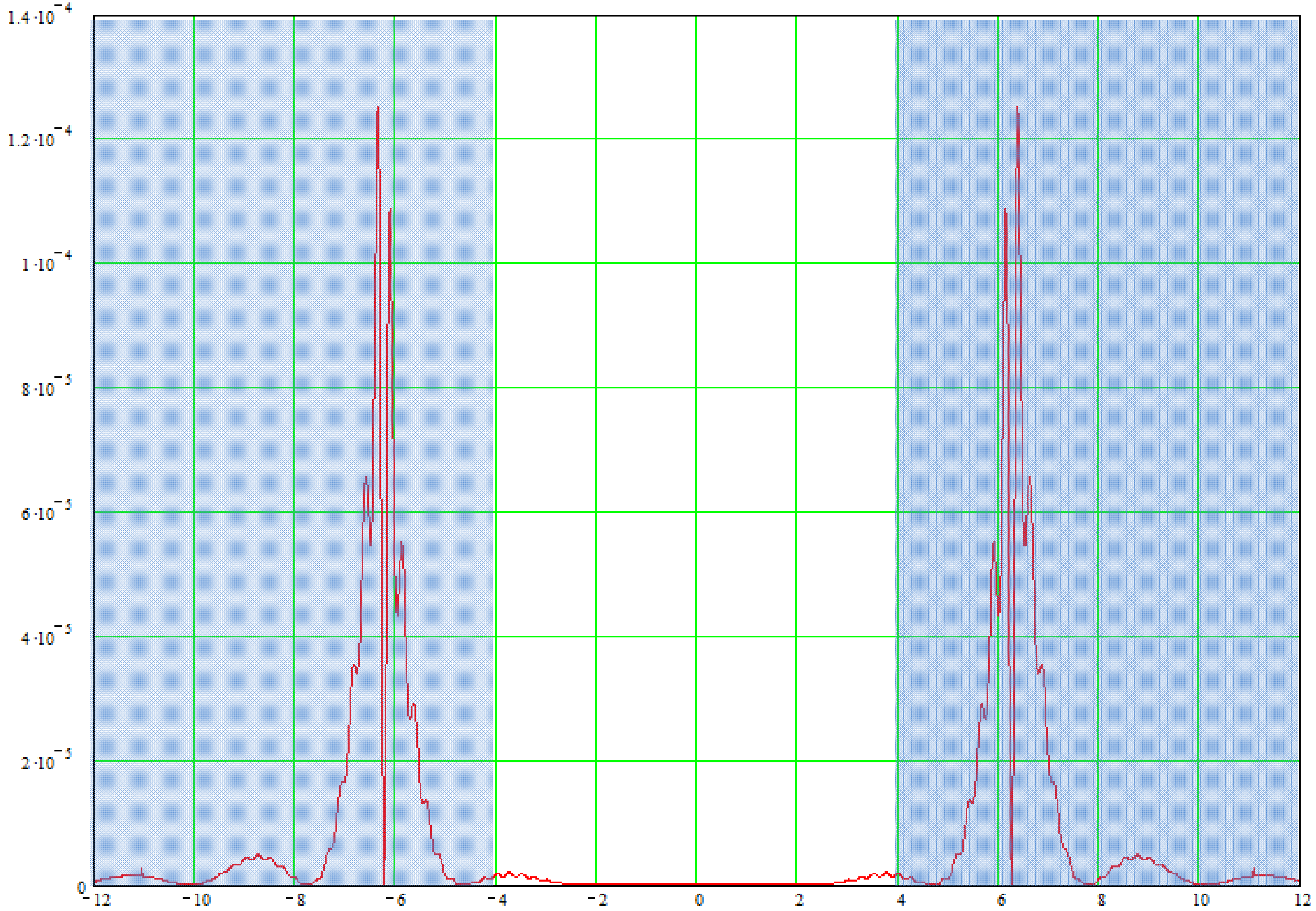
As in previous slide, the diffraction pattern produced by the field lens aperture has two kind of period;

1. **Rough period come from diameter of opaque disk**

2. **Fine period come from outer diameter of the field lens.**

The measure leakage of diffraction fringe in inside of Lyot stop is mainly come from the 1st one.

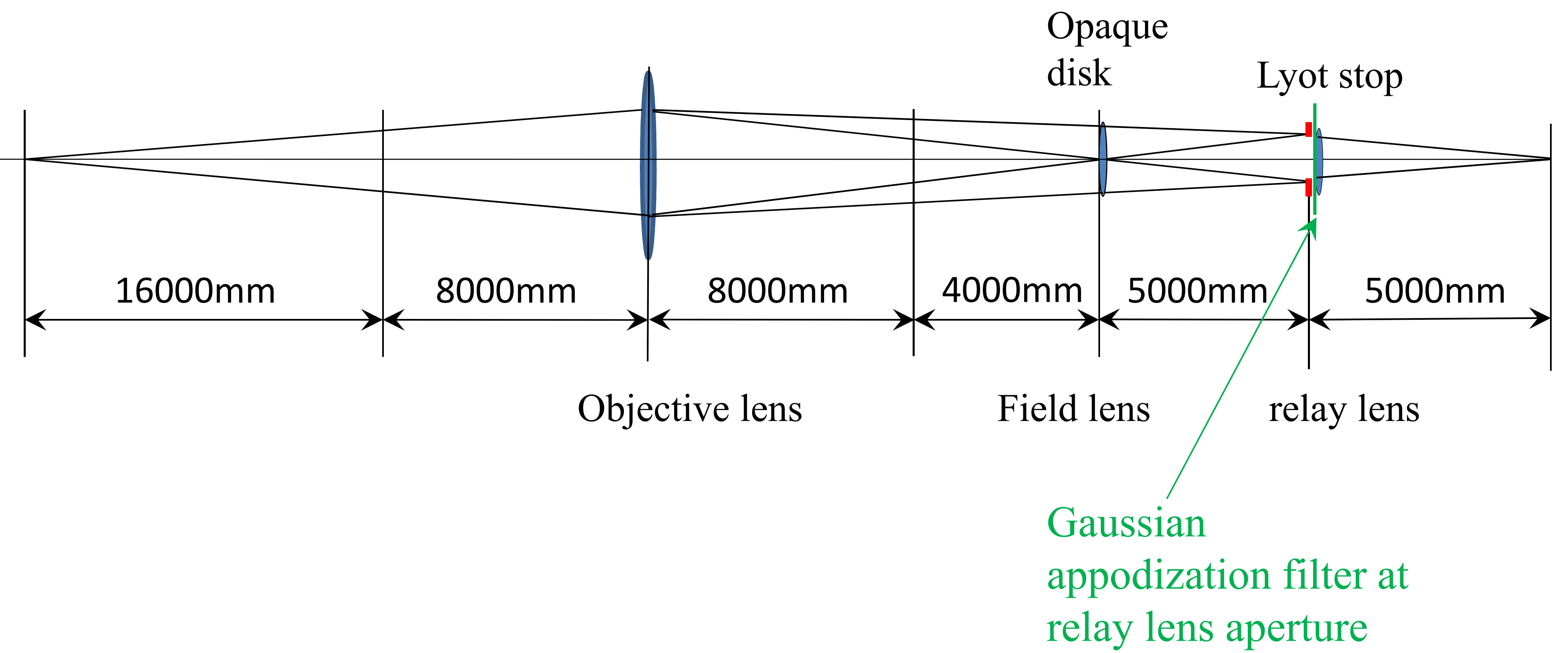
Lyot stop at +/-4mm



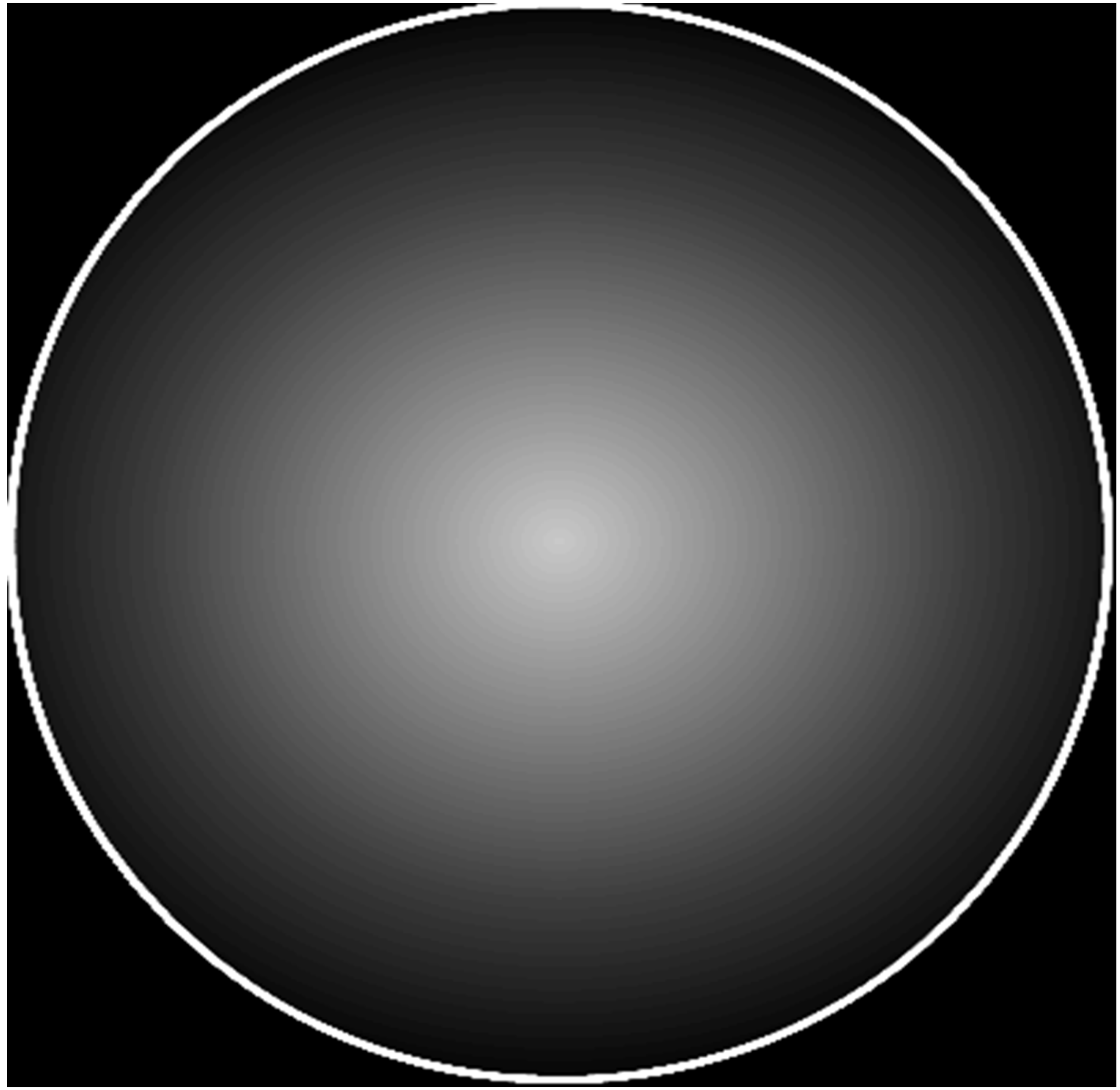
This leakage of diffraction fringe is the measure source of background in final imaging plain.

Therefore, we can reduce this background by killing the leakage of diffraction fringe using appodization for final lens aperture.

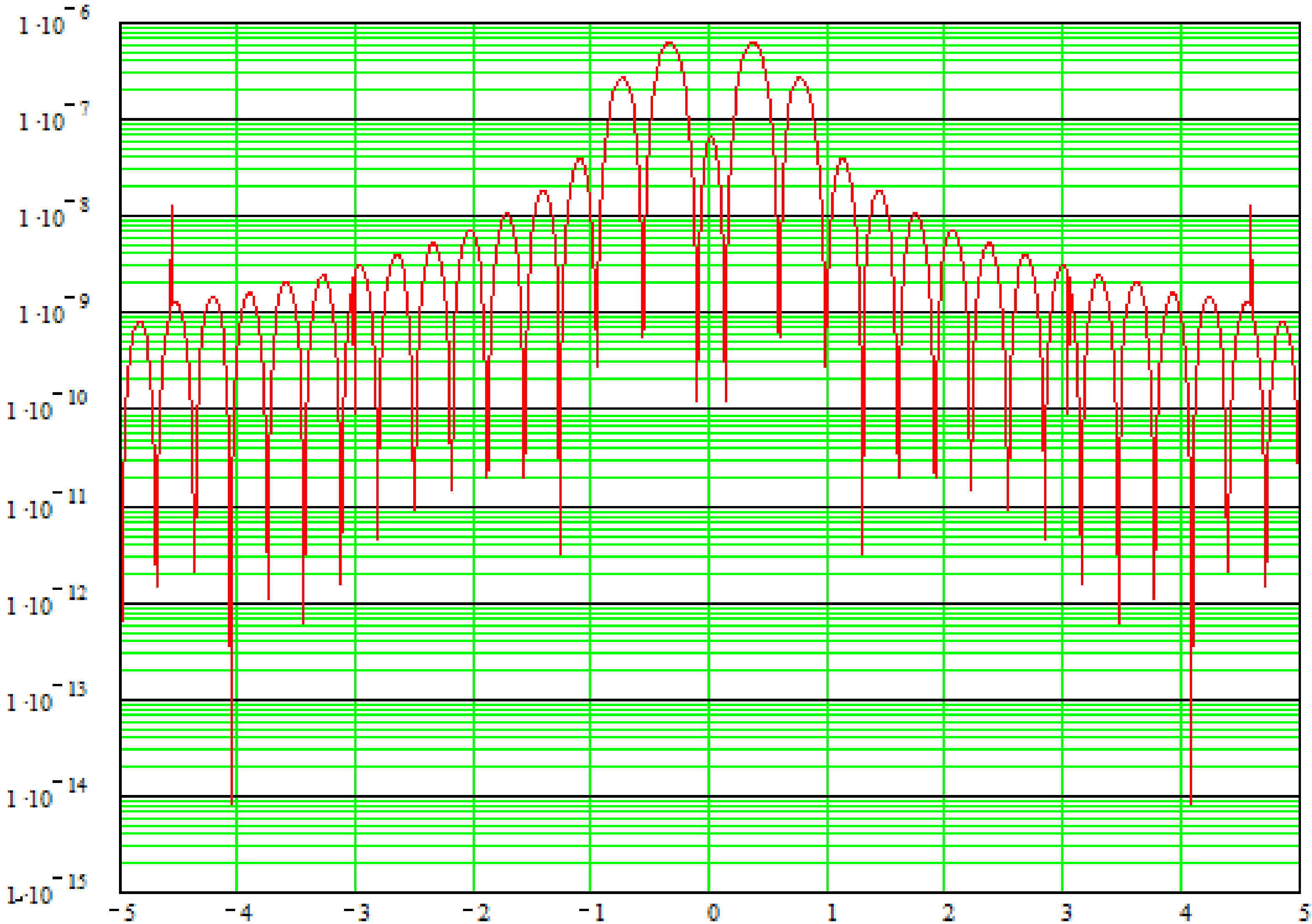
Please take care this kind appodization will reduce spatial resolution at final imaging plane in the same time!


Opaque
disk
Lyot stop
16000mm
8000mm
8000mm
4000mm
5000mm
5000mm
Objective lens
Field lens
relay lens
Gaussian
appodization filter at
relay lens aperture

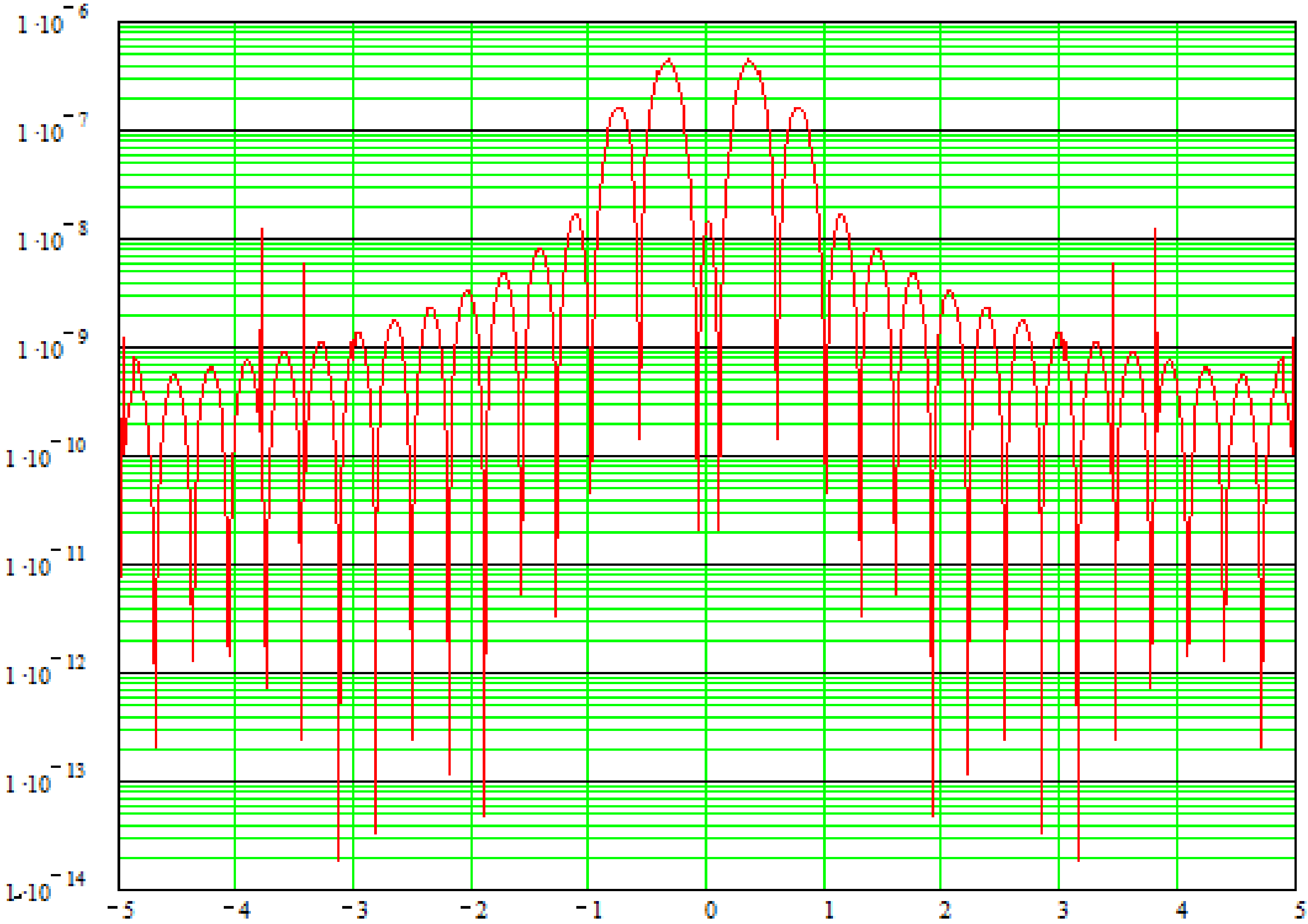
Appodization of Gaussian graduation On relay lens aperture



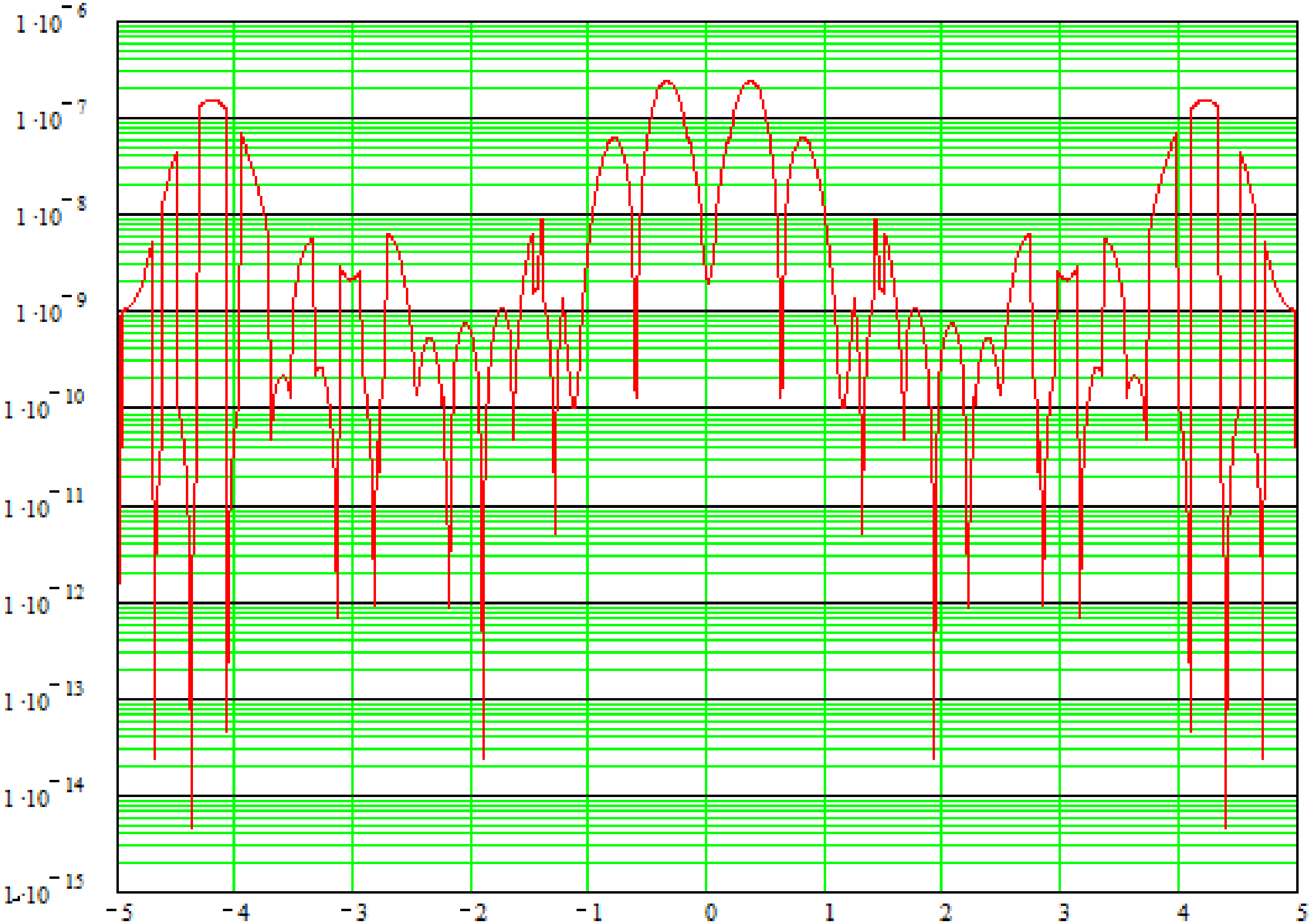
Gaussian appodization a=3mm



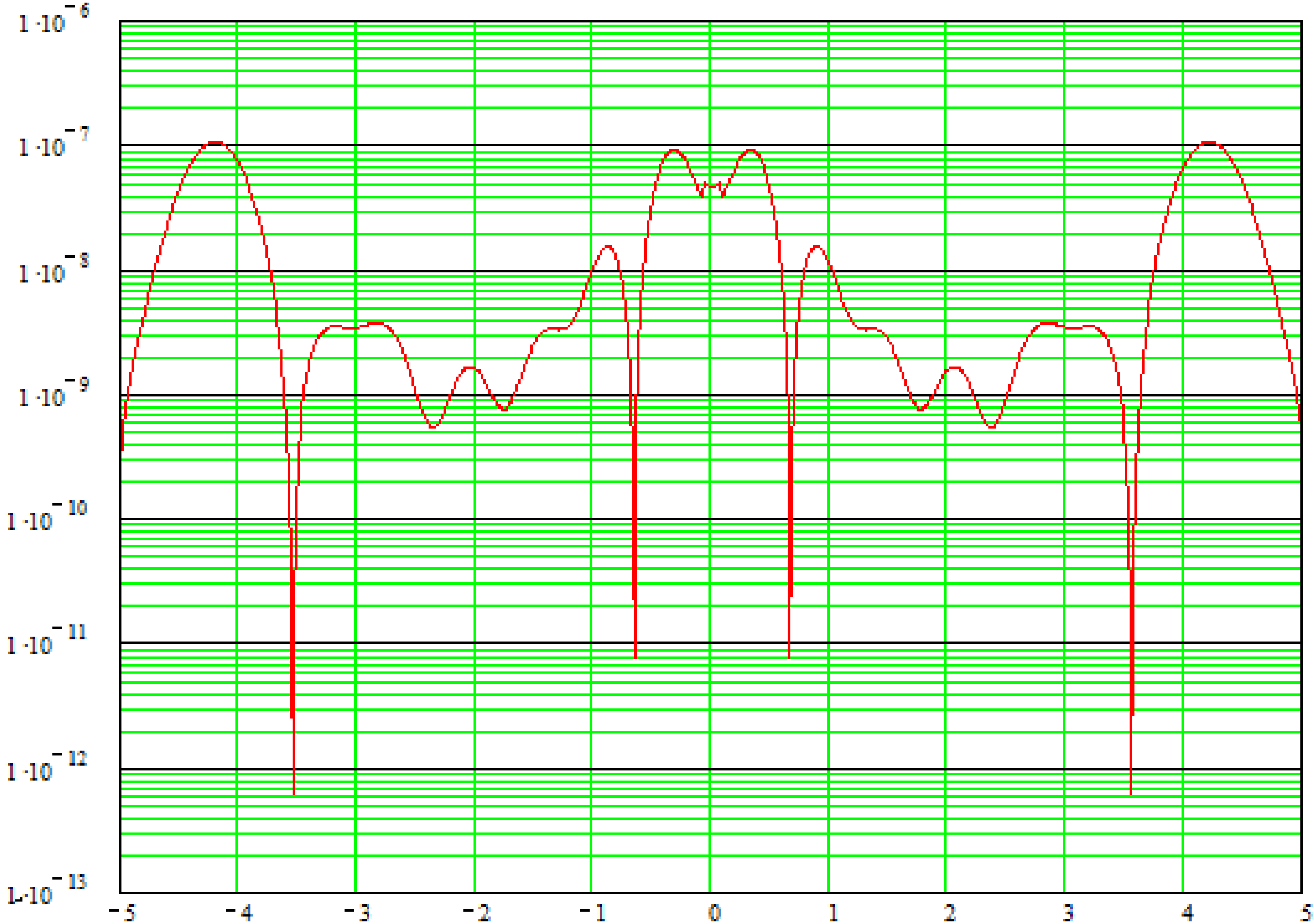
Gaussian appodization a=2.5mm



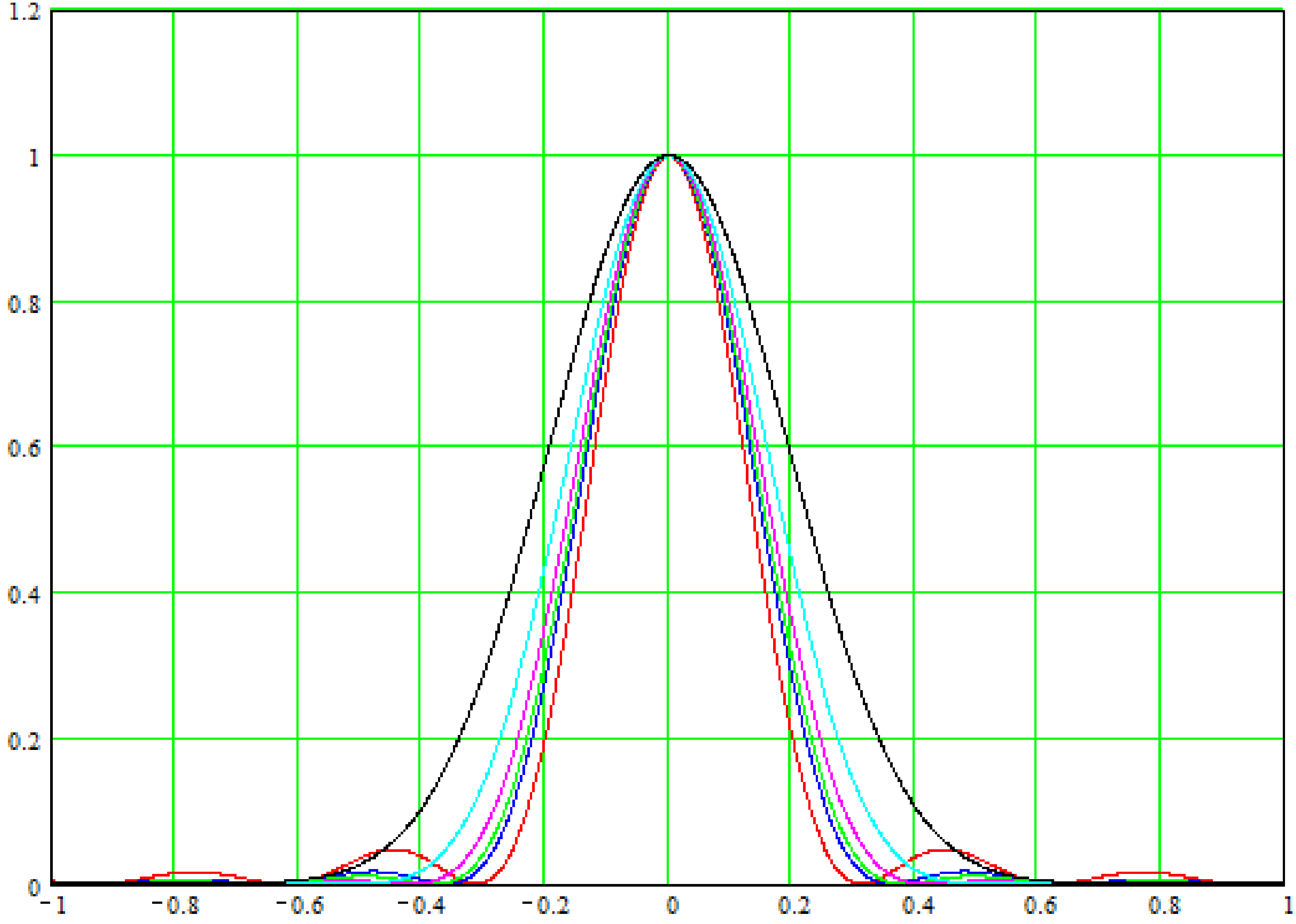
Gaussian appodization a=2mm



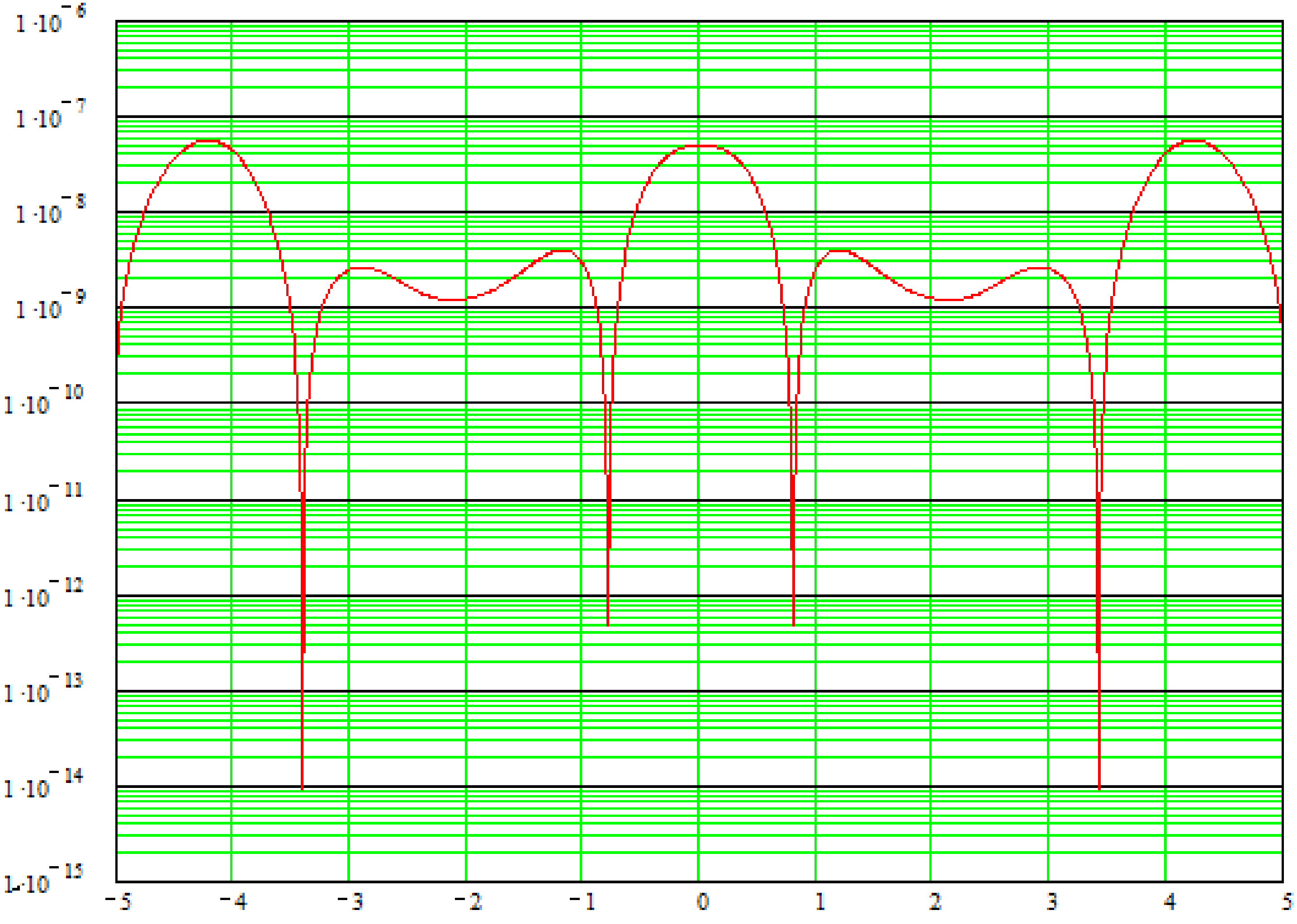
Gaussian appodization a=1.5mm

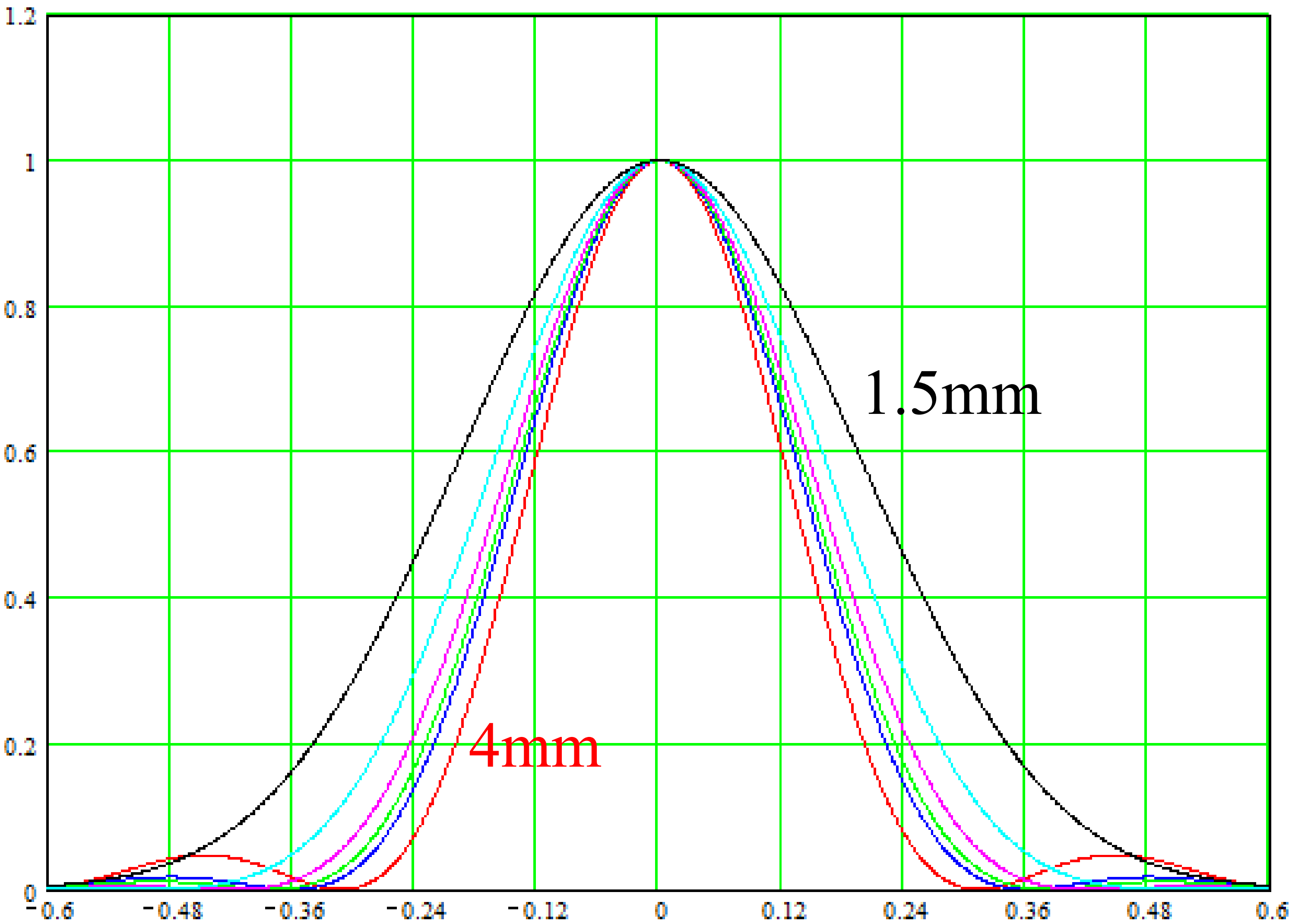


Diffraction in halo with Gaussian appodization



Gaussian appodization a=1mm




1.2
1
0.8
0.6
0.4
0.2
0
-0.6
-0.48
-0.36
-0.24
-0.12
0
0.12
0.24
0.36
0.48
0.6
1.5mm
4mm

Conclusion from Gaussian appodization

1. Gaussian appodization at relay lens aperture can improve the contrast of noise diffraction.
2. Such appodization increase width of diffraction for halo image, and will reduce spatial resolution.
3. Appodization also reduce illumination from halo onto the relay lens aperture and reduce the intensity of halo image. So careful comparison of contrast between noise diffraction and halo image will necessary

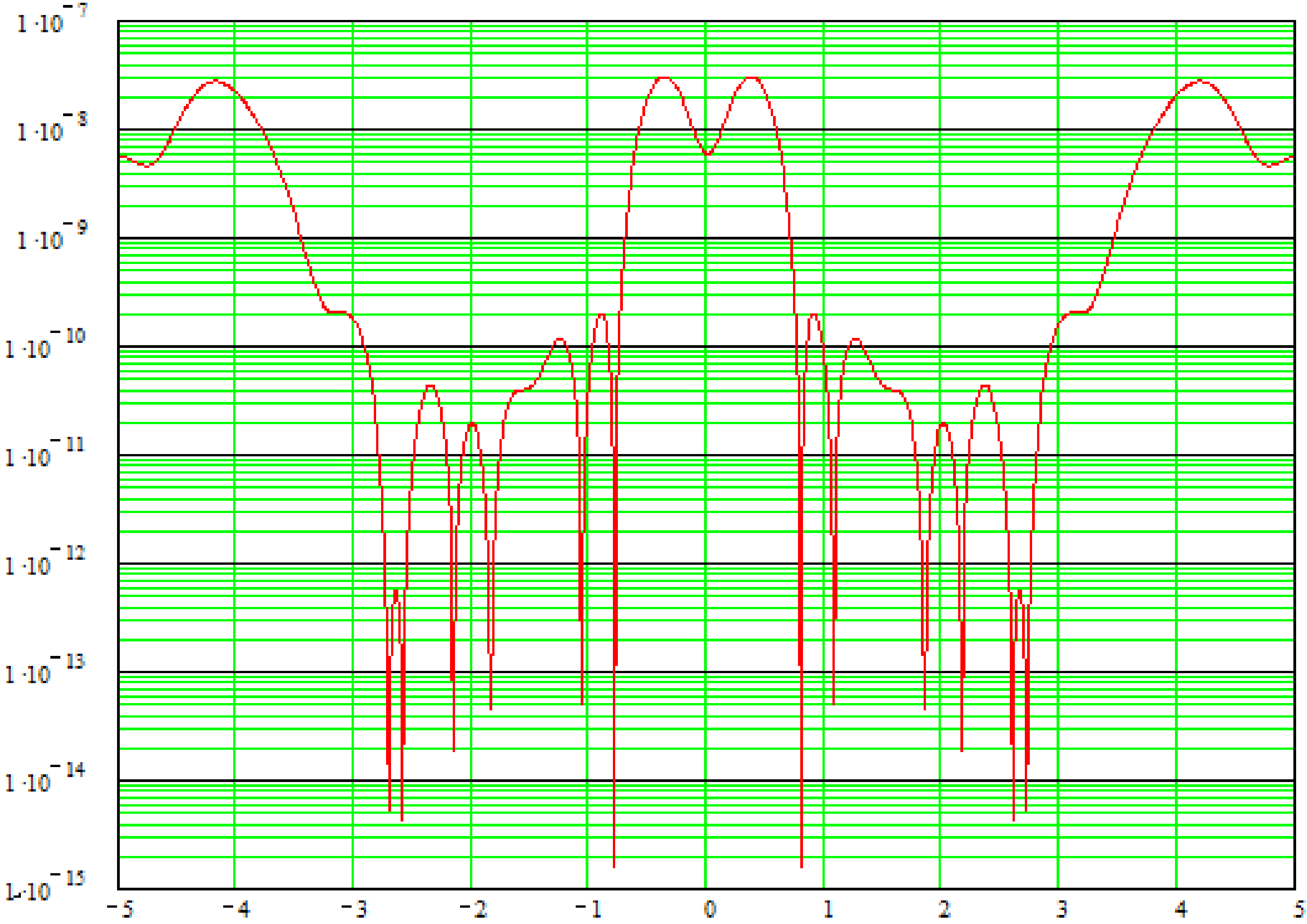
Background level for 1:1 magnification

I wrote following discussion for more general possibility of the coronagraph.
Since the entrance aperture is limited by the opening of the SR, following discussion is meaning less.

Following simulation is assumed 1:1 magnification with same diffraction width. This condition means the entrance aperture must be enlarge proportional to the magnification.

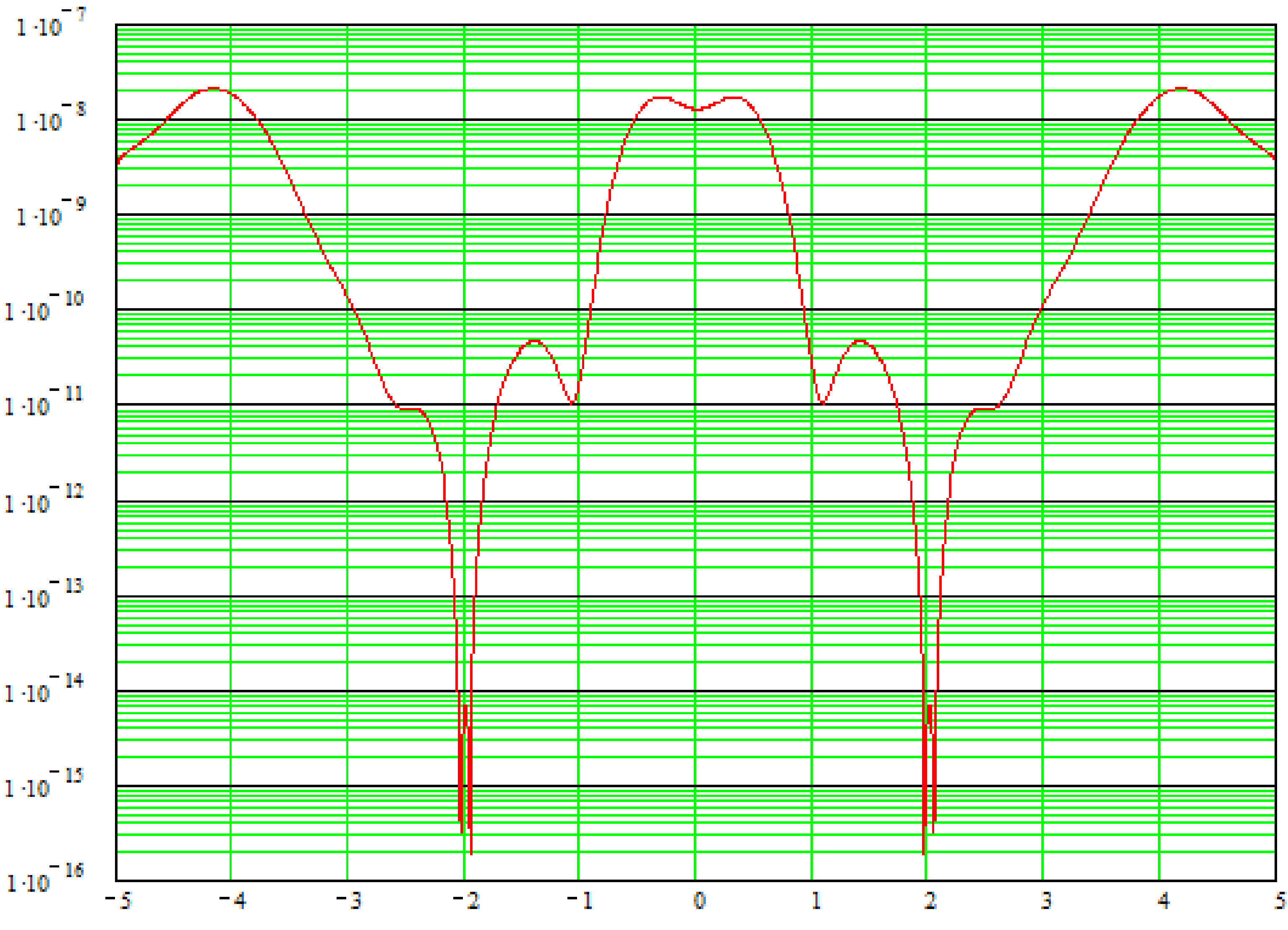
This is meaningless discussion for LHC, but one possibility to improve the coronagraph for exo-planet observation (it needs 10^{-10} background level).

1.5mm



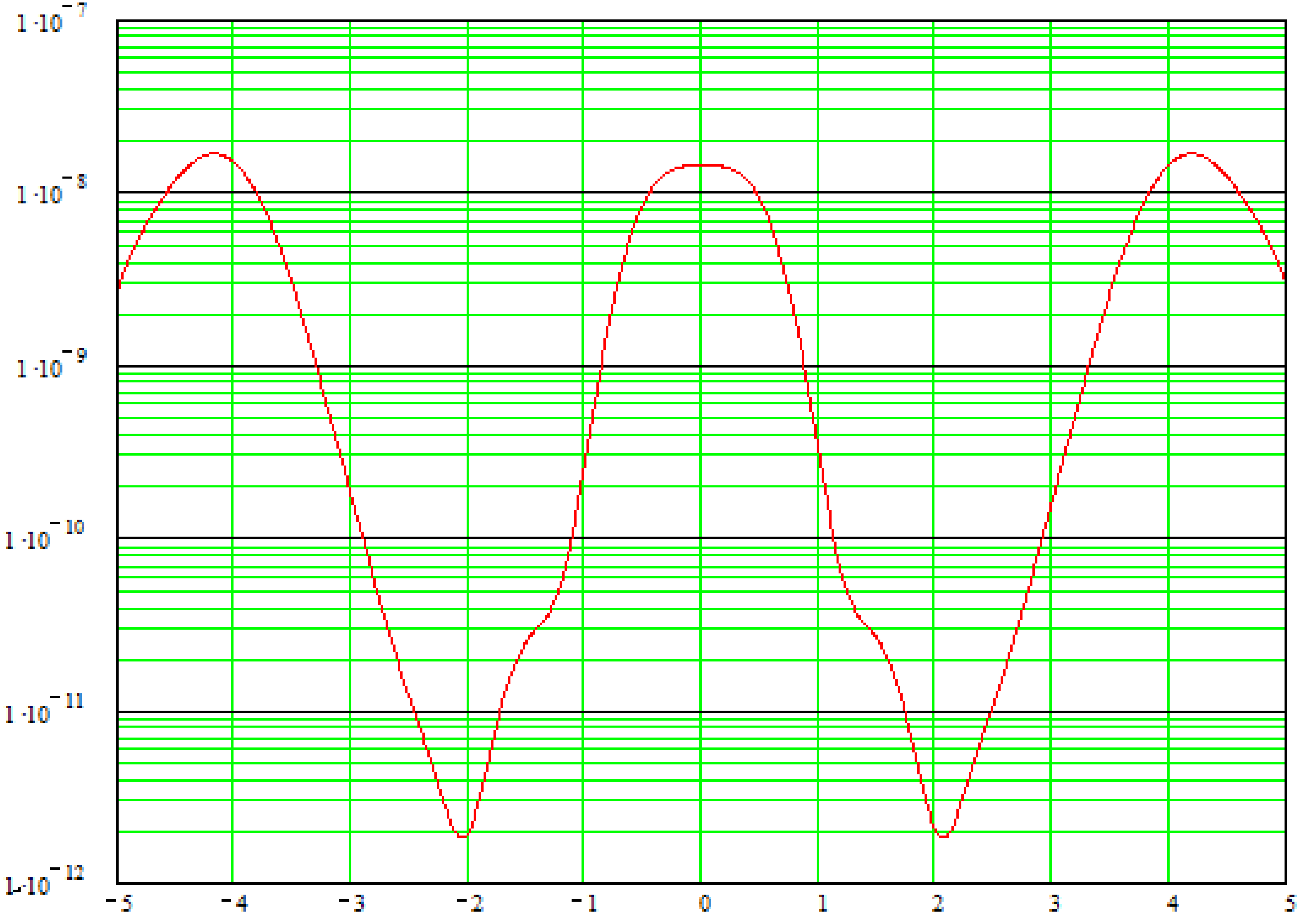
1·10⁻⁷
1·10⁻⁸
1·10⁻⁹
1·10⁻¹⁰
1·10⁻¹¹
1·10⁻¹²
1·10⁻¹³
1·10⁻¹⁴
1·10⁻¹⁵
−5
−4
−3
−2
−1
0
1
2
3
4
5

1.2mm

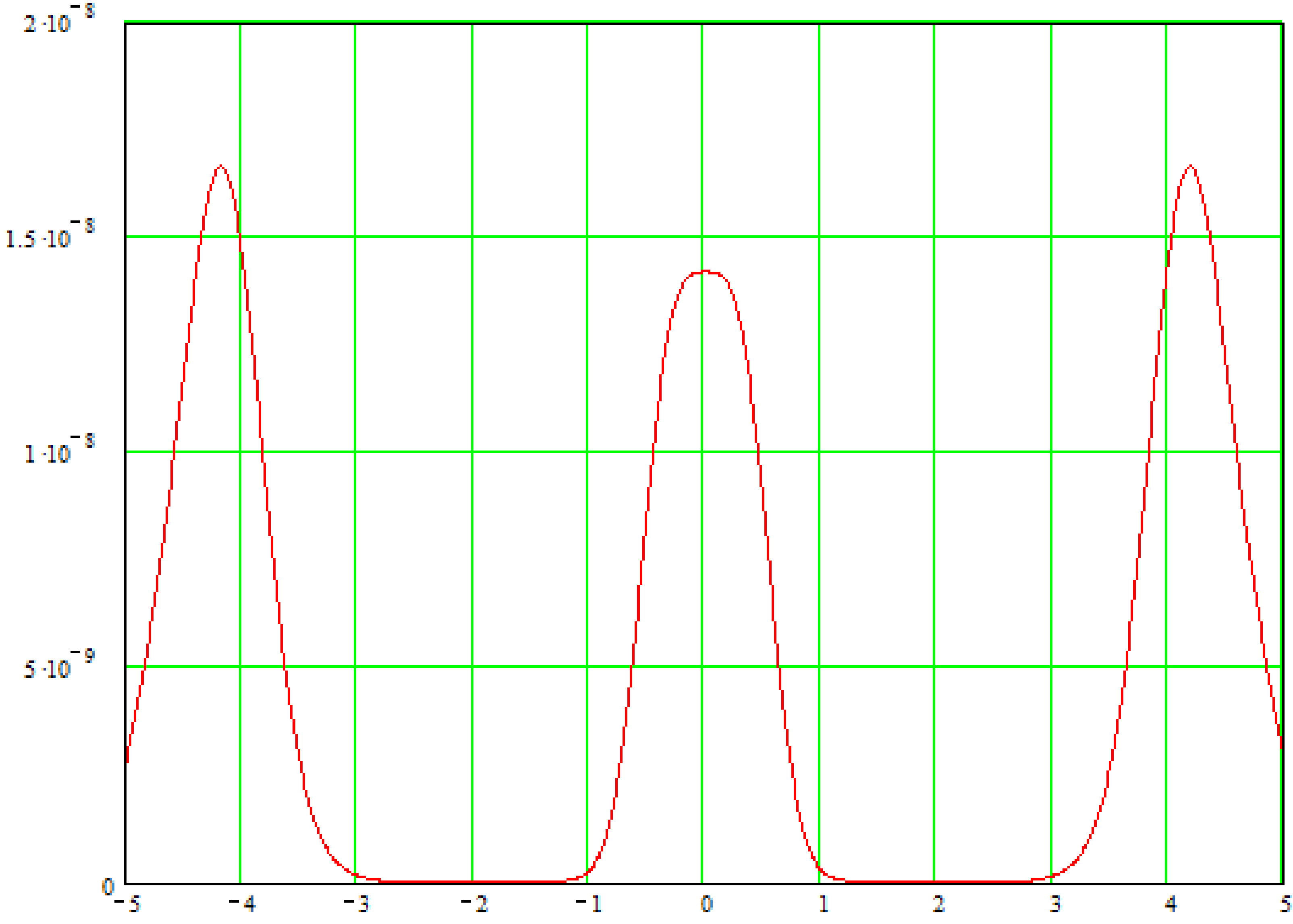


1·10^−7
1·10^−8
1·10^−9
1·10^−10
1·10^−11
1·10^−12
1·10^−13
1·10^−14
1·10^−15
1·10^−16
−5
−4
−3
−2
−1
0
1
2
3
4
5

1.0mm



Linear scale plot



Conclusion of further discussion of appodization for final lens aperture

To choosing a higher magnification and enlarge the diameter of entrance aperture, we can improve the background level smaller than 10^{-10}. It should be one of possible design for the coronagraph to exo-planet observation.

Please note this discussion is only for the theoretical background produced by diffraction phenomena. Reducing practical backgrounds such as Mie scattering from optical components are other issues.