Application of Coronagraph for Beam halo observation In the SuperKEKB

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Everything was start with astronomer's dream……

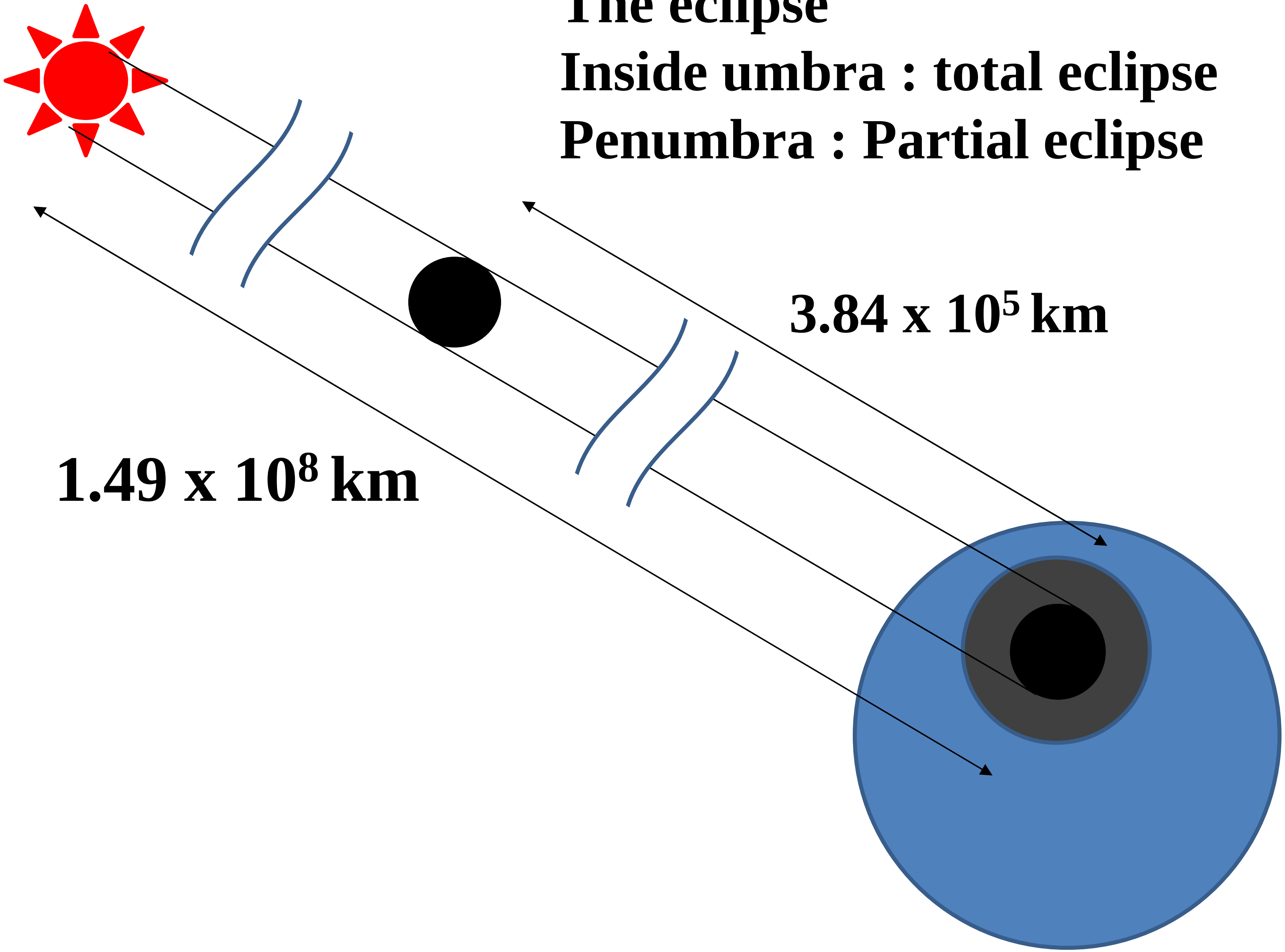
Eclipse is rare phenomena, and only few second is available for observation of sun corona, prominence etc.

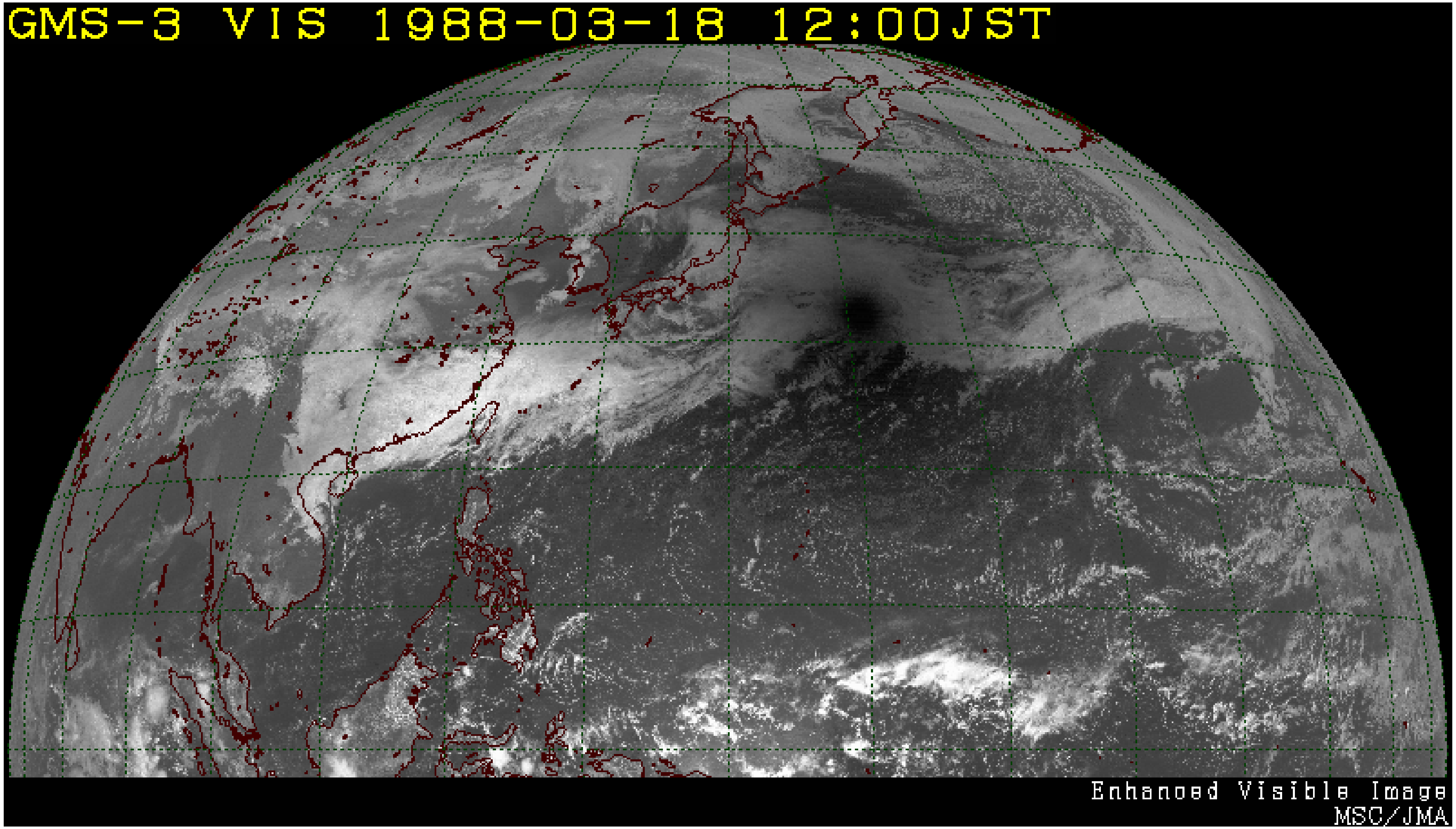
Artificial eclipse was dream of astronomers, but……..

The eclipse

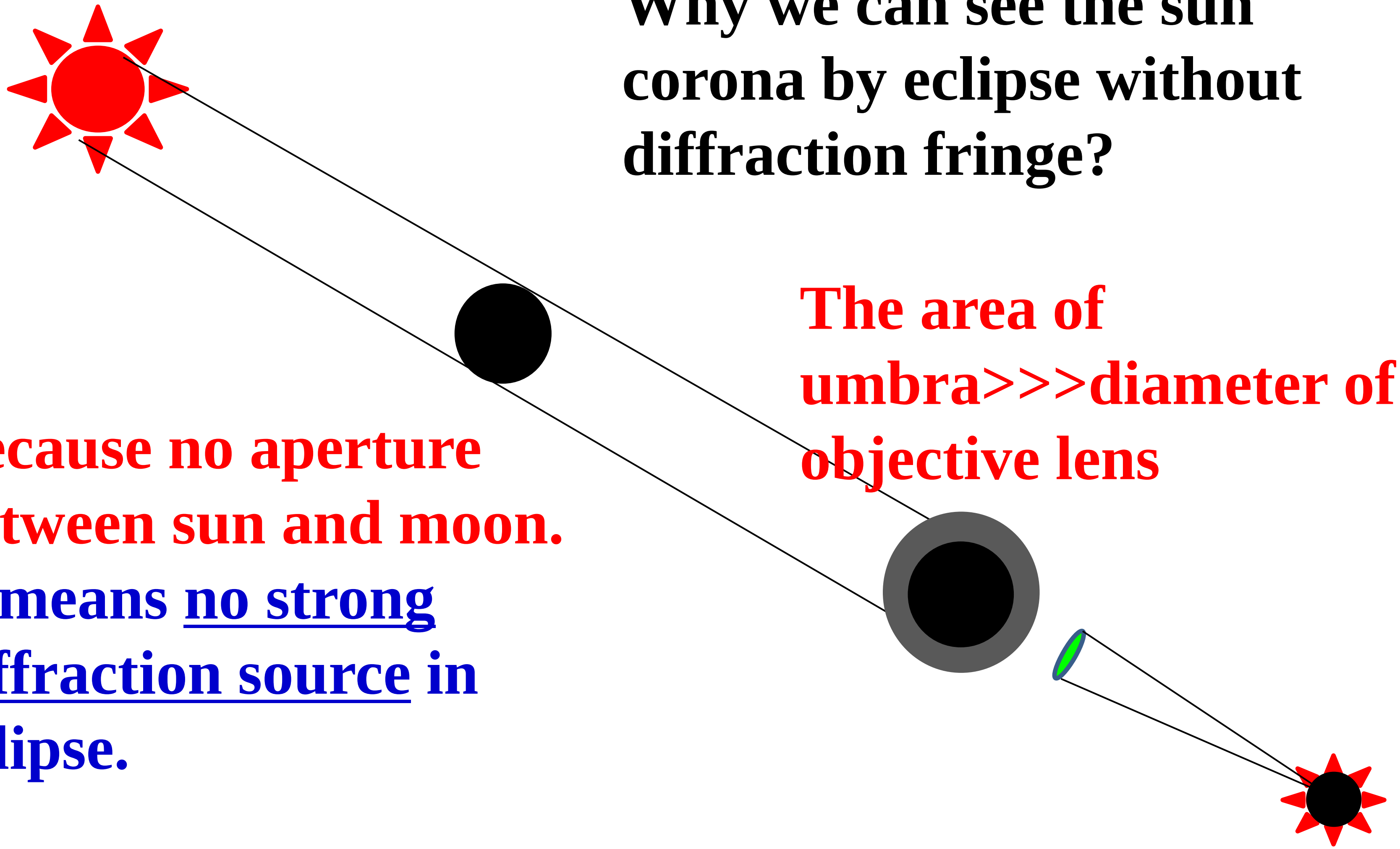
Inside umbra : total eclipse

Penumbra : Partial eclipse




GMS-3 VIS 1988-03-18 12:00JST
Enhanced Visible Image
MSC/JMA

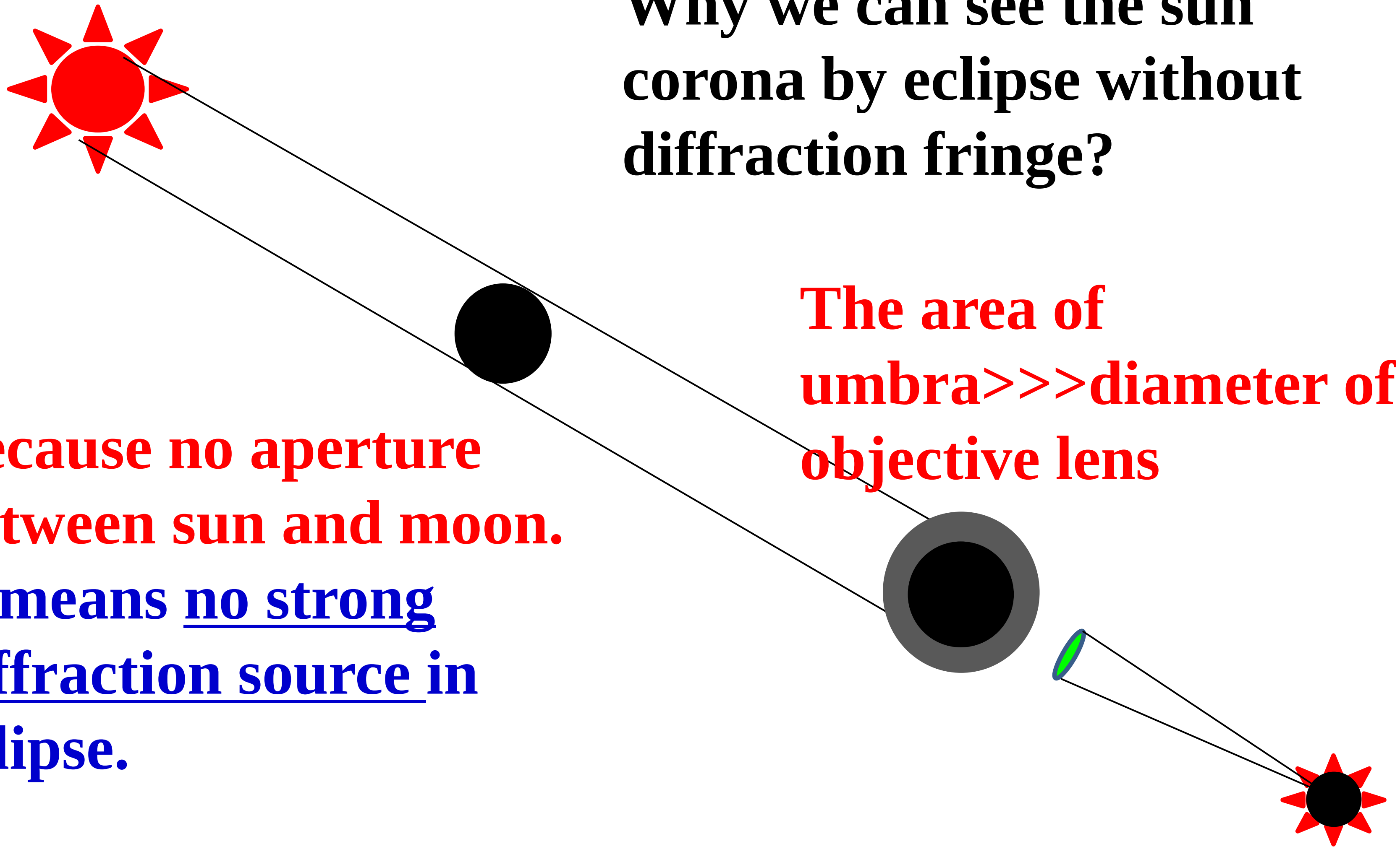
Why we can see the sun corona by eclipse without diffraction fringe?



The area of umbra>>>diameter of objective lens

Because no aperture between sun and moon.
It means <u>no strong diffraction source</u> in eclipse.

Why we can see the sun corona by eclipse without diffraction fringe?



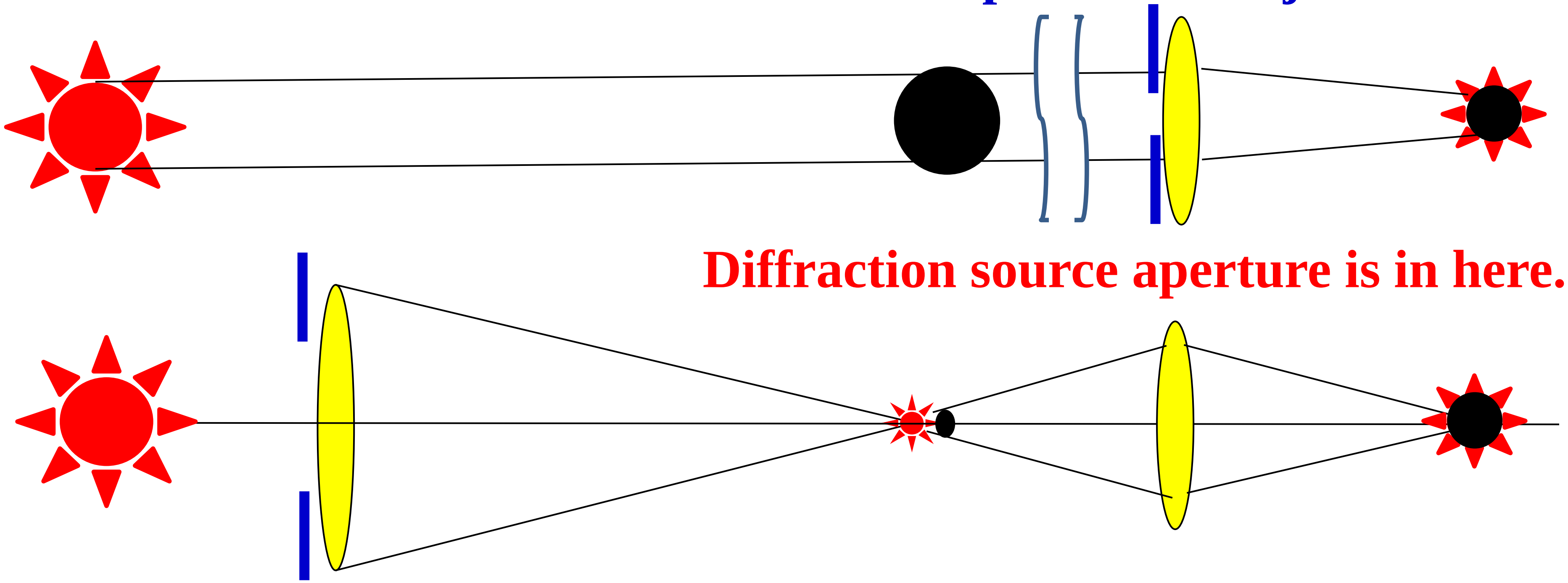
The area of umbra>>>diameter of objective lens

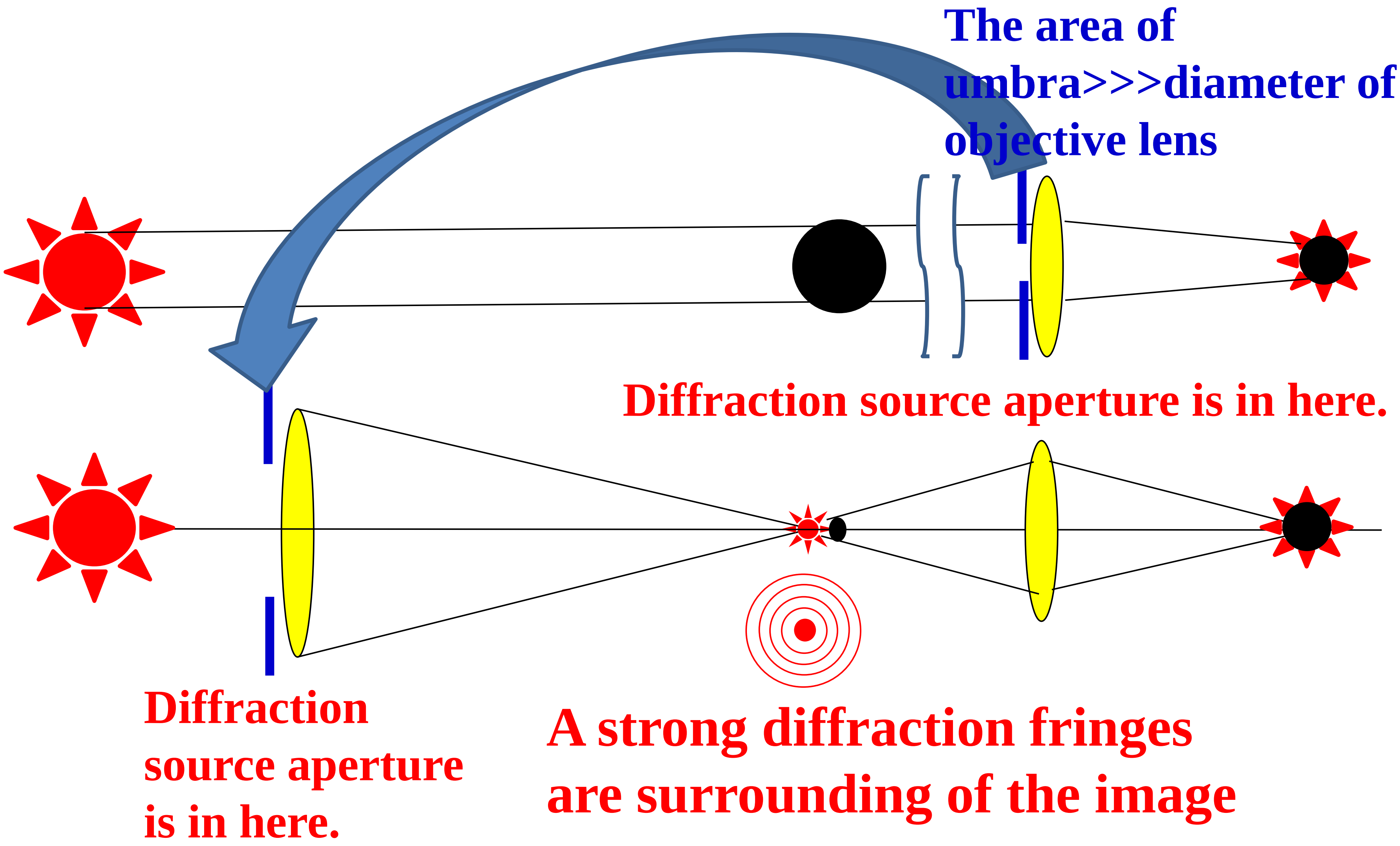
Because no aperture between sun and moon.

It means <u>no strong diffraction source</u> in eclipse.

Question is can we make same system with artificial way?

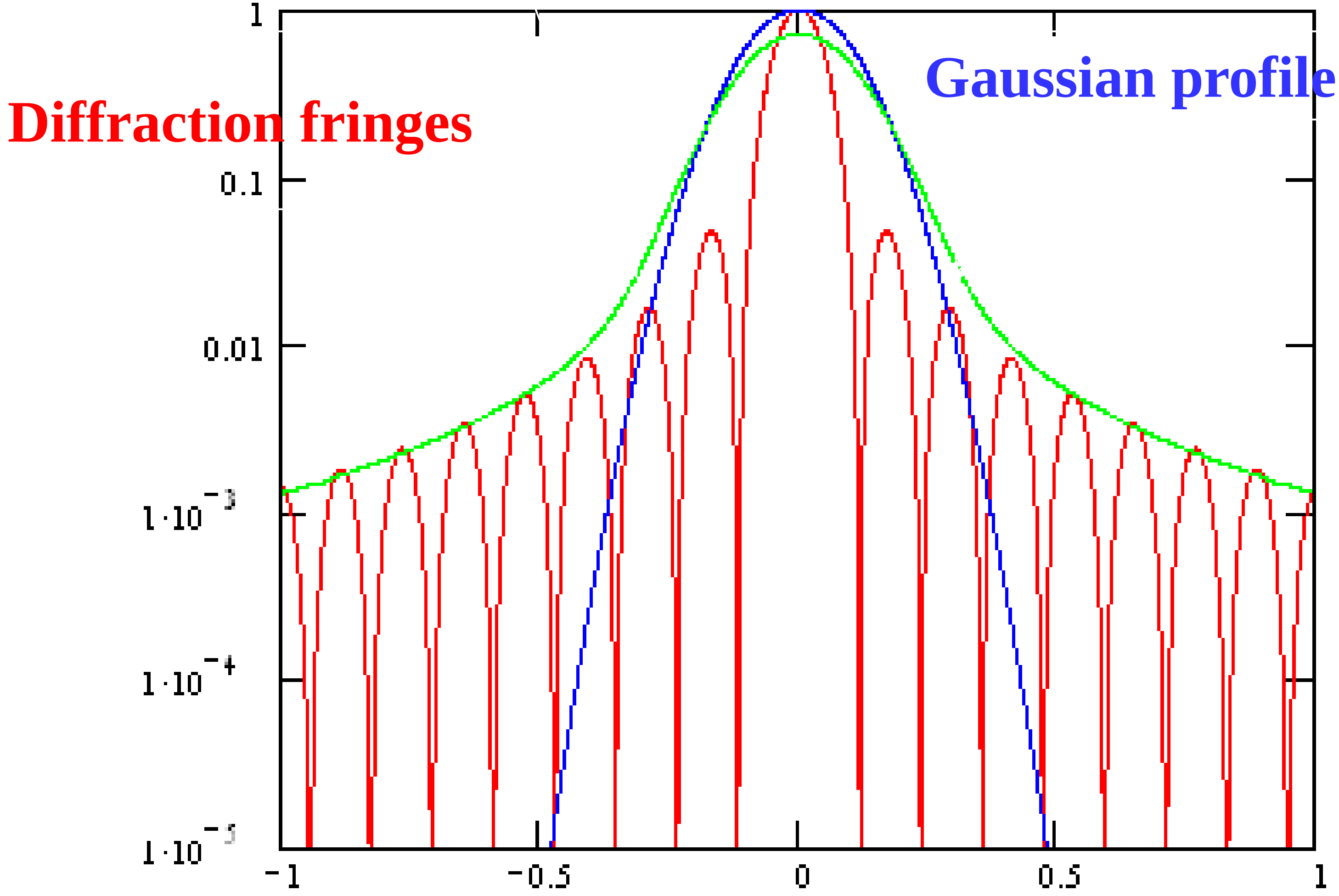
Compare two setup, eclipse and artificial eclipse.

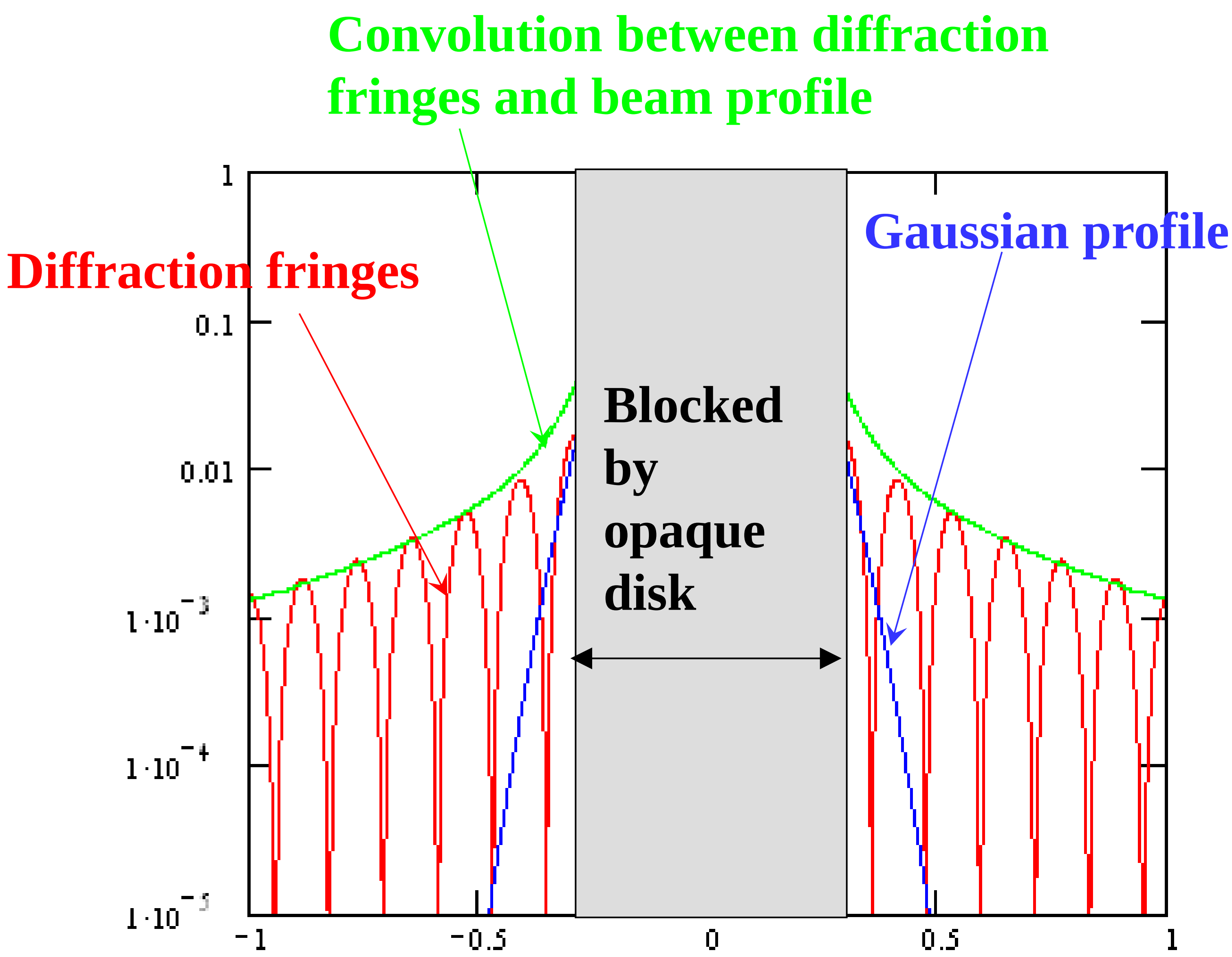




How to eliminate diffraction fringe from aperture.

Convolution between diffraction fringes and object profile





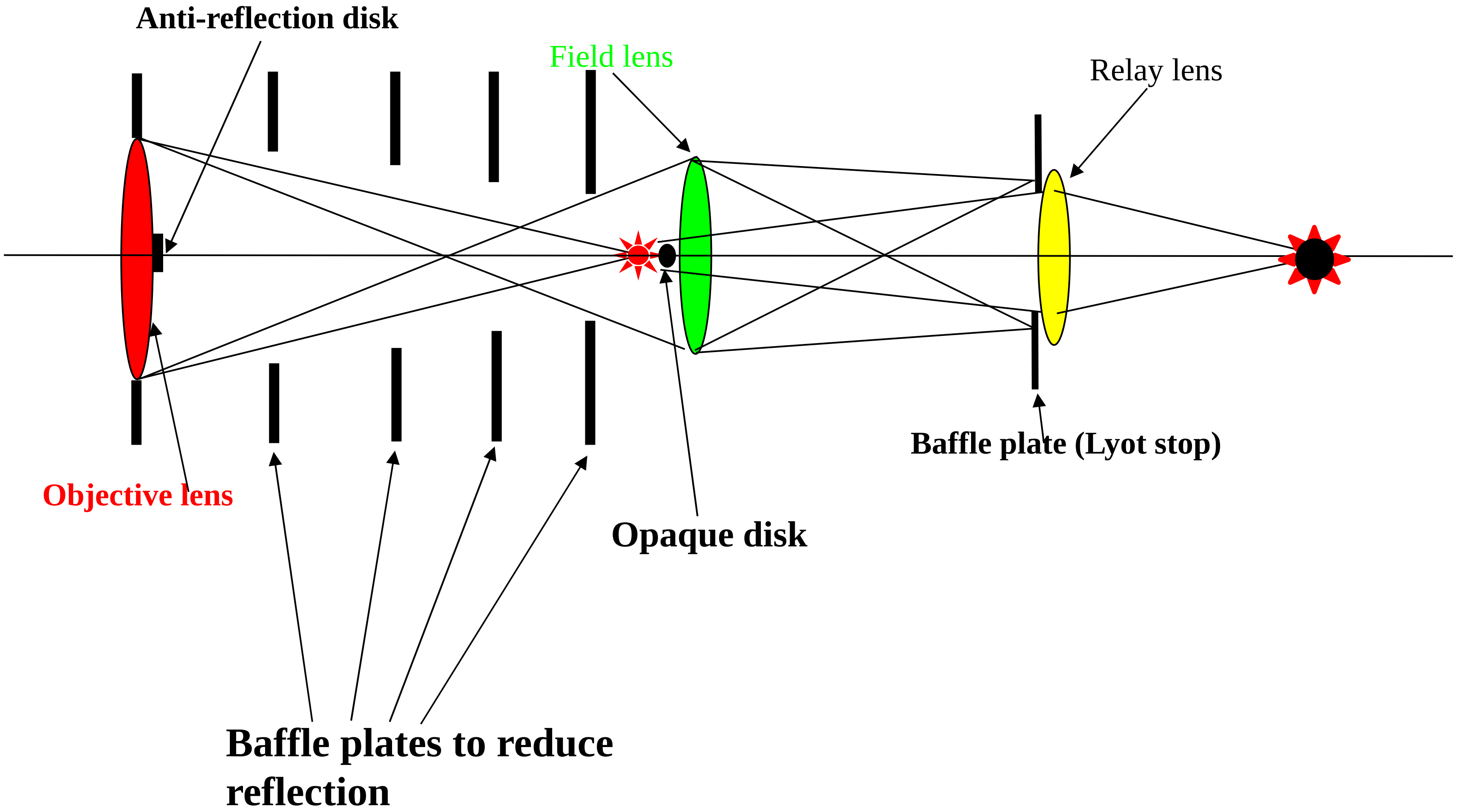
Convolution between diffraction fringes and beam profile
Diffraction fringes
Gaussian profile
Blocked by opaque disk
1
0.1
0.01
1·10⁻³
1·10⁻⁴
1·10⁻⁵
−1
−0.5
0
0.5
1

The coronagraph to observe sun corona

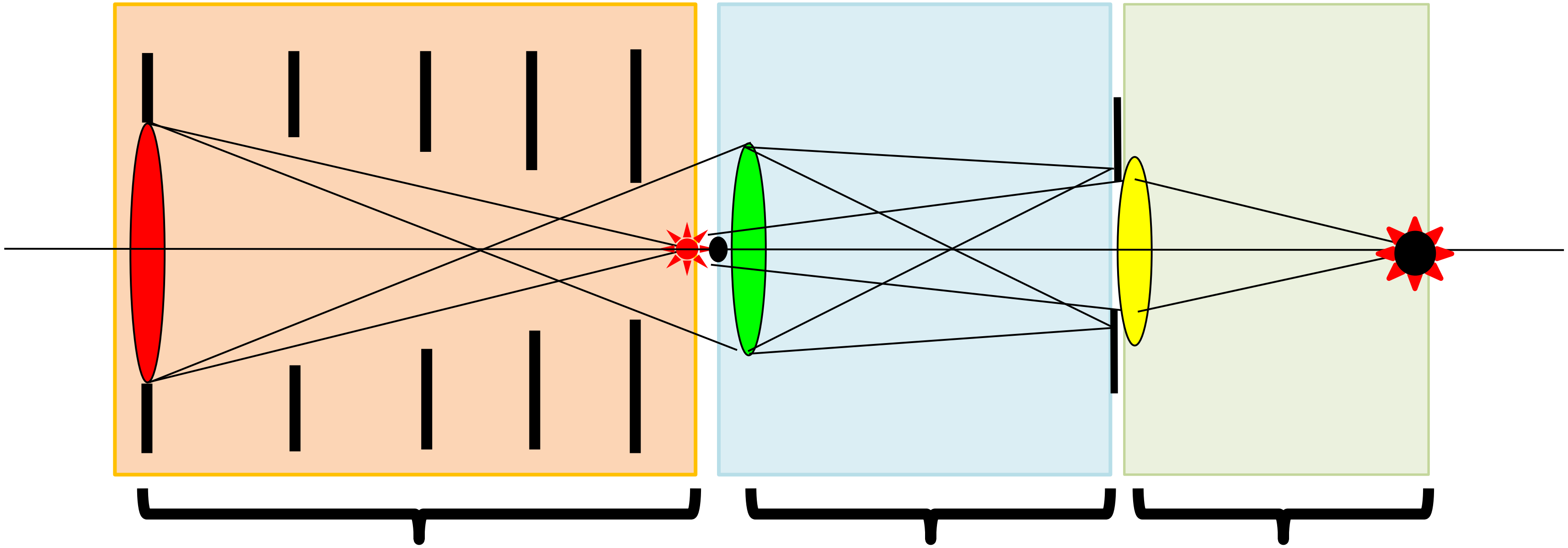
Developed by B.F.Lyot in 1934 for a observation of sun corona by artificial eclipse.

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

Optical system of Lyot's corona graph



3 stages-optical system in the Lyot's coronagraph



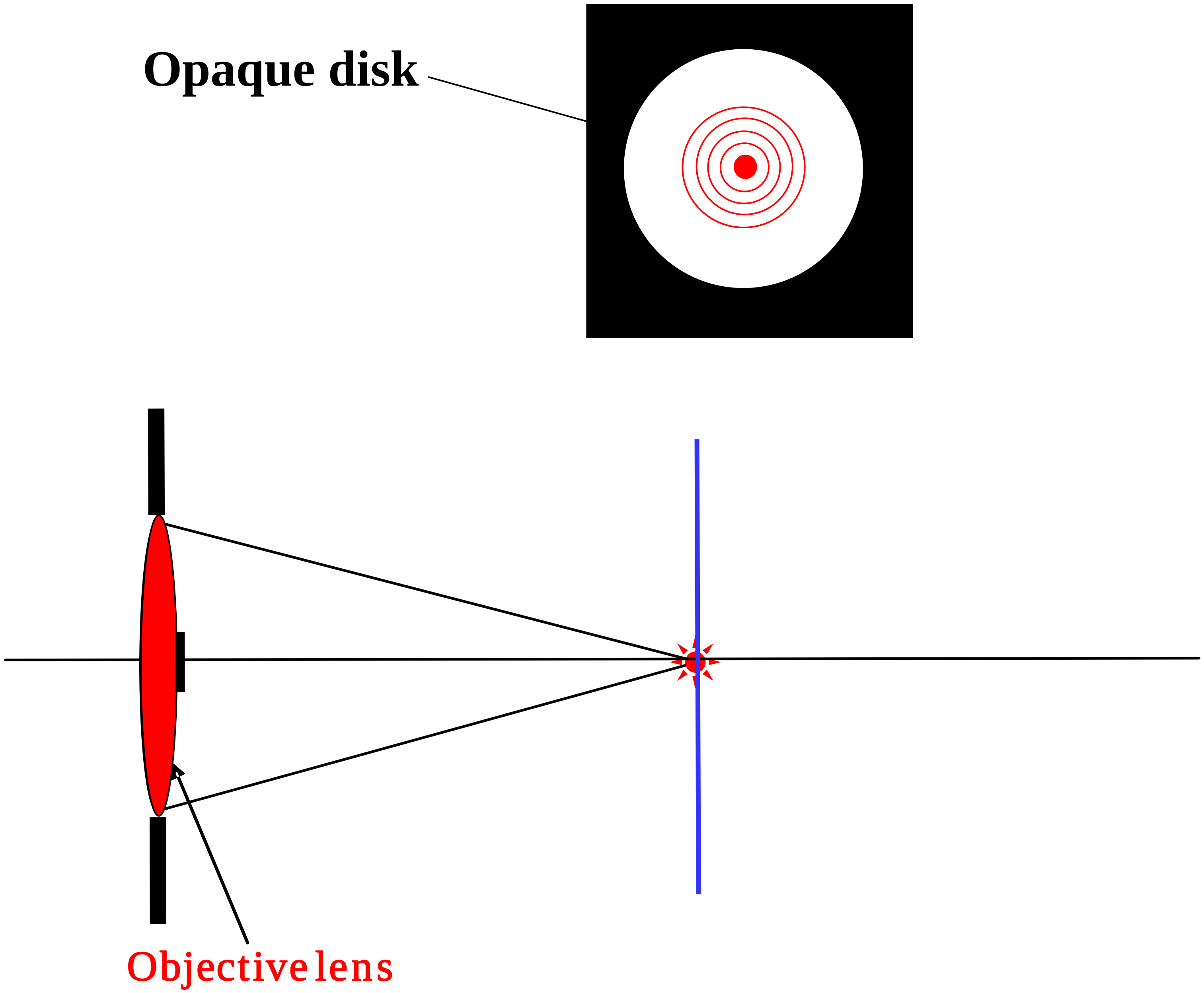
1st stage : Objective lens system

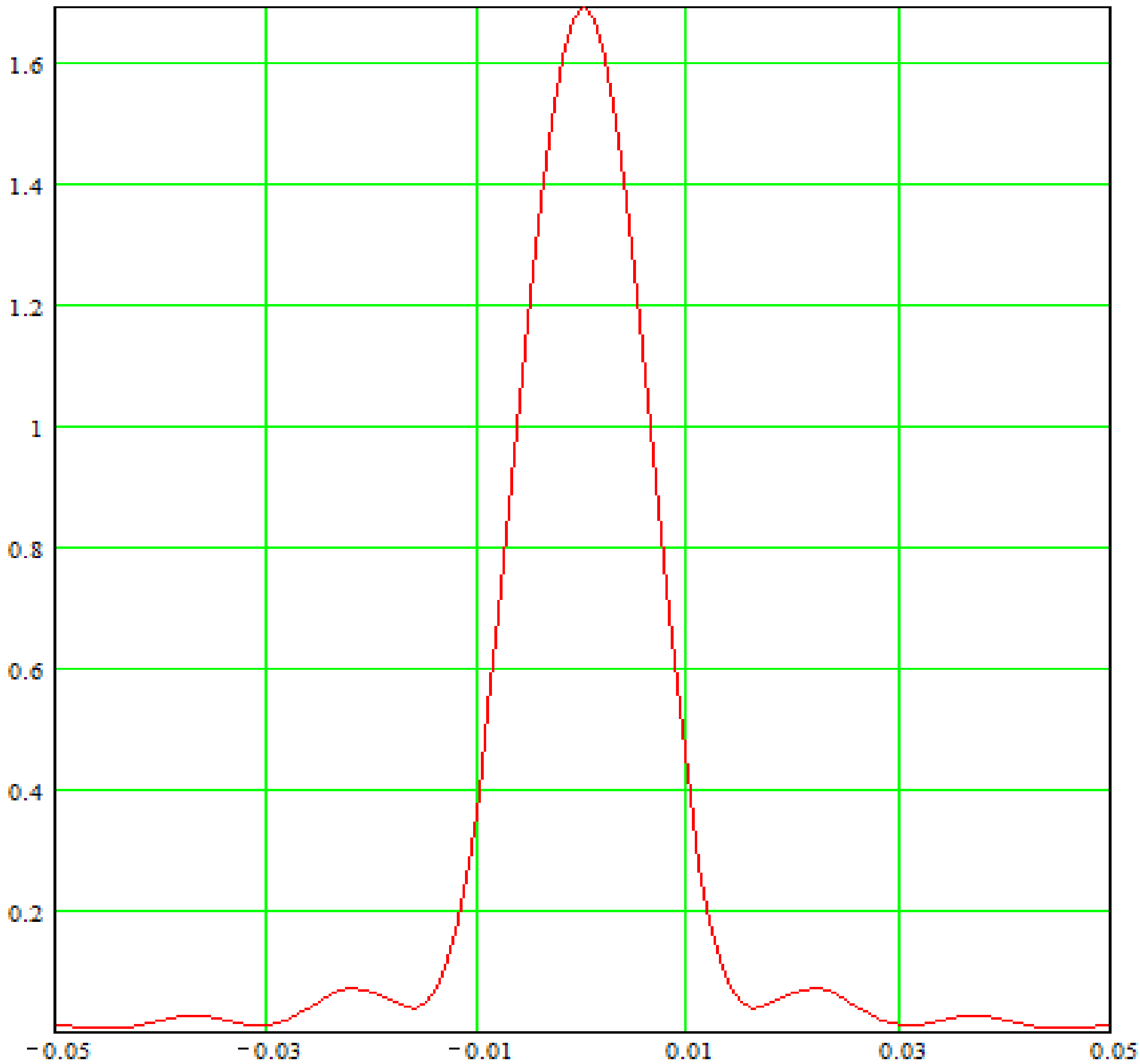
2ed stage : re-diffraction system

3ed stage : Relay lens

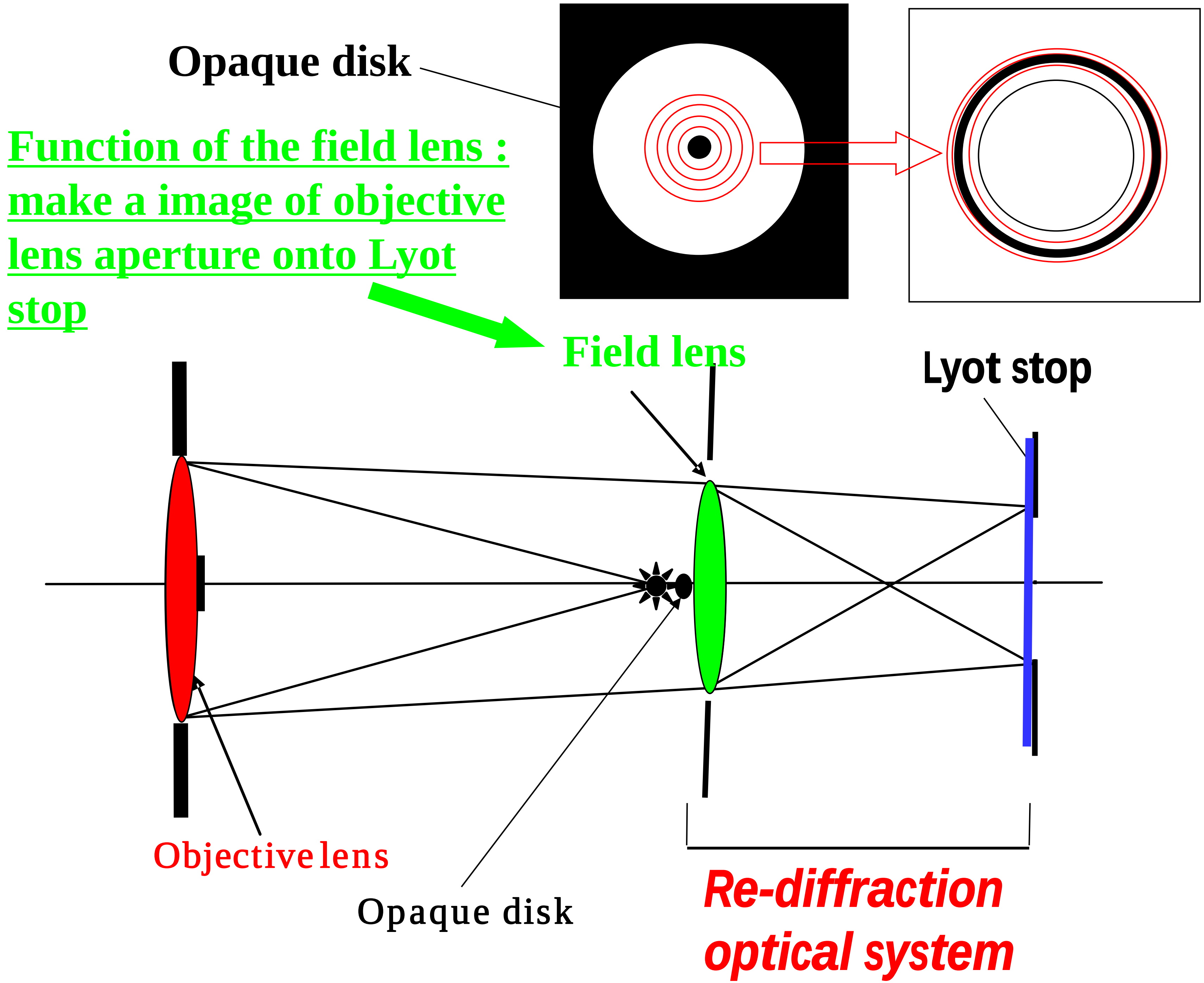
Re-diffraction optics system to
eliminate the diffraction fringe

Detail of the diffraction theory of coronagraph, please see appendix 1


Opaque disk
Objective lens

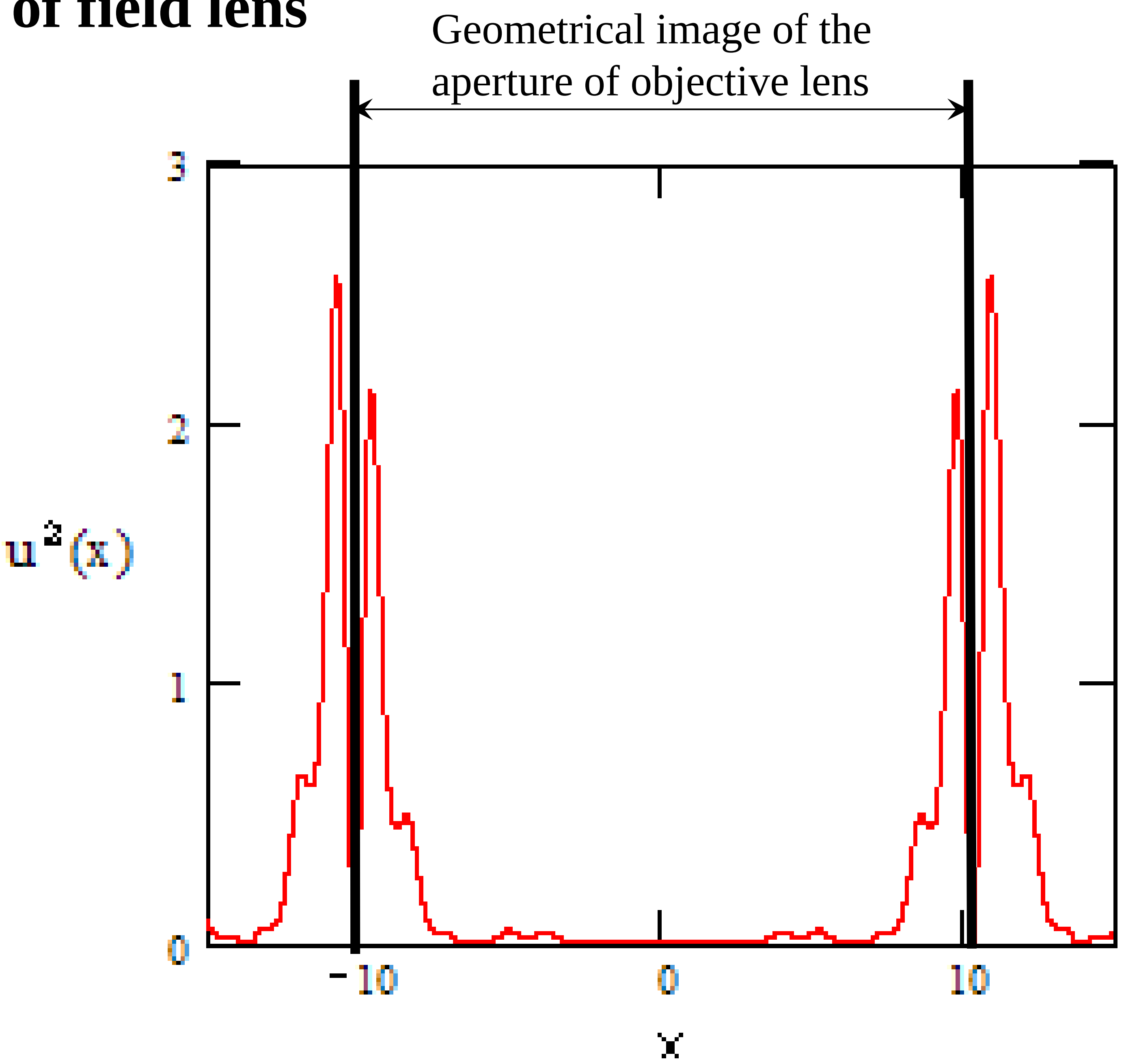


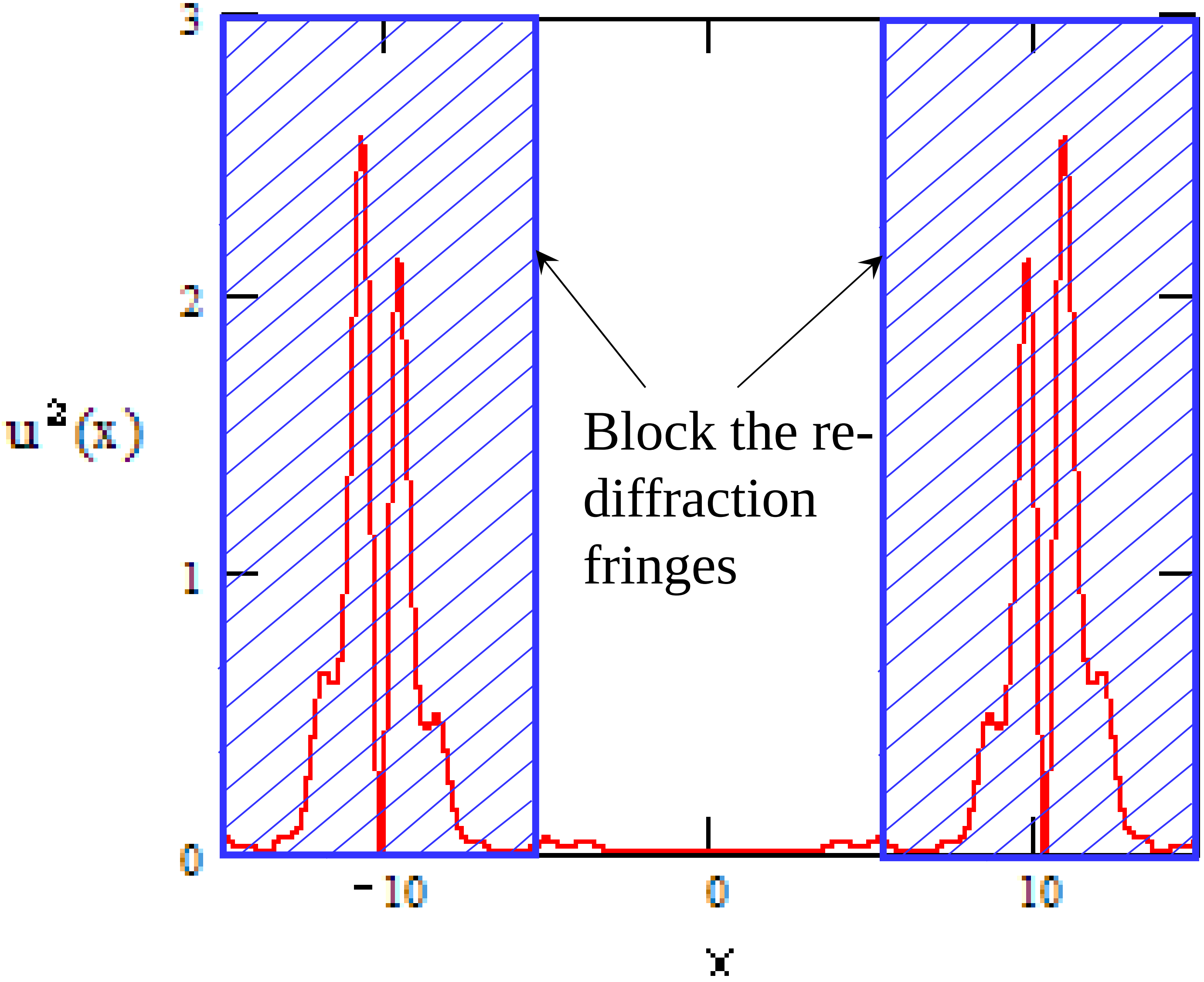
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
− 0.05
− 0.03
− 0.01
0.01
0.03
0.05



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

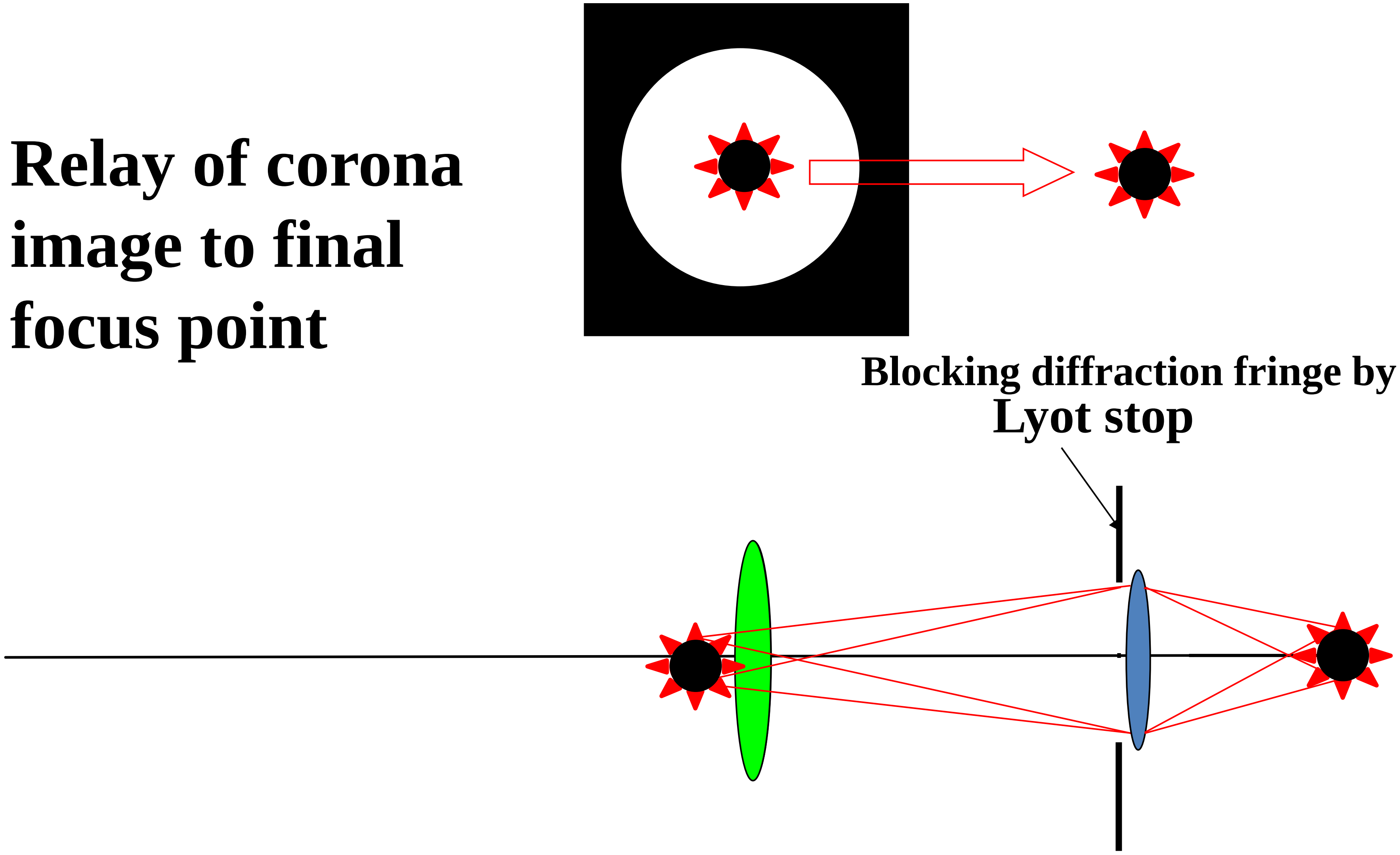
Intensity distribution of diffraction fringes on focus plane of field lens



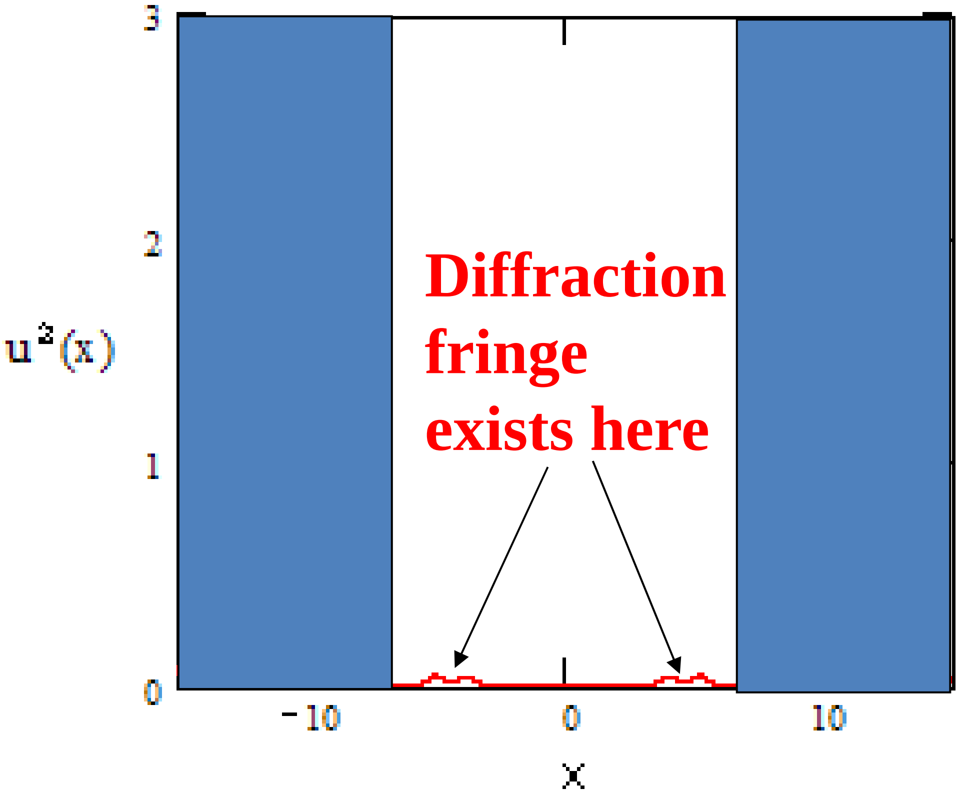


3
2
1
0
u²(x)
-10
0
10
x
Block the re-
diffraction
fringes

Relay of corona image to final focus point



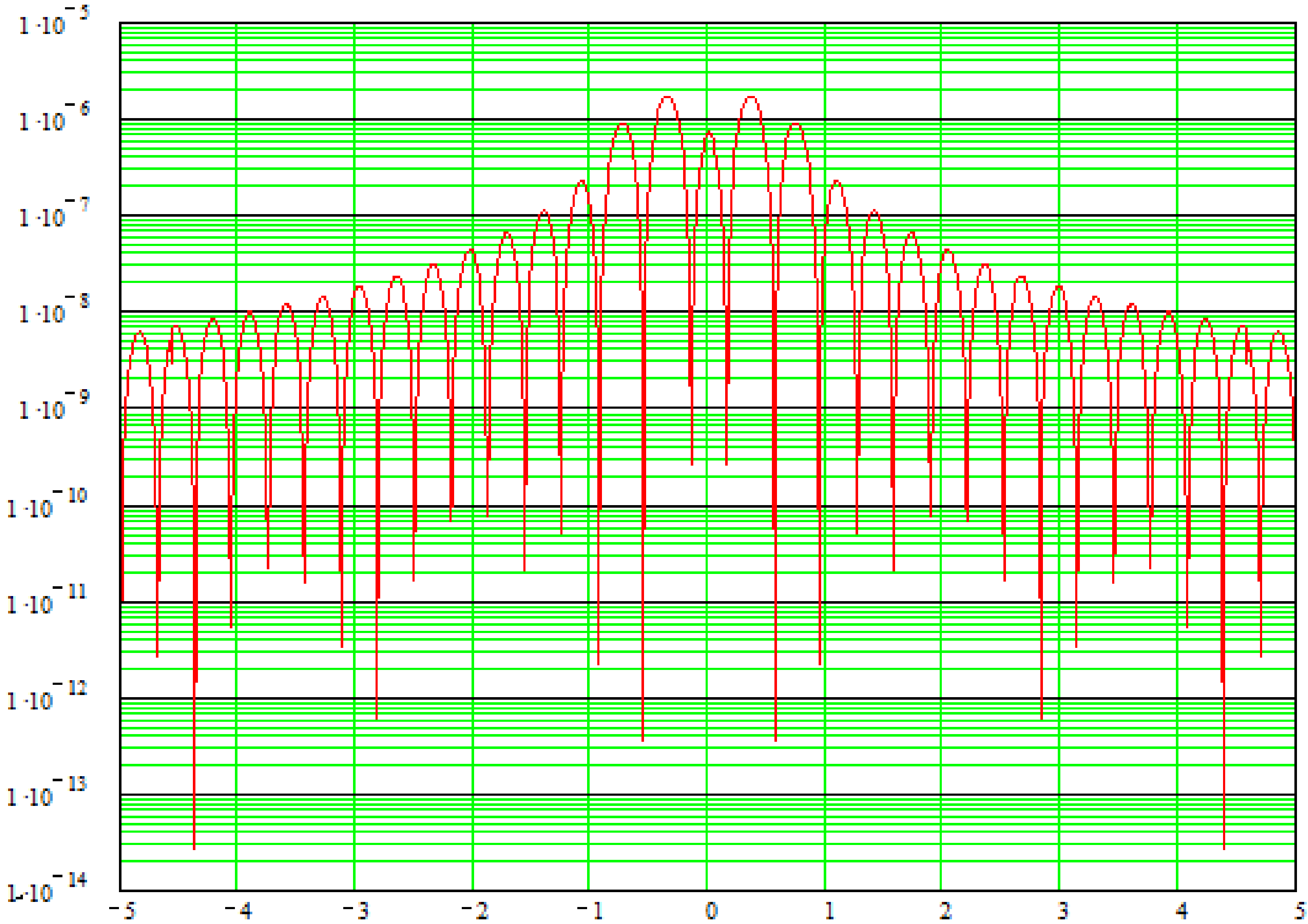
Background in classical coronagraph



This leakage of the diffraction fringe can make background level $10^{-6\text{-}8}$ (depends on Lyot stop condition).

Re-diffraction intensity on the Lyot stop

Diffraction background at 3ed stage
In Log scale $2x10^{-6}$ to 10^{-7}



Background source in coronagraph

1. Scattering by defects on the lens surface (inside) such as scratches and digs.
2. Scattering from the optical components (mirrors) near by coronagraph.
3. Reflections in inside wall of the coronagraph.

4. Scattering from dust in air.

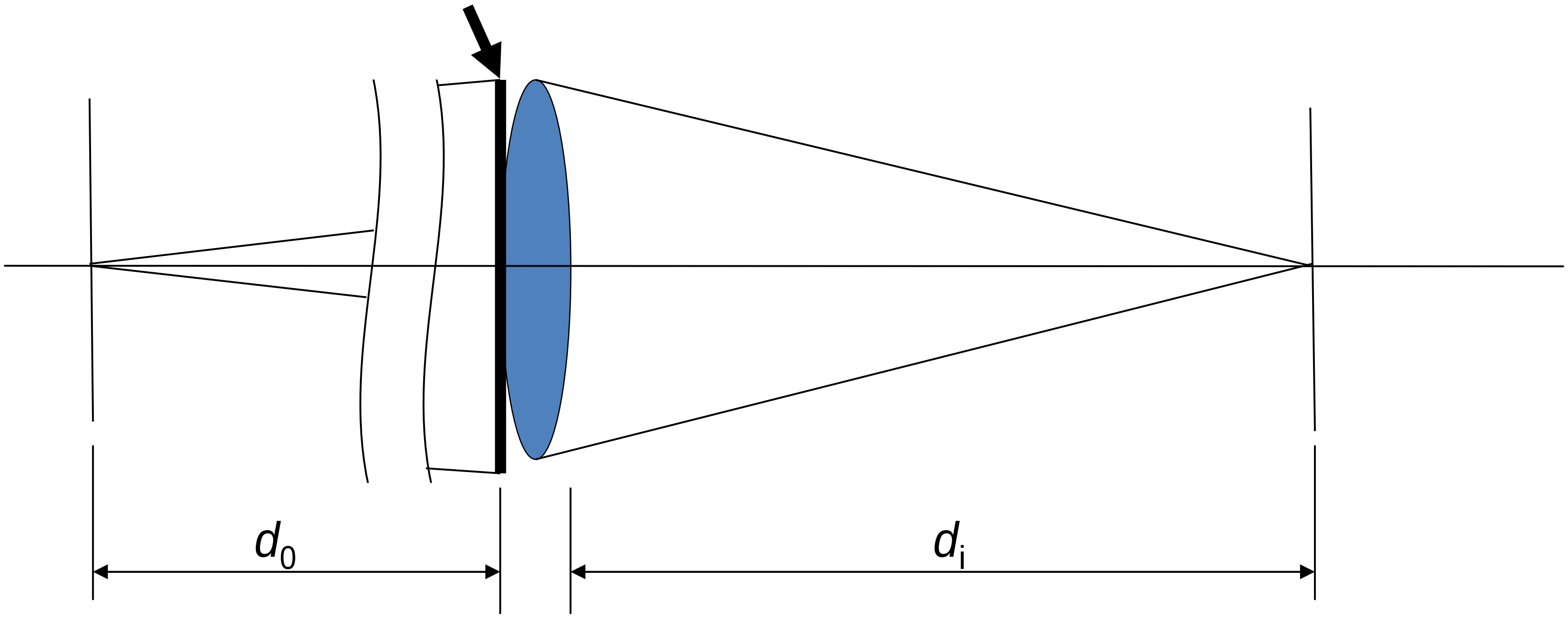
1. **Scattering by defects on the lens surface (inside) such as scratches and digs.**
2. **Scattering from the optical components (mirrors) near by coronagraph.**
3. **Reflections in inside wall of the coronagraph.** → **Cover the inside wall with a flock paper (light trapping material).**
4. **Scattering from dust in air.** → **Use the coronagraph in clean room.**

Scattering from the optical components (mirrors) in the coronagraph

Dtail of this subject ,please see appendix 2

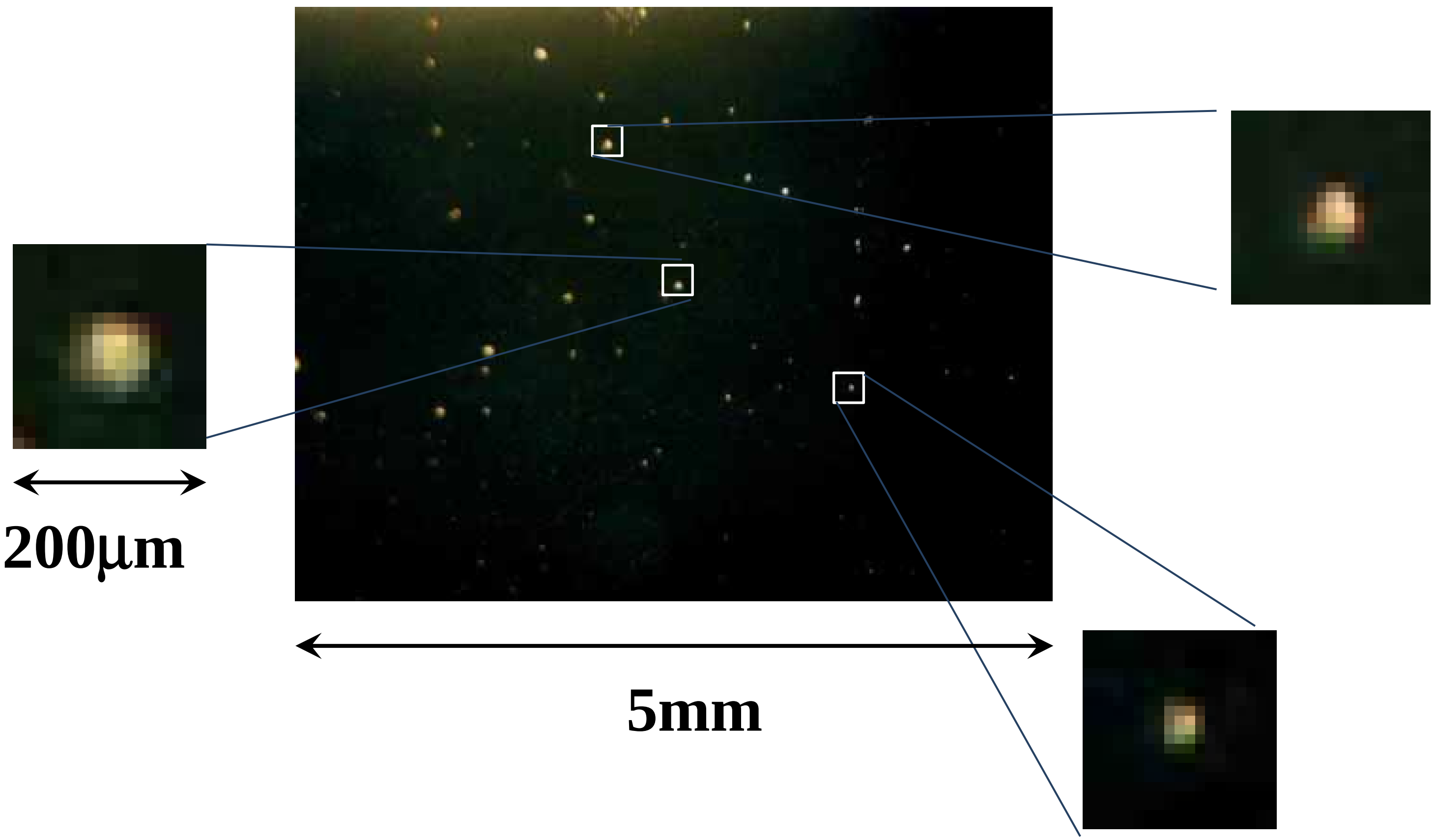
Case 1. Noise source in the entrance pupil of objective lens

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

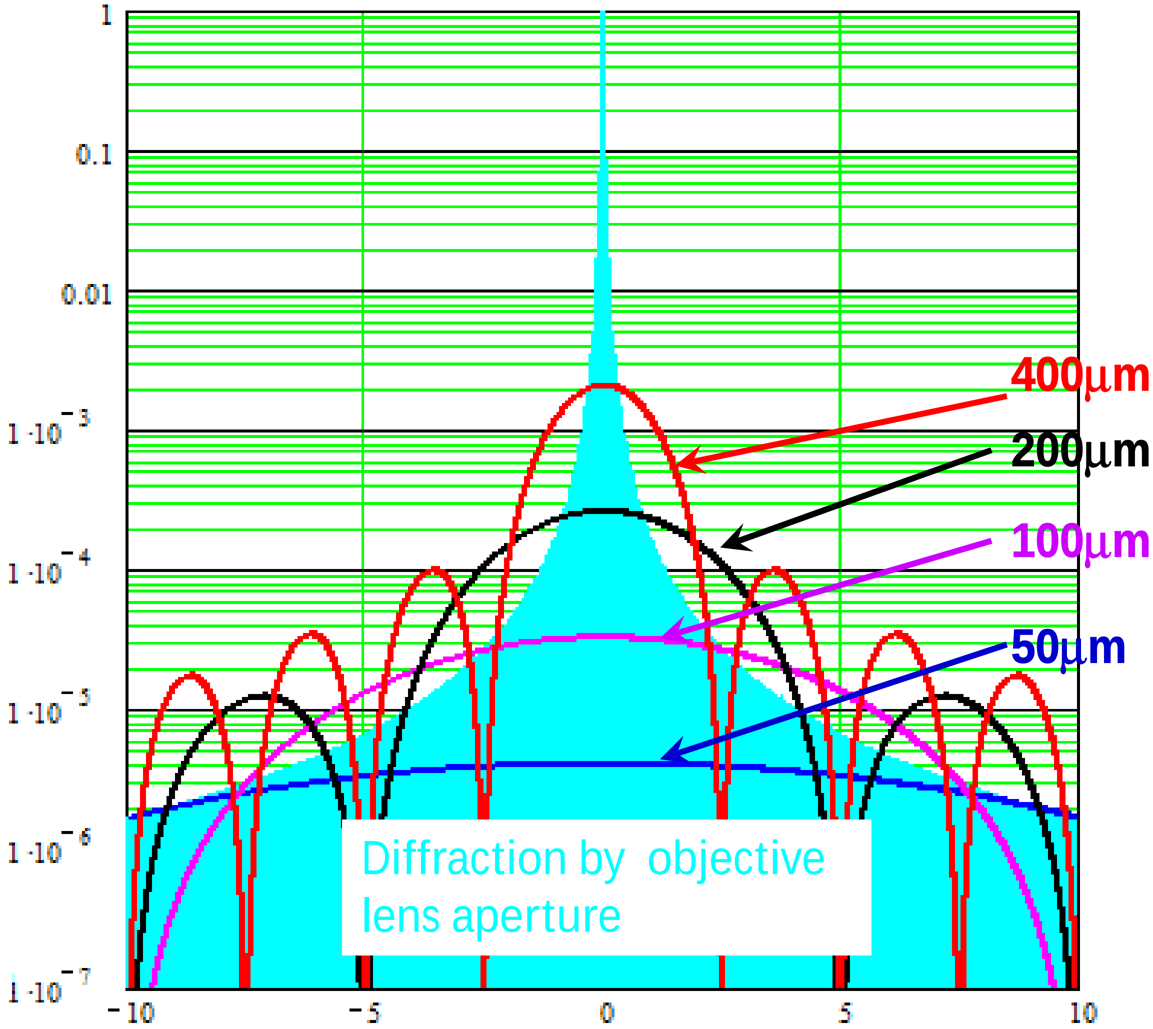


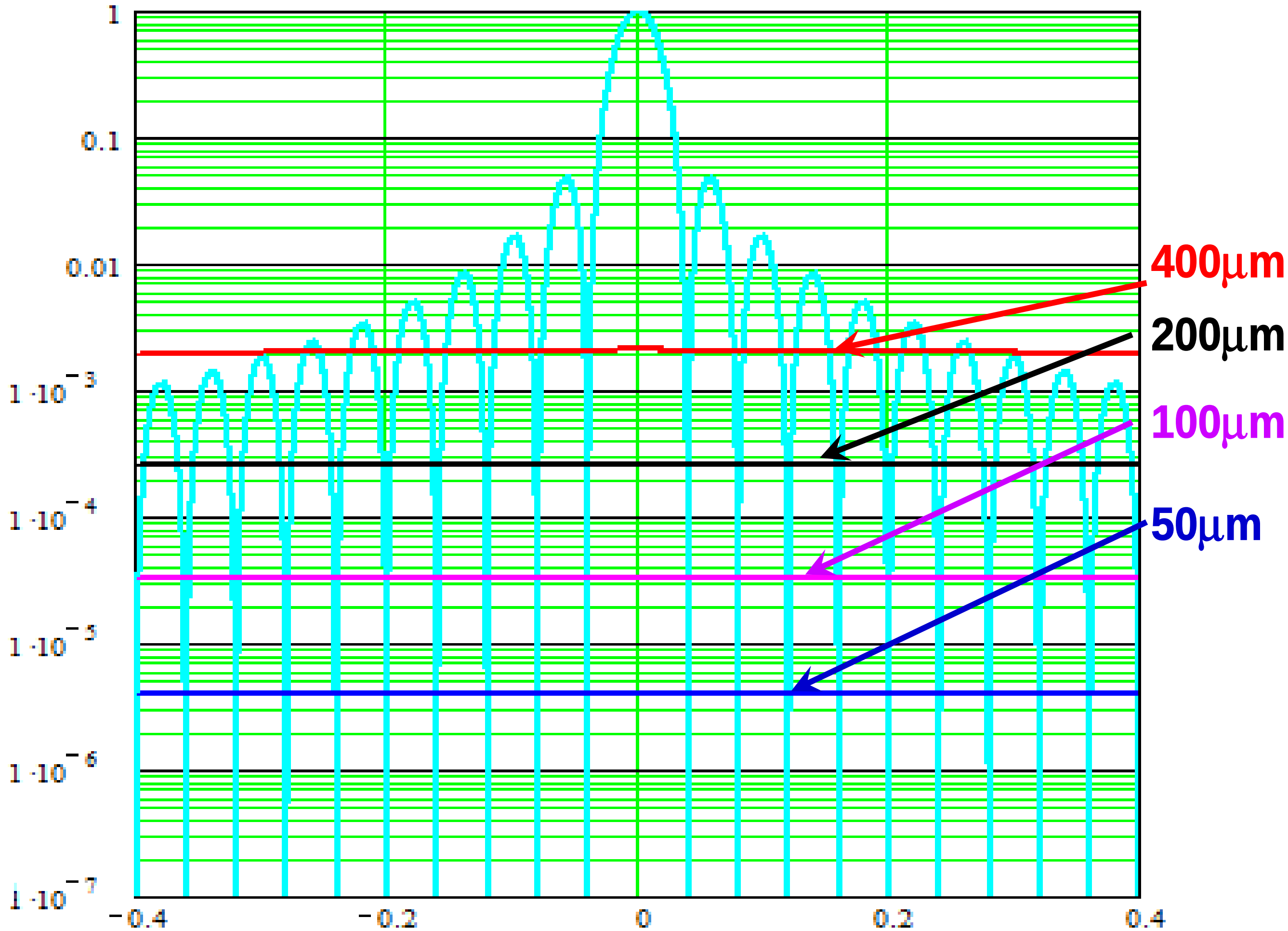
Digs on glass surface of scratch & dig 60/40

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



Simulation result of Background produced by dig on objective surface



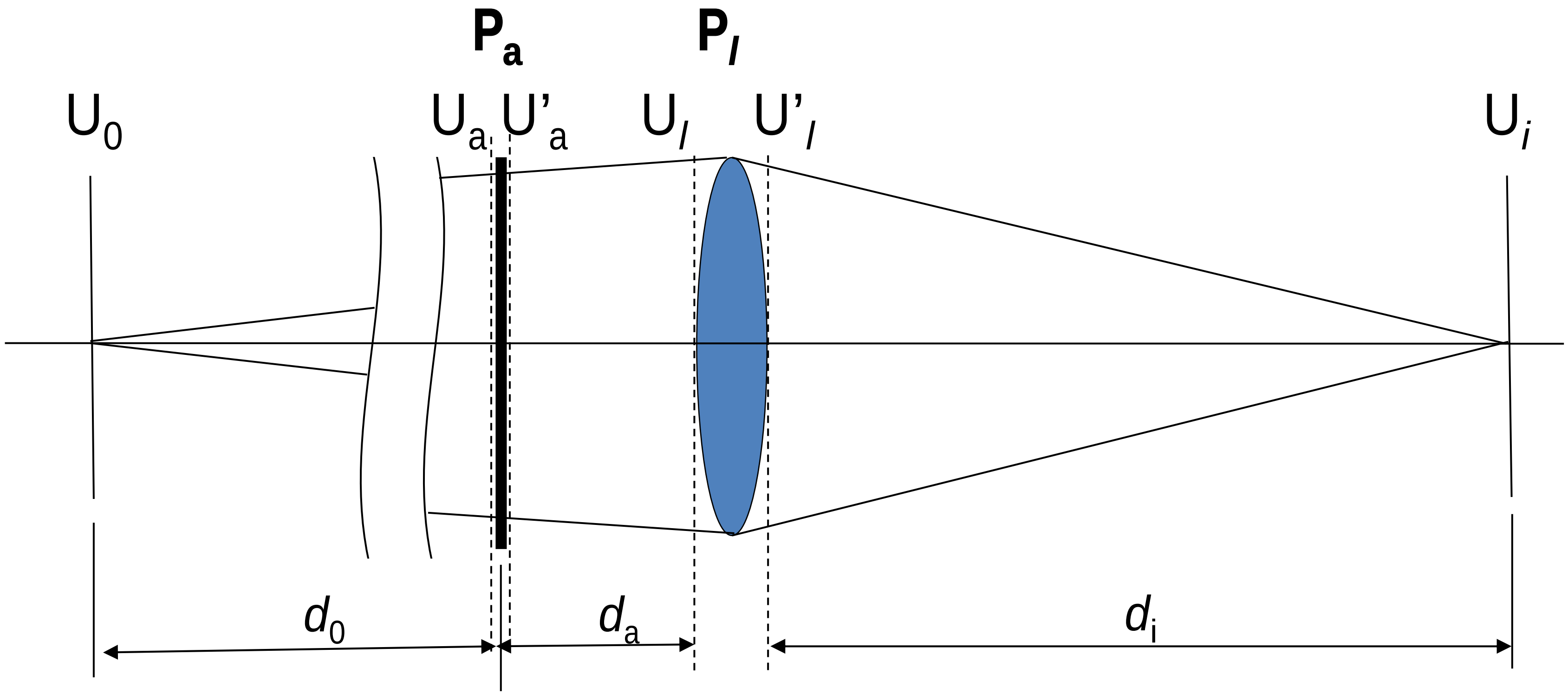

1
0.1
0.01
1·10^-3
1·10^-4
1·10^-5
1·10^-6
1·10^-7
-0.4
-0.2
0
0.2
0.4
400μm
200μm
100μm
50μm

Comparison between normal optical polish and careful optical polish for coronagraph

S&D 60/40 surface of the lens

Surface of the coronagraph lens

Scattering from the optical components (mirrors) between source point and coronagraph.



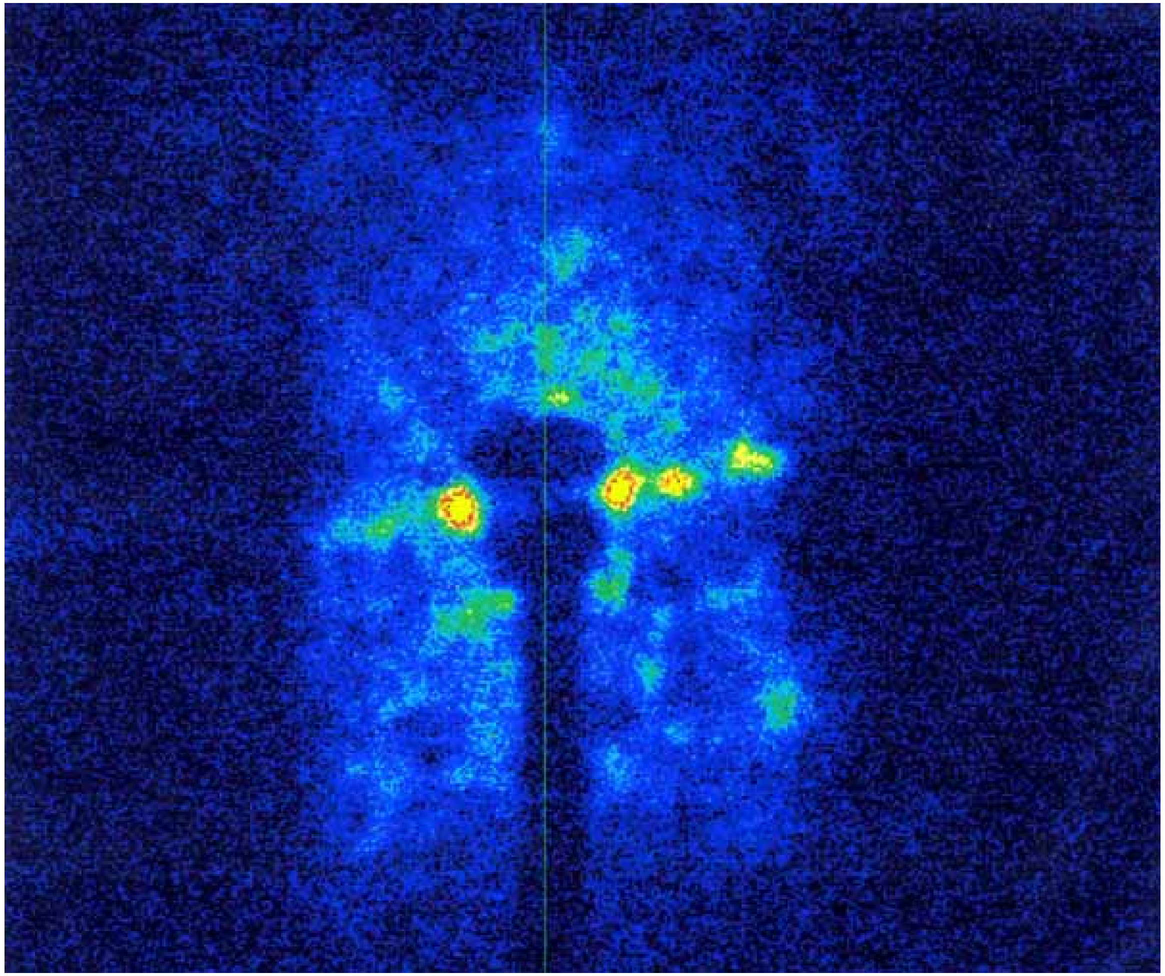
Noise source to objective lens   Fresnel like diffraction

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

Intentionally spread some dust on the mirror in 2m front of the coronagraph



Scattering background from mirrors near by coronagraph will not acceptable!

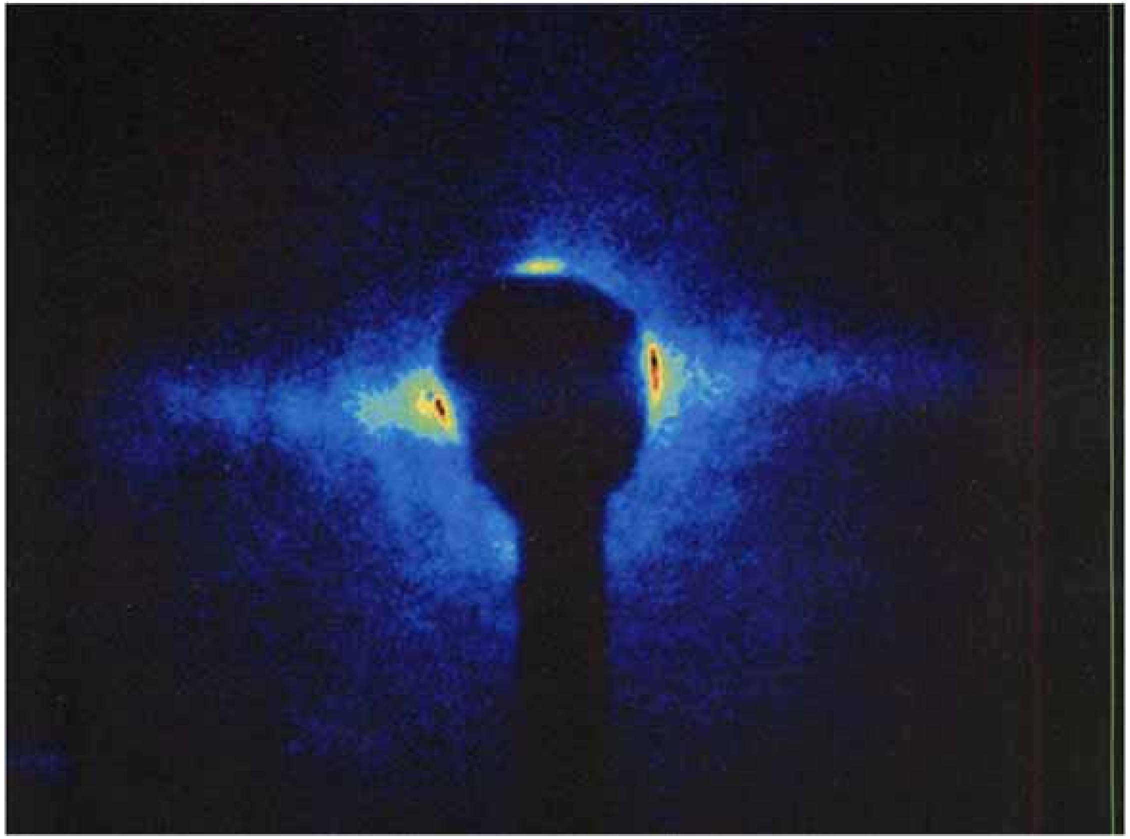
⇓

Use same quality of optical polishing for mirrors!
Clean optical elements are necessary for optical beam transport line.

Observation of beam halo at the Photon Factory, KEK

Beam profile

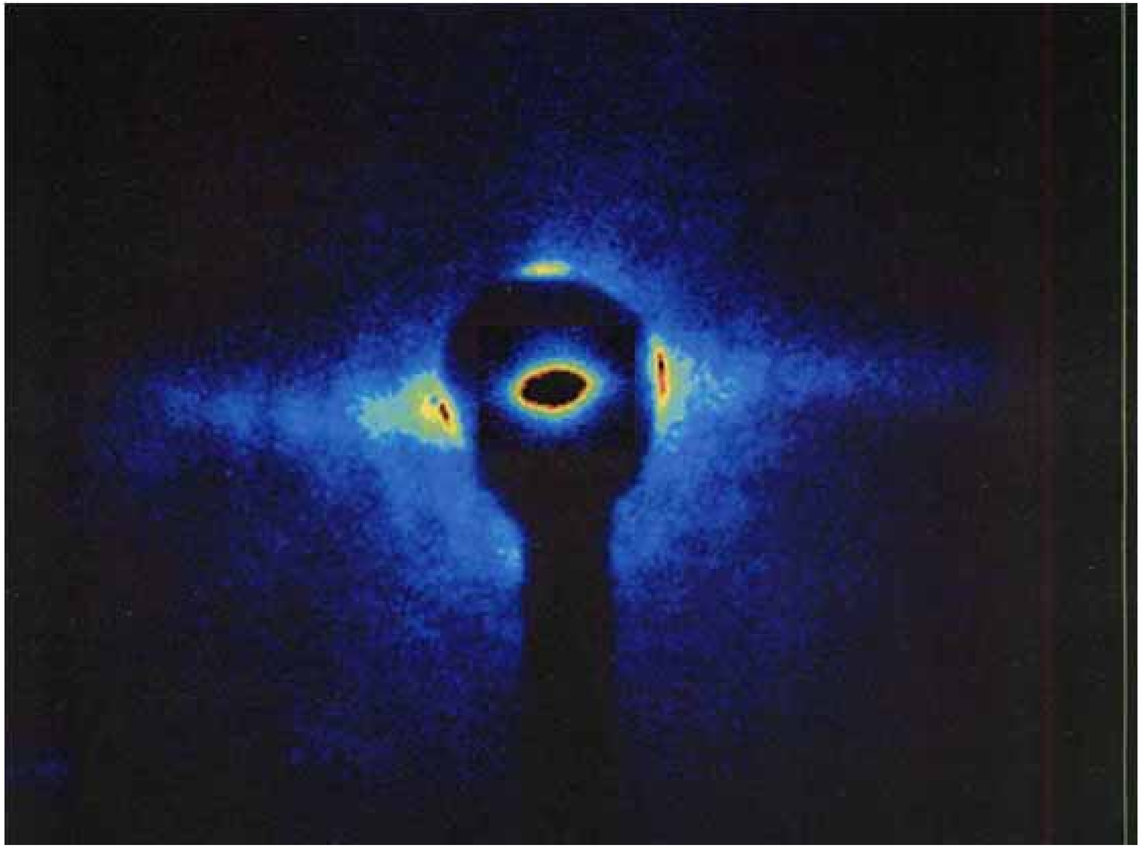
Beam halo



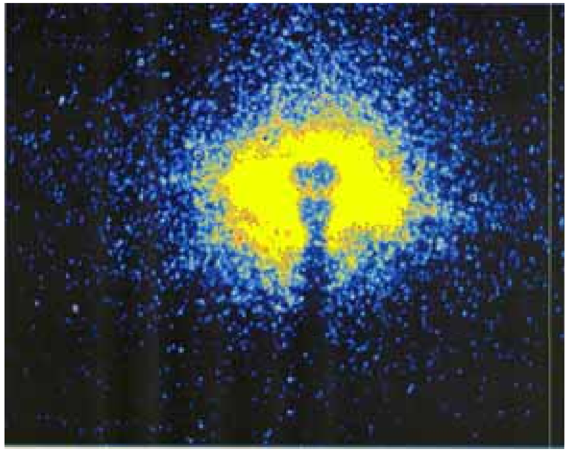
Observation inPF,KEK 2005

Beam core (superimposed) + halo

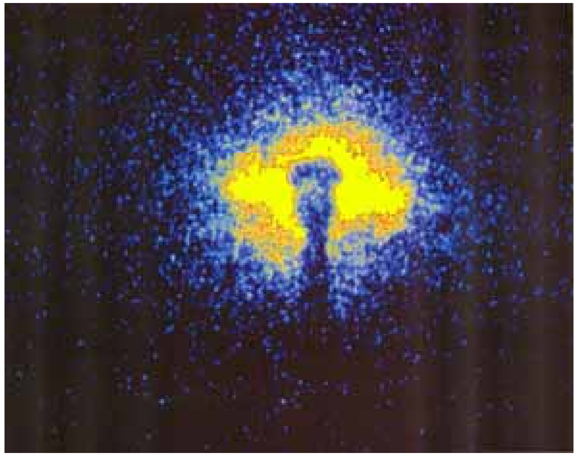
Observation with better than 6 order of magnitude



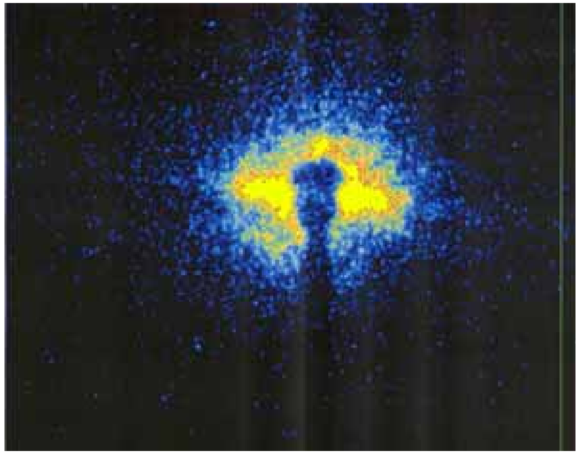
Beam tail images in the single bunch operation at the KEK PF measured at different current



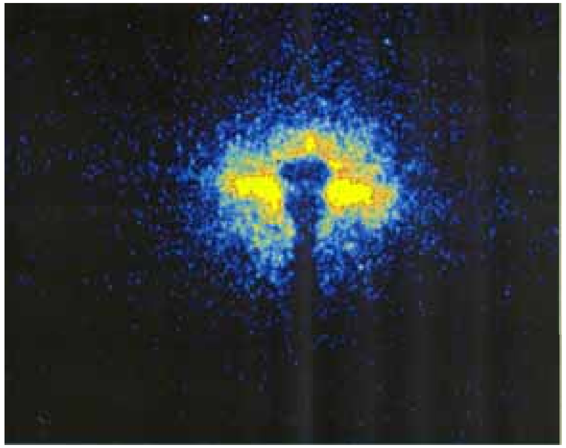
65.8mA



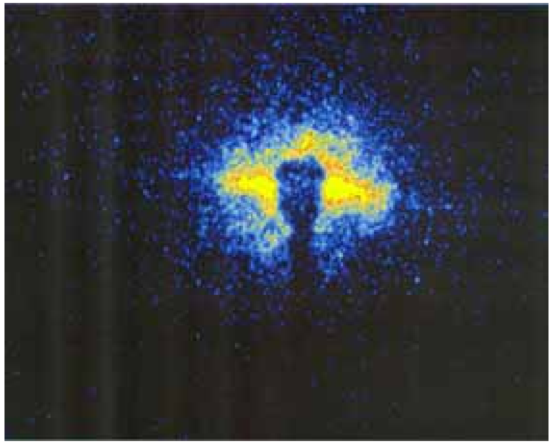
61.4mA



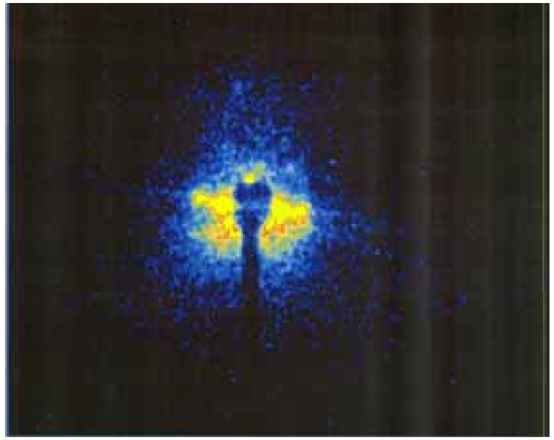
54.3mA



45.5mA



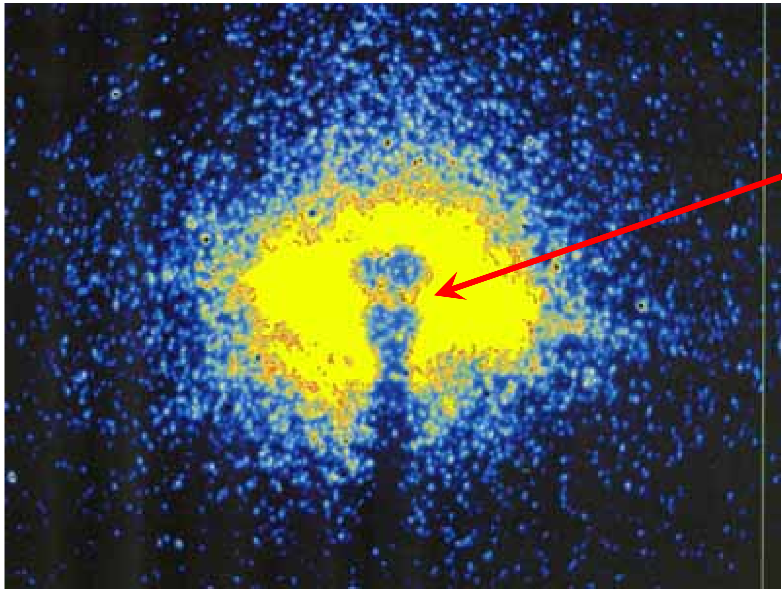
35.5mA



396.8mA
Multi-bunch
bunch current 1.42mA

Observation for the more out side

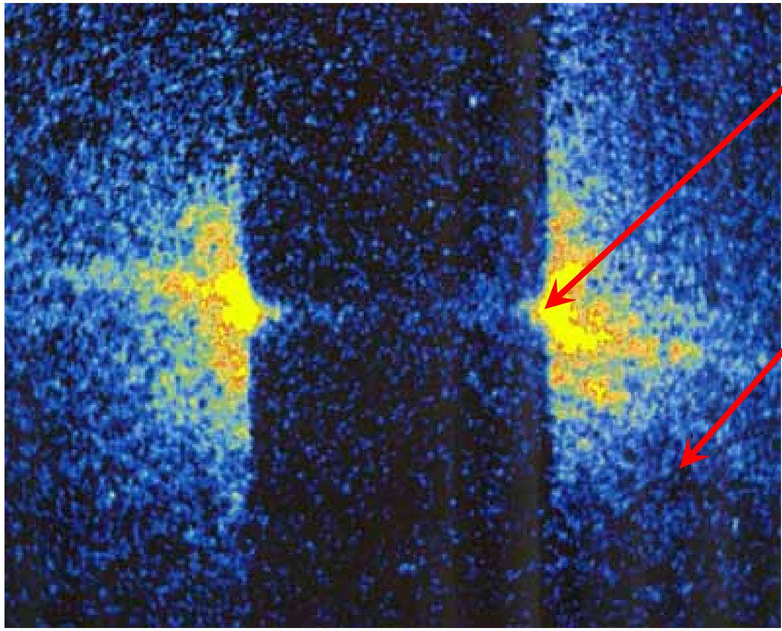
Single bunch
65.8mA
Exposure time of CCD : 3msec



Intensity in here : 2.05×10^{-4} of peak intensity

Halo in deep outside

Exposure time of CCD : 100msec



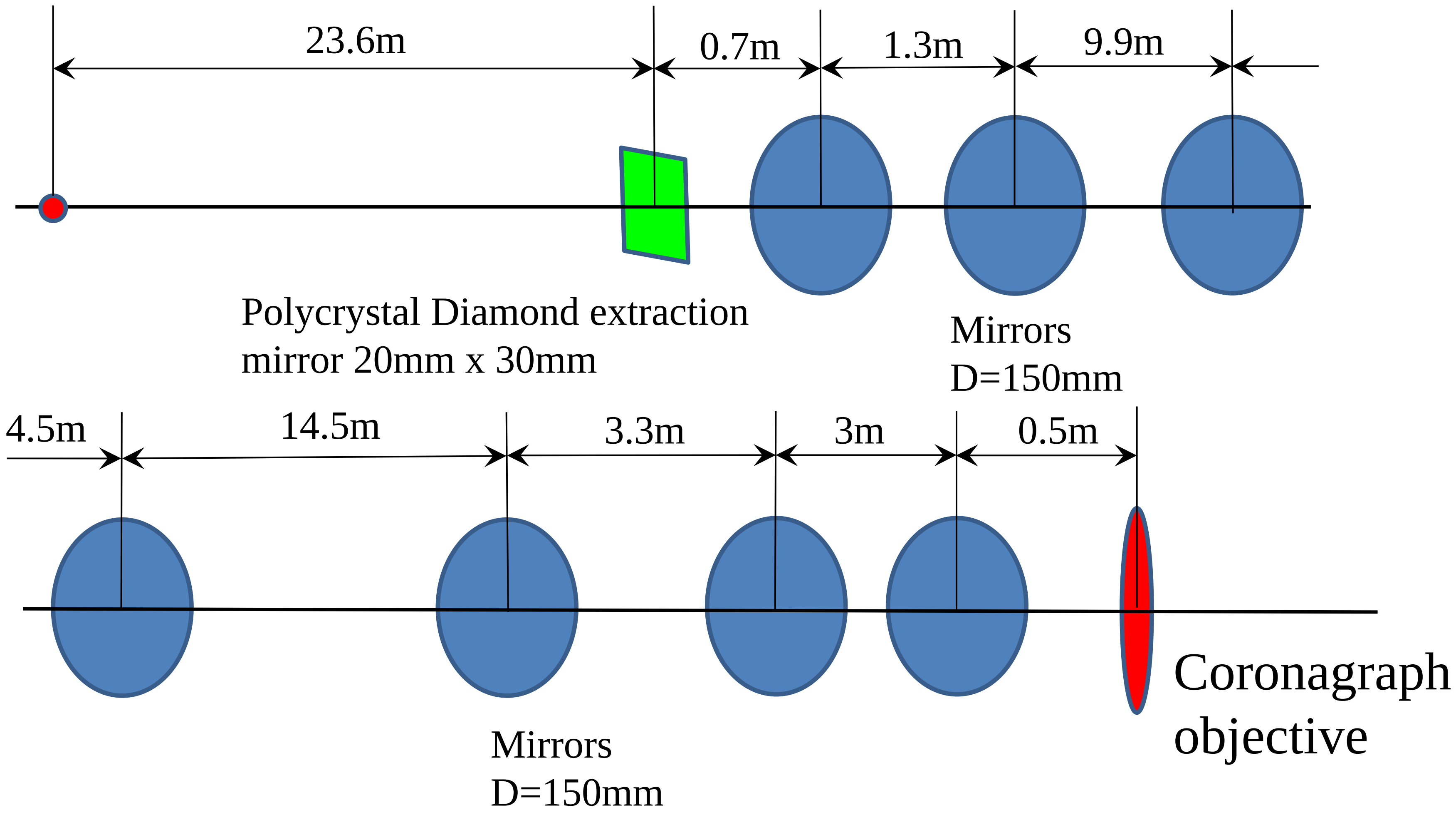
2.55×10^{-6}

Background leavel : about 6×10^{-7}

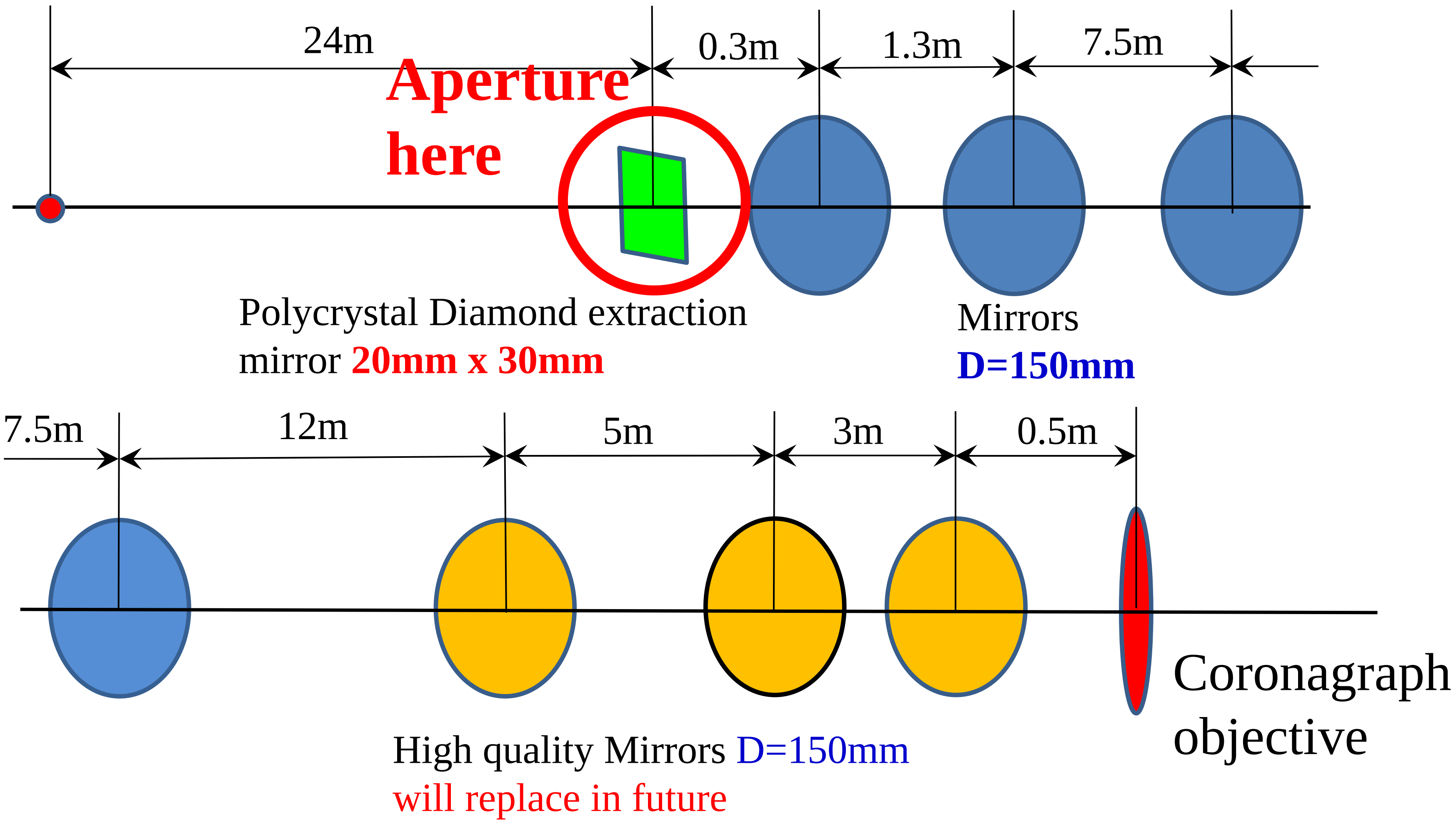
Coronagraph for SuperKEKB

1. Optical design

Optical configuration of SR monitor line in SuperKEKB total optical path=60m



Optical configuration of SR monitor line in SuperKEKB



Design of the objective

1. Due to diffraction theory of the coronagraph, leakage background in 3ed stage is roughly proportional to transverse magnification of the objective system.

Large transverse magnification will necessary

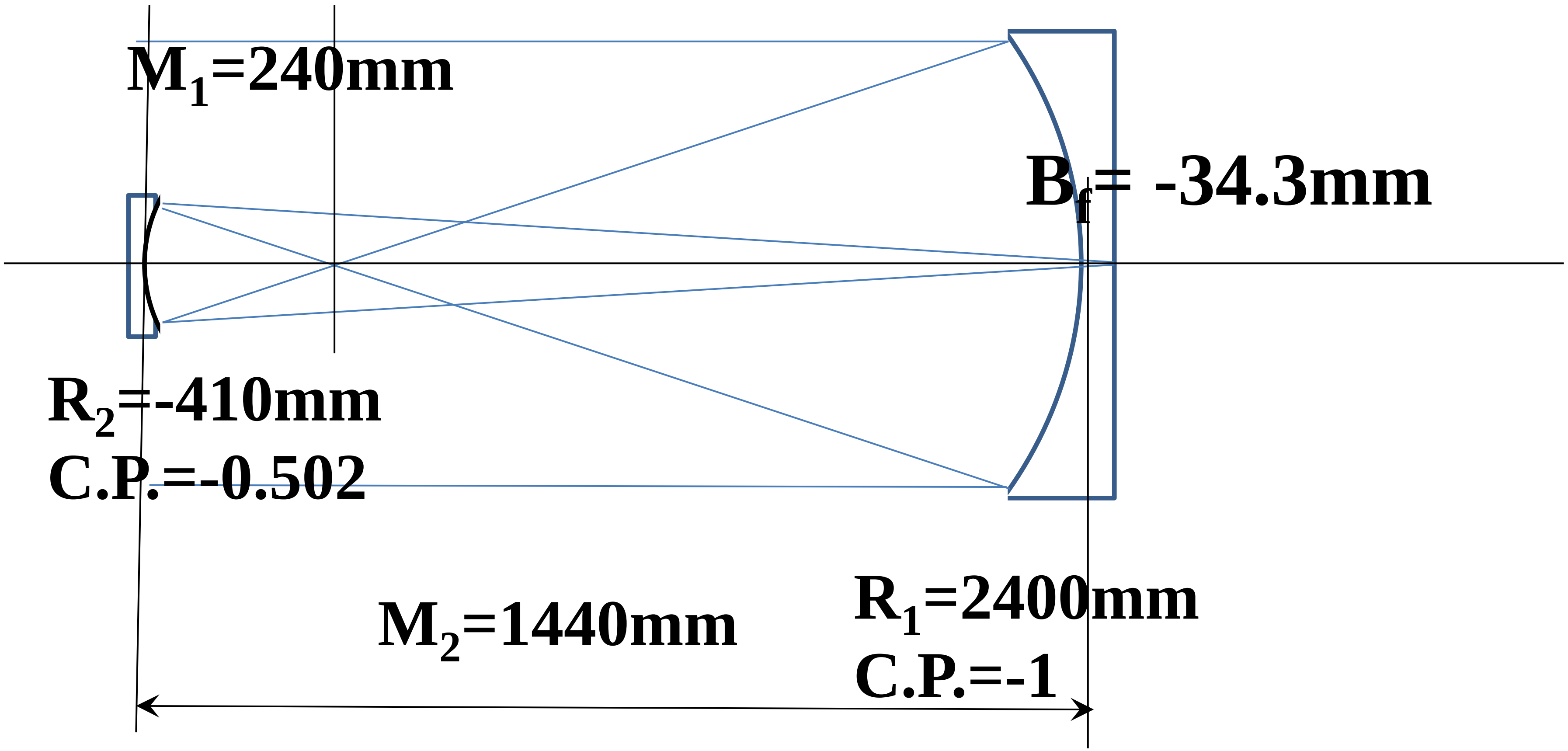
→ **long focal length**

2. Diamond mirror aperture must set at the front principal point of Objective

→ ***Use the telephoto system***

Detail of optical design of telephoto-objective system, Please see appendix 3

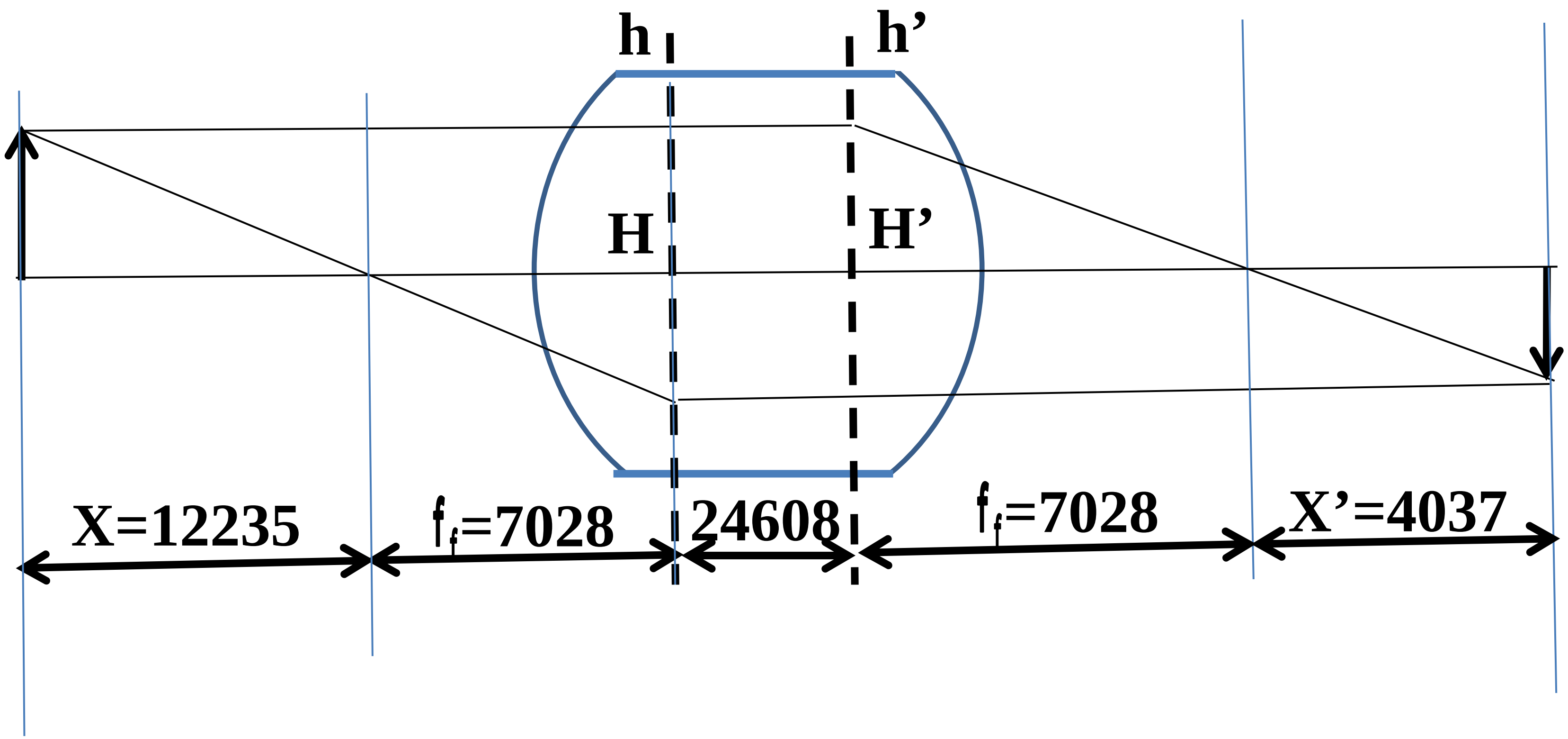
Optical design of Gregorian system for SuperKEKB



$$f = M\frac{R_1}{2} = 7028\text{mm}$$

Gregorian extension ratio=5.857

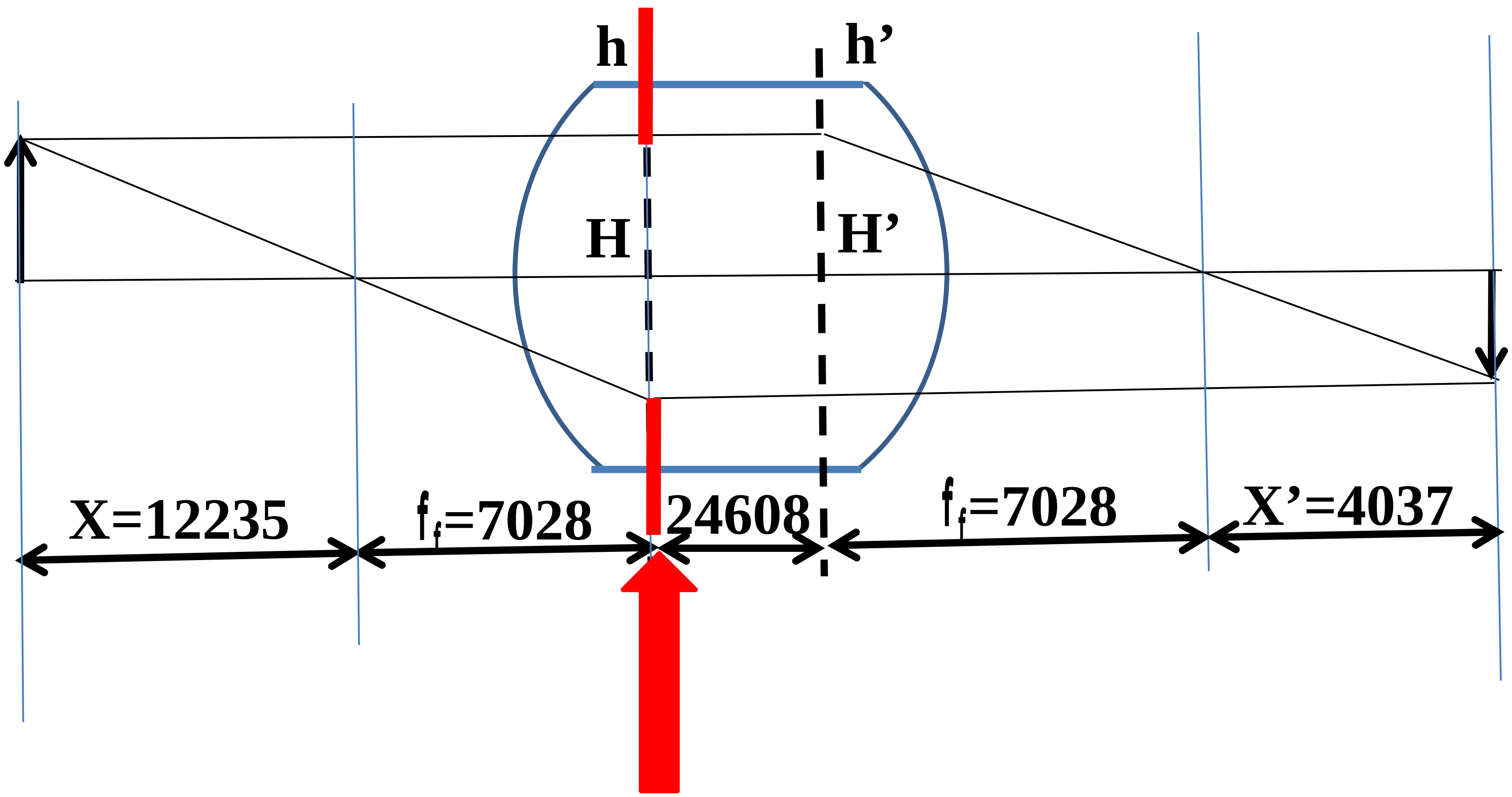
Relation of conjugation points (between source point and beam image)



Magnification=0.574

Distance between H and H' is 24608mm

Relation between source point and beam image



Set diamond mirror aperture at here

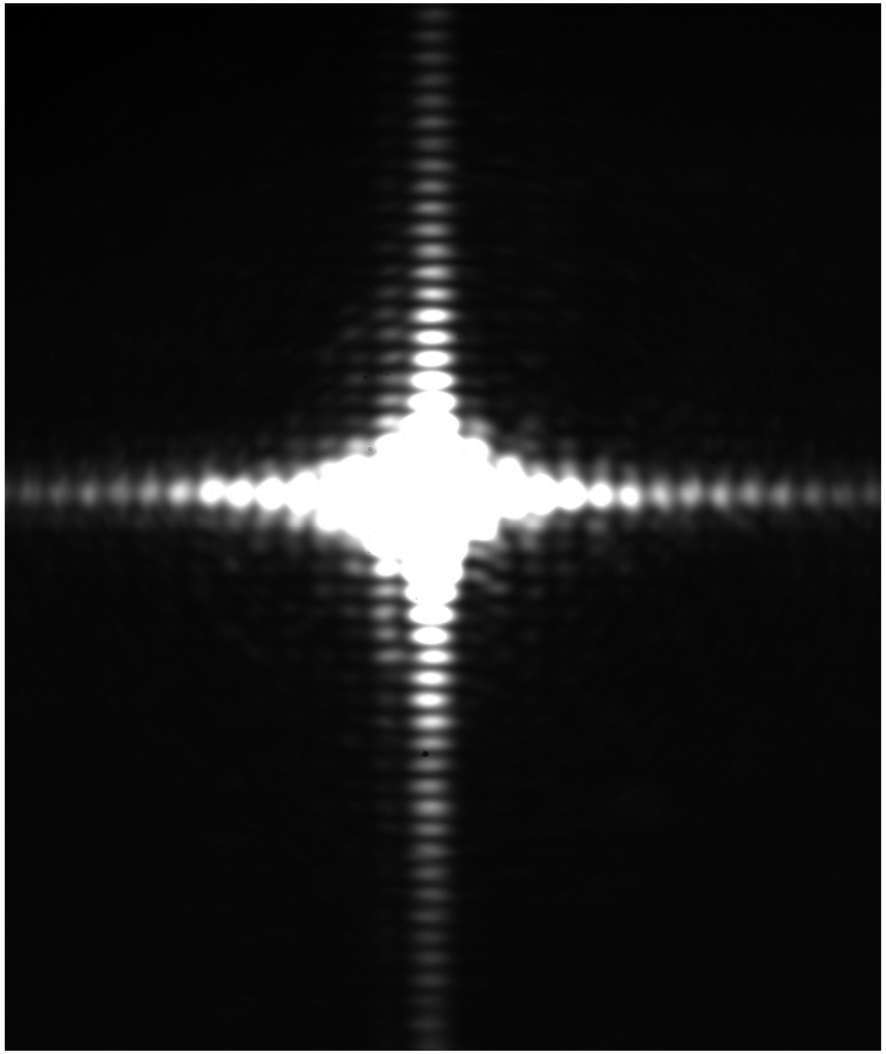
Designed magnification 0.574
Measurement 0.606

Error is about 5%

Majority source should be Focal length error (2% each) and distance error.

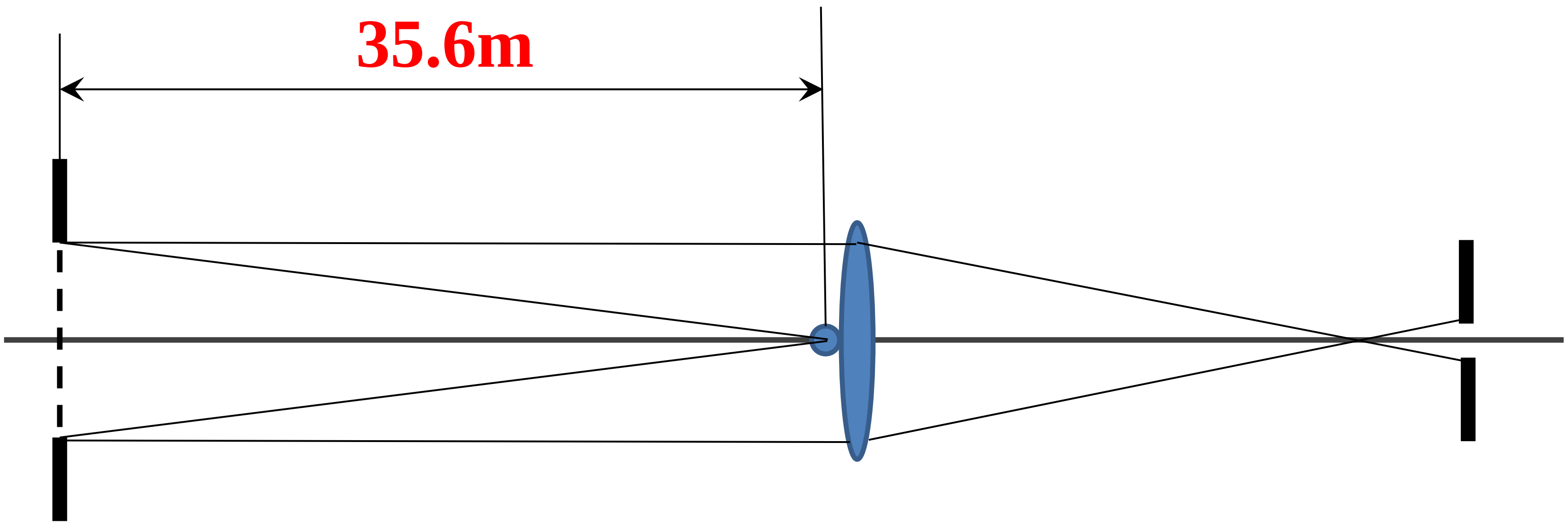
Wonderful agreement!

Observed beam image and diffraction fringes



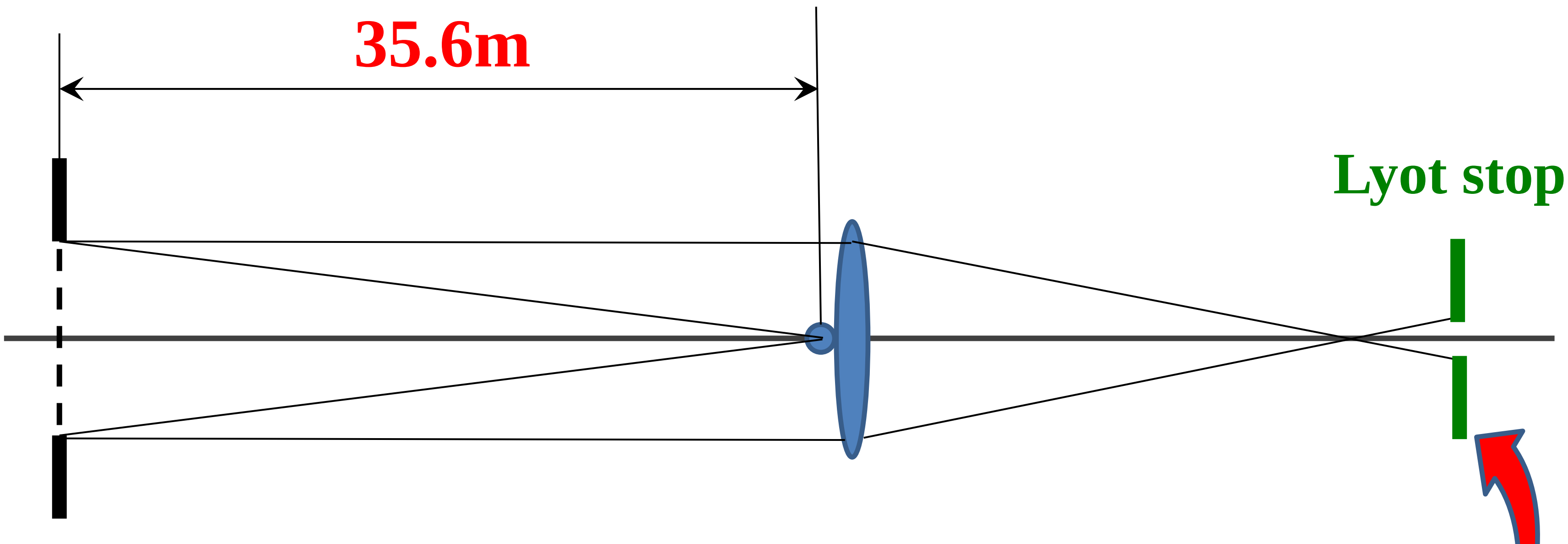
Higher order fringes are clealy observed

2ed stage, Re-diffraction system



Big problem is long distance between aperture and field lens

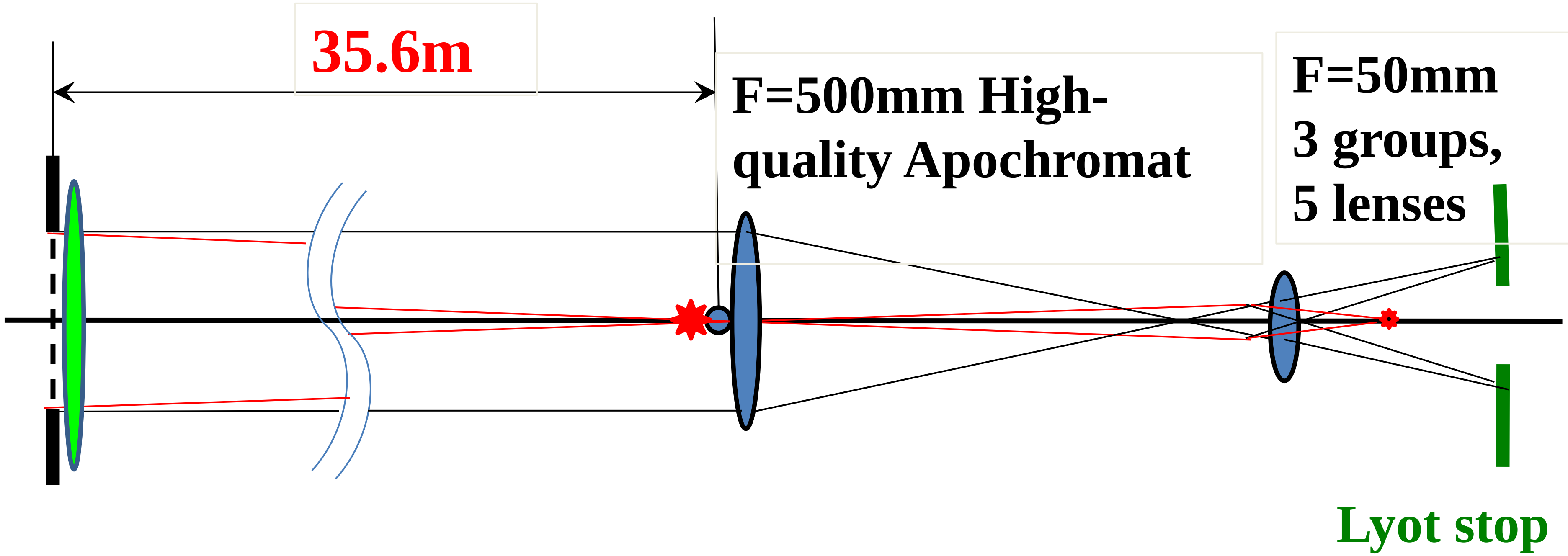
Design of re-diffraction system



Big problem is long distance between aperture and field lens

Difficult to obtain enough size of aperture image on Lyot stop!

Use Kepler system for obtain enough magnification



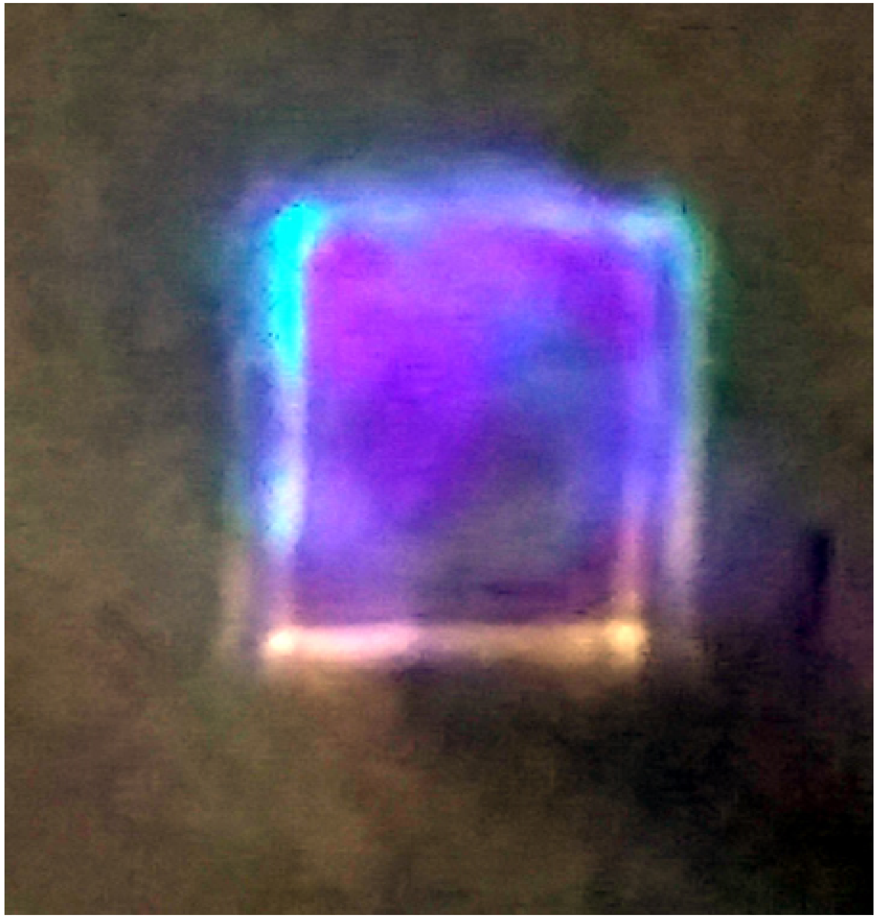
Expected problem

Focusing system has all + , +, + power

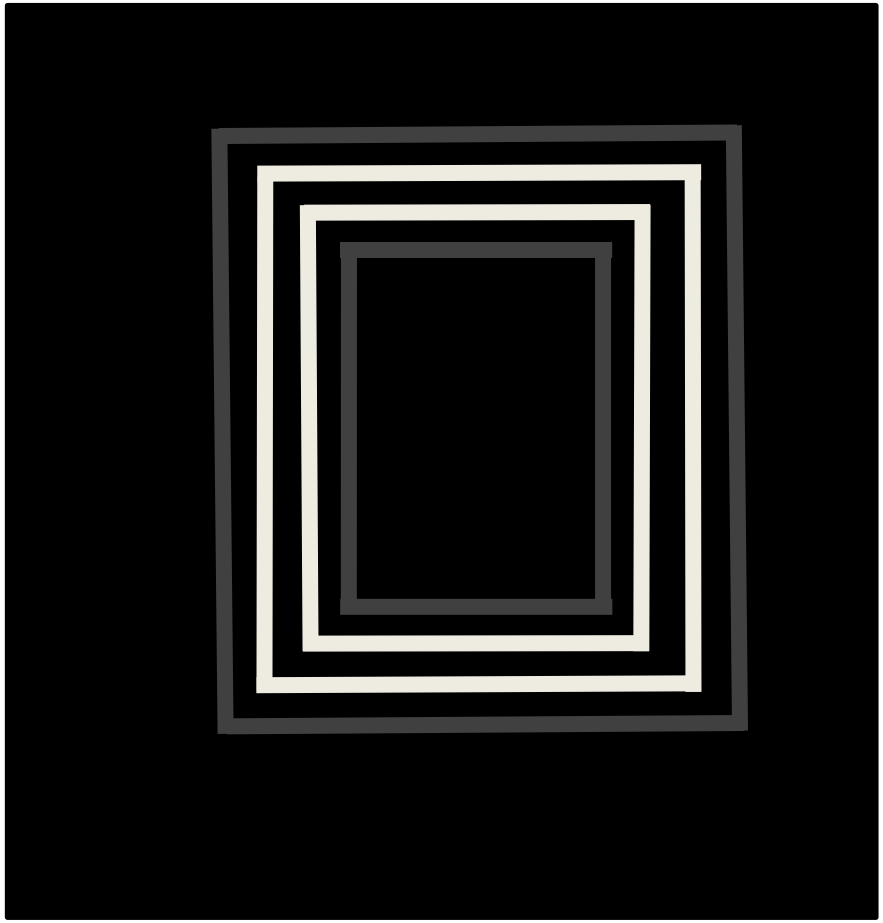
Enhancing the aberration

Especially for field flatness

Diffraction image on Lyot stop

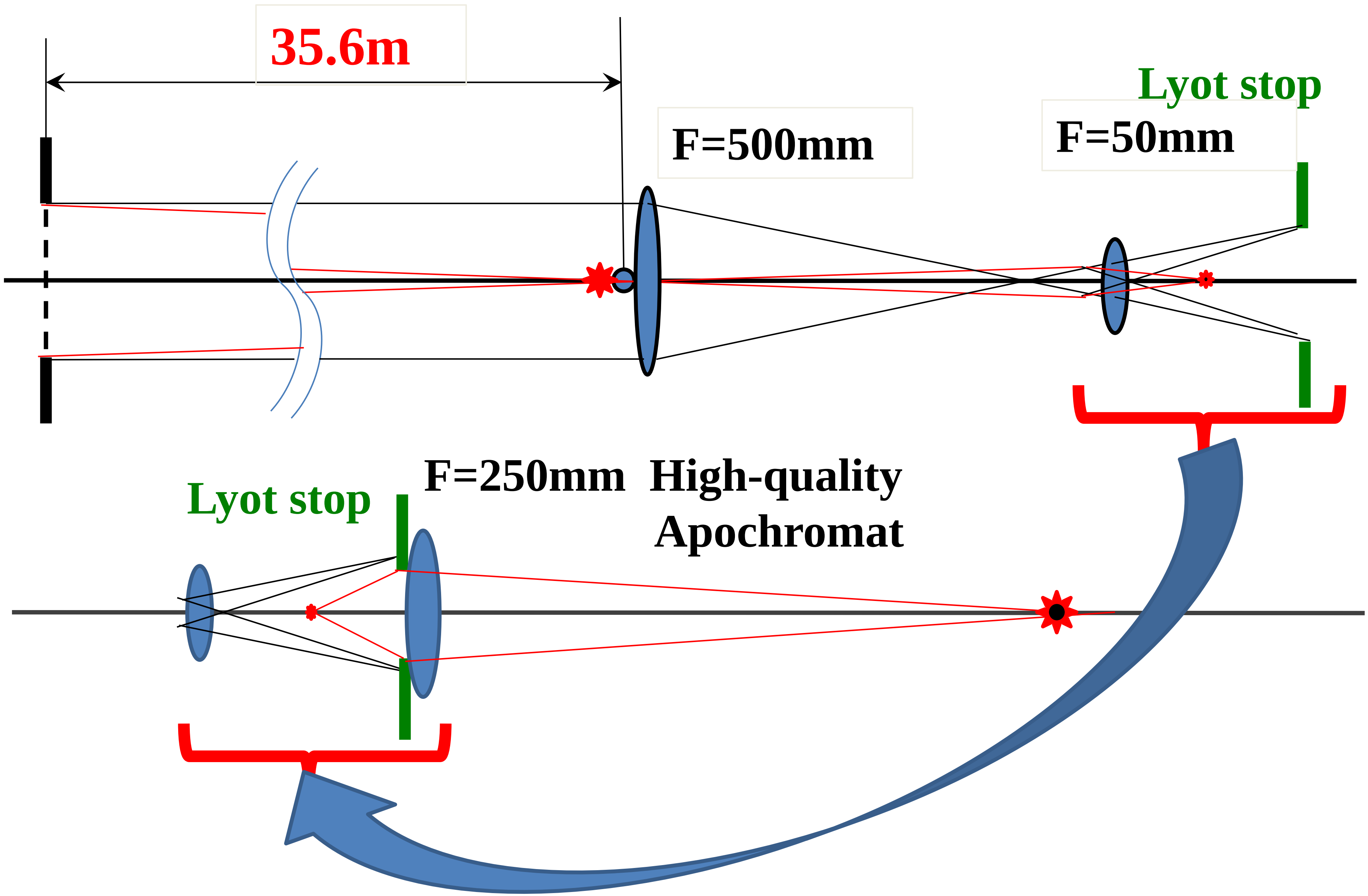


Observation



Graphical indication of double peaked diffraction pattern

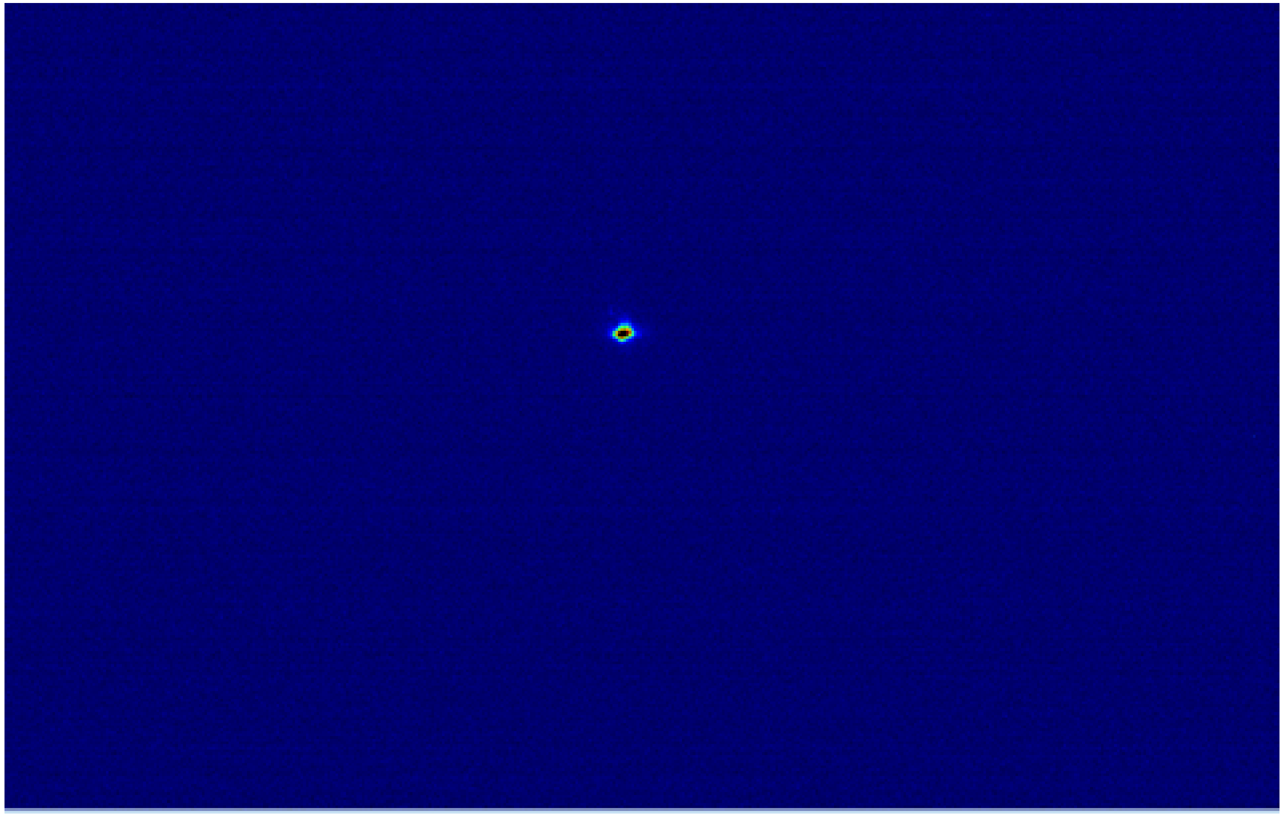
Adding 3ed stage, Relay optics



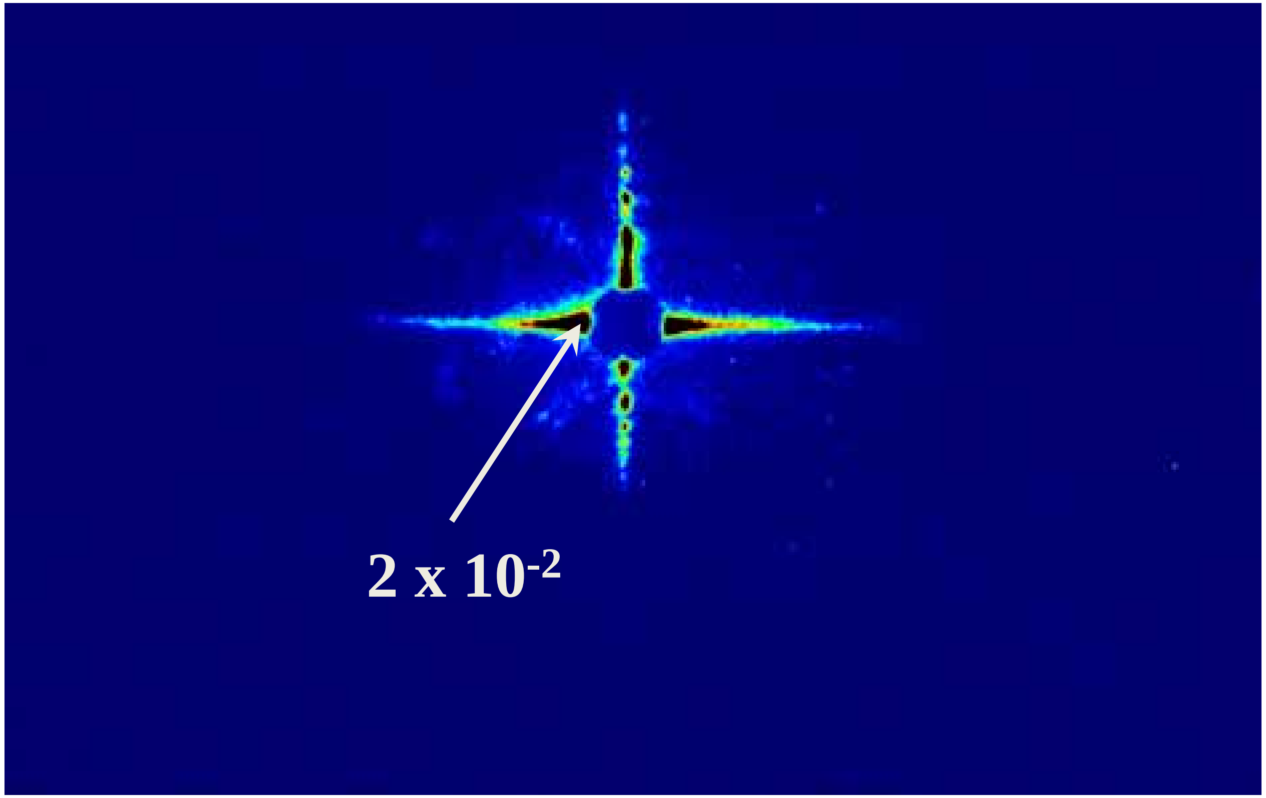
35.6m
F=500mm
Lyot stop
F=50mm
F=250mm High-quality
Apochromat
Lyot stop

Results of observation from last operation

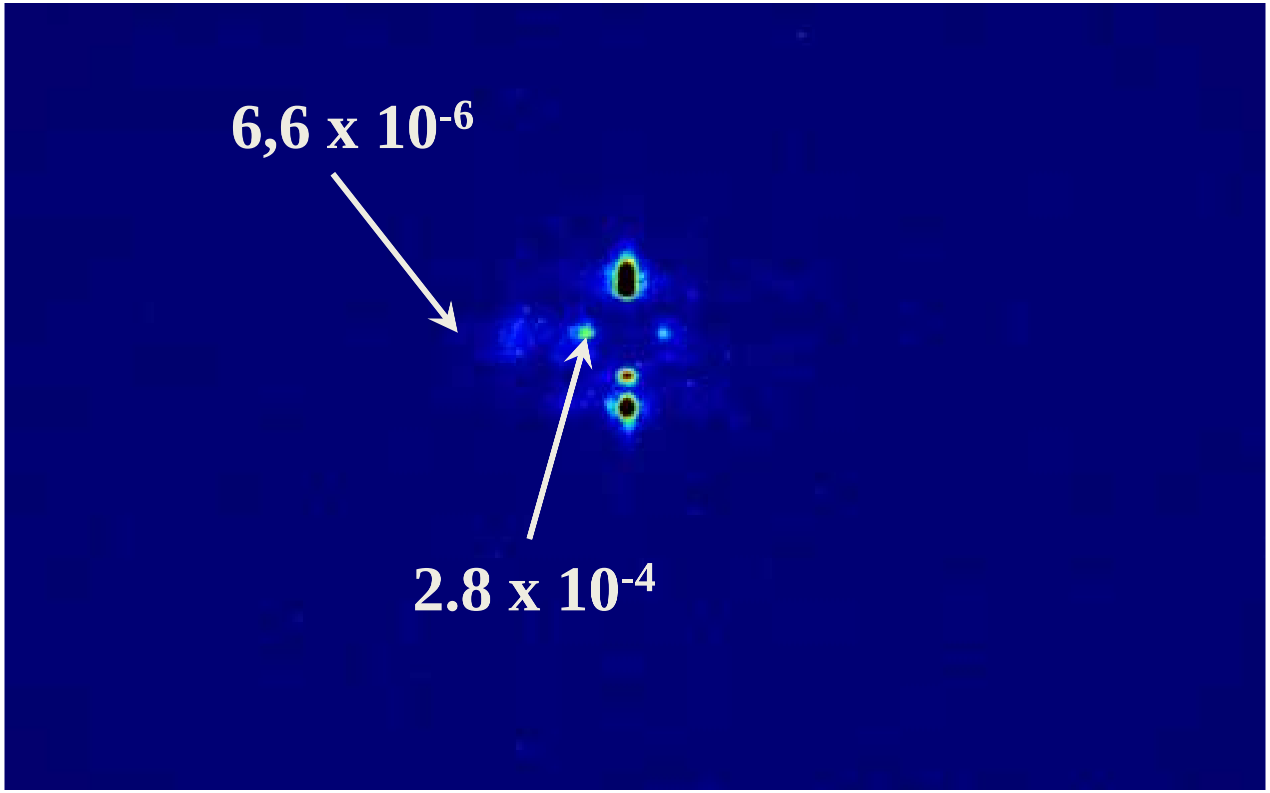
Stored beam with total optics



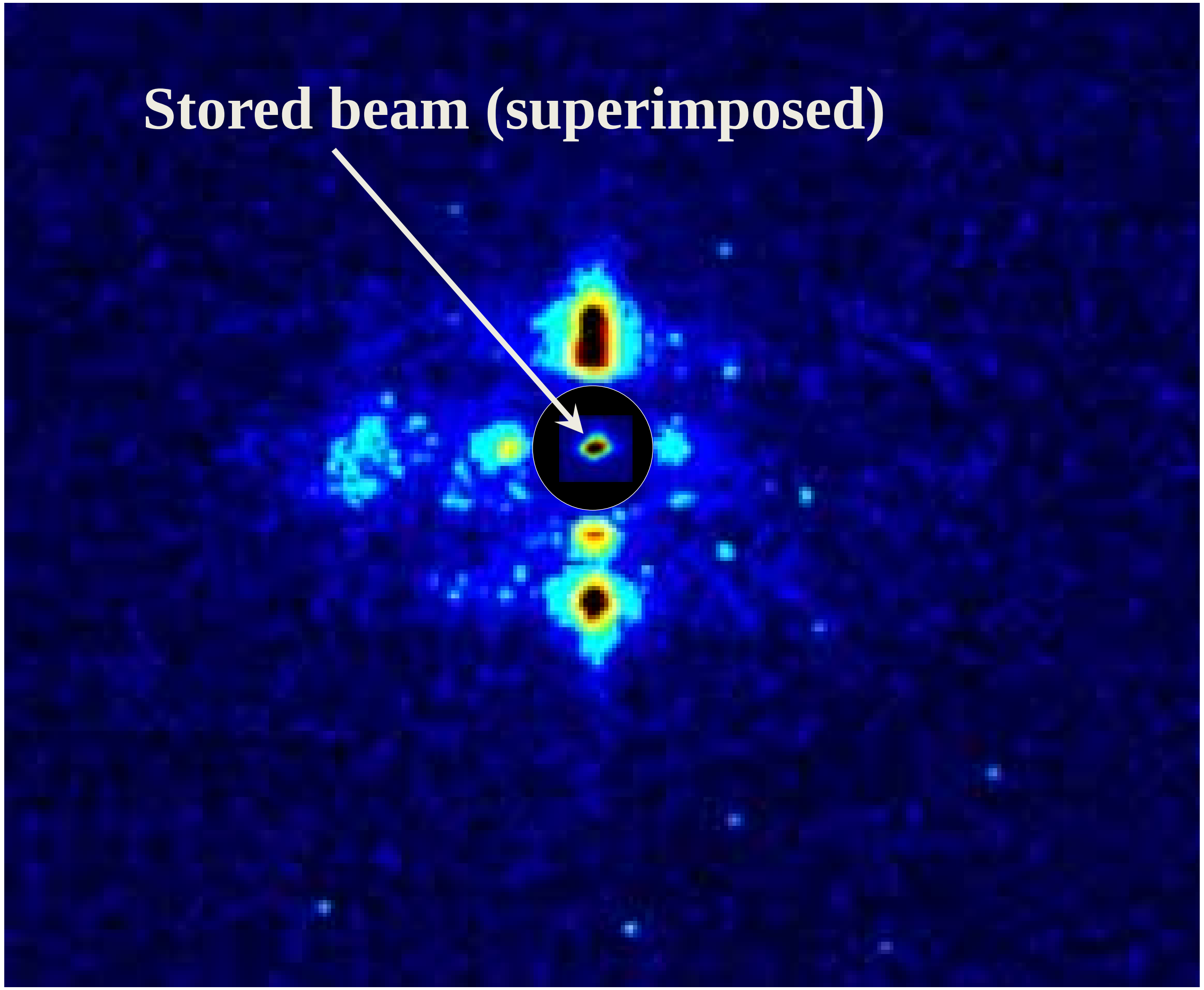
5mm opaque disk is applied



Close horizontal Lyot stop



vertical Lyot stop is slightly closed



Scattering noise or something beam origin??

Conclusions

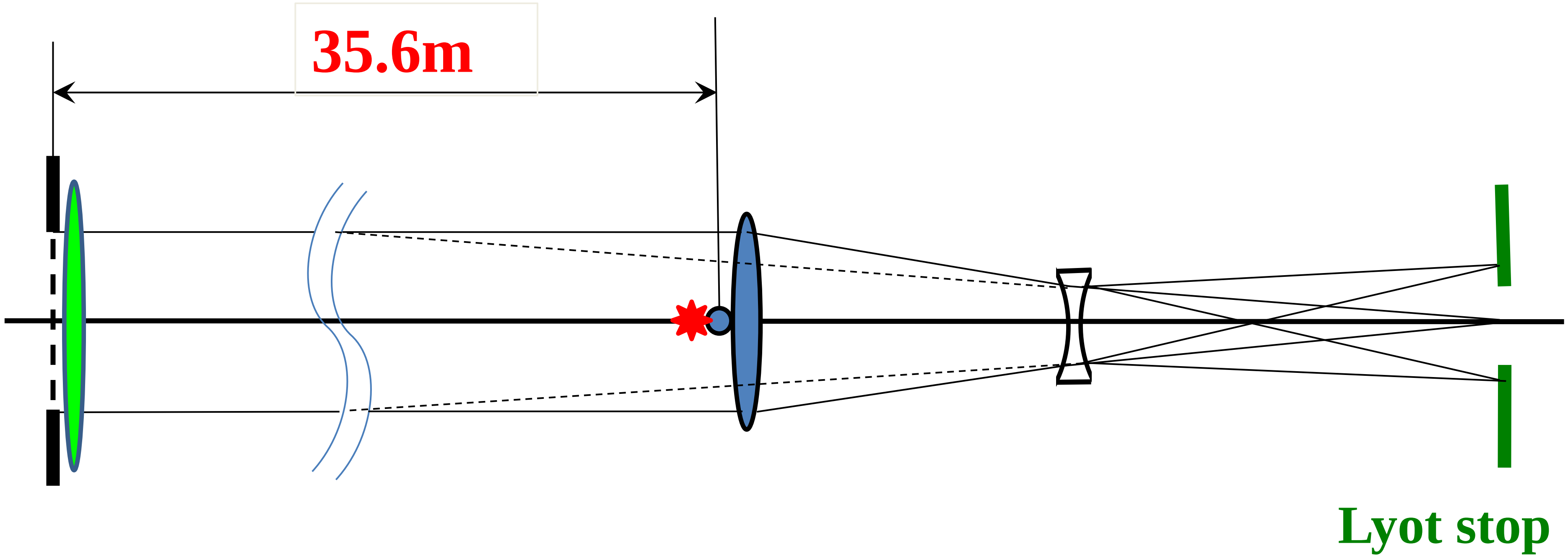
1. **We design Gregorian objective having a diffraction limited quality for SuperKEKB.**
2. **A Kepler type re-diffraction system is applied.**
3. **With third relay system, we got beam image and we established basic function of coronagraph with Lyot stop (elimination of diffraction fringe).**

Problems

Kepler style re-diffraction system enhanced the field distortion.
Difficult to reach more large transverse magnification in total system.
Difficult to further elimination of diffraction fringe.

To solve these problems, Galileo type re-diffraction system will test in next operation

Galileo type re-diffraction system



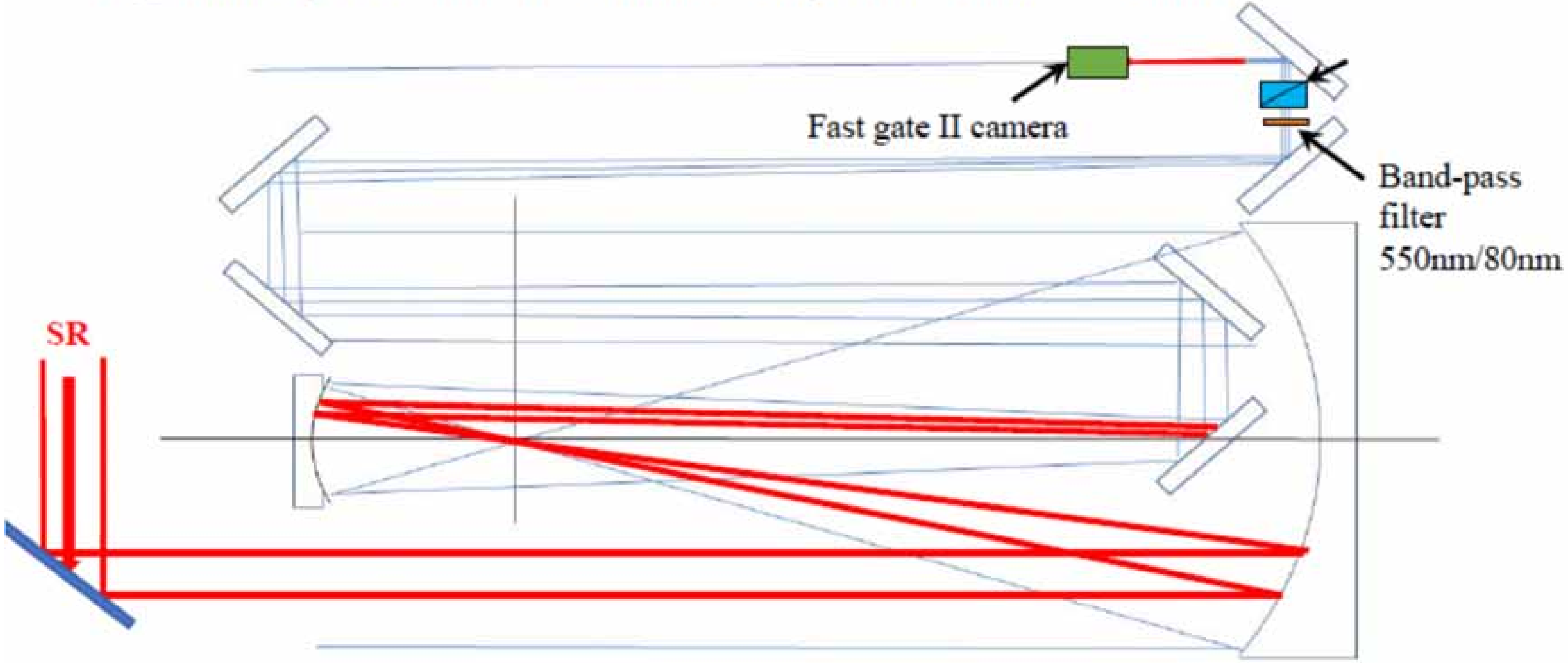
Focusing system has all + , +, - power

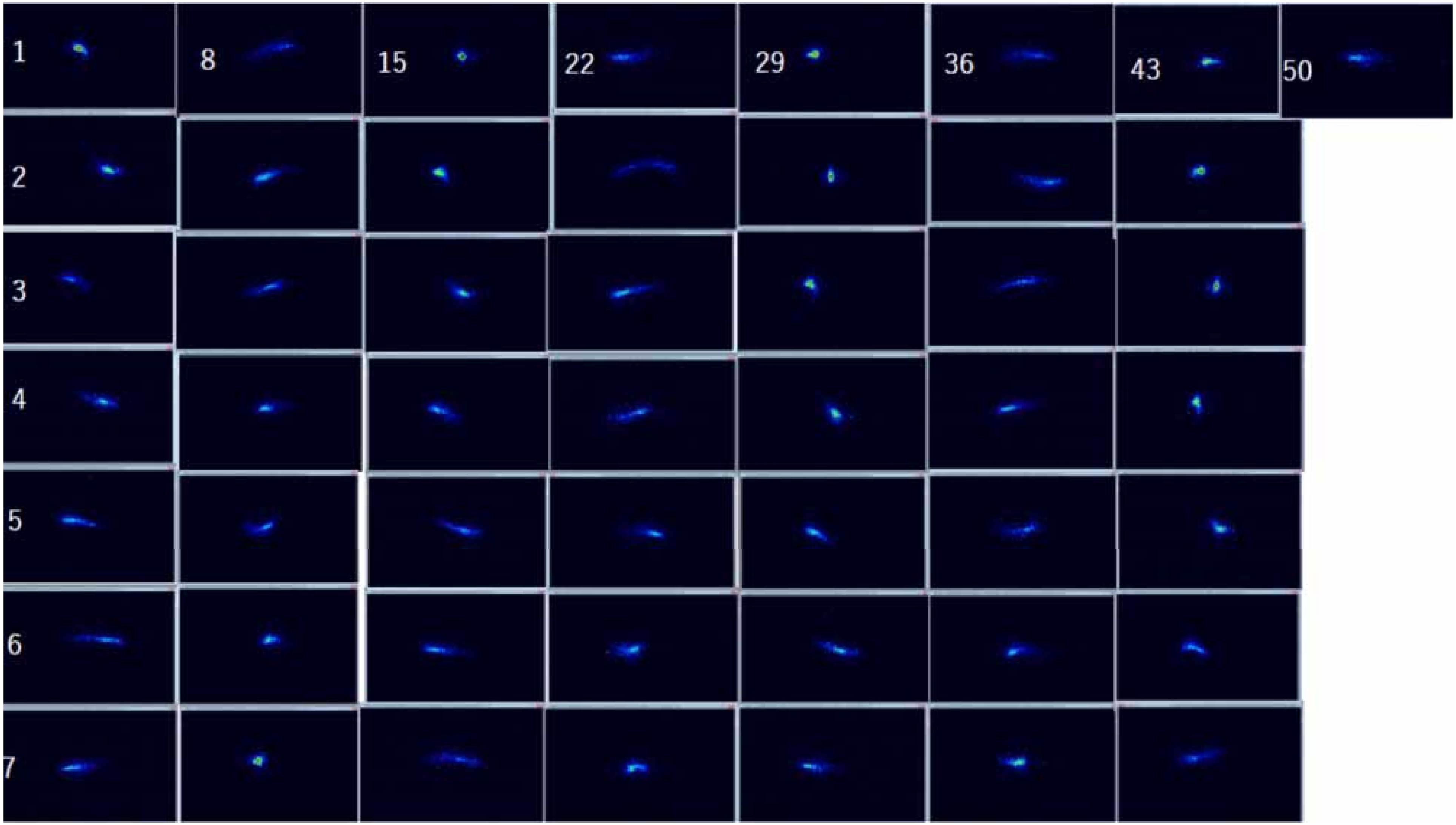
Learned from SuperKEKB

1. **High quality (low noise) Optical beam line is necessary to coronagraph.**
2. **New polycrystal Diamiond mirror can establish perfect wavefront transfer withour significant distortion.**
3. **Using Gregorian objective, we can optimize coronagraph design for long optical beam line (60m in the Super KEKB).**

Application of coronagraph objective for turn by turn observation of injected beam profile

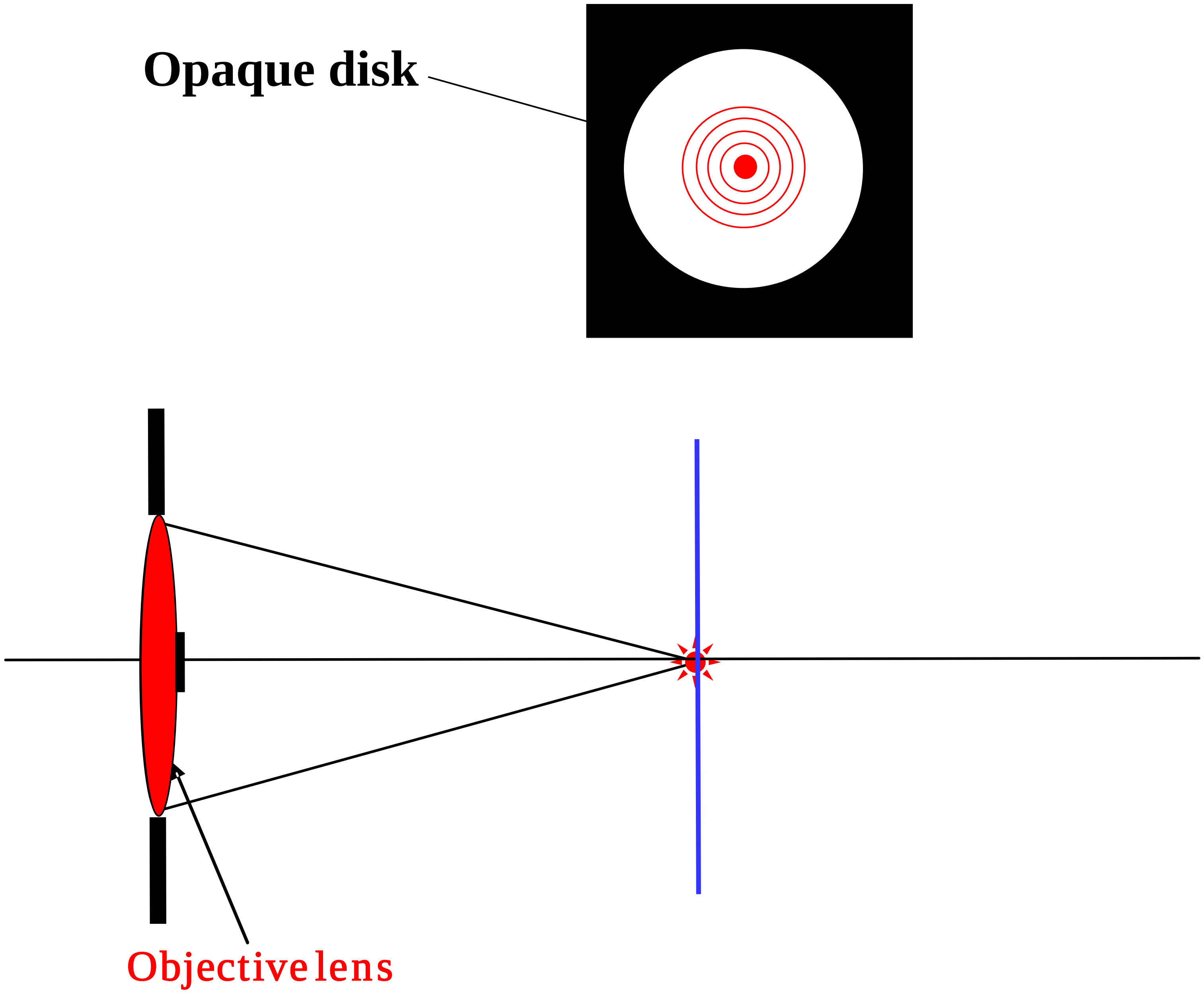
Gregorian objective for observation of injected beam f=7028mm




1
8
15
22
29
36
43
50
2
3
4
5
6
7

Appendix 1

Diffraction theory for the Coronagraph


Opaque disk
Objective lens

Instantaneous diffraction pattern at focus point of Objective lens is given by,

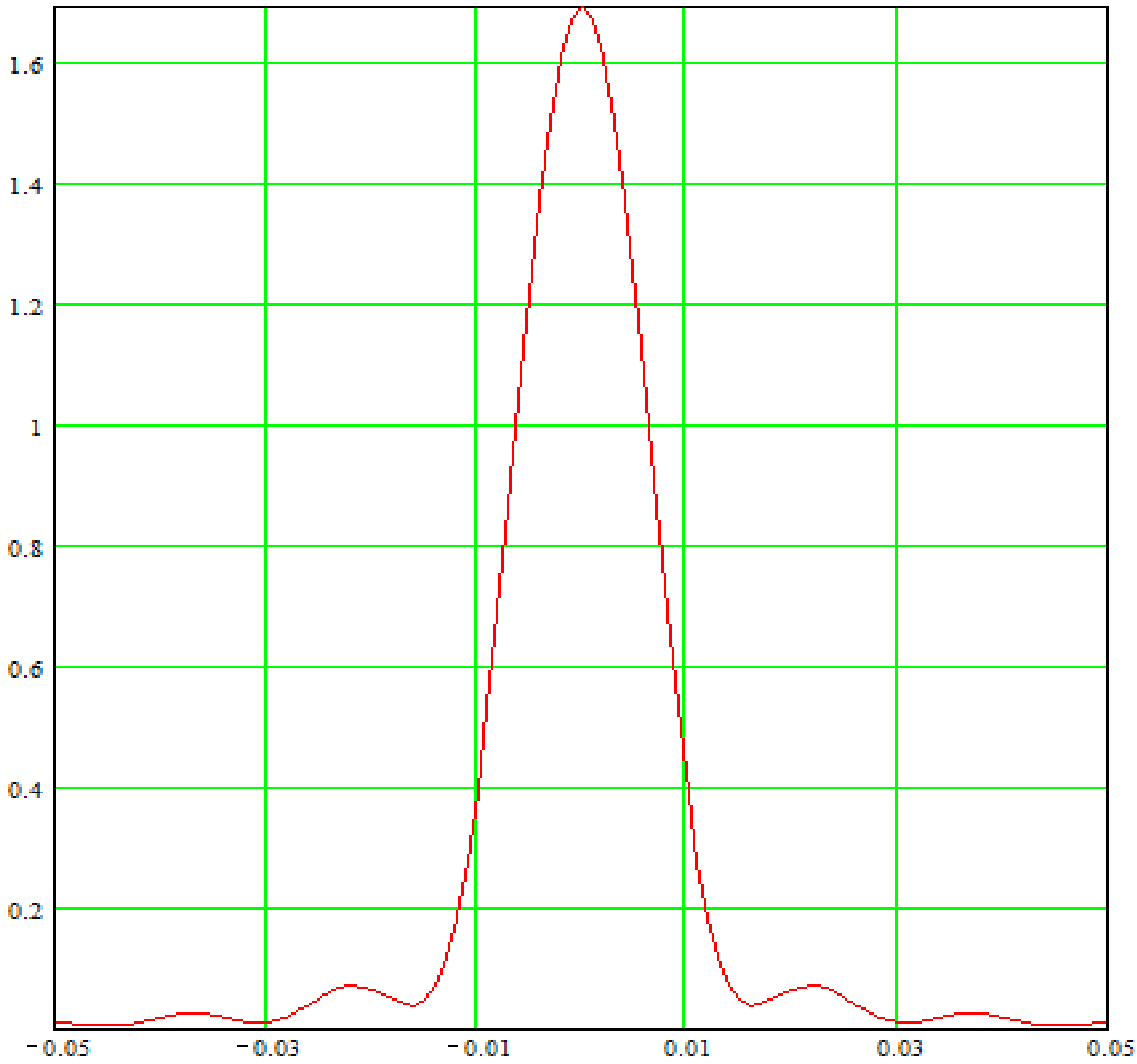
$$\boldsymbol{F}\left(x_{obj},y_{obj},\theta\right)=\frac{1}{\boldsymbol{i}\cdot\lambda\cdot f_{\boldsymbol{obj}}}\iint F_0\boldsymbol{(}x+R\theta,y\boldsymbol{)}\,\mathbf{exp}\left\{-\frac{\boldsymbol{i}\cdot 2\cdot\pi\cdot\left(x\cdot x+y\cdot y\right)}{\lambda\cdot f_{\boldsymbol{obj}}}\right\}dx\,dy$$

$$F_0(x,y)=\left\{\frac{e^2}{3\pi^2 c}\left(\frac{\omega\rho}{c}\right)^2\left(\frac{1}{\gamma^2}+\left(\frac{x}{R}\right)^2+\left(\frac{y}{R}\right)^2\right)^2\left[K_{2/3}^2(\zeta)+\frac{\psi^2}{\frac{1}{\gamma^2}+\left(\frac{x}{R}\right)^2+\left(\frac{y}{R}\right)^2}K_{1/3}^2(\zeta)\right]\right\}^{\frac{1}{2}}$$

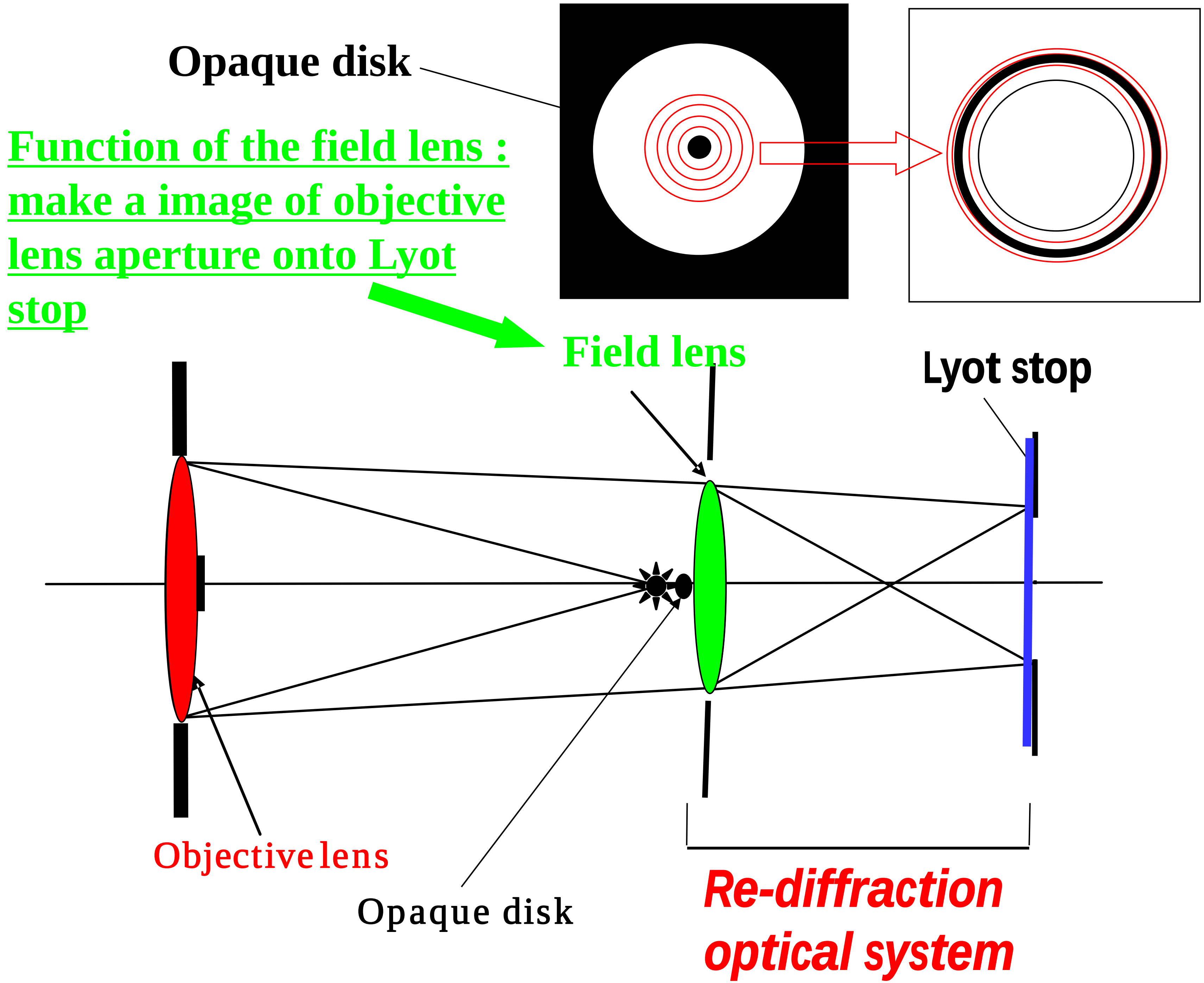
$$\zeta=\frac{\omega\rho}{3c}\left(\frac{1}{\gamma^2}+\left(\frac{x}{R}\right)^2+\left(\frac{y}{R}\right)^2\right)^{\frac{3}{2}}$$

Apparent diffraction pattern on focus point is given by integrating instantaneous diffraction pattern in incoherent manner ,

$$\boldsymbol{I}_{\boldsymbol{obj}}\left(x_{obj},y_{obj}\right)=\int\left|\boldsymbol{F}^2\left(x_{obj},y_{obj},\theta\right)\right|d\theta$$



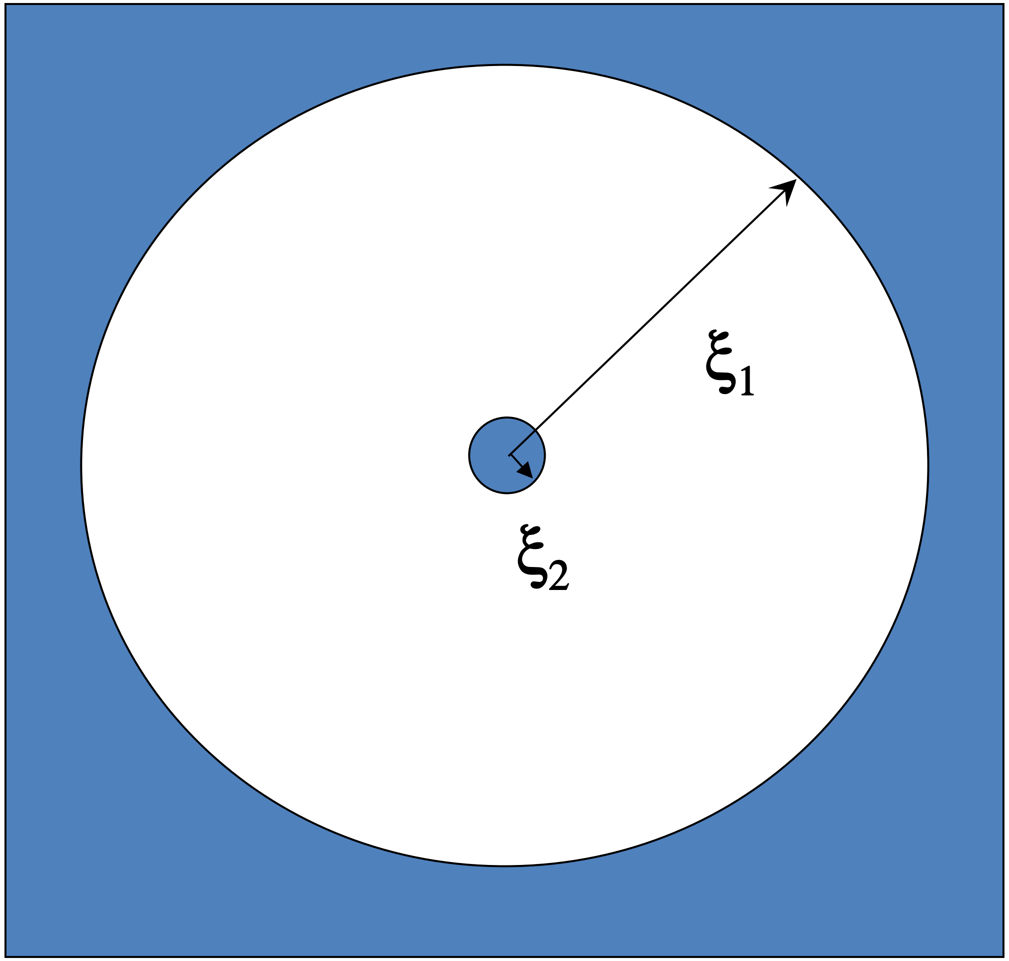
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
− 0.05
− 0.03
− 0.01
0.01
0.03
0.05



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

Field lens diffraction

The integration performs ξ_1 and ξ_1



ξ_1: radius of field lens

ξ_2: radius of opaque disk

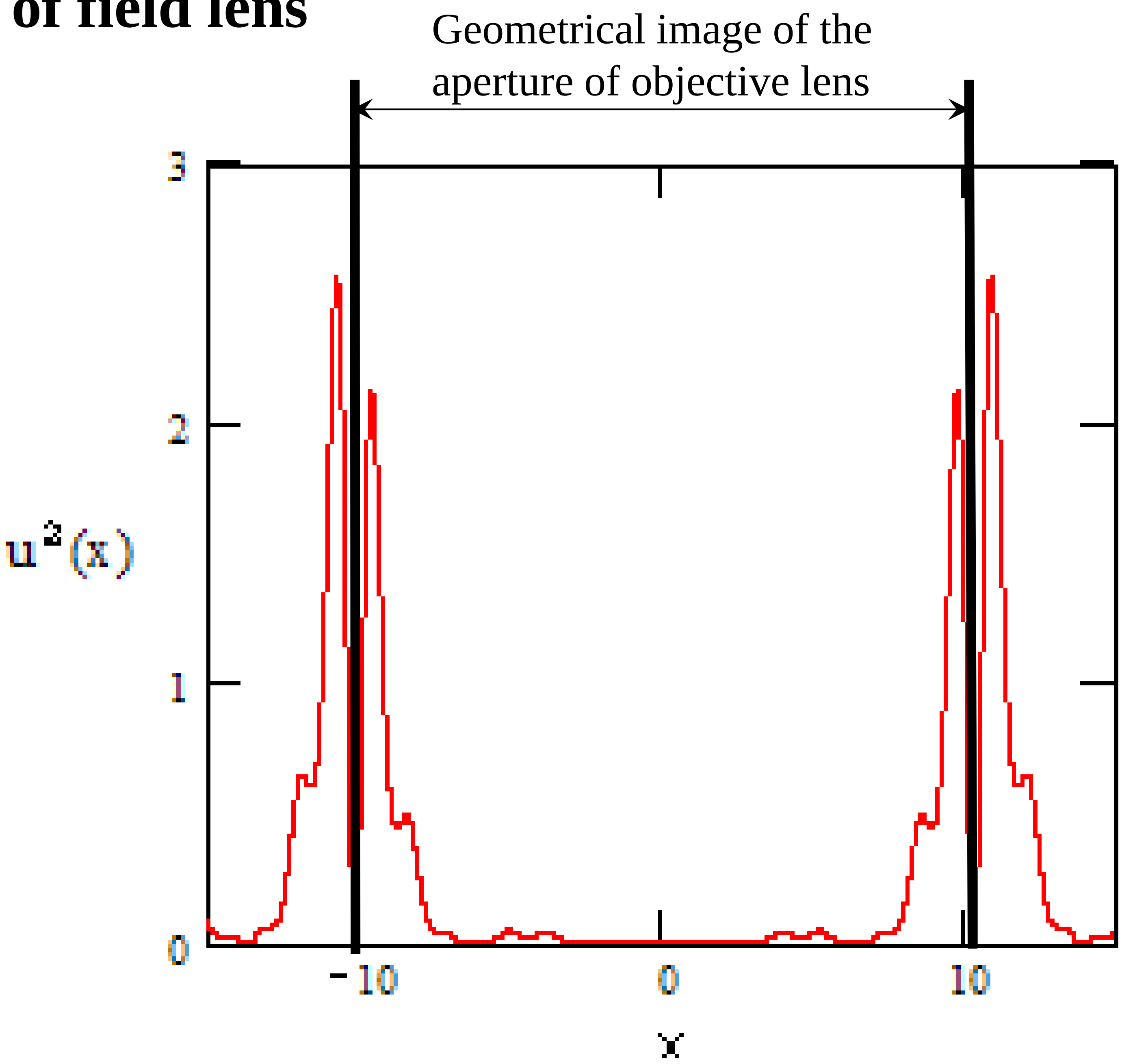
Disturbance of light on Lyot's stop by re-diffraction system is given by;

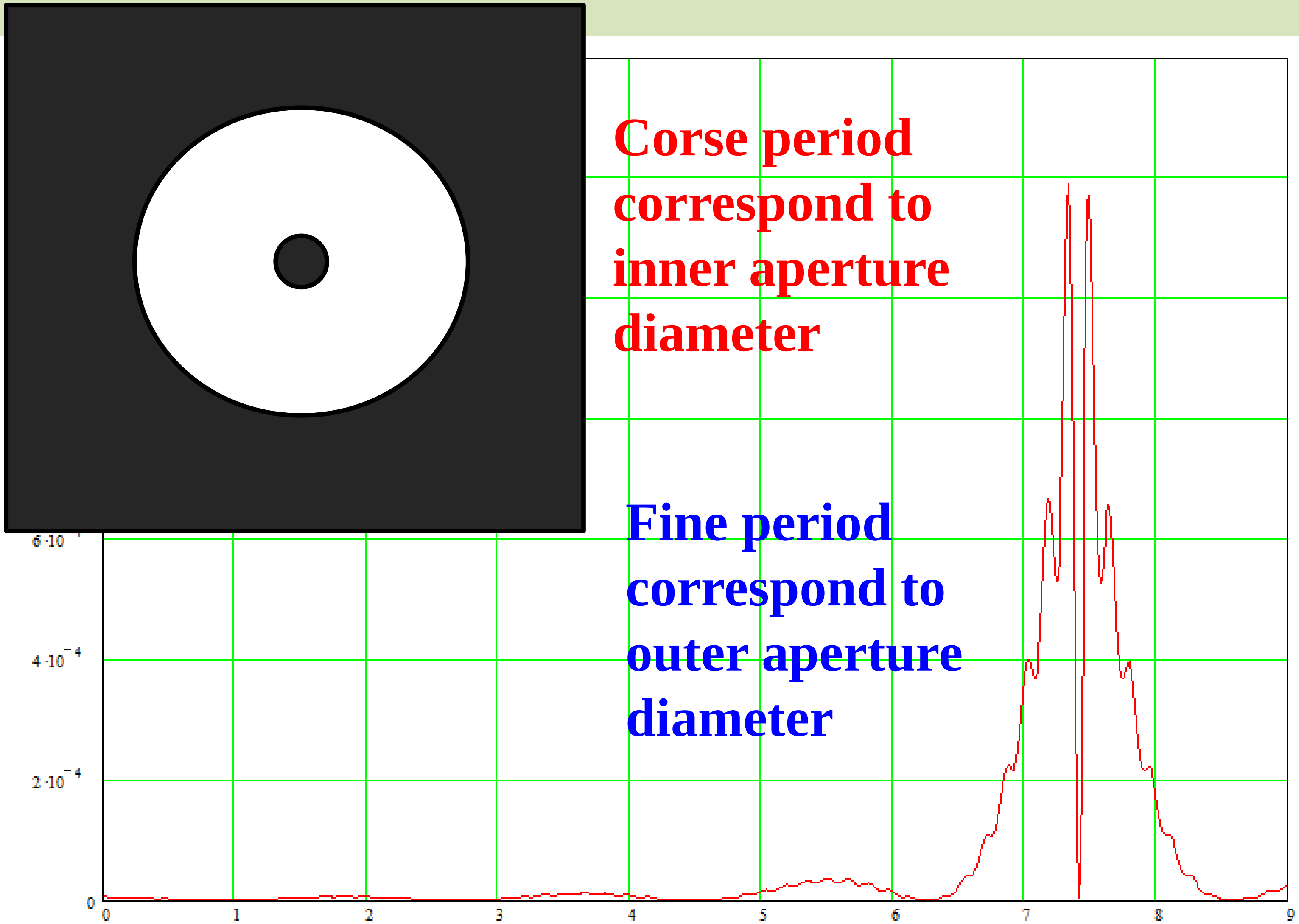
$$u(x) = \frac{1}{i \cdot \lambda \cdot f_{field}} \left[\int_0^{\xi 2} F(\xi) exp\left\{ -\frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{field}} \right\} d\xi - \int_0^{\xi 1} F(\xi) exp\left\{ -\frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{field}} \right\} d\xi \right]$$

$$= \frac{1}{i \cdot \lambda \cdot f_{field}} \left[\int_0^{\xi 2} F(\xi) exp\left\{ -\frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{field}} \right\} d\xi + \int_{\xi 1}^{0} F(\xi) exp\left\{ -\frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{field}} \right\} d\xi \right]$$

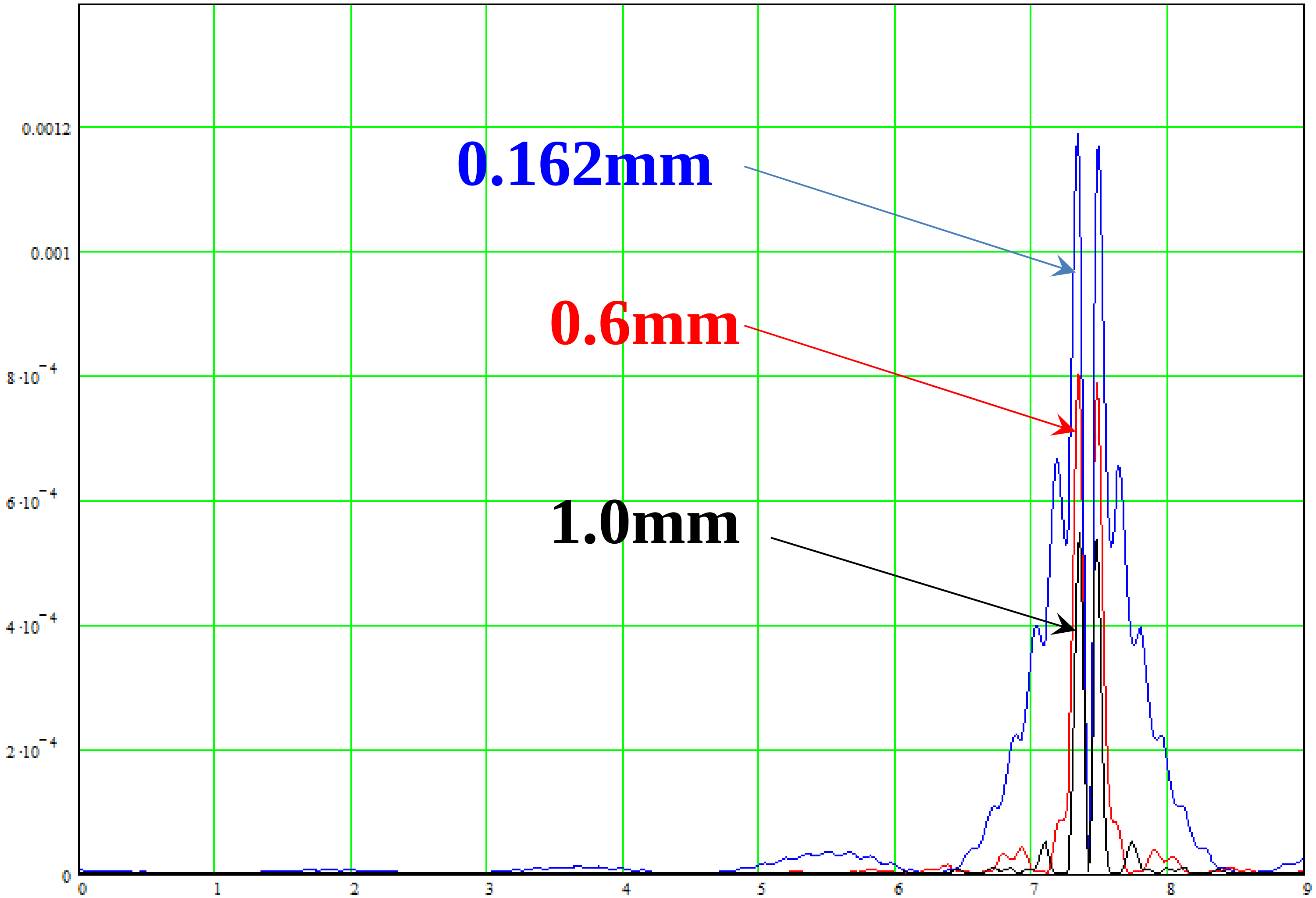
$$= \frac{1}{i \cdot \lambda \cdot f_{field}} \left[\int_{\xi 1}^{\xi 2} F(\xi) exp\left\{ -\frac{i \cdot 2 \cdot \pi \cdot x \cdot \xi}{\lambda \cdot f_{field}} \right\} d\xi \right]$$

Intensity distribution of diffraction fringes on focus plane of field lens

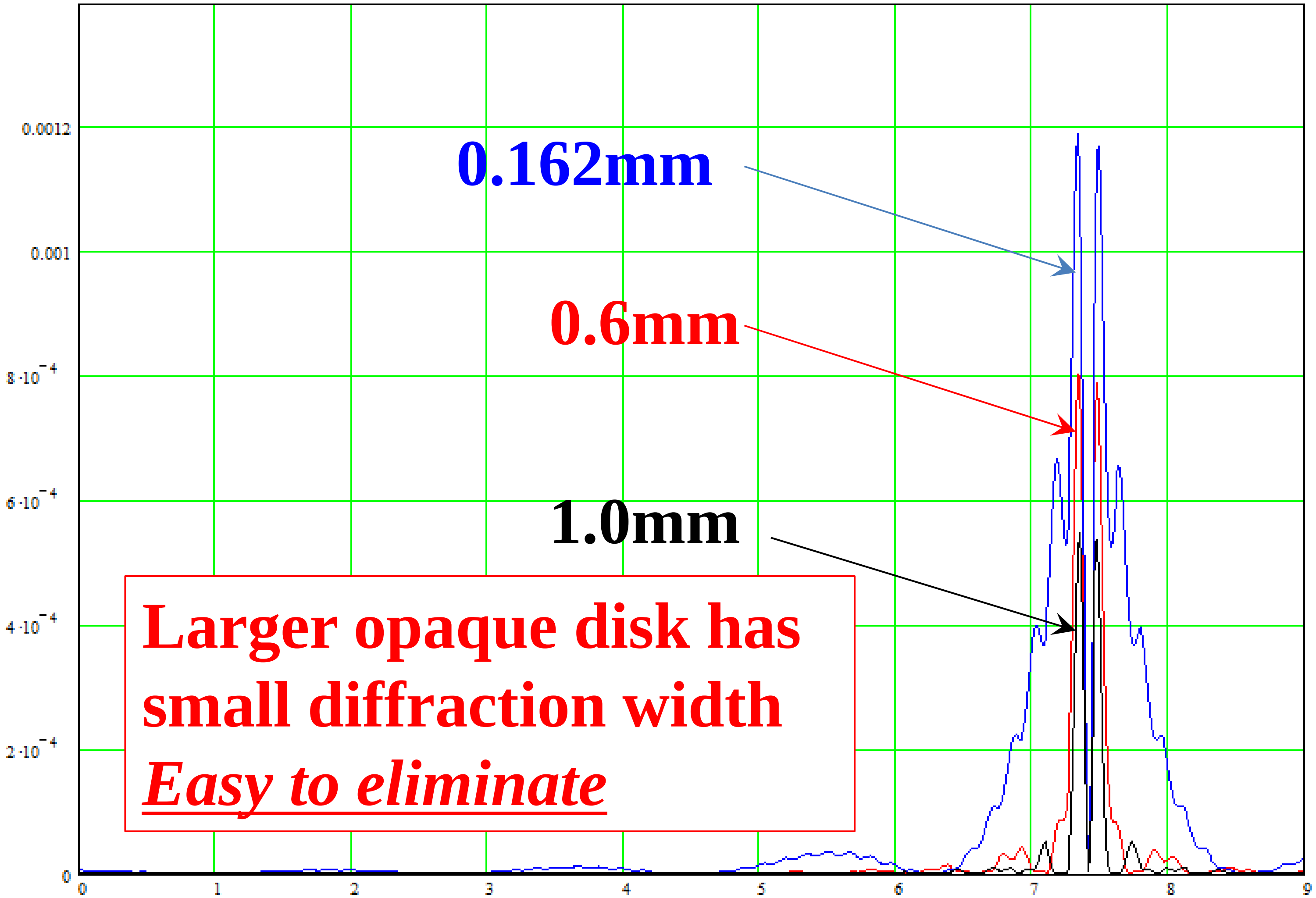


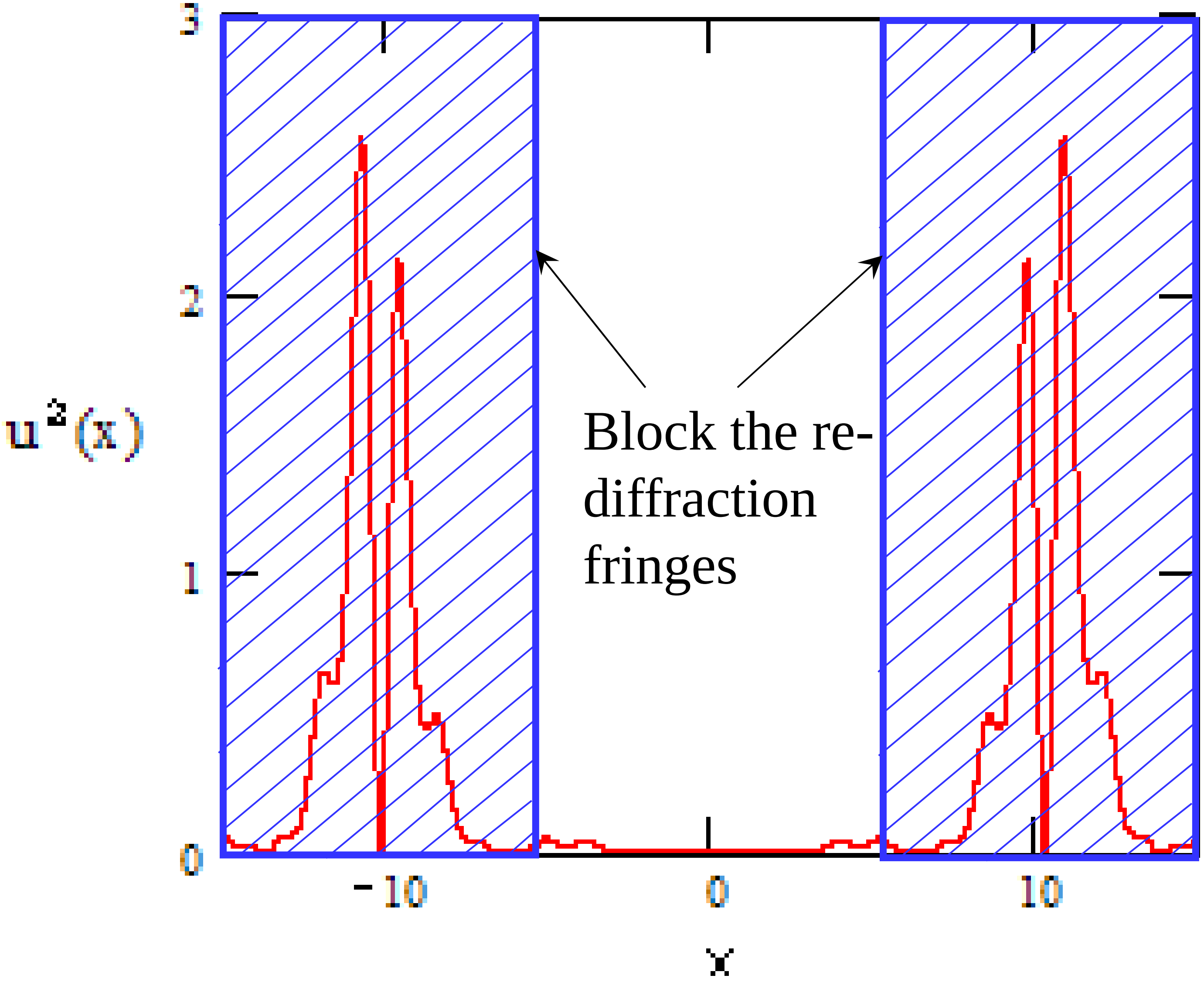

Corse period correspond to inner aperture diameter
Fine period correspond to outer aperture diameter
6·10⁻⁴
4·10⁻⁴
2·10⁻⁴
0
0
1
2
3
4
5
6
7
8
9

dependence of diffraction width for different diameter of oparque disk



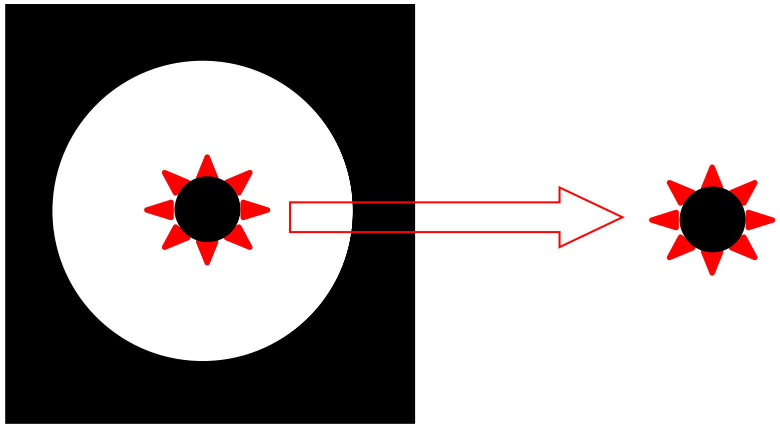
diffraction fringe on Lyot stop

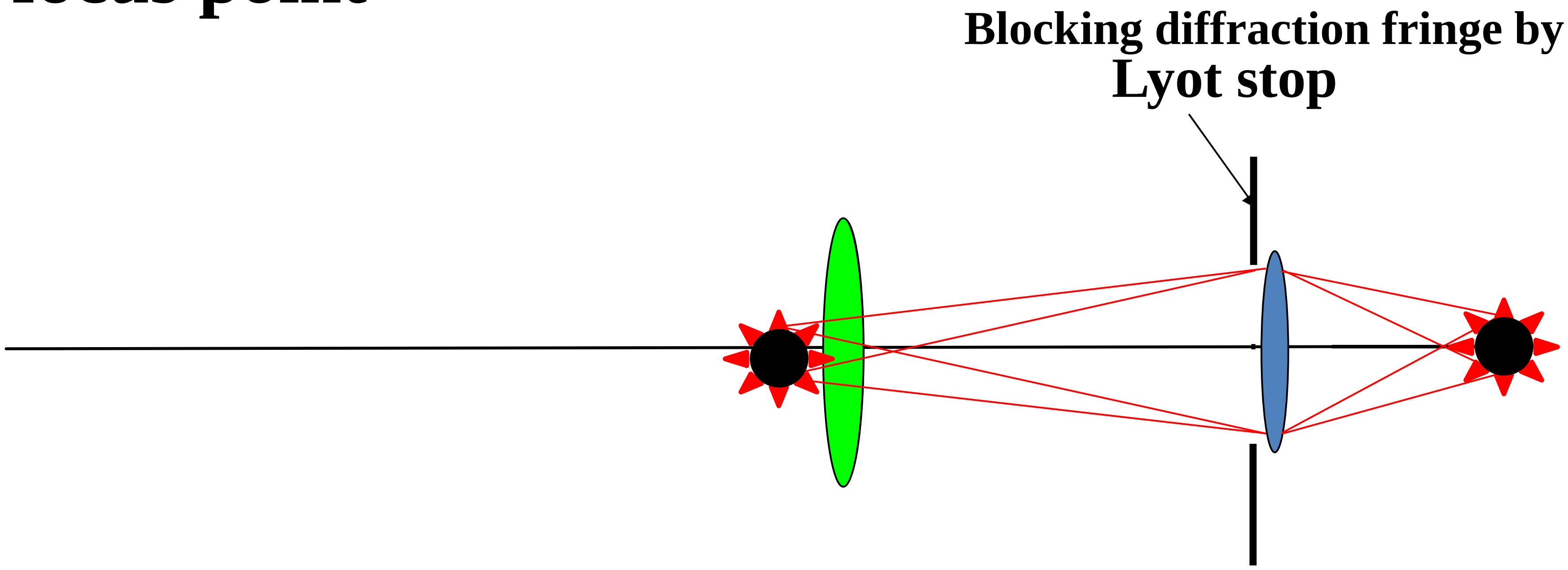




3
2
1
0
$u^2(x)$
Block the re-
diffraction
fringes
-10
0
10
x

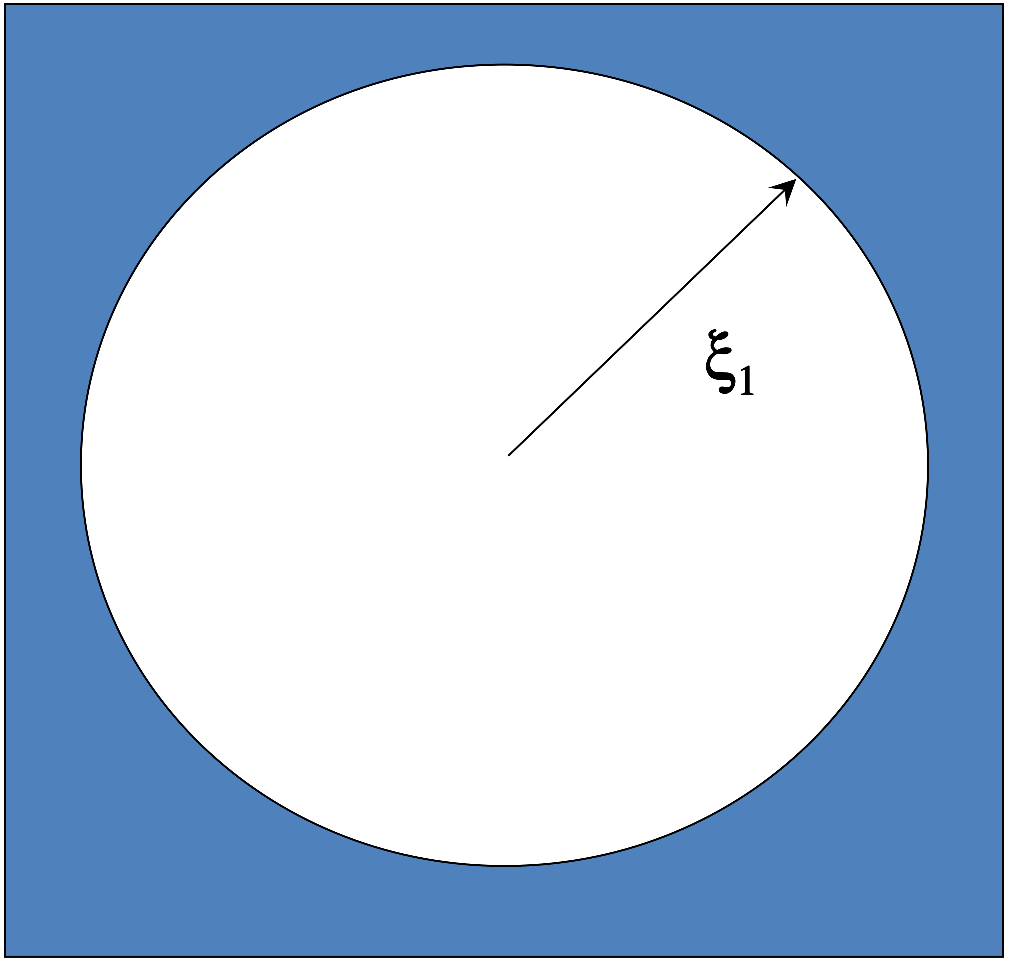
Relay of corona image to final focus point





Relay lens diffraction

The integration performs η_1



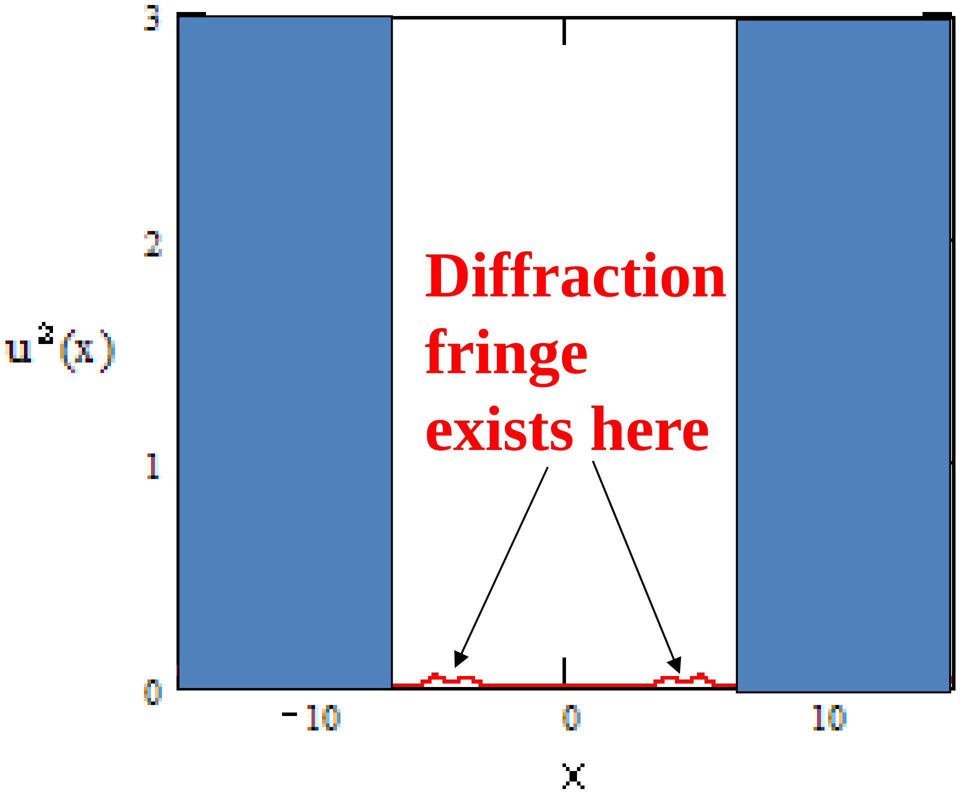
η_1: radius of Lyot stop

Disturbance of light on final focus point V(x) is given by;

$$V(\phi) = \frac{1}{i \cdot \lambda \cdot f_{relay}} \int_0^{\phi 1} u(x) \exp\left\{ - \frac{i \cdot 2 \cdot \pi \cdot \phi \cdot x}{\lambda \cdot f_{relay}} \right\} dx$$

U(x) is still not 0 inside of relay lens pupil!

Background in classical coronagraph

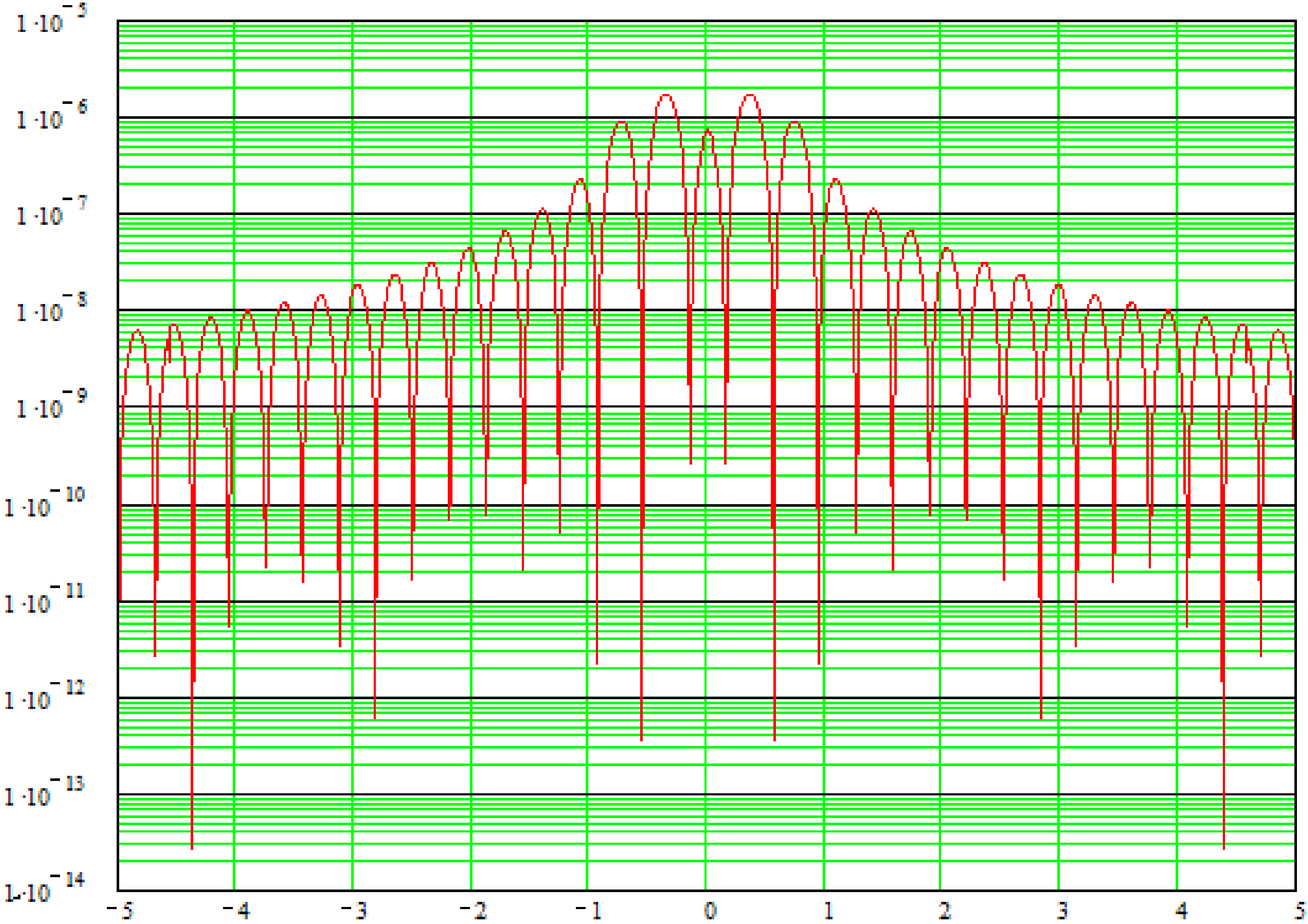


This leakage of the diffraction fringe can make background level 10^{-8} (depends on Lyot stop condition).

Re-diffraction intensity on the Lyot stop

Diffraction background at 3ed stage

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



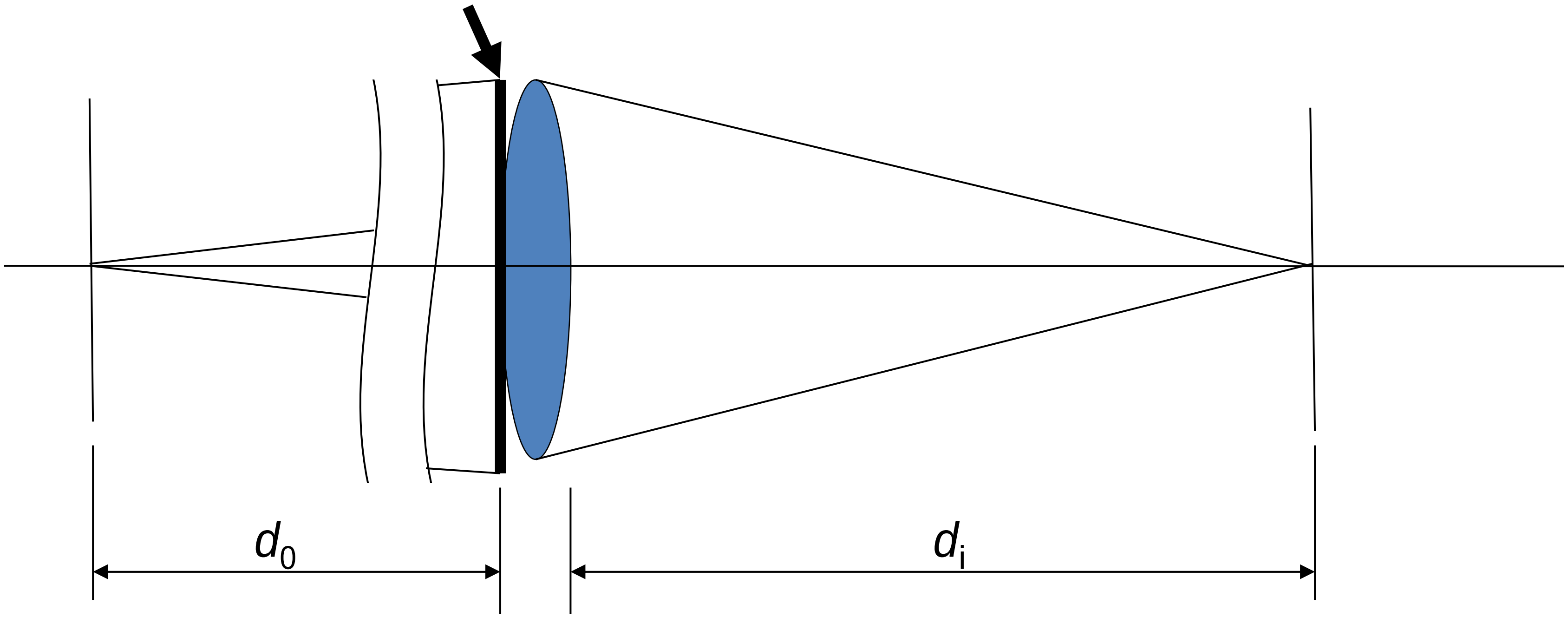
Appendix 2

Mie scattering,

it's diffraction treatment

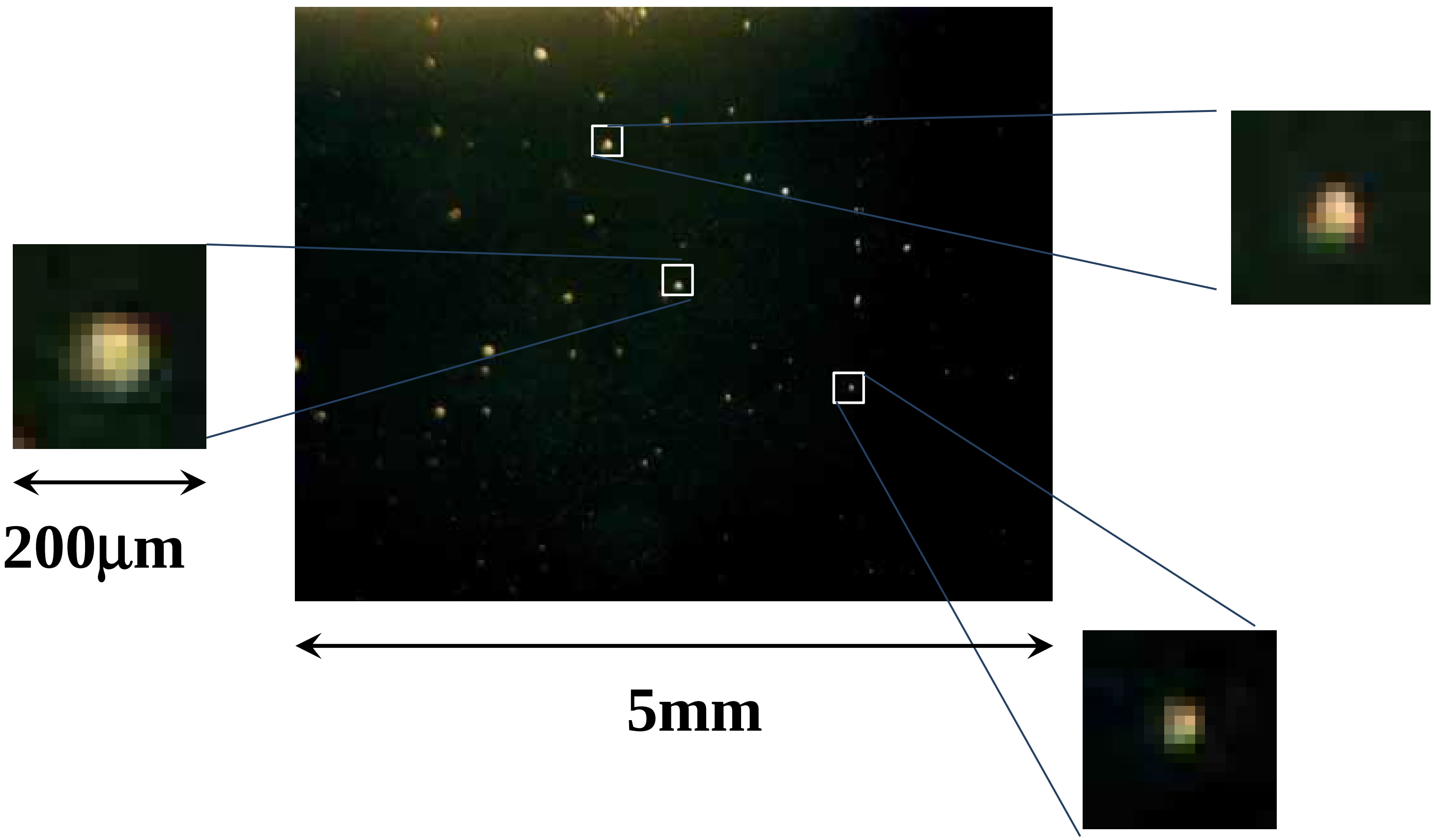
Case 1. Noise source in the entrance pupil of objective lens

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

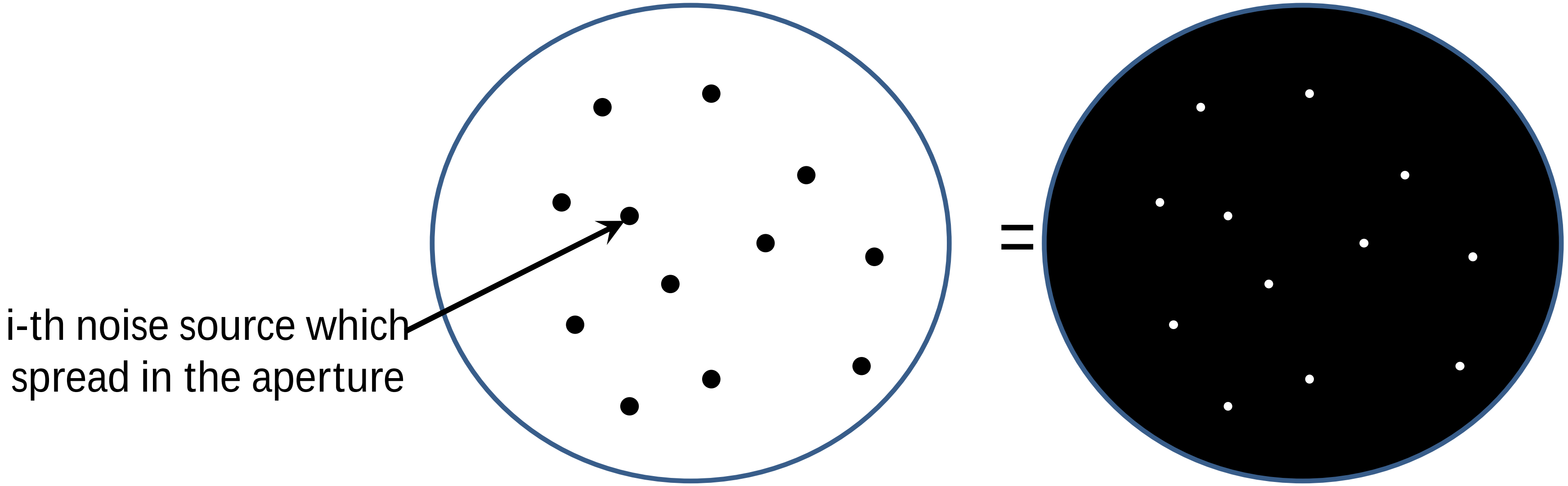


Digs on glass surface of scratch & dig 60/40

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



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,**

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

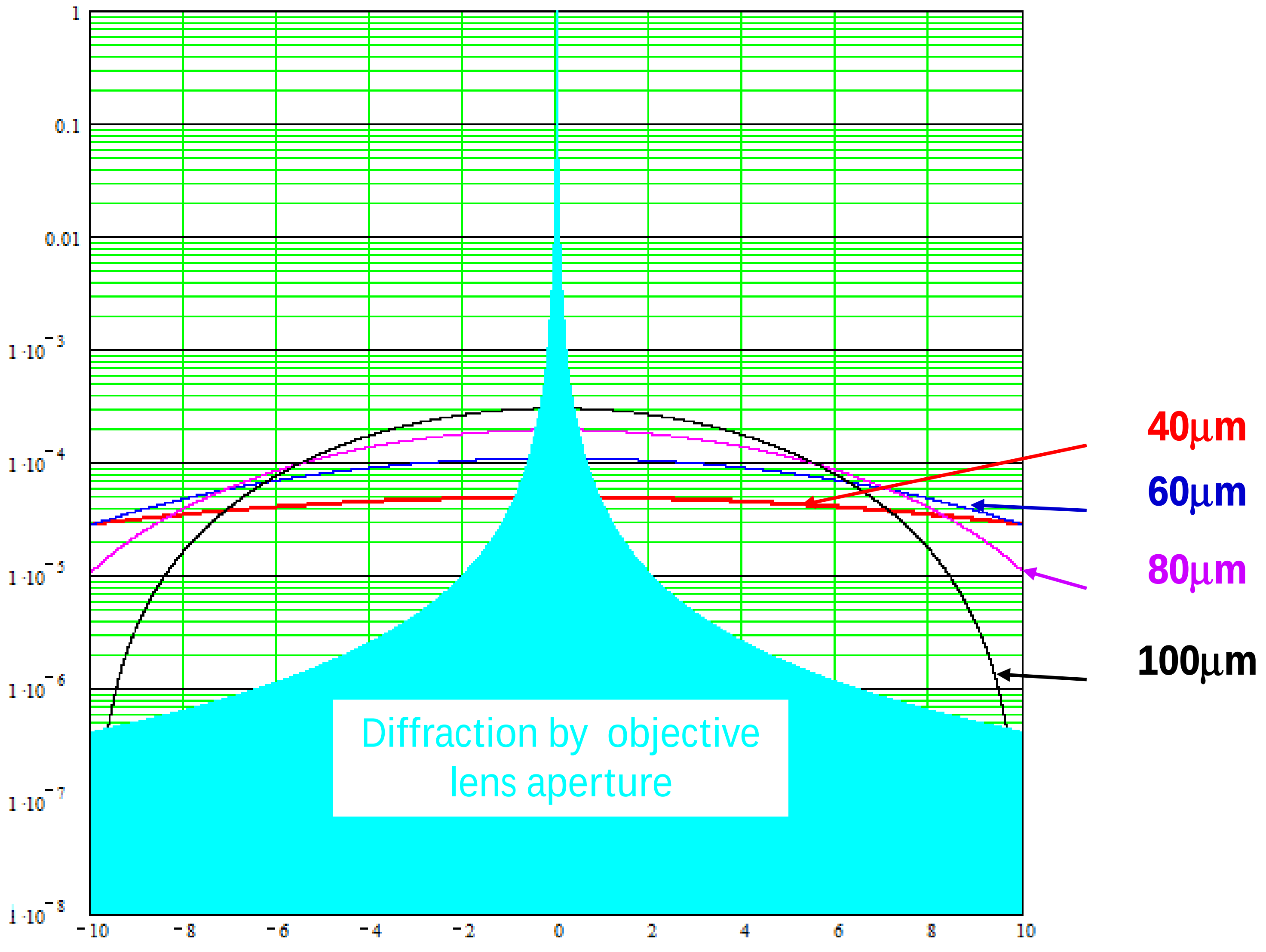
in here, $M = d_i / d_0$ denotes geometrical magnification.

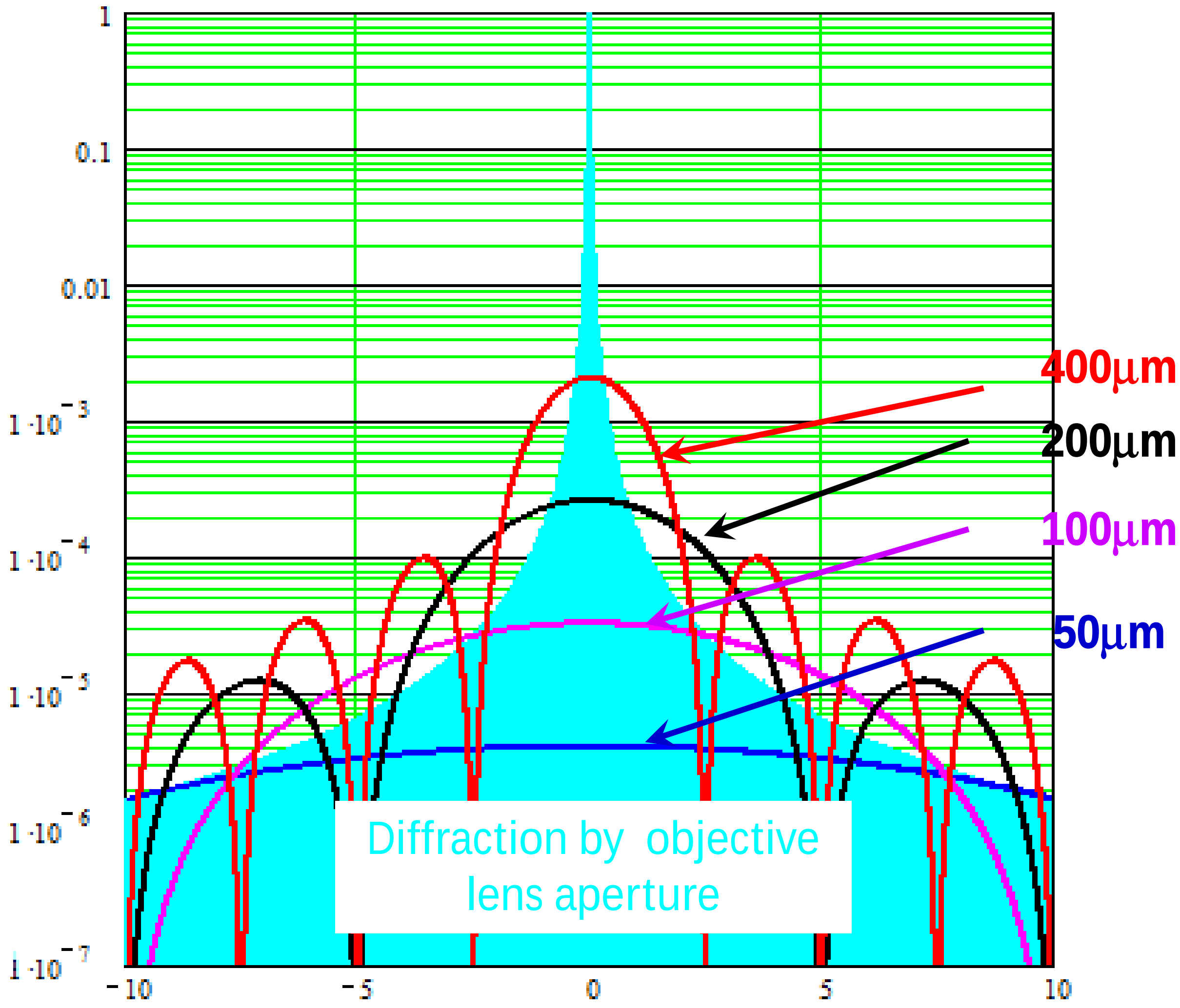
The intensity of diffraction from noise sources is inverse-proportional to extinction rate,

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

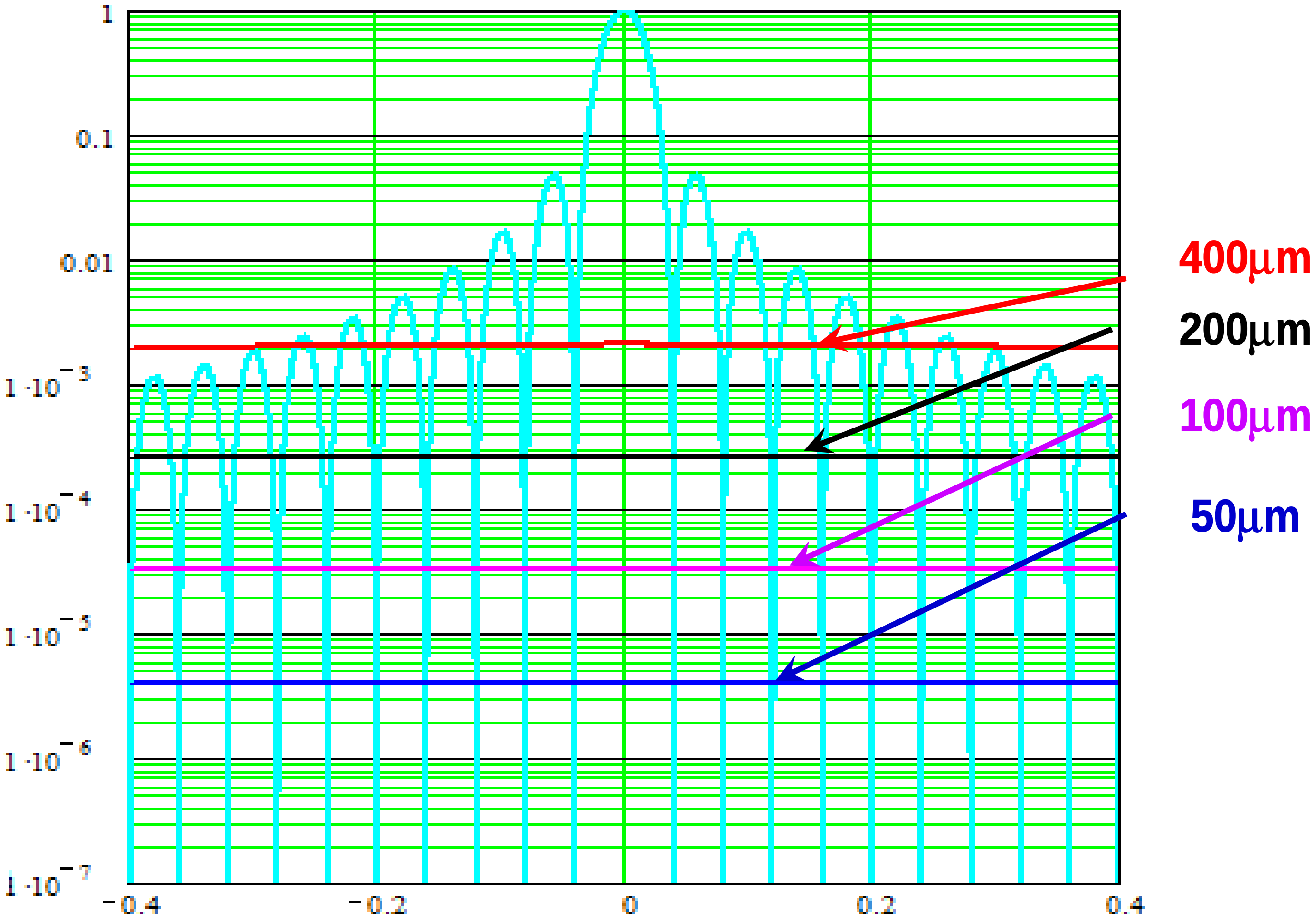
To escape from noise produced by the objective lens is most important issue in the coronagraph!!

Simulation result of Background produced by dig on objective surface





1
0.1
0.01
$1 \cdot 10^{-3}$
$1 \cdot 10^{-4}$
$1 \cdot 10^{-5}$
$1 \cdot 10^{-6}$
$1 \cdot 10^{-7}$
−10
−5
0
5
10
400μm
200μm
100μm
50μm
Diffraction by objective lens aperture


1
0.1
0.01
1·10⁻³
1·10⁻⁴
1·10⁻⁵
1·10⁻⁶
1·10⁻⁷
−0.4
−0.2
0
0.2
0.4
400μm
200μm
100μm
50μm

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.

A careful optical polishing for the objective lens

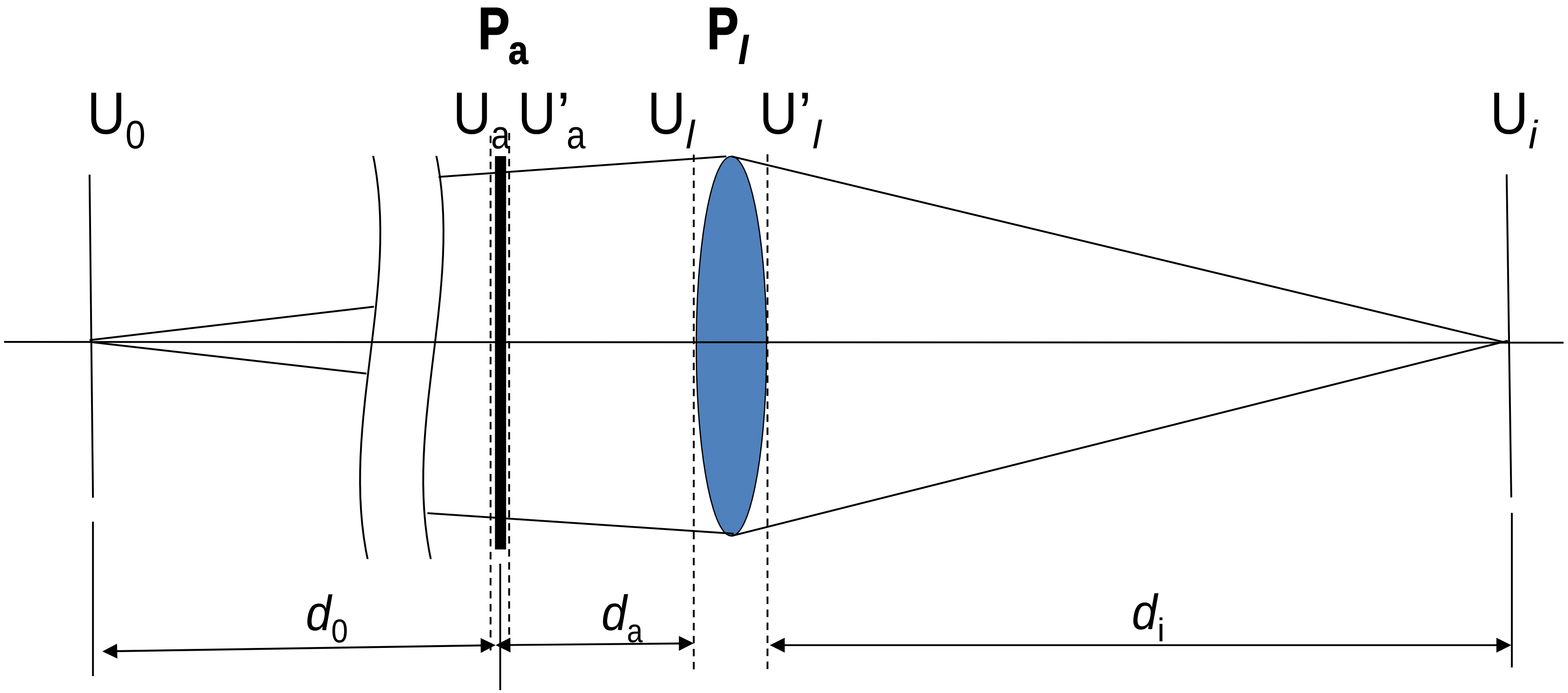
5mm

Comparison between normal optical polish and careful optical polish for coronagraph

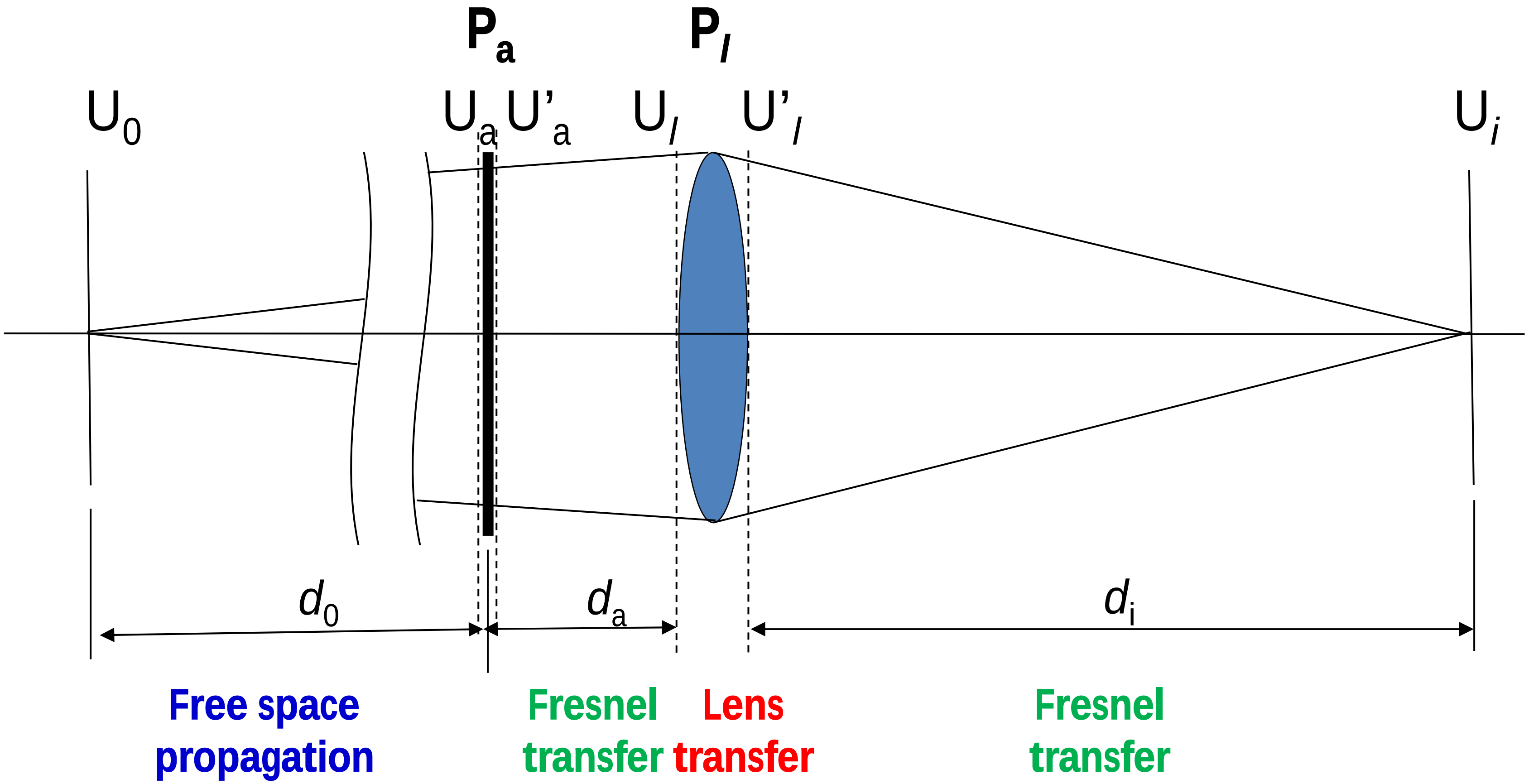
S&D 60/40 surface of the lens

Surface of the coronagraph lens

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

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

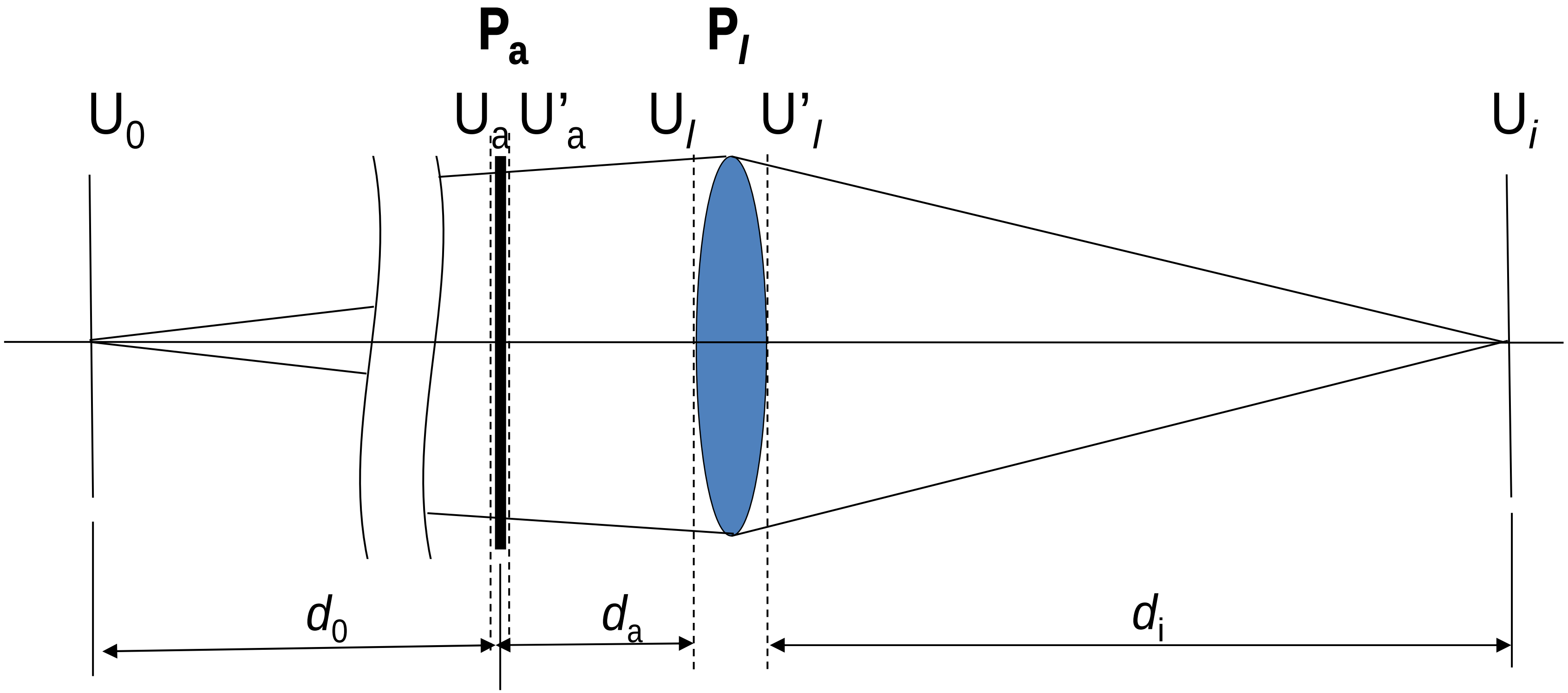
$$\left. \cdot\, exp\left\{ -ik\left(\left(\frac{x_0}{d_0 - d_a} + \frac{x_l}{d_a}\right)x_a + \left(\frac{y_0}{d_0 - d_a} + \frac{y_l}{d_a}\right)y_a\right)\right\} dx_a dy_a \right]$$

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

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

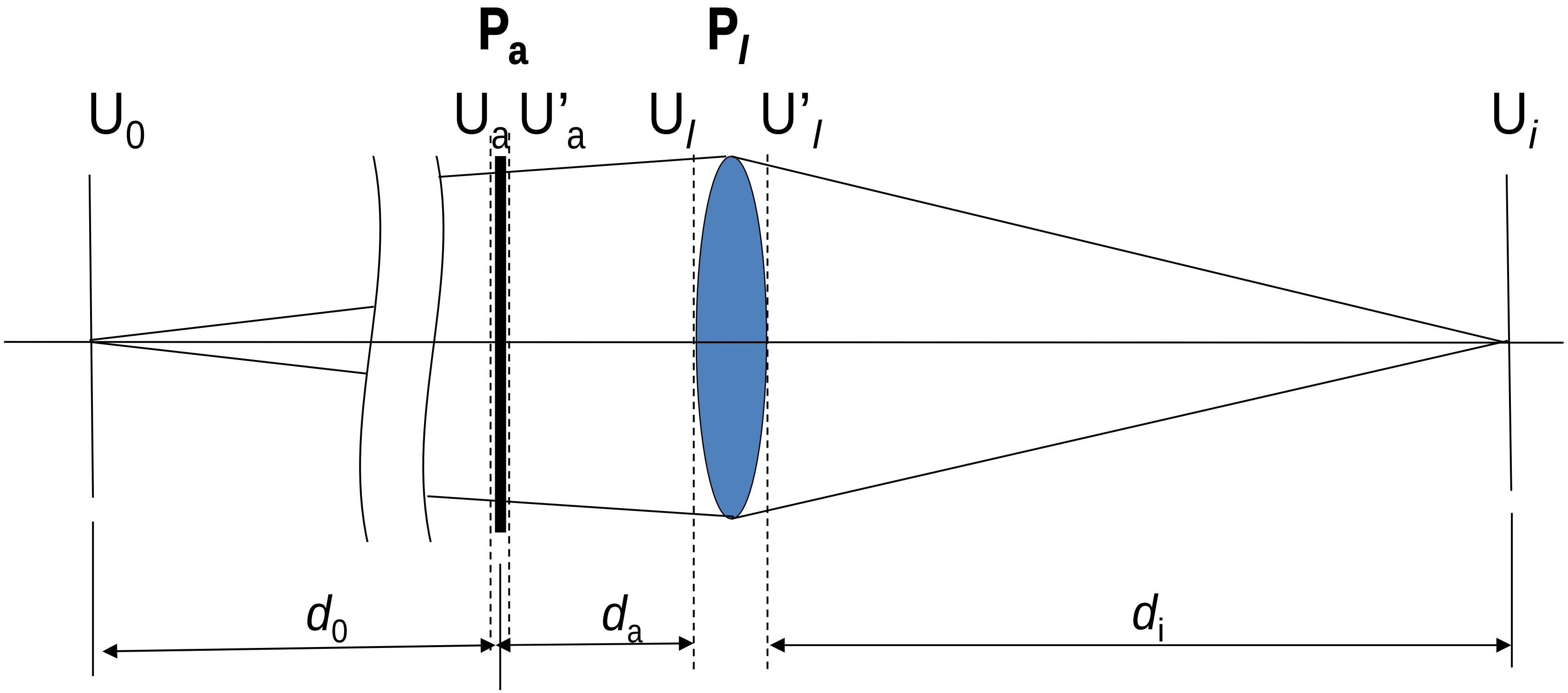
Diffraction by lens pupil

Noise source in front of the lens



Noise source ⟹ Fresnel diffraction

Then re-diffracted by lens pupil



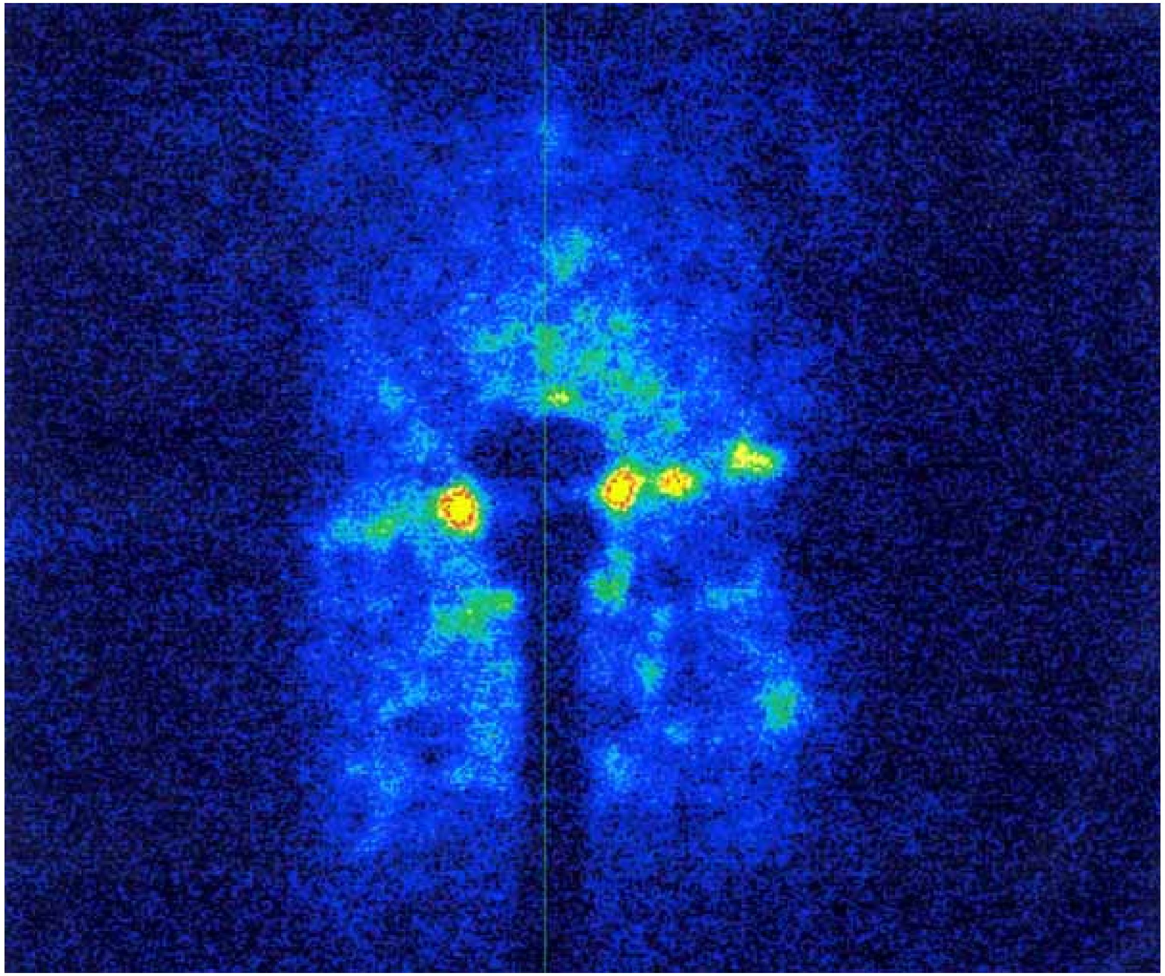
Noise source to objective lens ⇨ Fresnel like diffraction

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

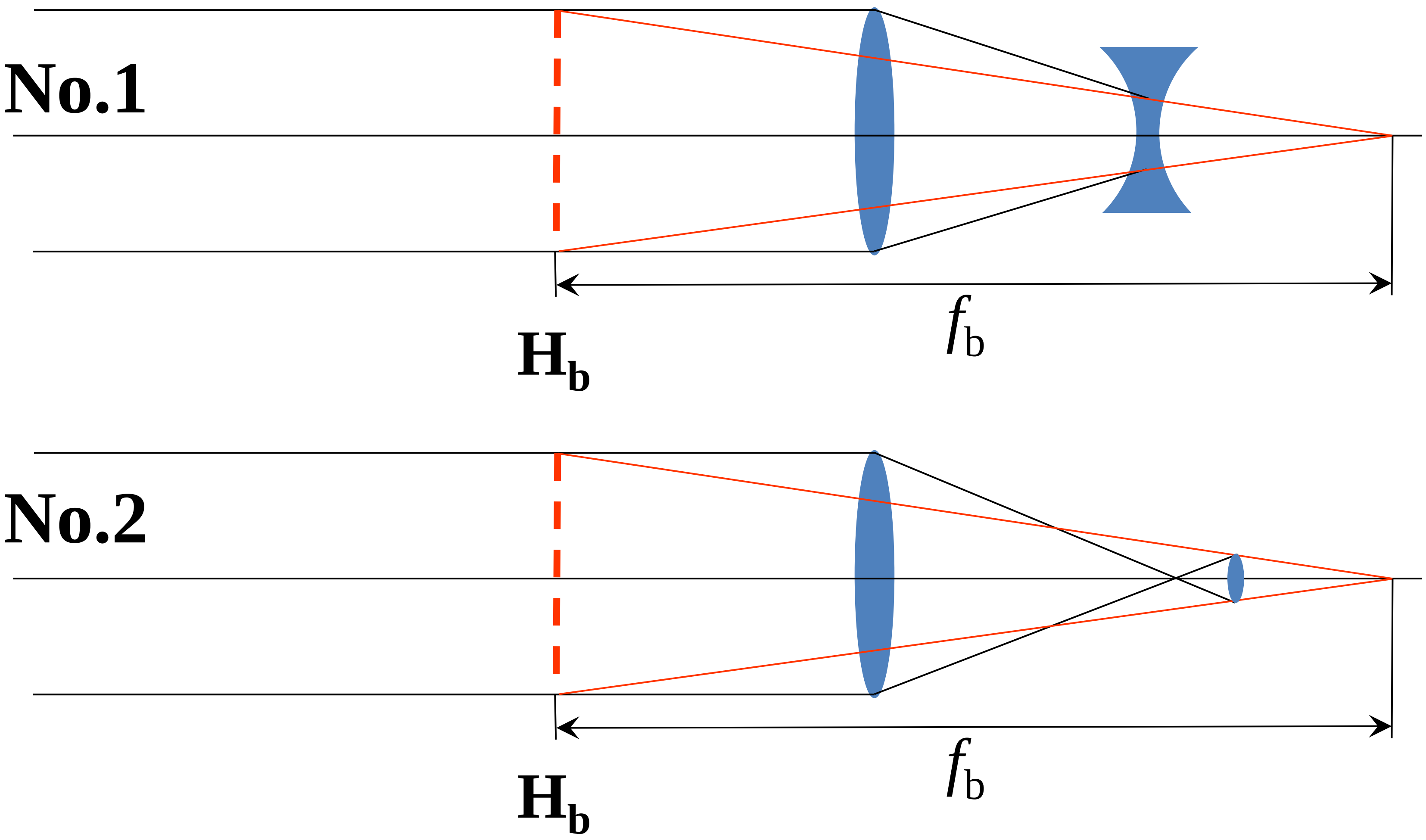
Intentionally spread some dust on the mirror in 2m front of the coronagraph



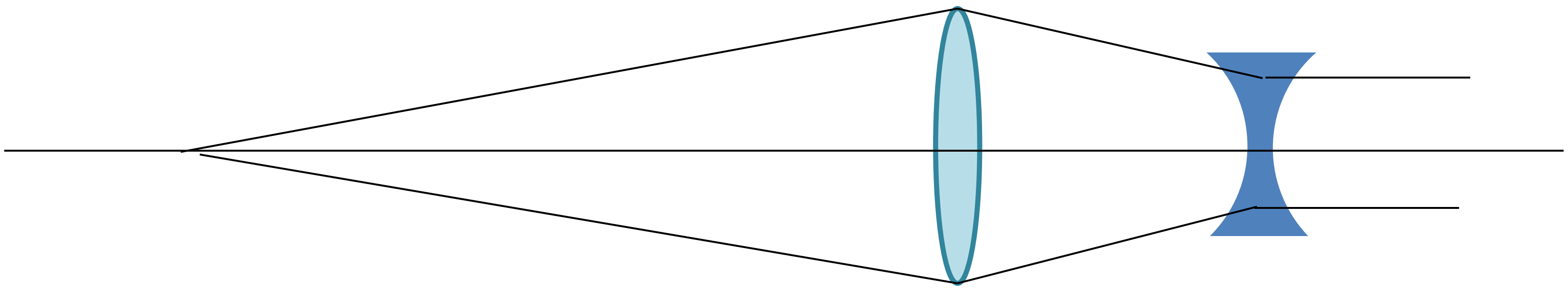
Appendix 3

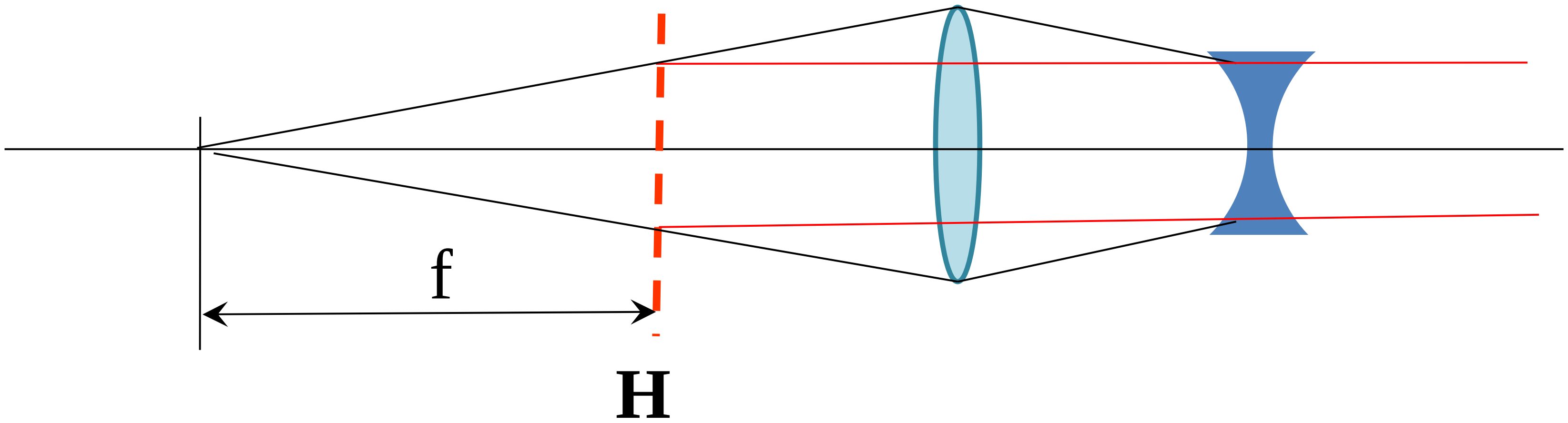
Telephoto system

Two kinds of telephoto lens



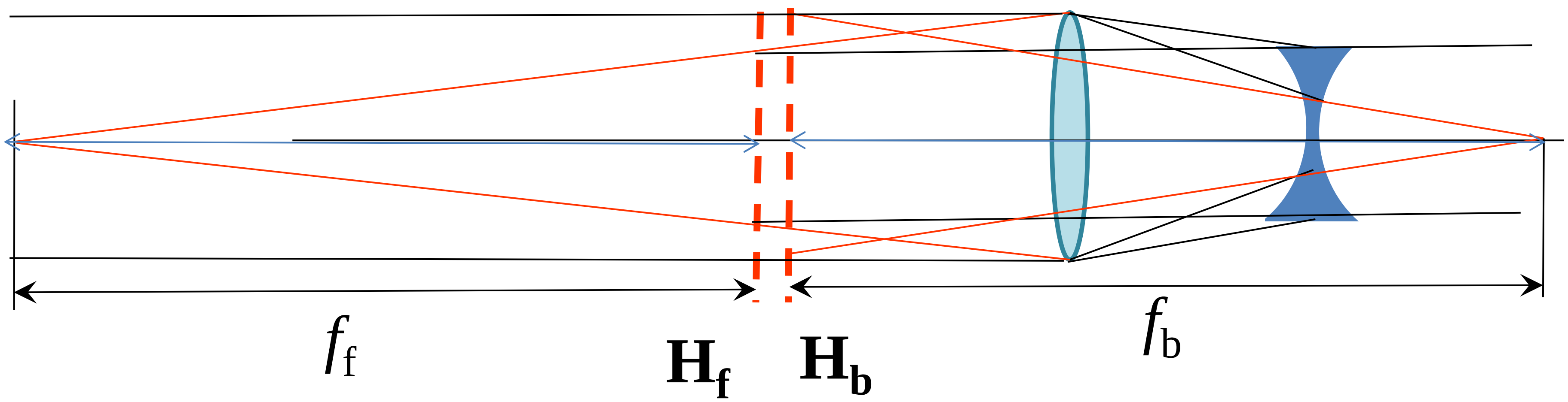
Where is front principal point for No.1 ?
Analyze opposite side

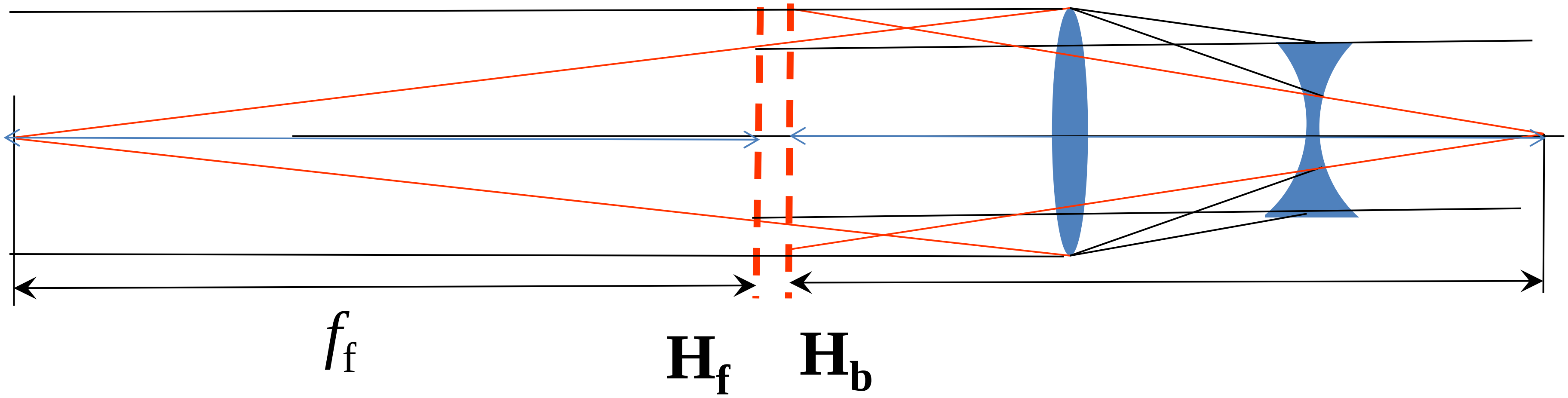




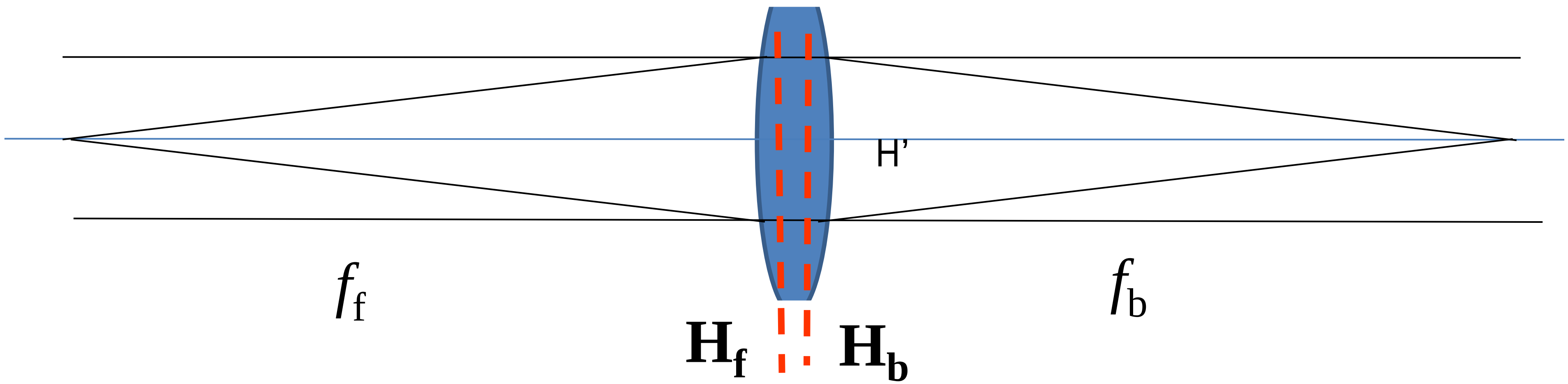
Retro focus lens

All together,

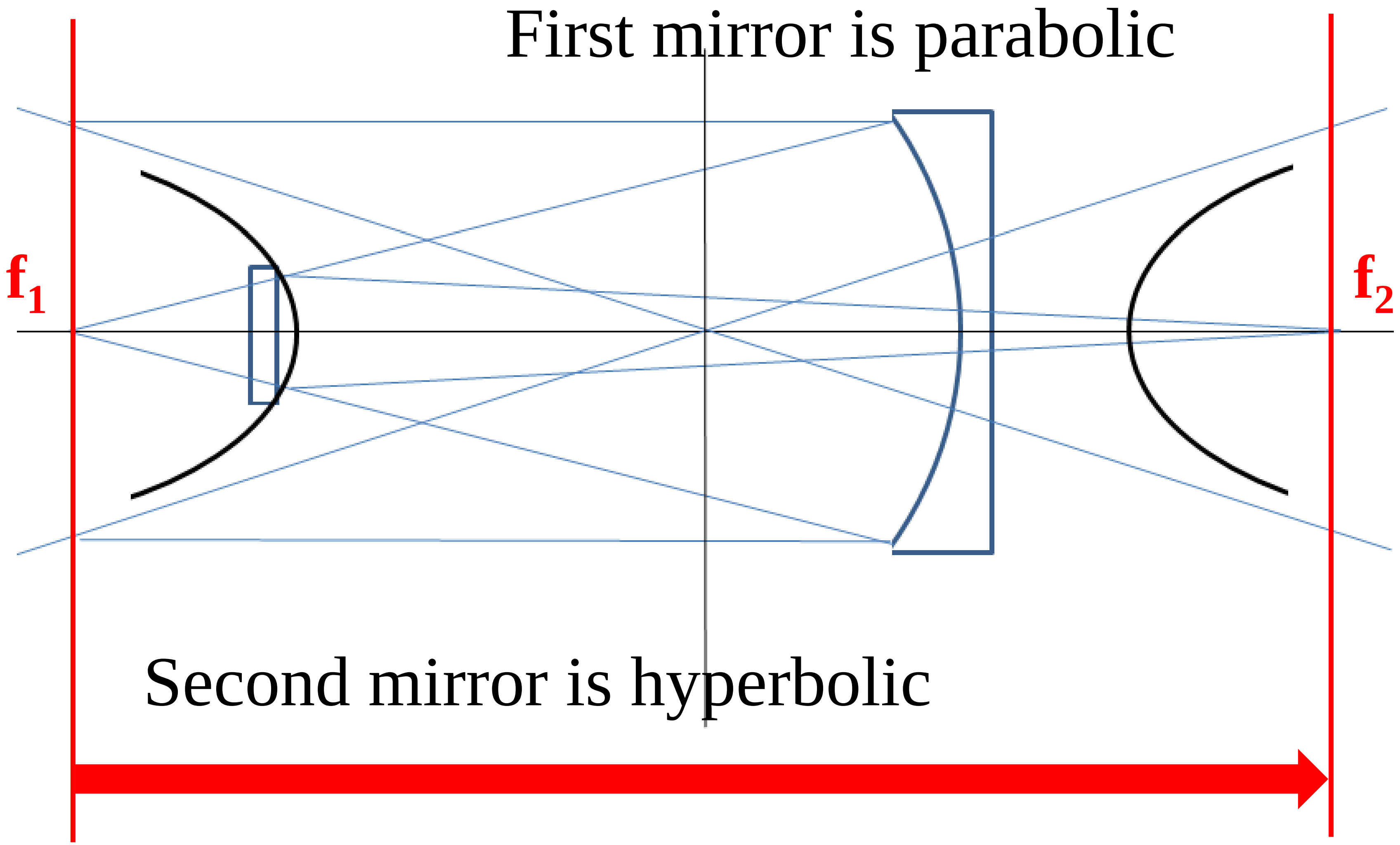




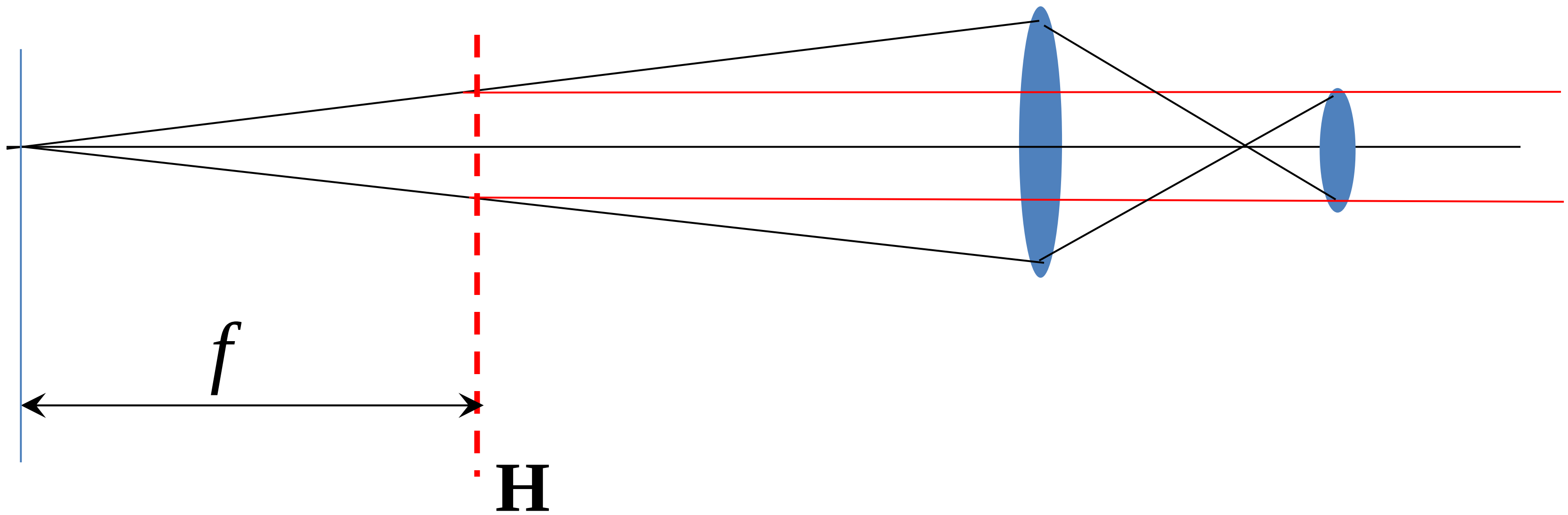
Equal to following lens



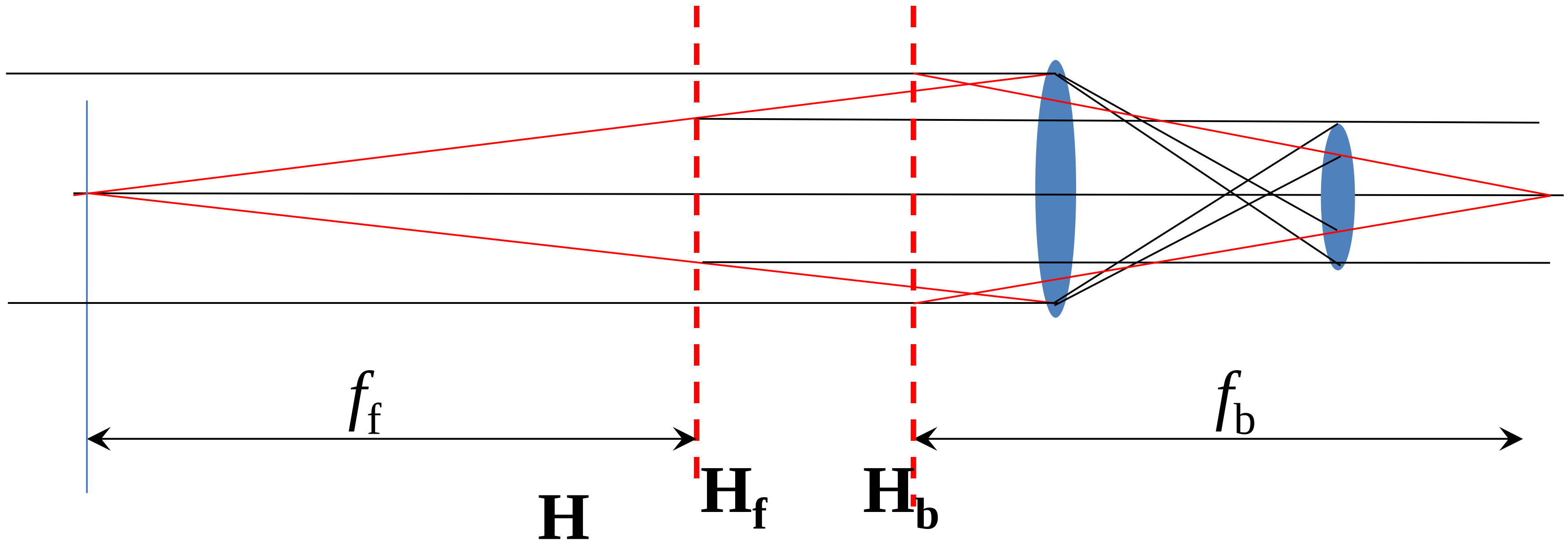
Corresponding reflective system is Cassegrain system

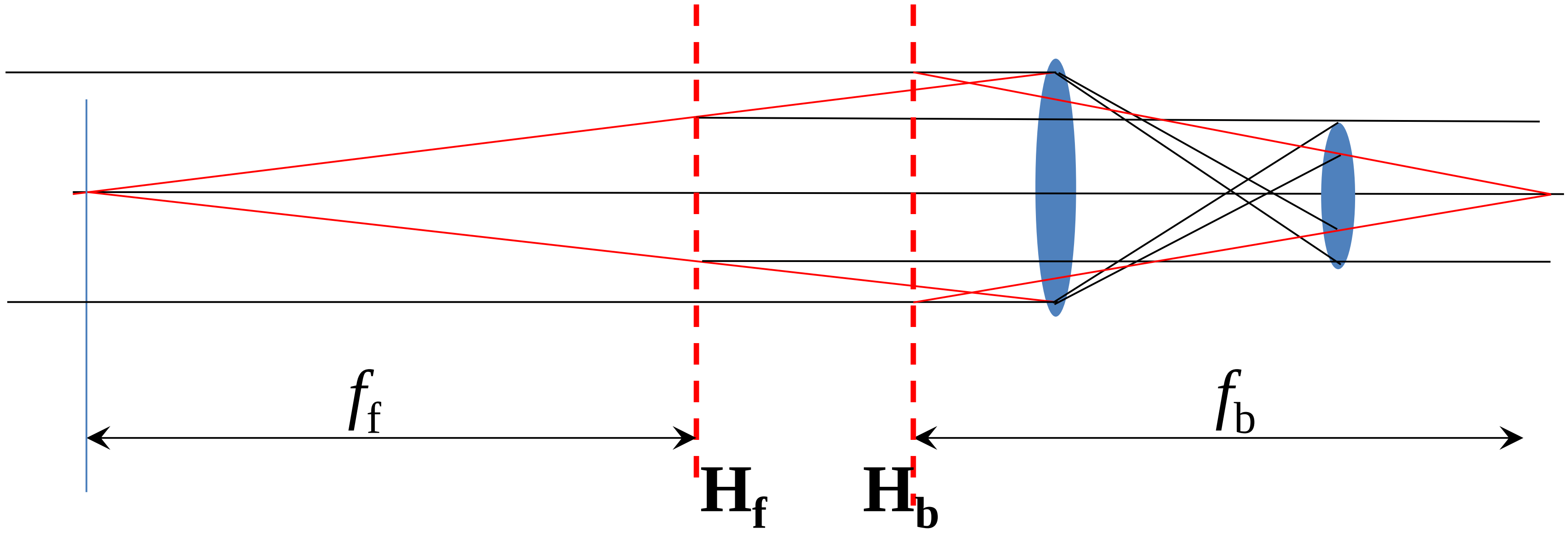


Where is front principal point for No.2 ?
Analyze opposite side

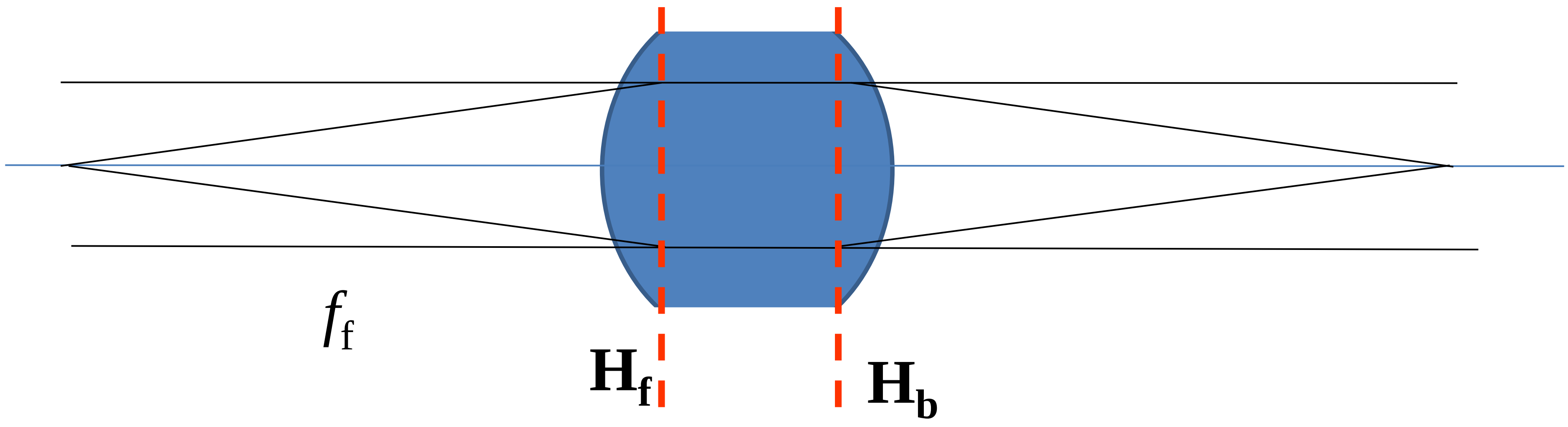


All together,

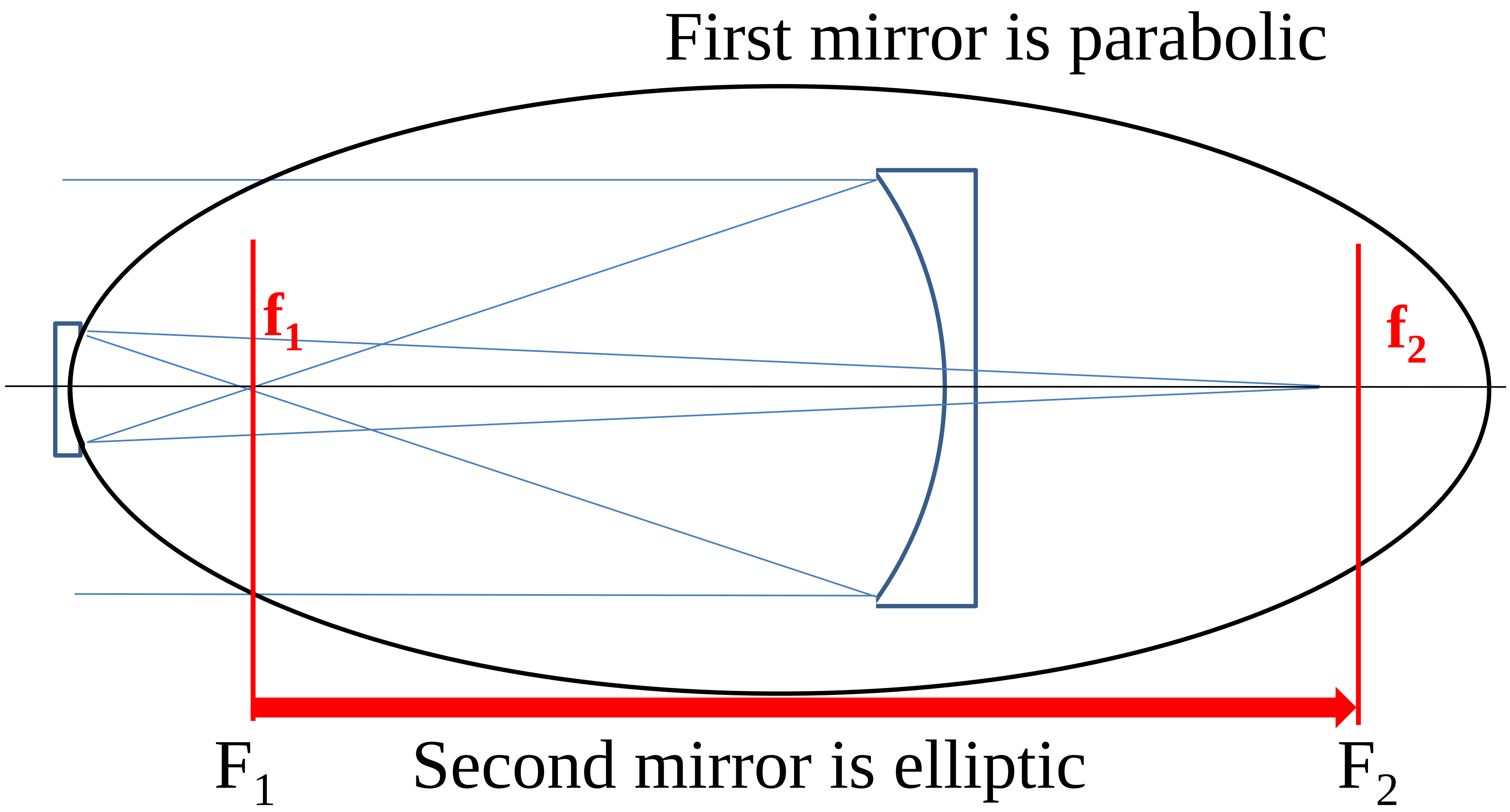




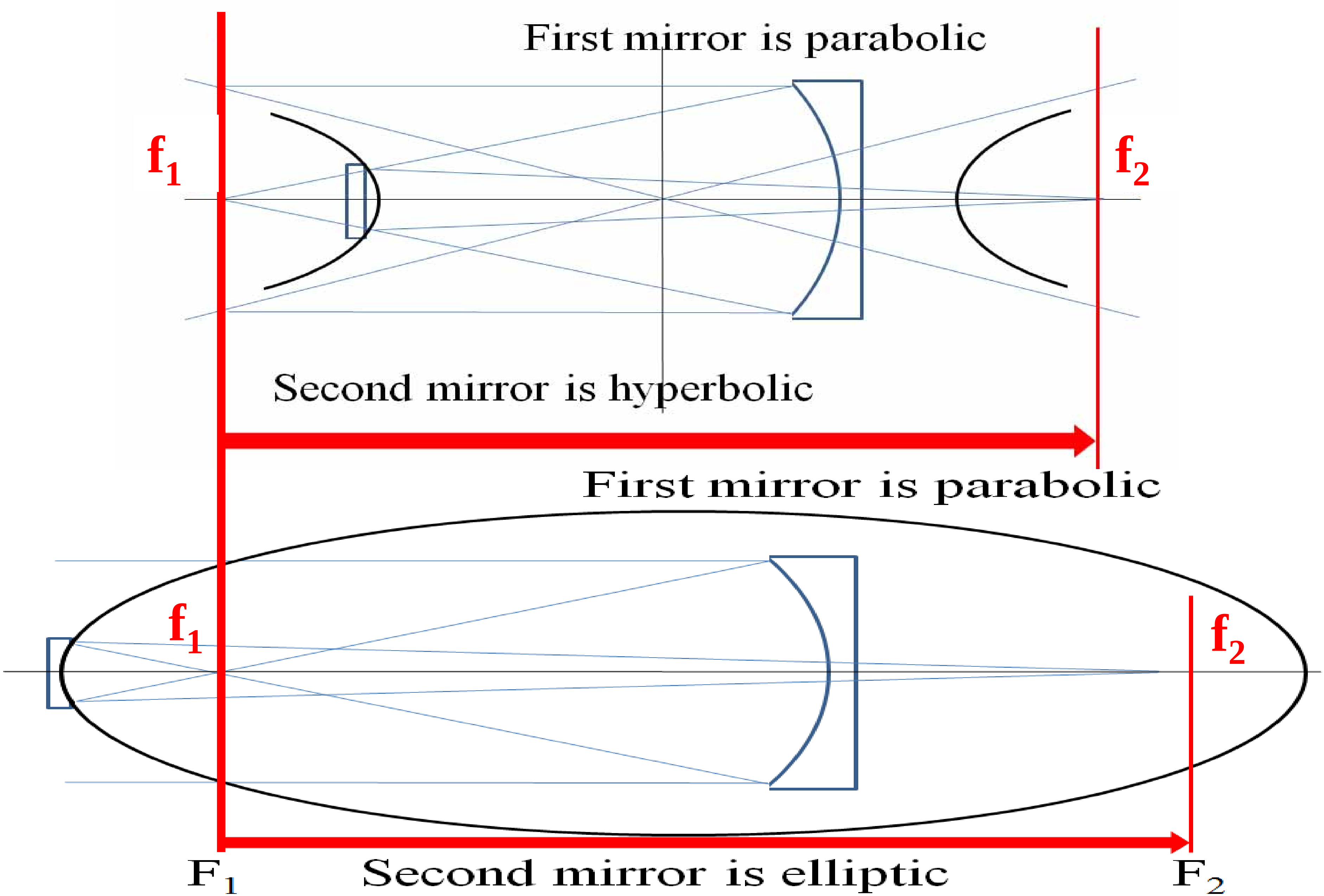
Equal to following lens



Corresponding reflective system Gregory system



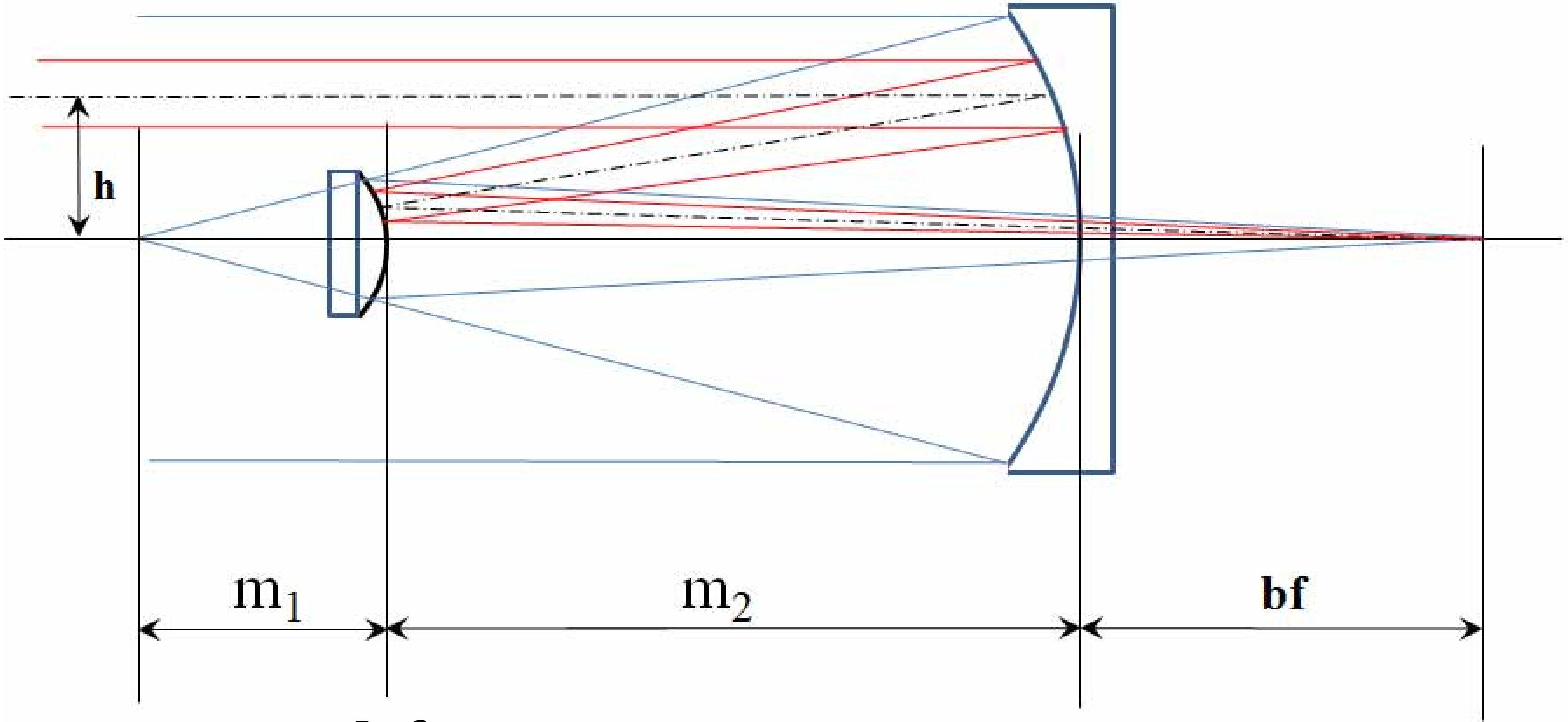
Difference between Cassegrain and Gregory



Optical design of Cassegrain objective in Supper B factory

Existing Cassegrain system f=5000mm for streak camera

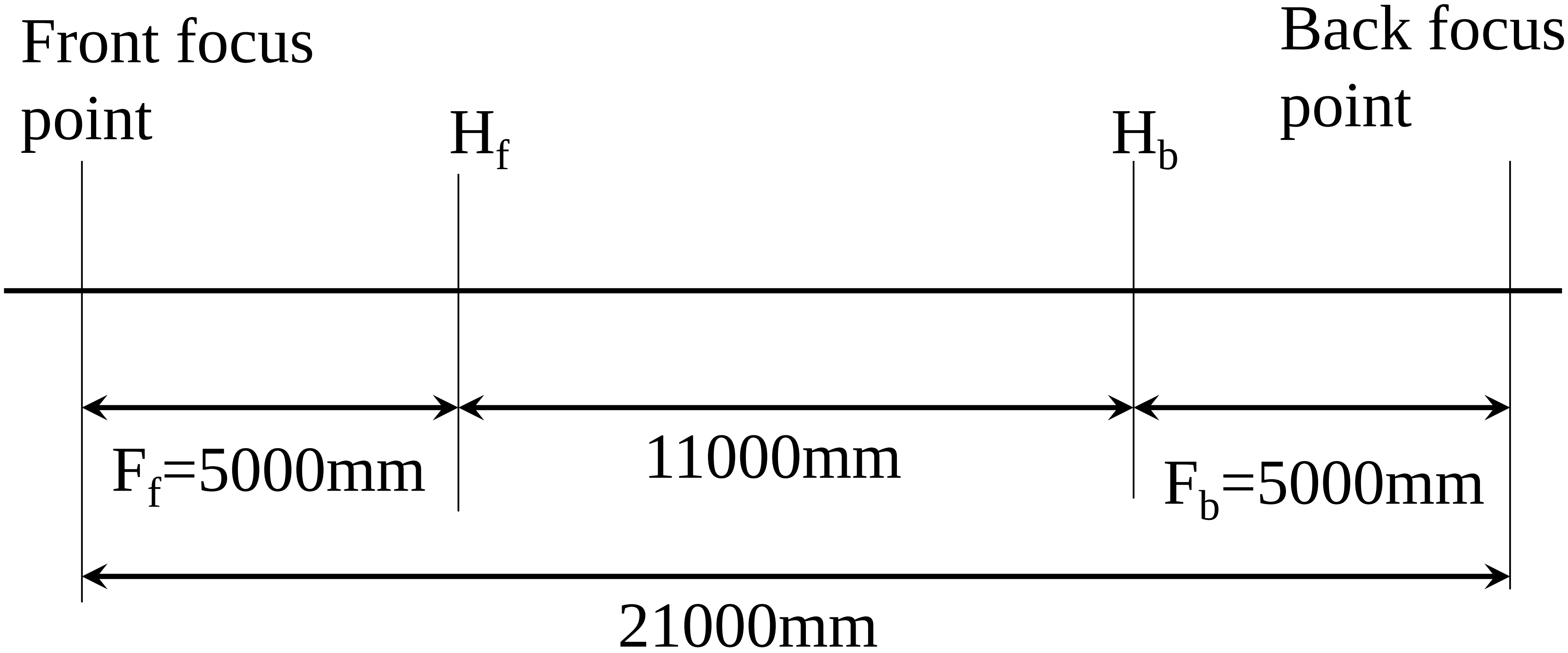
Put an aperture at certain height h

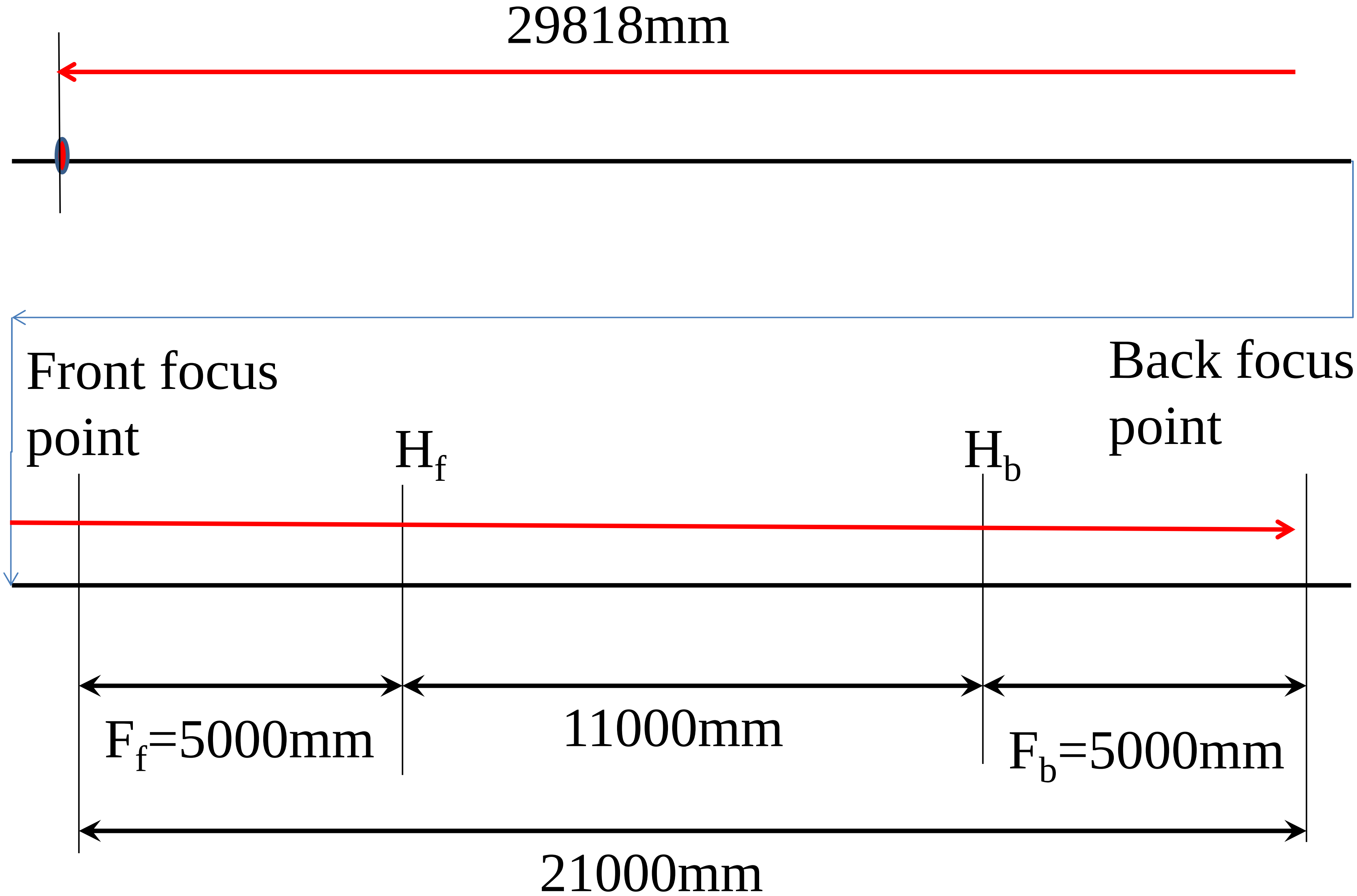


$$M = \frac{m_2 + bf}{m_1} \quad Cf = M \cdot \frac{R_1}{2} \quad R_2 = \frac{2 \cdot m_1 \cdot m_2}{m_2 - m_1}$$

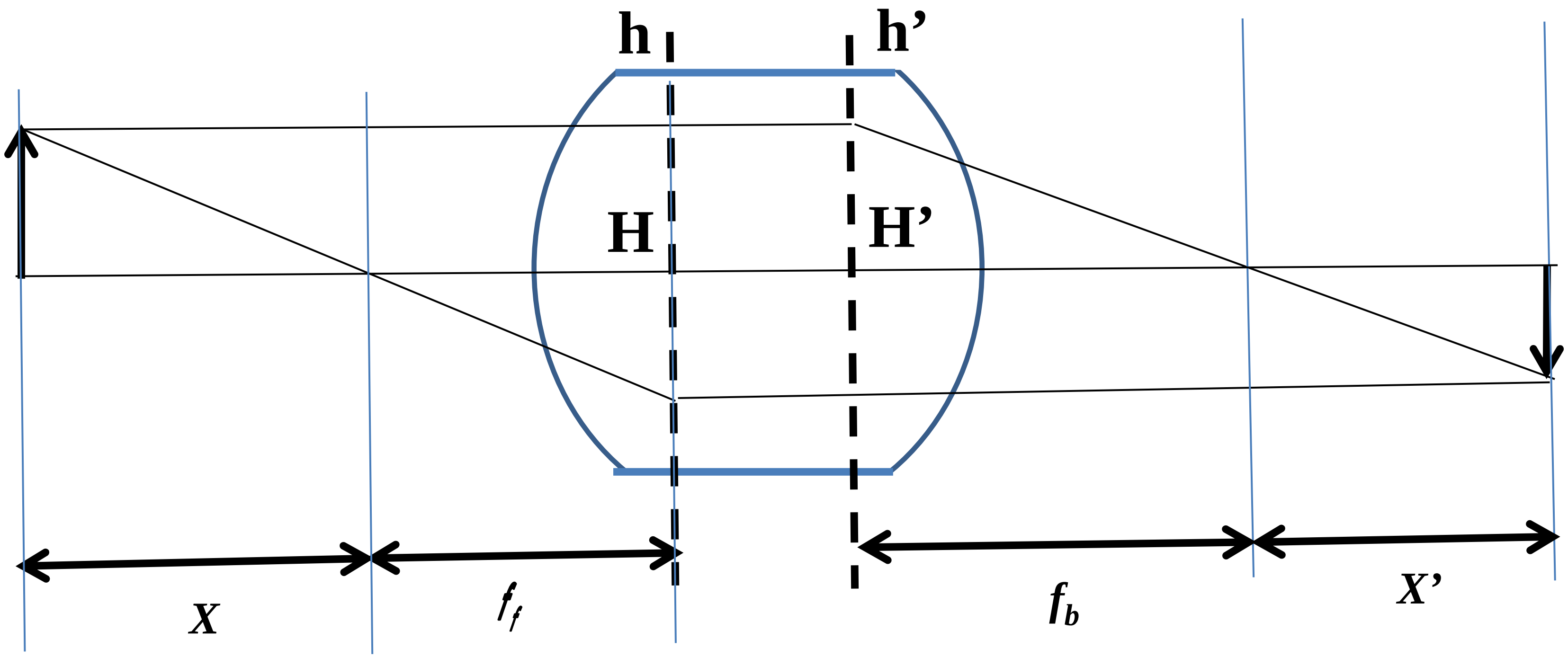
R_1=2000mm, M=4, Cf=5000mm, R_2=500mm

Corresponding conjugation points




29818mm
Front focus point
Back focus point
H_f
H_b
F_f=5000mm
11000mm
F_b=5000mm
21000mm

With geometrical optics



$$\frac{f}{x} = -\frac{x'}{f}$$

Using the Newton's equation,

$$\frac{f}{x} = -\frac{x'}{f}$$

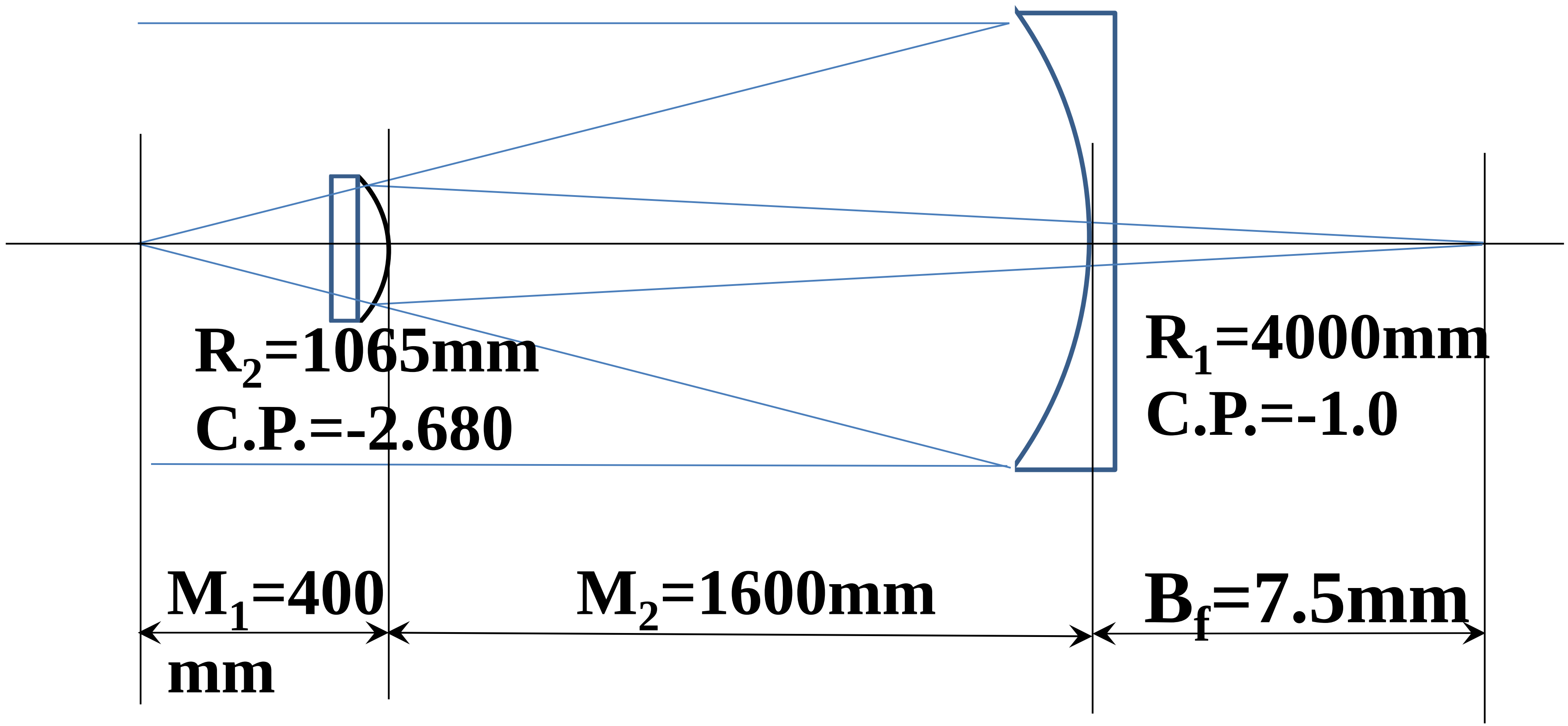
f **= 5000mm**

x=9018mm

x'=2772

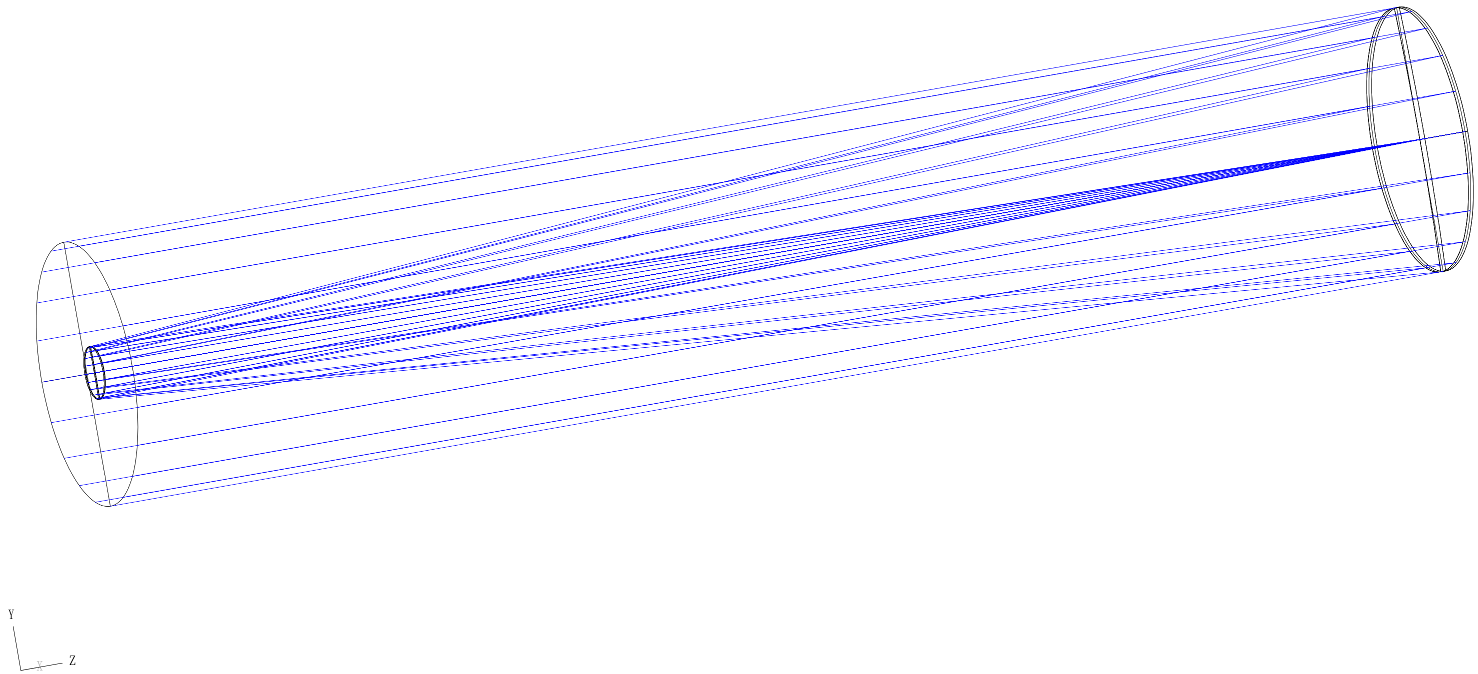
Transverse magnification=0.554

Optical design of Cassegren objective in Super B factory



Cassegrain focal length=8038mm

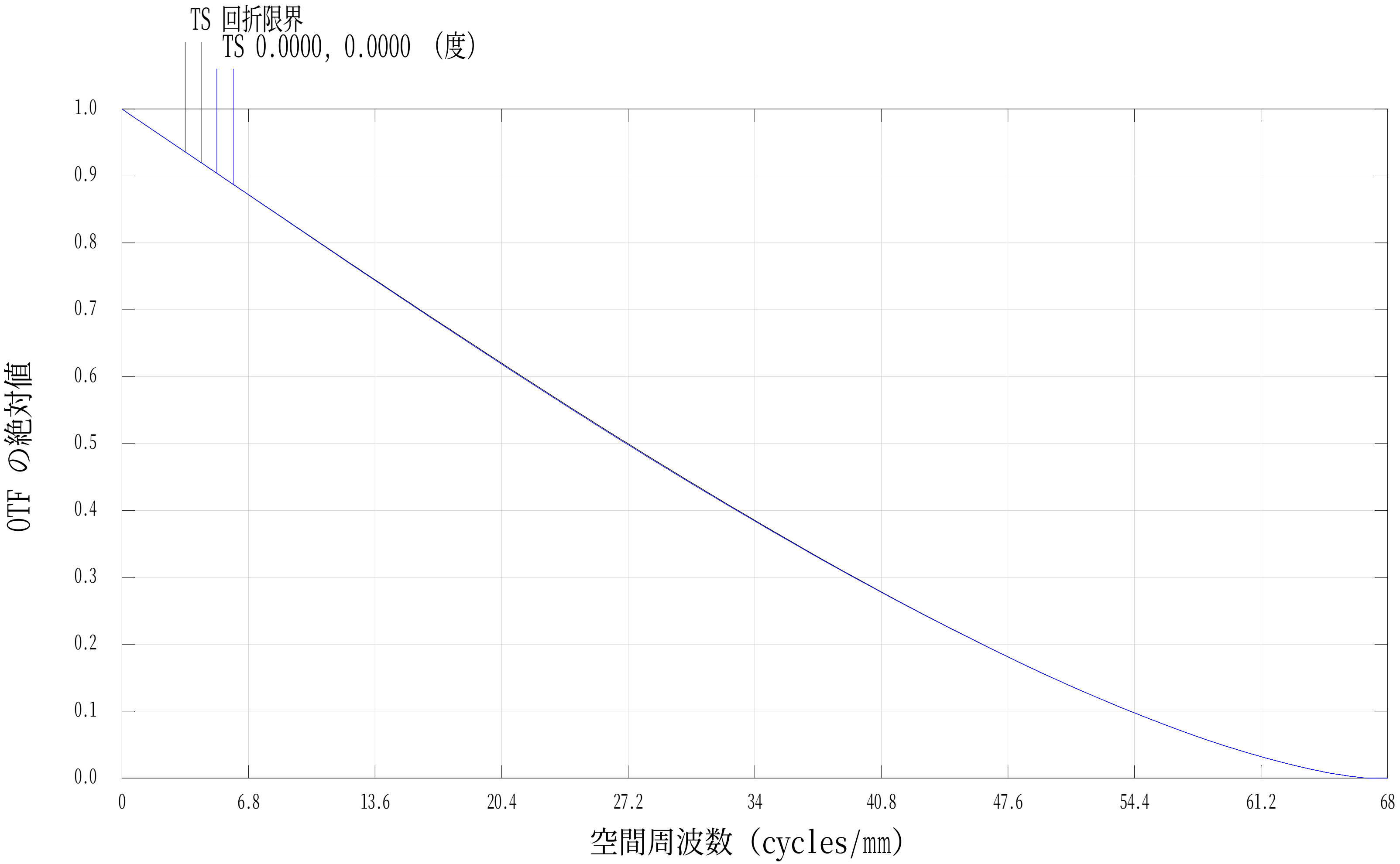
Cassegrain extension ratio=4.018



3D レイアウト

2019/05/12

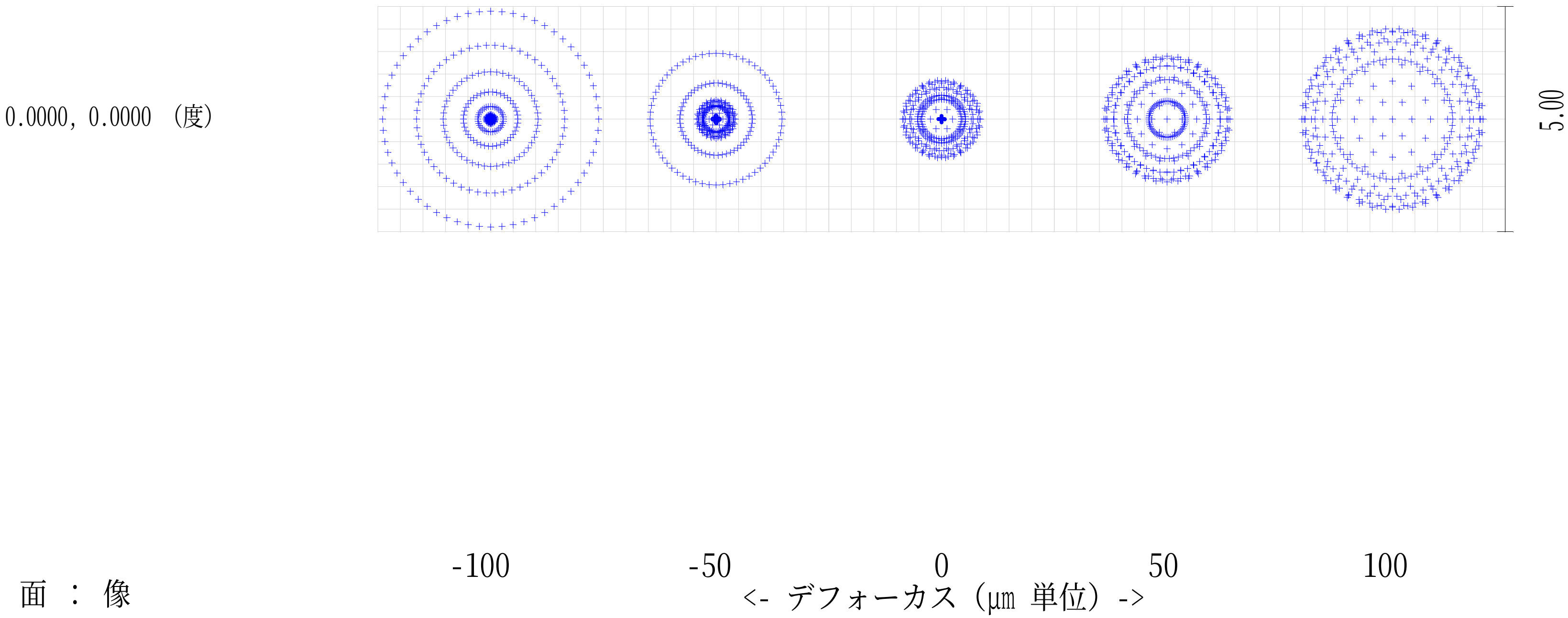
カセグレンsuperB07.ZMX
コンフィグレーション 1 / 1



多色回折 MTF

2019/05/12
0.5500 から 0.5500 µm までのデータです。
面 : 像面

カセグレンsuperB07.ZMX
コンフィグレーション 1 / 1



面 : 像

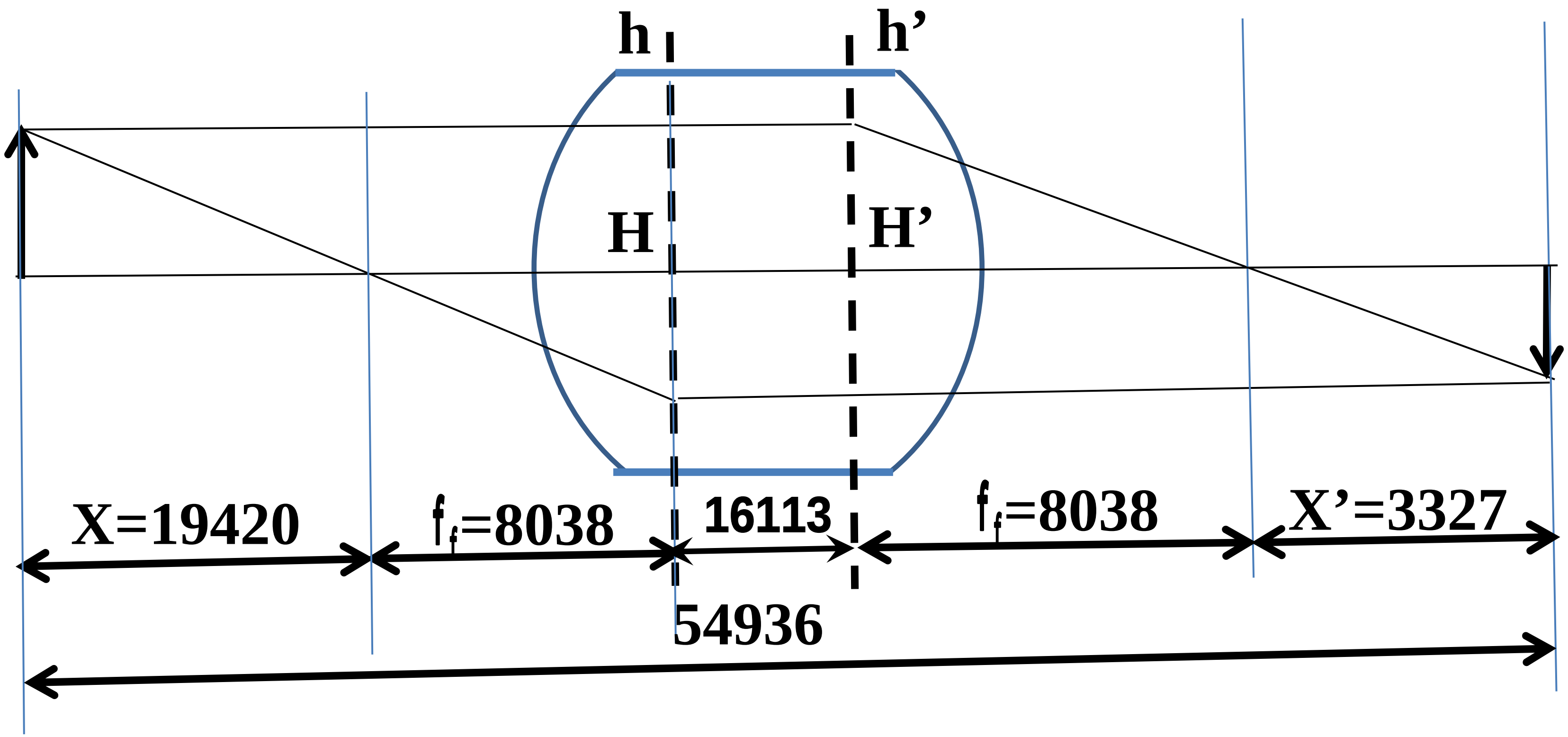
スルーフォーカス スポットダイアグラム

2019/05/12 単位は μm です。
視野 : 1
RMS 半径 : 0.604
GEO 半径 : 0.863
スケールバー : 5

基準 : 主光線

カセグレンsuperB07.ZMX
コンフィグレーション 1 / 1

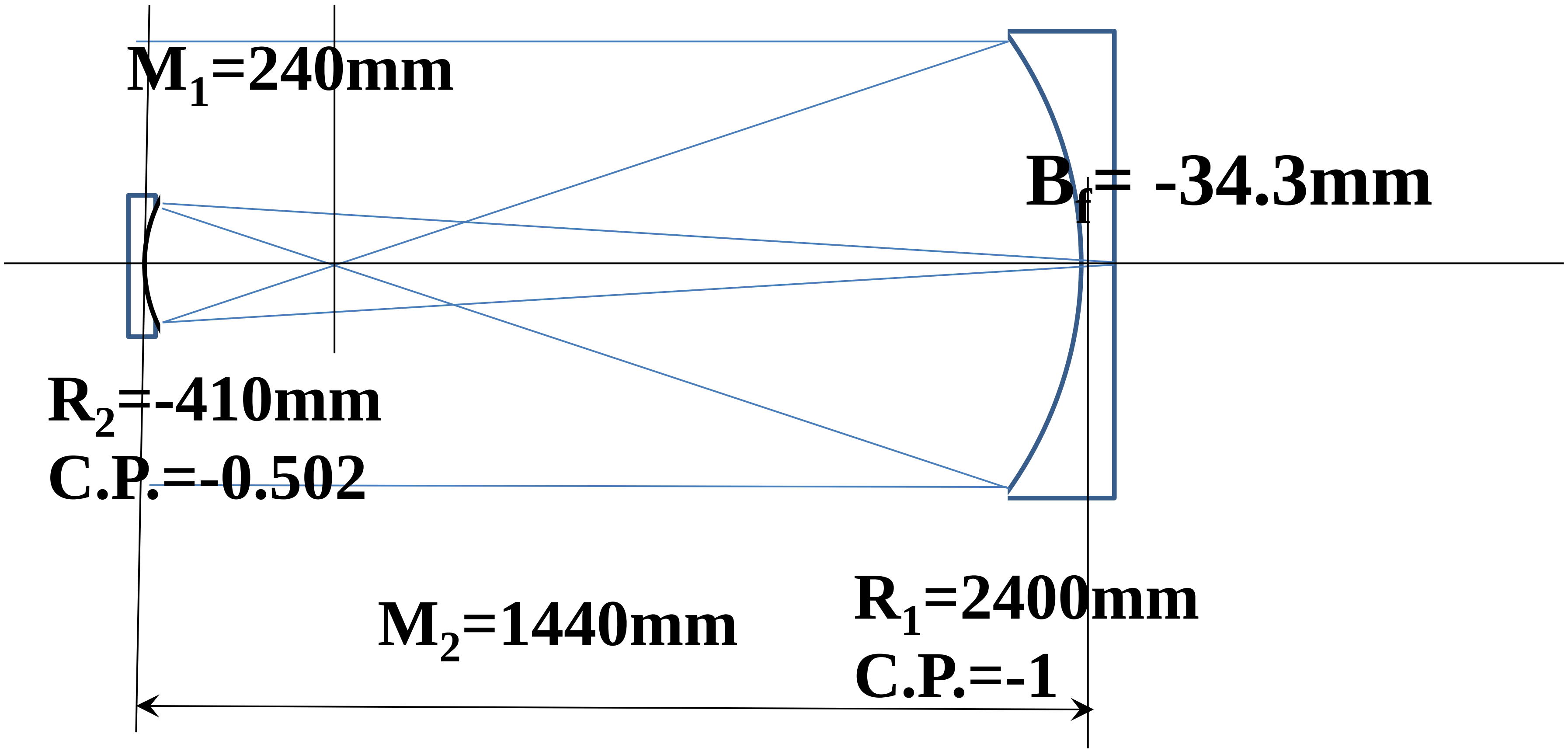
Relation between source point and beam image



Magnification=0.414

Distance between H and H' is 16113mm

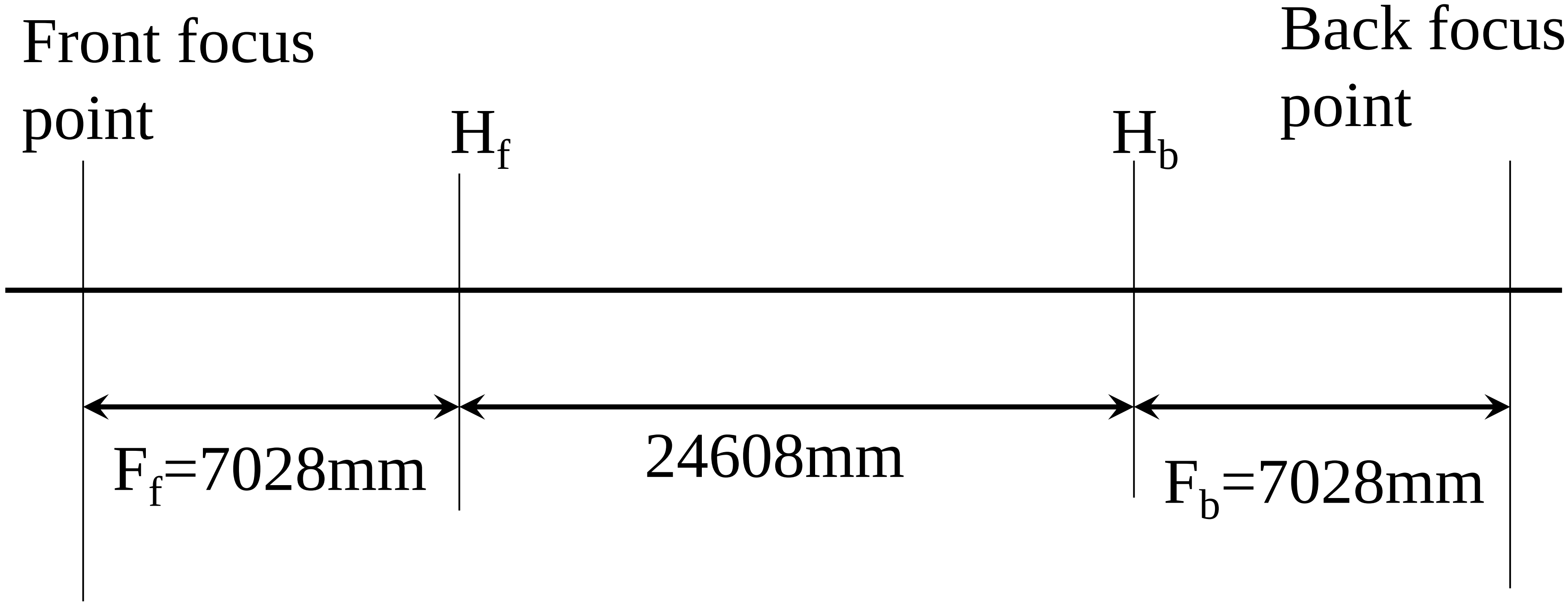
Optical design of Gregory system for SuperKEKB

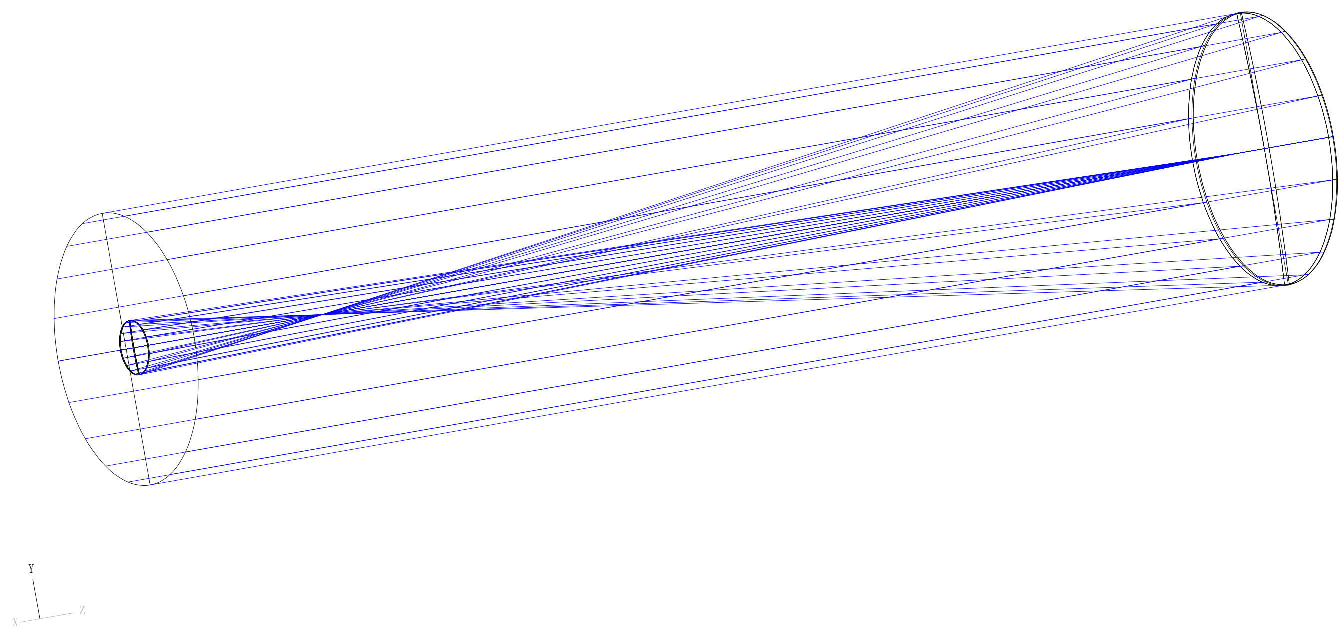


$$f = M\frac{R_1}{2} = 7028\text{mm}$$

Gregorian extension ratio=5.857

Corresponding conjugation points

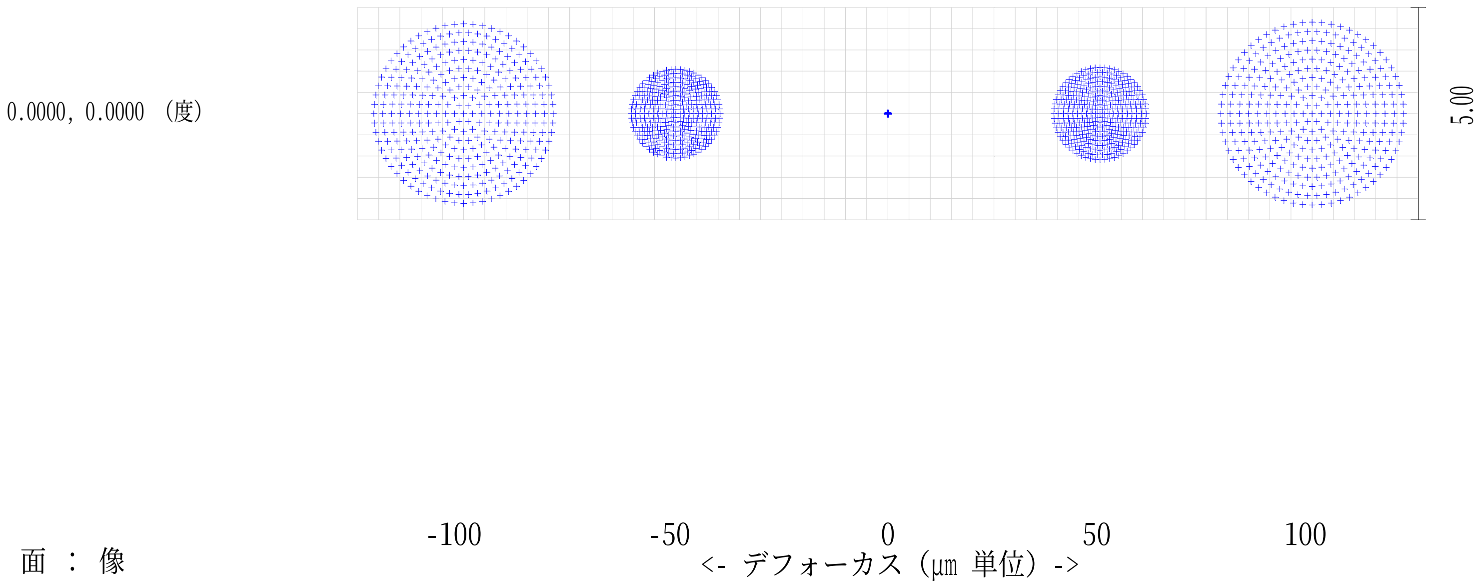




3D レイアウト

2019/05/12

Gregorian superB12 fine.ZMX
コンフィグレーション 1 / 1

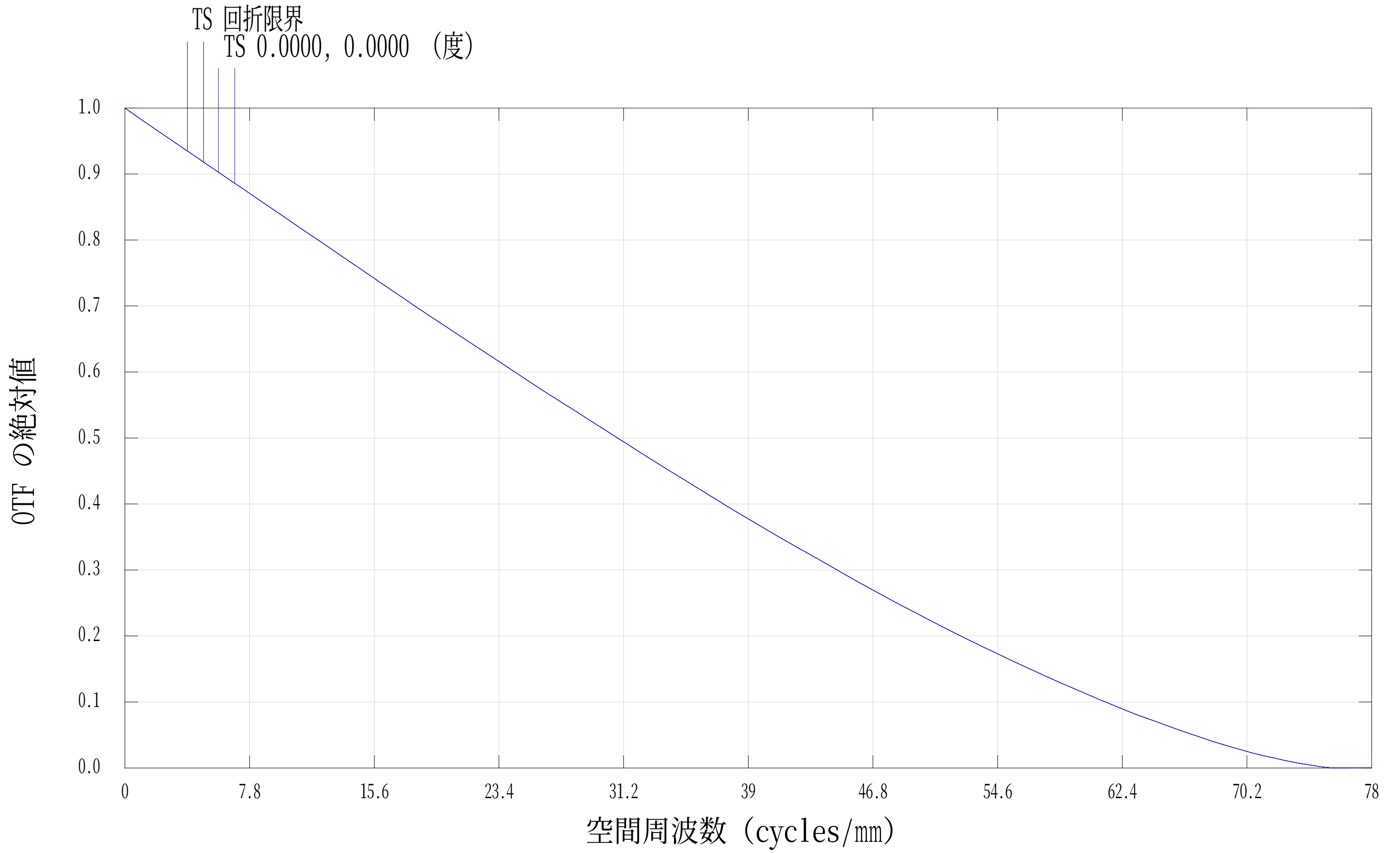


スルーフォーカス スポットダイアグラム

2019/05/12 単位は µm です。
視野 : 1
RMS 半径 : 0.011
GEO 半径 : 0.020
スケールバー : 5

基準 : 主光線

Gregorian superB12 fine.ZMX
コンフィグレーション 1 / 1

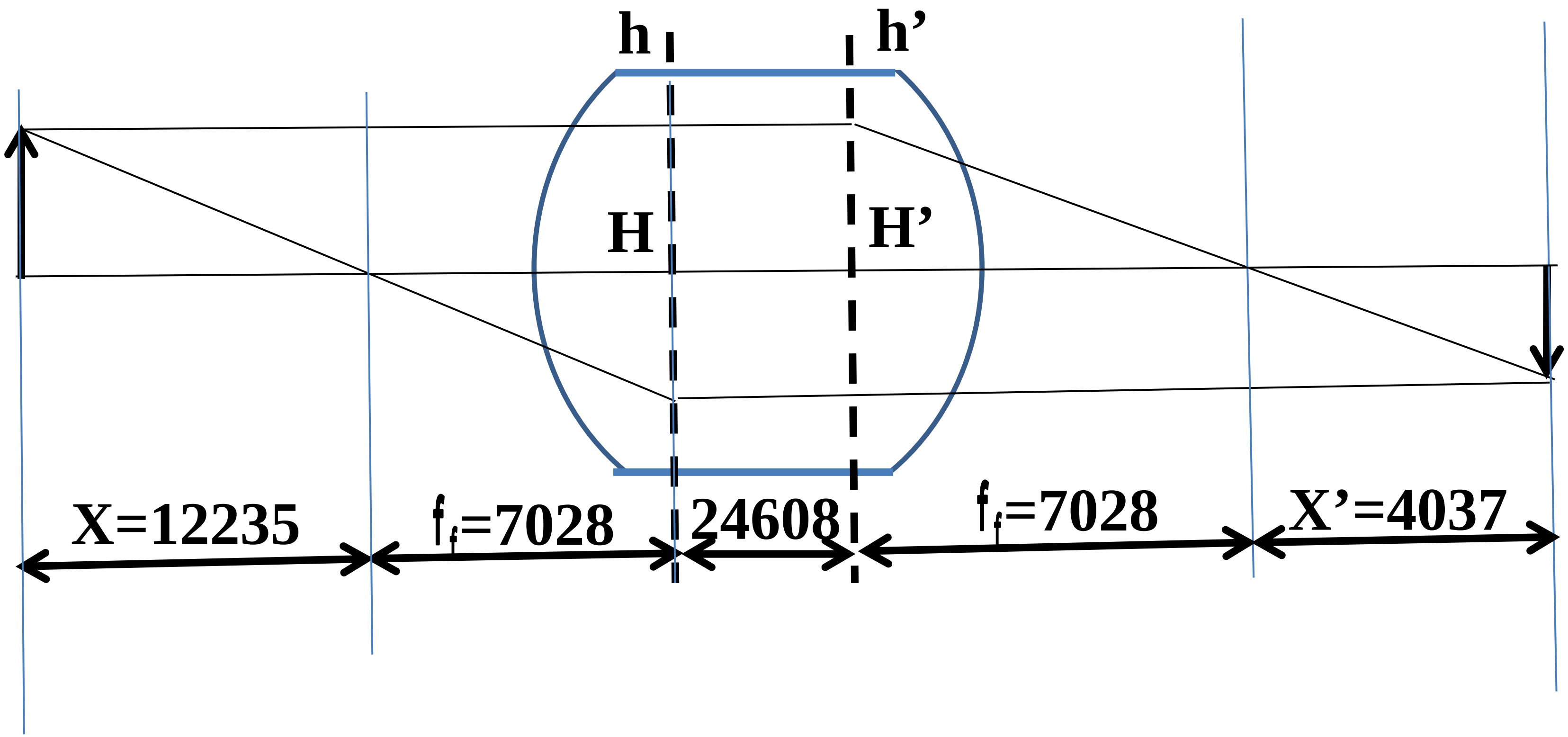


多色回折 MTF

2019/05/12
0.5500 から 0.5500 µm までのデータです。
面 : 像面

Gregorian superB12 fine.ZMX
コンフィグレーション 1 / 1

Relation between source point and beam image



Magnification=0.574

Distance between H and H' is 24608mm