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# Beamline design

## 4<sup>th</sup> School on Synchrotron Light Sources and their Applications

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# Goal of beamline design

Design a photon transport system connecting the light source to the experimental station within a set of specific parameters:

- Photon flux
- Photon energy
- Photon energy bandwidth
- Photon beam spatial size
- Coherence
- ...

# Beamline design process

## Requirements

- Flux?
- Energy?
- Energy range?
- Energy resolution?
- Spatial size?
- ...

## Optics

Source type

Monochromator choice

Pre-mono collimation

Focussing system

## Engineering

Thermal load

Rad protection

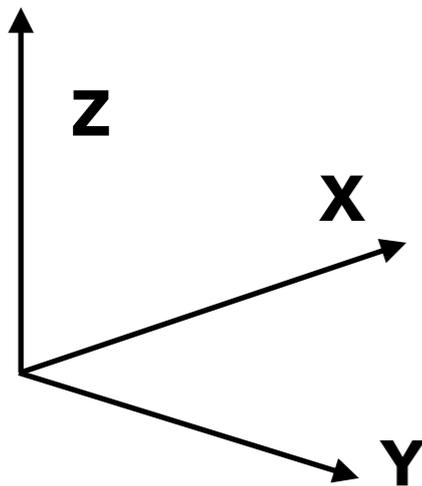
Beamline length



# Tools available

- Physics side: Photons' interactions with matter
  - Refraction
  - Reflection
  - Diffraction
- Design side: Simulators
  - Ray tracers
  - Wave optics
  - Finite Elements

# Quick word about simulators



By SHADOW convention,  
Y is the BEAM PROPAGATION D

C. Welnak, P. Anderson, M. Khan, S. Singh, and F. Cerrina, "Recent developments in SHADOW," *Review of Scientific Instruments*, vol. 63, p. 865, 1992.  
O. Chubar, P. E. P. O. T. E. Conference, 1998, "Accurate and efficient computation of synchrotron radiation in the near field region," *accelconf.web.cern.ch*  
L. Rebuffi, M. Sanchez del Rio, "OASYS (OrAnge SYNchrotron Suite): an open-source graphical environment for x-ray virtual xperiments", Proc. SPIE 10388, 103880S (2017) . DOI: 10.1117/12.2274263

L. Rebuffi, M. Sanchez del Rio, "ShadowOui: A new visual environment for X-ray optics and synchrotron beamline simulations", *J. Synchrotron Rad.* 23 (2016).  
DOI:10.1107/S1600577516013837



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# A quick recap

just to set the scene...



# Handles available for “manipulating” x-ray photons

## Usage

### Diffraction

$$2d \cdot \sin\theta = m\lambda$$

$$d \cong \lambda$$

Monochromatization  
Focussing

### Reflection

$$\sin\phi' = \frac{\sin\phi}{n} \cong \frac{\sin\phi}{1-\delta}$$

$$\theta_C \approx \sqrt{2\delta} \quad (\text{rad})$$

$$\theta_C \approx 81\sqrt{\delta} \quad (\text{degrees})$$

Transport  
Divergence corrections  
Focussing  
Basic energy filtering

### Refraction

$$n = 1 - \delta + i\beta$$

$$\delta = 10^{-1} \div 10^{-6}$$

$$\beta = 10^{-1} \div 10^{-8}$$

Focussing

# Synchrotron beam emitted by source

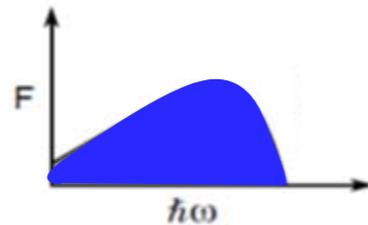
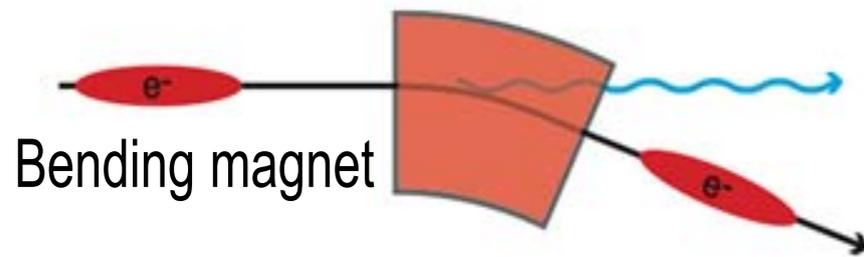
$$\gamma = 1957 E_e[\text{GeV}]$$

Beam size  
@ 20 m

Source

Spectrum

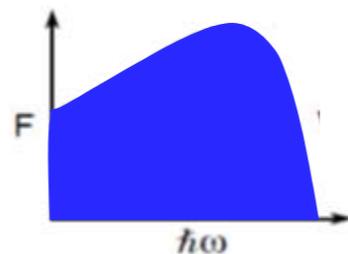
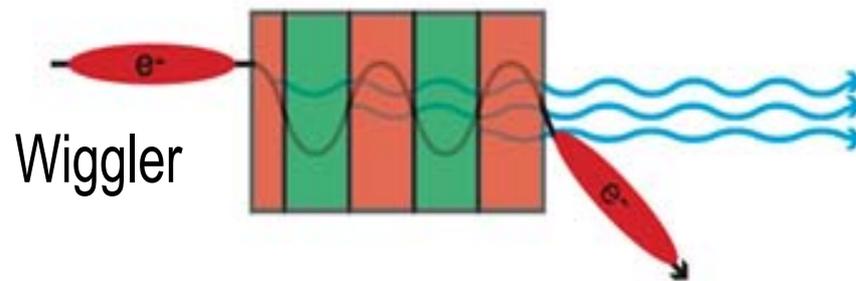
Divergence  $\sigma$



$$\sim \frac{I}{\gamma}$$

$\sim$  mrad

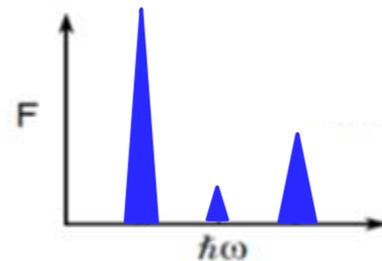
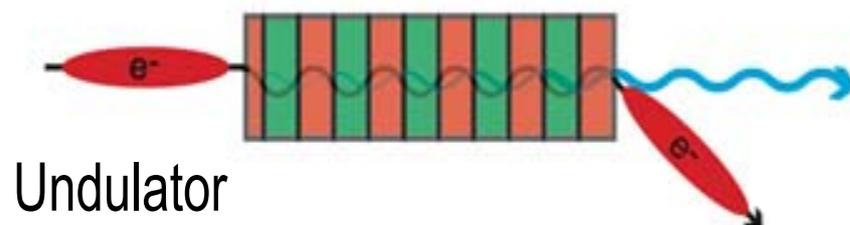
$\sim$  1 - 10's mm



$$\sim \frac{I}{\gamma}$$

$\sim$  mrad

$\sim$  1 - 10's mm



$$\sim \frac{I}{\gamma \sqrt{N}}$$

$\sim$  100's  $\mu$ rad

$\sim$  mm

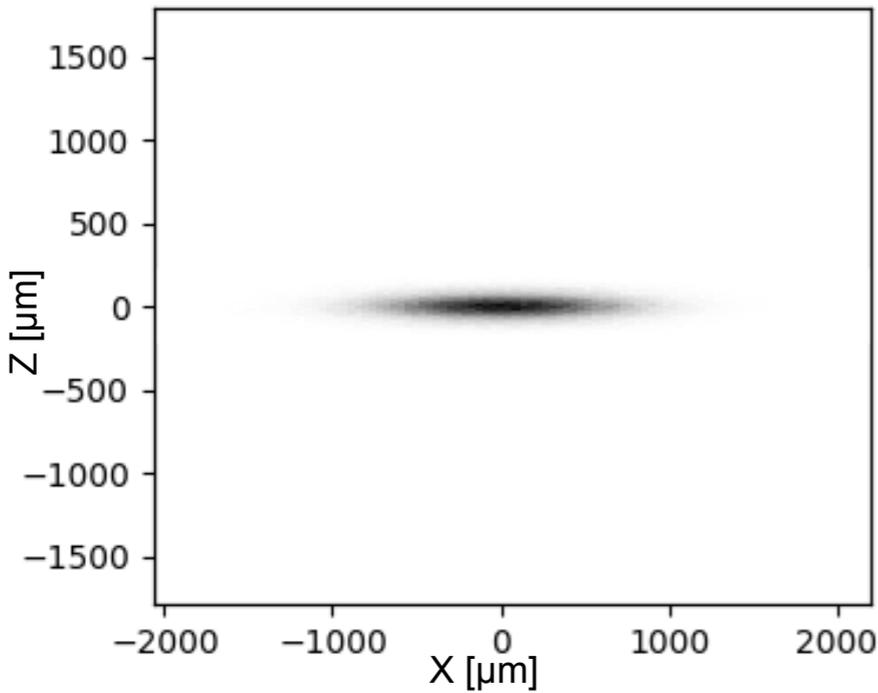
For a typical experiment: required beam size  $\sim$  0.01 to 10's of  $\mu$ m



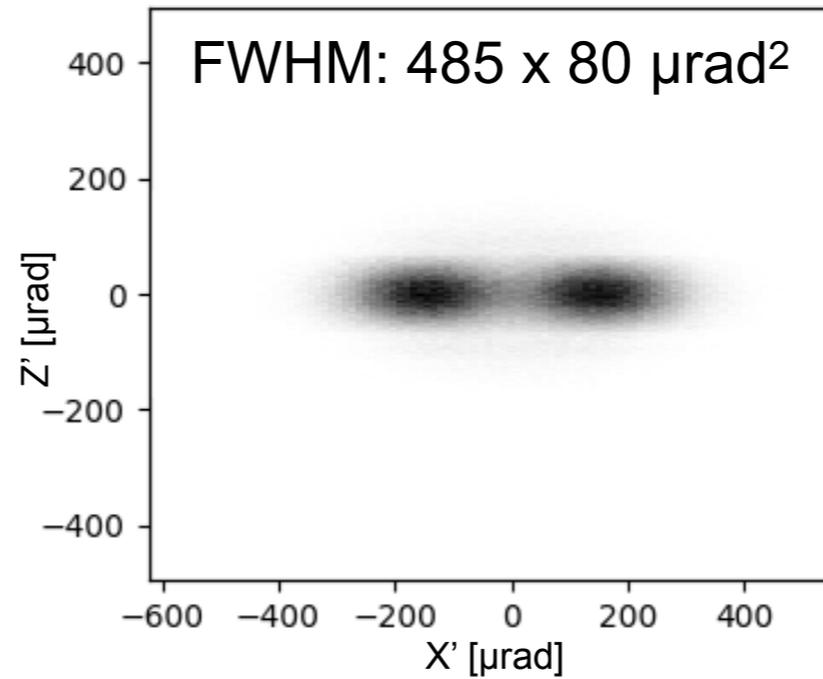
# A couple of undulator simulations

$E_e=2.4\text{GeV}$ ,  $N = 17$ , period = 56mm, first harmonic only

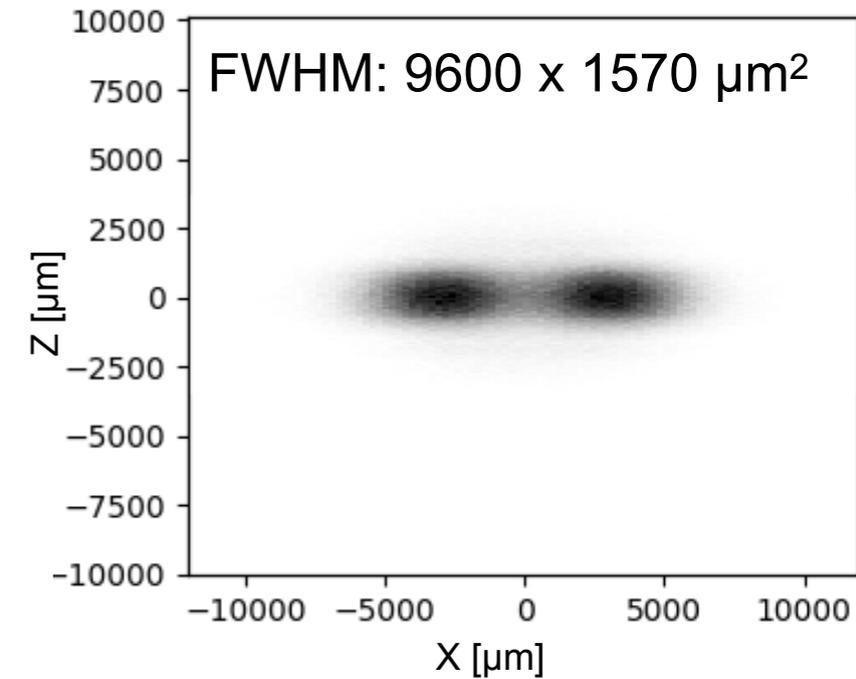
### Source Size



### Divergence

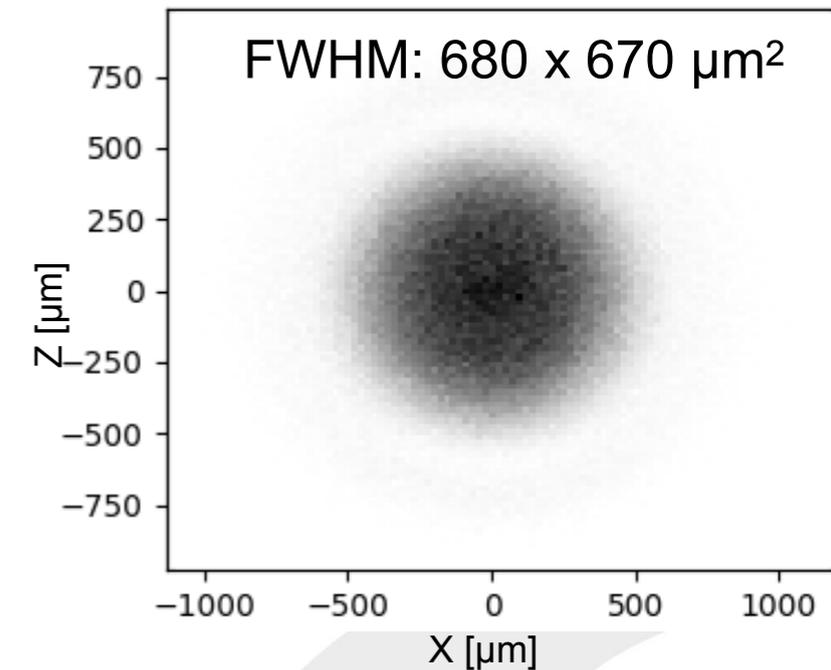
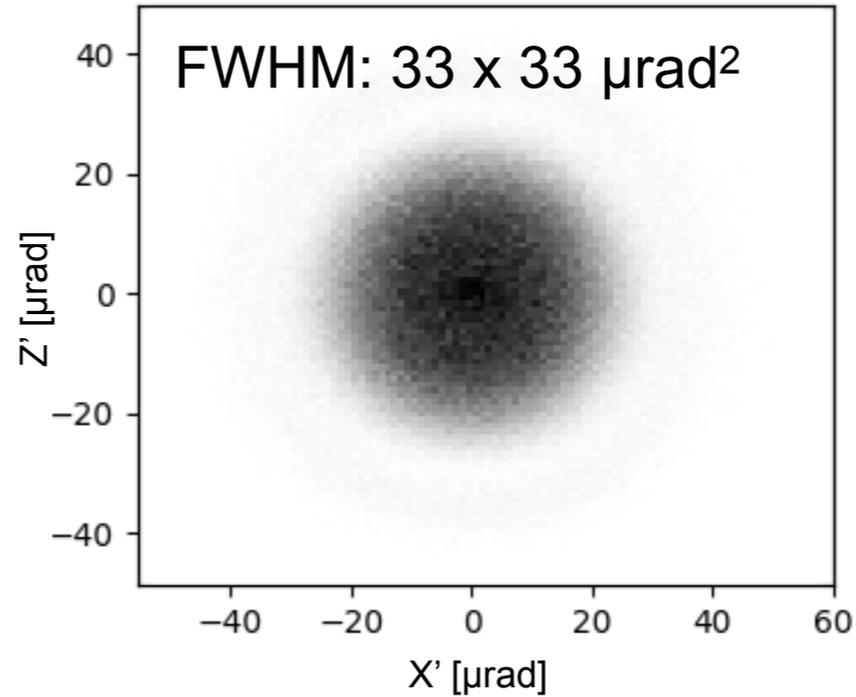
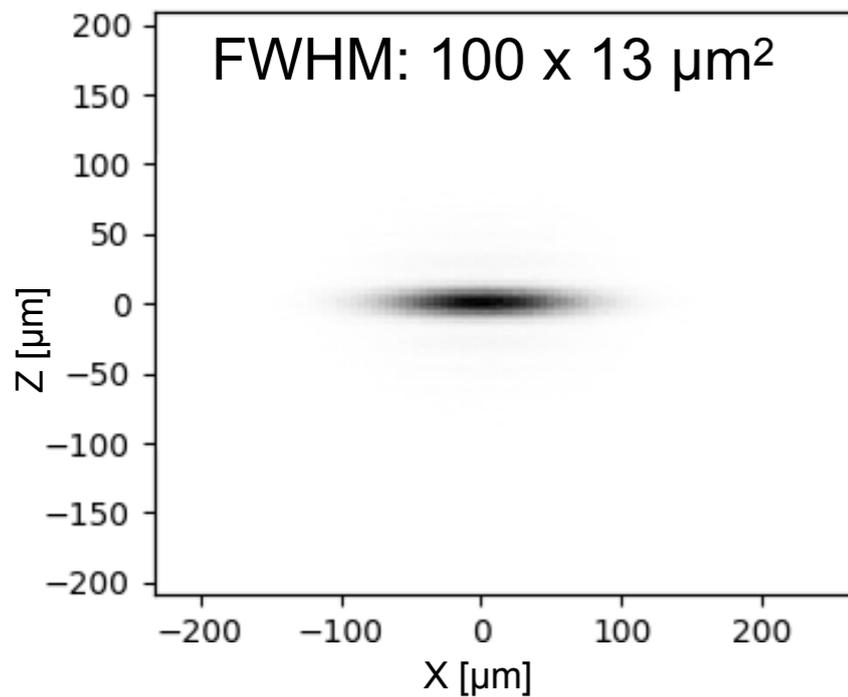


### Beam 20 m from source



(3<sup>rd</sup> gen storage ring)

(Next gen storage ring)

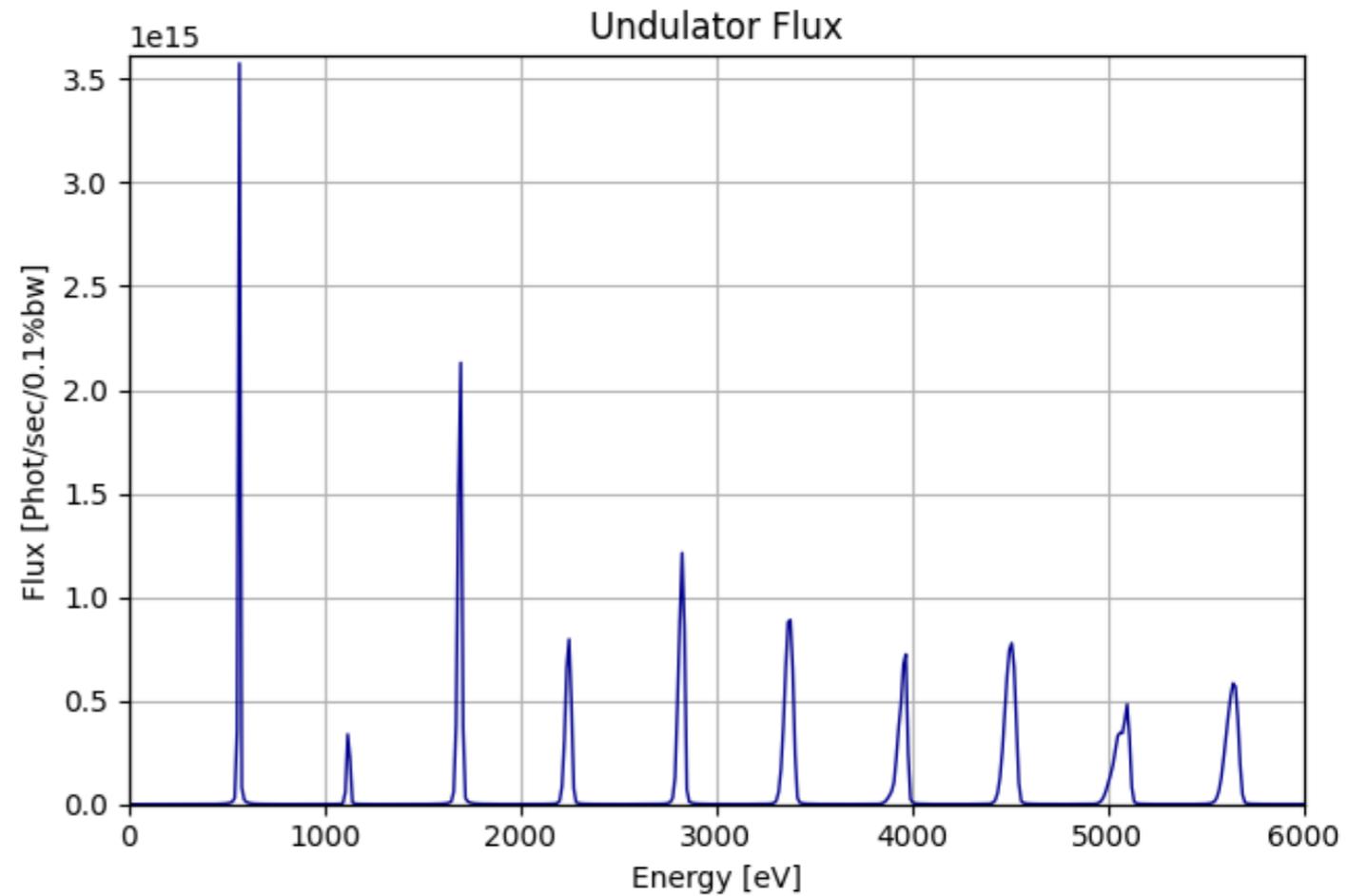
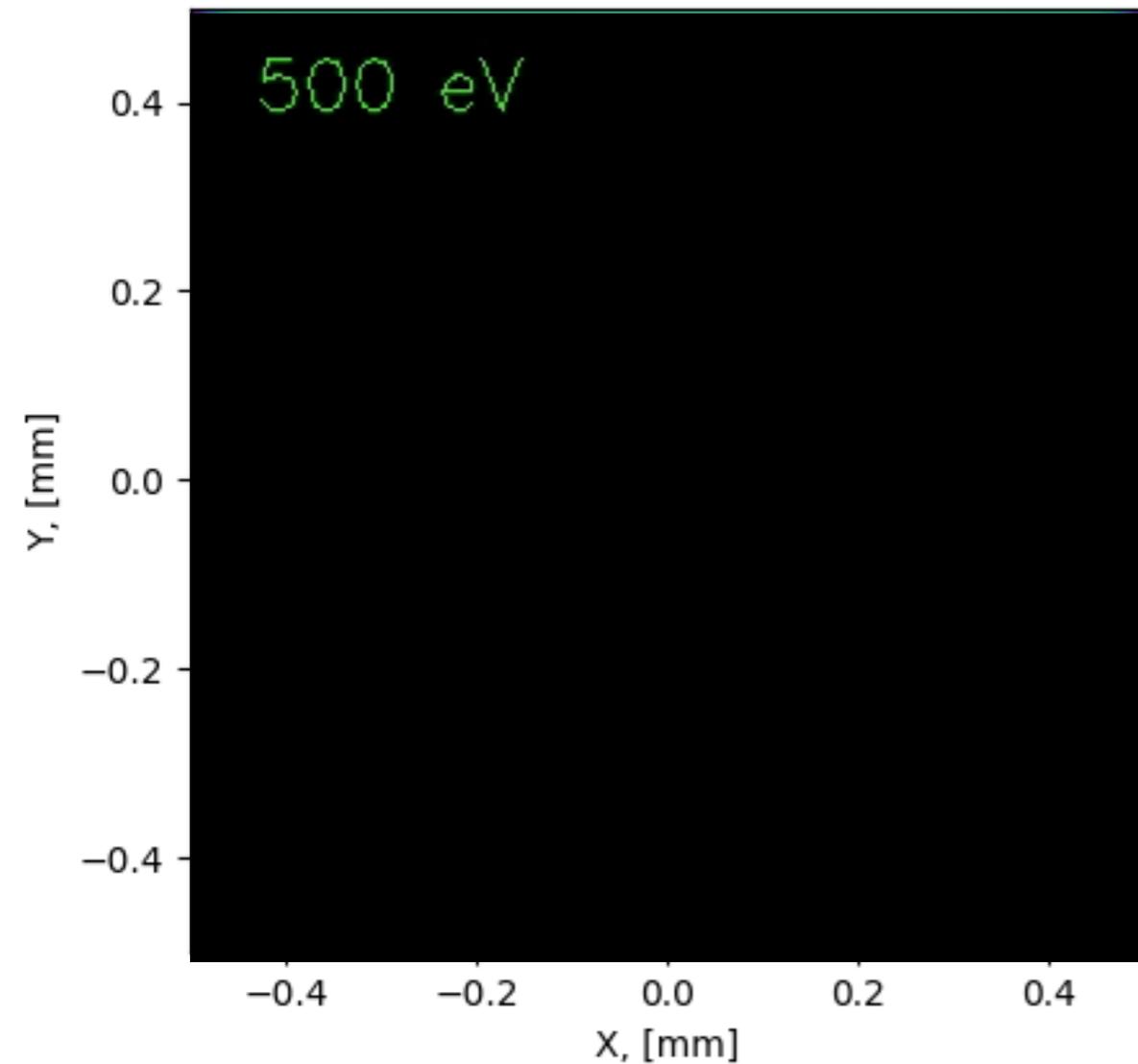




# It's even more complicated...

$E_e=2.4\text{GeV}$ ,  $N = 90$ , period = 22 mm,  $K_{\text{max}} = 2.6$

seen 10 m away through a 1 x 1 mm aperture





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# So what am I going to talk about??

- Mirrors for X-rays
- Basics of diffracting elements
- Monochromators for X-rays
- The thermal load issue



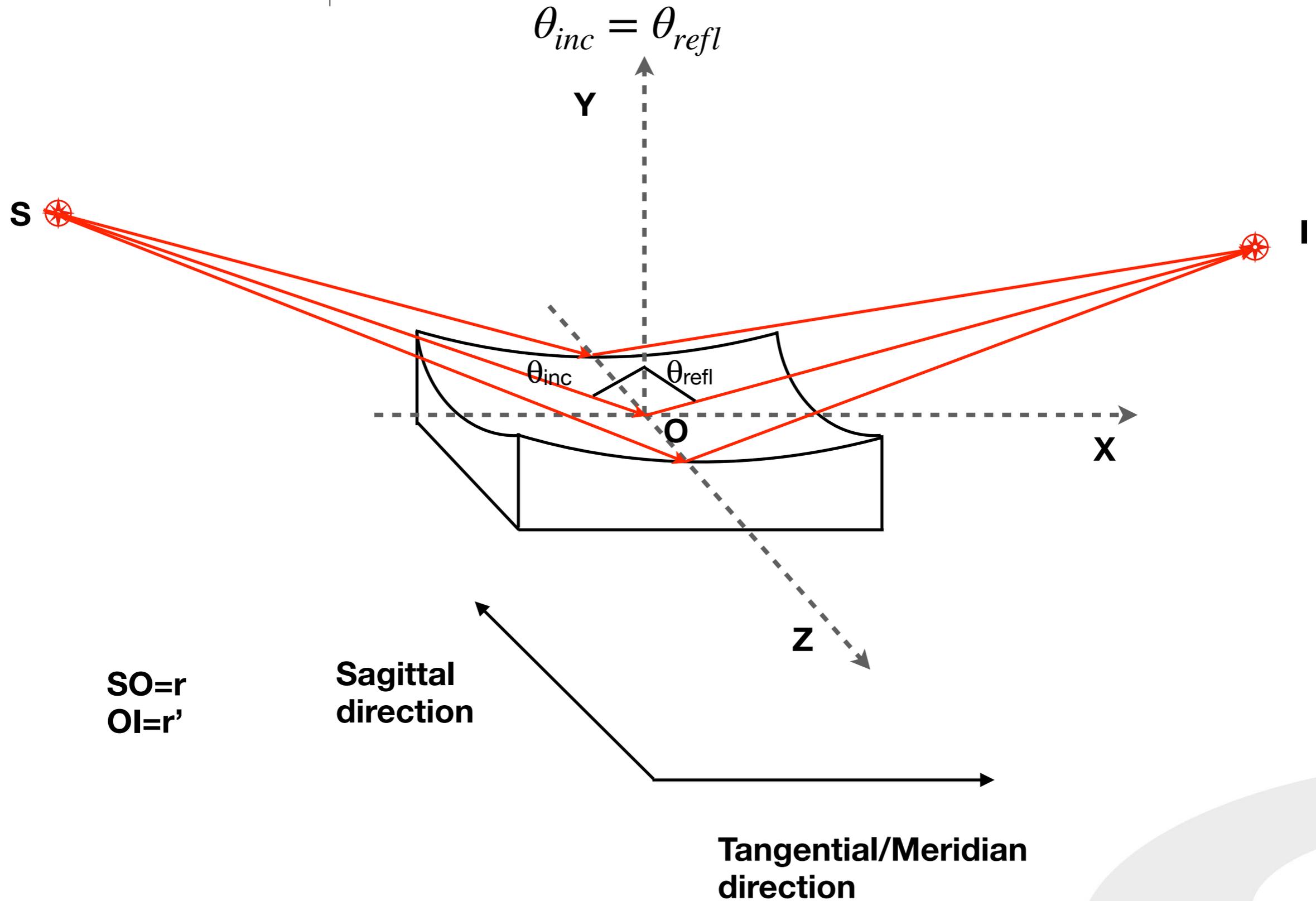
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# Mirrors for x-rays

Transport  
Divergence corrections  
Focussing  
Basic energy filtering



# Some nomenclature



$SO=r$   
 $OI=r'$

**Sagittal  
direction**

**Tangential/Meridian  
direction**

# Mirror figures used in synchrotron beamlines

		<b>Some numbers</b>
<b>Plane</b>	Re-direction/filtering	$R > 100\text{km}$
<b>Cylindrical</b>	1D focusing	$R \sim 100\text{'s m}$
<b>Spherical</b>	2D focusing	$R \sim 100\text{'s m}$
<b>Paraboloid</b>	Infinity to point (or viceversa)	$a \sim \text{cm}, f \sim \text{m}$
<b>Elliptical</b>	Point to point focusing	$r \gg r'$
<b>Toroidal</b>	Astigmatic focusing	$R \sim 100\text{m}, \rho \sim 10\text{'s cm}$

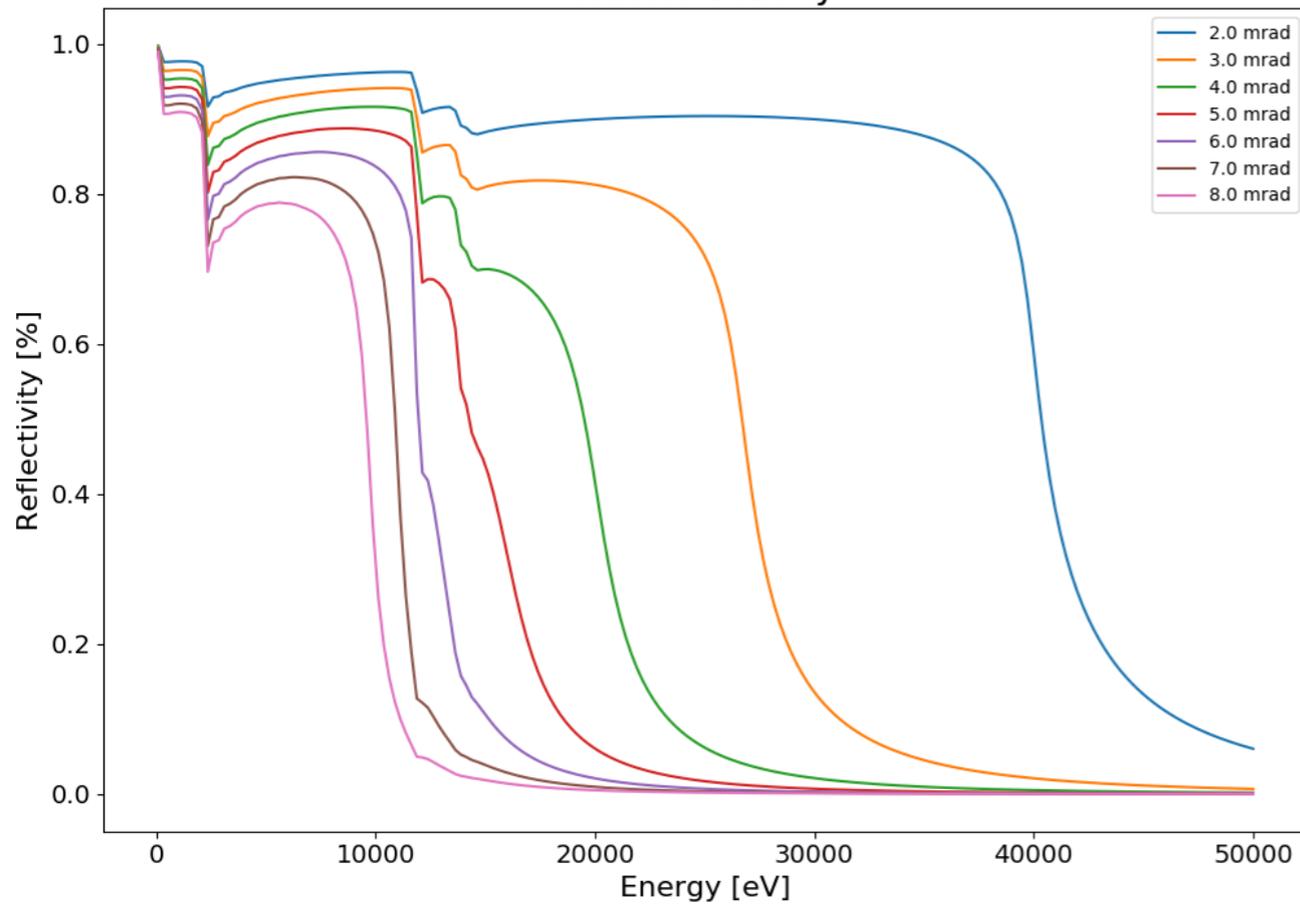
All this with a surface rms roughness  $\sim \text{nm}$  or less

# A quick look at reflectivities

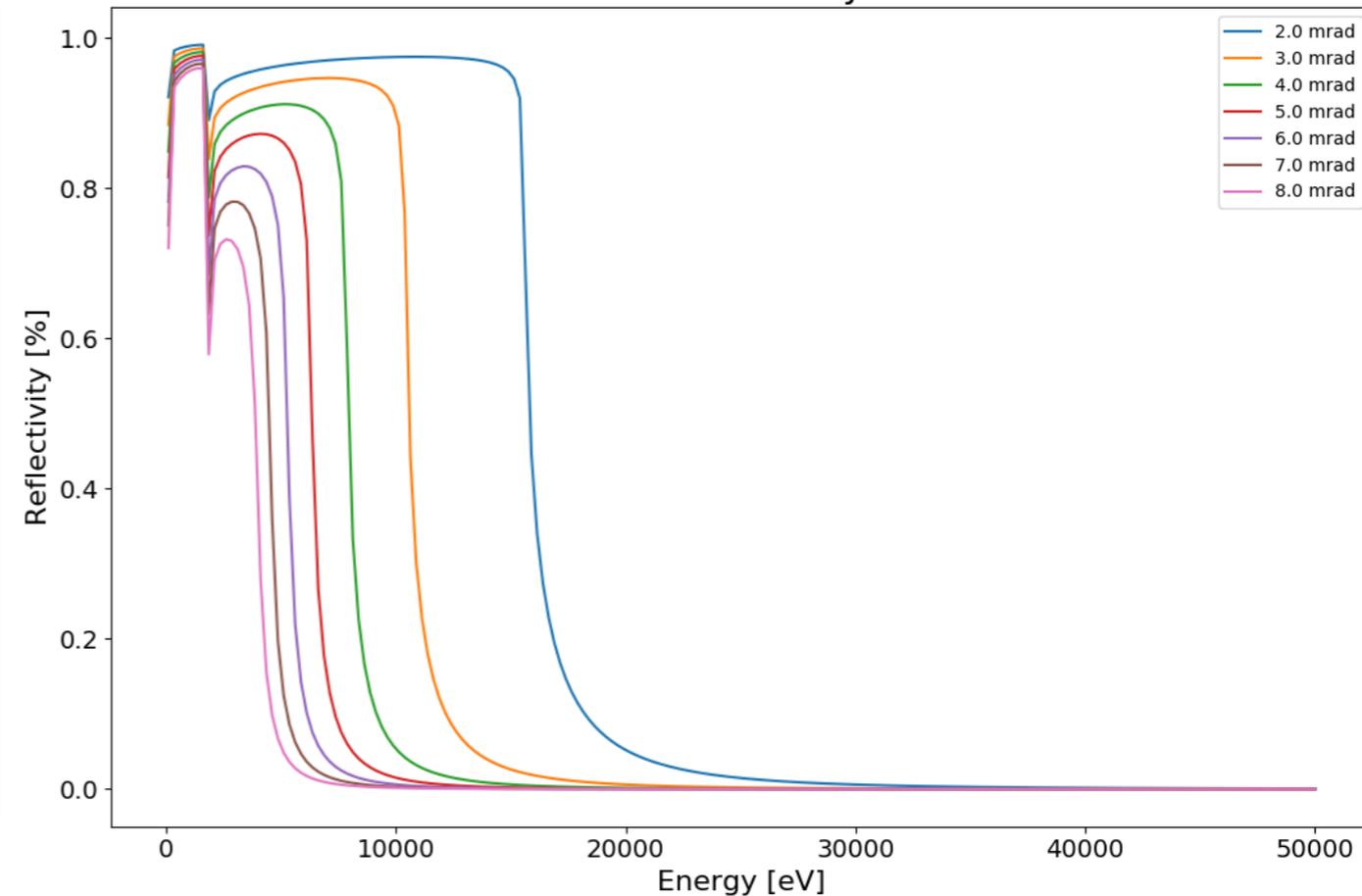
$$n = 1 - \delta + i\beta$$

$$\theta_c = \sqrt{2\delta} \propto \lambda\sqrt{Z}$$

Au Reflectivity



Si Reflectivity

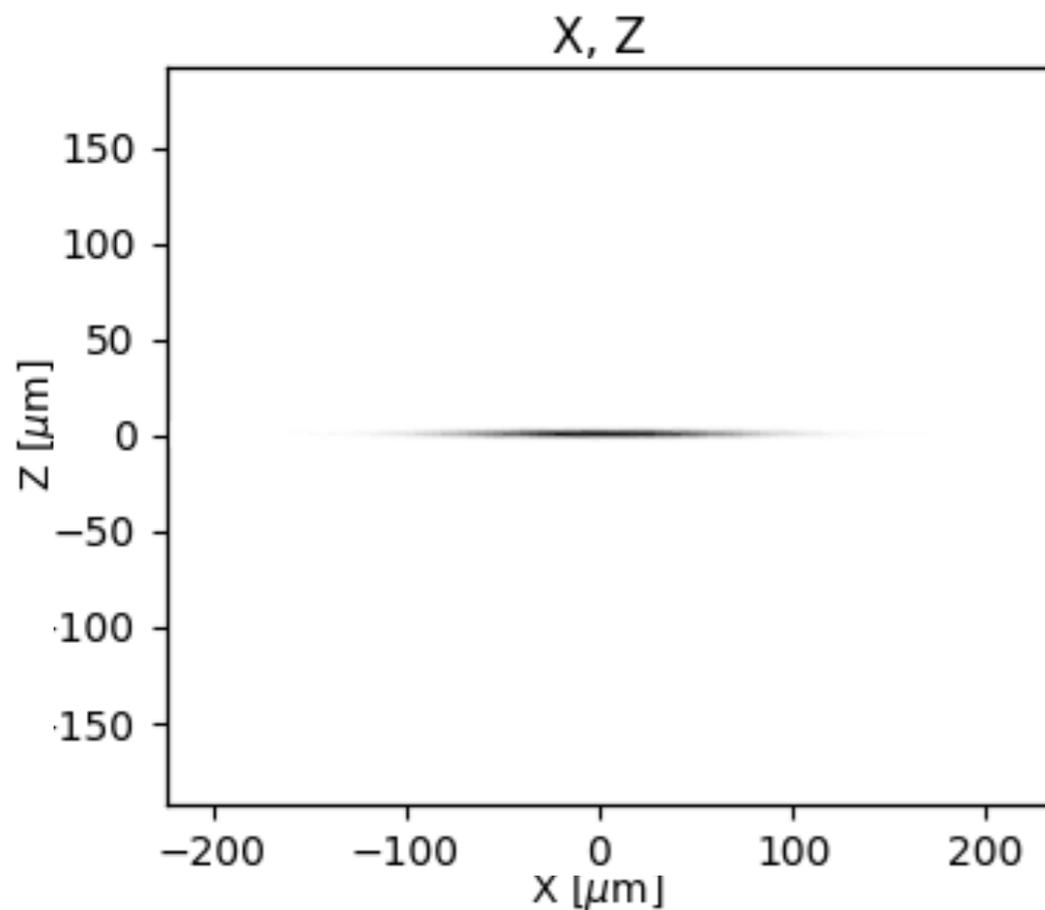


The higher the energy, the more grazing the incidence angle  
(1mrad = 0.057°, 1° = 17mrad, **8 mrad ~ 0.5°**)

Spatial Dimensions:

$$\sigma_x = 48\mu m \quad \sigma_z = 1.3\mu m$$

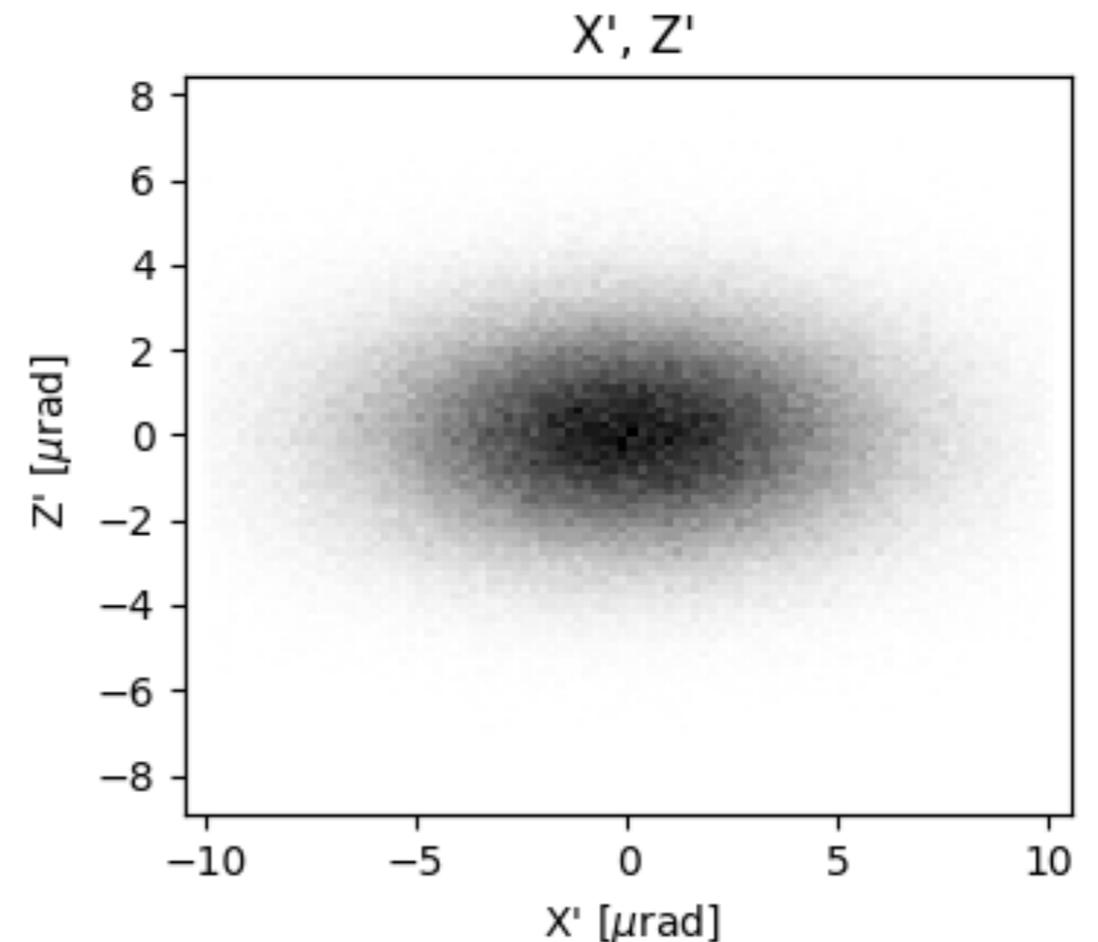
FWHM (X)=105  $\mu m$  FWHM(Z)=3  $\mu m$



Angular dimensions:

$$\sigma'_x = 3.8\mu rad \quad \sigma'_z = 1.82\mu rad$$

FWHM (X')=8.6  $\mu rad$  FWHM(Z')=4.2  $\mu rad$

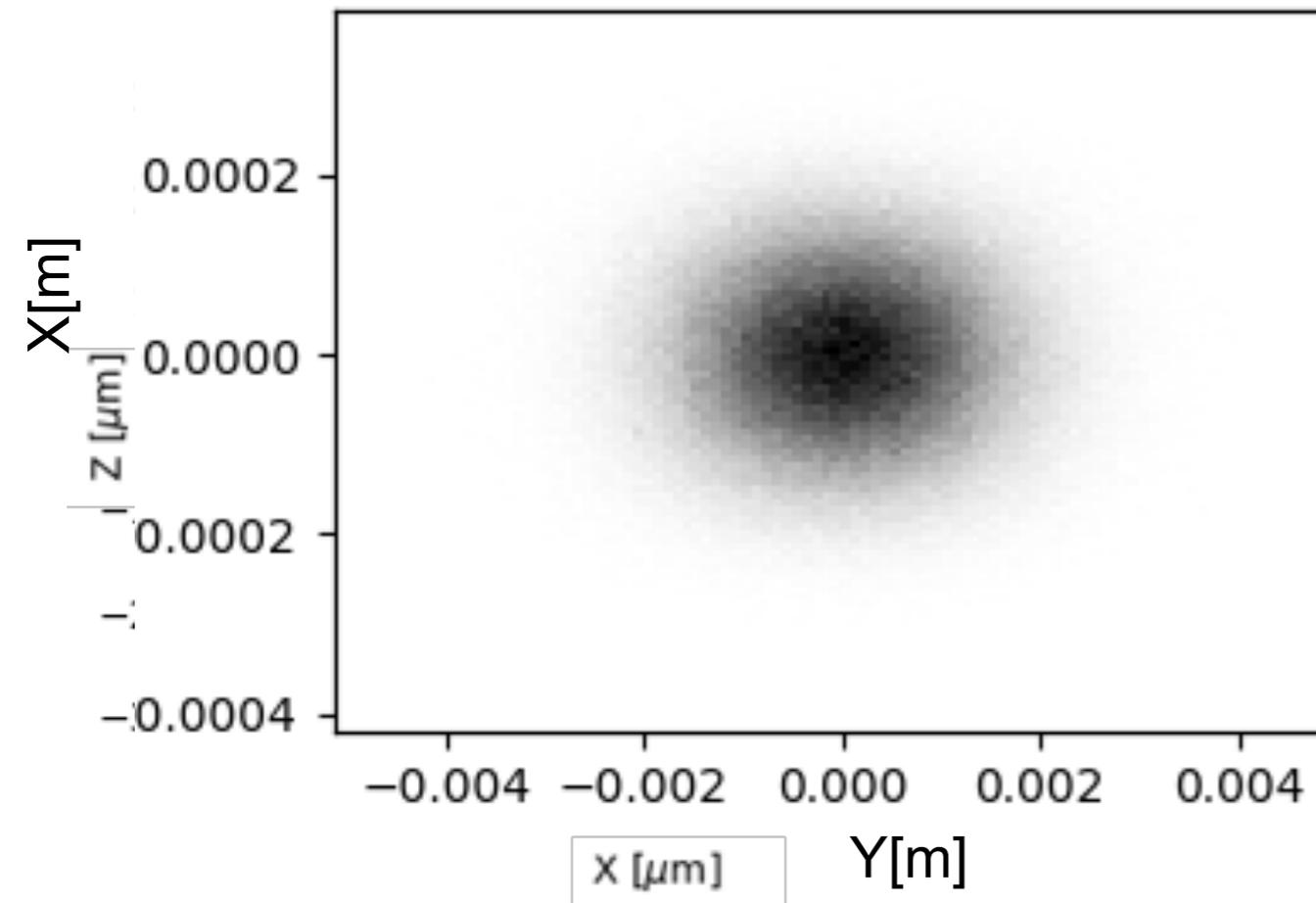




# Plane mirror, $r = 20 \text{ m}$ , $r' = 20 \text{ m}$ , $\theta = 88^\circ$

Spatial Dimensions:

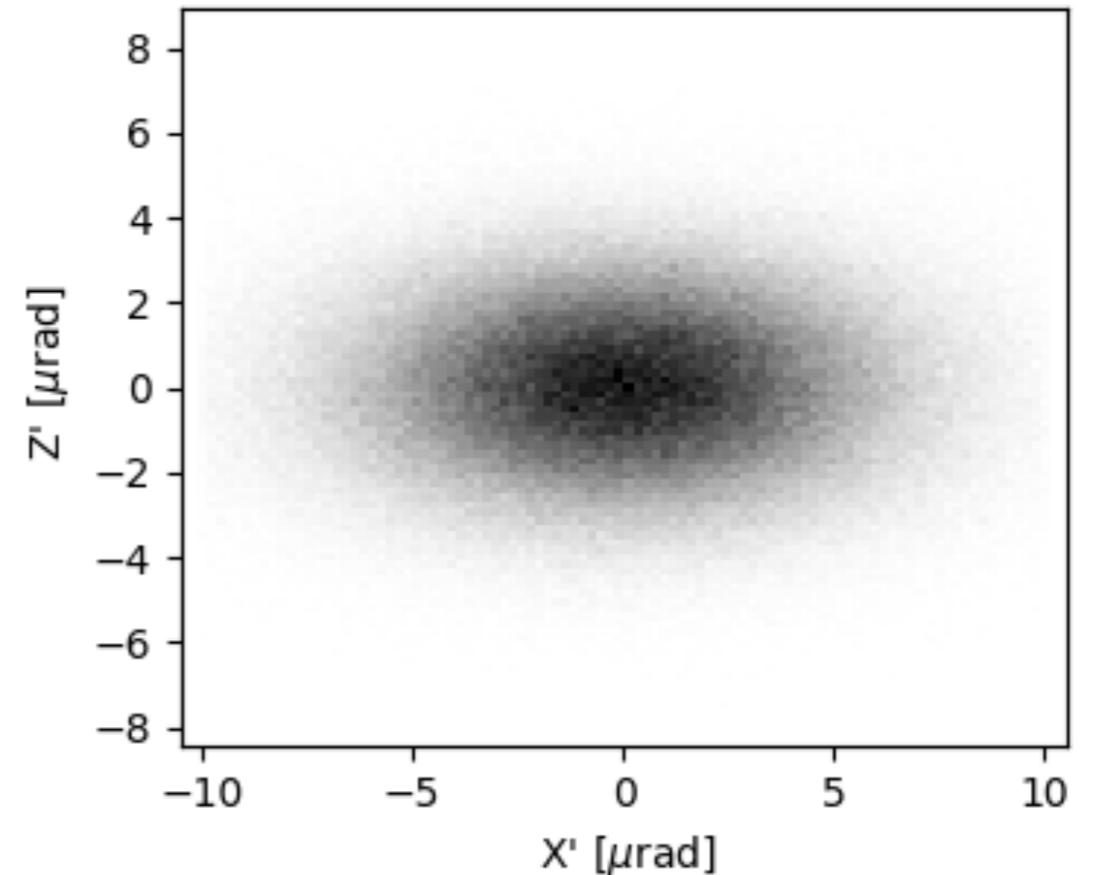
Footprint



FWHM (X)=250  $\mu\text{m}$  FWHM(Z)=250  $\mu\text{m}$

Angular dimensions:

$X', Z'$



FWHM ( $X'$ )=8.6  $\mu\text{rad}$  FWHM( $Z'$ )=4.2  $\mu\text{rad}$



# Toroidal mirror: focussing properties

$$\left(\frac{1}{r} + \frac{1}{r'}\right) \frac{\cos\theta}{2} = \frac{1}{R}$$

Tangential focusing

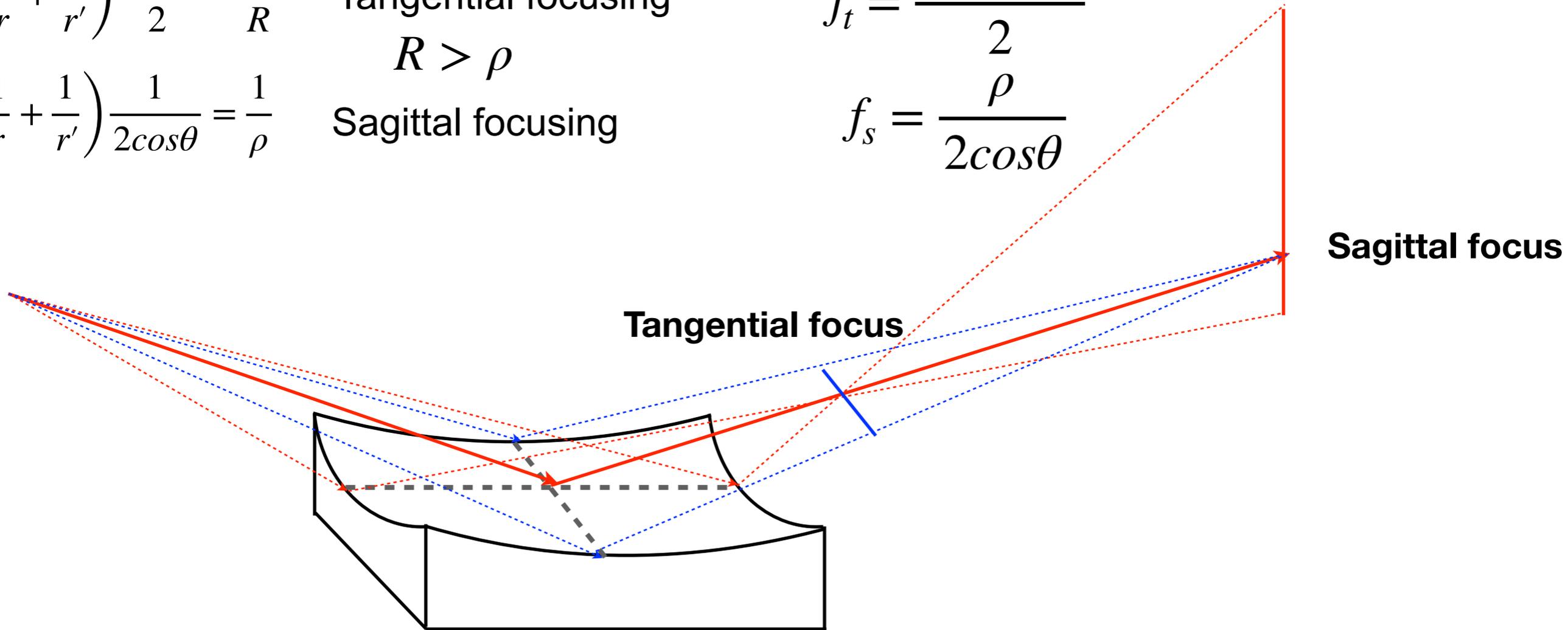
$$R > \rho$$

$$f_t = \frac{R \cdot \cos\theta}{2}$$

$$\left(\frac{1}{r} + \frac{1}{r'}\right) \frac{1}{2\cos\theta} = \frac{1}{\rho}$$

Sagittal focusing

$$f_s = \frac{\rho}{2\cos\theta}$$



Condition for a stigmatic image of a point source:

$$\frac{\rho}{R} = \cos^2\theta$$

# Toroidal mirror, $r = 20 \text{ m}$ , $r' = 10 \text{ m}$ , $\theta = 88^\circ$

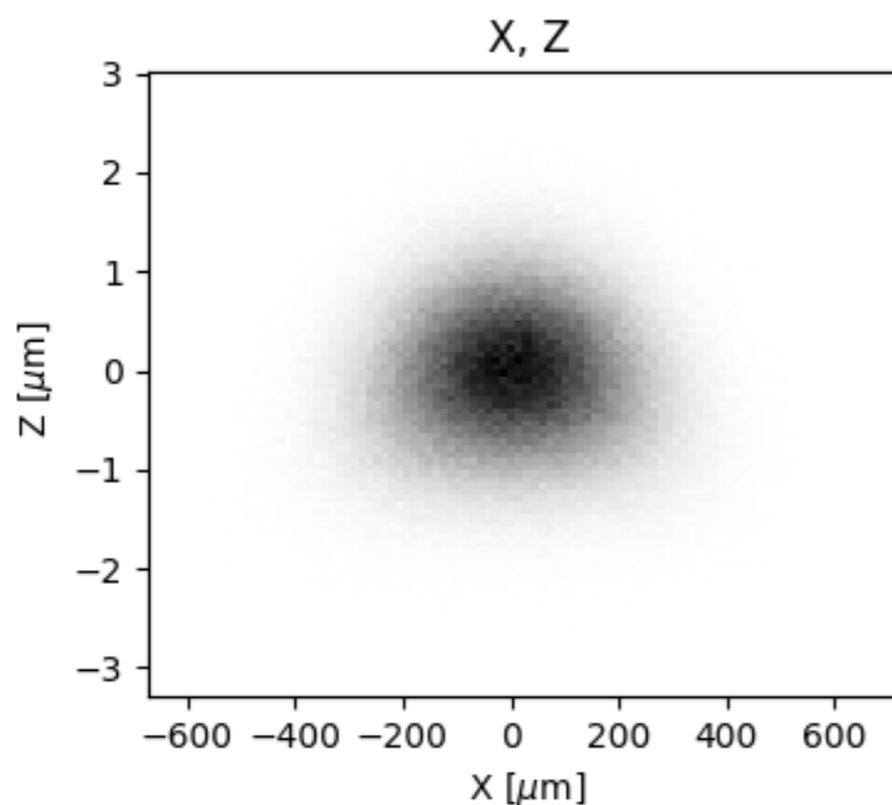
$$R = \left( \left( \frac{1}{r} + \frac{1}{r'} \right) \frac{\cos\theta}{2} \right)^{-1} = 382 \text{ m} \quad \rho = \left( \left( \frac{1}{r} + \frac{1}{r'} \right) \frac{1}{2\cos\theta} \right)^{-1} = 0.23 \text{ m}$$

$$f_t = \frac{R \cdot \cos\theta}{2} = 6.6 \text{ m}$$

$$f_s = \frac{\rho}{2\cos\theta} = 3.3 \text{ m}$$

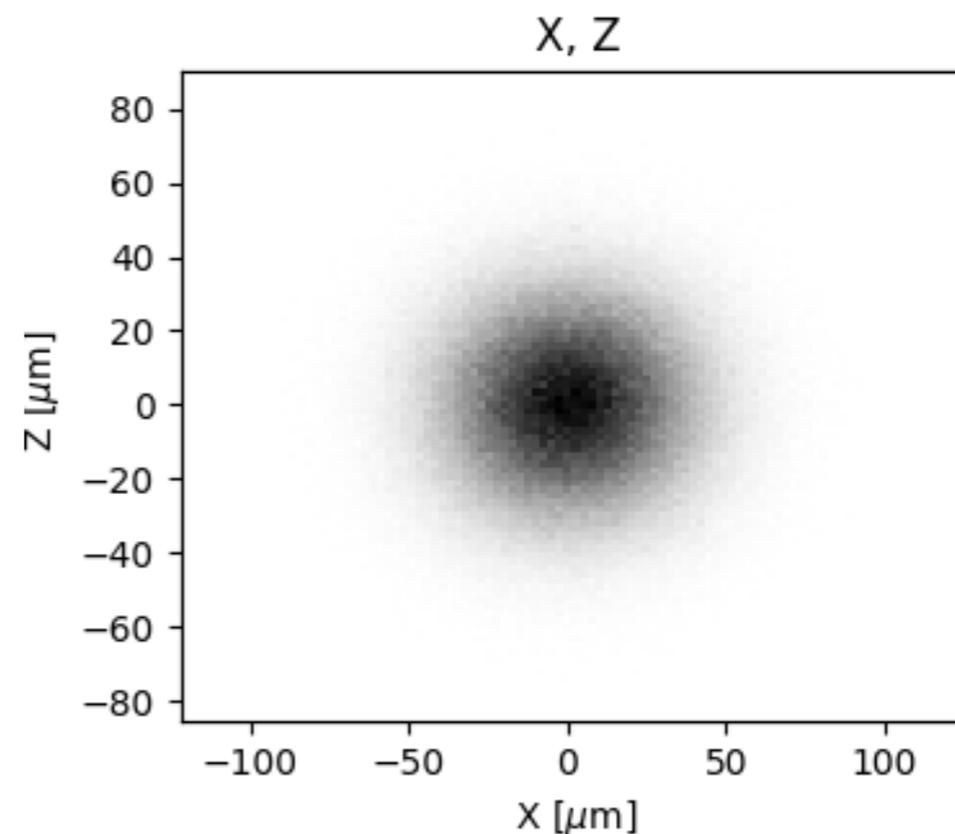
Source size, FWHM:  $105 \times 3 \mu\text{m}^2$

Tangential focus (along Z)



FWHM (X)=333  $\mu\text{m}$  FWHM(Z)=1.5 $\mu\text{m}$

Sagittal focus (along X)



FWHM (X)=56  $\mu\text{m}$  FWHM(Z)=42 $\mu\text{m}$



# Spherical mirrors

Same as toroidal mirrors with:

$$R = \rho$$

$$\left(\frac{1}{r} + \frac{1}{r'}\right) \frac{\cos\theta}{2} = \frac{1}{R}$$

$$\left(\frac{1}{r} + \frac{1}{r'}\right) \frac{1}{2\cos\theta} = \frac{1}{R}$$

$$f_t = \frac{R \cdot \cos\theta}{2}$$

$$f_s = \frac{R}{2\cos\theta}$$

A stigmatic image is only possible if:

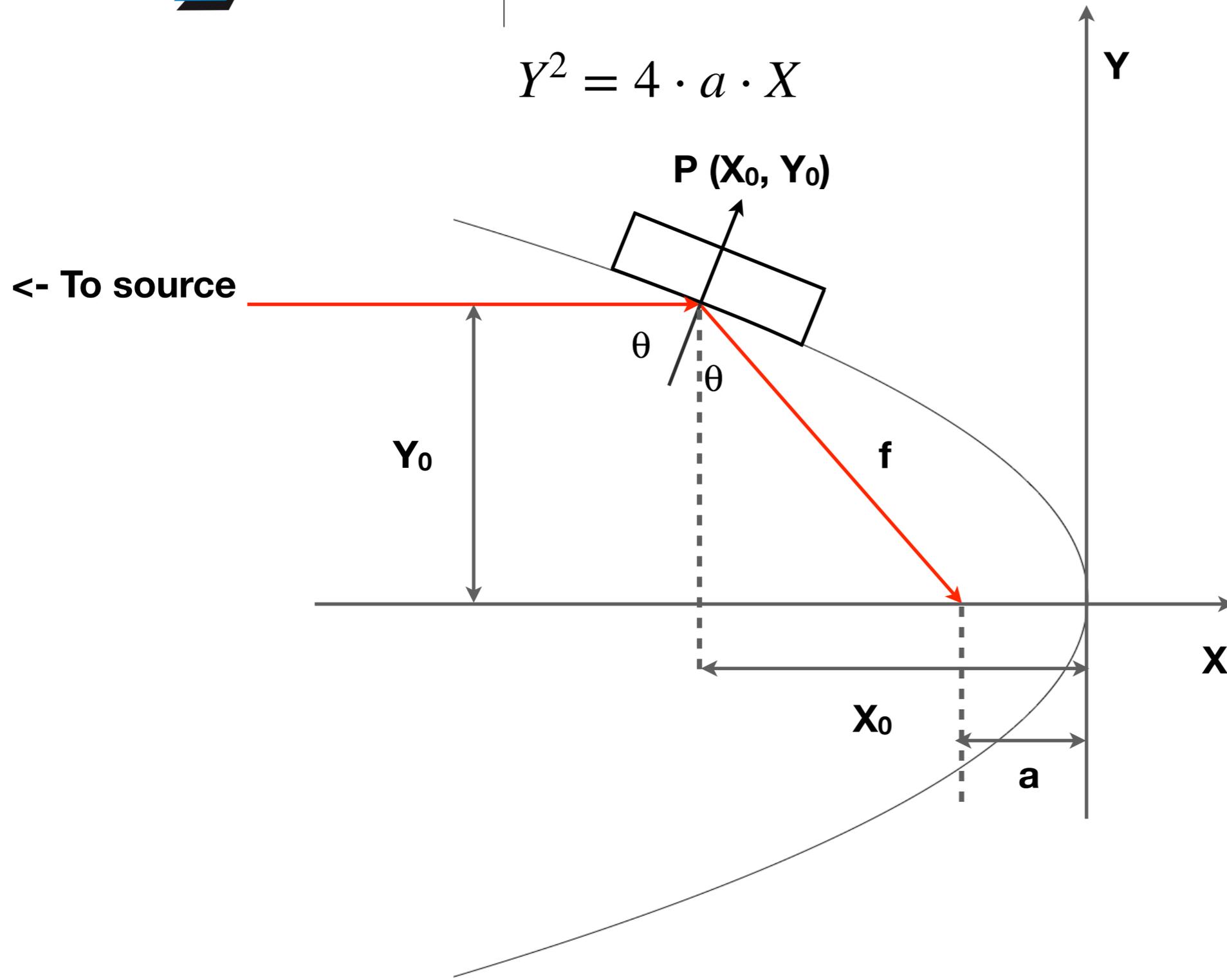
$$\frac{\rho}{R} = \cos^2\theta = 1$$

i.e. this is possible only for normal incidence!



# Paraboloidal mirror

$$Y^2 = 4 \cdot a \cdot X$$



P ( $X_0$ ,  $Y_0$ ):

$$X_0 = a \cdot \tan^2 \theta$$

$$Y_0 = 2a \cdot \tan \theta$$

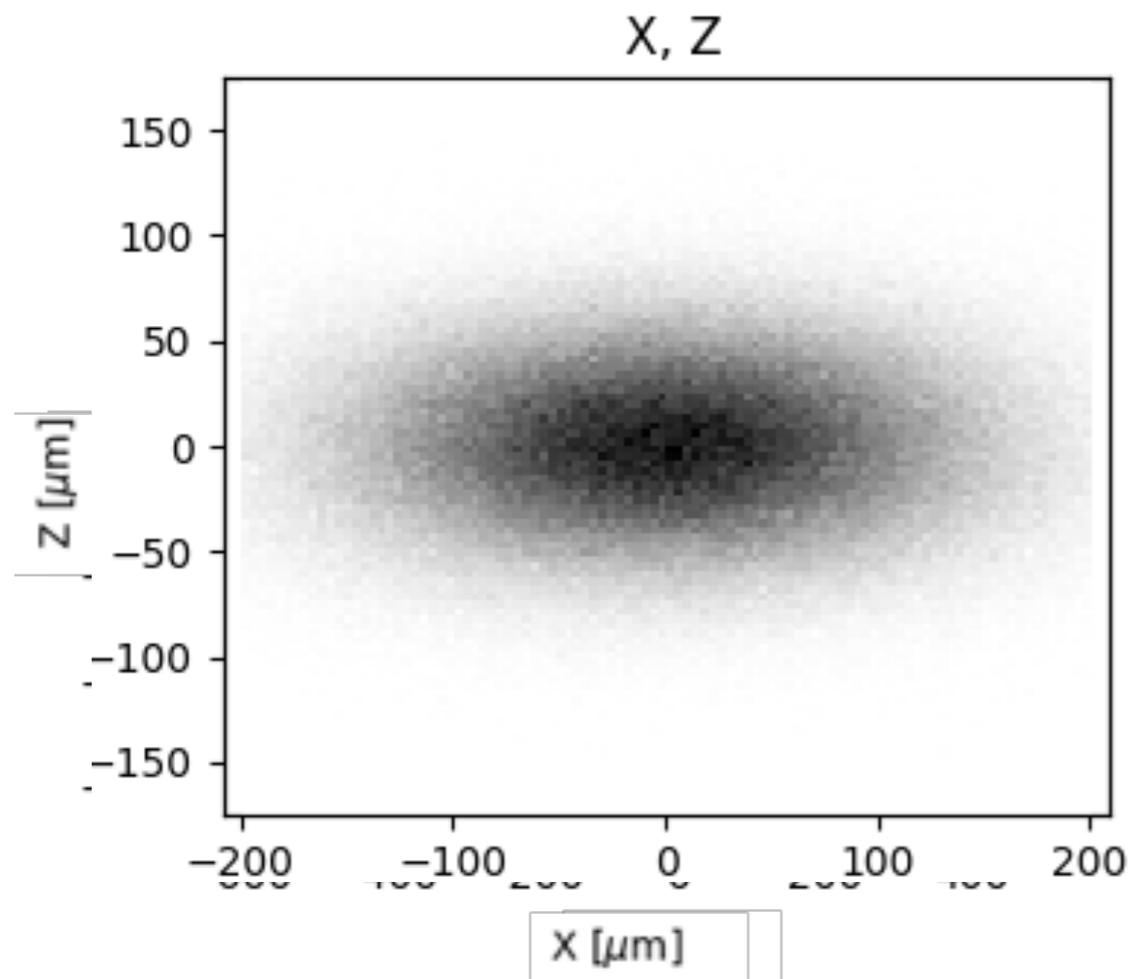
$$f = \frac{a}{\cos^2 \theta}$$



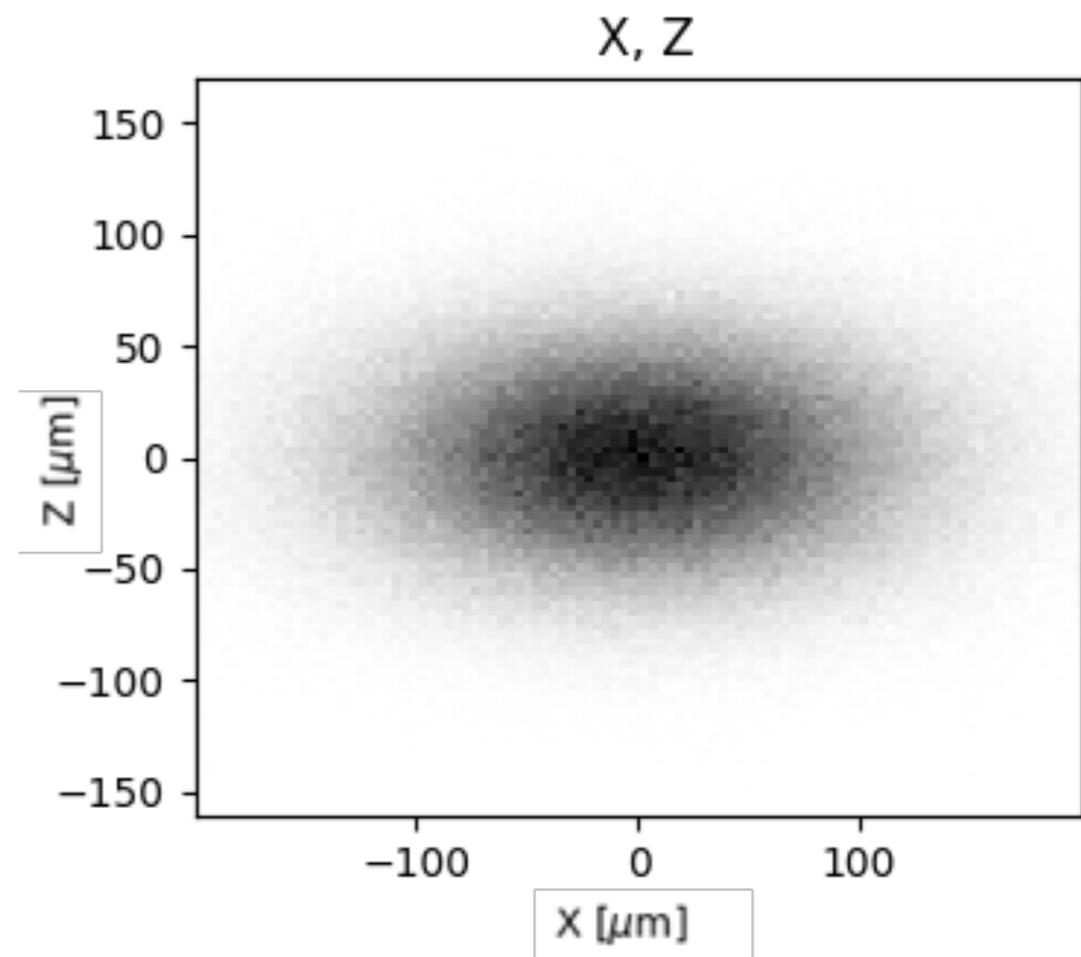
# Paraboloidal mirror, $r = 20 \text{ m}$ , $r' = 20 \text{ m}$ , $\theta = 88^\circ$

Parabola parameter  $a = f \cos^2 \theta = 0.02435 \text{ m}$

### Source image @ 20 mt



### Paraboloidal Mirror image



FWHM (X) = 235  $\mu\text{m}$  FWHM (Z) = 815  $\mu\text{m}$

FWHM (X') = 8.6  $\mu\text{rad}$  FWHM (Z') = 4.2  $\mu\text{rad}$

FWHM (X) = 172  $\mu\text{m}$  FWHM (Z) = 83  $\mu\text{m}$

FWHM (X') = 5.2  $\mu\text{rad}$  FWHM (Z') = 0.1  $\mu\text{rad}$



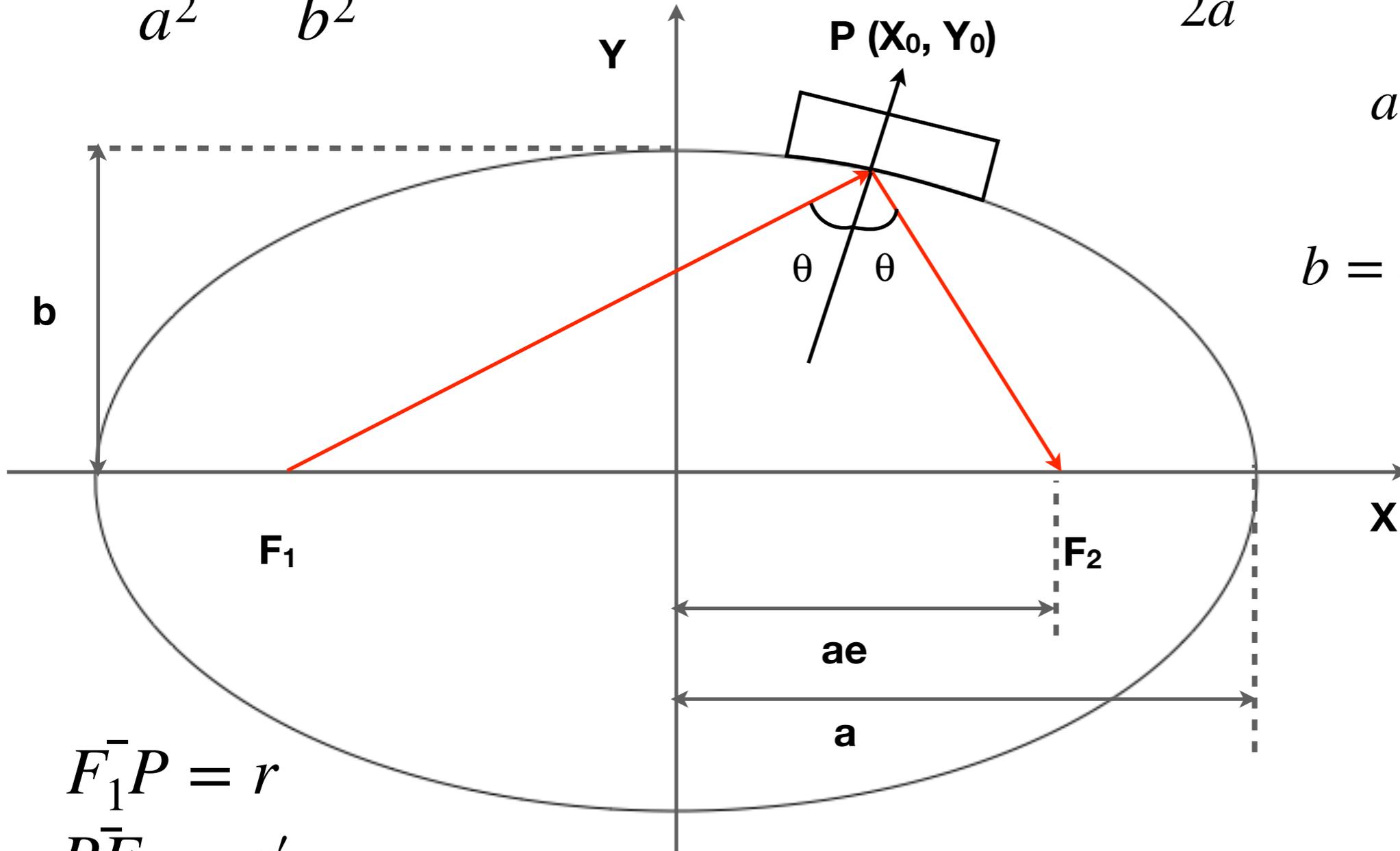
# Ellipsoidal mirror

$$\frac{X^2}{a^2} + \frac{Y^2}{b^2} = 1$$

$$e = \frac{1}{2a} \sqrt{r^2 + r'^2 - 2rr' \cos 2\theta}$$

$$a = \frac{(r + r')}{2}$$

$$b = \sqrt{a^2 (1 - e^2)}$$



$$\overline{F_1 P} = r$$

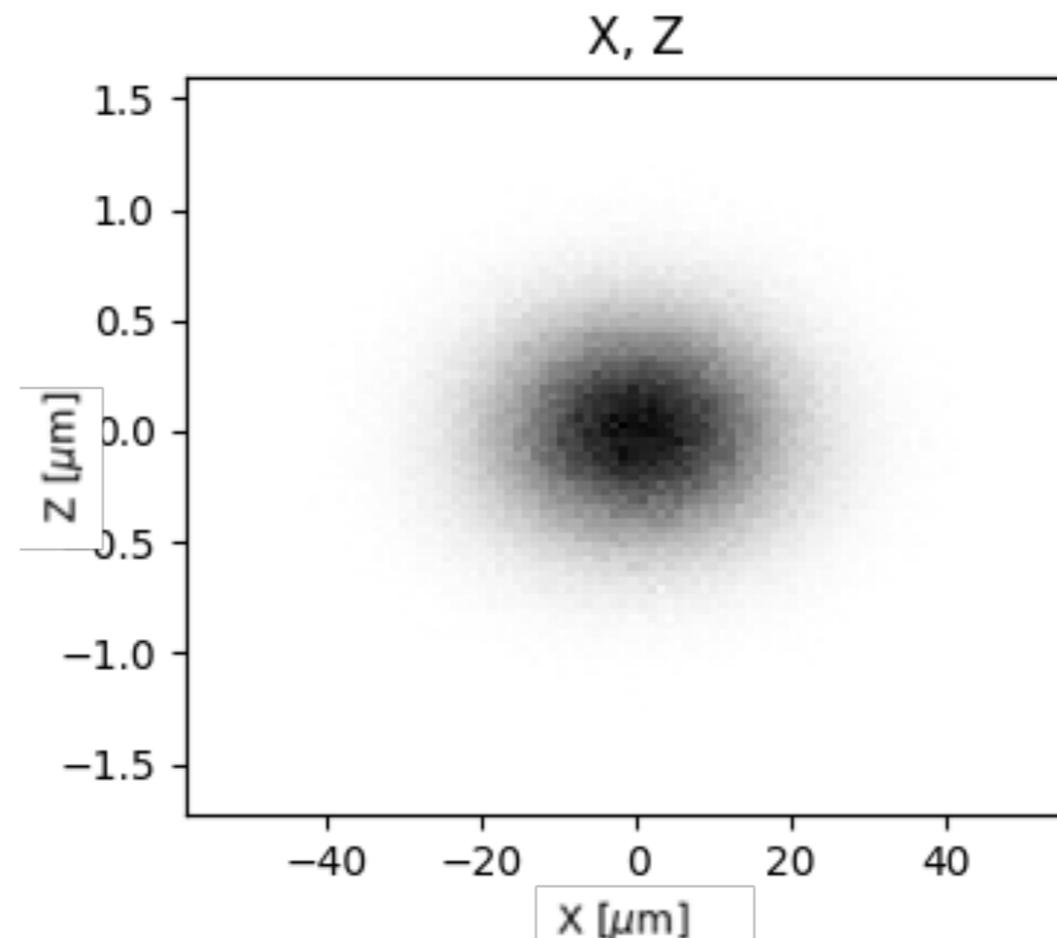
$$\overline{P F_2} = r'$$

# Ellipsoidal mirror, $r = 20$ m, $r' = 5$ m, $\theta = 88^\circ$

$$a = 12.5 \text{ m}, b = 0.349 \text{ m}, e = 0.999610$$

Our source dimensions are: FWHM (X)=105  $\mu\text{m}$  FWHM(Z)=3  $\mu\text{m}$

$$M = \frac{r'}{r} = 0.25 \quad \text{i.e. we expect a focus of } \sim 26 \times 0.75 \text{ } \mu\text{m (FWHM)}$$



$$\text{FWHM (X)} = 26 \text{ } \mu\text{m} \quad \text{FWHM(Z)} = 0.7 \text{ } \mu\text{m}$$



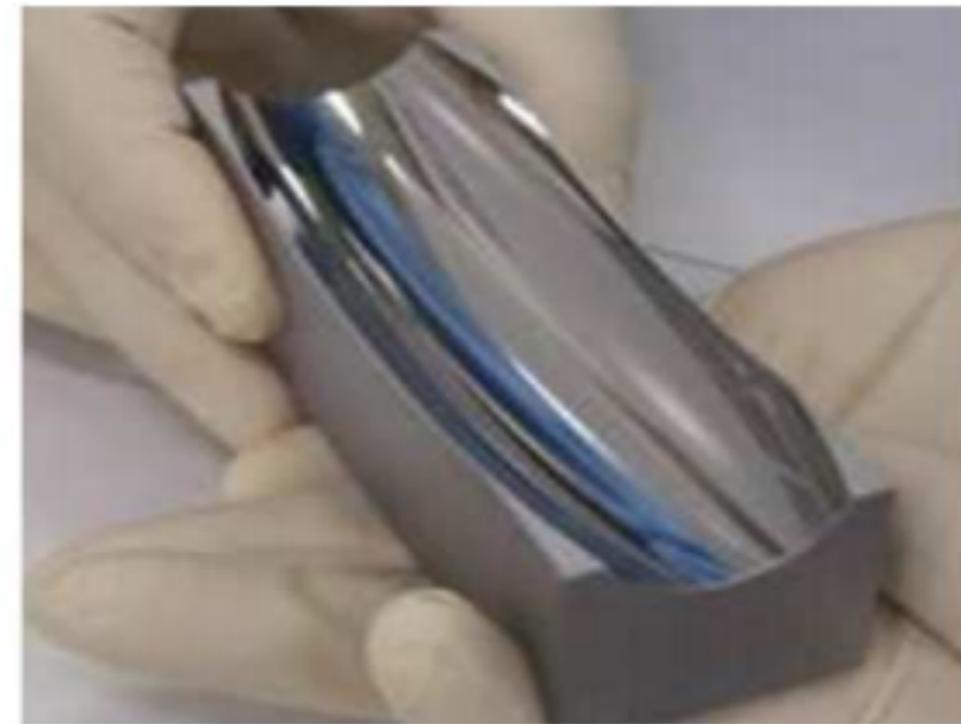
# WARNING!

All the simulations above are for educational purposes!

- Reflectivity set to 1, and independent of energy
- Ideal source
- No mirror errors (roughness, figure errors, etc)



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<http://www.esrf.eu/home/UsersAndScience/Experiments/CBS/ID09/OpticsHutch/mirror.html>

[http://www.crystal-scientific.com/mirror\\_plano.html](http://www.crystal-scientific.com/mirror_plano.html)

R. Radhakirshnan et al,  
DOI 10.1149/07711.1255ecst





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# Diffraction elements

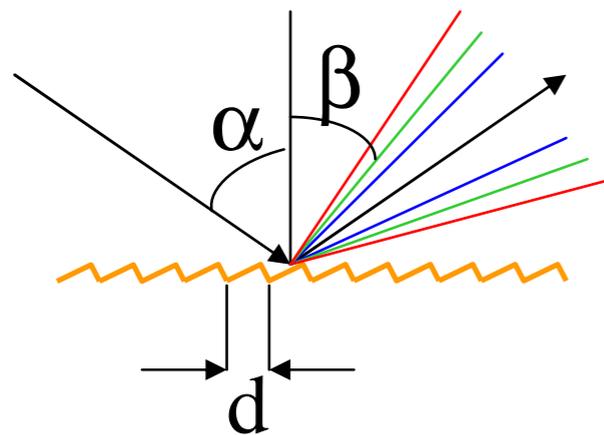
Gratings  
Crystals  
Multilayers  
Zone Plates

Monochromatization  
Focussing

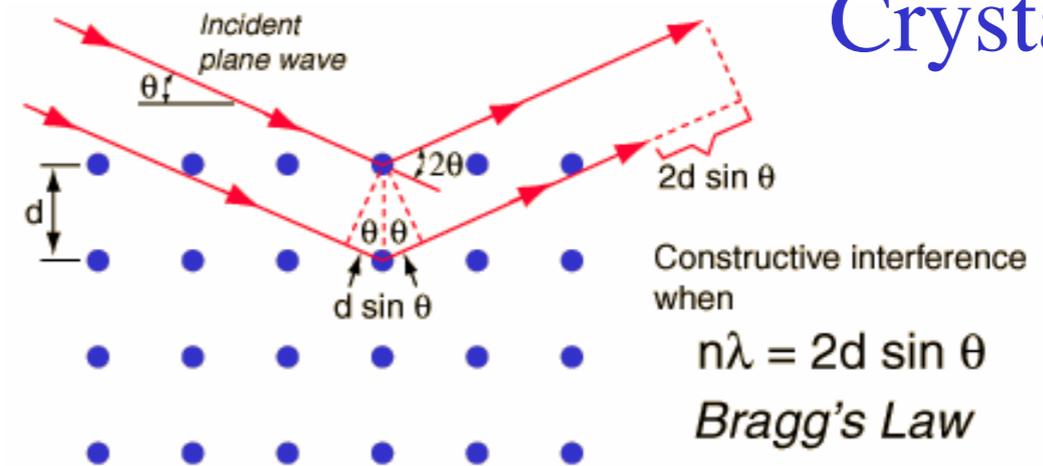
# Usage: Overwhelmingly for monochromatization

Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray
------------	------	---------	------	------------	------------

Micro wave	I.R.	Visible	U.V.	Soft X-ray	Hard X-ray
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Grating

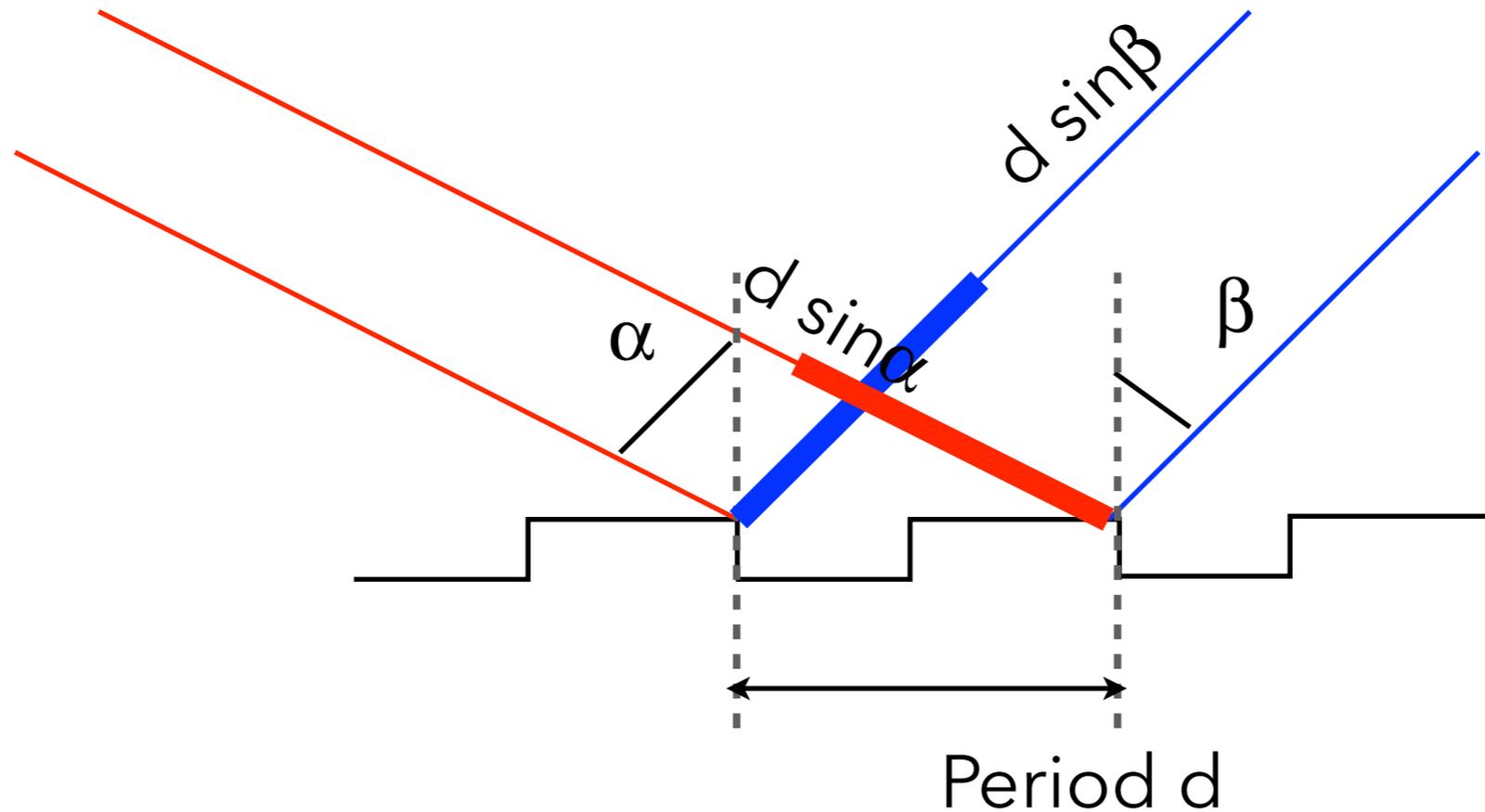


Crystal



# Diffraction gratings

Artificial periodic structure, with a precisely defined period  $d$ .



Grating equation

$$\sin \alpha + \sin \beta = L m \lambda$$

$m$  is the diffraction order

$\alpha$  and  $\beta$  have opposite signs if on opposite side of the surface normal

Line density

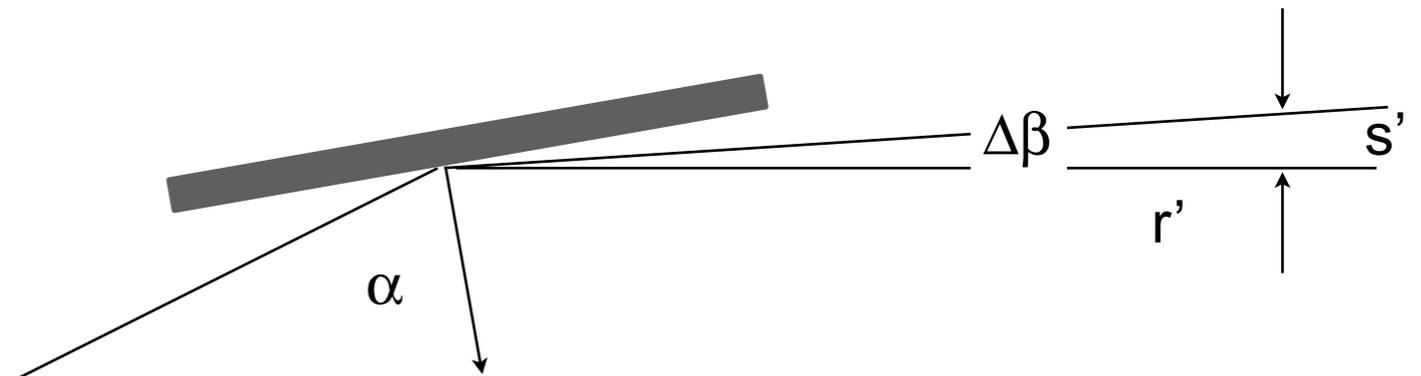
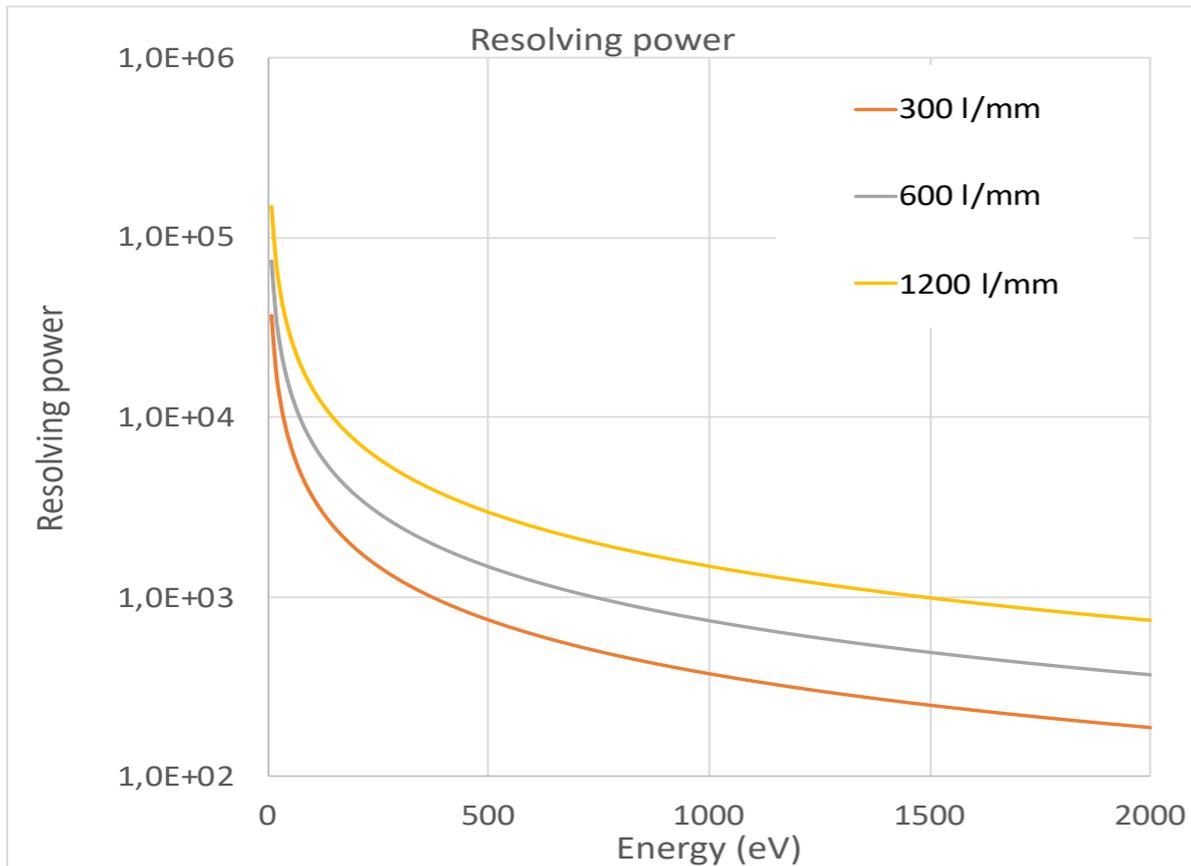
$$L = \frac{1}{d}$$



# Grating resolving power

Angular dispersion of a grating with line density  $L$ : 
$$\Delta\lambda = \frac{s' \cos\beta}{Lmr'}$$

Resolving power  $R$ : 
$$R = \frac{E}{\Delta E} = \frac{\lambda}{\Delta\lambda} = \frac{\lambda Lmr'}{s' \cos\beta}$$

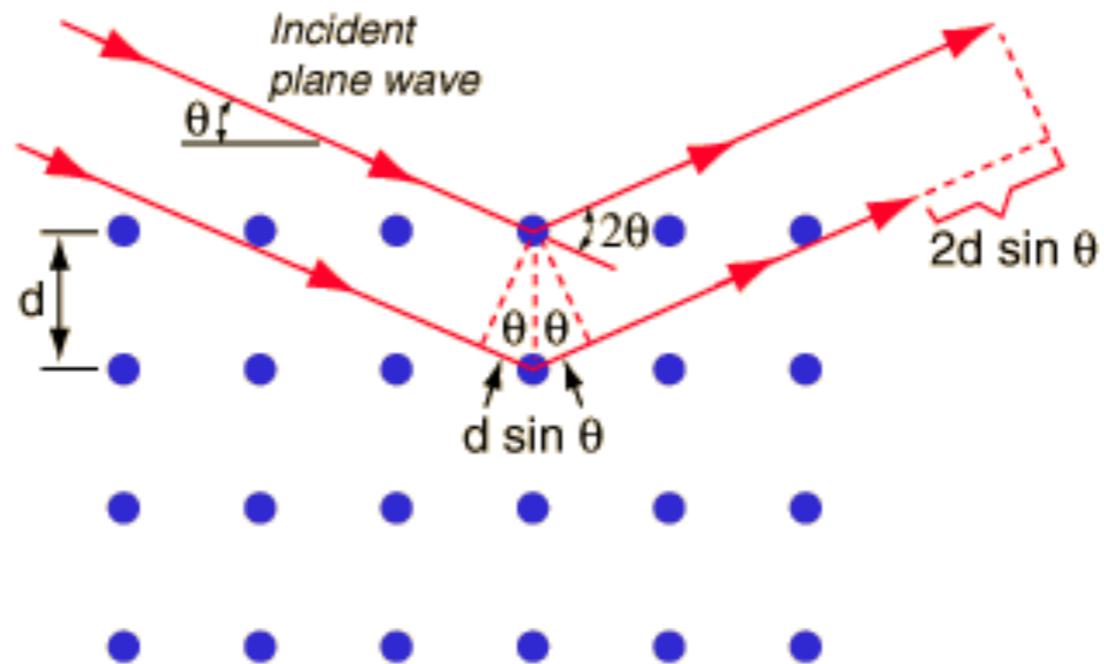


If  $R=1000$ , @ 100eV:  
 $\Delta E = 100\text{meV}$



# Crystals

Based on Bragg's law:  $2d\sin\theta = m\lambda$



Since  $\sin\theta \leq 1$ ,  $\lambda \leq \lambda_{MAX} (E \geq E_{MIN}) = 2d$

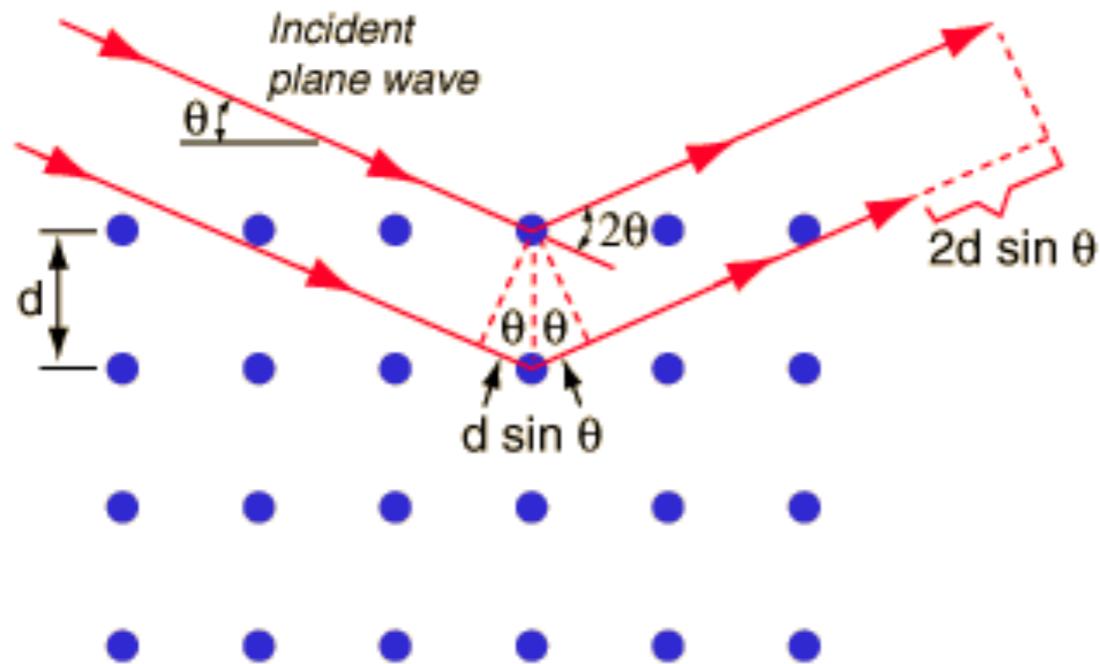
Si(111):  $d=3.13 \text{ \AA}$  ( $E_{MIN} \sim 2\text{keV}$ )

Si(311):  $d=1.64 \text{ \AA}$  ( $E_{MIN} \sim 3.8\text{keV}$ )

InSb(111):  $d=3.74 \text{ \AA}$  ( $E_{MIN} \sim 1.7\text{keV}$ )



# Crystals' resolving power



$$\frac{\Delta E}{E} = \frac{\Delta \lambda}{\lambda} = \Delta \theta \frac{\cos \theta}{\sin \theta}$$

Angular spread

Where does  $\Delta \theta$  come from?

$\Delta \theta_{beam}$

Angular divergence of the incoming beam \*

$\omega_{crystal}$

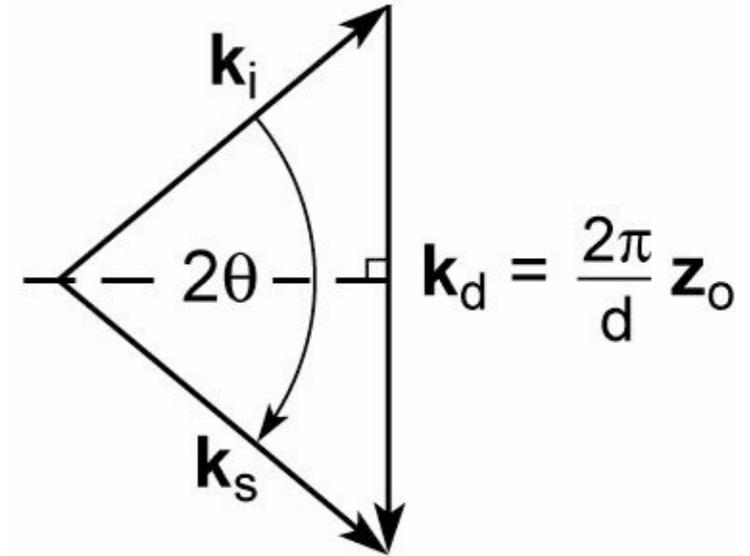
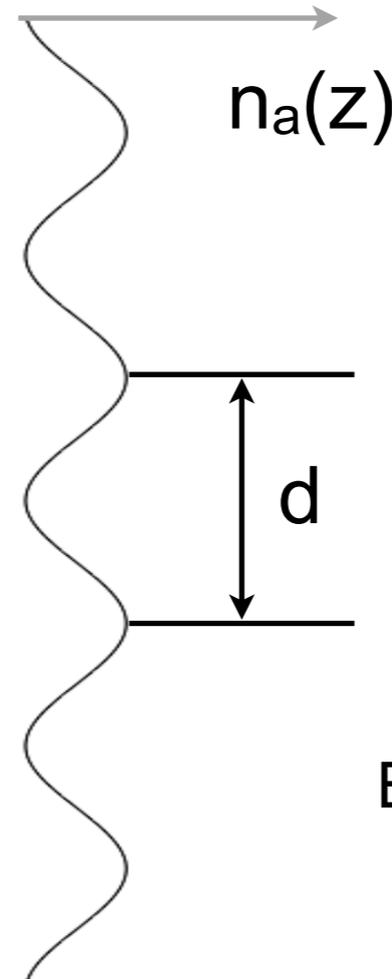
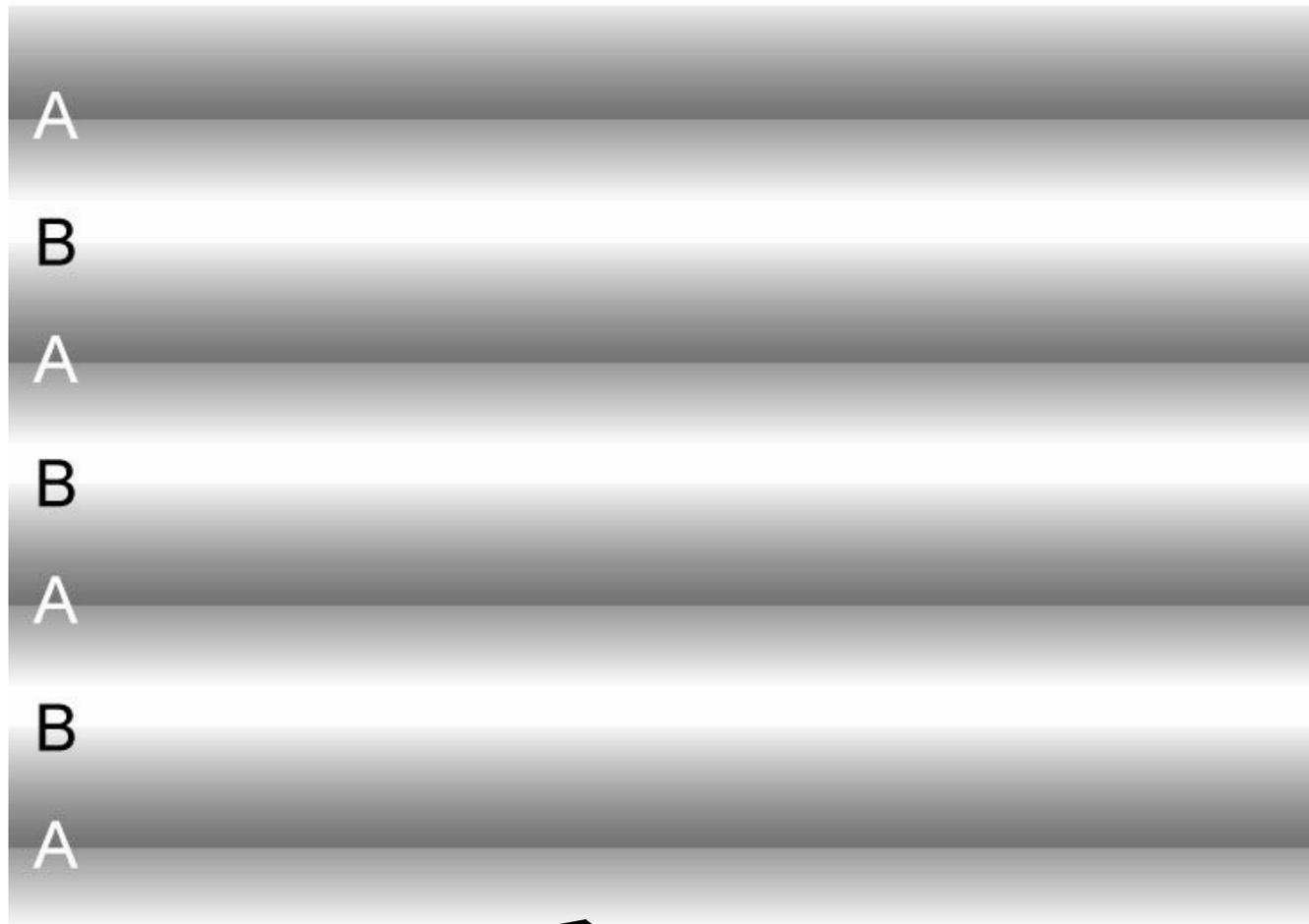
Intrinsic width of Bragg reflection, the Darwin curve

\* more on this later...





# Multi-layer mirrors



$$\omega_s = \omega_i + \omega_d$$

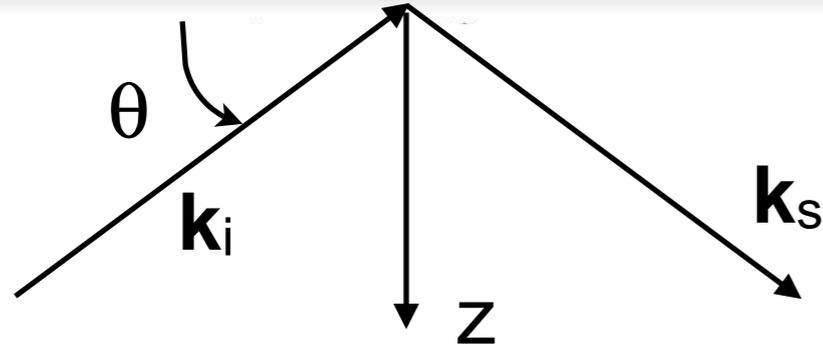
$$\mathbf{k}_s = \mathbf{k}_i + \mathbf{k}_d$$

But  $\omega_d = 0$ , therefore:

$$|\mathbf{k}_s| = |\mathbf{k}_i| = 2\pi/\lambda$$

$$\sin\theta = \frac{k_d/2}{k_i}$$

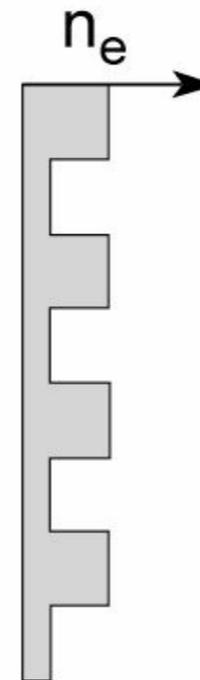
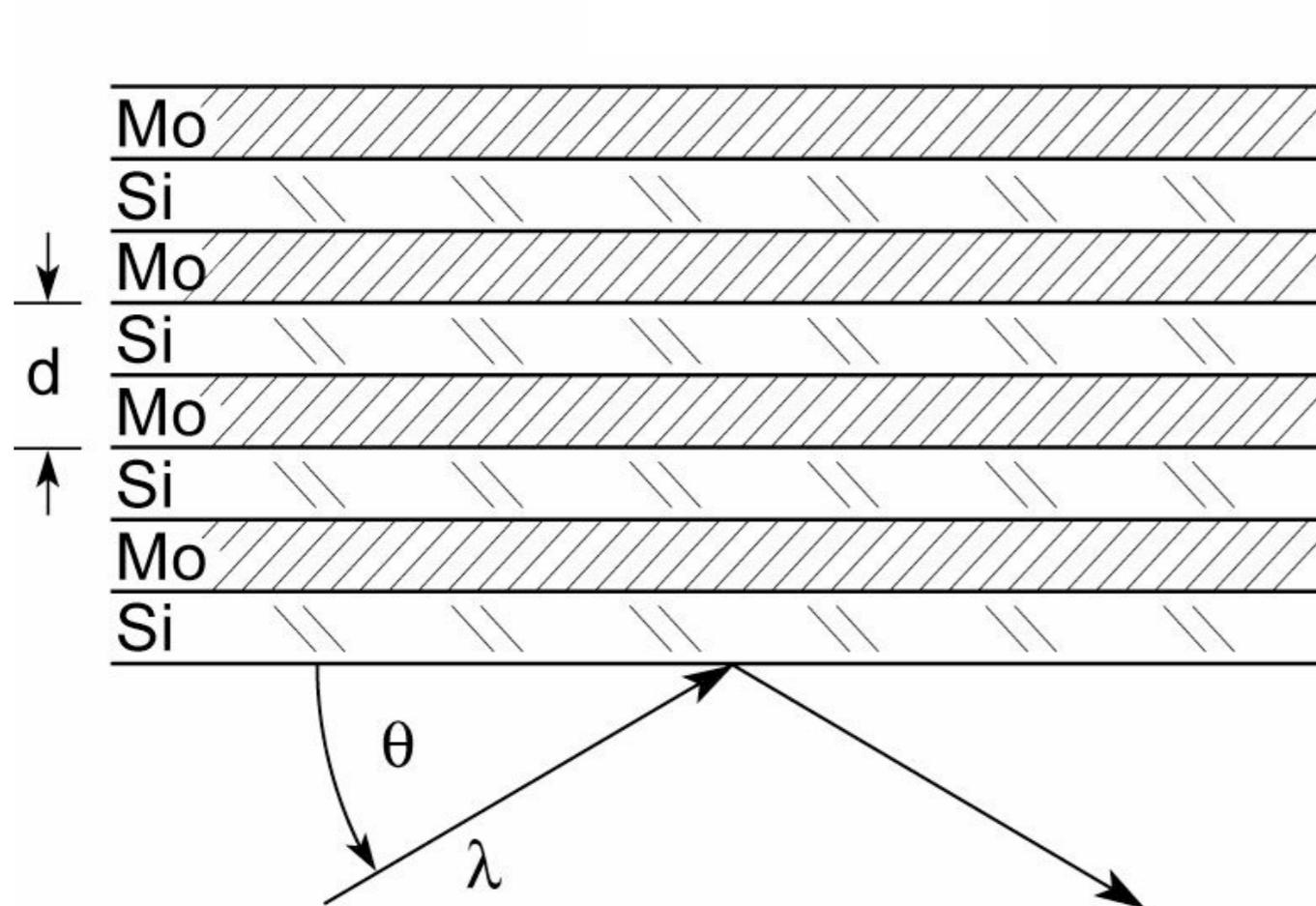
$$\lambda = 2d\sin\theta$$





# Multi-layer mirrors

What if  $n_a(z)$  is still periodic, but not a simple sinusoid?



$$m\lambda = 2d\sin\theta$$

If  $\theta = \pi/2$ , and  $m=1$ :

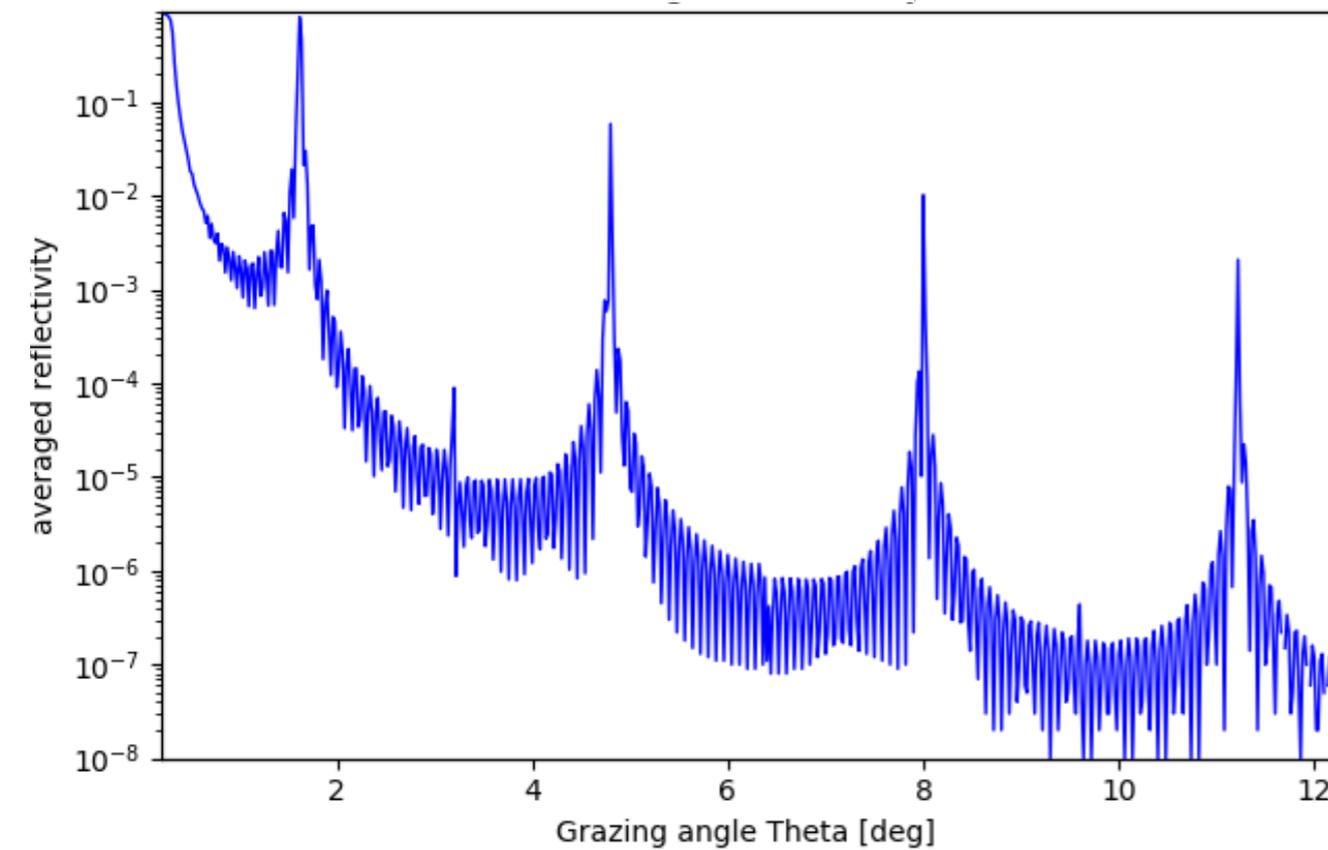
$$\lambda = 2d$$



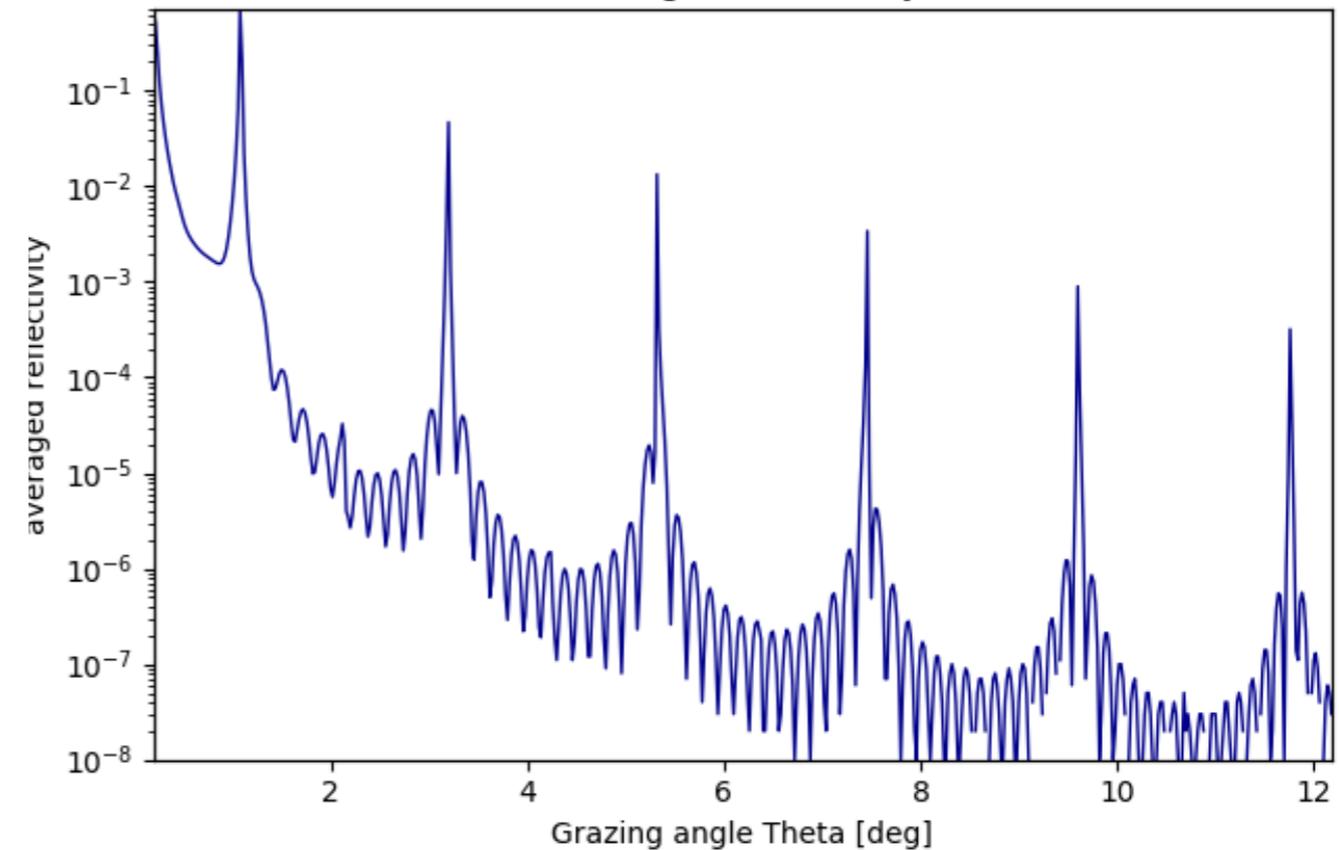
# Multi-layer mirrors

W/C,  $d=22.3 \text{ \AA}$ ,  $\Gamma=0.5$ ,  $N= 100$

E=10keV



E=15keV





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# Monochromators



# The need for collimated illumination

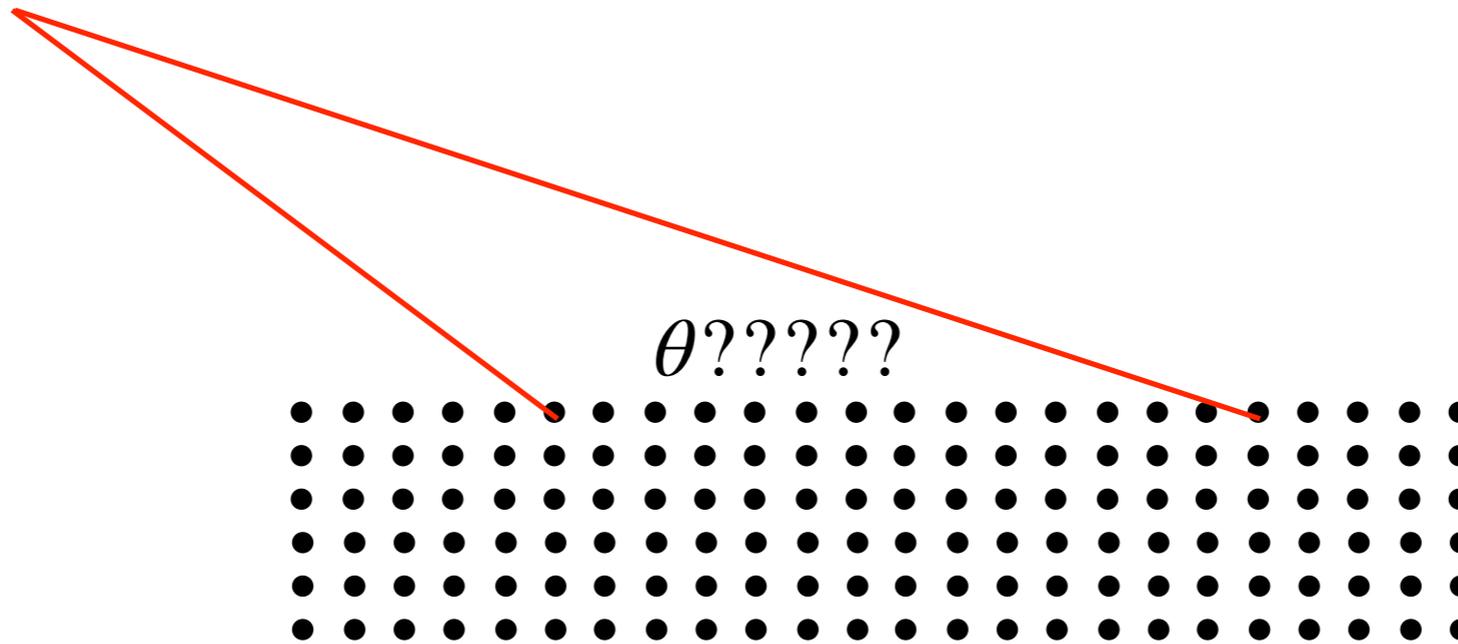
Crystals Energy resolution:

$$\frac{\Delta E}{E} = \frac{\Delta \lambda}{\lambda} = \boxed{\Delta \theta} \frac{\cos \theta}{\sin \theta}$$

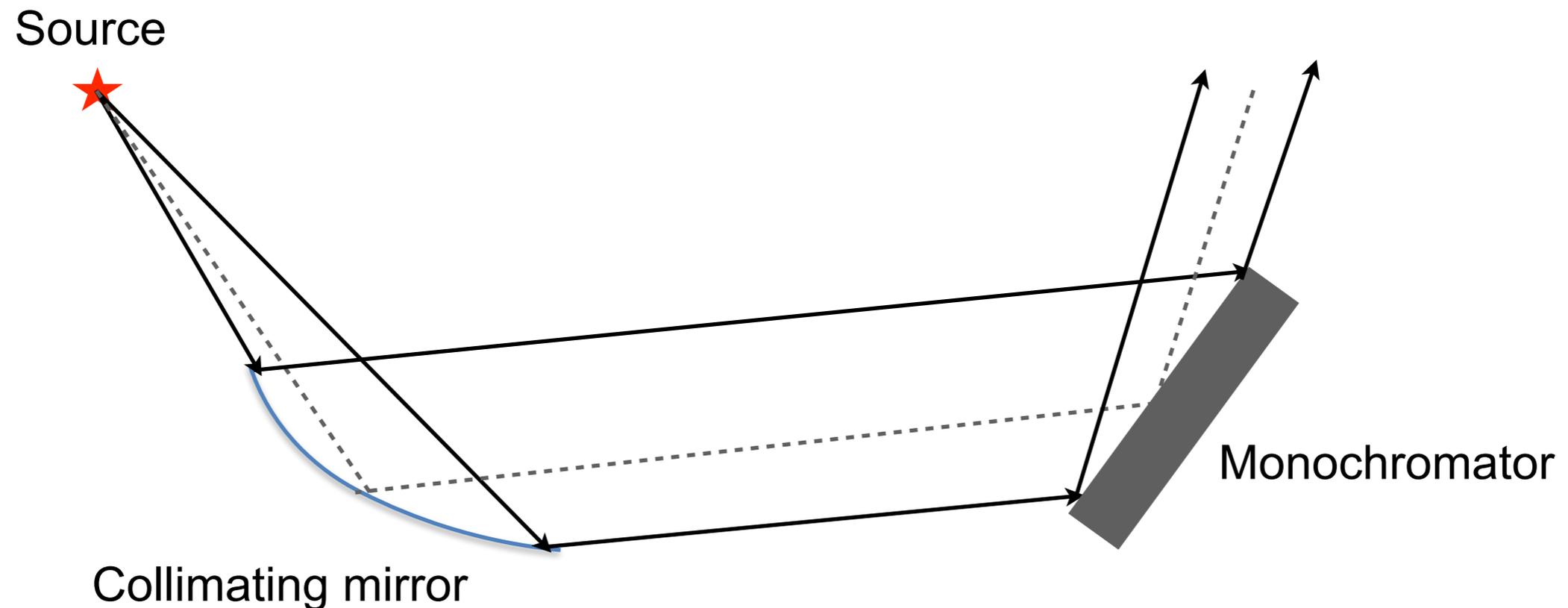
Same for multilayers

Gratings

$$\frac{\Delta E}{E} = \frac{\Delta \lambda}{\lambda} = \frac{\cos \beta}{\lambda L m r'} \Delta \beta$$



## Collimating mirror before monochromator



Mirror calculated setting virtual source distance ( $r$ ) very far ( $\sim 100$ s m) \*

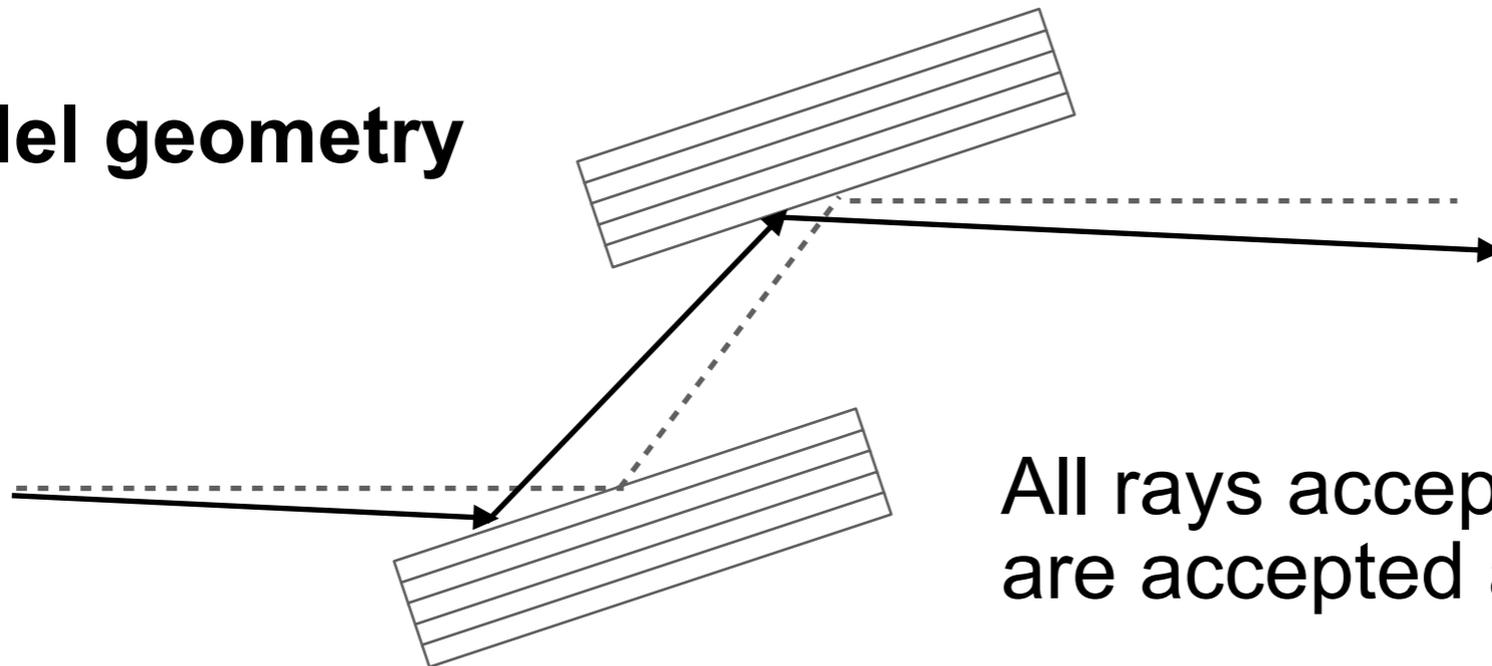
\* more on this later...

# Double Crystal Monocromator (DCM)

$$2d\sin\theta = m\lambda$$

$$\frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda} = \Delta\theta \frac{\cos\theta}{\sin\theta}$$

**Parallel geometry**

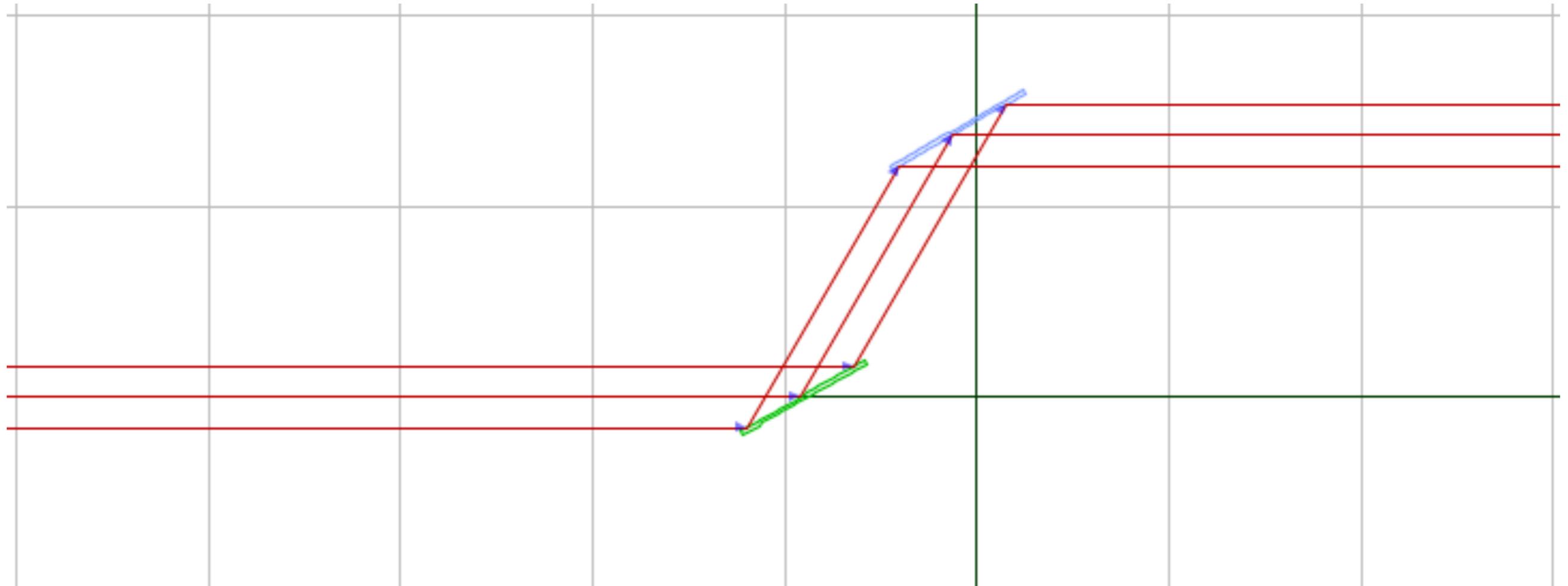


All rays accepted by first crystal are accepted also by the second

Second crystal acts merely as a mirror

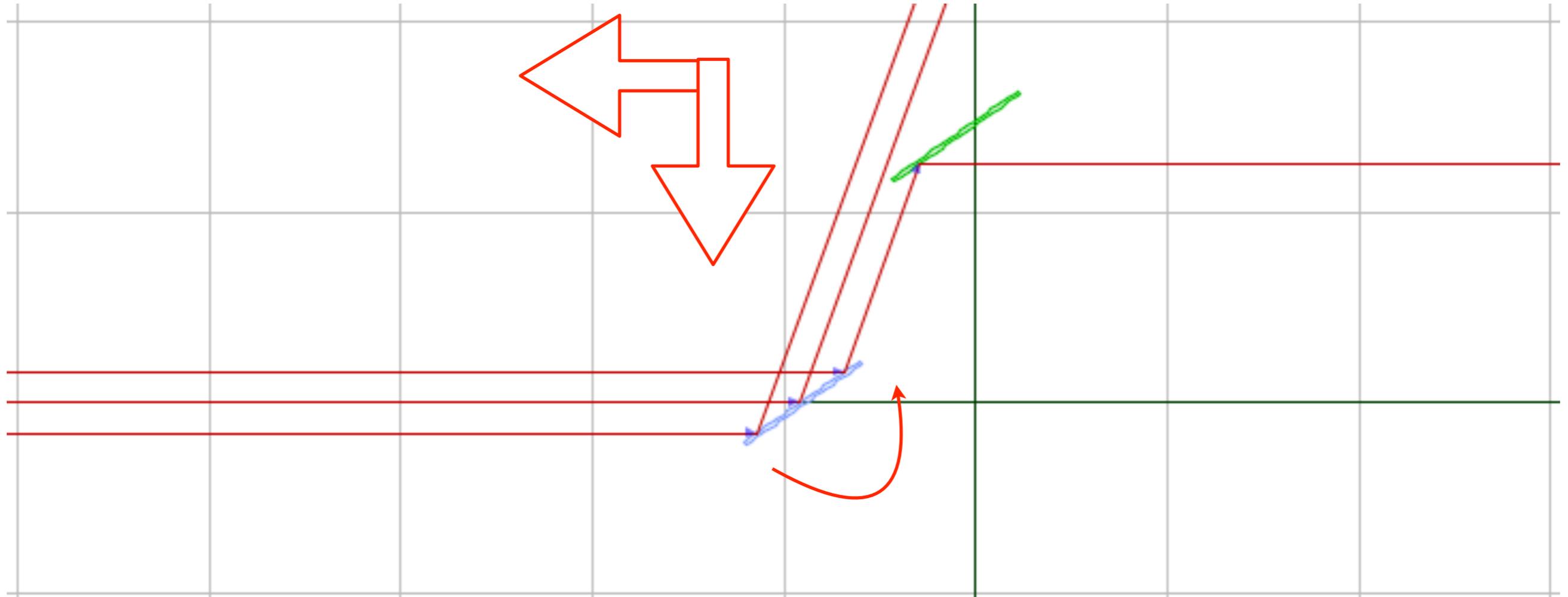


# DCM in parallel configuration



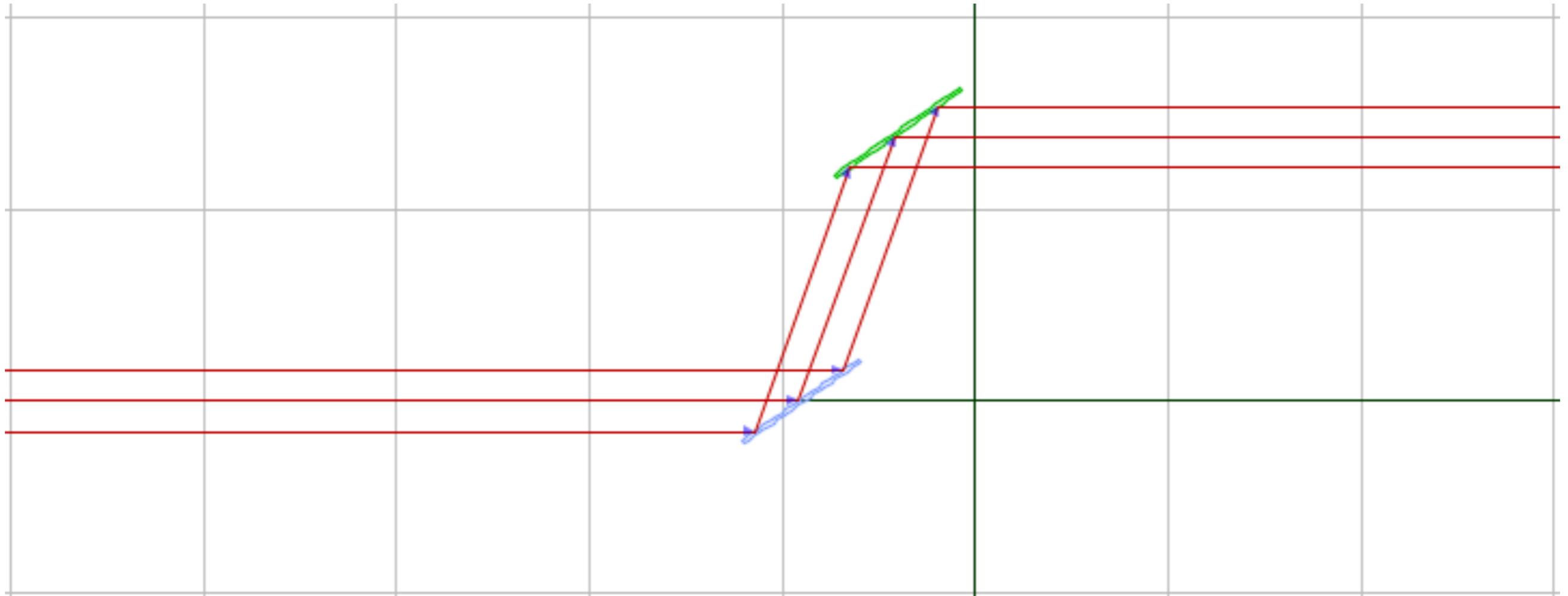


# DCM in parallel configuration



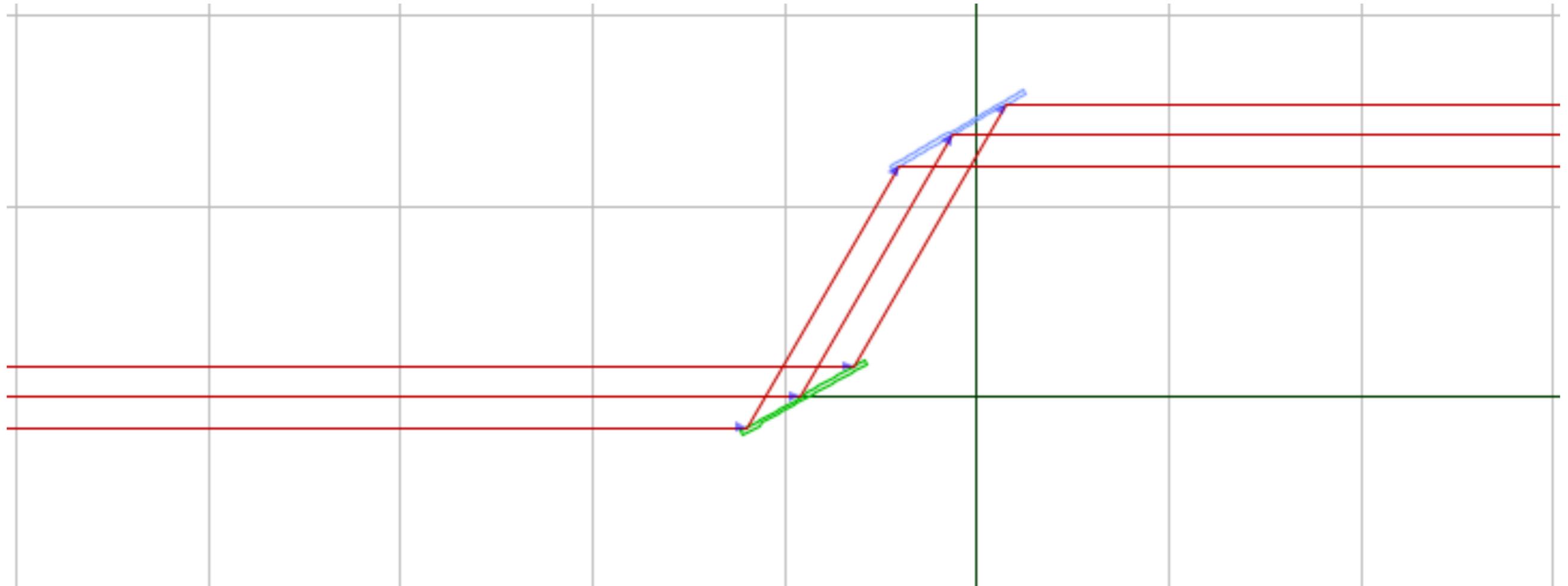


# DCM in parallel configuration



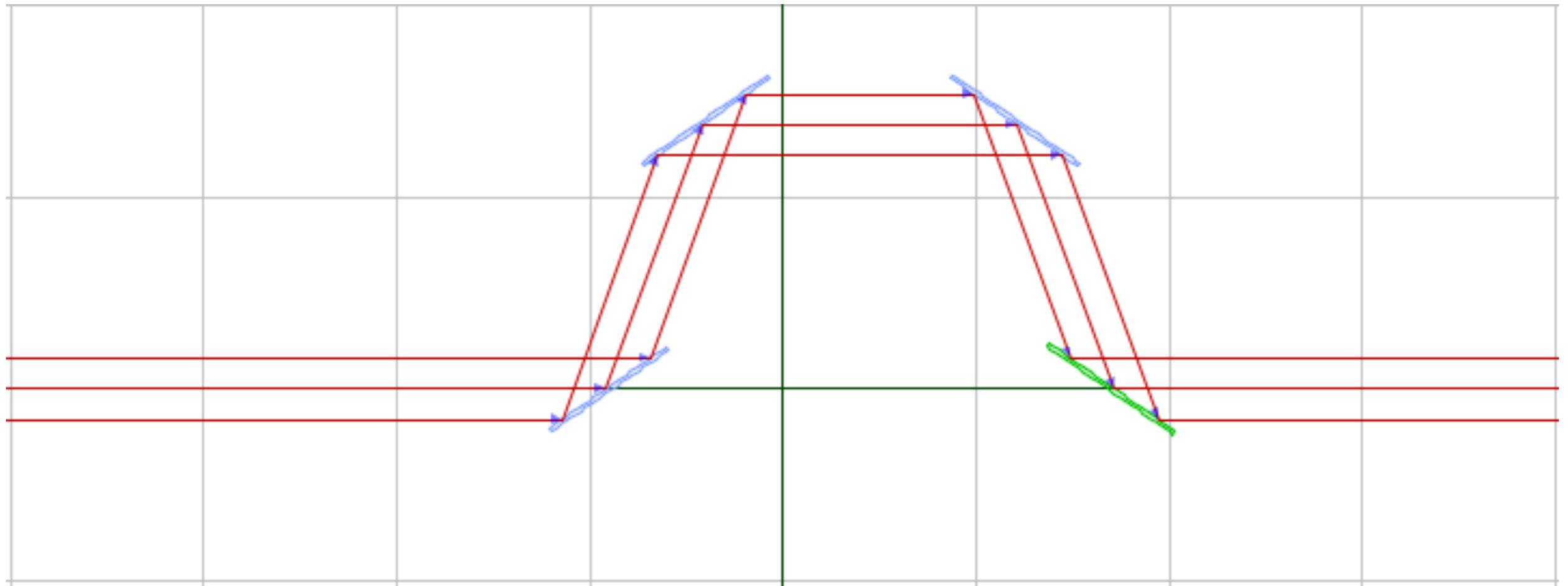


# DCM in parallel configuration

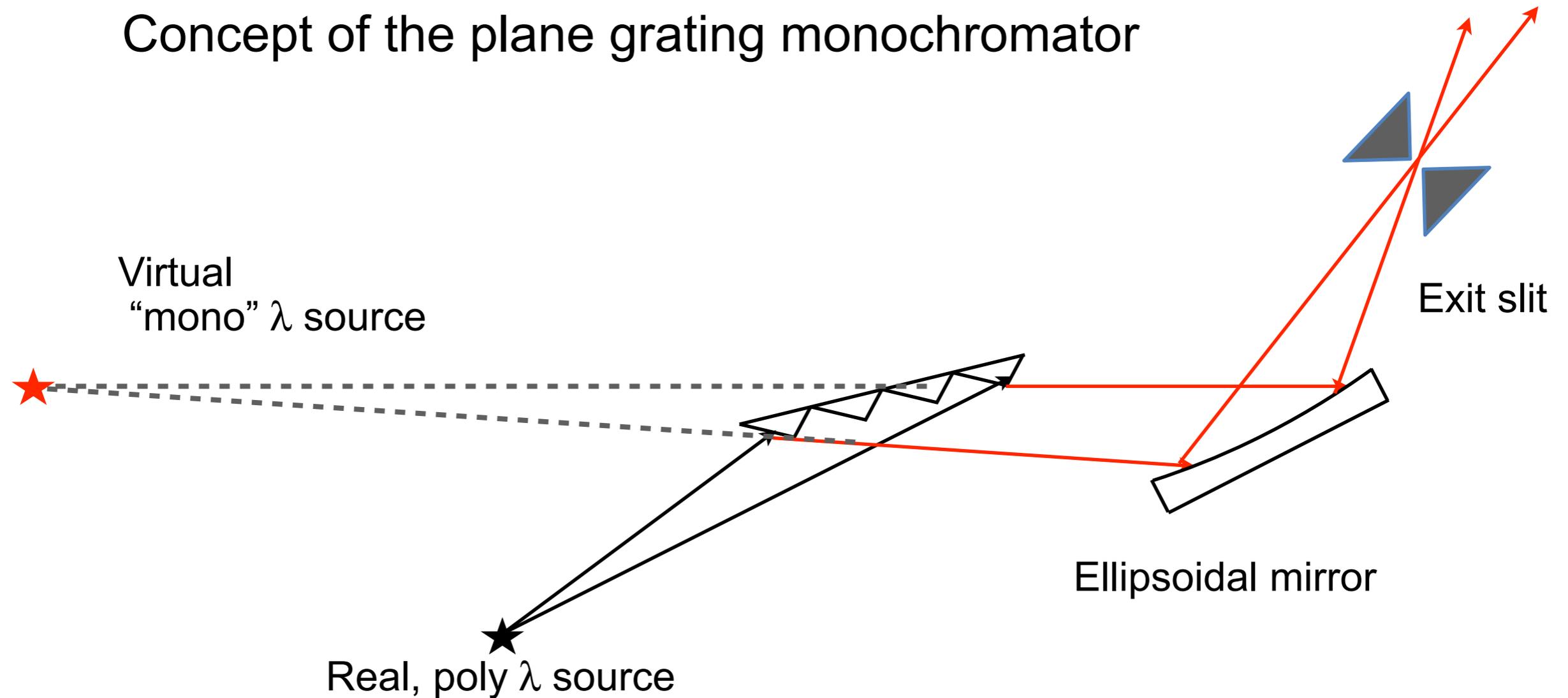




# 2 X DCM in parallel configuration



## Concept of the plane grating monochromator

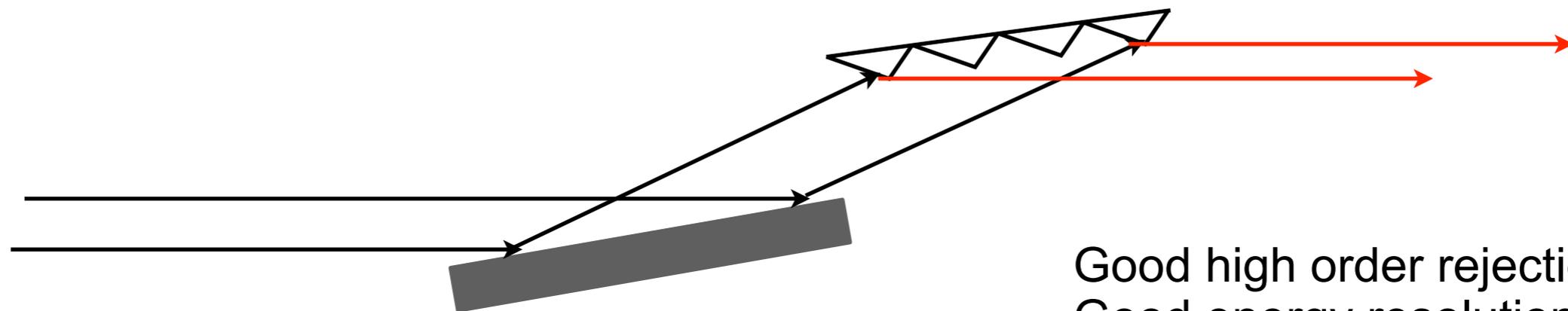
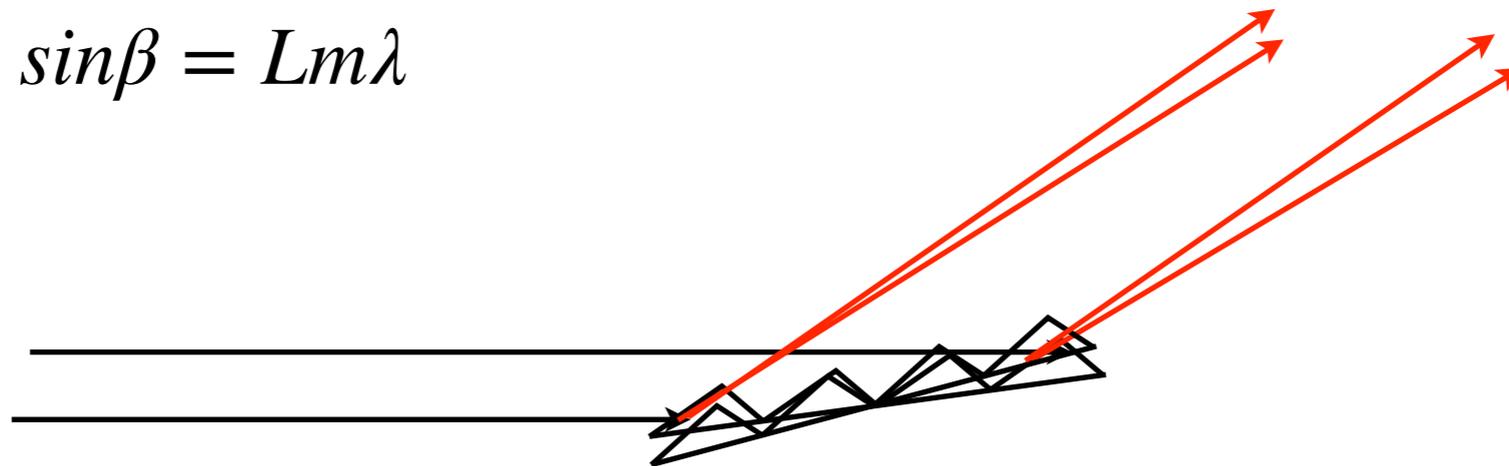


H. Petersen. O. Communication, vol. 40, no. 6. 1982, pp. 402–406.



# Plane grating monochromator

$$\sin\alpha + \sin\beta = Lm\lambda$$



Plane pre-mirror

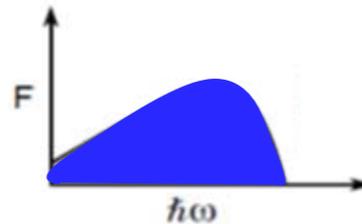
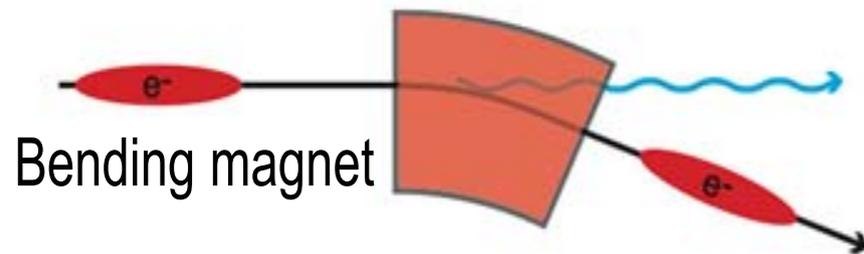
Good high order rejection  
Good energy resolution  
Fixed exit slit

# Something to keep in mind: thermal loads!

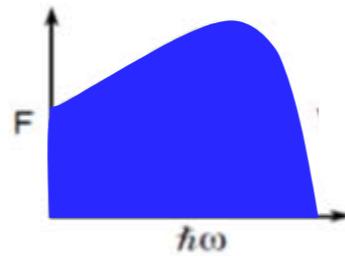
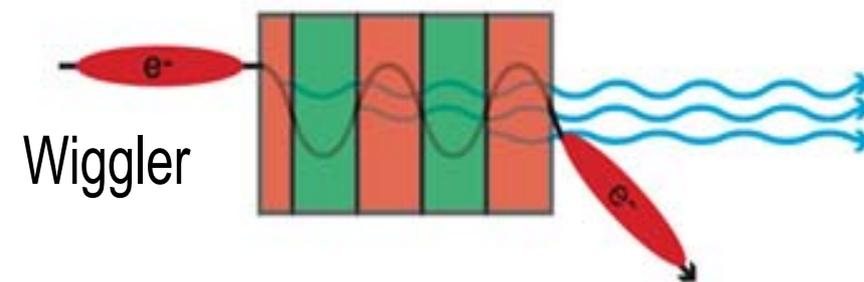
Source

Spectrum

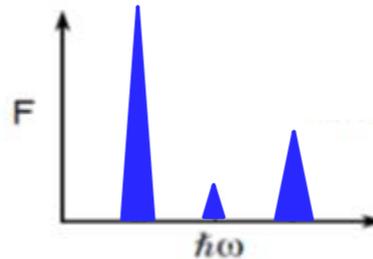
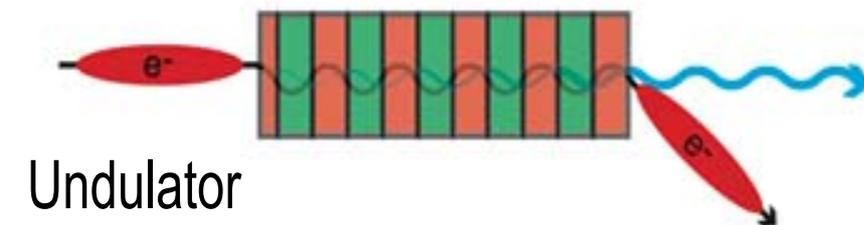
Typical (total) power emitted



~ 100's W



~ few kW

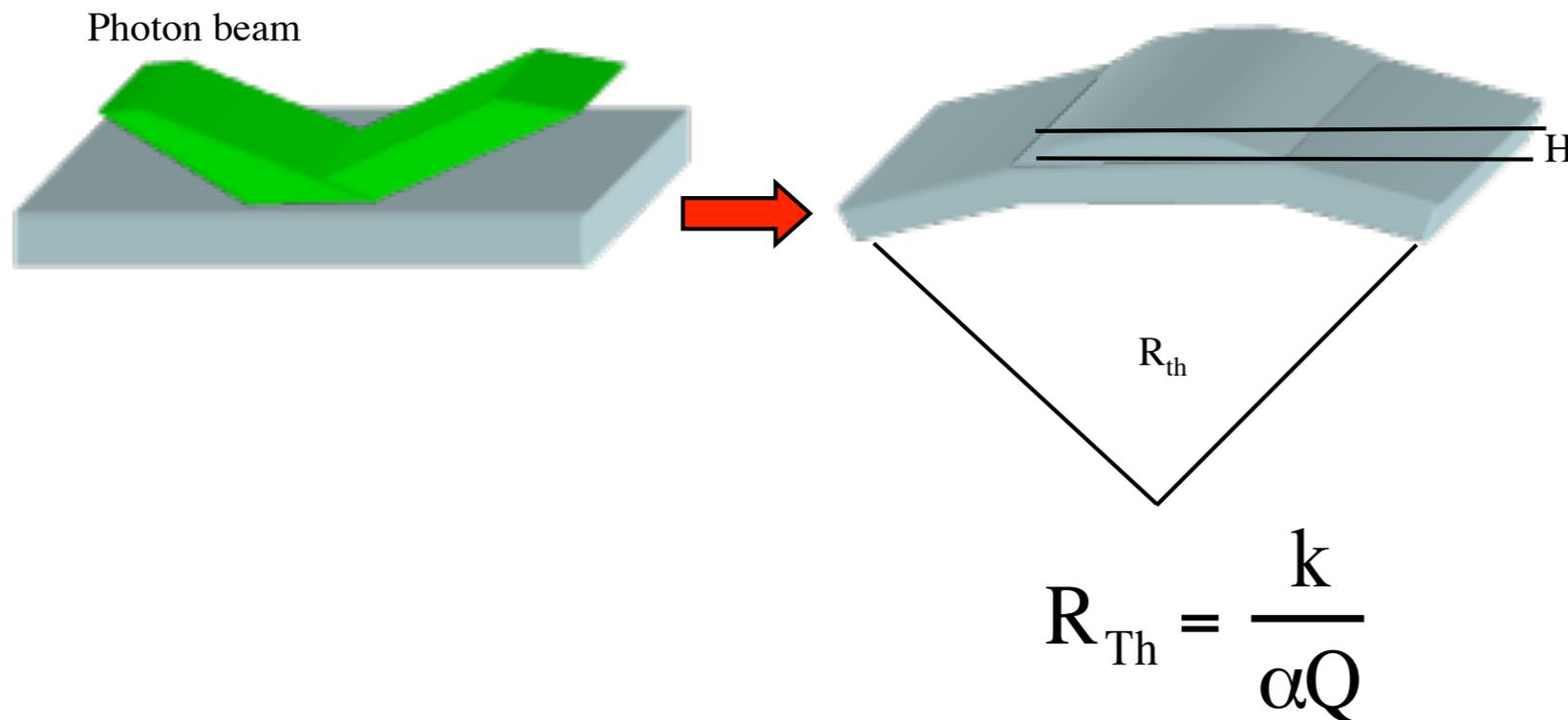


~ 0.1 - 1 kW

**From first mono element standpoint: kW in, NOTHING out!**

# Thermal load issues (besides melting)

Q is the incoming power, D the mirror/crystal thickness



$$H = \alpha \left( \frac{QD^2}{2k} + \frac{QD}{h} \right)$$

For H<sub>2</sub>O - cooled Si:

$$\alpha = 4.2 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1}$$

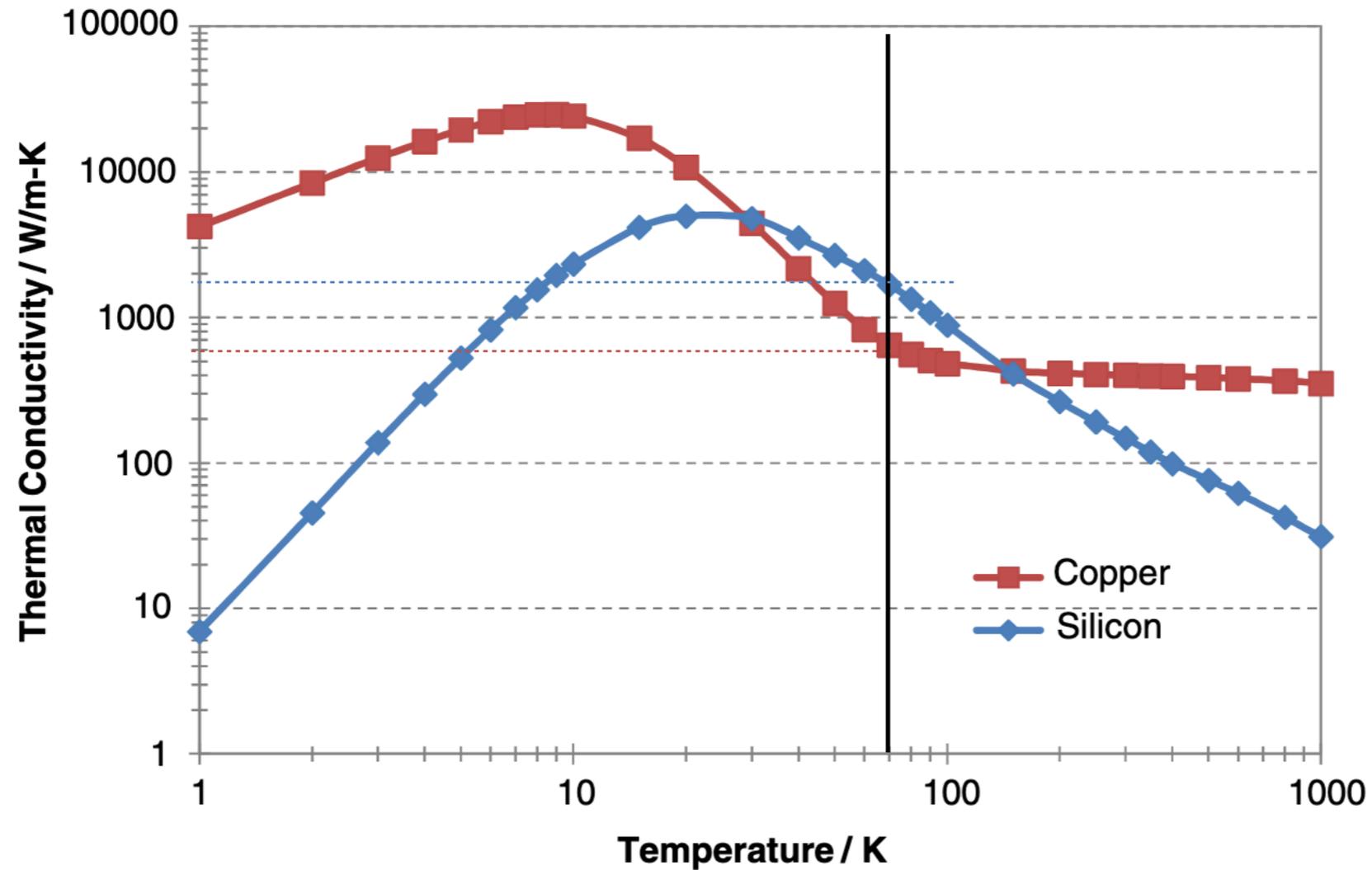
$$k = 1.2 \text{ W/cm } ^\circ\text{C}$$

$$h = 1 \text{ W/cm}^2$$

Smither, Nucl. Instr. Meth. in Phys. Res. **A291** (1990)



# Silicon vs Copper Thermal conductivity



M White *et al* 2014 *Metrologia* 51 S245



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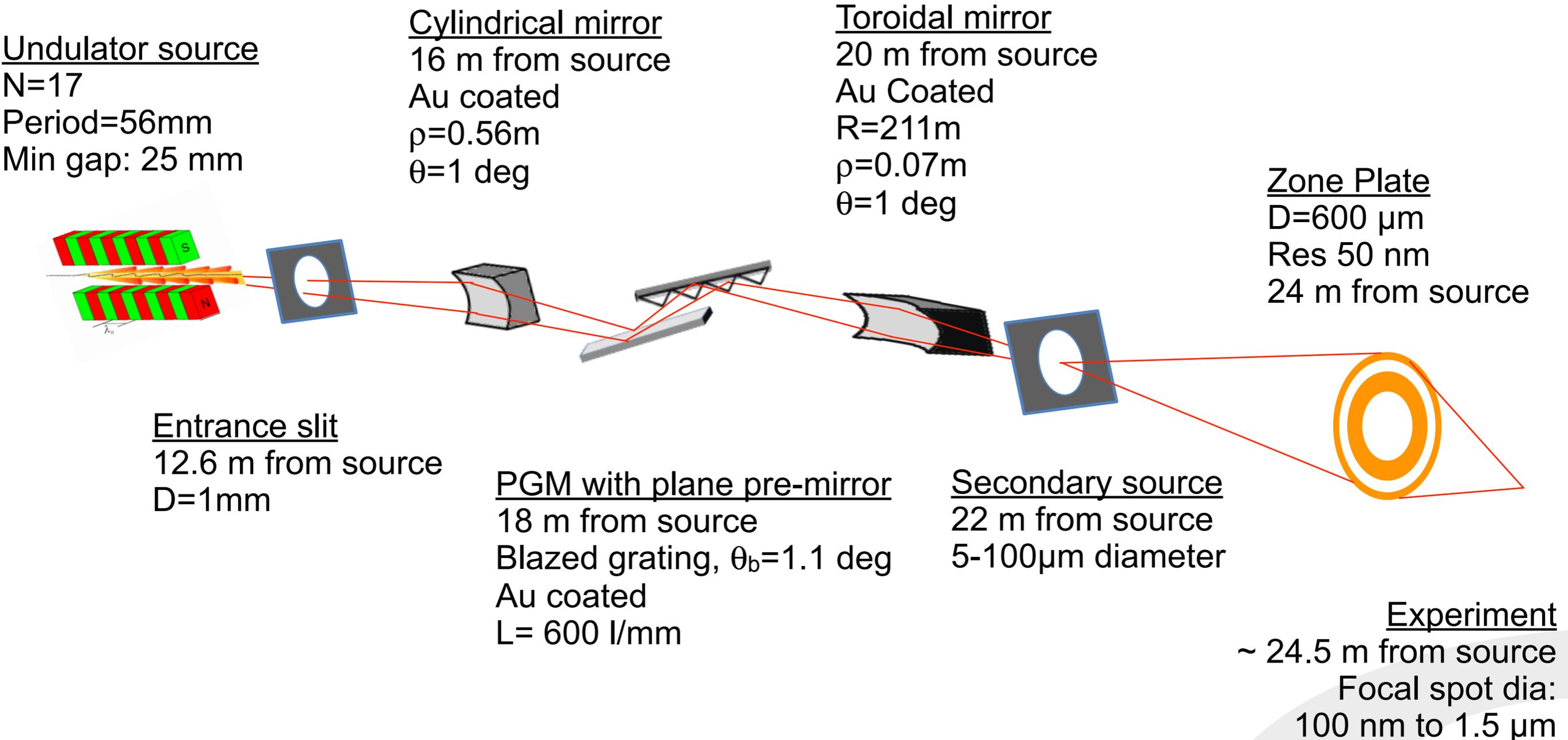
**... finally a couple of examples**



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# TwinMic Beamline @ Elettra

Photon energy: 400eV to 2 keV  
X-ray microscopy and microFluorescence





Elettra  
Sincrotrone  
Trieste

# Diffraction Beamline @ Elettra

Photon energy: 4 to 21 keV

## Cylindrical mirror for vertical collimation

22 m from source  
Pt Coated  
R=14km  
 $\theta=0.172$  deg  
Length: 1.4 m

## Toroidal focussing mirror

28 m from source  
Sagittally cylindrical, bendable  
R=9km (5km to  $\infty$ )  
 $\rho=0.055$  m

## Experiment

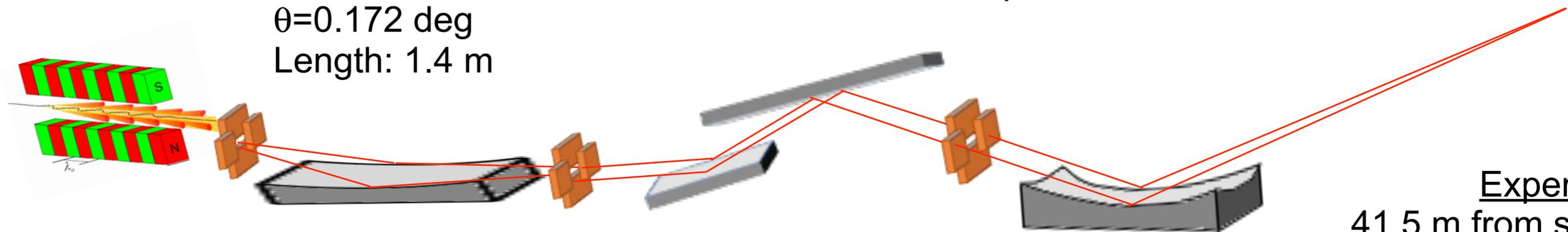
41.5 m from source  
Focal spot:  
0.7 x 0.2 mm<sup>2</sup>  
 $\Delta E/E \sim 4000$

## Double crystal mono

24 m from source  
Si(111),  $\omega_s=25$   $\mu$ rad @ 8keV

## Multi-pole wiggler

N=54, 1.5T mag field  
Period=140mm  
Critical Energy: 5.8keV @ 2.4GeV  
5kW total power @ 140 mA





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# Thank you!

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