Innovation in Optical Design – a short history

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David Shafer Optical Design

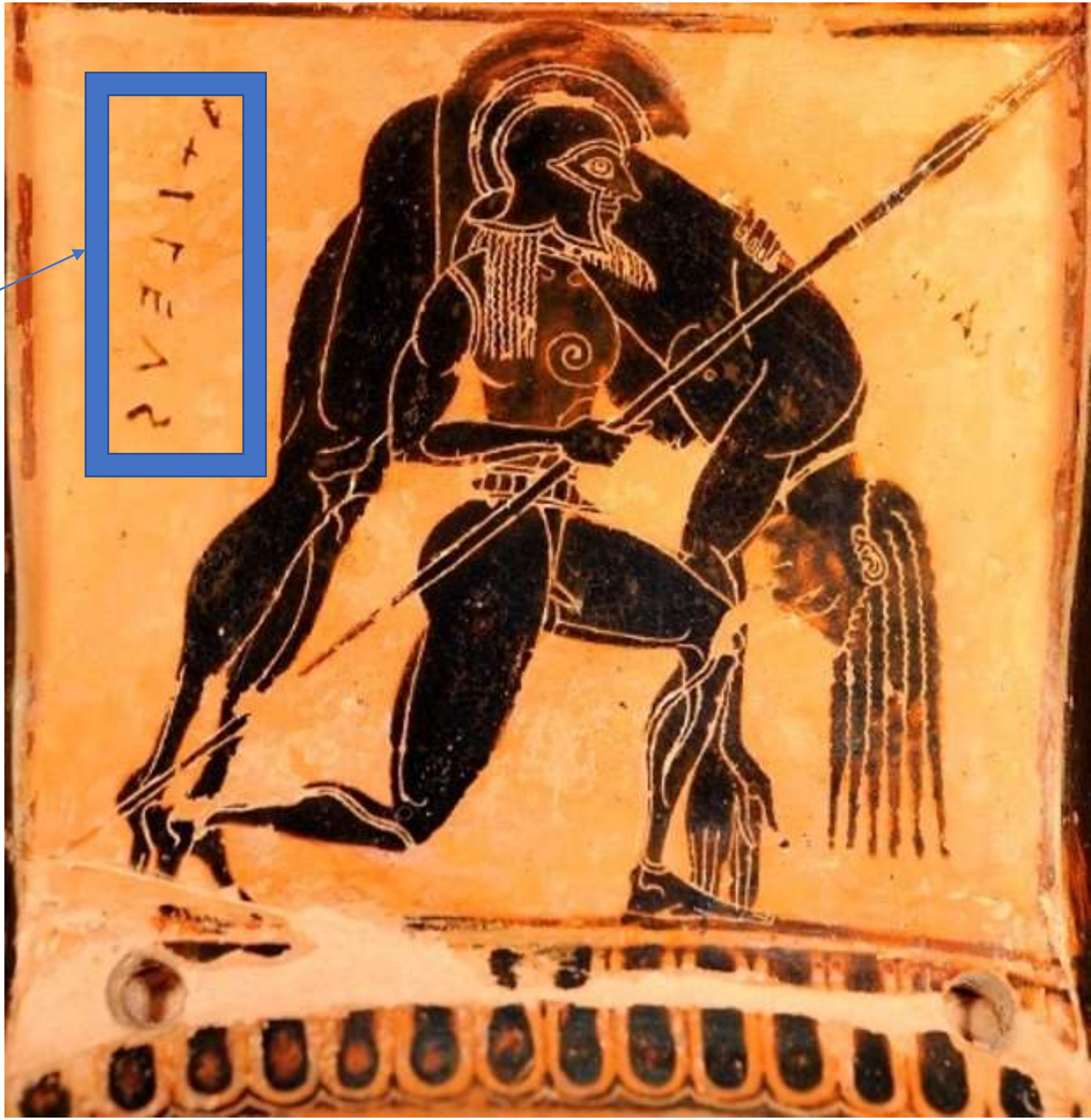
"Thinking outside the box" is usually regarded as a metaphor, but some innovation consists of actually thinking of a different way to view a particular spatial region, such as a box.

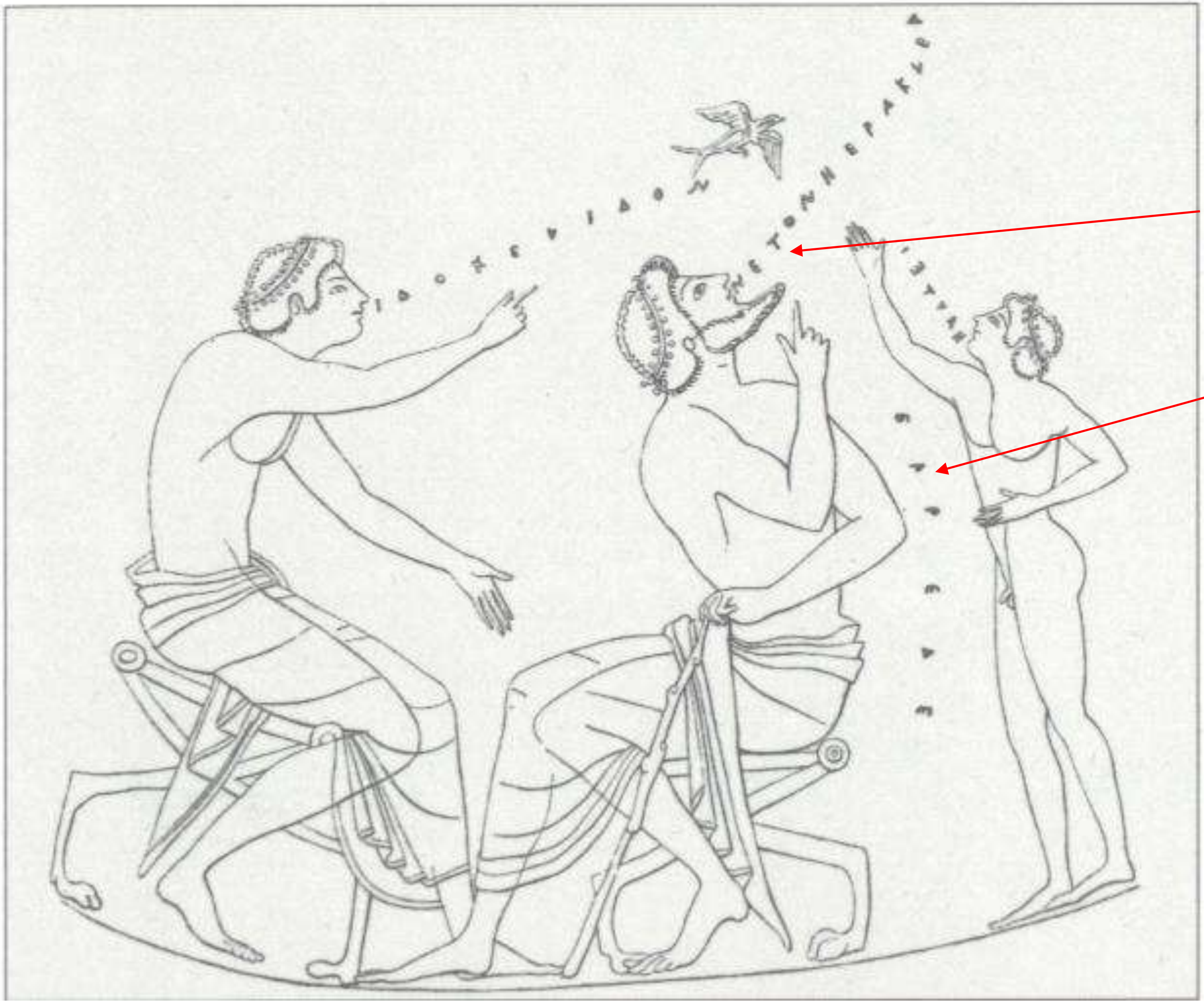
I have always been interested in the history of early inventions. One invention from 2,700 years ago seems completely obvious to us now but was a very original idea at that time – the picture caption. You will be seeing lots of them here.

In ancient Greece vases were usually painted with scenes from Greek mythology. Usually it would be clear to everyone what the pictures were intended to show. On the right here is Helios the sun god driving his chariot across the sky. On the left is a scene from Homer's *Odyssey* with Odysseus and the Sirens. But sometimes it would <u>not</u> be obvious who the people were or what the scene was supposed to show. Around 700 B.C. some brilliant person invented the picture caption - a completely original idea back then.

This ancient artist got the idea of putting the name of the person next to them on the vase, so we would know who it was. Here it is Ajax carrying the body of Achilles, a scene from Homer. After this 700 BC invention people went crazy with it and started labelling everything in sight, like below here.

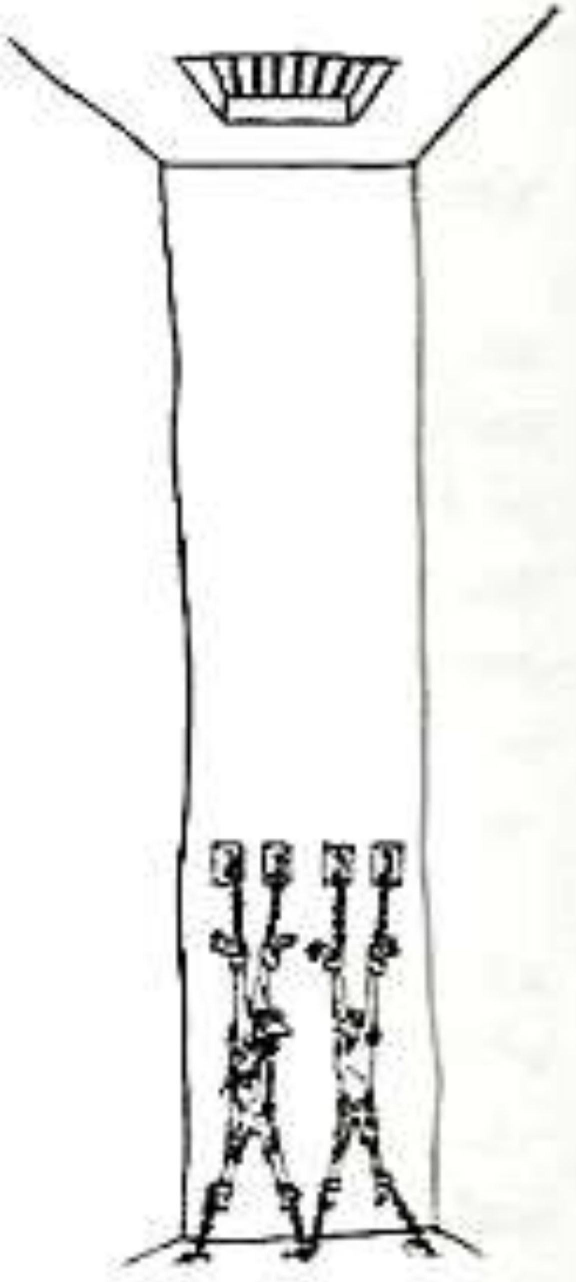
This required two new ideas. The first is that of putting the name of something together with its picture. The second idea is that of putting the name next to the picture, instead of right on it. That is a particular idea about how to use the space around the picture.





Around 500 BC someone got the idea of showing speech by having words coming from a person’s mouth. Instead of words next to a person, like their name here, this indicates that they are speaking the words. **A new idea!**

1807 political cartoon



Now, 2,700 years later than those ancient inventions, we have this cartoon here, with some words being said. It is very hard for us to appreciate that this idea of a picture caption was not always completely obvious. Like most great inventions it is obvious after the fact. It required thinking of a way to use the space around a picture or image.

Now let us look at some simple optical inventions that show some very original thinking. They all show "thinking outside the box" – literally, in the sense of getting a new idea about how to use a particular spatial volume.

The history of eyeglasses and how they were used gives some interesting examples of multiple solutions to a simple problem and a new innovative idea.

That idea involves a way of looking at the <u>space</u> surrounding a person's face and head.

Here is a detail from a 1403 painting that shows a man using some of the first eyeglasses. The history of eyeglasses and especially their frames shows an interesting evolution of ideas about how to manage this extremely important invention. As usual there are several valid solutions to this and the one that is universally used today is so obvious to us now that it is hard to realize that it was an invention or innovation at some earlier time.

At first the glasses were simply held right against the face.

Then the lorgnette was invented and it kept the hands from blocking part of the face. It came in one or two lens versions.



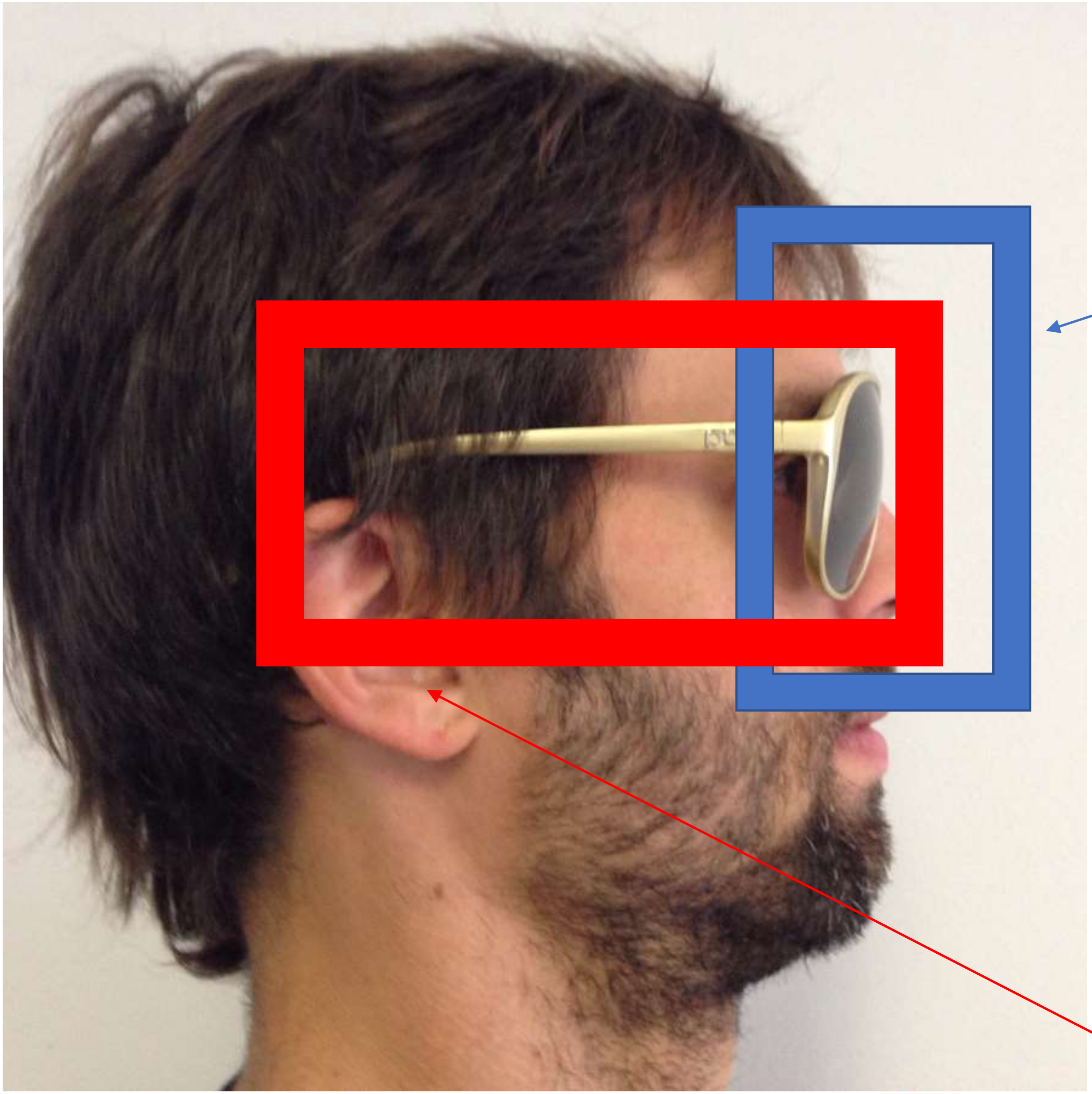
The pince-nez came next and let one's hands be free. But it required balancing the frame on the bridge of the nose, with a slight pinching action. That is unstable so a thin chain or string at one end would keep it from falling to the floor if it came off the nose. Teddy and Franklin Roosevelt wore a pince-nez.

A monocle, with or without a chain or string, was an alternate solution, but it was only for one eye and it required facial muscle control.

It is hard to imagine that this idea of frames that go over the ears was not always obvious. But just think –

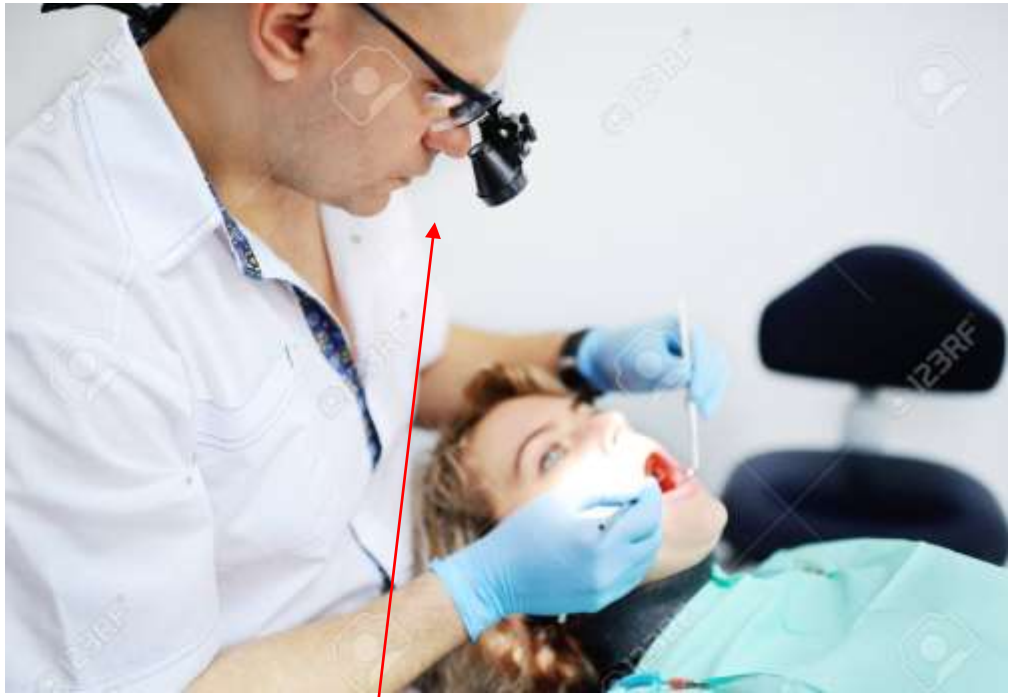
1) The ears are not near the eyes

2) This solution goes at <u>right angles</u> to the plane of the face, unlike all other previous solutions over the previous 300 years. <u>It is really a new spatial idea.</u> It literally thinks outside the spatial box of all previous solutions.



Previous space
for solutions,
in **front** of face

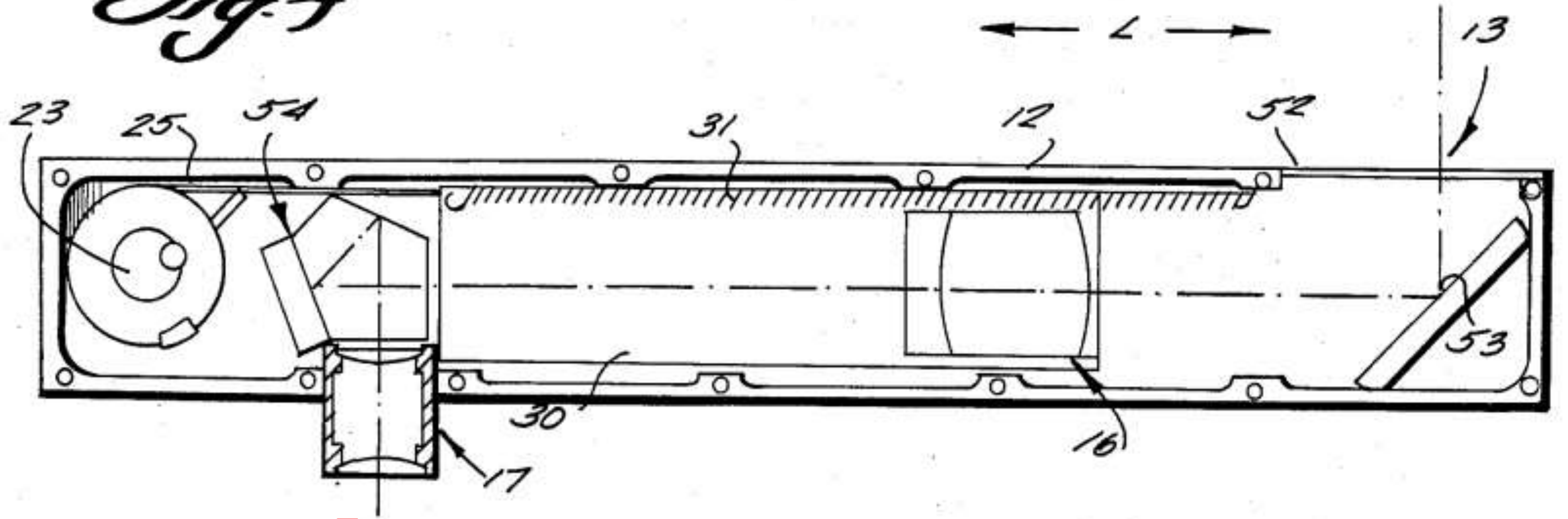
New space
for solutions,
behind eyes



A brilliant invention by J. Pekar, whose daughter had severe low-vision (a retinal problem), is this telescope/periscope system. People with low vision can barely read large letters of print and they need about 3X magnification of the world around them to function well. Dentist binoculars would work well but immediately draw very unwanted attention to anyone wearing them in public, since they stick out so much from the face. Pekar realized that low-vision sufferers do not need stereo vision so he devised this very clever idea. One eye looks into a folded periscopic system that puts a long optical path horizontally across the face in a very low-profile system. A tilt of the head switches back and forth between the normal glasses view and the 3X magnified view. A very original idea.

Input rays

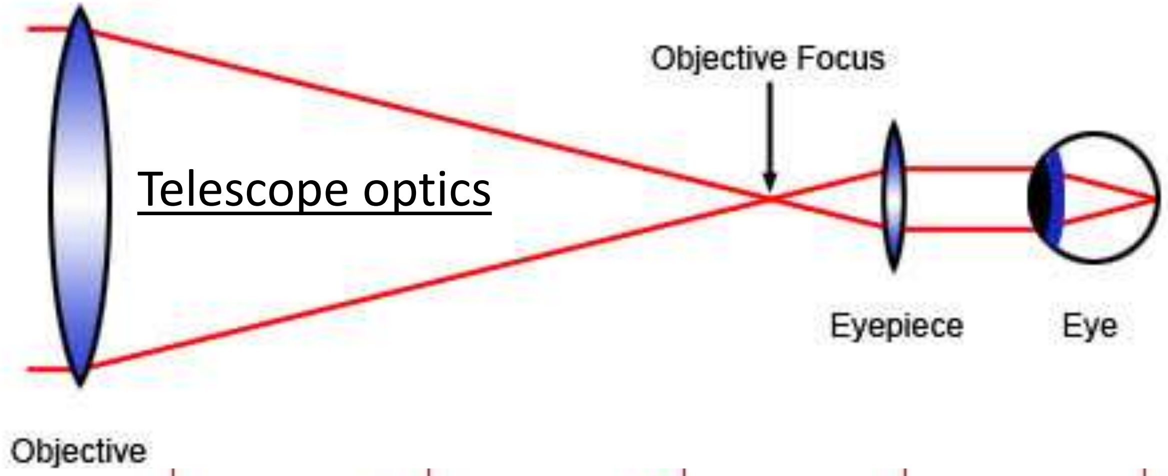
Fig-4



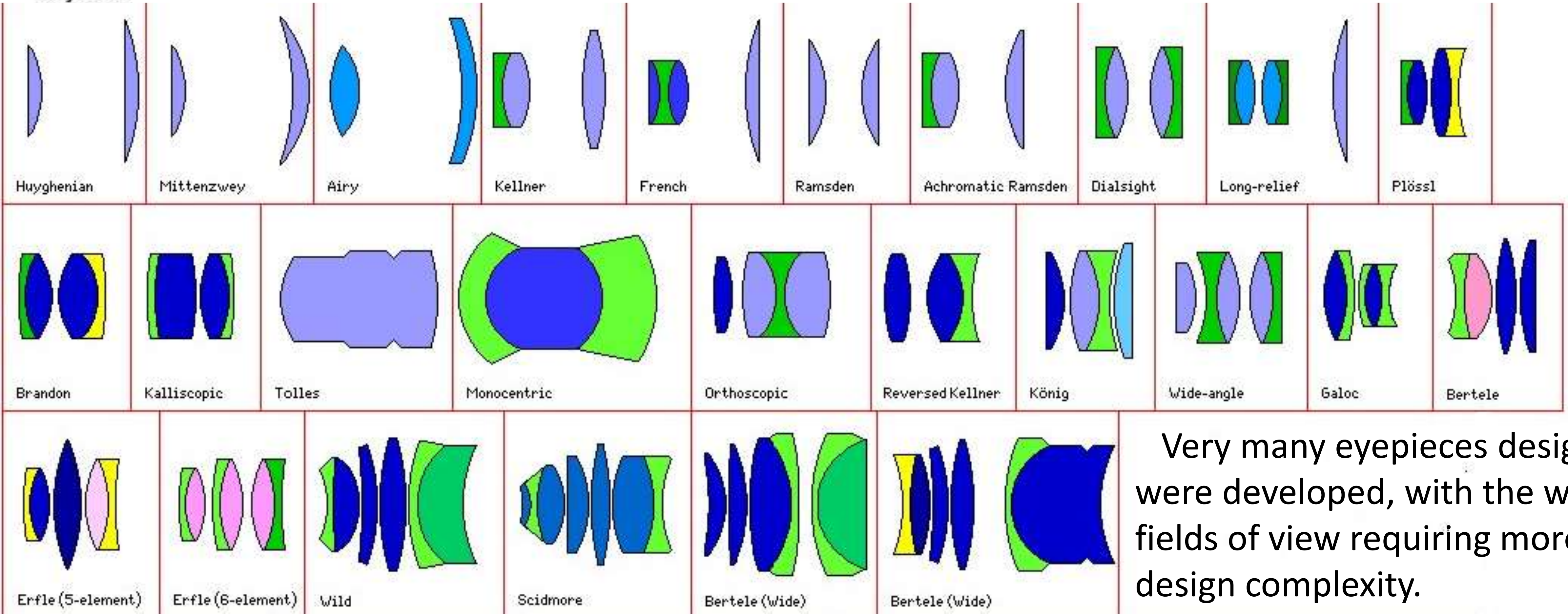
Eye

Folded horizontal optical path across face

This system perfectly illustrates the kind of “thinking outside the box” that creative invention requires. The modern eyeglass frames extend back to the ears and enter a different dimension perpendicular to the plane of the face, where all previous solutions lay – like the pince-nez, monocle, lorgnette, etc. Now here, with the low-vision optical invention, the reverse happens. The normal situation with binoculars, monoculars, and other optical equipment is for the line of sight of the eye to extend directly outwards from the plane of the face, like the dentists binoculars. But the Pekar invention stays in the plane of the face, with folded optics, and avoids the protruding size of the dentist device.   Questioning assumptions about the package space that optics can occupy was the key to this solution.

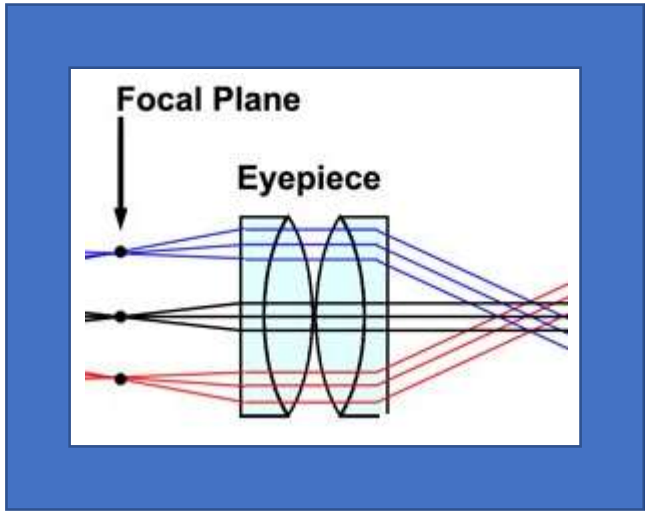


Telescope eyepieces have historically been thought of as like a jeweler's loupe – to look at an object or a telescope image and magnify it.

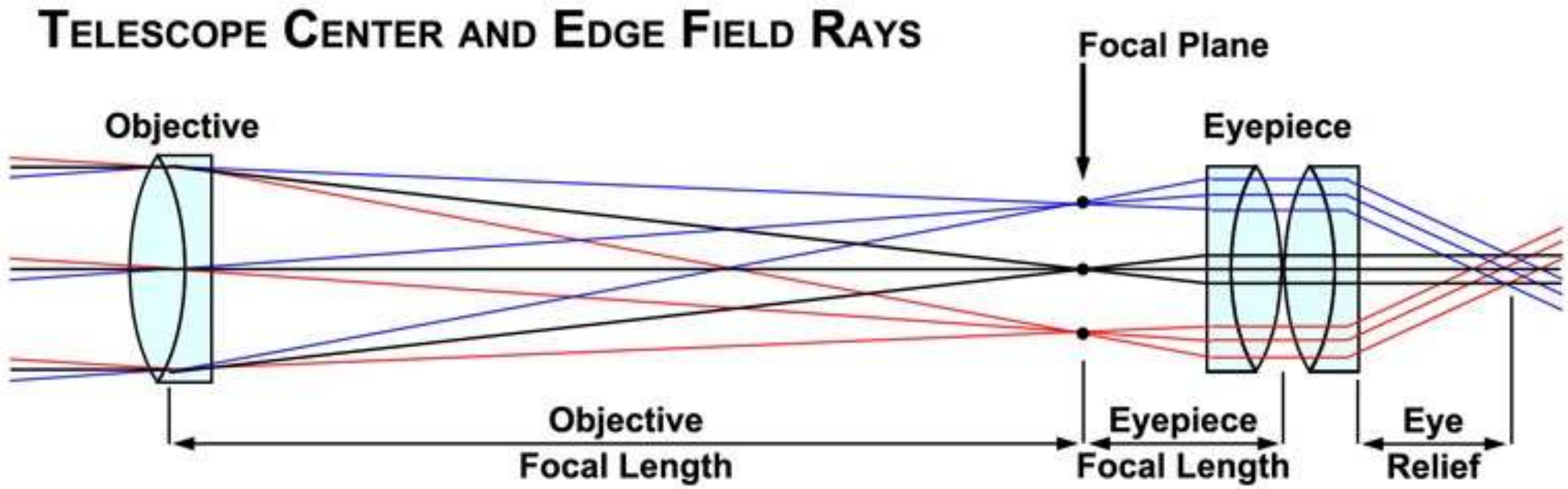


Very many eyepieces designs were developed, with the wider fields of view requiring more design complexity.

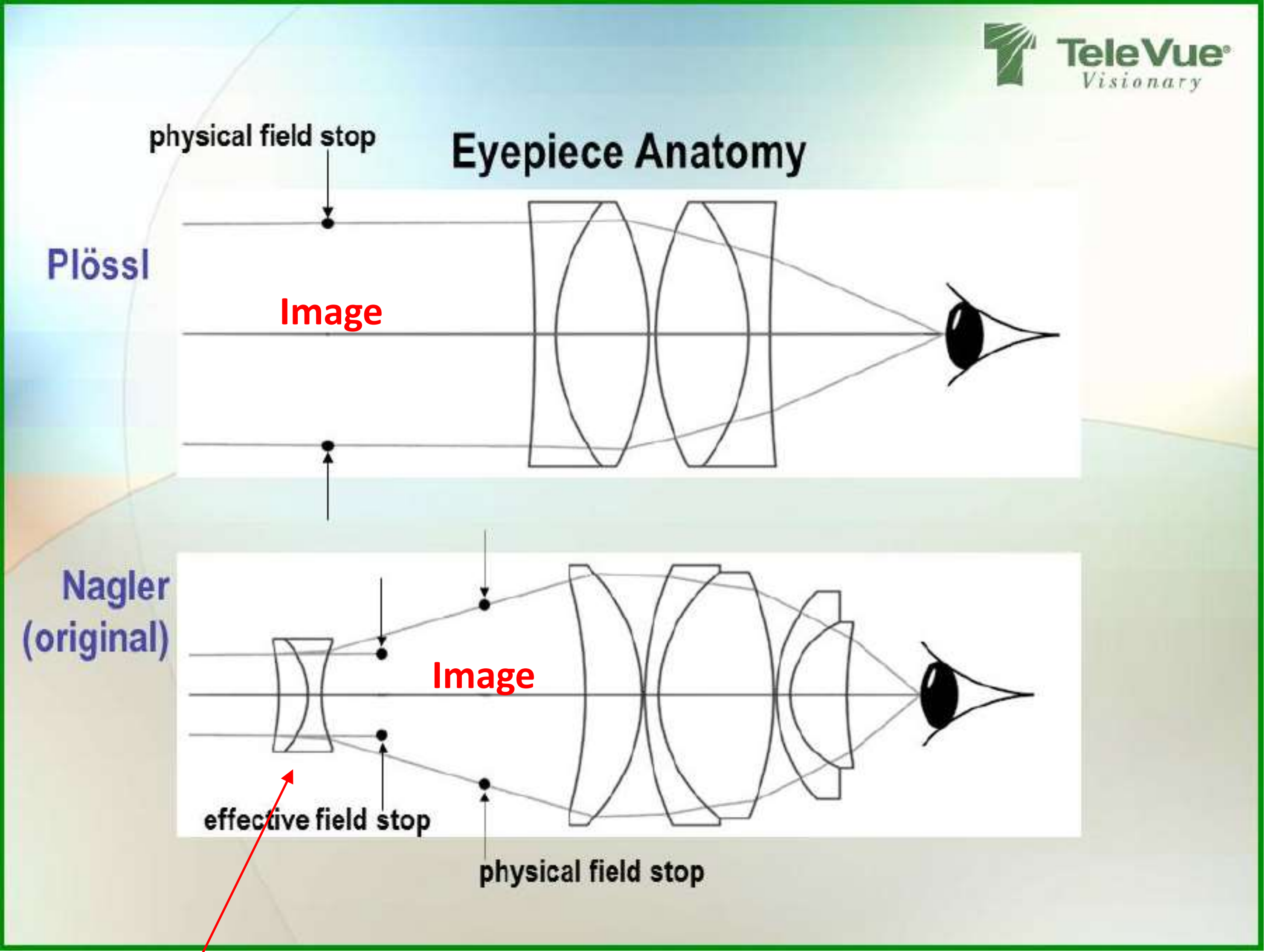
The image aberrations of eyepieces get bad for large fields of view and very little can be done about that as long as the eyepiece is thought of as being confined to this box



The focal plane of the eyepiece is the same as the focal plane of the telescope



All of these different eyepiece designs were thought of as having a real image and they could be used to look at something, like a diamond here, as well as be used as a telescope eyepiece.



Lenses outside the "normal" space box of eyepieces

A breakthrough in eyepiece design happened when someone thought of moving outside the conceptual "box" that eyepieces up until then had occupied. Lenses were added on the other side of the image (focal plane) and that then allows much better image quality and wider fields of view.

These new eyepieces cannot be used as a loupe because the image is inside the design (a virtual image)

New kind
of eyepiece

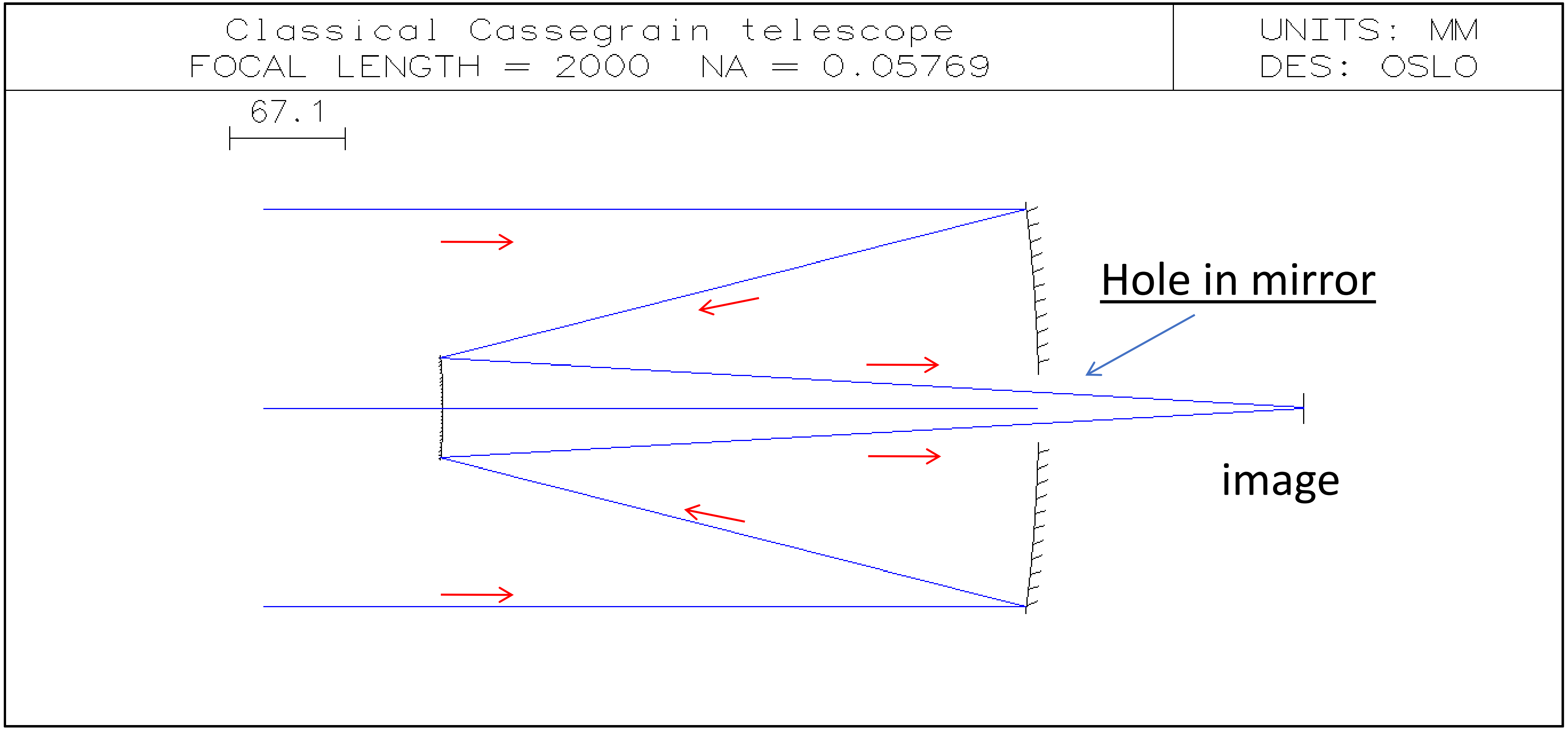
The new kind of eyepieces <u>cannot</u> be used as a loupe or magnifying glass because they don’t have a real image but instead a virtual one. So you have to <u>get away from that mindset</u>, of a useful device to look at a diamond, like here.

An aide to innovation –

Question hidden assumptions in any diagrams/drawings/ photos

An example – a simple telescope

Simple telescope example



Picture seen everywhere in textbooks

It contains a hidden assumption

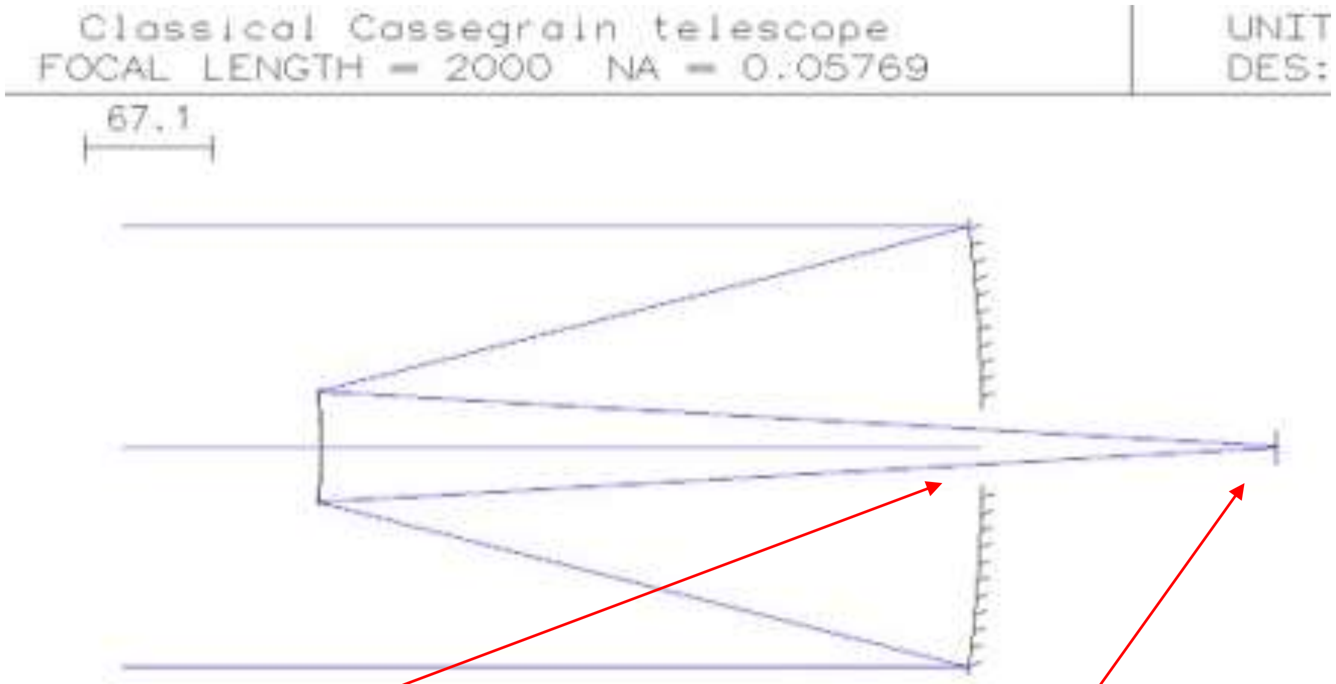
Insight

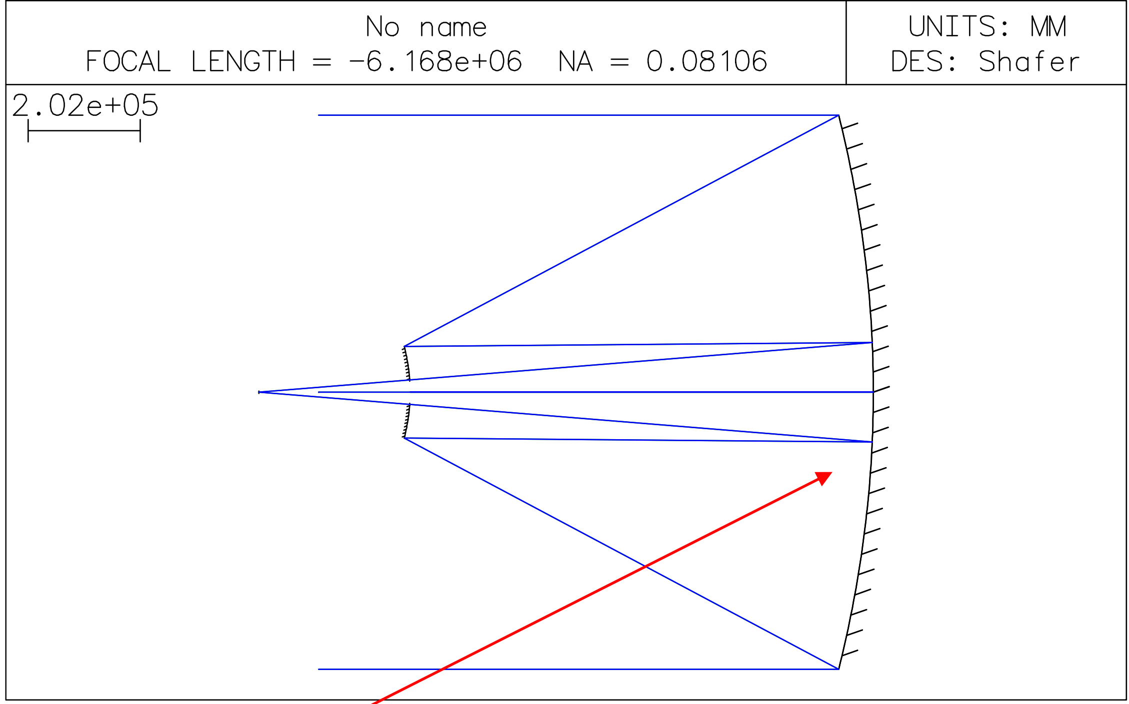
- The hole in the mirror is not part of the optics and is not an optical surface

- Don't assume a hole – only consider the optical surfaces

- Consequence – light reflects again at the primary mirror

- Explore opportunities to use that

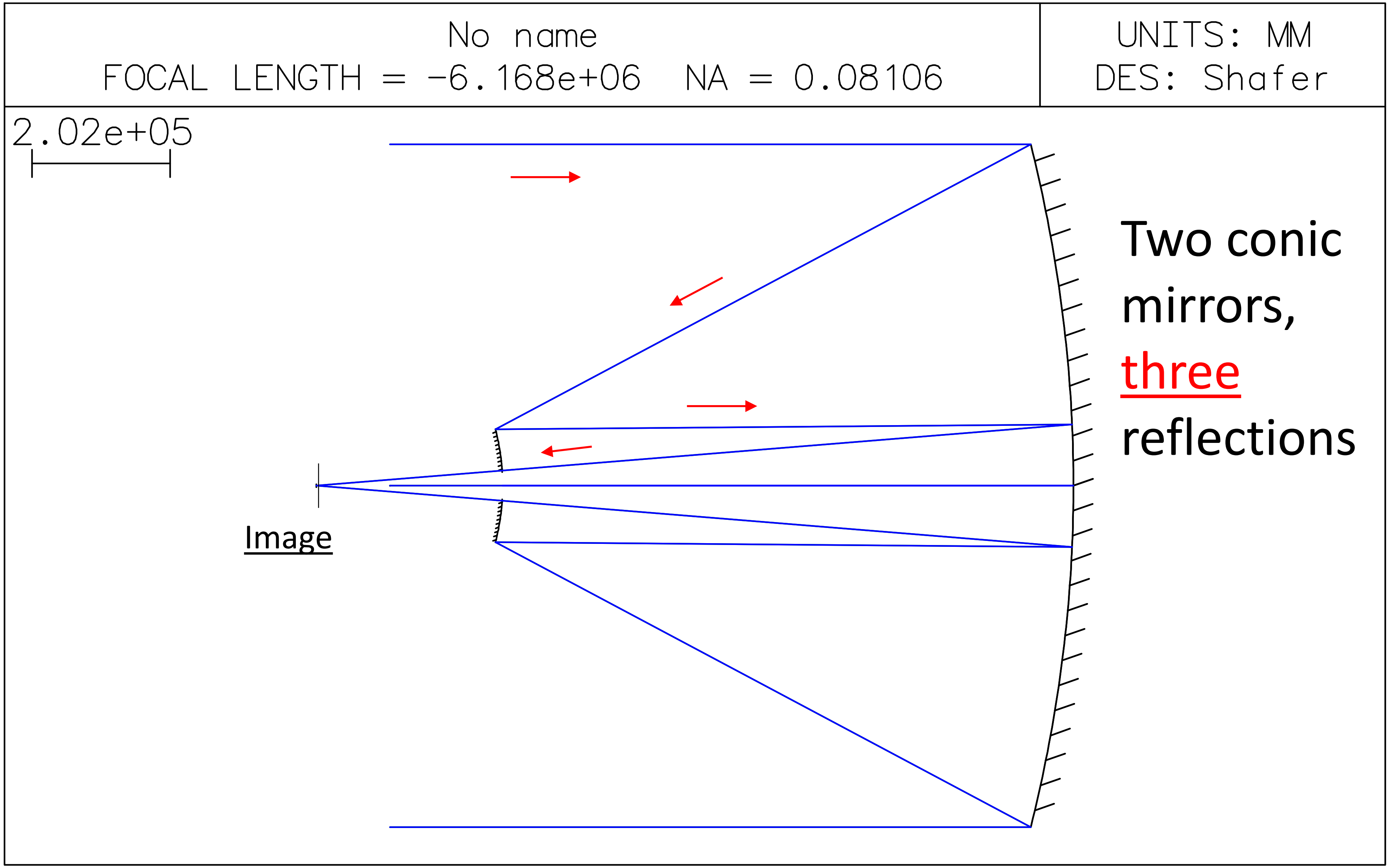




Hole in mirror allows expanded space for light rays to move into

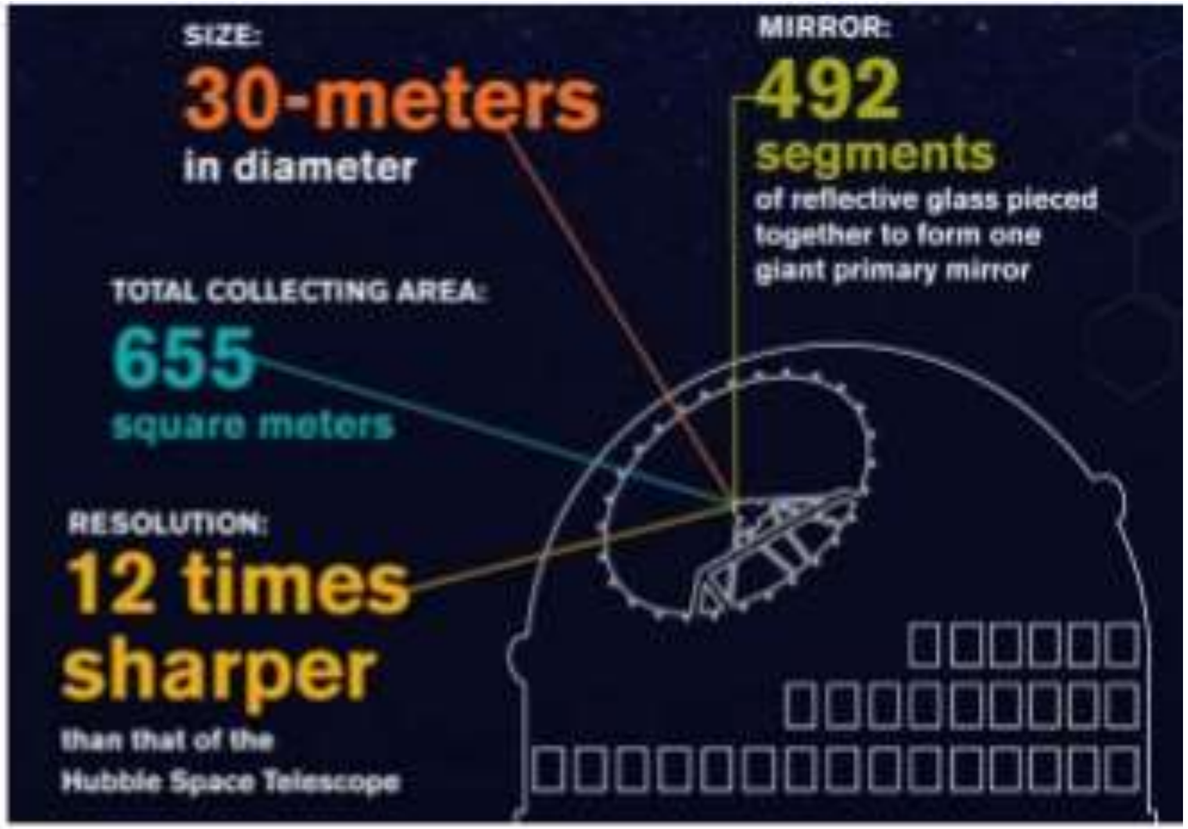
Blocking hole changes the space envelope and leads to a new type of design. A new idea! The rays reflect twice from the large mirror.

Thinking inside the box – keep the image from being outside the mirror to mirror space, by eliminating the mirror hole.



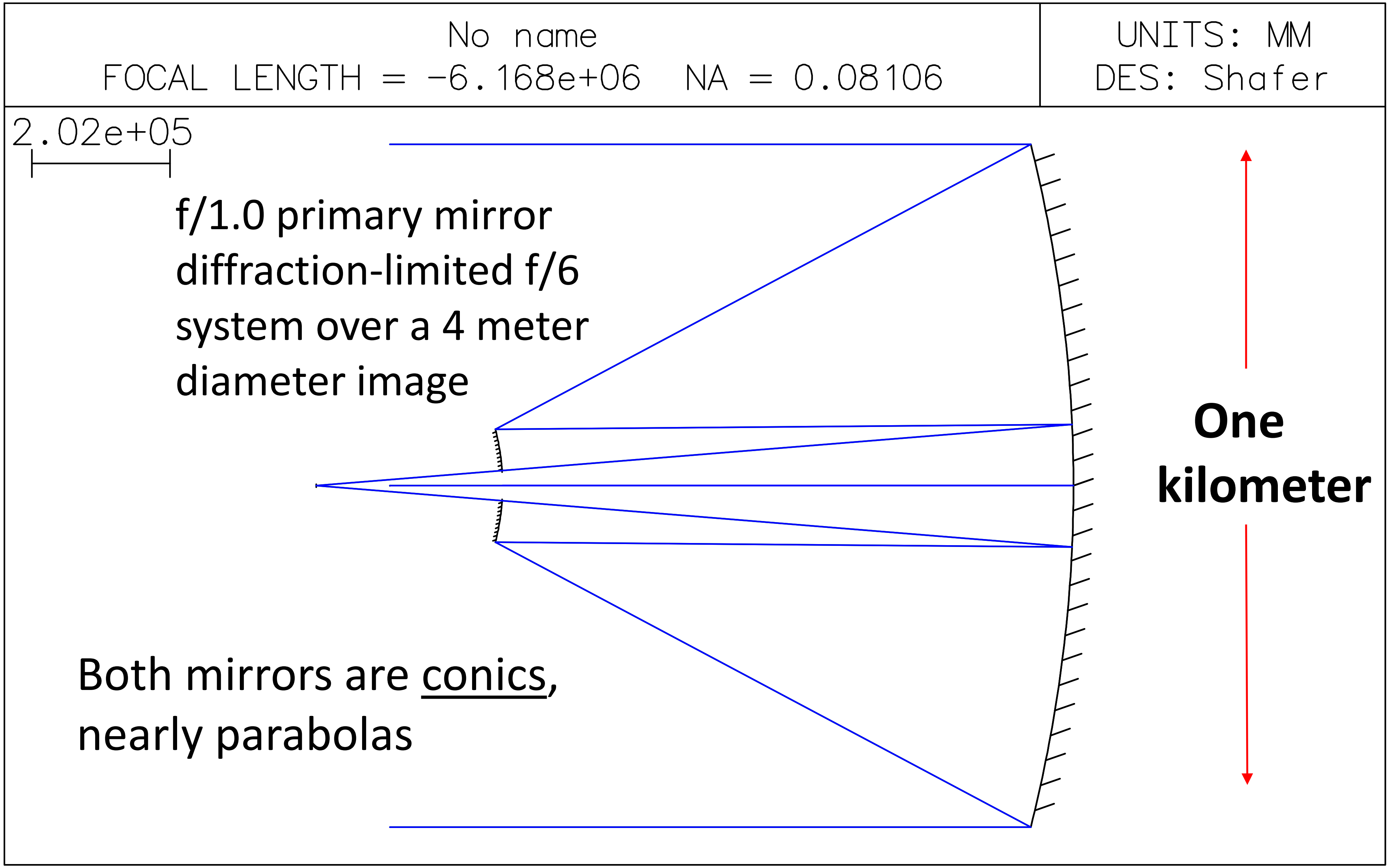
Corrected for spherical aberration, coma, and astigmatism

My 1974 discovery

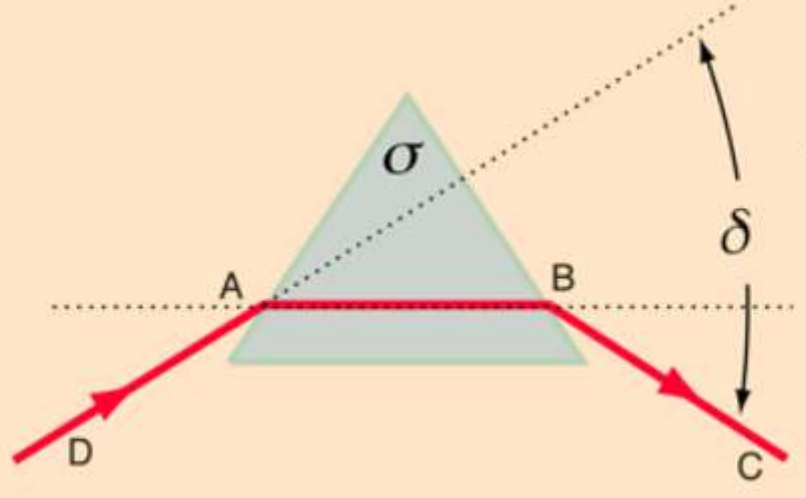


A 30 meter diameter telescope is being built for a new observatory in Hawaii

There are other huge telescopes that have been approved or proposed



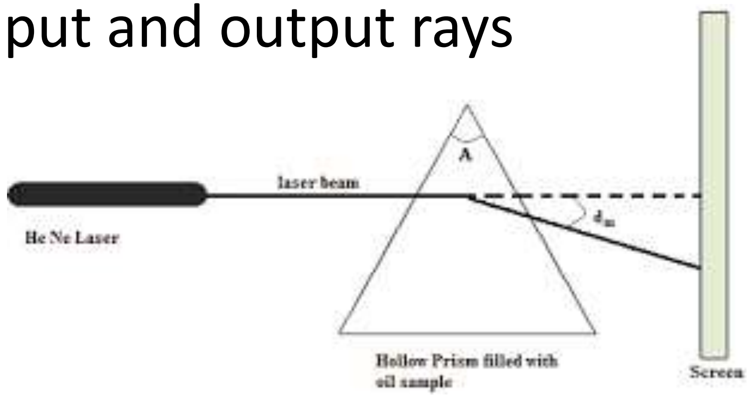
The Kilometer-Scope!!



$$\frac{n_{prism}}{n_0} = \frac{\sin\frac{1}{2}(\sigma+\delta)}{\sin\frac{1}{2}\sigma}$$

The index of refraction of glass can be measured by making a prism and finding the angle of minimum deviation of a ray going through it. For an equilateral prism it can be proven that minimum deviation occurs when the ray is parallel to the base of the prism. But the total deviation does not change much as different incidence angles are chosen, making it hard to accurately find the minimum.

Parallel input and output rays

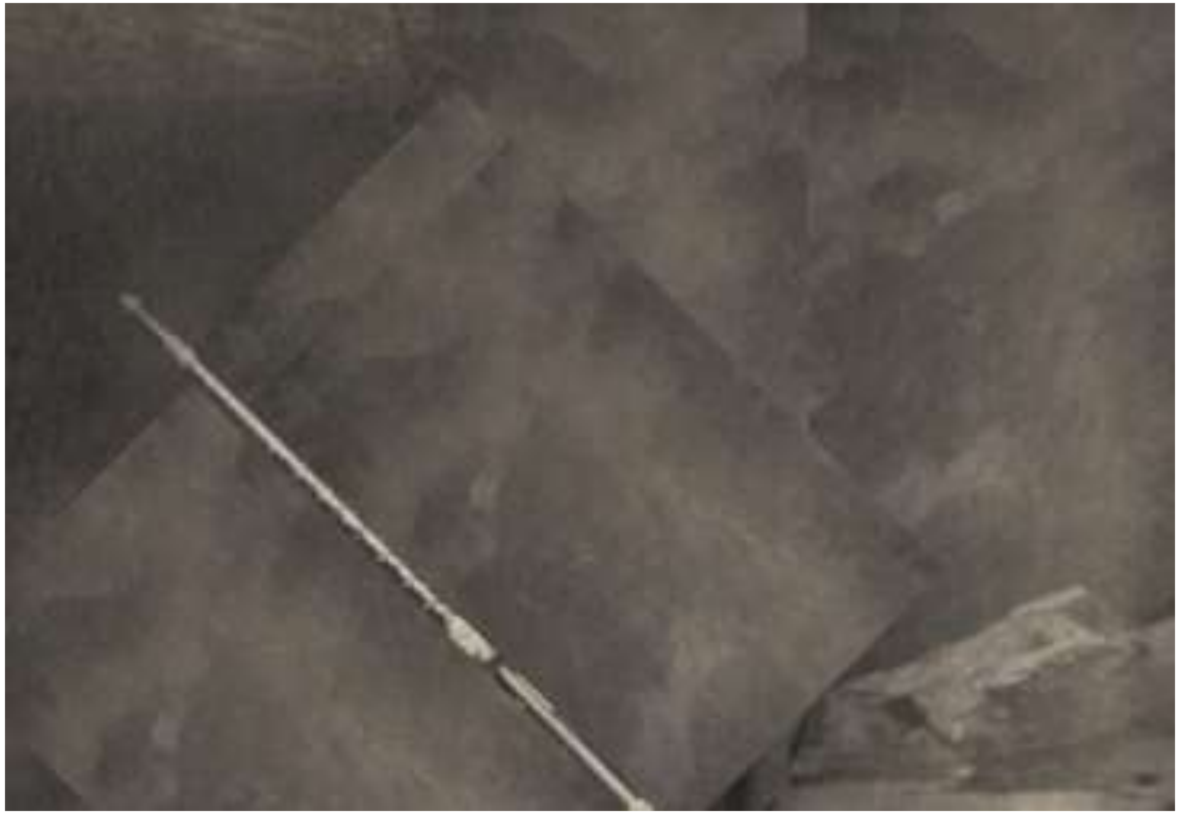


The deviated ray does not change very fast but the reflected ray off the base does. When the rays coincide it is minimum deviation! Thinking **outside** the box (prism)

A very hot topic in the media these days is optical cloaking, or making something invisible.

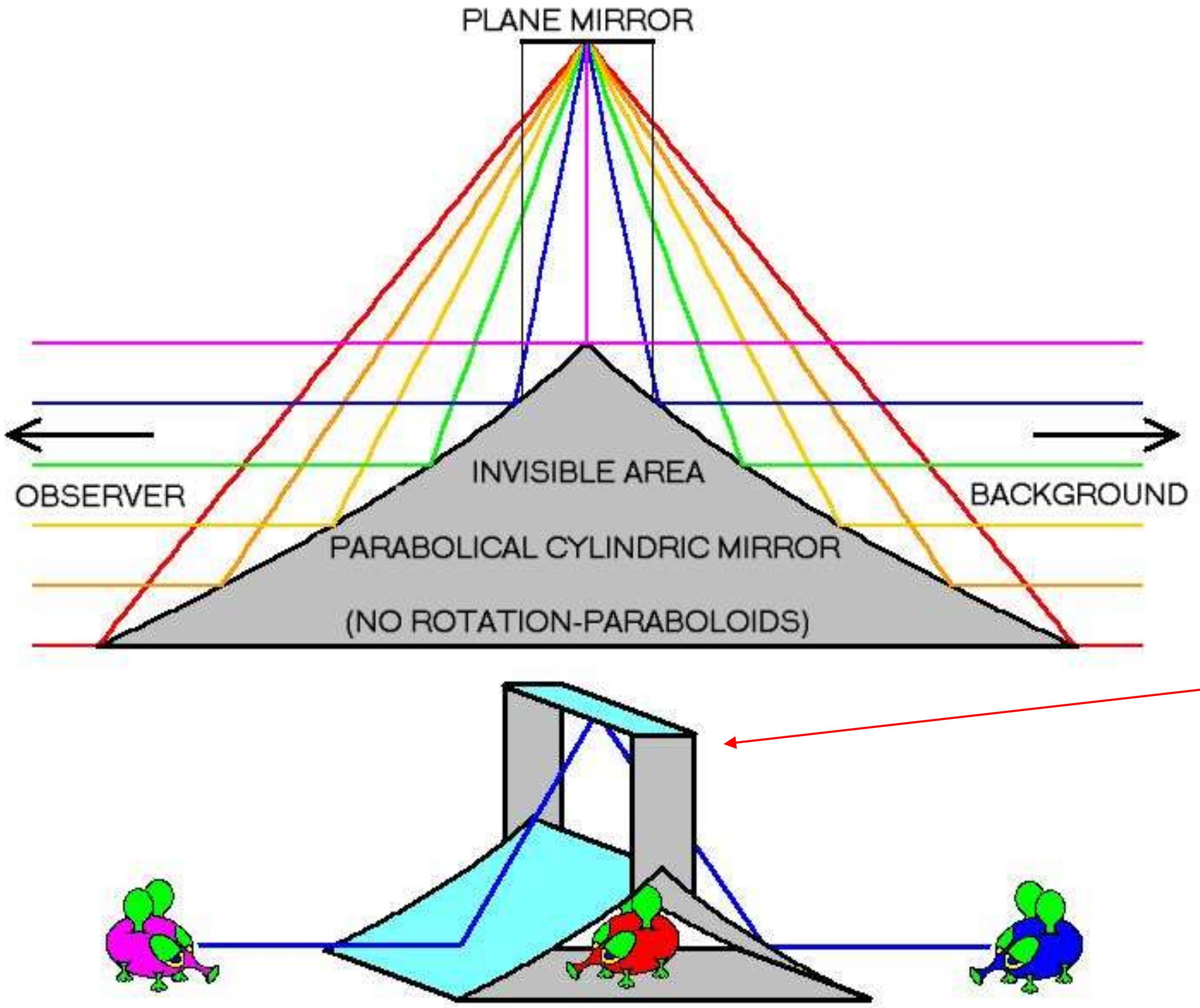
Metasurfaces – optical surfaces with sub-wavelength size surface structures – are being studied to see if they might make invisibility possible. In an ideal form an invisibility cloak would bend light around an object so that you would not see it but would see what is directly behind it.

Wotan **not** wearing Tarnhelm

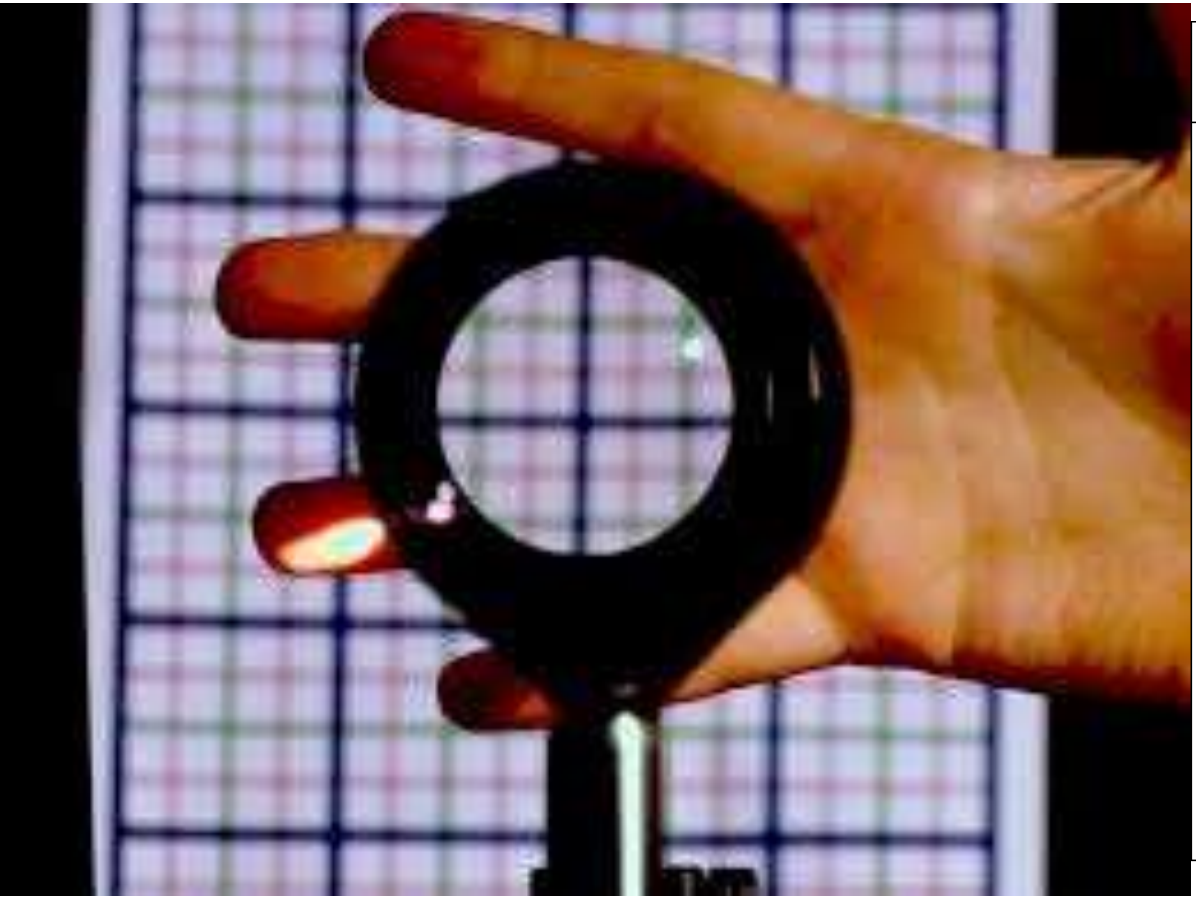


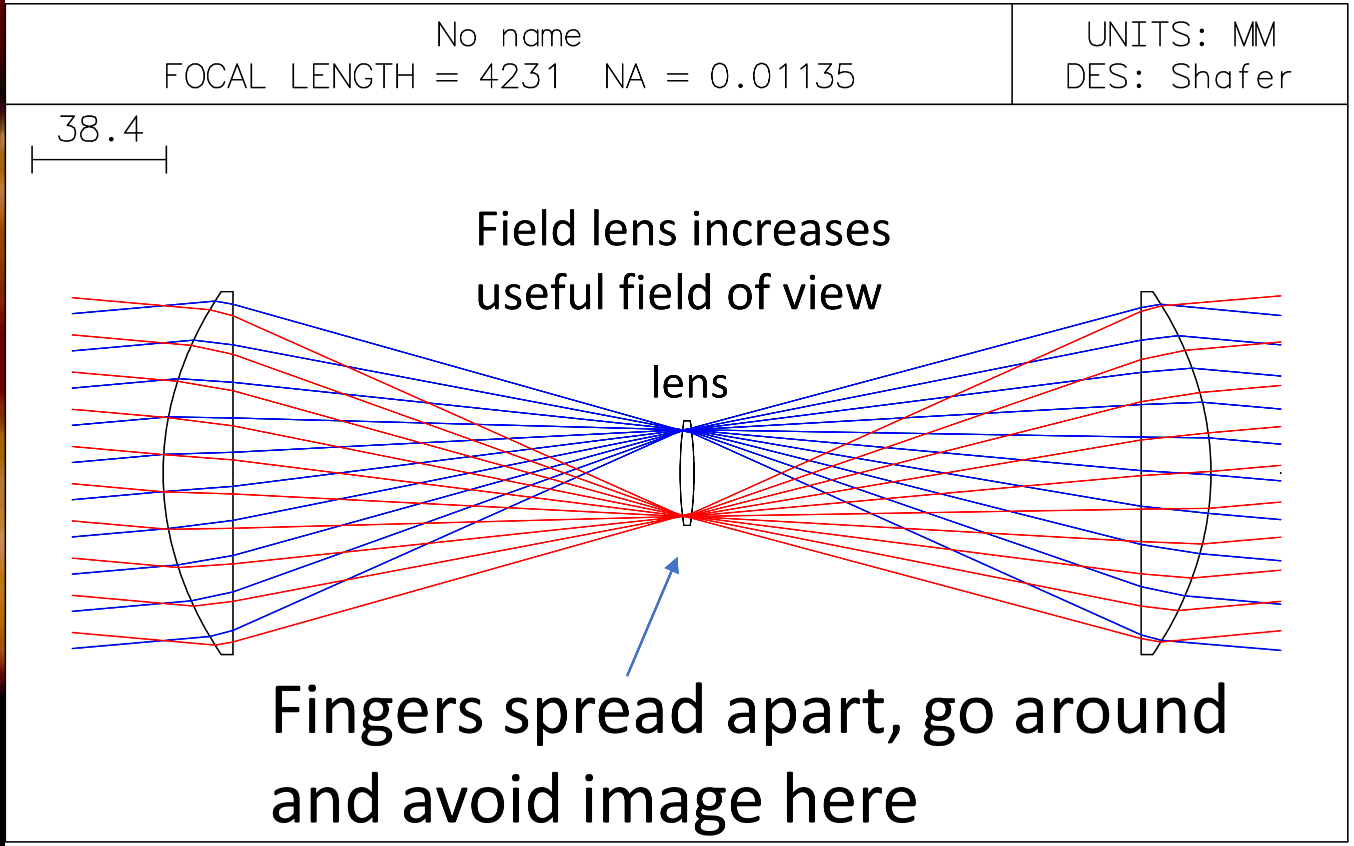
Wotan wearing Tarnhelm

Tarnhelm was a cloaking device featured in some Wagner operas and it made the wearer invisible.

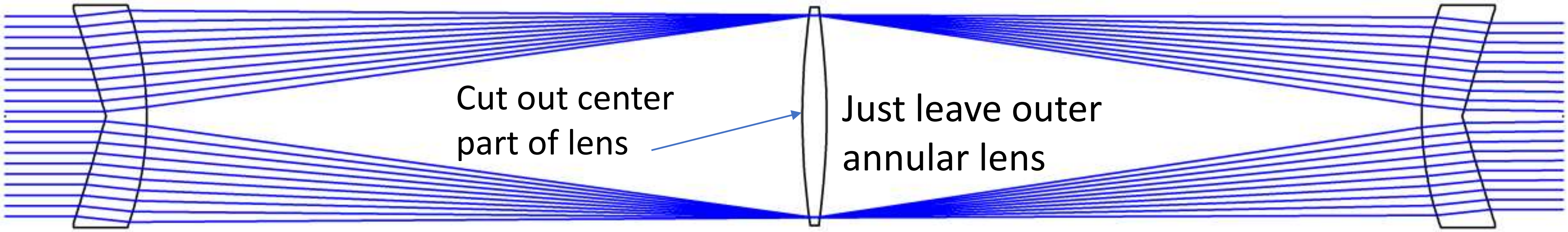


The ideal invisibility (cloaking) system would make some object invisible but would **<u>also</u>** be invisible itself. This system here does not do that since the plane mirror at the top is clearly visible.





University of Rochester low-tech system

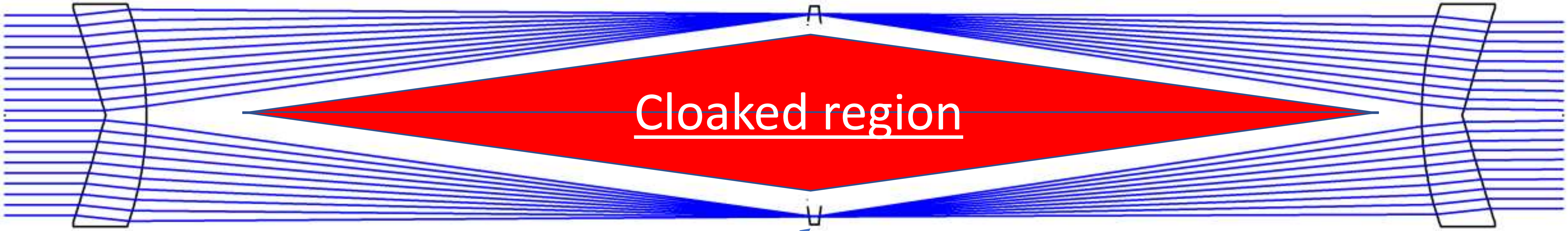


Aspheric axicons

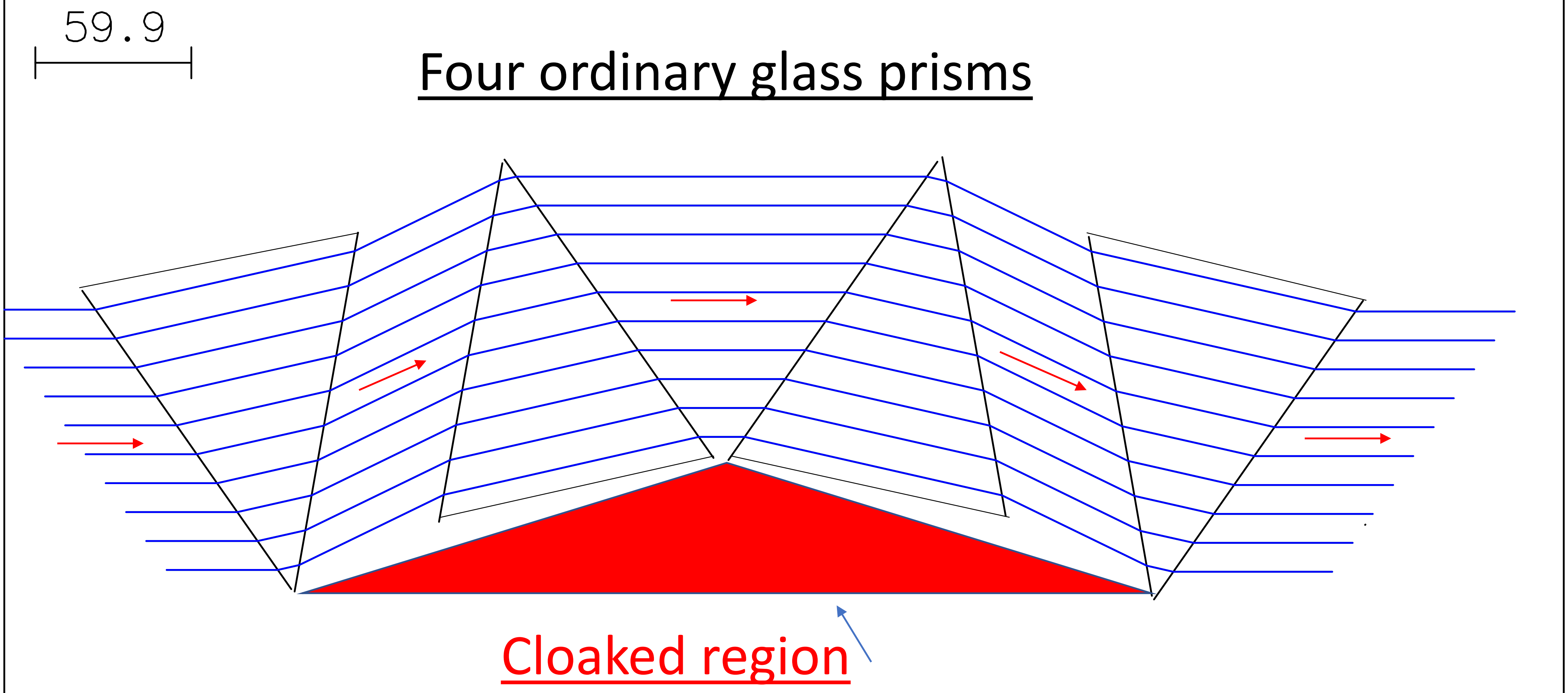
System has no net energy redistribution = no coma

Output is upside down, right/left reversed

Cloaked region is nearly 100% of device diameter



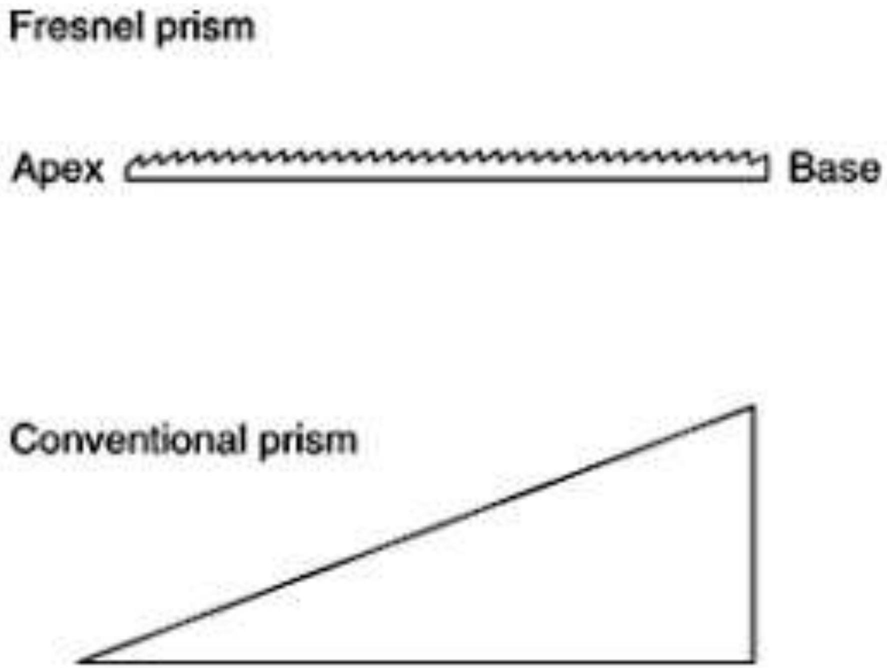
Four ordinary glass prisms



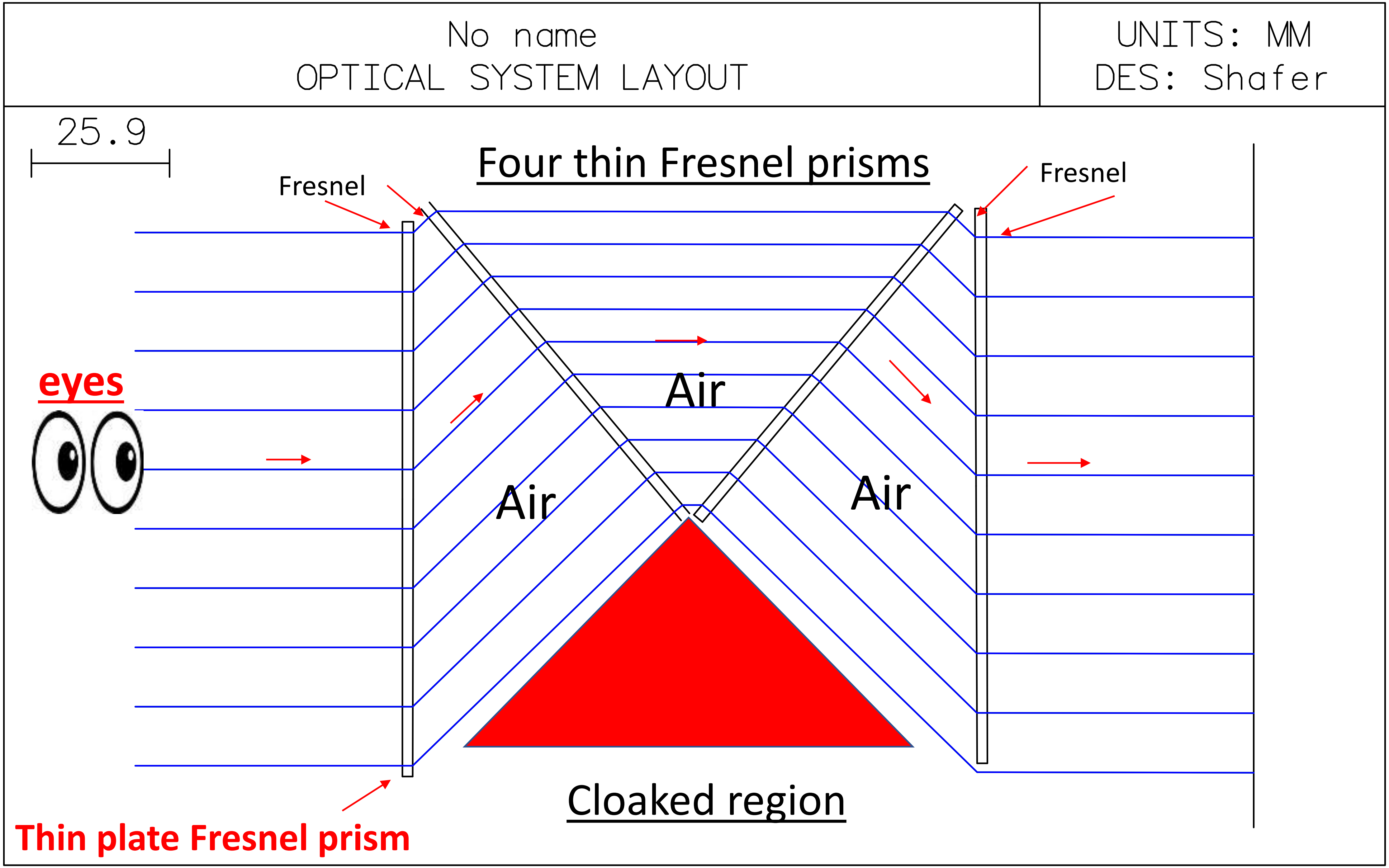
Impractical in large sizes – very heavy and expensive prisms

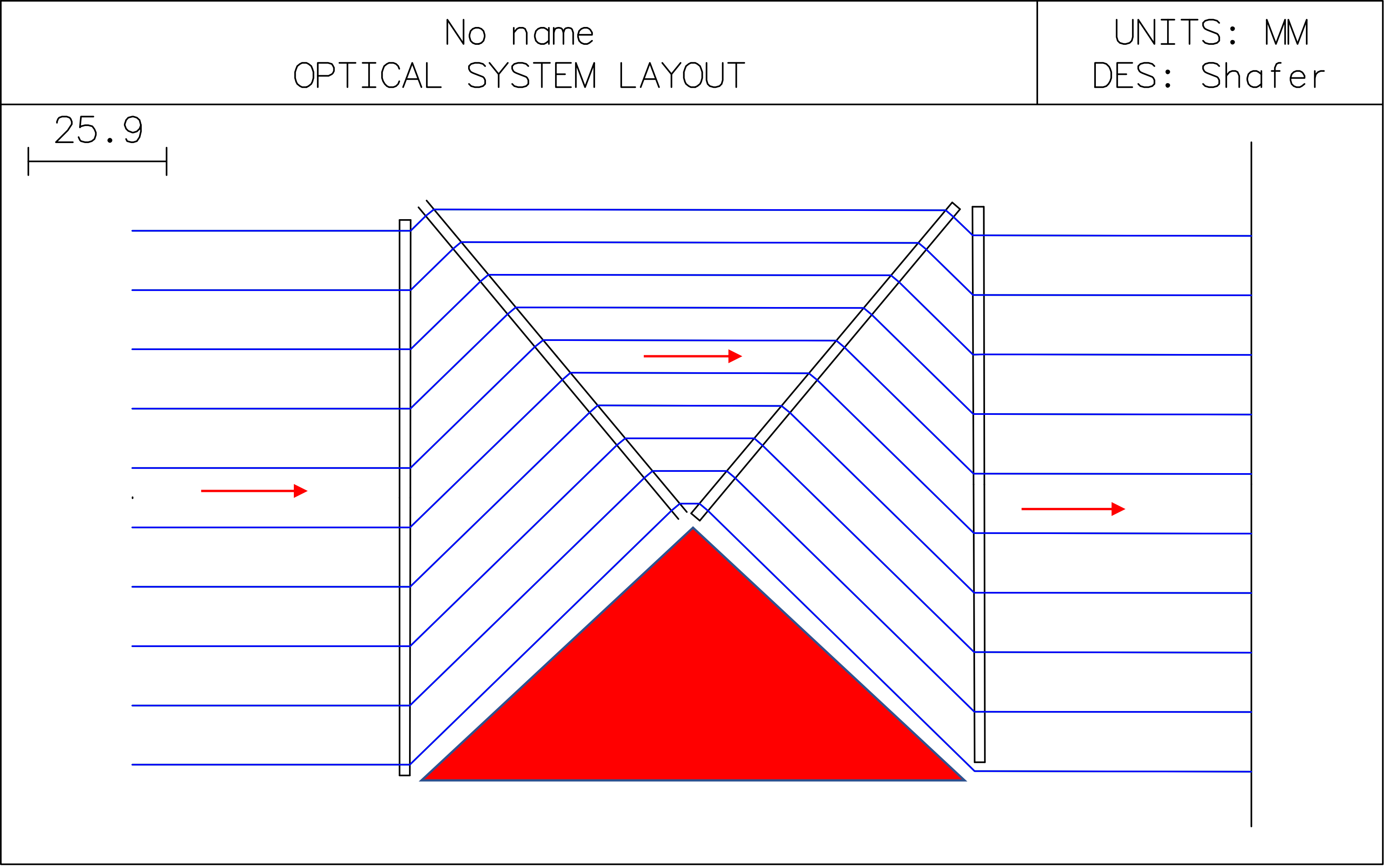
One way to think of the spatial volume of the prism system is that there might be way to get rid of all that glass and the weight.

Successful weight loss



A Fresnel prism deviates light just as a conventional prism does, but without the weight or volume

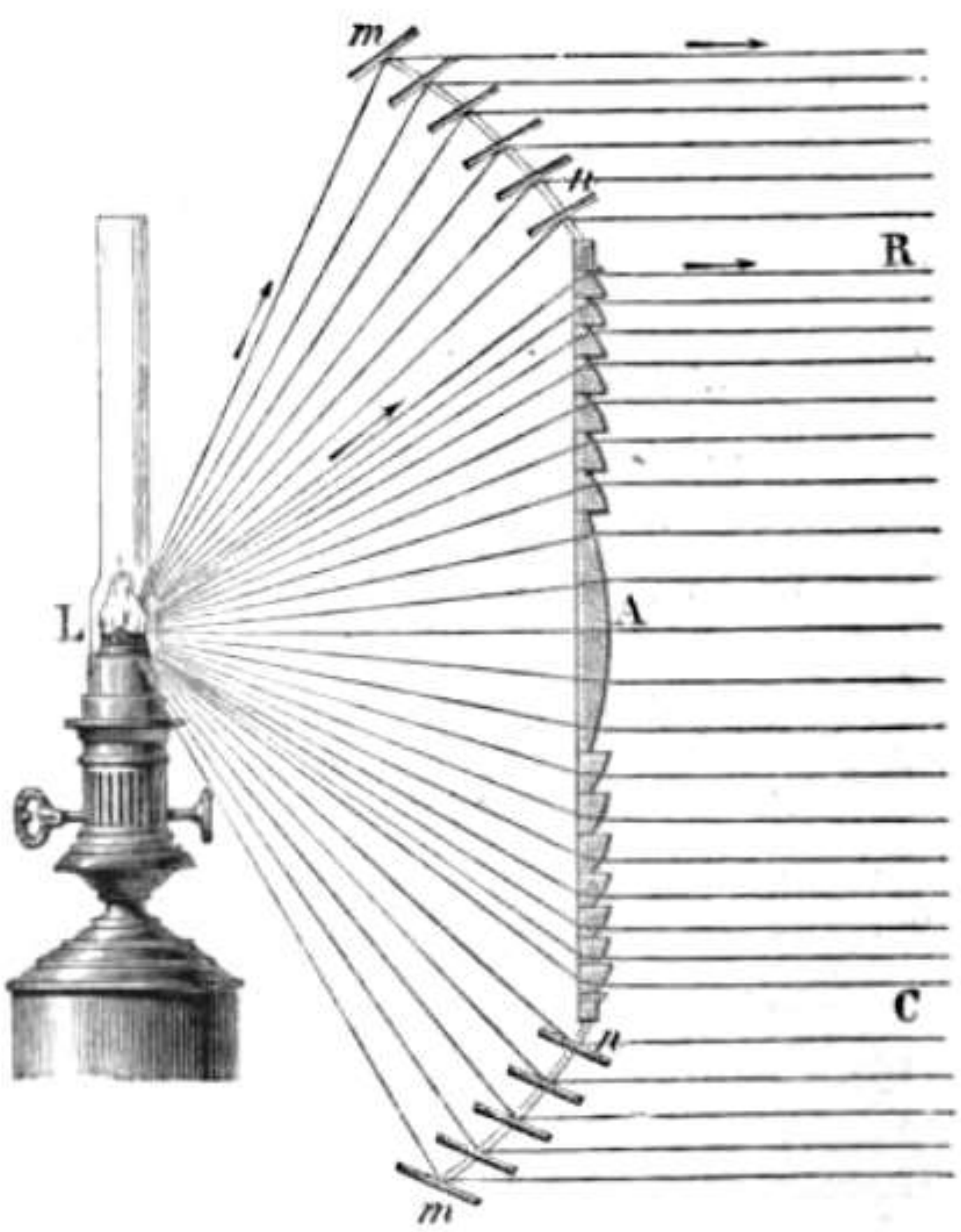

No name
OPTICAL SYSTEM LAYOUT
UNITS: MM
DES: Shafer
25.9
Four thin Fresnel prisms
Fresnel
Fresnel
eyes
Air
Air
Air
Cloaked region
Thin plate Fresnel prism

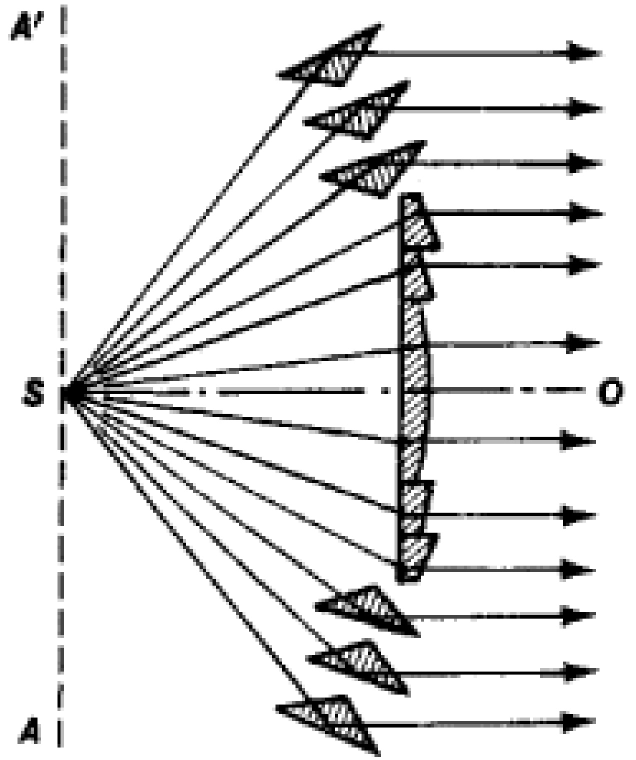


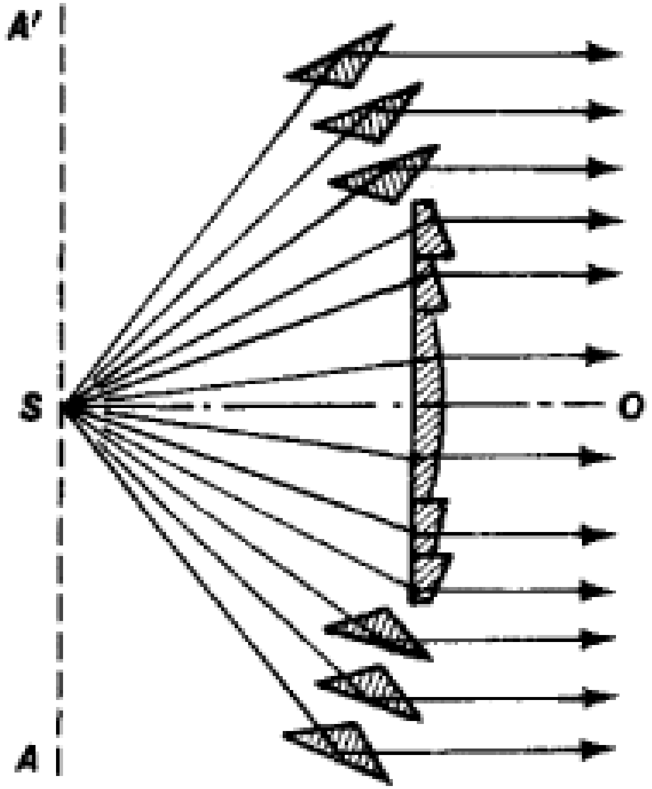
Flexible plastic sheets of very thin Fresnel prisms could be stretched tight on frames into flat planes and arranged like this to cover large objects.

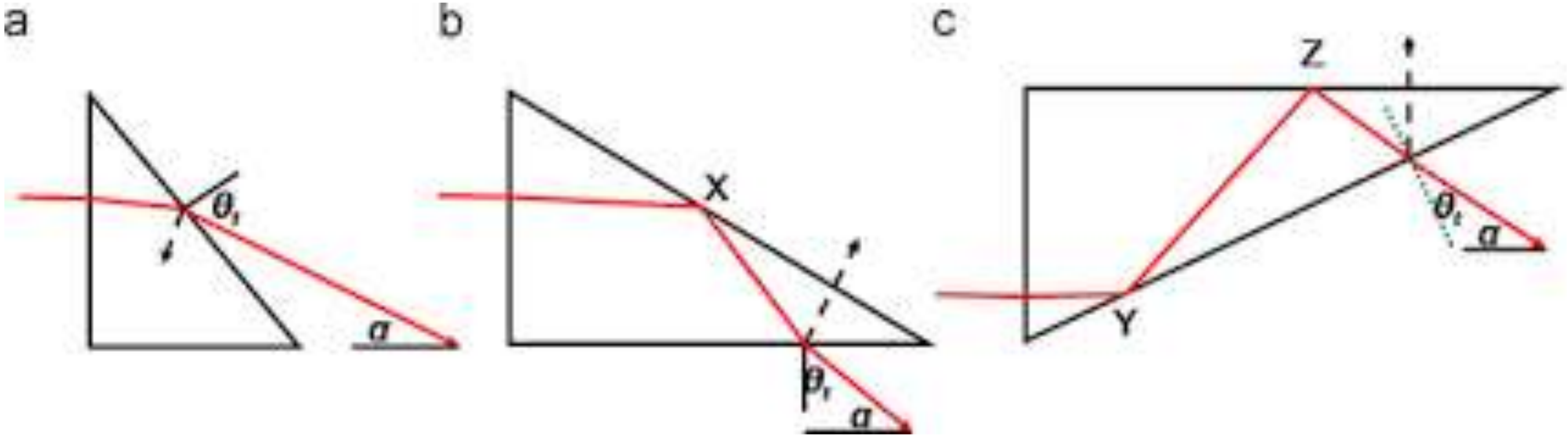
This gives correct right/left and rightside up view orientation

Fresnel lenses that deviate light by large angles, as in the outer parts of a lighthouse lens, use either tiny mirrors or catadioptric prism elements. They result in large ray deviation angles with no color effects.





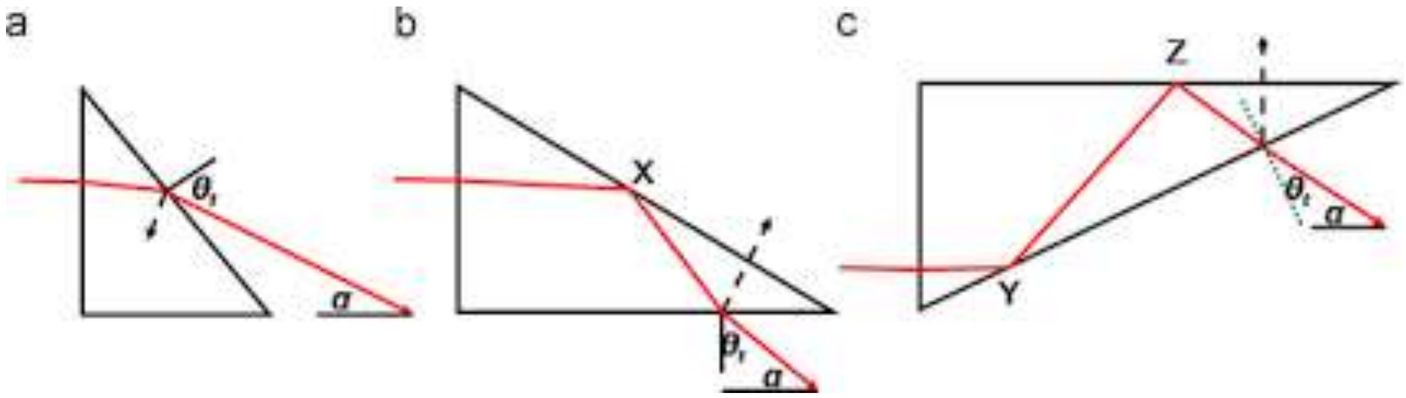




Lots of color | some color | little or no color effects

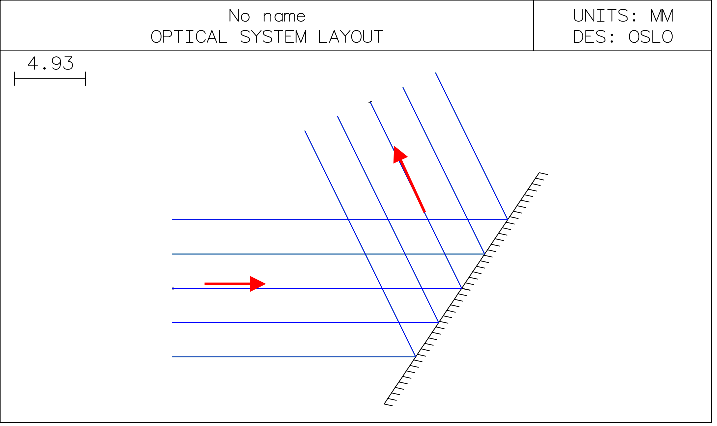
Dispersion effects in Fresnel elements

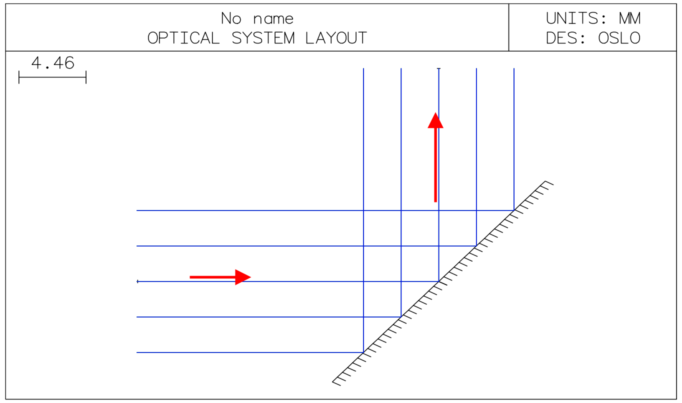
In principle you could make low or zero dispersion sheets of plastic Fresnel prisms. This shows how thinking of different ray path through the interior space of a prism can eliminate color effects.

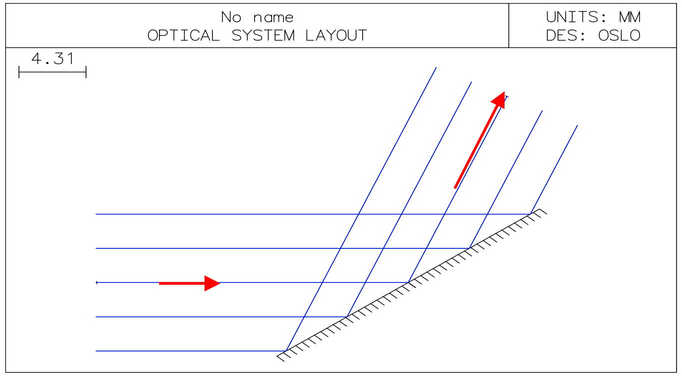


Lots of color some color <u>little or no color effects</u>

Even in extremely simple systems there are usually more choices available than you might think of

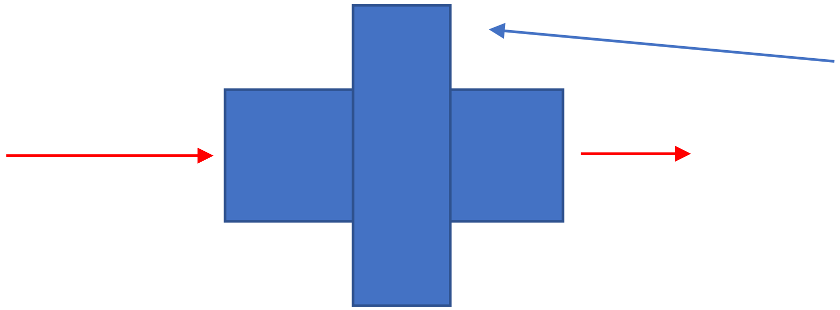






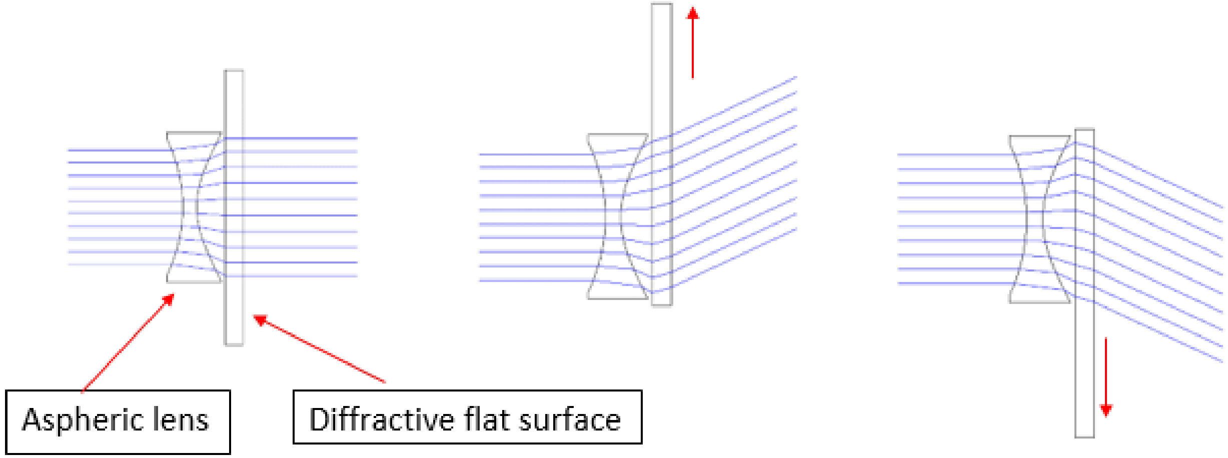
Scanning system/ beam steering system

- Tilting a flat mirror changes direction of reflected light beam
- But then also changes package shape and size
- An in-line scanning system would be attractive
- How to do?



Answer = use space outside the in-line box, in the other direction

In-line laser beam steering with a flat diffractive element

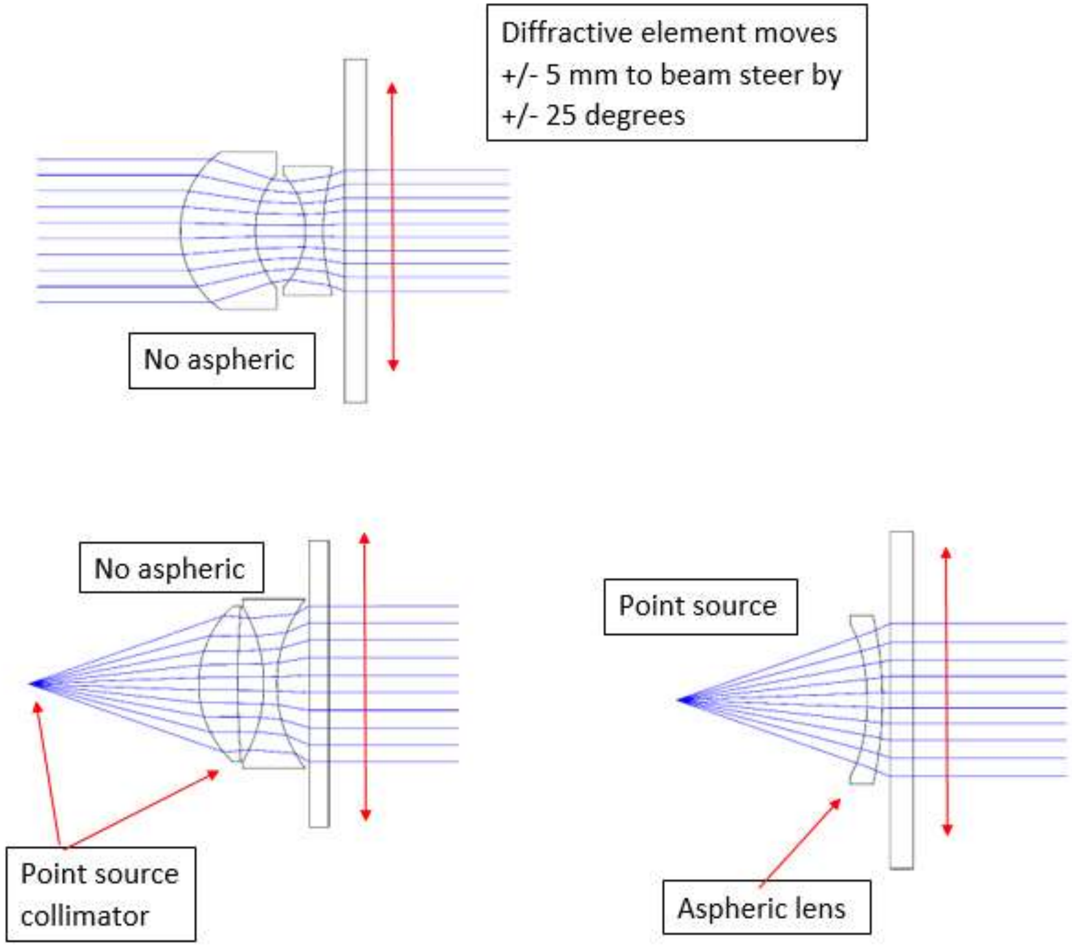


The diffractive surface element moves up and down by +/- 5 mm to steer a 10 mm diameter beam by +/- 25 degrees, with diffraction-limited correction at a .55u wavelength. It is continuous, not discrete beam steering

Advantages over other beam steering methods –

1) In-line optical path
2) Very compact package
3) Can be extended to larger steering angles, like +/- 45 degrees

A clever idea from Dr. Markus Seesselberg



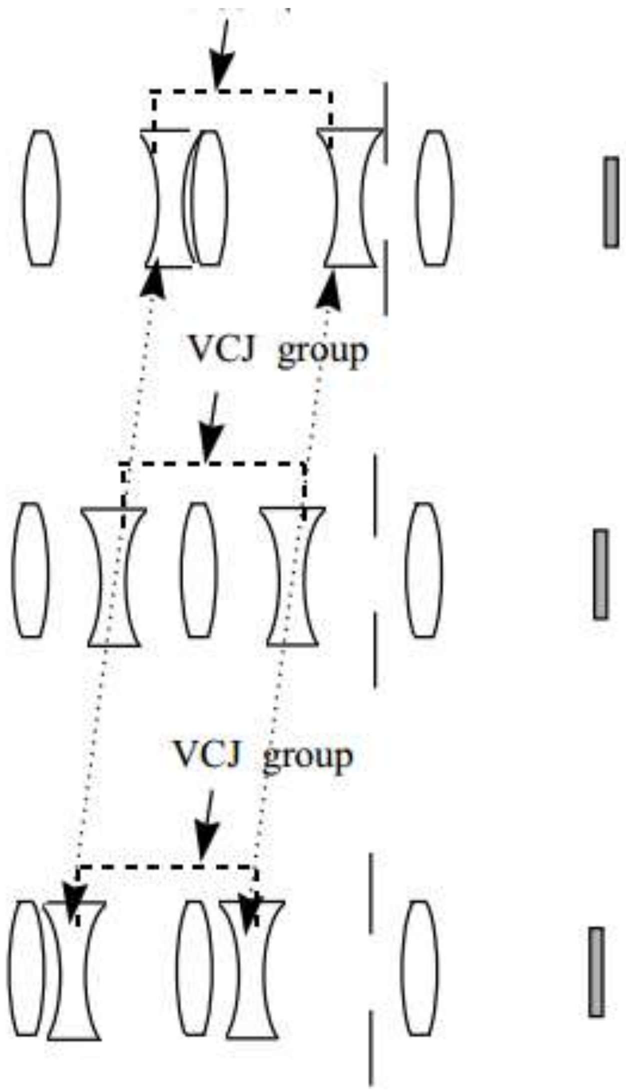
With X and Y lateral motion can scan/steer in any direction

You never know when it might rain and you will need an umbrella.

The Japanese invention shown next takes care of that situation.

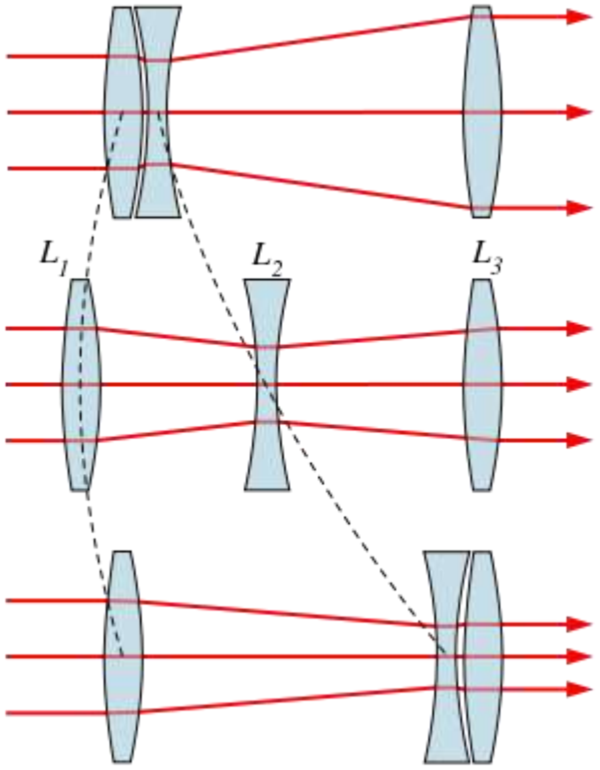
I like the idea of having two unrelated functions occupy the <u>same space</u> – putting more into the available “spatial box”

Next is an optical design based on that kind of idea – an unusual optically compensated zoom system.



Optically compensated single motion zoom

In a conventional zoom system there are two moving components – one to change the system focal length and the other to keep the focus stationary. In an optically compensated zoom there is only one motion but it is of linked moving lenses with a stationary lens(s) in between.



Two motion afocal zoom

I wondered if there was a way to fold the optically compensated system back onto itself so that the two linked negative lenses became a single lens = two lenses occupying the same space that become a single moving lens, but seen twice – in double pass.

Moving element

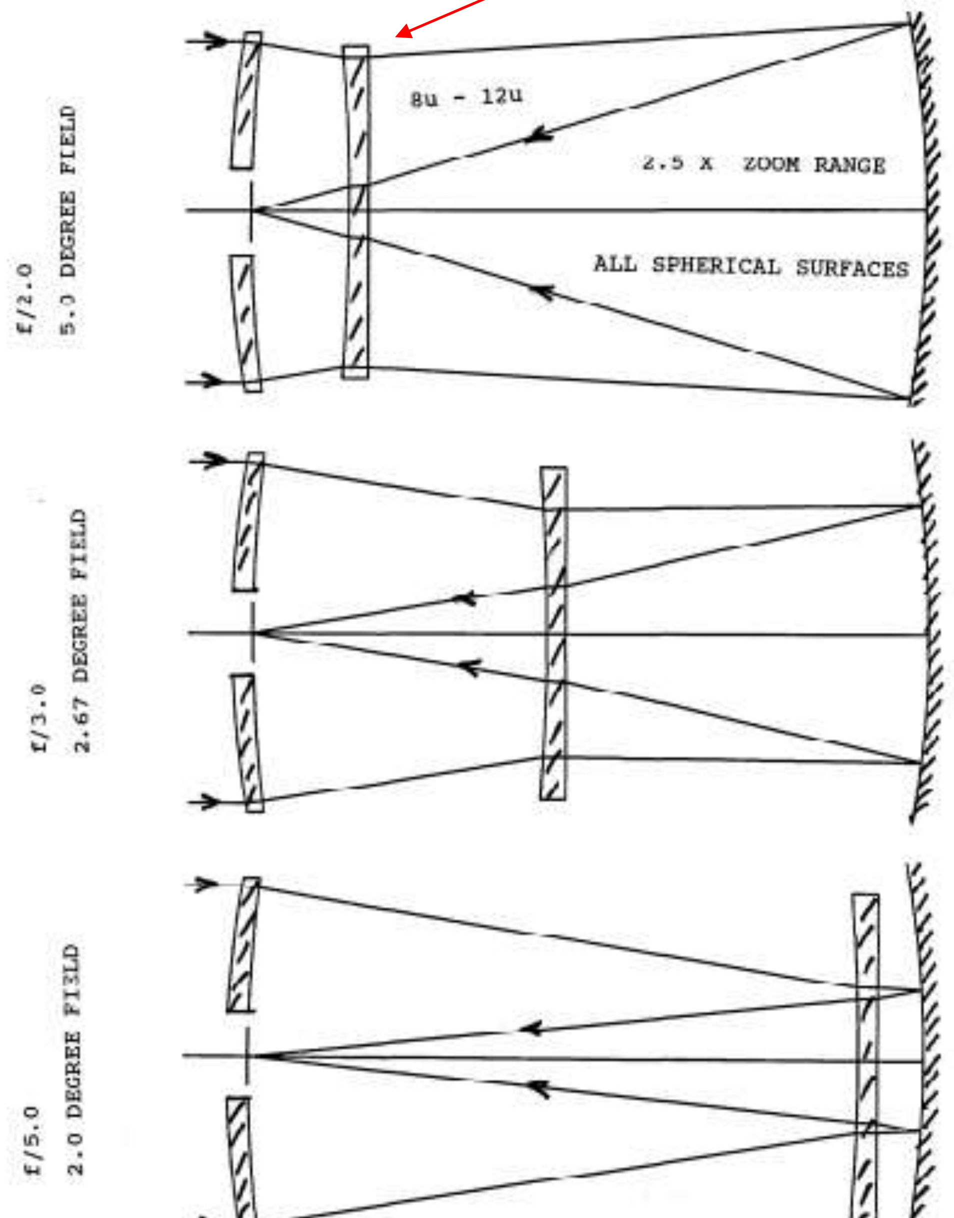
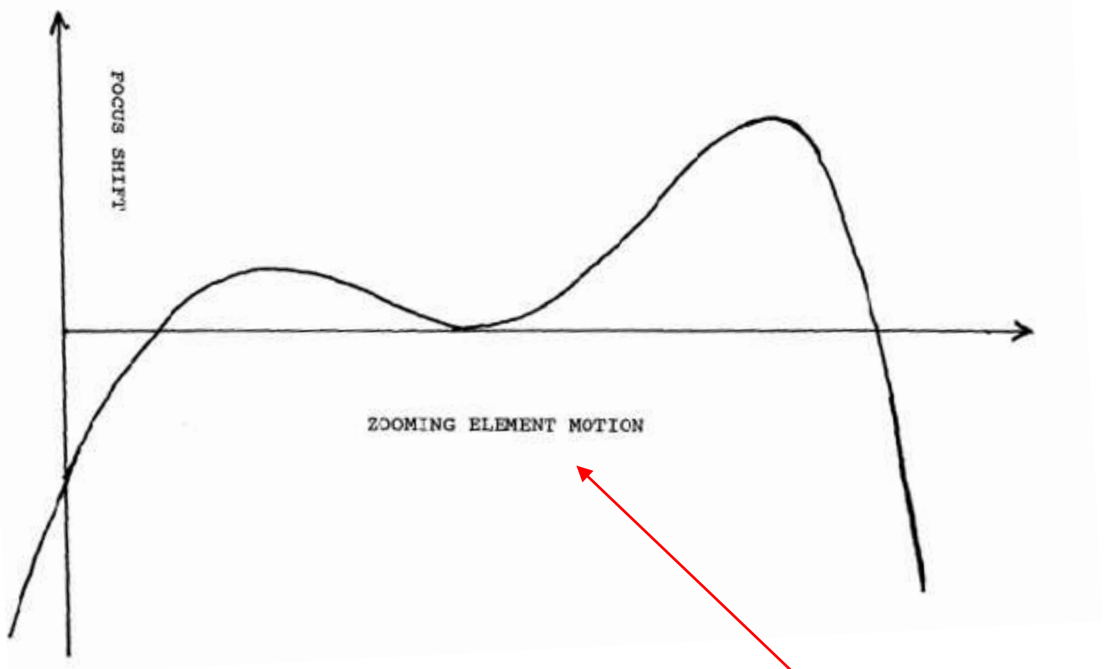


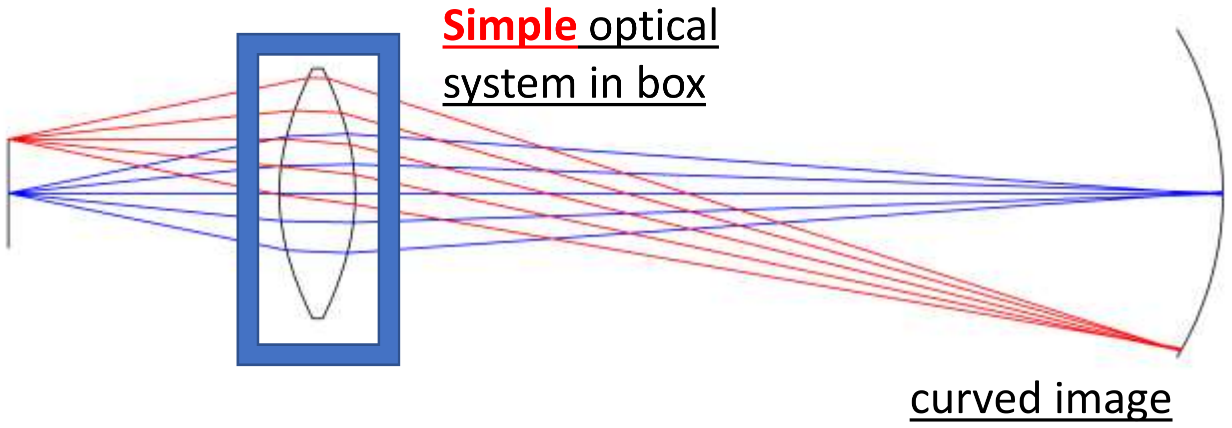
FIGURE 1



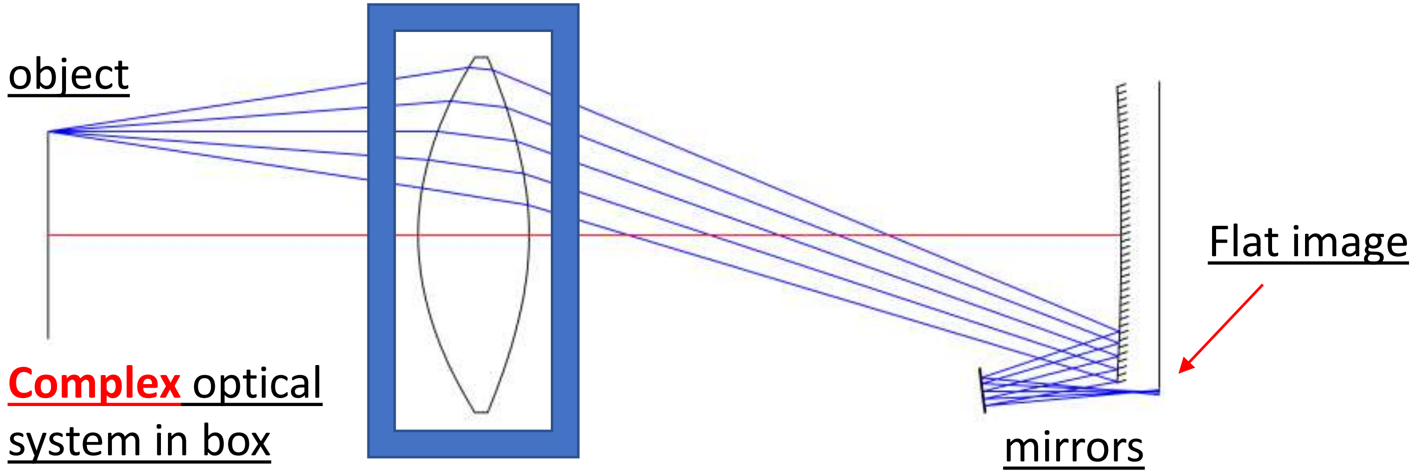
Single moving element optically compensated 2.5X zoom, with quartic focus shift.

During a huge winter snow storm about 14 years ago Willi Ulrich came to my house in the US and we brainstormed about getting some new lithographic design ideas. Zeiss had a range of lens/mirror designs for lithography but they all had problems –

with the package size or shape, the right/left orientation of the image, the image quality, too many mirrors, etc., etc. Willi hoped that maybe something had been missed and so he came to see me for that last push for some new kind of design.

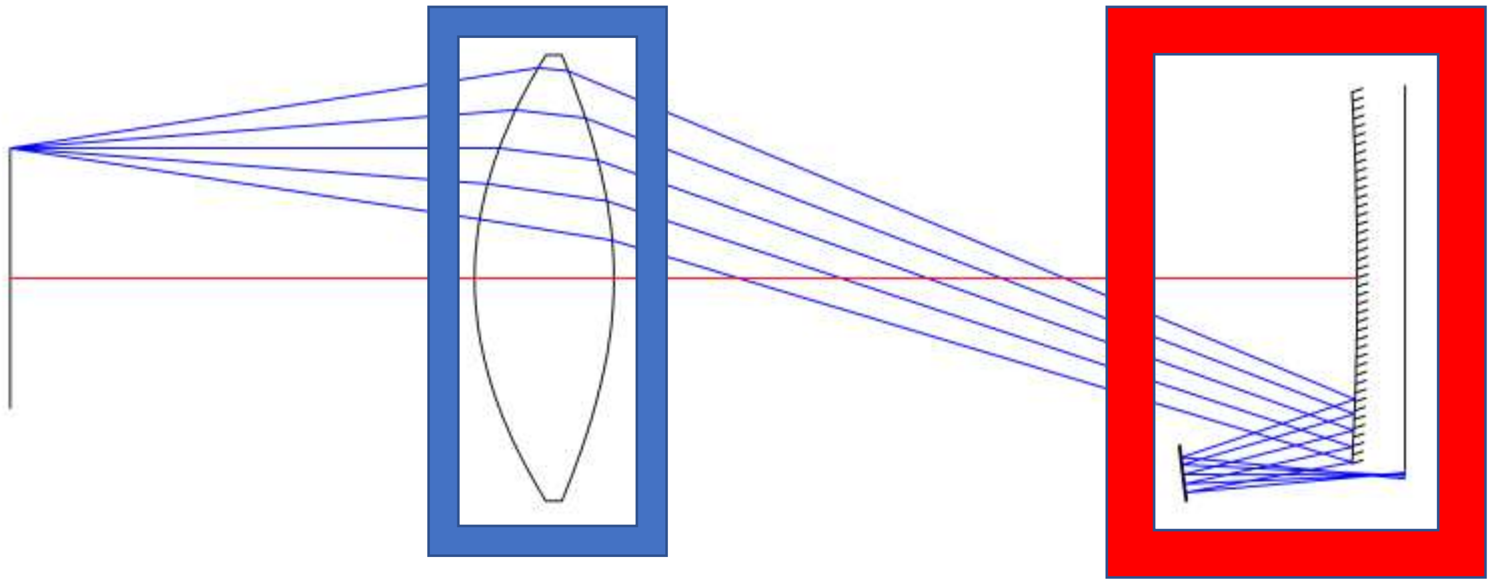


If a curved image is allowed then a relatively simple lens system can give good image quality over a large image size. But we need a flat image and that greatly increases the design complexity and cost.

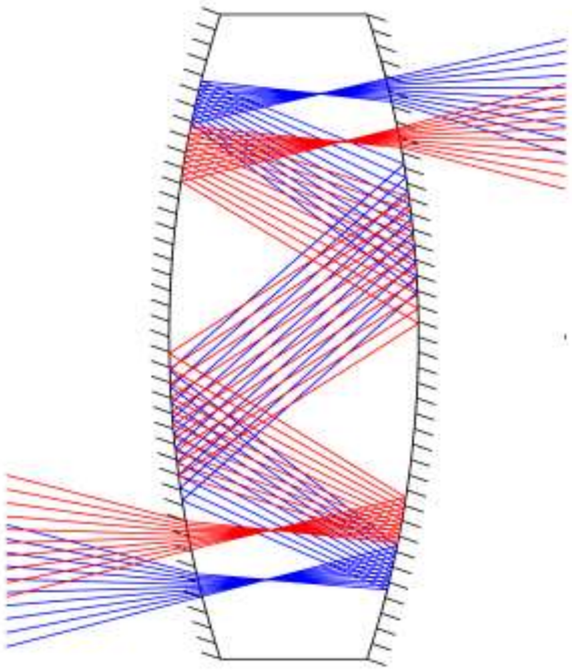


Adding two curved mirrors near the image can result in a flat image, but requires greater lens complexity

If mirrors are combined with lenses a flat image can be obtained without excessive design complexity. But there are always problems in making the light rays avoid being blocked by the mirrors. The penalty is usually obscuration, vignetting, or having to work far off-axis to avoid ray/mirror interference. That then gives bad image aberrations. **What to do?**

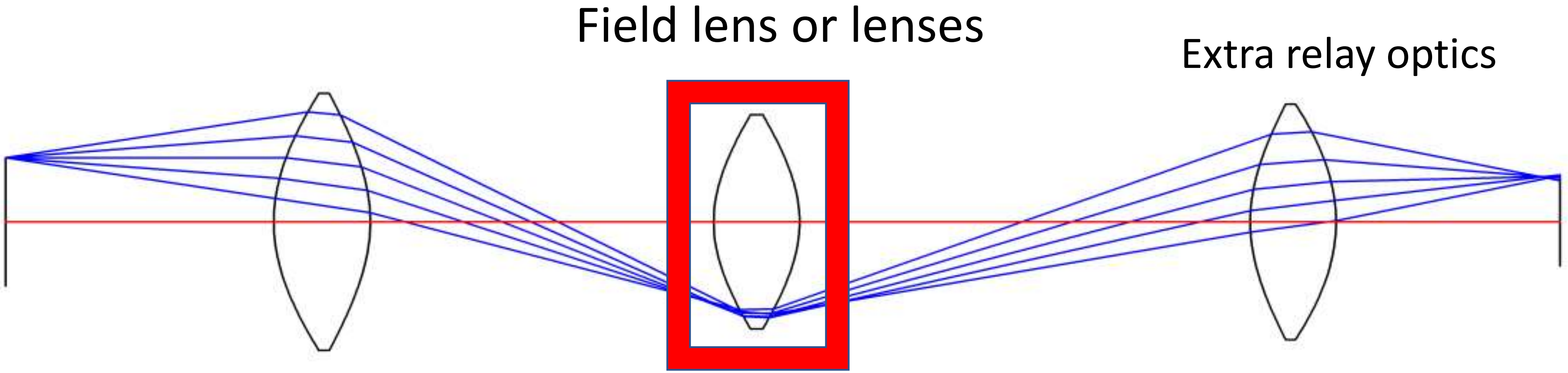


<u>One solution</u>

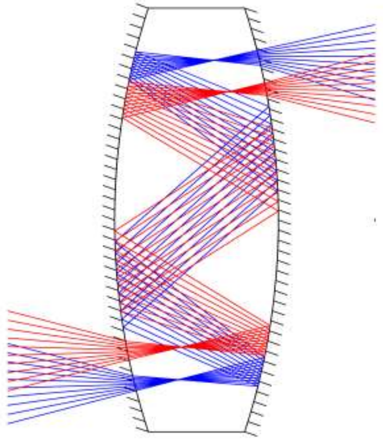


Think outside the box here – accept a <u>virtual</u> image here instead of a <u>real</u> image, then relay that with other lenses.

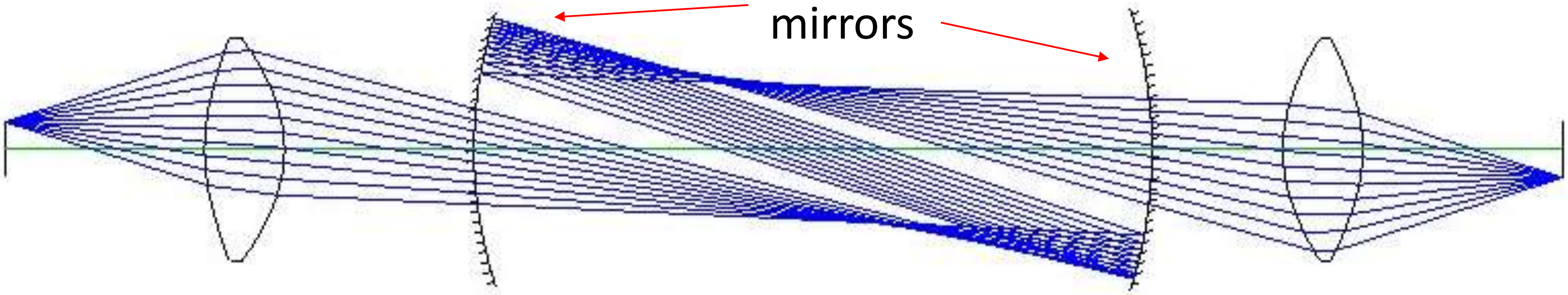
Here, at right, is a 4 reflection catadioptric field lens idea that gives a <u>virtual</u> image. Then we need relay lenses outside the box.



Replace refractive field lens with catadioptric or reflective field group to get a flat image.



There are problems with this kind of design and it did not look too promising at first. But Willi urged me to keep working along these lines and eventually a simpler and better solution was found, over the Christmas holiday.

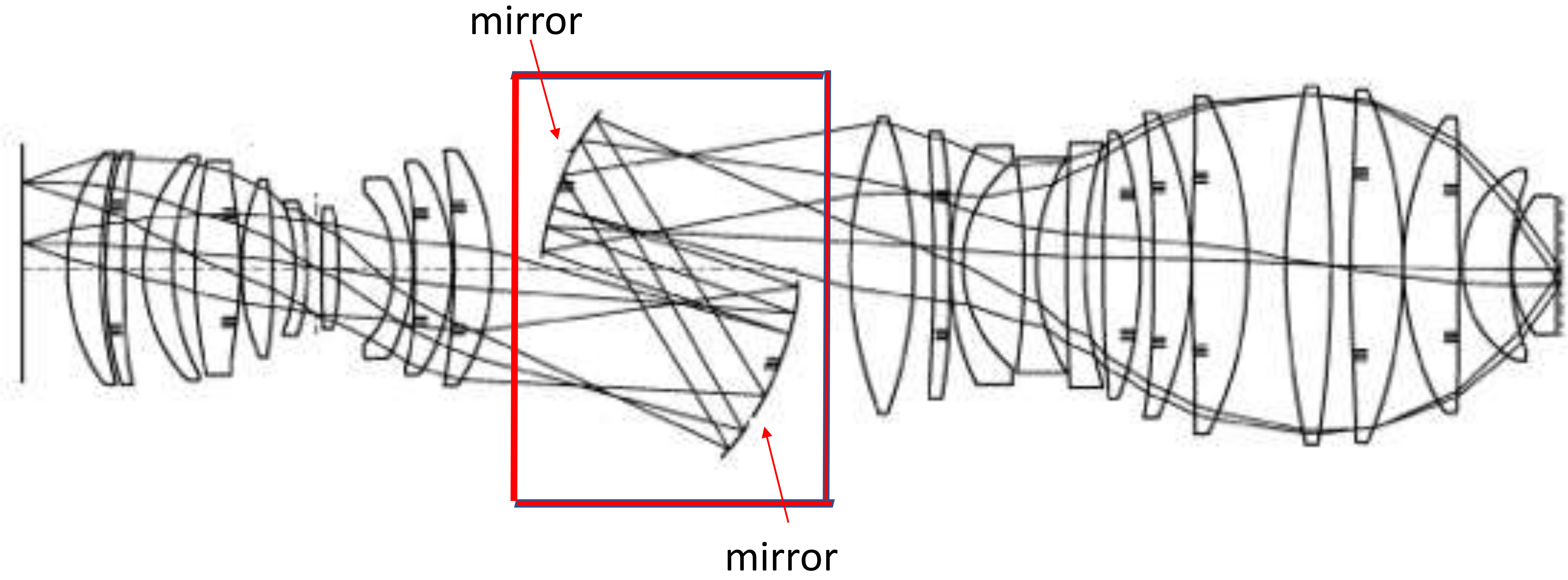


Simple 1.0 X magnification flat image design with aspheric elements

This is the conceptual basis for many Zeiss design patents for catadioptric lithography. Pretty obvious now, but not back then.

Typical Zeiss patent design for 4X magnification immersion lithography

Approximately collimated rays between the mirrors

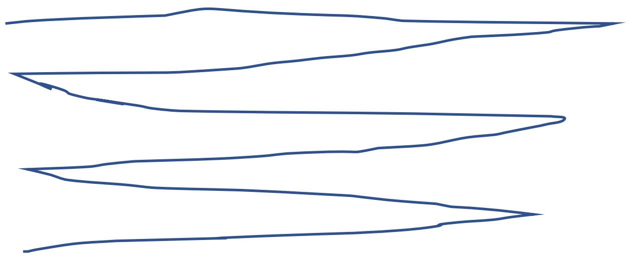


Here is a woman who can see far back towards where she has been and also very much has her eye on where she is going.

In business it is important to learn from the past but also to plan far ahead and try to spot hazards and opportunities in the path in front of you.

To close this talk I will show you a brilliant invention by a professional magician/inventor, who came up with an extremely simple idea about how to use a small space. It really shows thinking outside the box. <u>Literally</u> outside the box!

This extremely simple invention allows you to take a 2 ½ meter long pole from a small space, like a hat here. You may have ideas about how this can be done, but it is important to know that the pole diameter is exactly the same along its whole length.



And there are <u>no bends</u> in it when it is inside the box