OSHER LIFELONG LEARNING INSTITUTE

Opticks:

Optical Instruments

from Ancient Times to the Present

Session 4
Modern Instruments

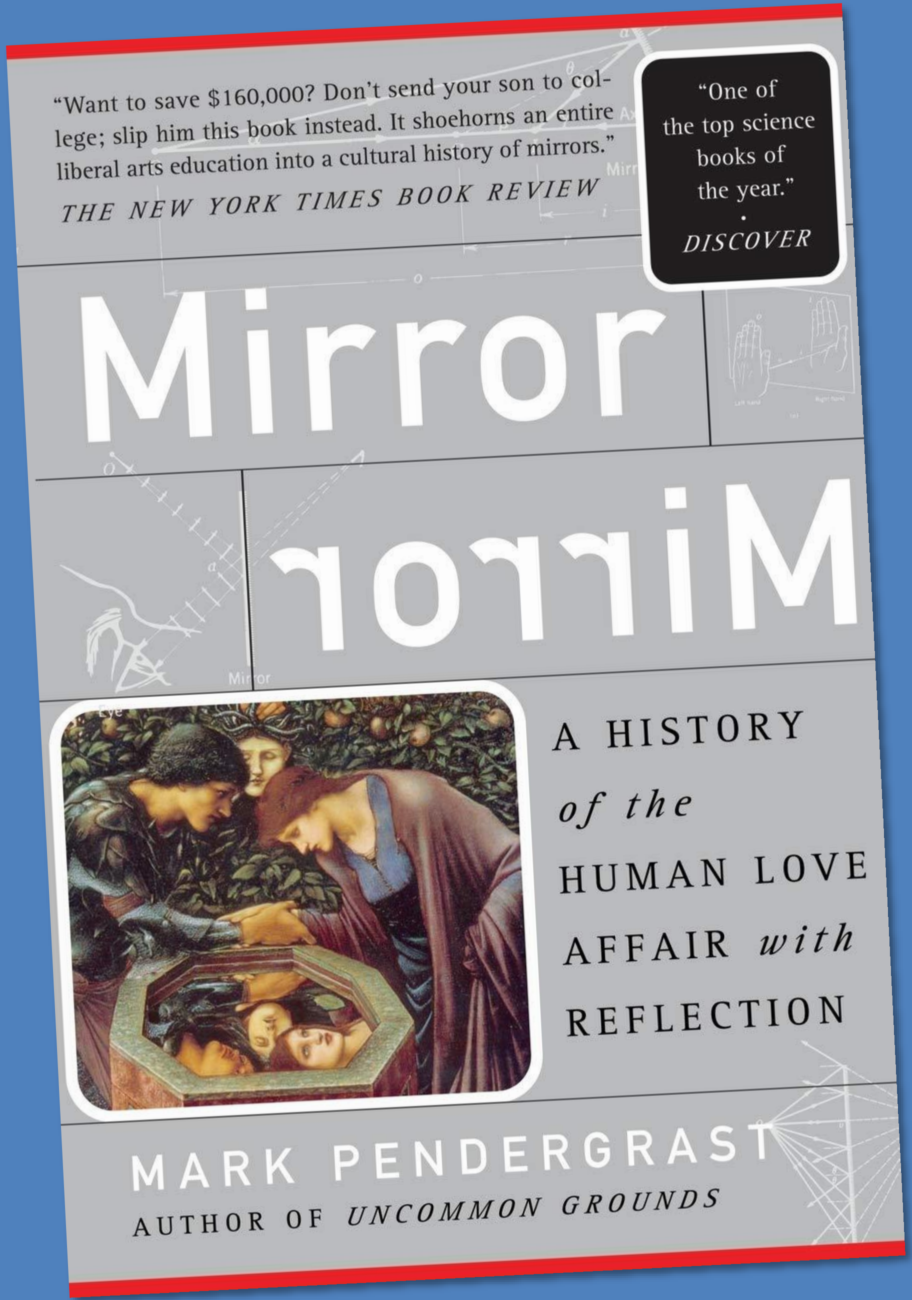
OLLI at Illinois

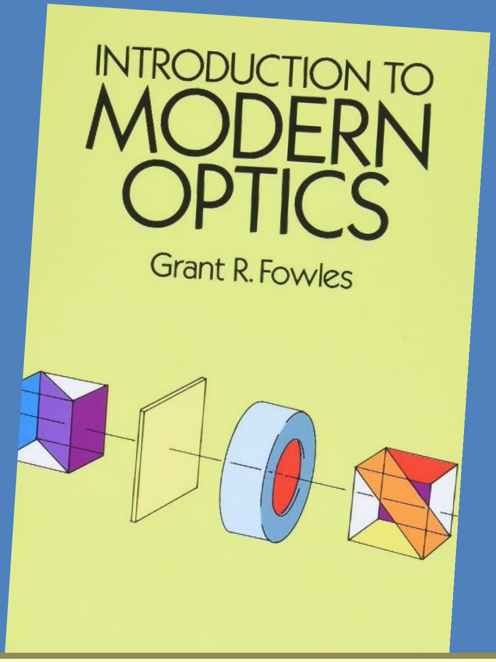
Spring 2022

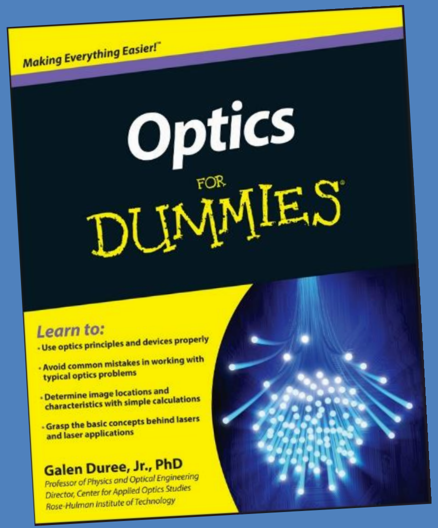
D. H. Tracy

Course Outline

1. Beginnings: Optics in the Ancient World and the Middle Ages; Mirrors and Lenses
2. Renaissance and Pre-Renaissance developments, culminating in Newton's Opticks. The eye. Early telescopes & microscopes. Art and Optics.
3. 18th and 19^{th} Century developments, including Maxwell and the modern understanding of light.
4. Modern Optics and the methods used to design and build them. Lasers, fiberoptics, holograms, space telescopes, semiconductor lithography, gravity wave detectors, and the camera in your cell phone.

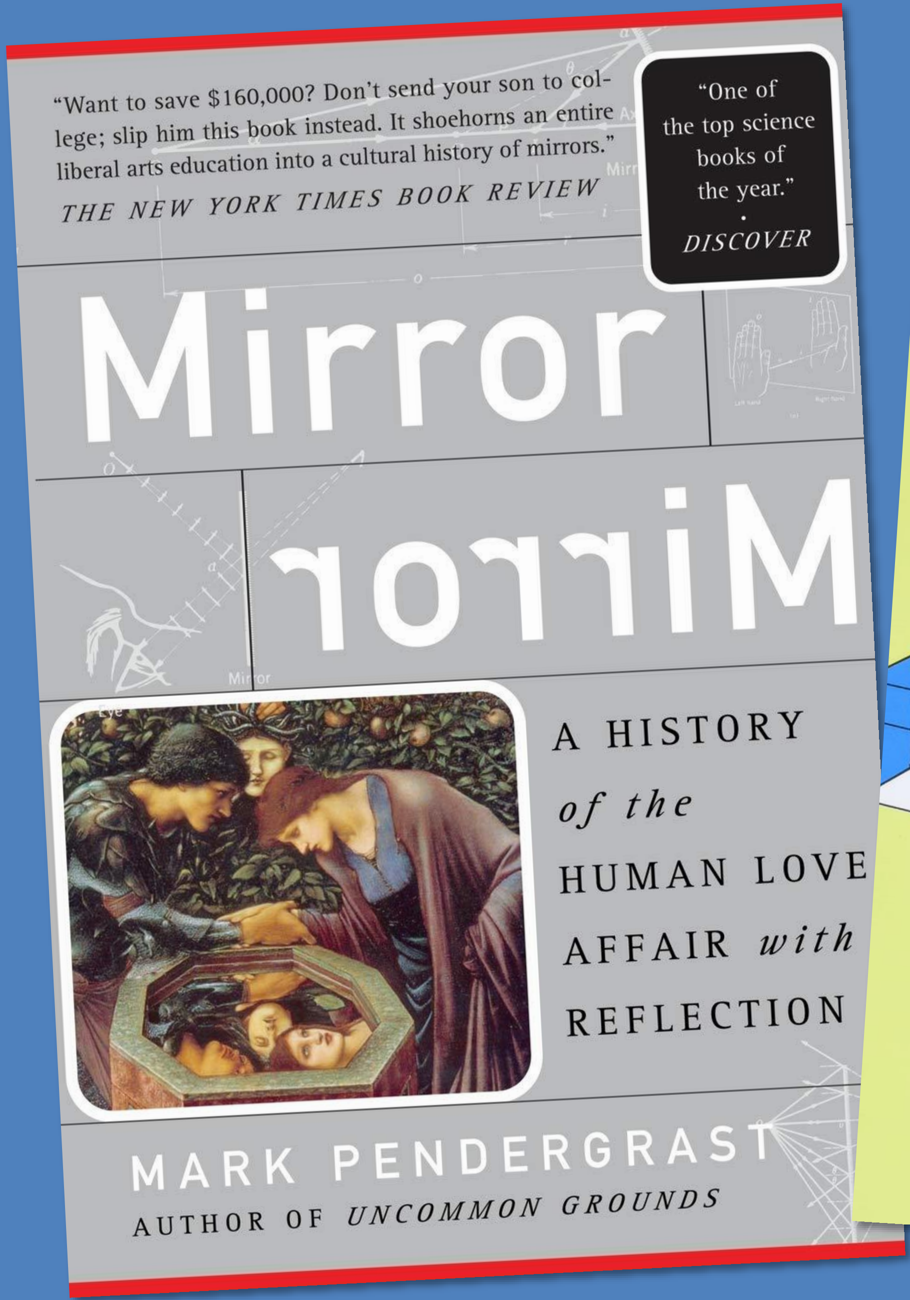






"Want to Save $160,000? Don't send your son to college: slip him this book instead. It shoehorns an entire liberal arts education into a cultural history of mirrors."

New York Times Book Review



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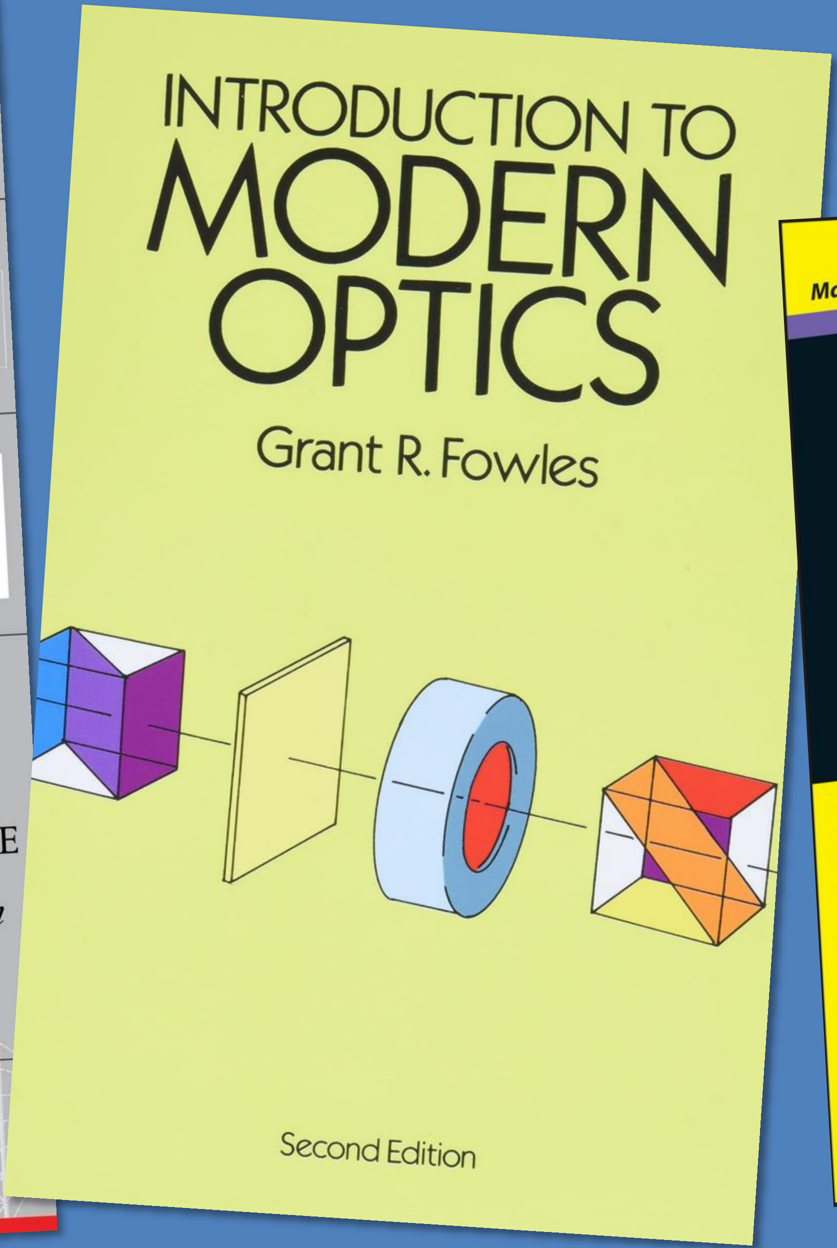
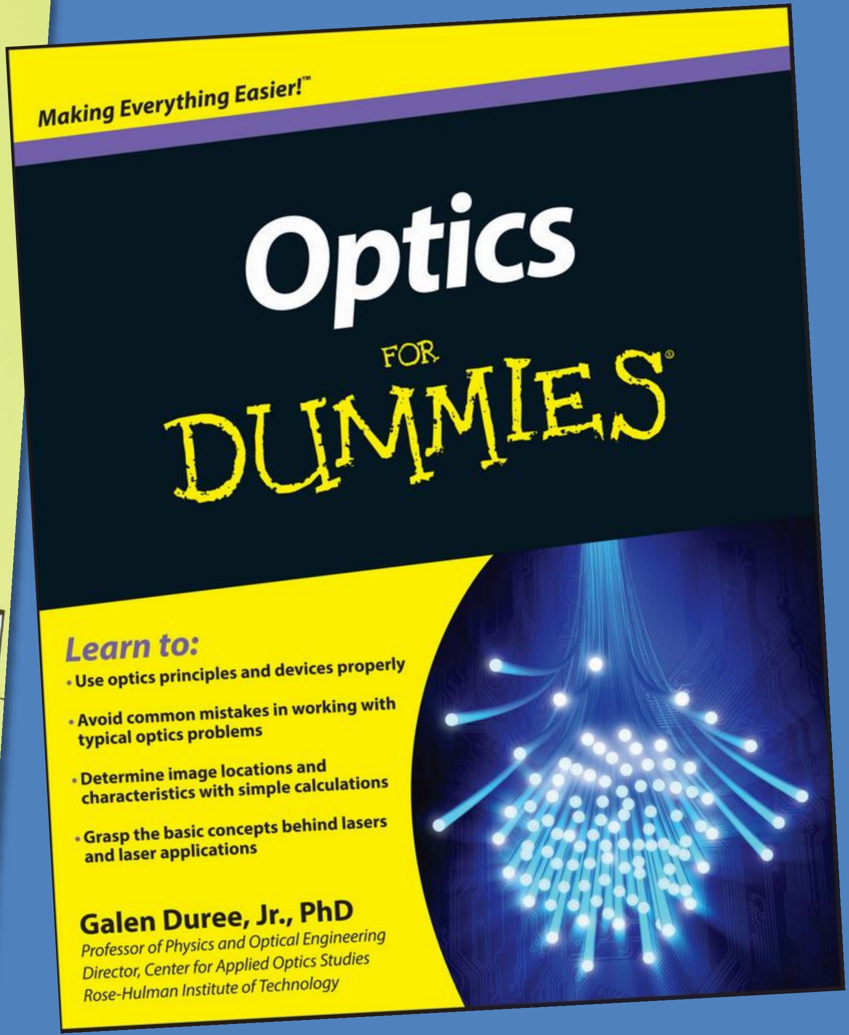
THE NEW YORK TIMES BOOK REVIEW
"One of the top science books of the year." • DISCOVER
Mirror Mirror
A HISTORY of the HUMAN LOVE AFFAIR with REFLECTION
MARK PENDERGRAST
AUTHOR OF UNCOMMON GROUNDS



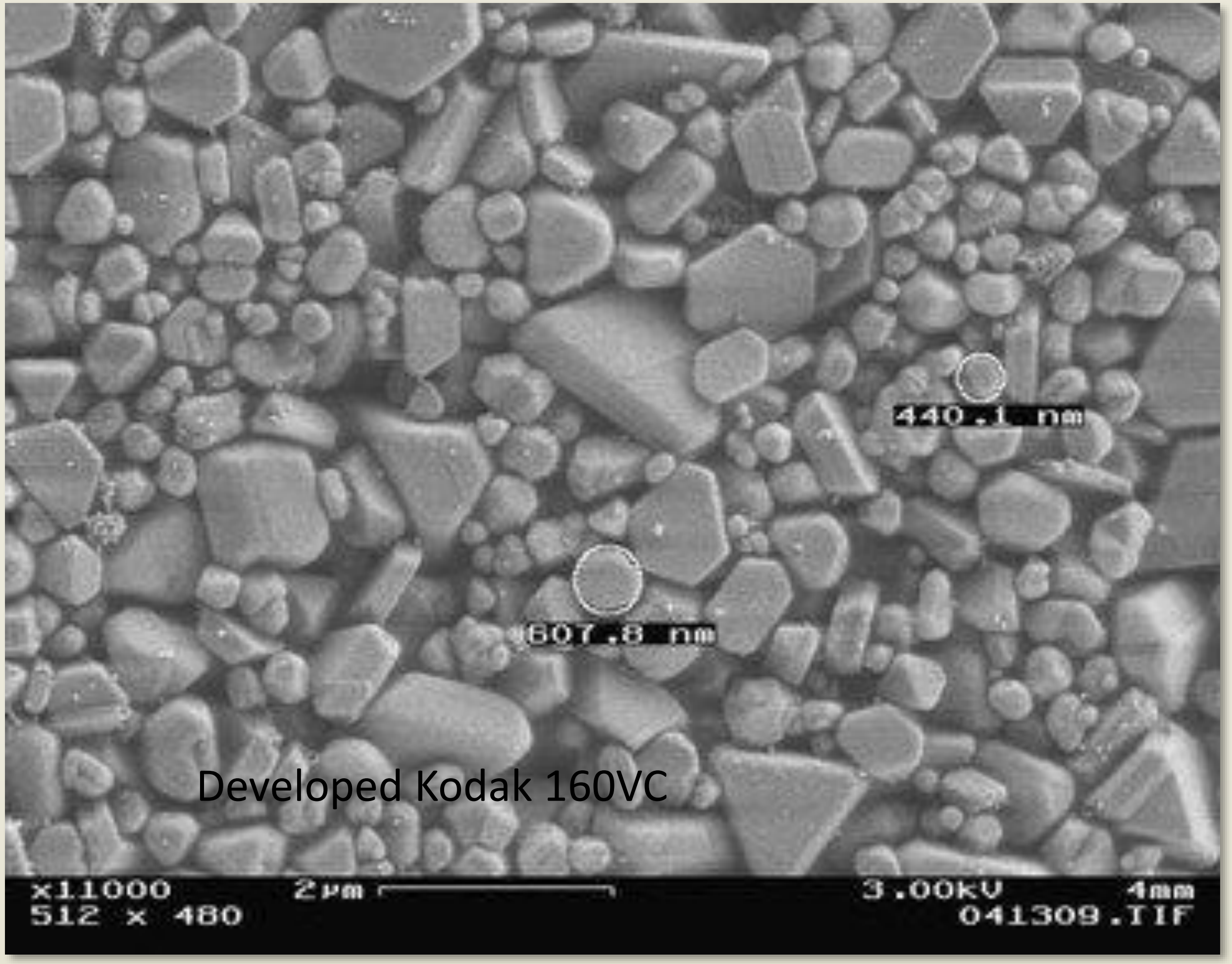
INTRODUCTION TO MODERN OPTICS
Grant R. Fowles
Second Edition



Making Everything Easier!™
Optics FOR DUMMIES®
Learn to:
• Use optics principles and devices properly
• Avoid common mistakes in working with typical optics problems
• Determine image locations and characteristics with simple calculations
• Grasp the basic concepts behind lasers and laser applications
Galen Duree, Jr., PhD
Professor of Physics and Optical Engineering
Director, Center for Applied Optics Studies
Rose-Hulman Institute of Technology

Photography

Silver Halide micro-crystals (AgI, AgBr, AgCl) prepared in the dark are light sensitive



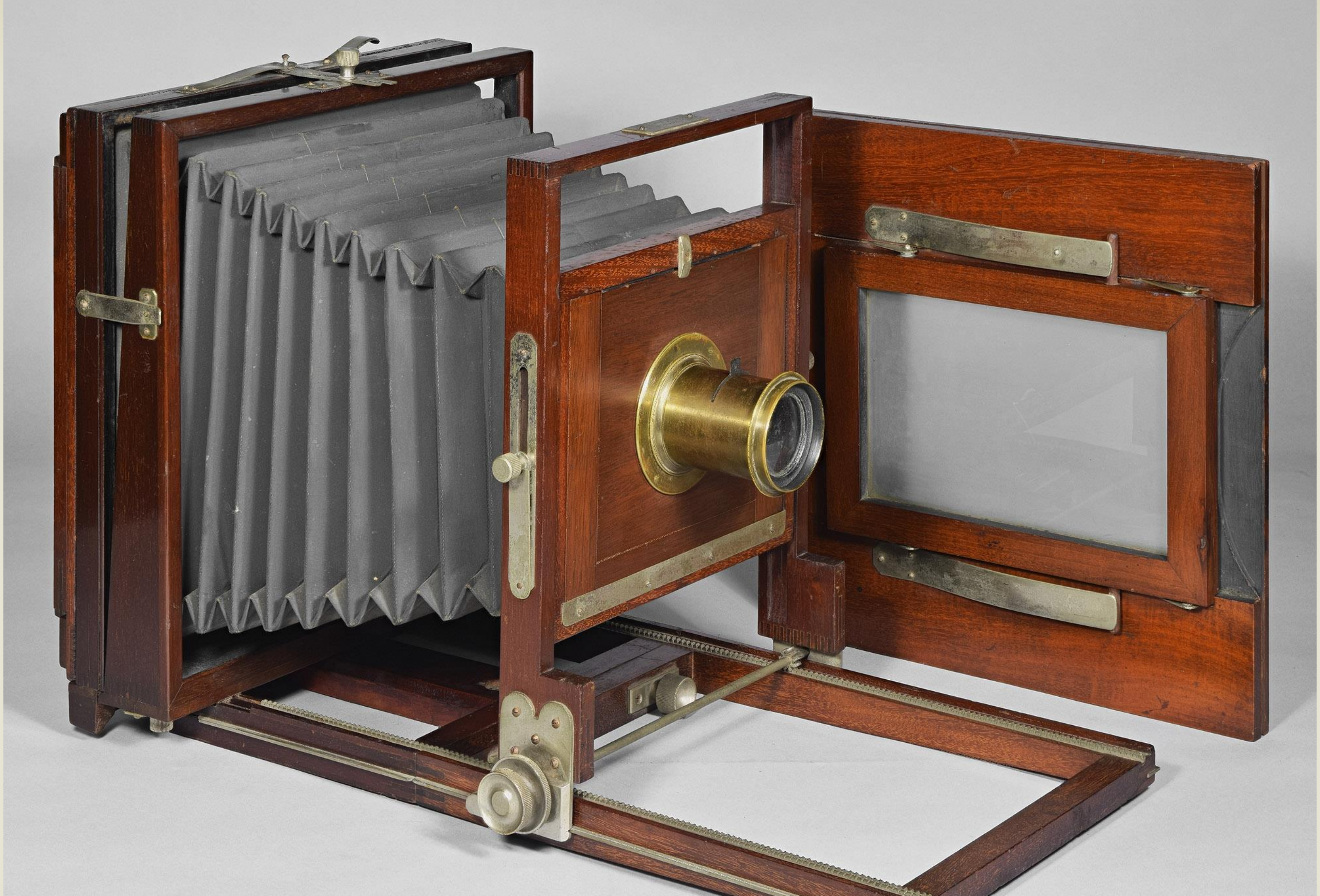
Developed Kodak 160VC

The first Silver Halide Camera: Giroux Daguerreotype Camera (1839)

400 Francs
(6 months' wages)

Photographic Cameras

- Silver halides as light sensing media
- Lens similar to Camera Obscura or Magic Lantern, but
  - Aperture a priority with initial slow photo plates
- Special requirements:
  - Keeping all light out
  - Shutter, adjustable time
  - Focusing means – *big deal*
  - High speed (large aperture, small f/Number)
    - Iris diaphragm (variable aperture)
  - Wide field angle

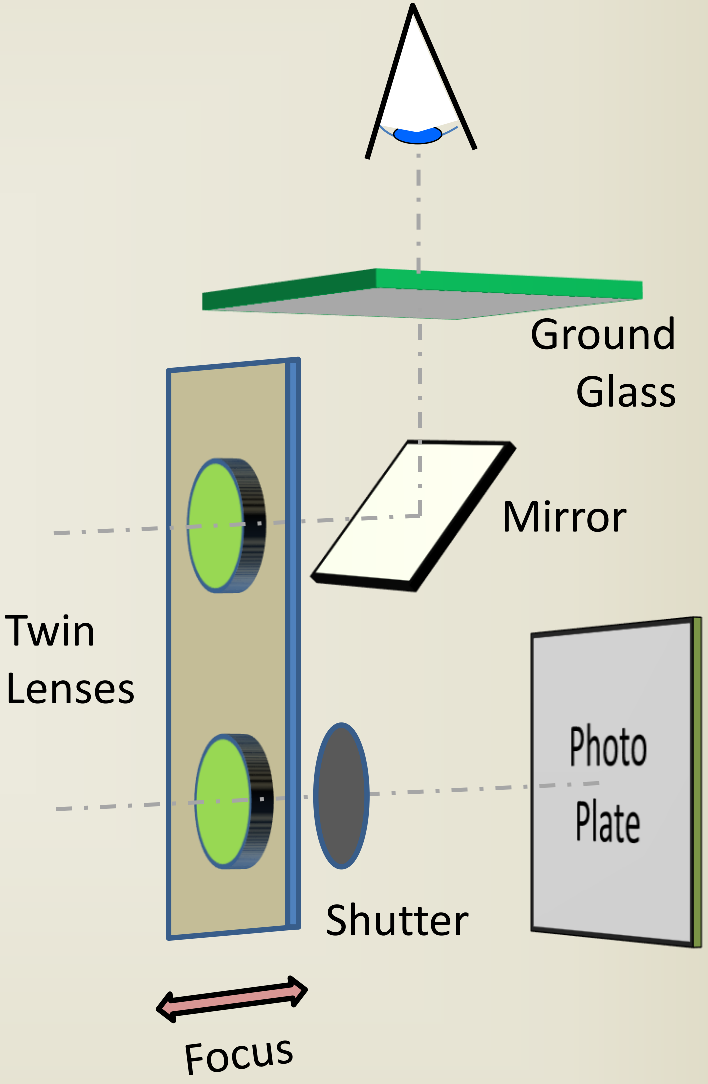


Blair Tourograph & Dry Plate Co. (1884)

Focus by observing image on ground glass plate

Another Way of Focusing:

Twin Lens Reflex

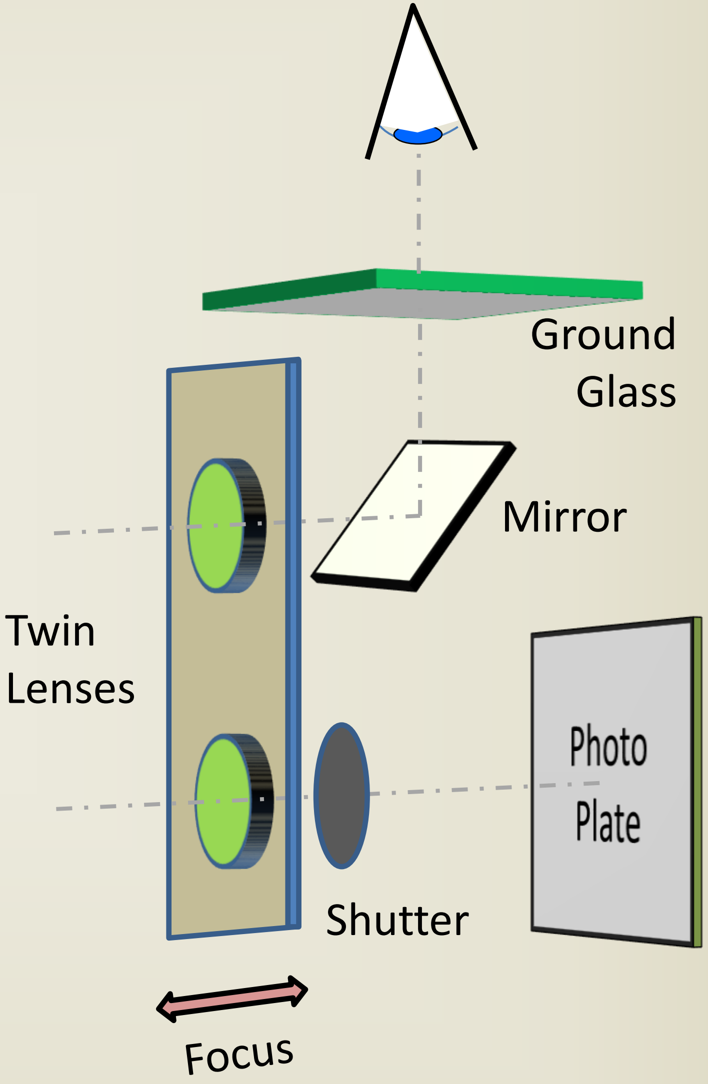


Another Way of Focusing:

Twin Lens Reflex


London Stereoscopic Carlton (ca 1884)

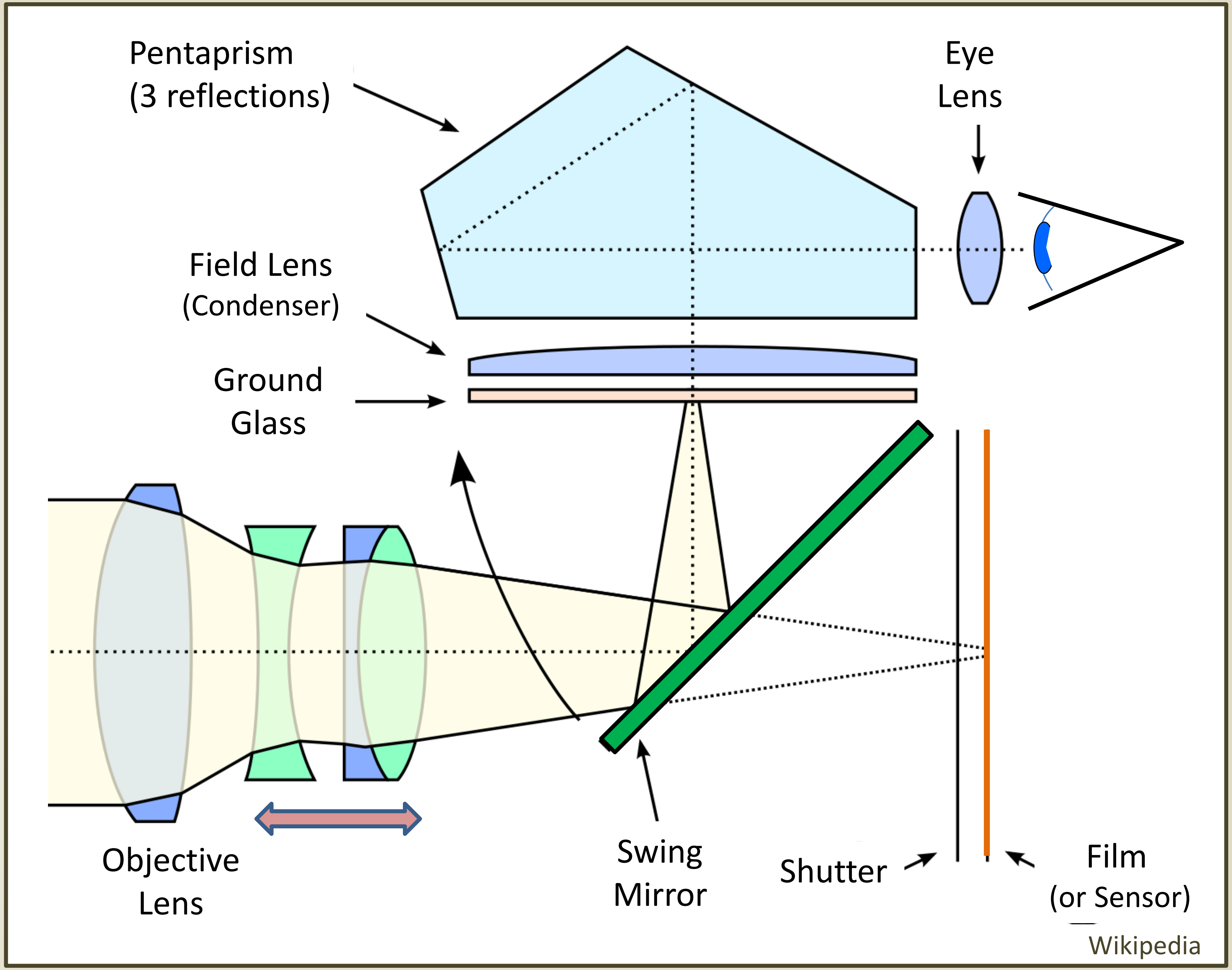
Wikipedia



Still Another Focus Method: Single Lens Reflex (SLR)

Focusing and Film Exposure Use the same Lens.

A fold mirror quickly swings out of the way for the exposure.



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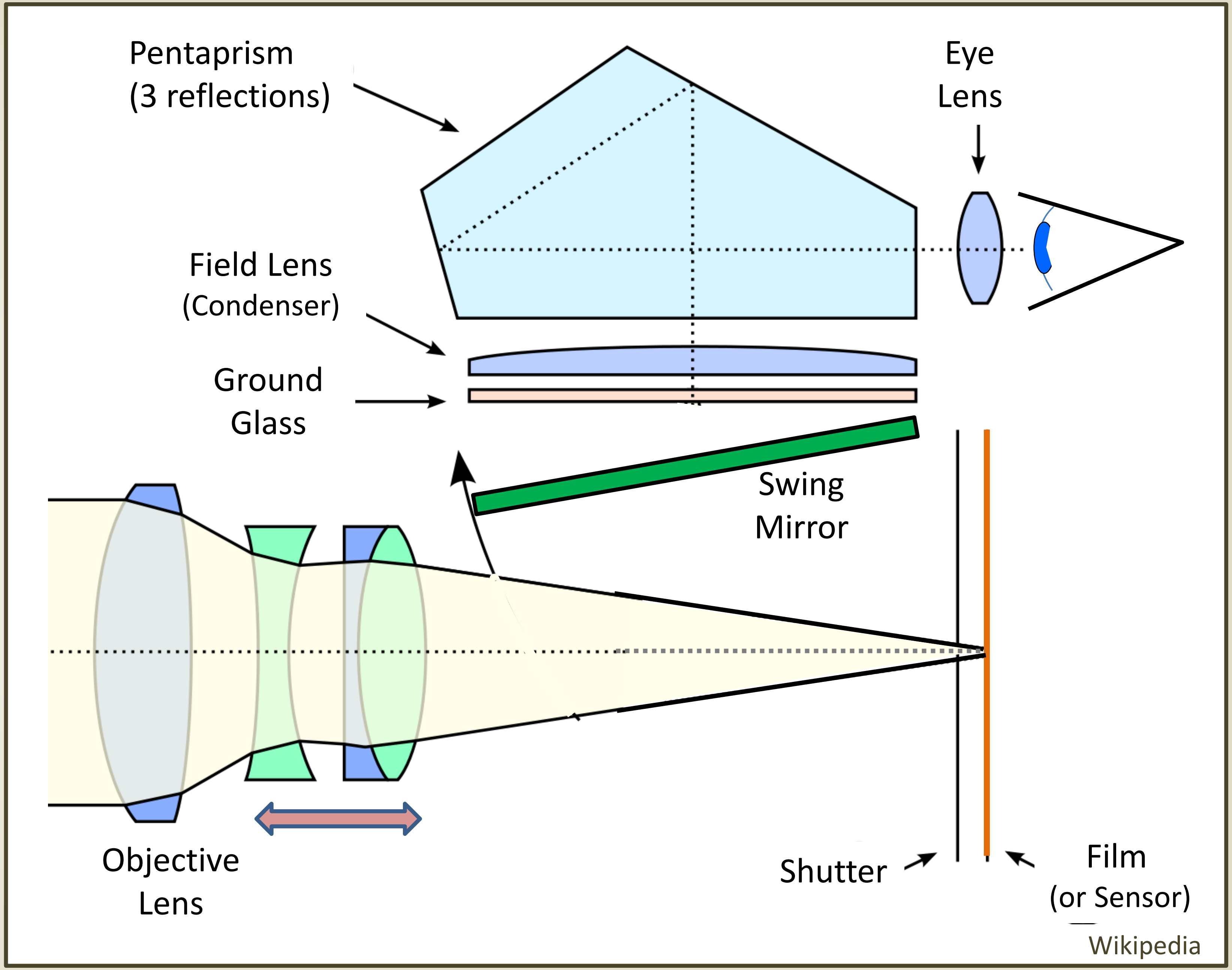

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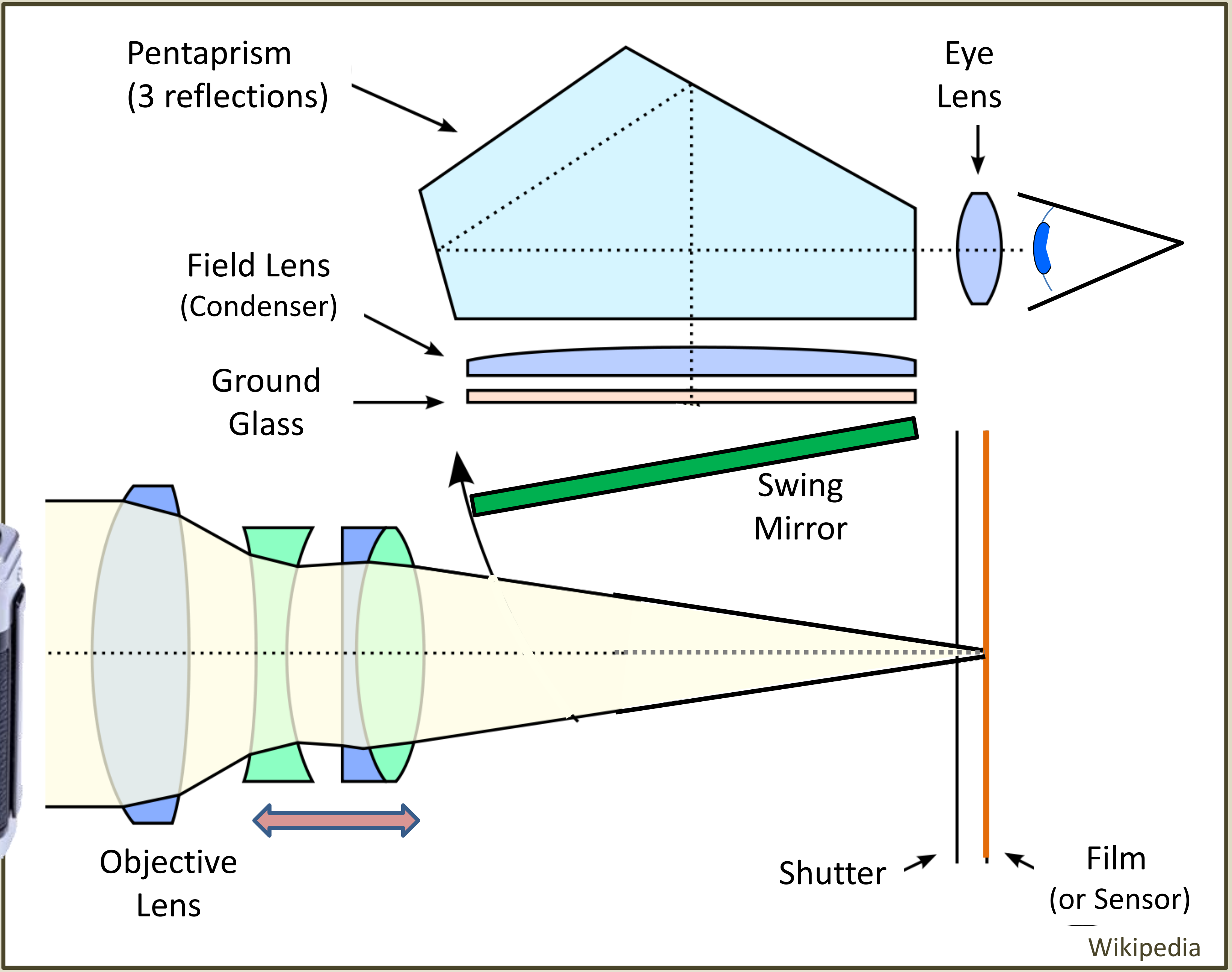
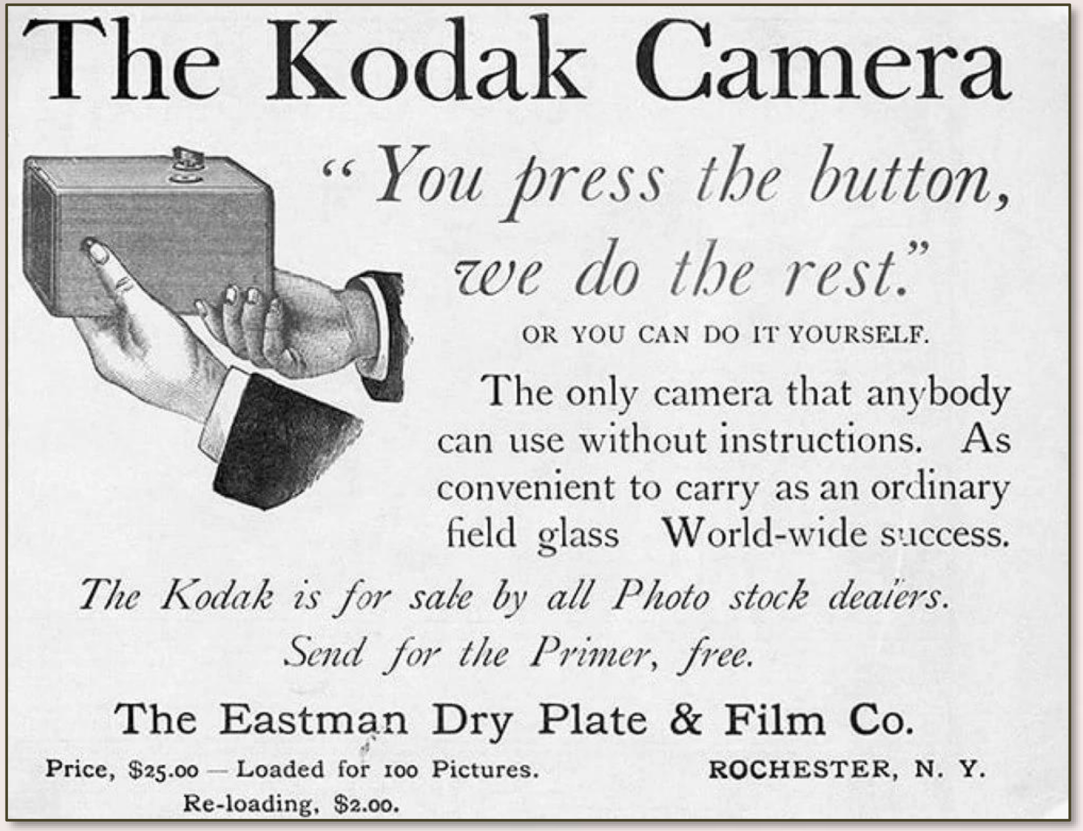


Fixed Focus


The Kodak Camera
"You press the button,
we do the rest."
OR YOU CAN DO IT YOURSELF.
The only camera that anybody can use without instructions. As convenient to carry as an ordinary field glass World-wide success.
The Kodak is for sale by all Photo stock dealers.
Send for the Primer, free.
The Eastman Dry Plate & Film Co.
Price, $25.00 — Loaded for 100 Pictures.
Re-loading, $2.00.
ROCHESTER, N. Y.

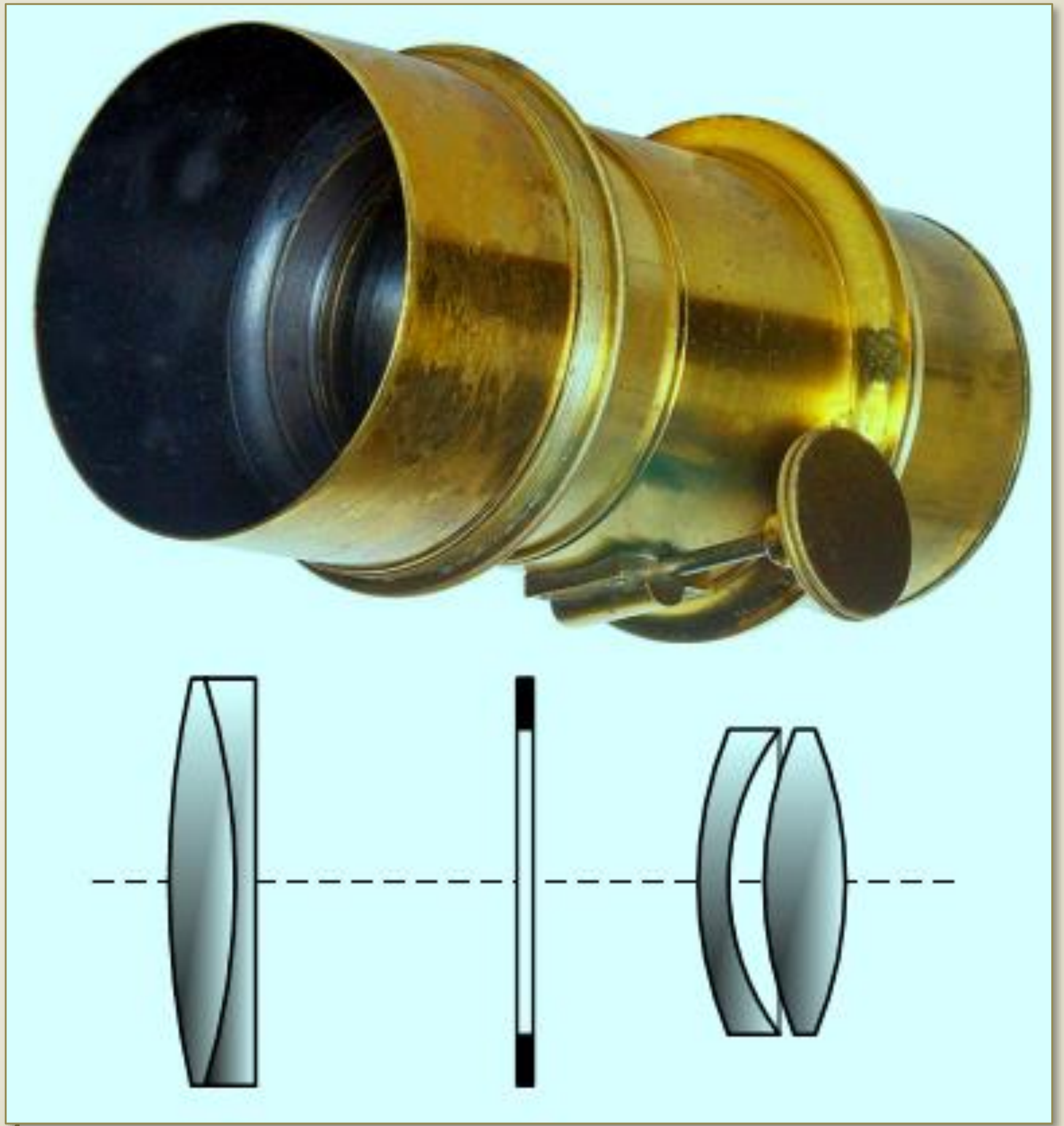
Joseph Petzval
Viennese
Mathematician

Breakthrough:

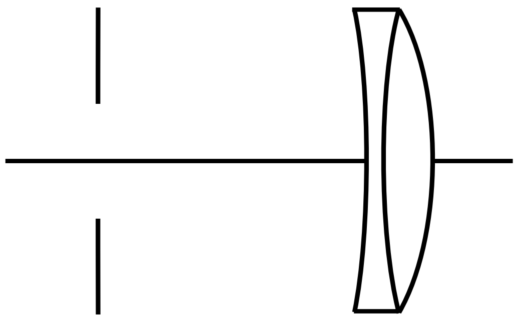
The Petzval Portrait Lens
1840
Large Aperture (f/3.6)
Exposure time reduced by 22x

The first fully mathematically calculated lens design

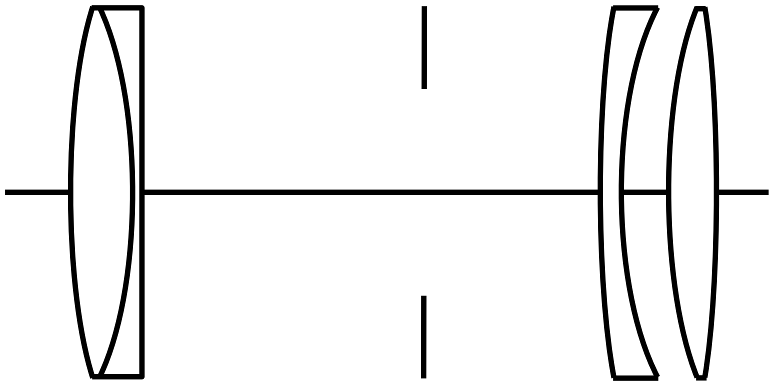
Borrowed the services of
11 Artillery Gunners
for calculations
(Archduke Louis of Austria)



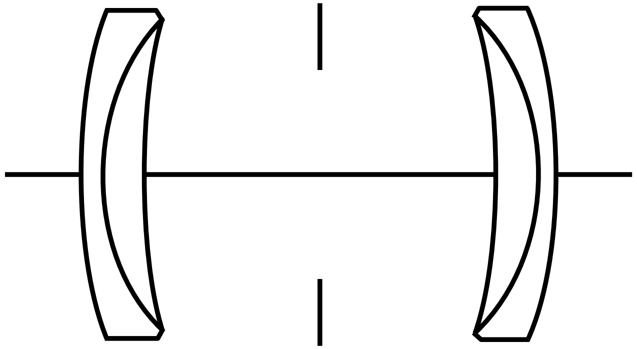
Basic 19th Century Photography Lens Arsenal



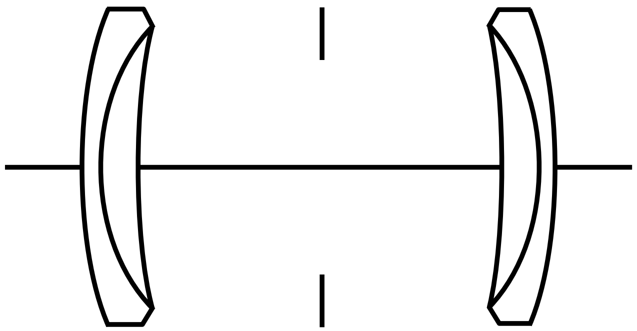
Chevalier Achromat Landscape, 1839



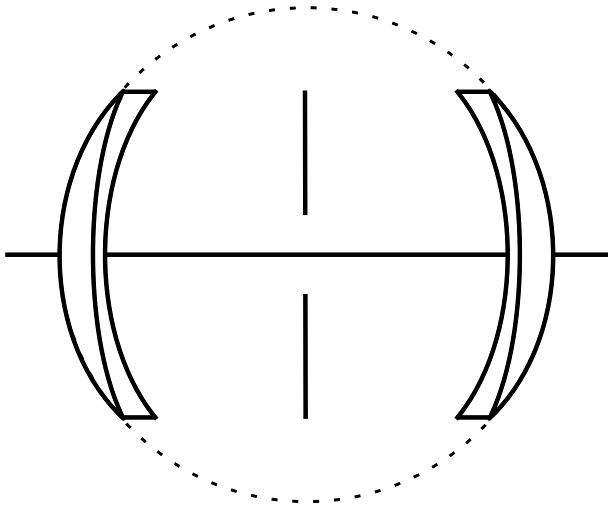
Petzval Portrait, 1840



Dallmeyer Rapid-Rectilinear, 1866



Steinheil Aplanat, 1866

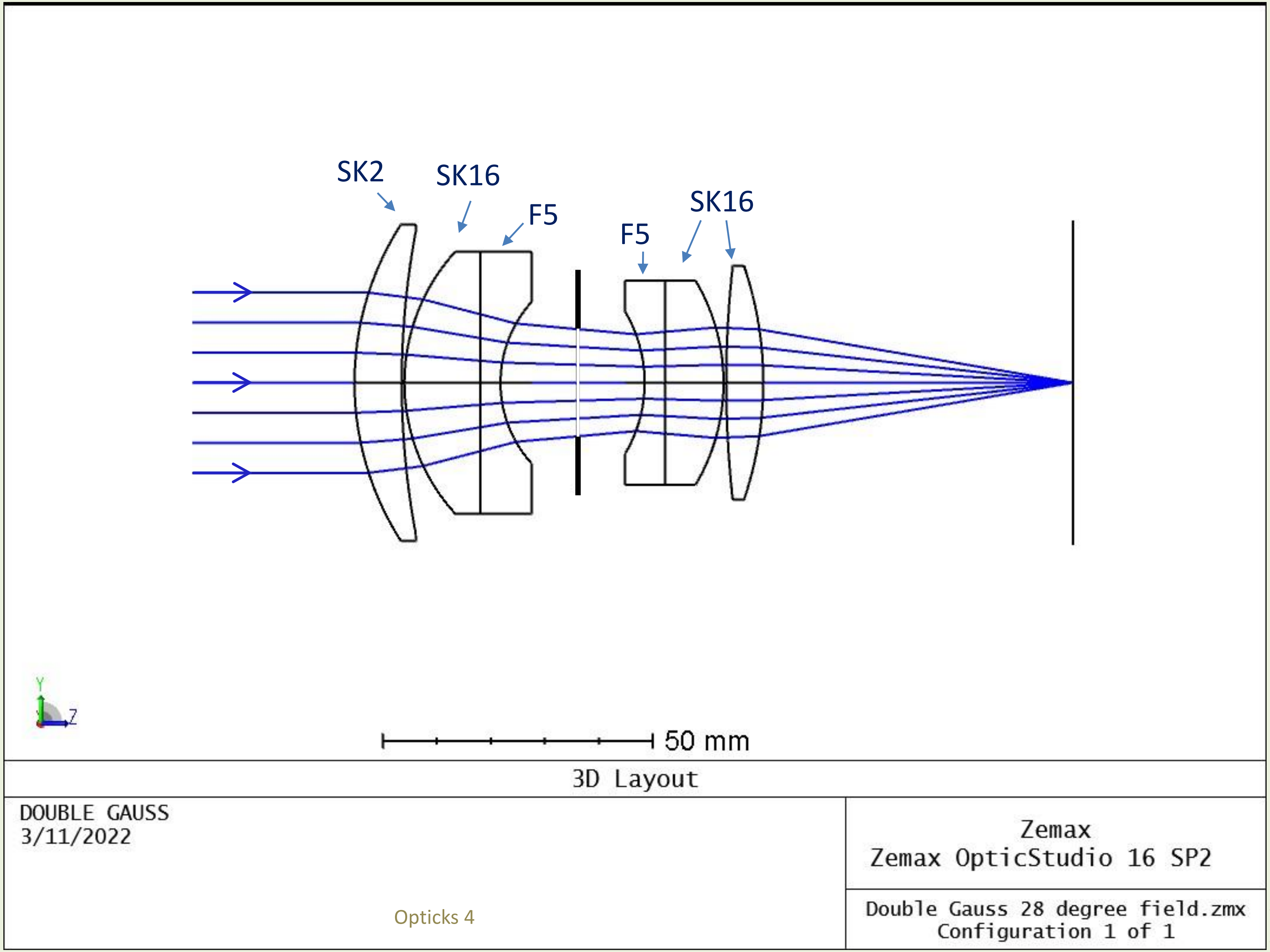


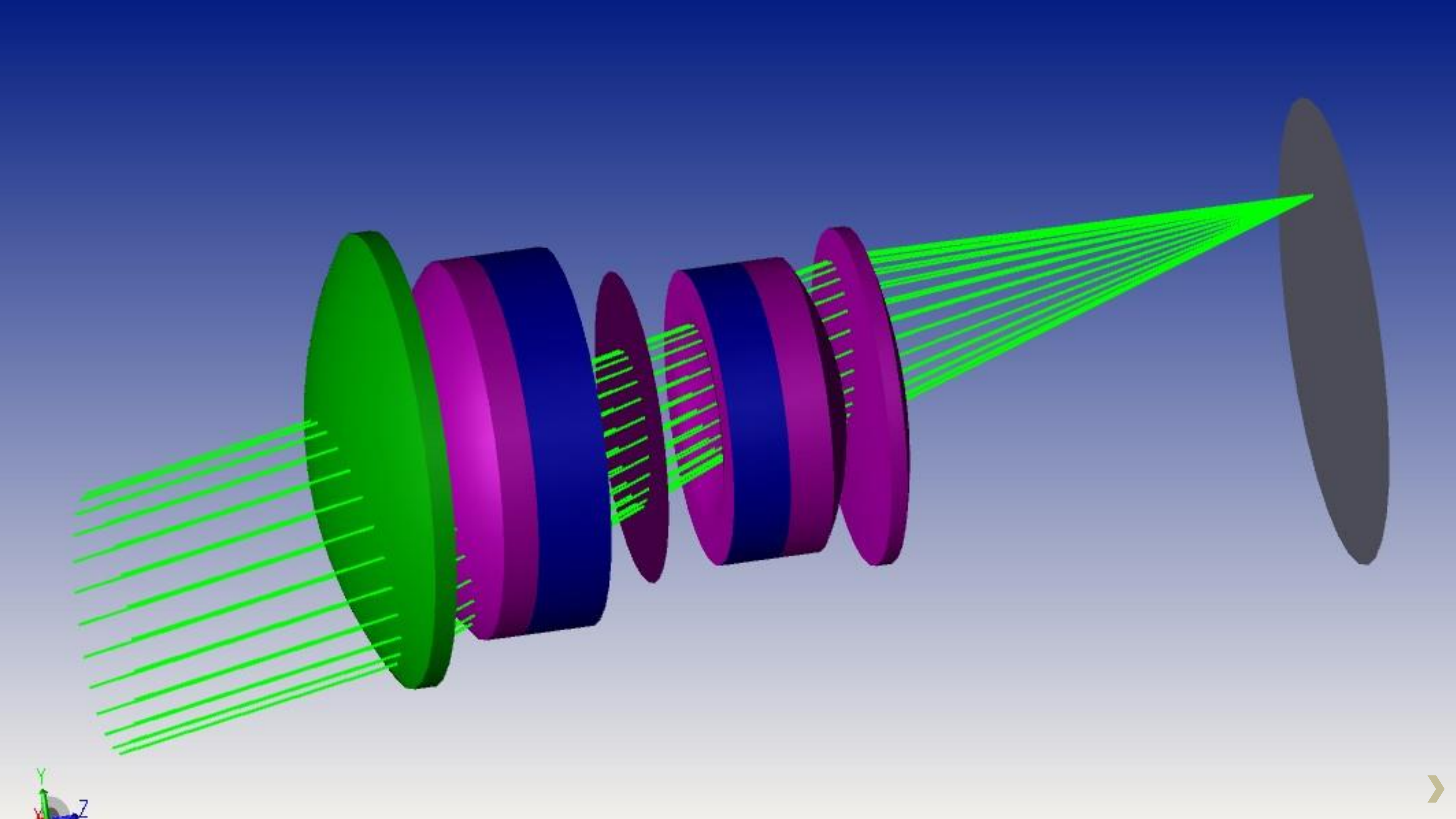
Harrison & Schnitzer Globe, 1862

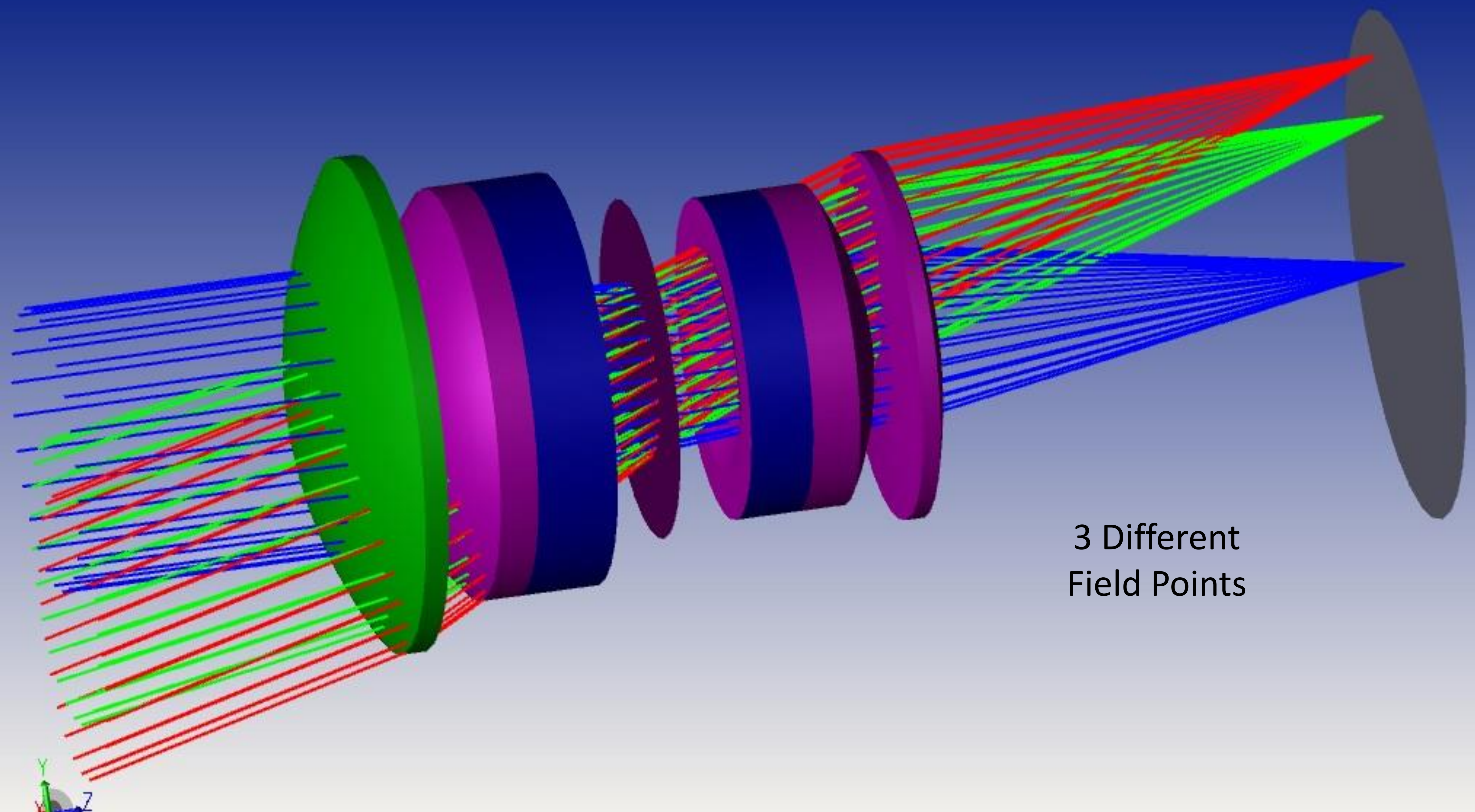
Wikipedia

Example of a Photographic Lens Model in a Ray Tracing Program

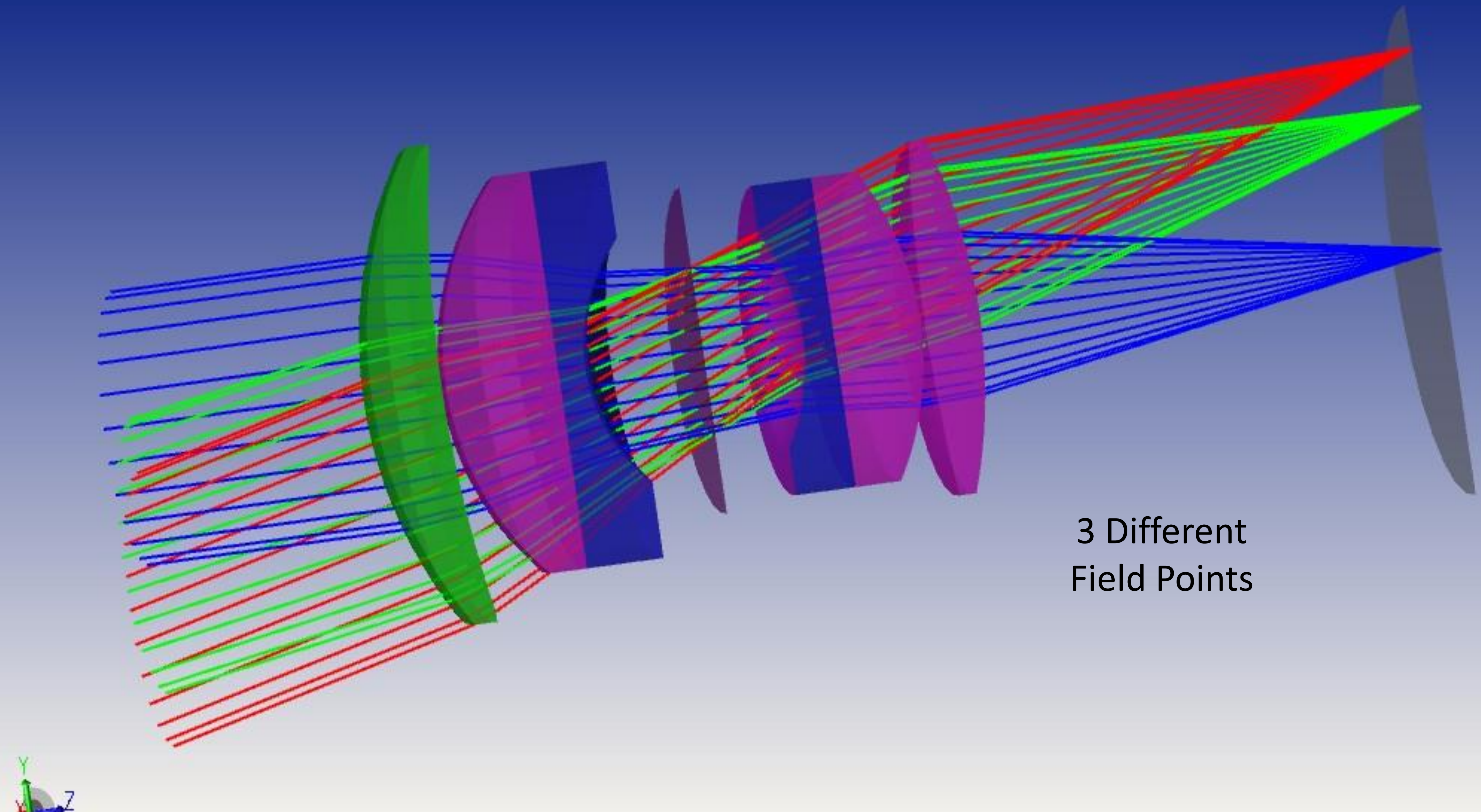
How are optical systems designed?




Y
Z



3 Different
Field Points



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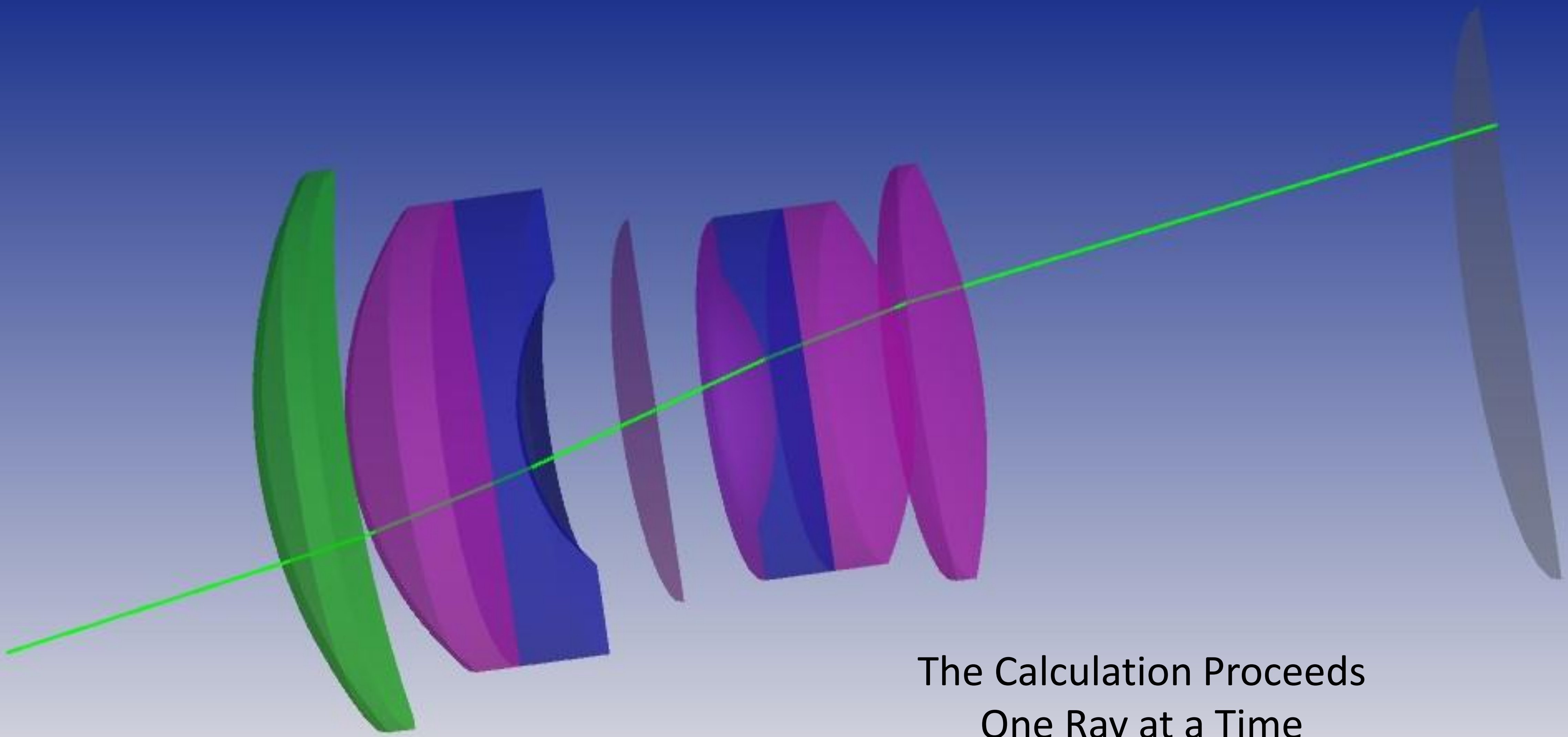
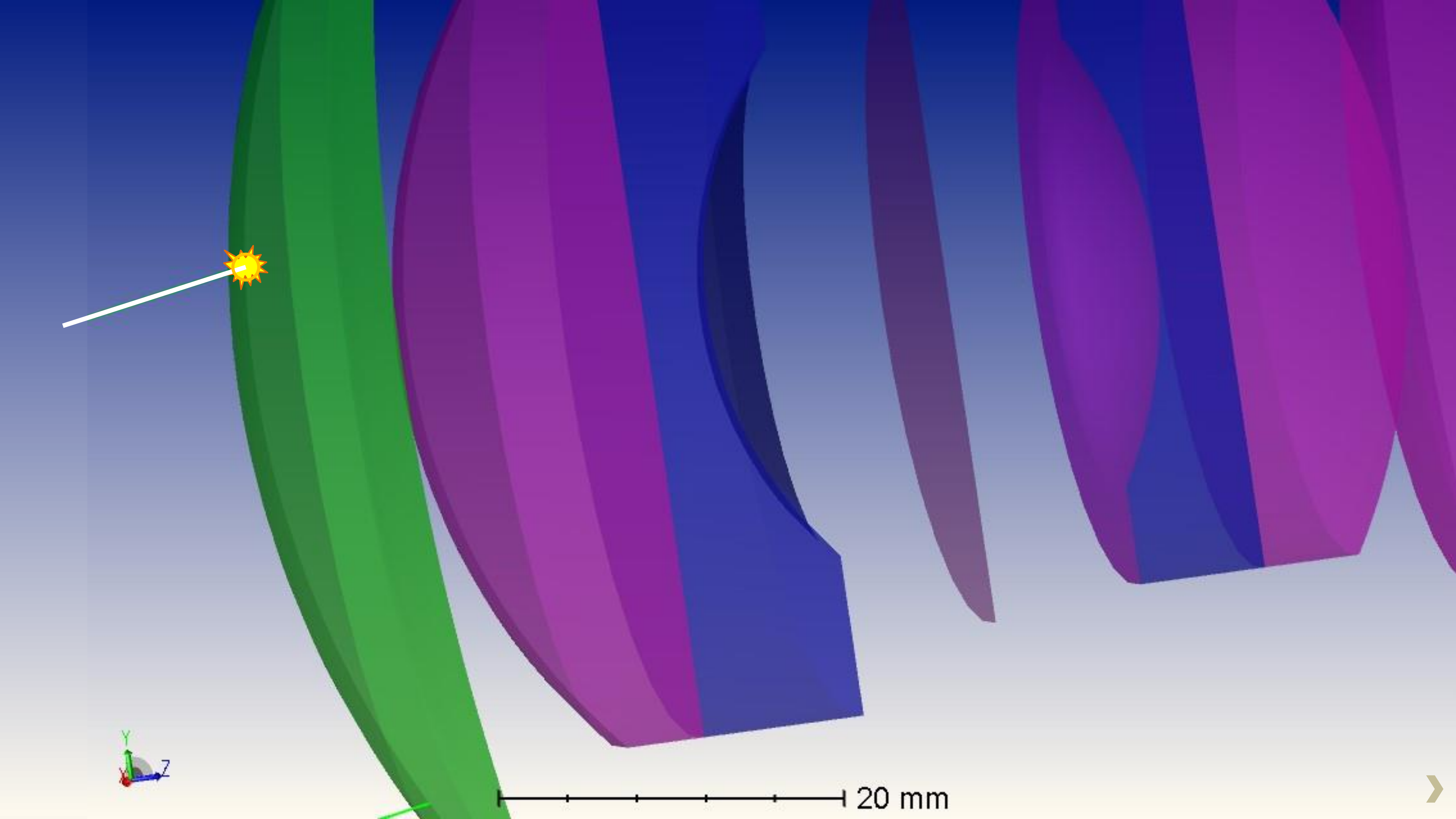
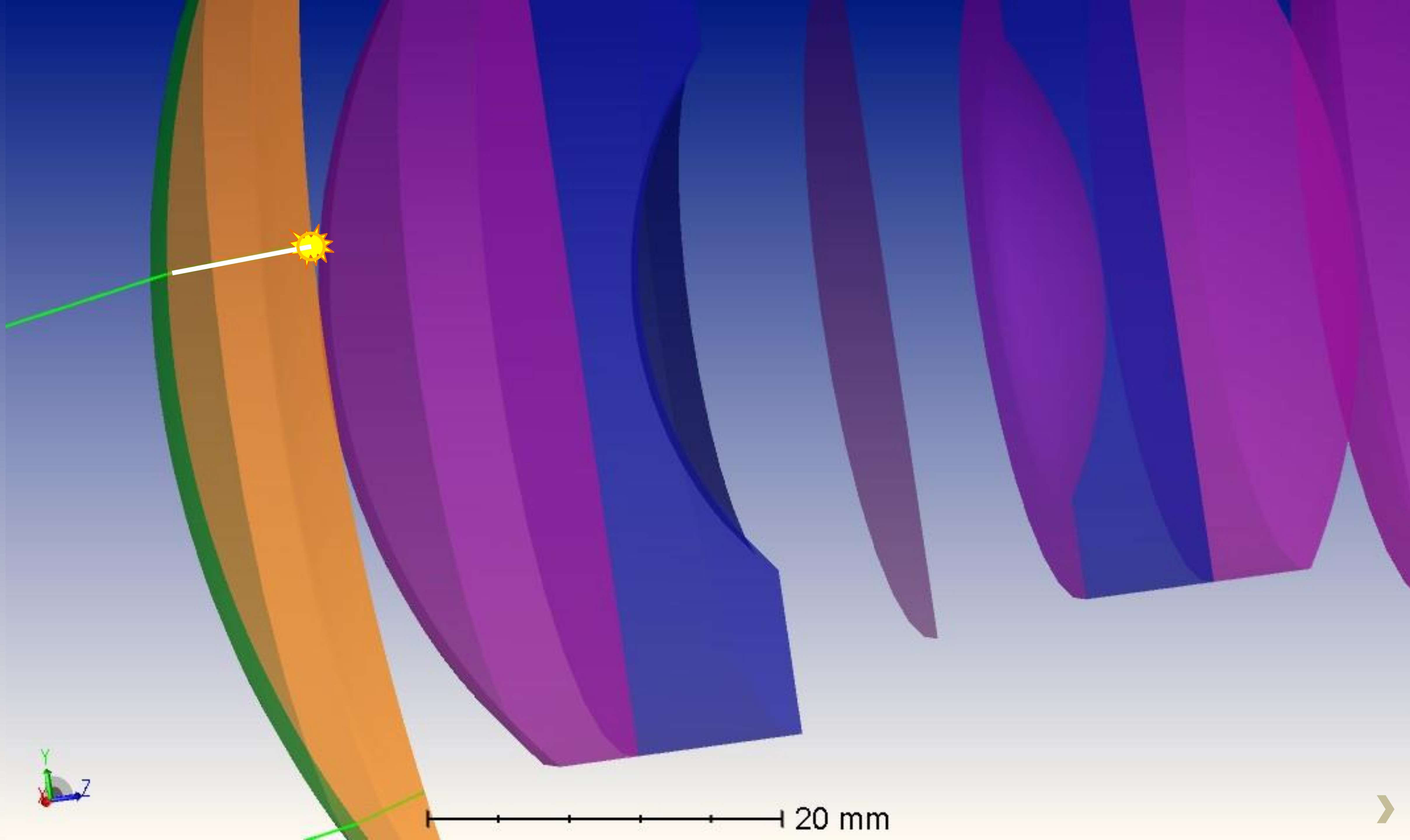
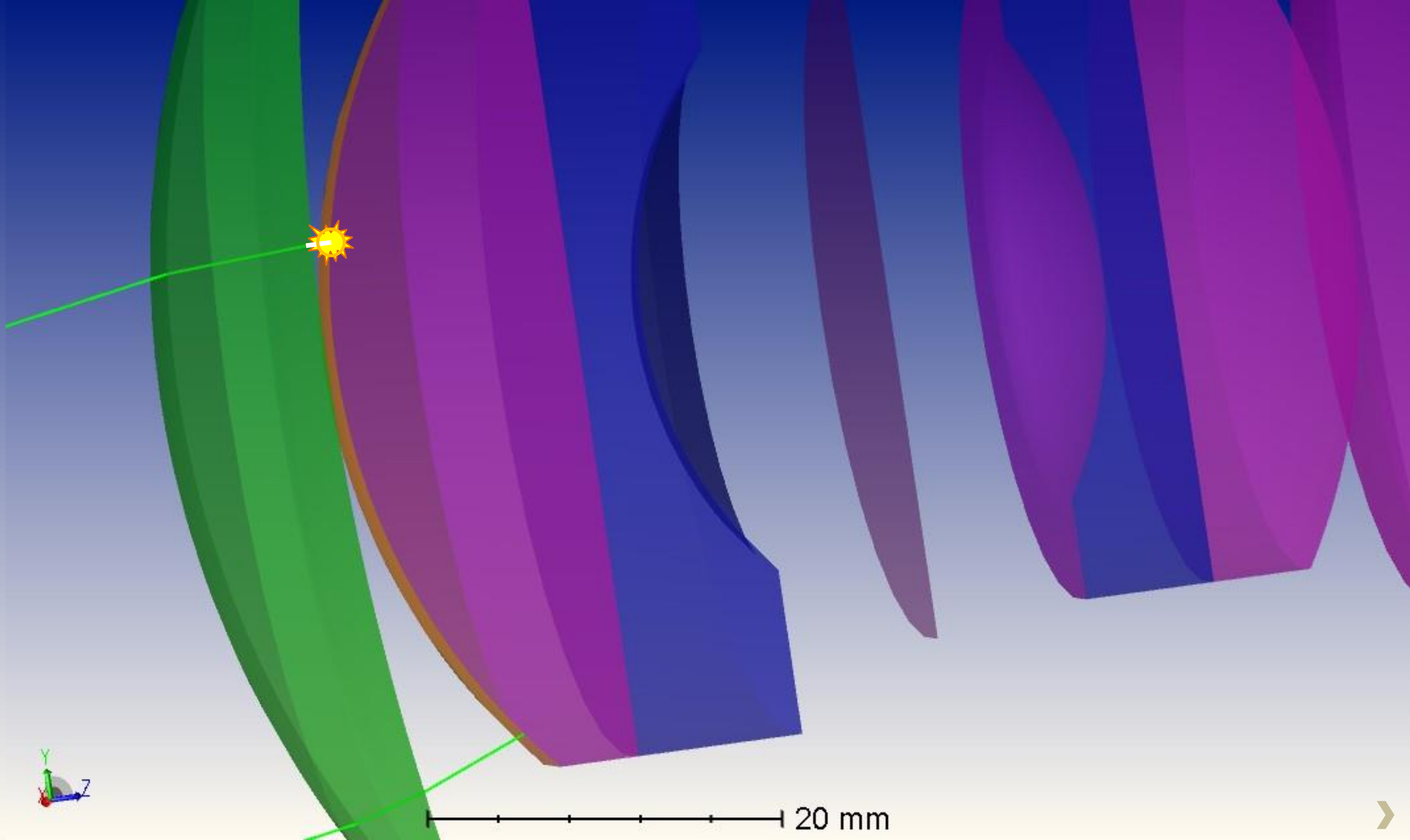
Field Points

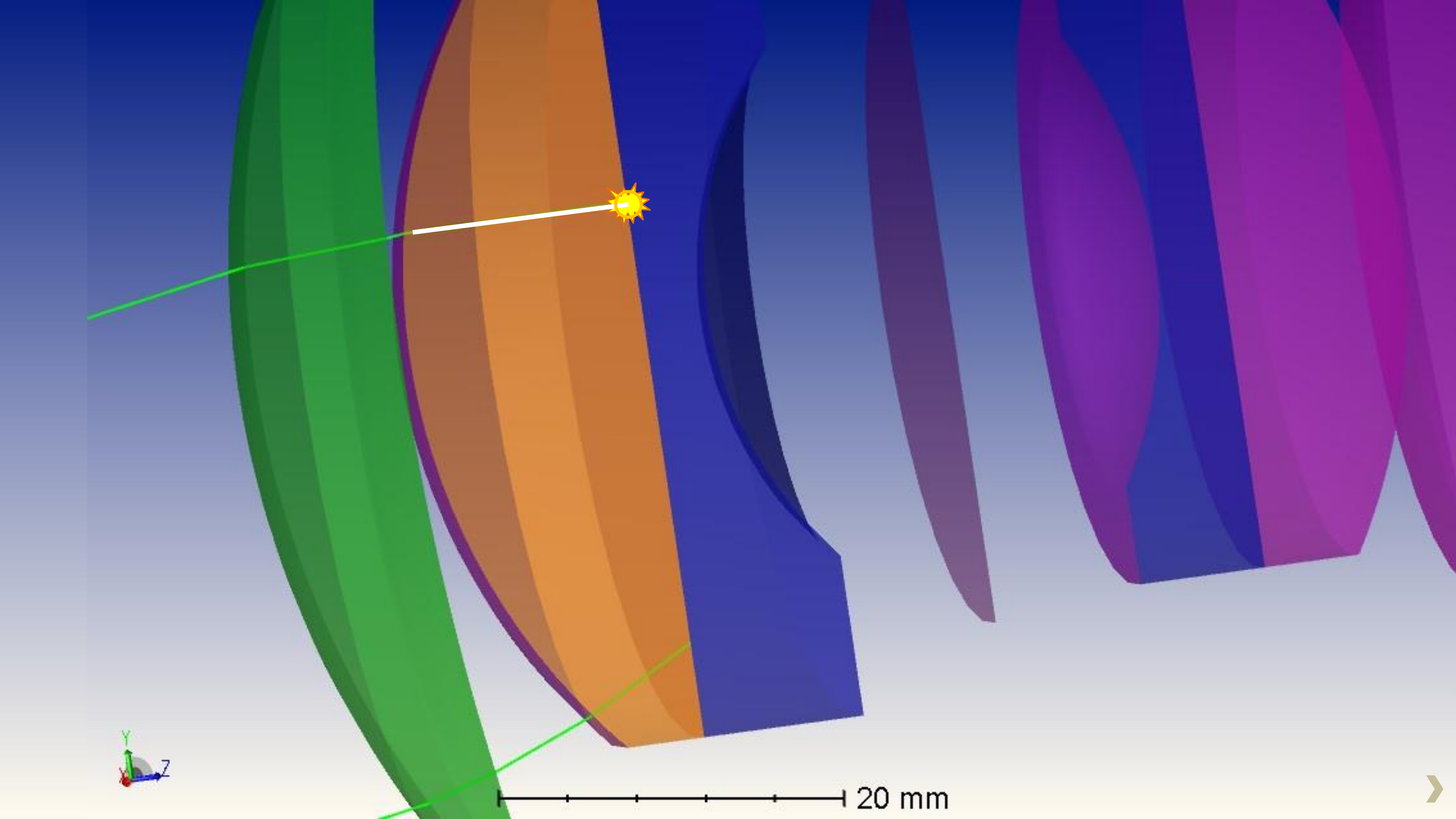


The Calculation Proceeds
One Ray at a Time


Y
Z
20 mm


Y
Z
20 mm


Y
Z
20 mm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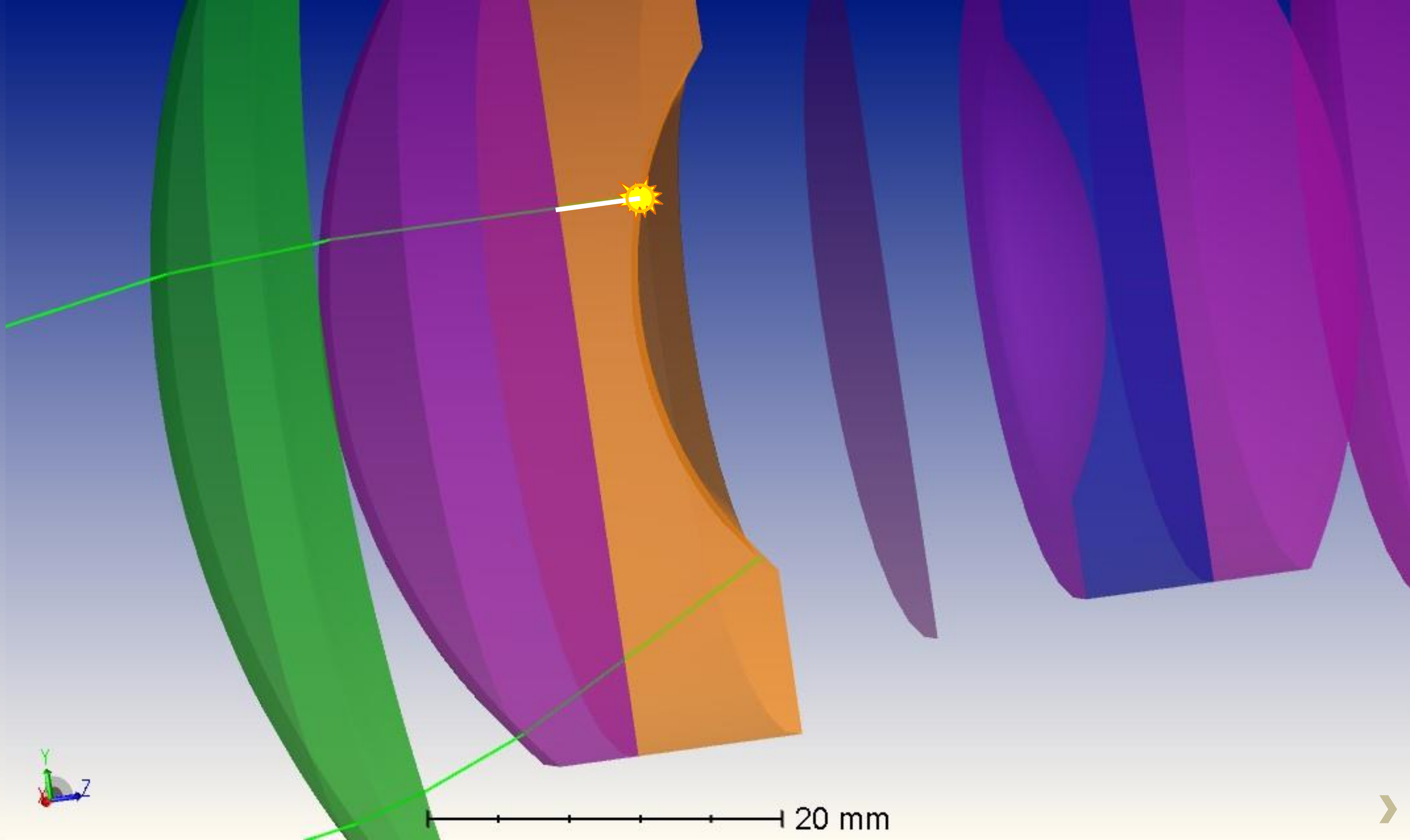
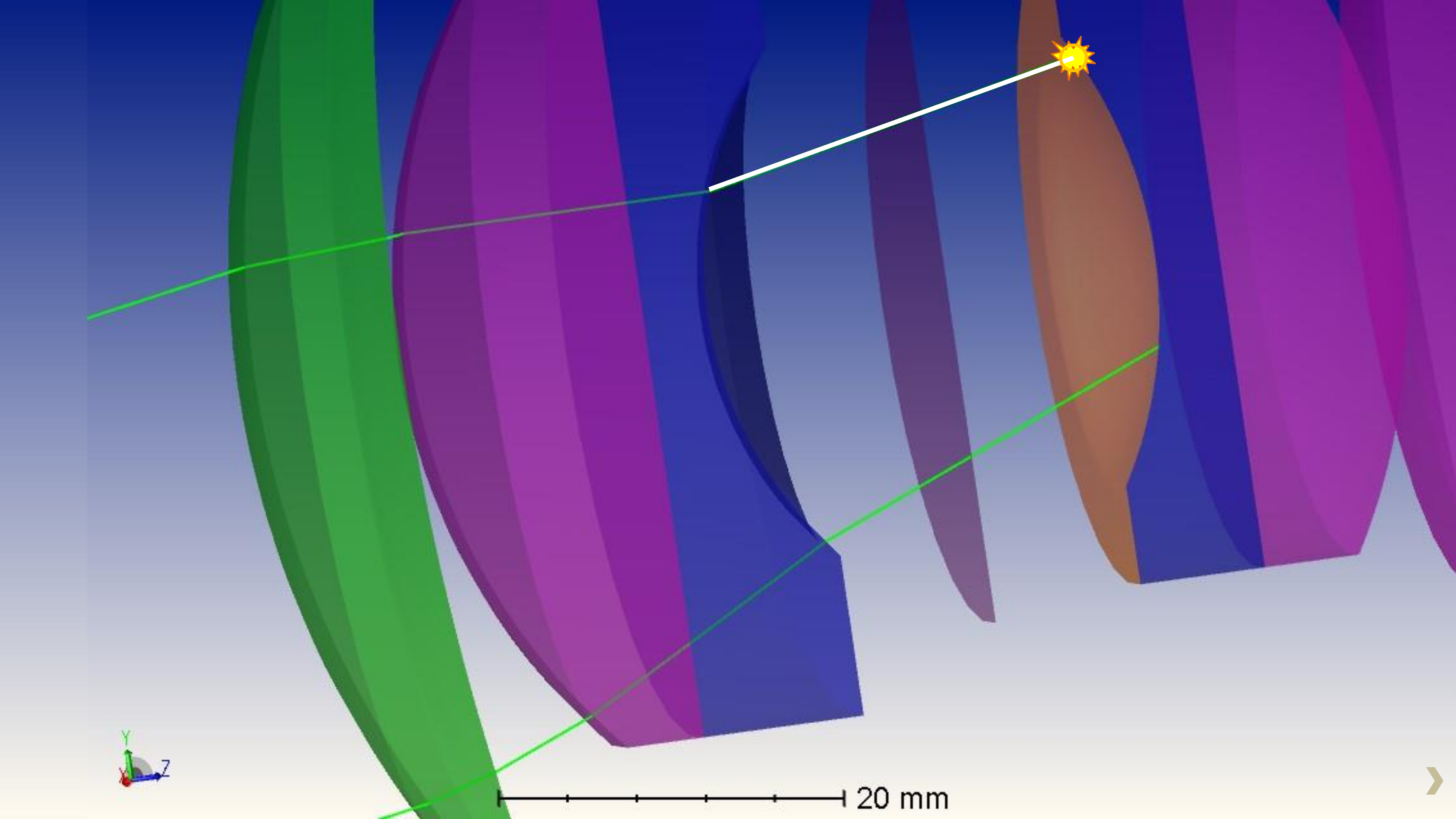
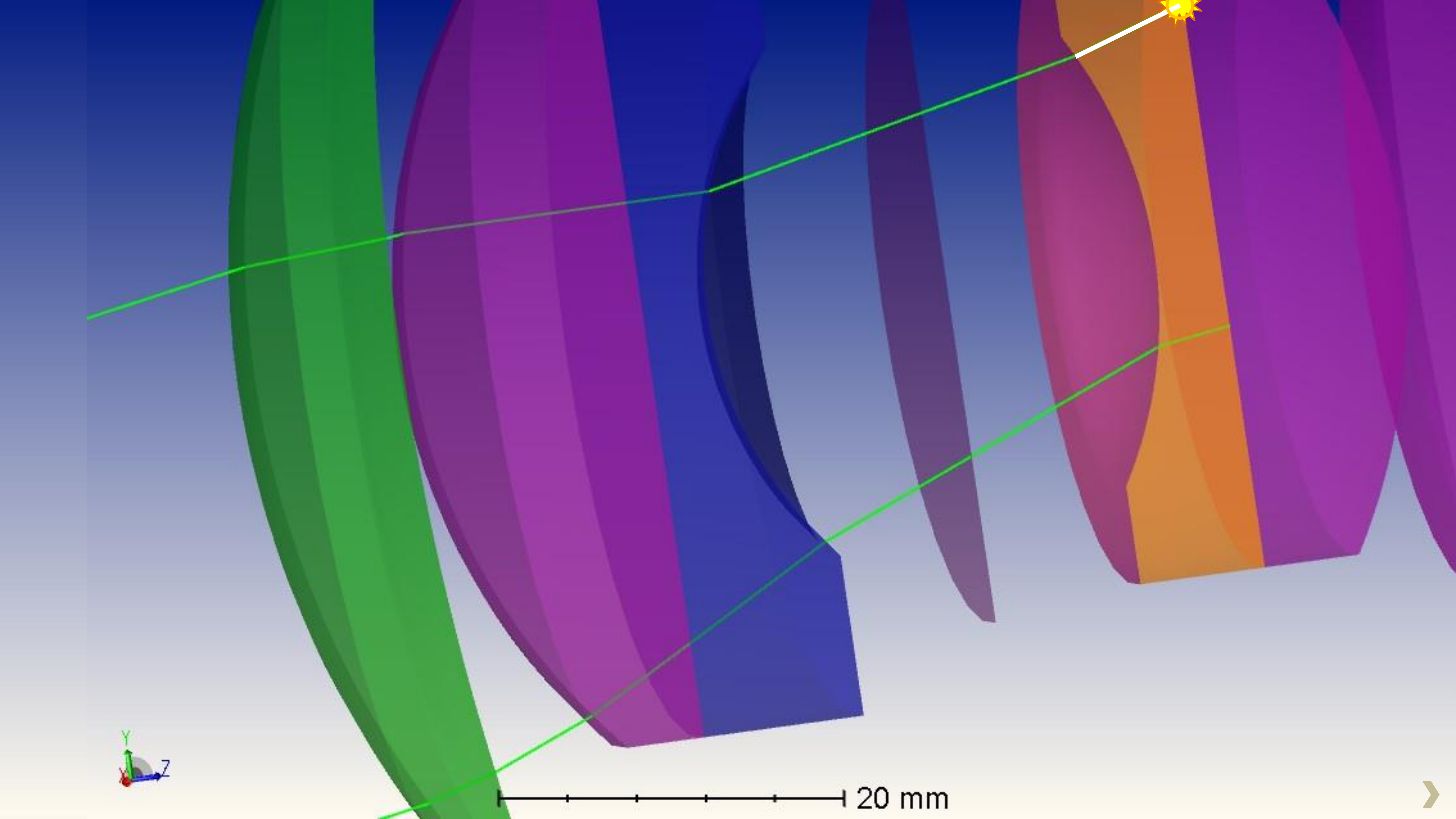
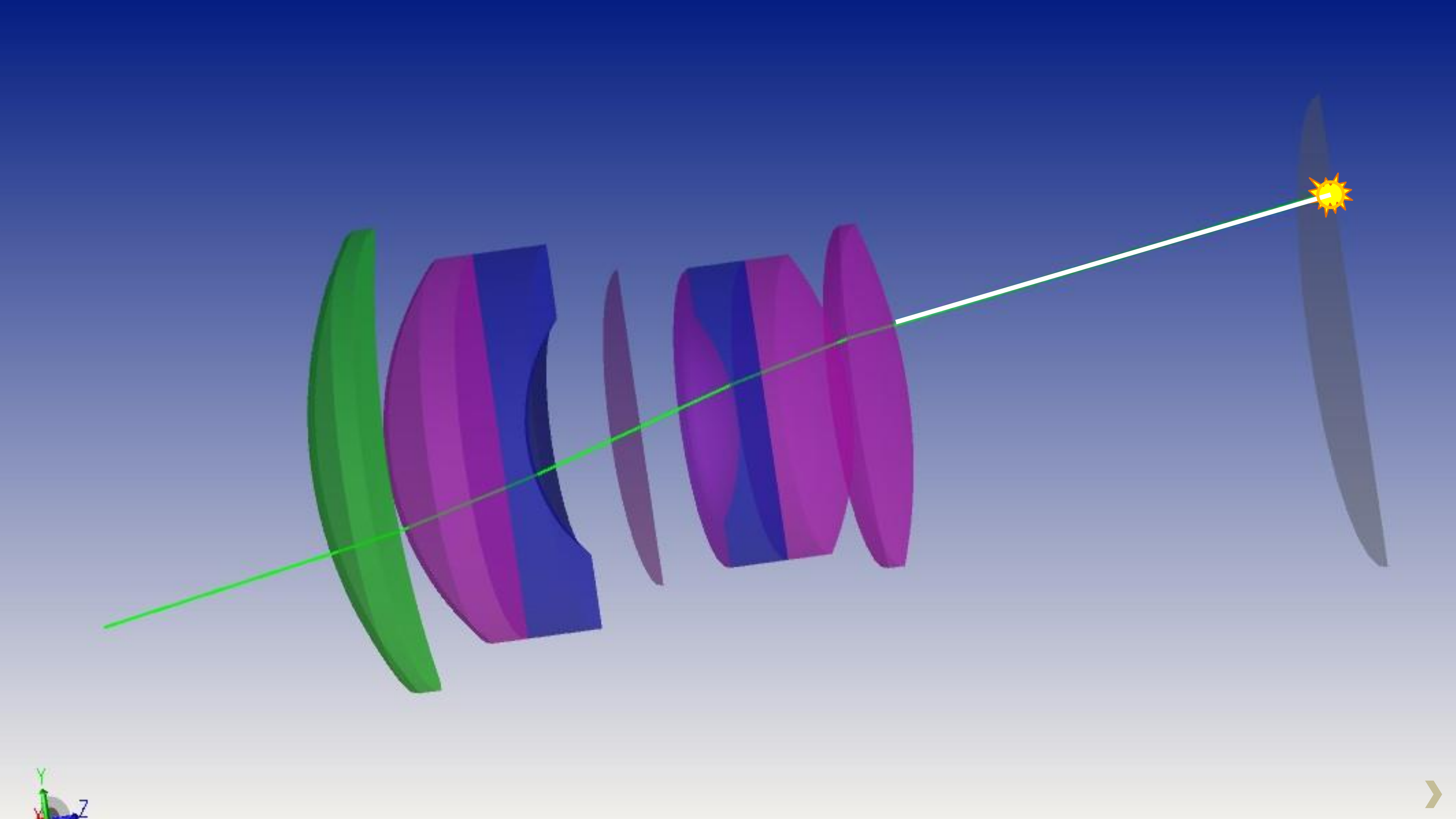
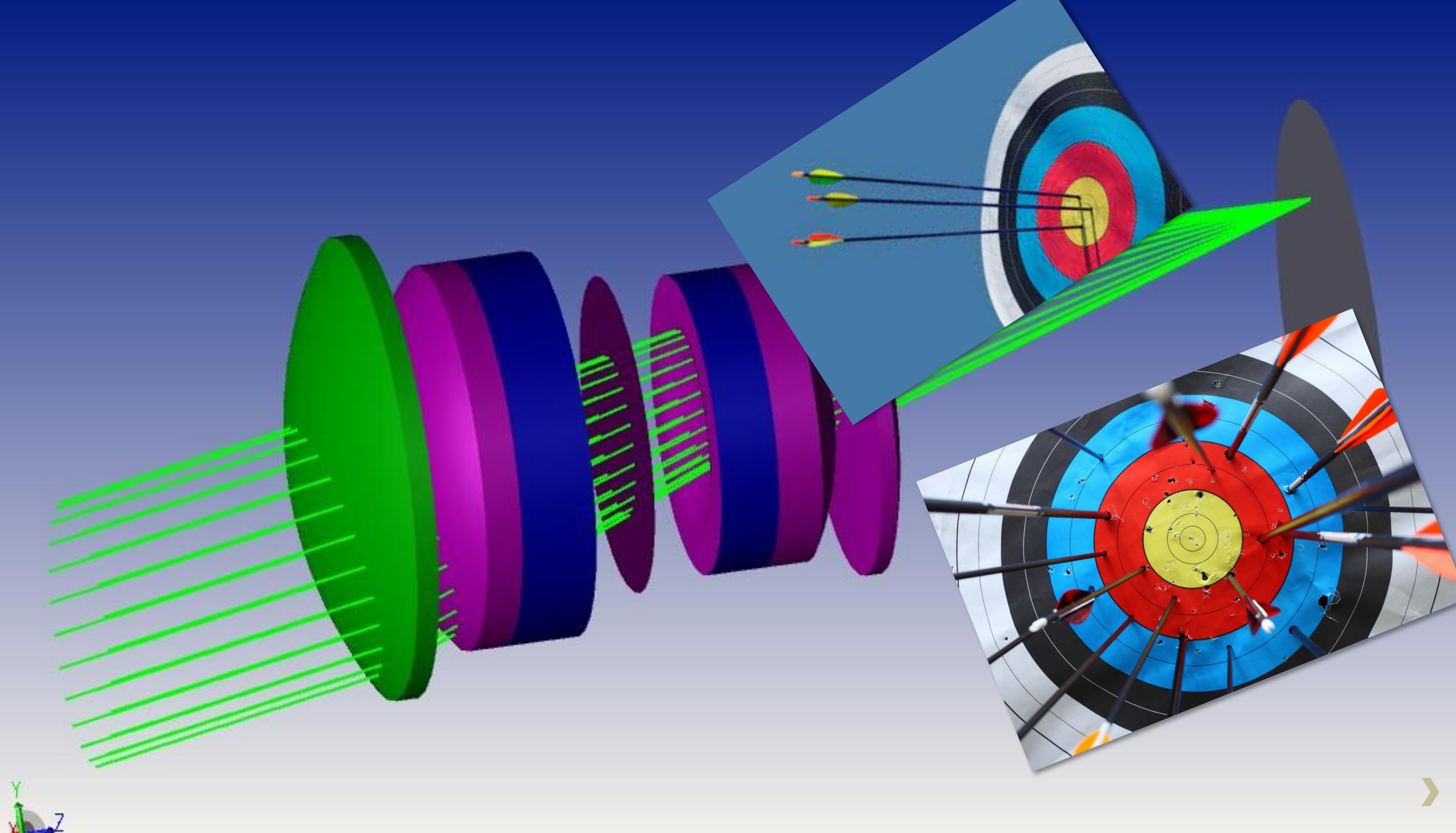


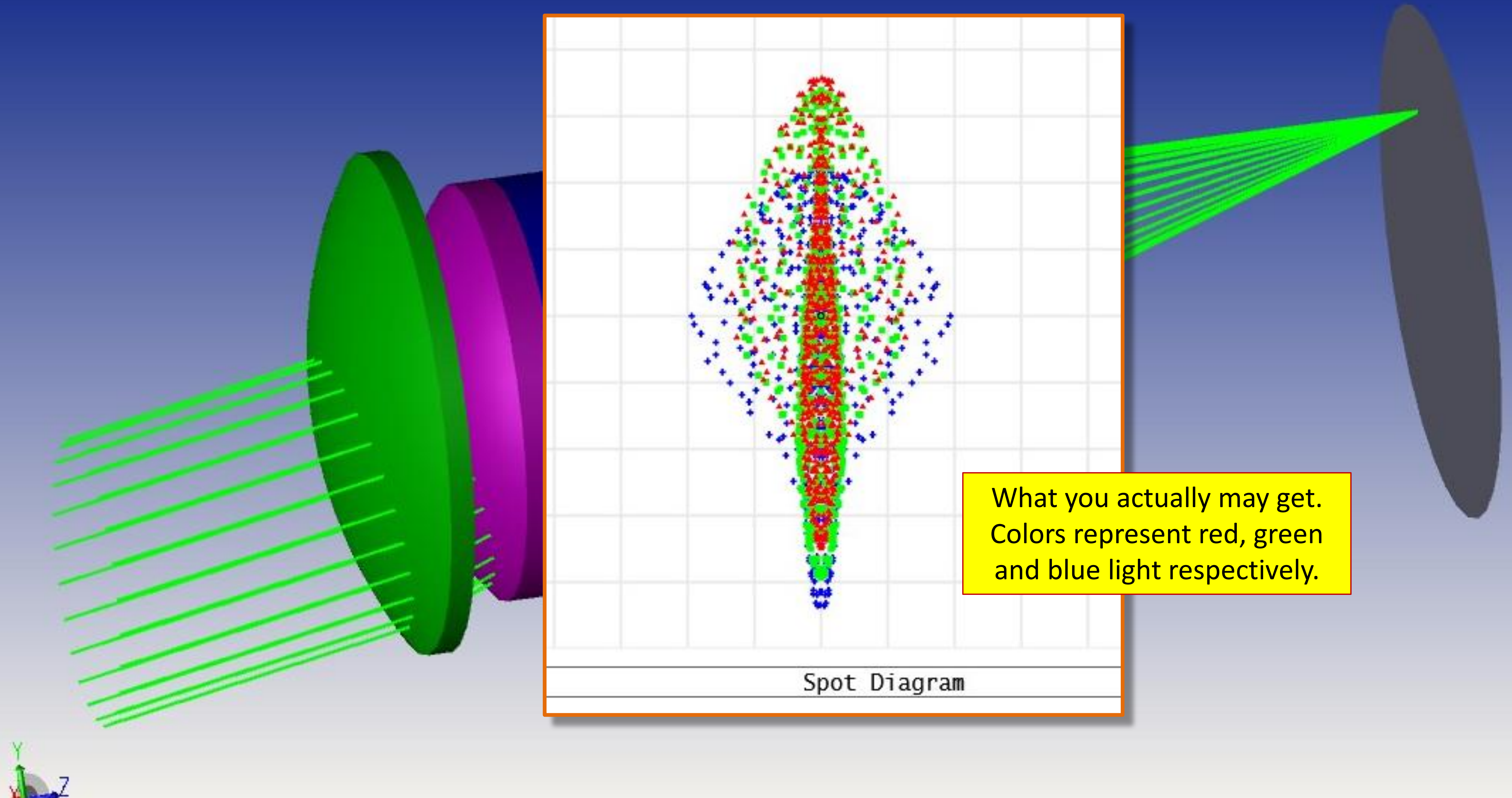
Y
Z
20 mm


Y
Z
20 mm


Y
Z
20 mm

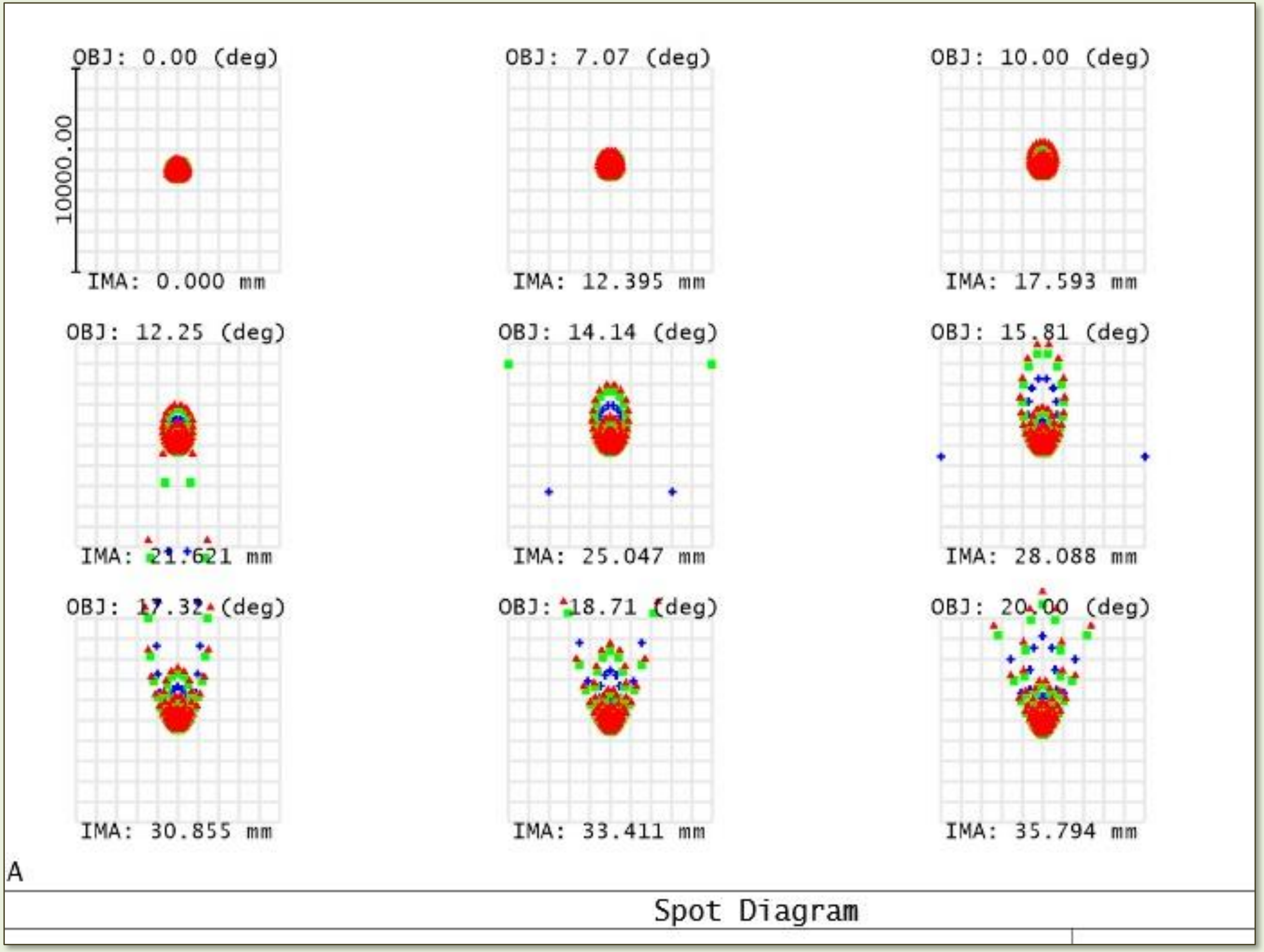

Y
Z



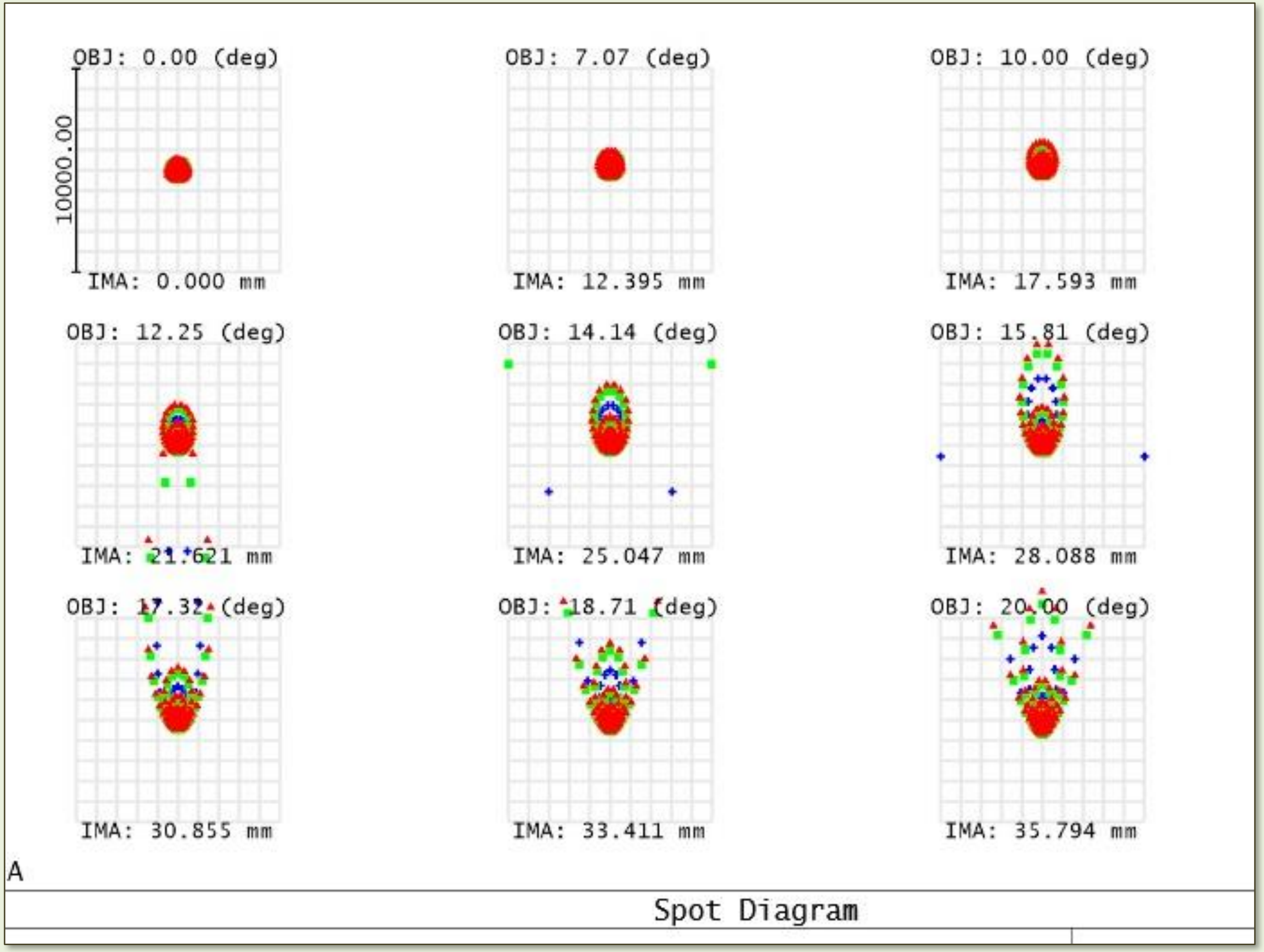


What you actually may get. Colors represent red, green and blue light respectively.

The Calculated Spot Size Varies over the Field of View



As the Optical Design is Refined, Spot Sizes Improve



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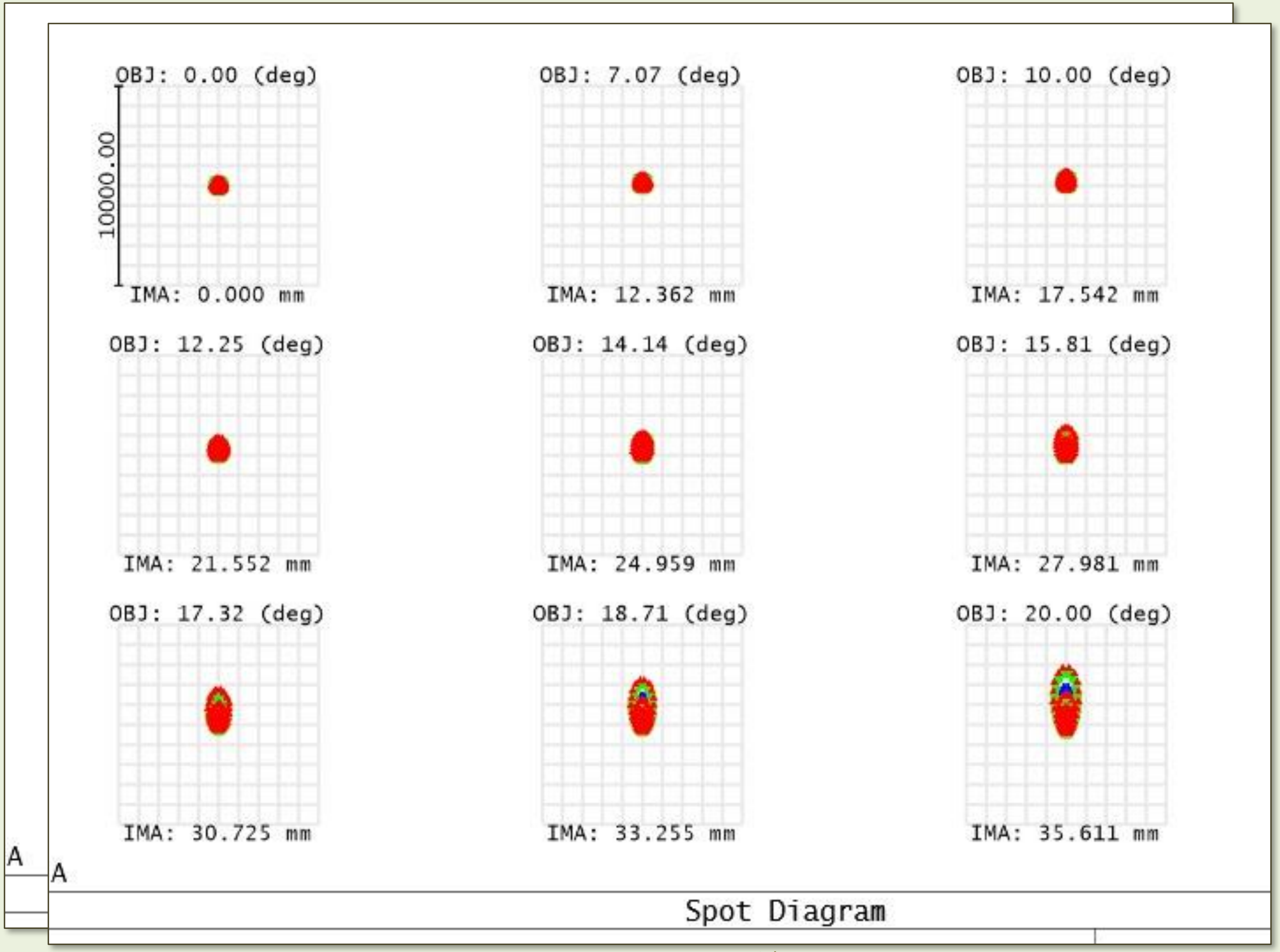

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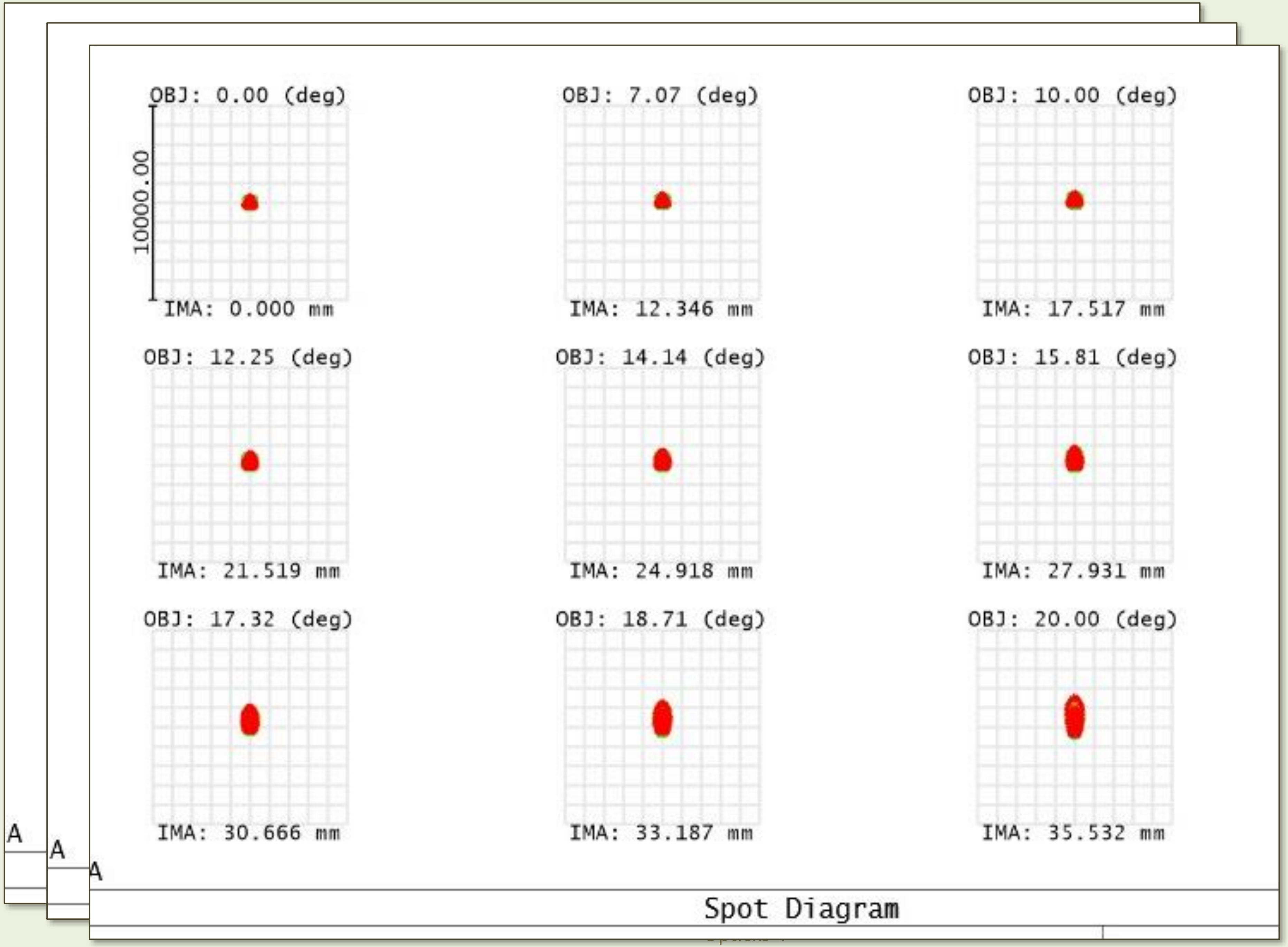

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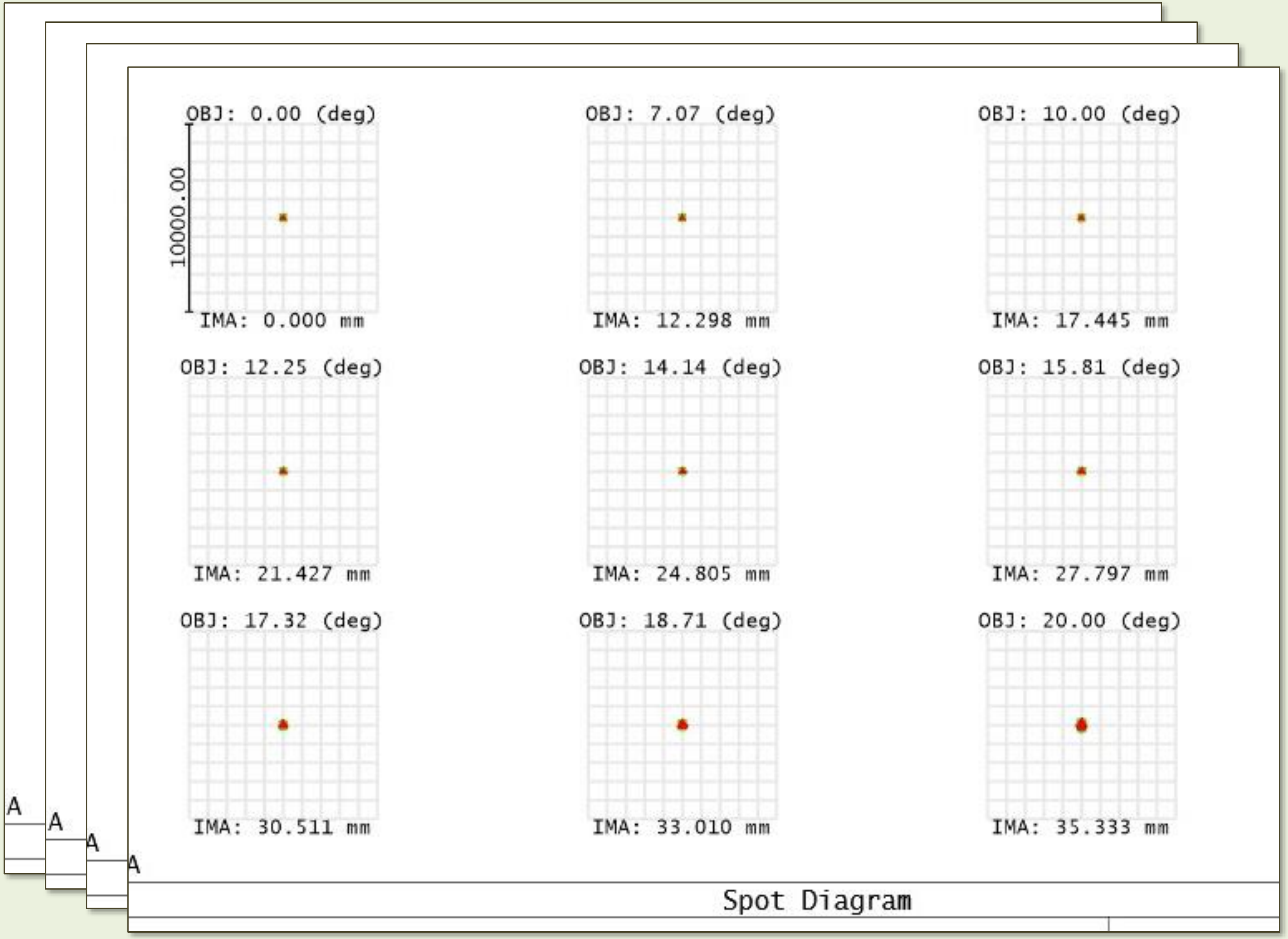
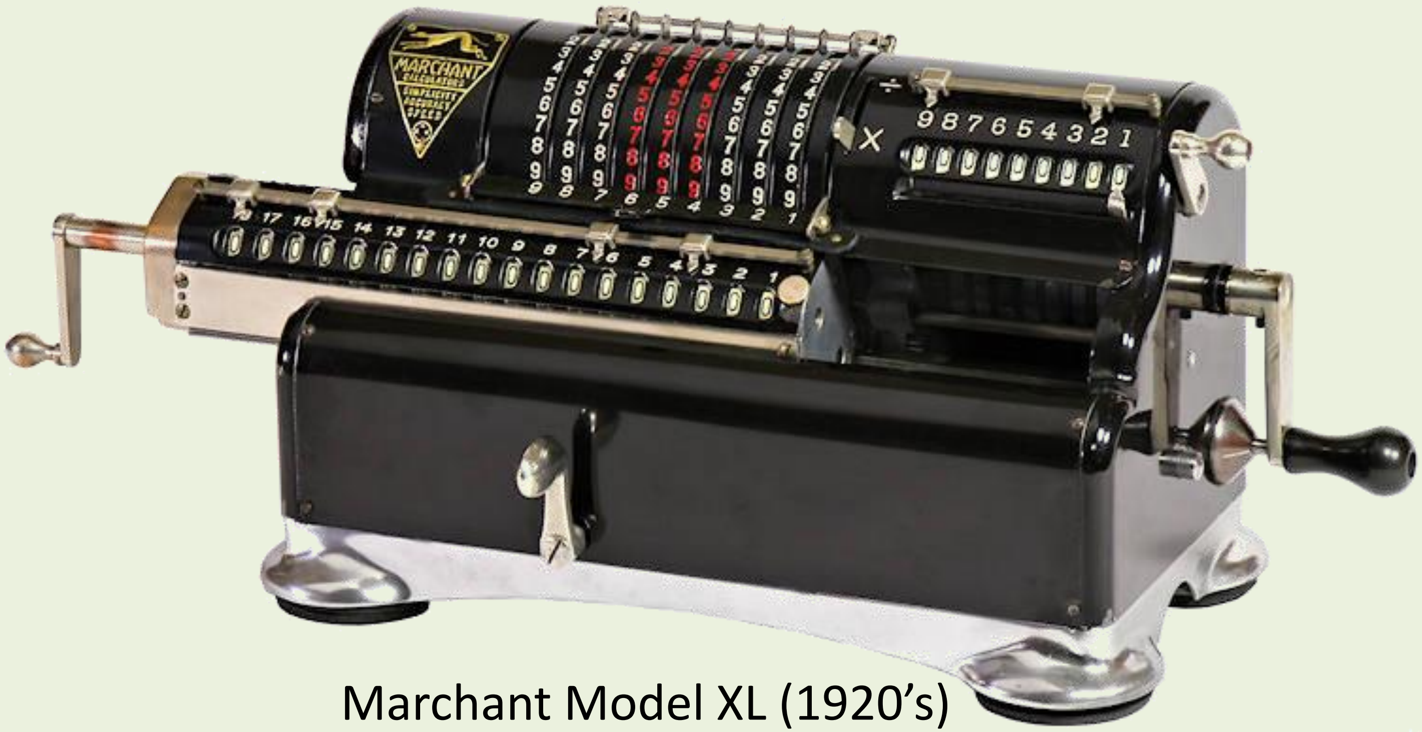


Mechanical Calculators Eased the Burden



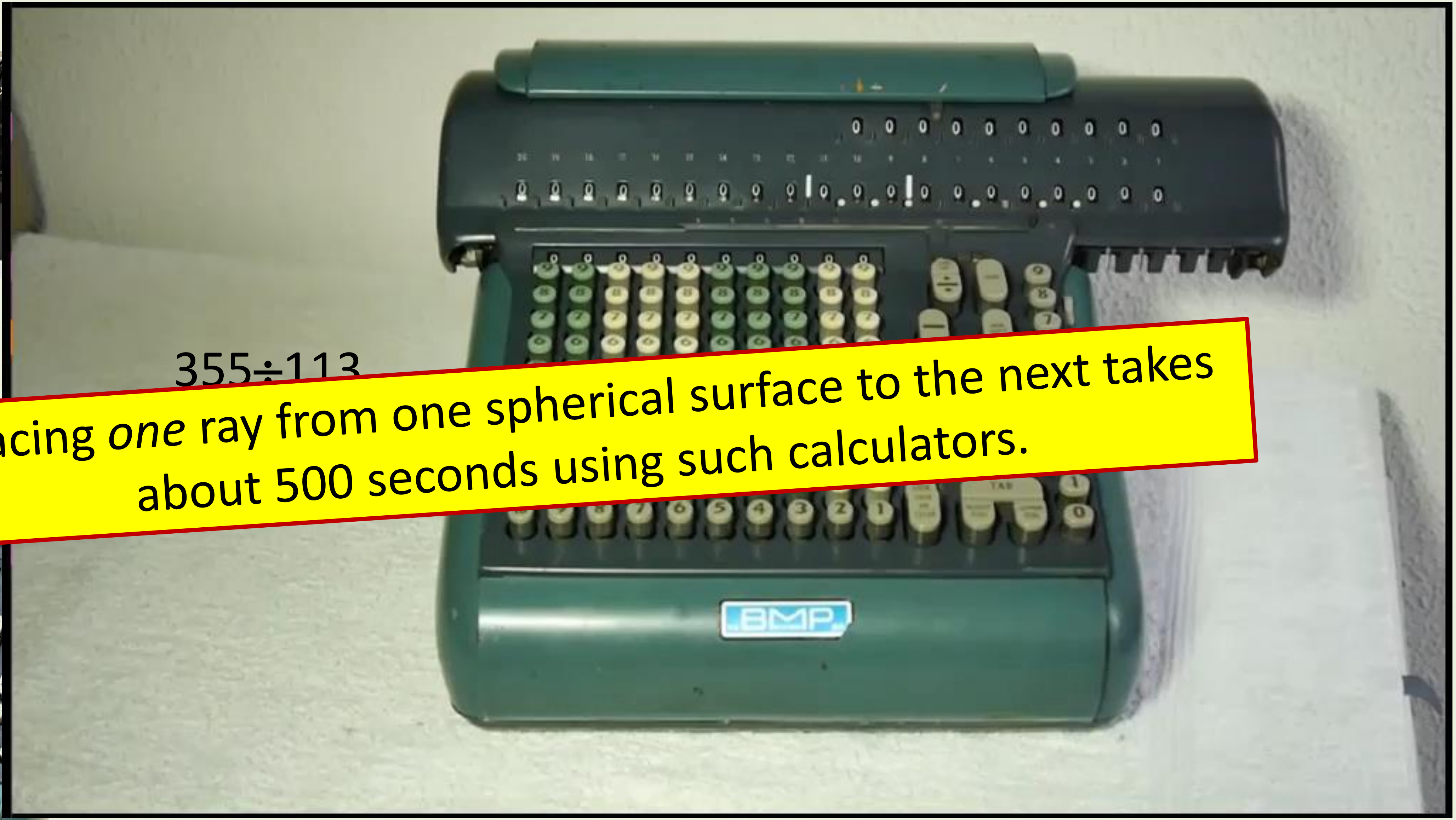
Marchant Model XL (1920’s)

Marchant Figurematic
(1950’s)

Photos:
John Wolff

355÷113

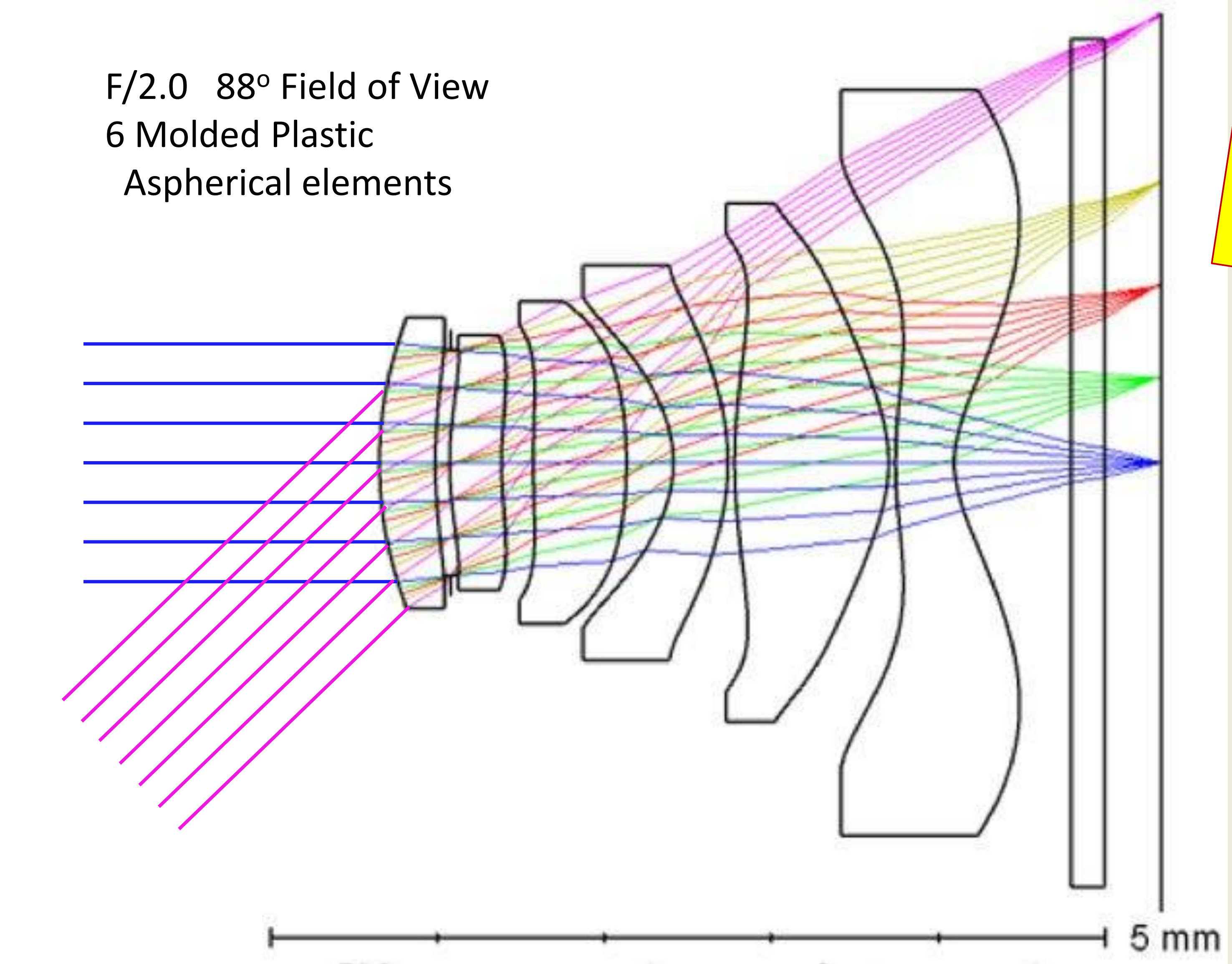
= 3.14159292



355÷113

Tracing *one* ray from one spherical surface to the next takes about 500 seconds using such calculators.

Typical Recent Cell Phone Camera Lens Design



Note insanely aspherical surfaces!

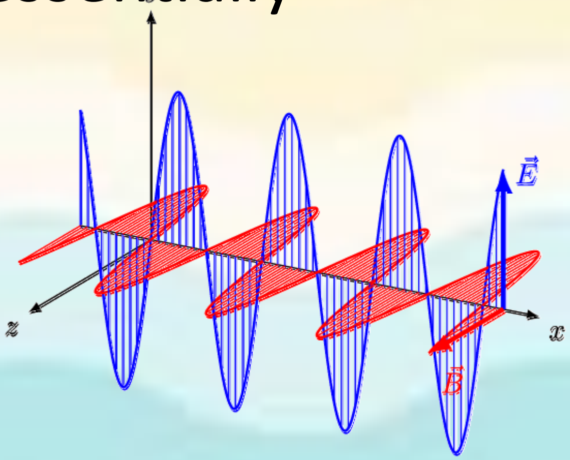
12 MegaPixel CMOS Sensor

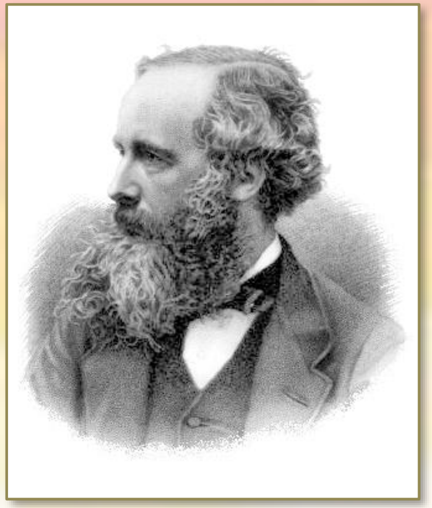
Joo & Alisafaee, SPIE Optical Engineering (2020)

Wave Nature of Light

Wave Nature of Light

- Strong indications from the 17th Century
  - Completely clear by the late 19th Century, with the identification by Maxwell of light as essentially **Electromagnetic Waves**

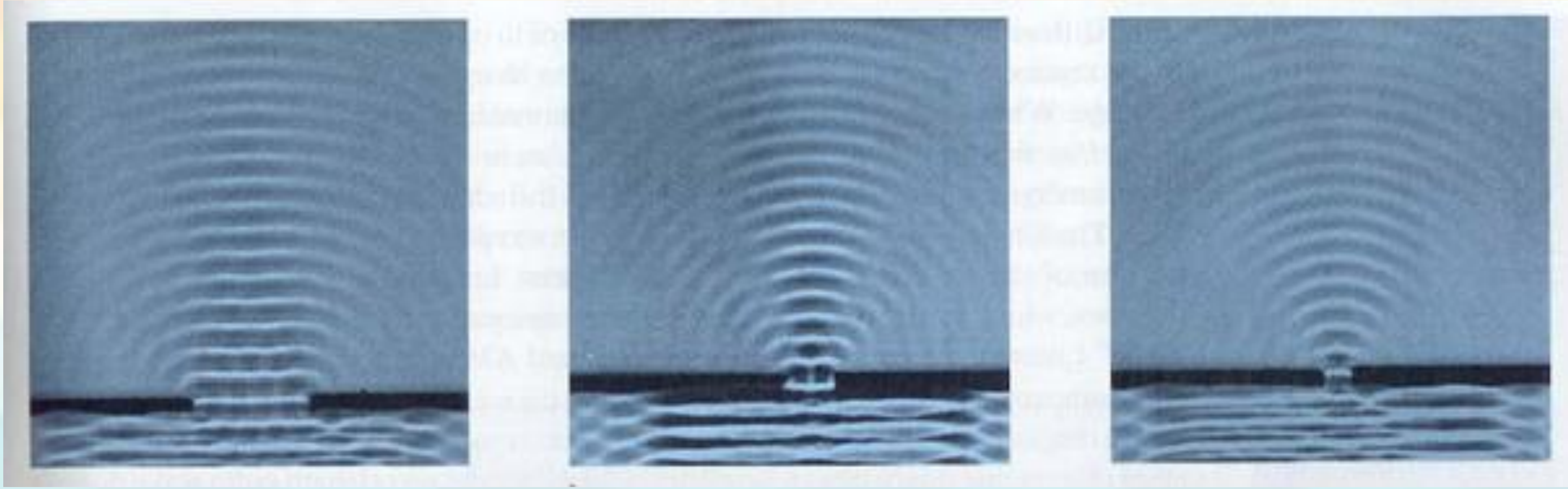


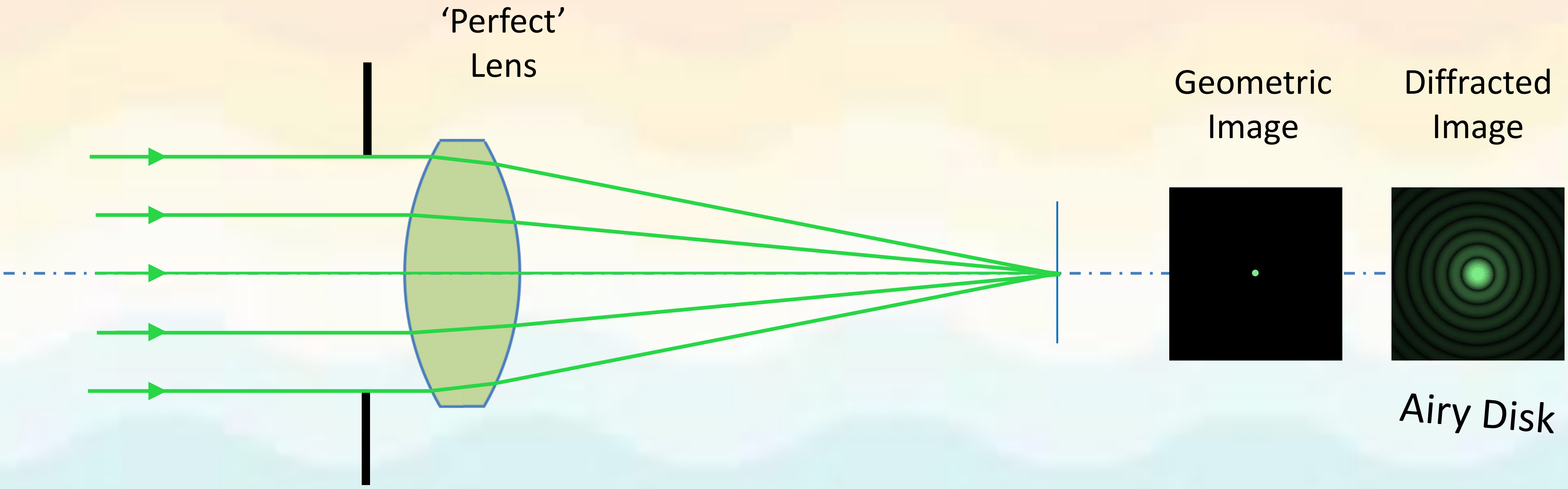


James Clerk Maxwell
Scottish Physicist
1831-1879

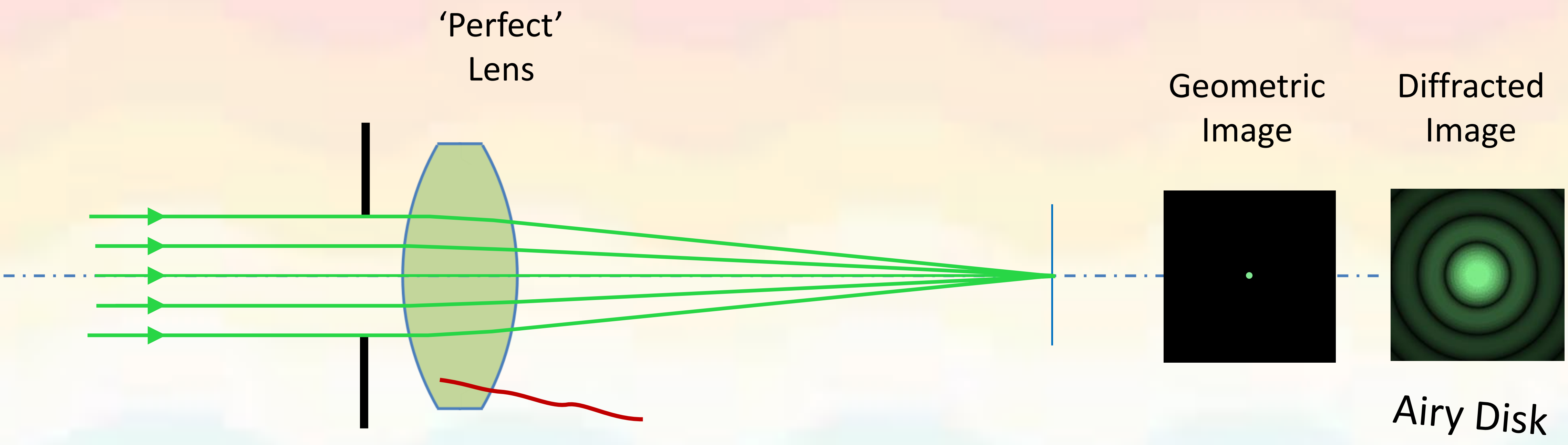
- Two Major Consequences:
  - **Diffraction** – Light bends around corners
  - **Interference** – Multiple waves can *reinforce* or *cancel* one another

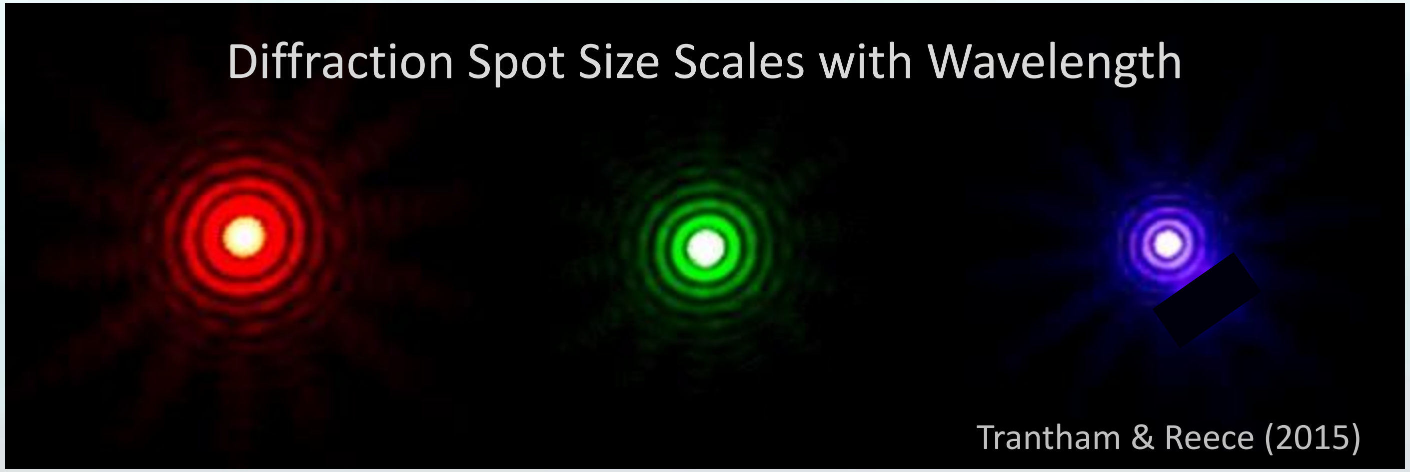
Diffraction of Surface Waves in Water



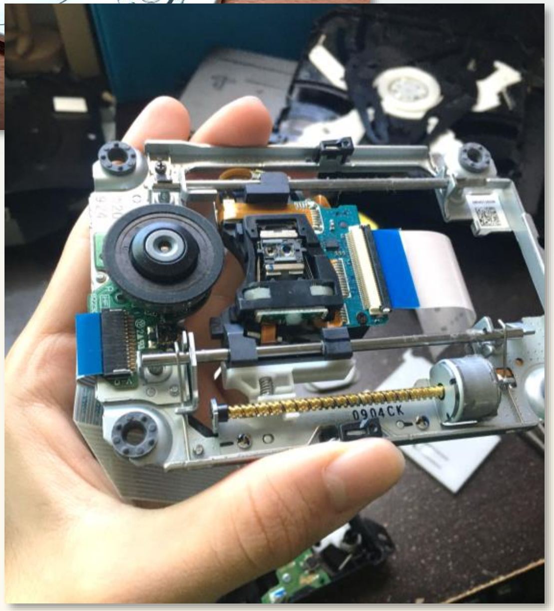


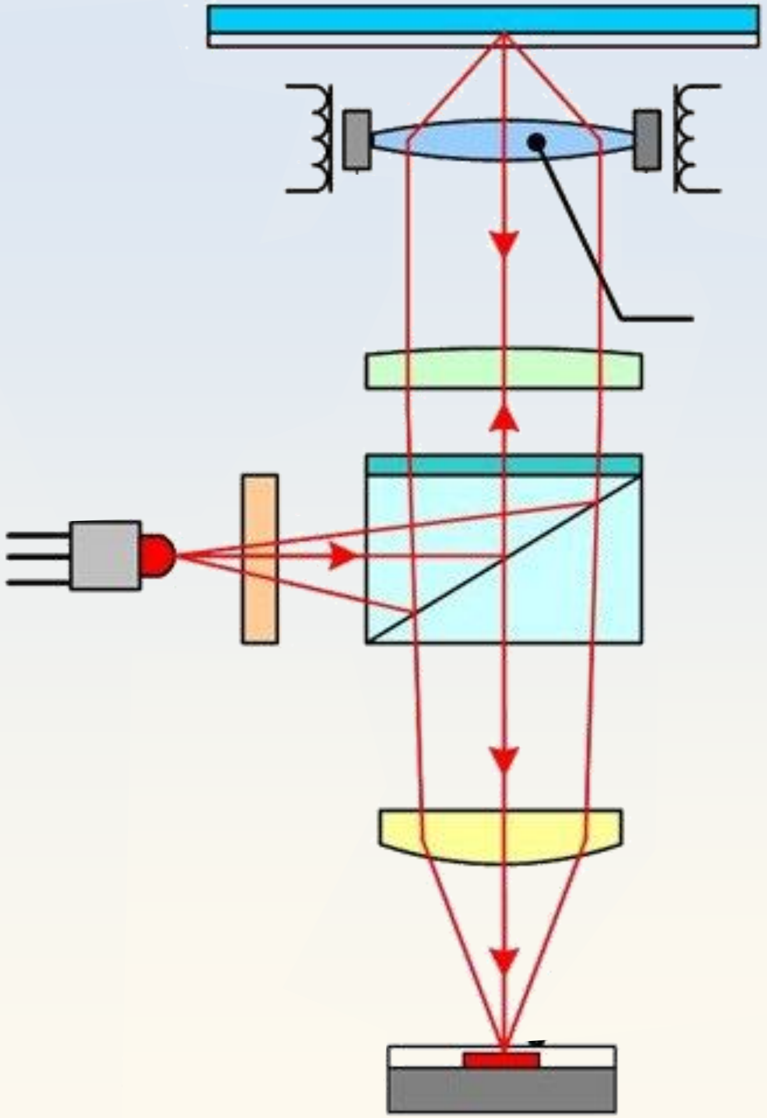
Light is a Wave – Diffracts and Spreads
when passing through apertures


'Perfect'
Lens
Geometric
Image
Diffracted
Image
Airy Disk

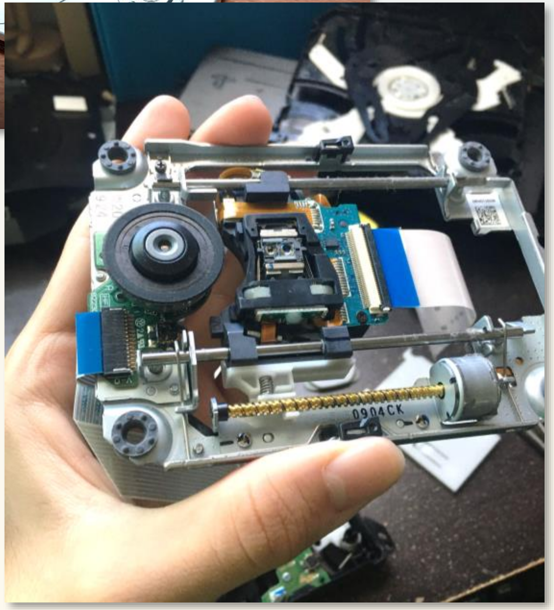

Diffraction Spot Size Scales with Wavelength
Trantham & Reece (2015)

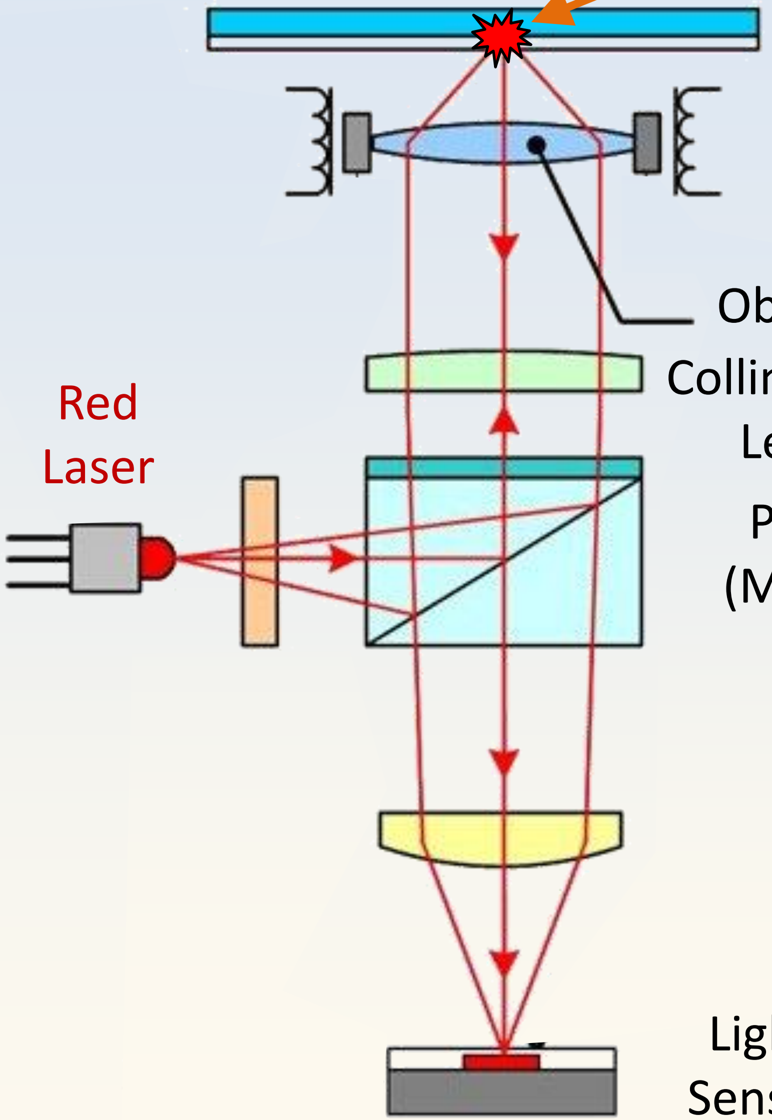
CD or DVD Player



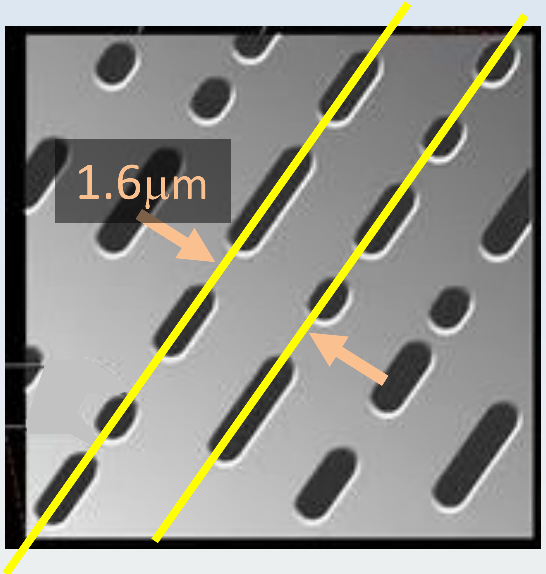


CD or DVD Player

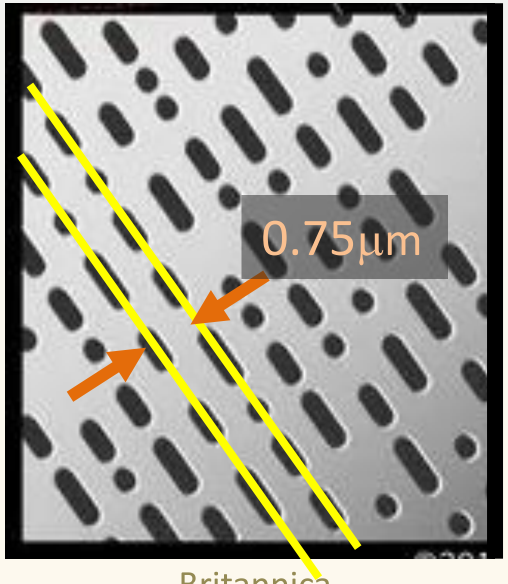




CD

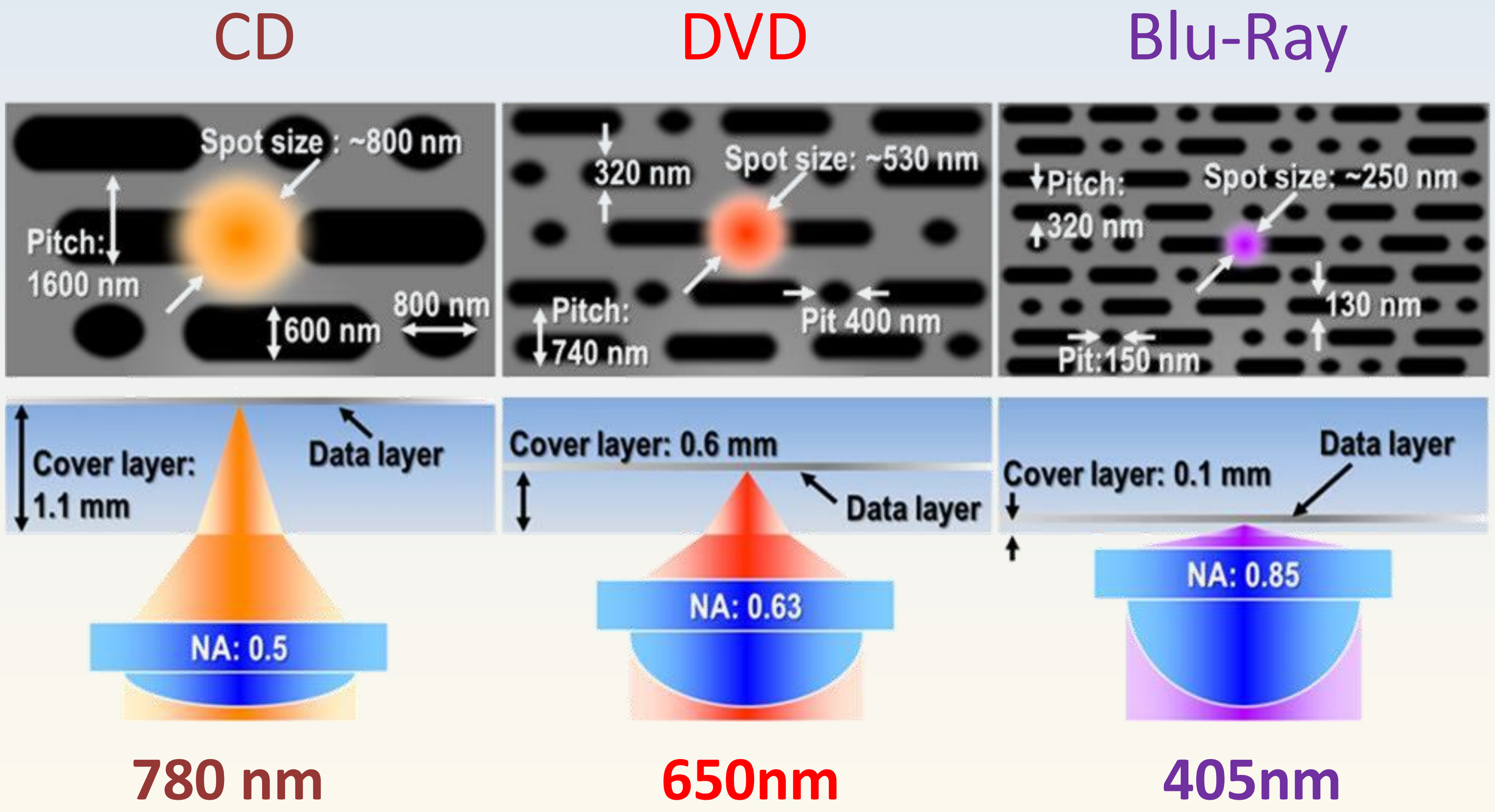


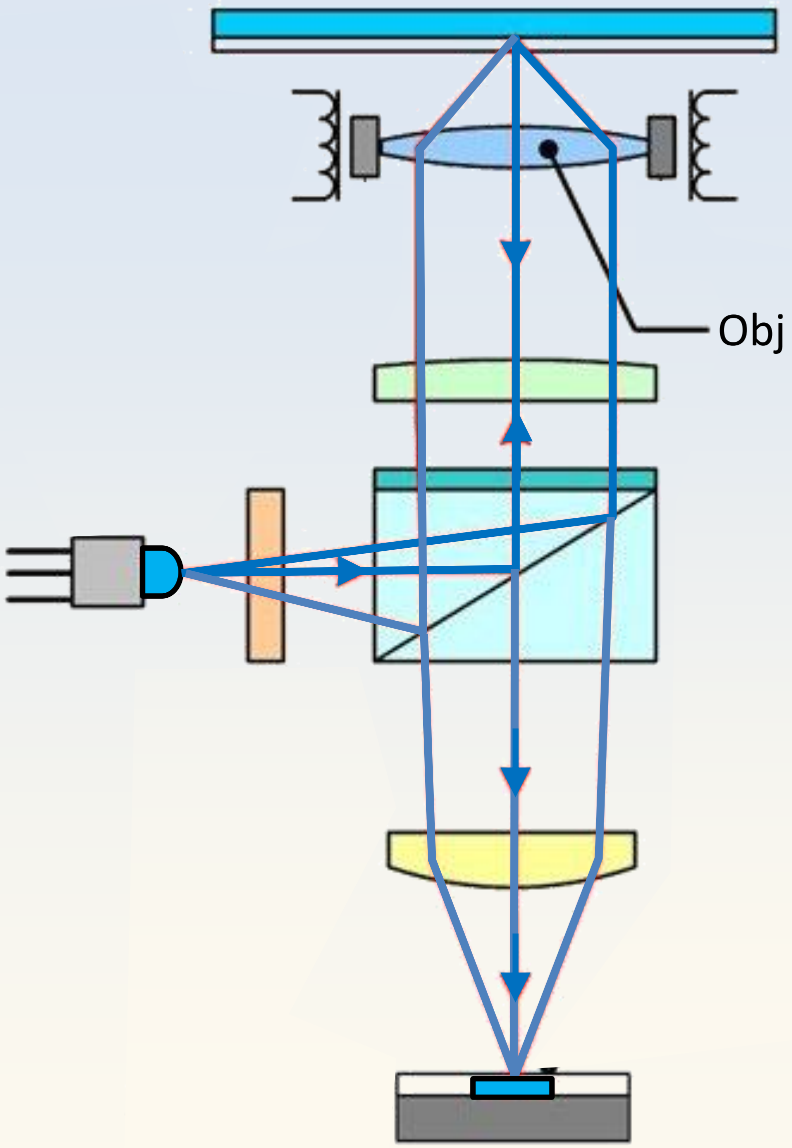
DVD



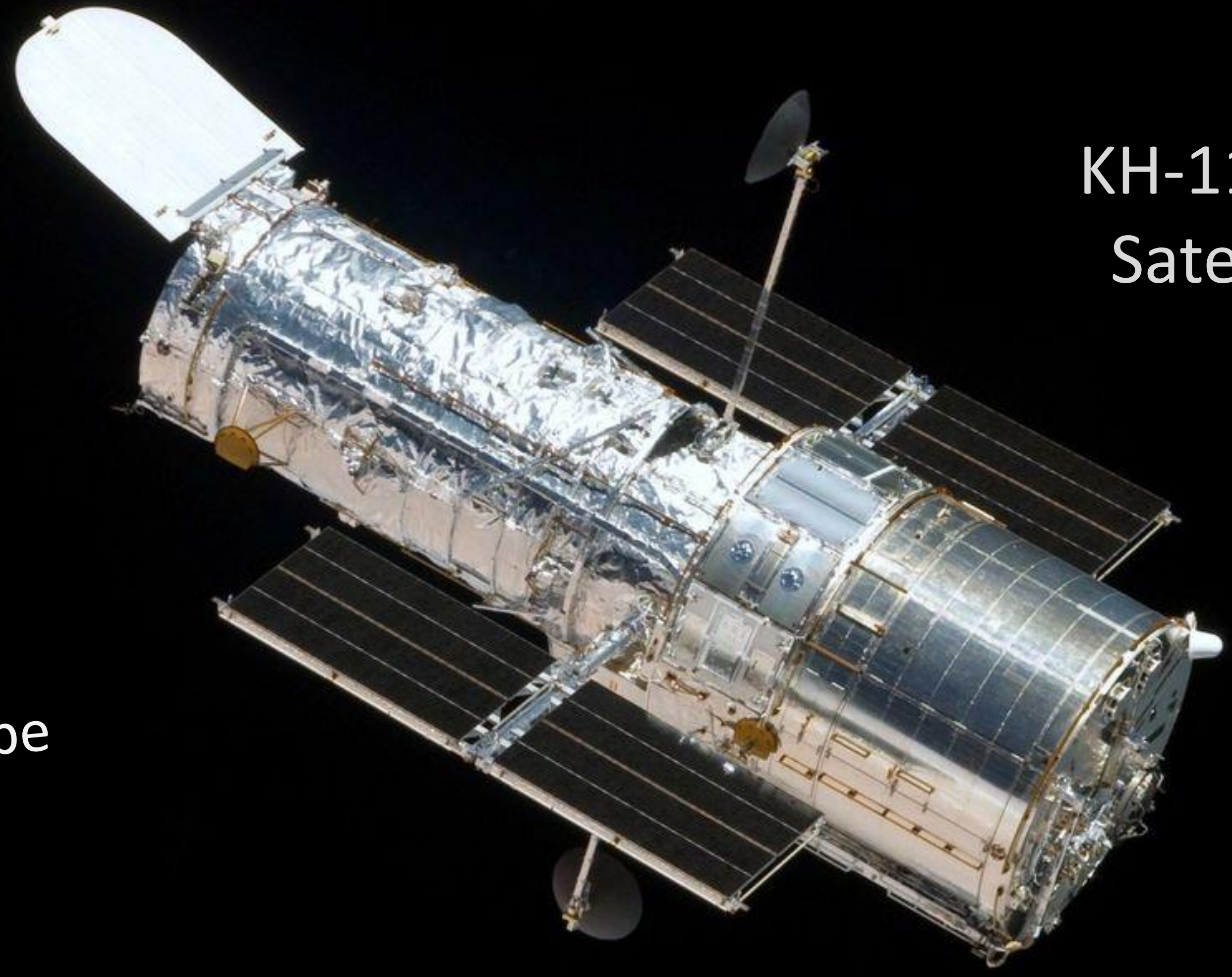
Britannica

Blu-Ray Player Allows Still Smaller Features





Hwu & Boisen, ACS Sensors (2018)



2.4 m

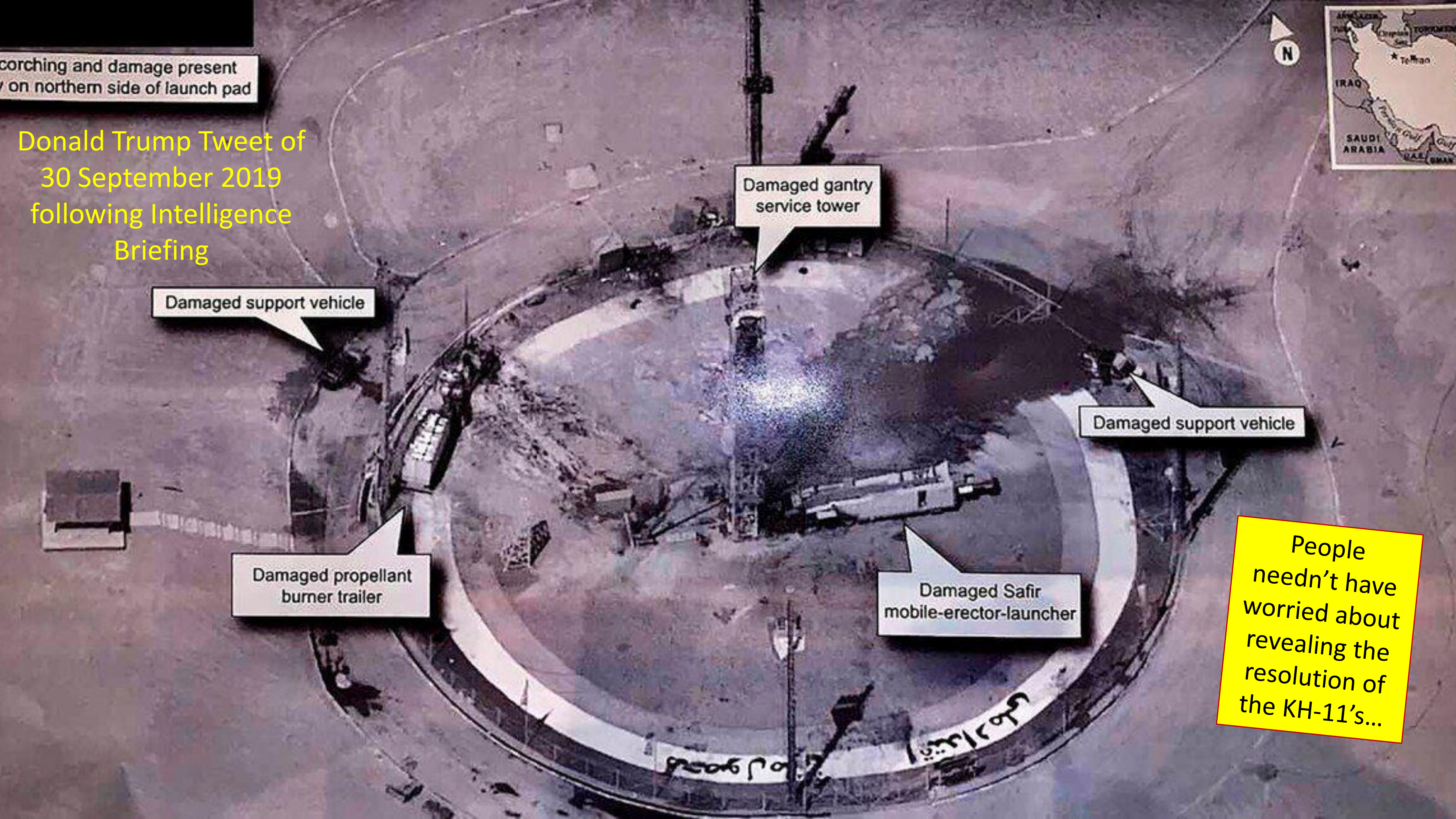
KH-11 Spy Satellite

This actually the Hubble Telescope – they wouldn't give me pics of the KH-11

Perigee
> 160 miles

Guaranteed to be Diffraction Limited

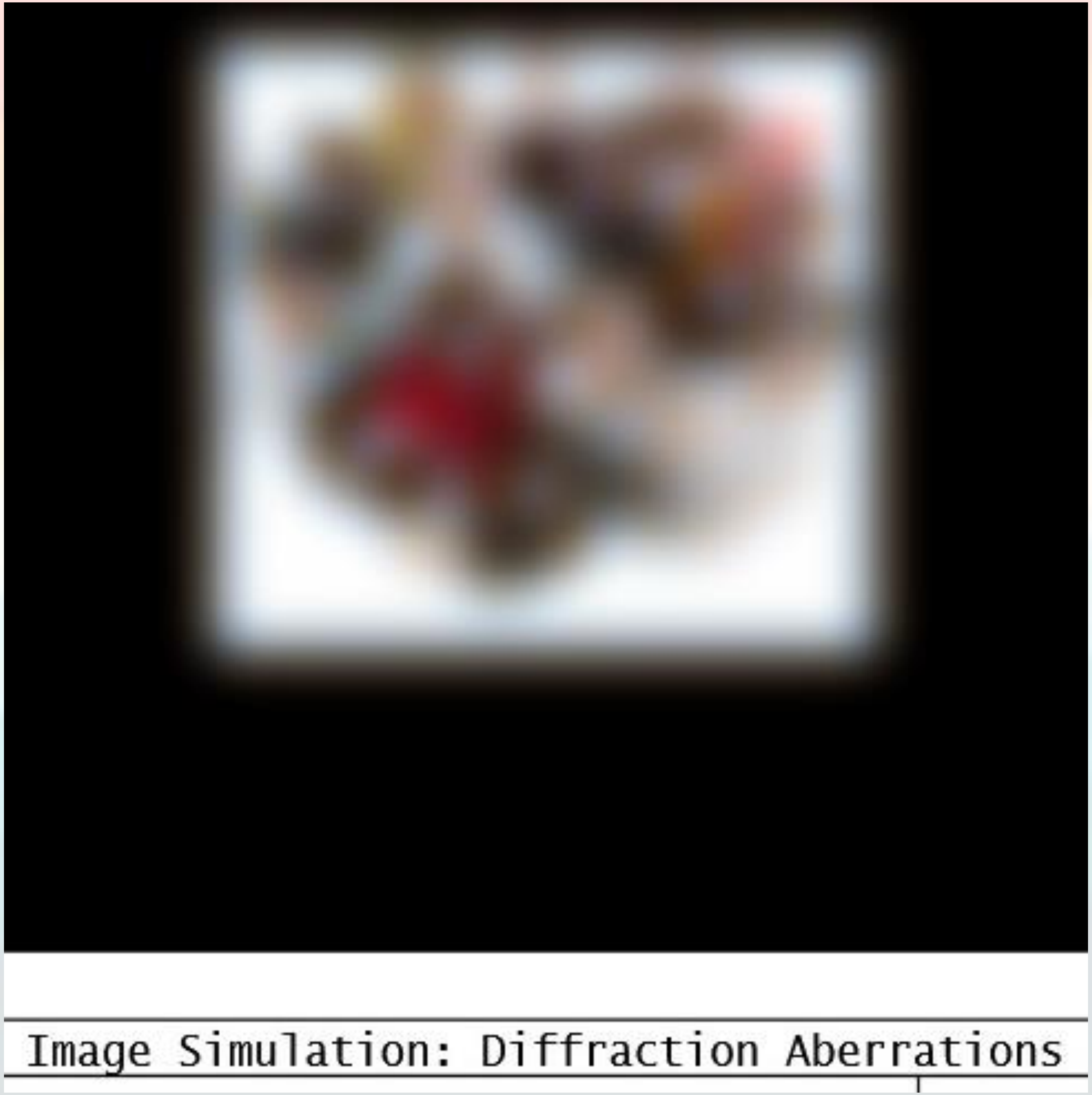
Donald Trump Tweet of 30 September 2019 following Intelligence Briefing



People needn't have worried about revealing the resolution of the KH-11's…

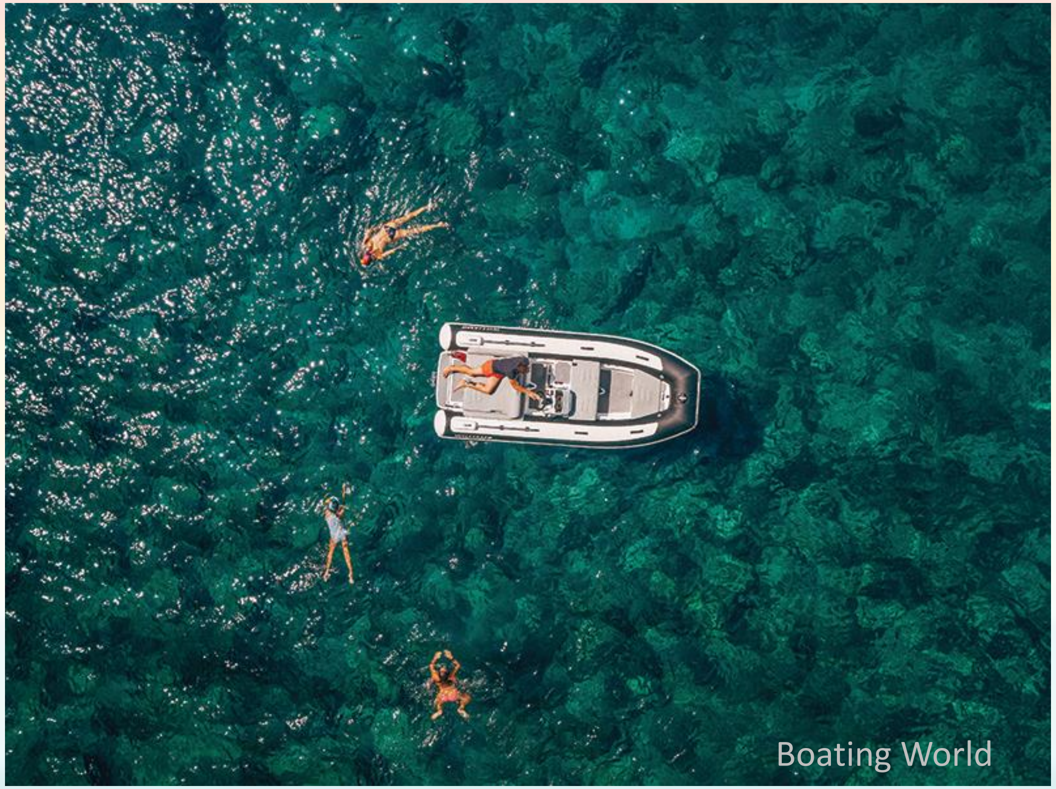
Resolution $\approx 1.22\ \lambda\ h/D$

≈ 6 cm



Friends as they would be seen by KH-11 from 160 miles above on a clear day

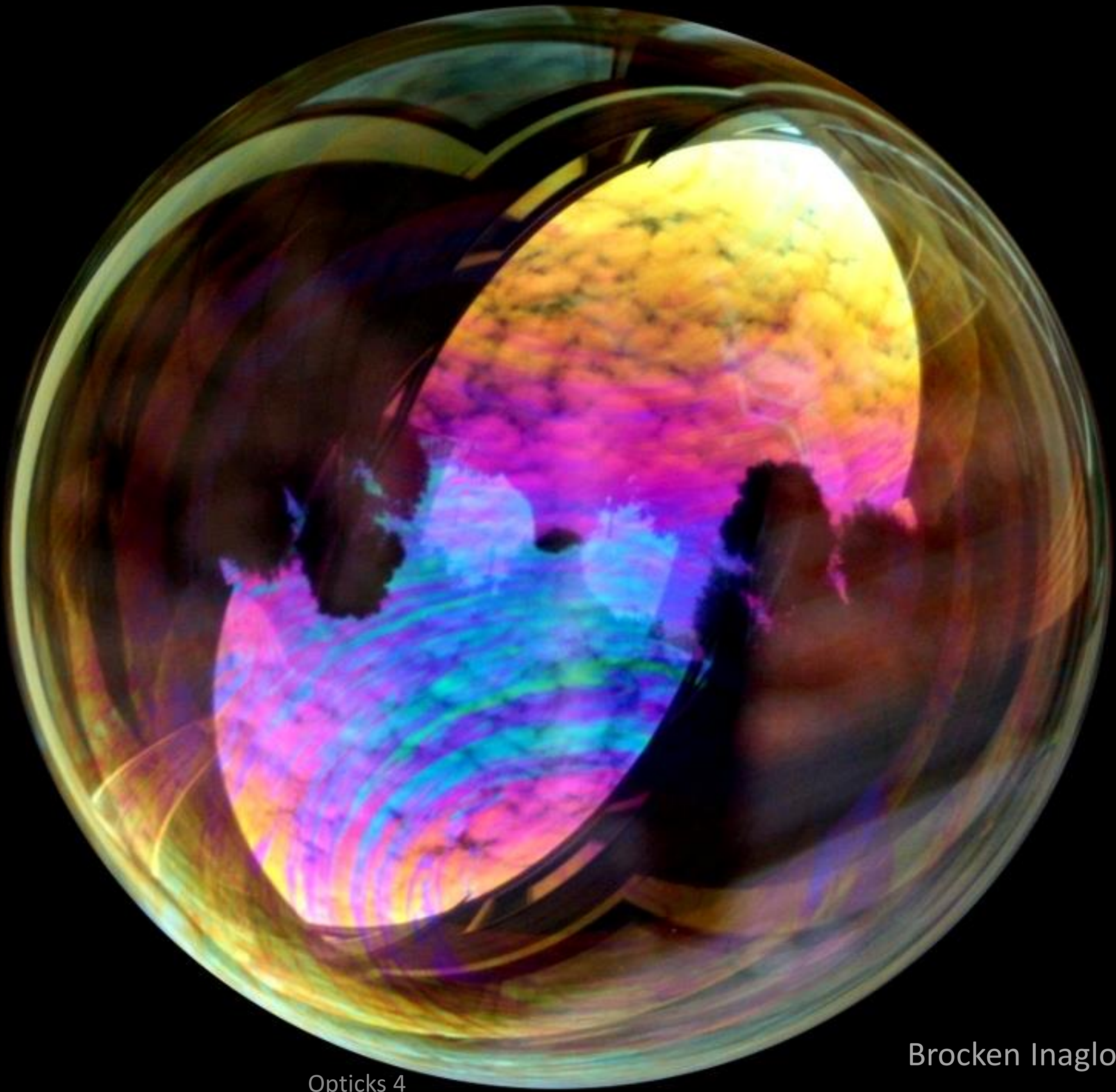
Backyard Scene as it would be seen by KH-11 from 160 miles above



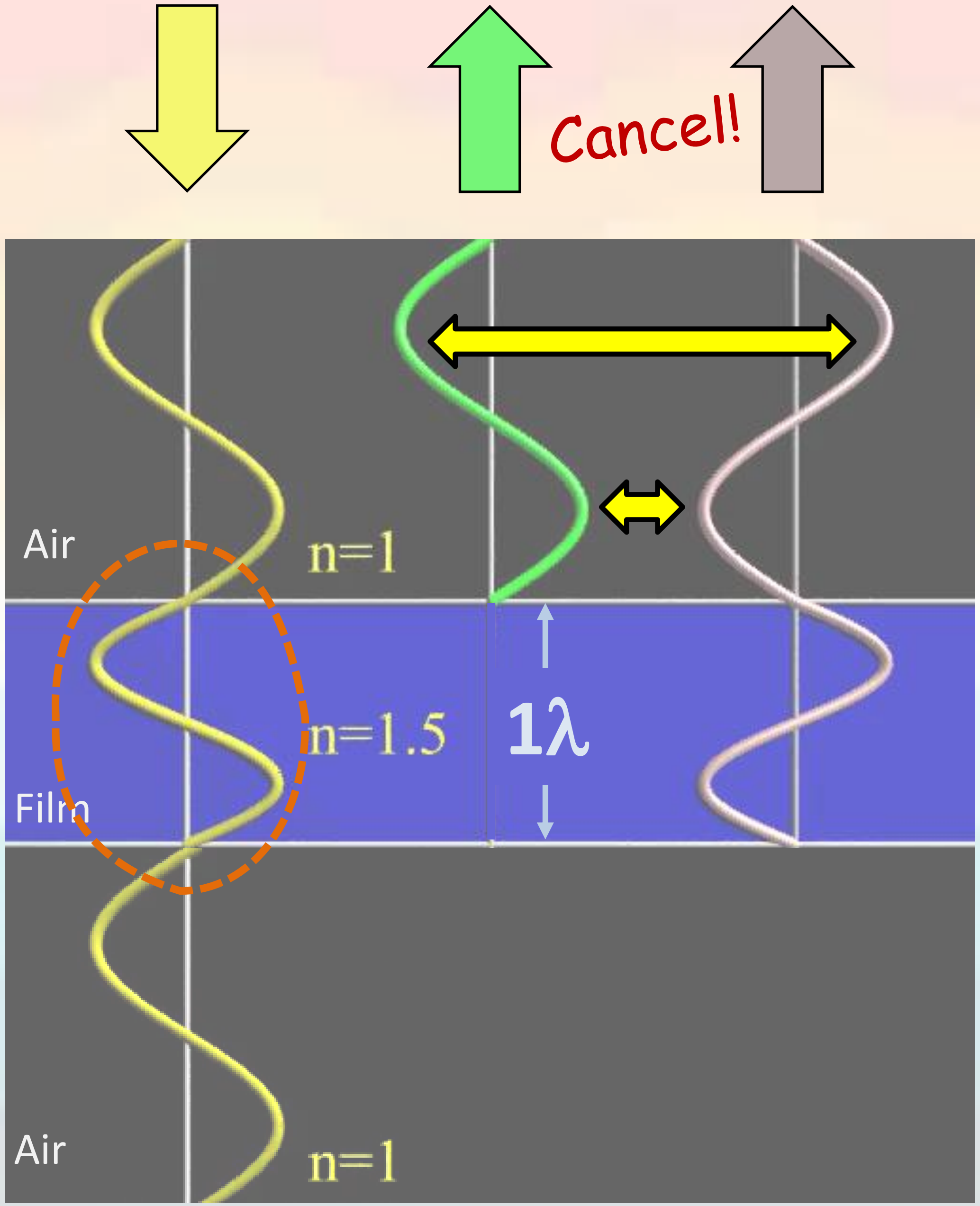
Swimmers as they would be seen from a drone

Swimmers as they would be seen by KH-11 from 160 miles above

Thin Film Interference



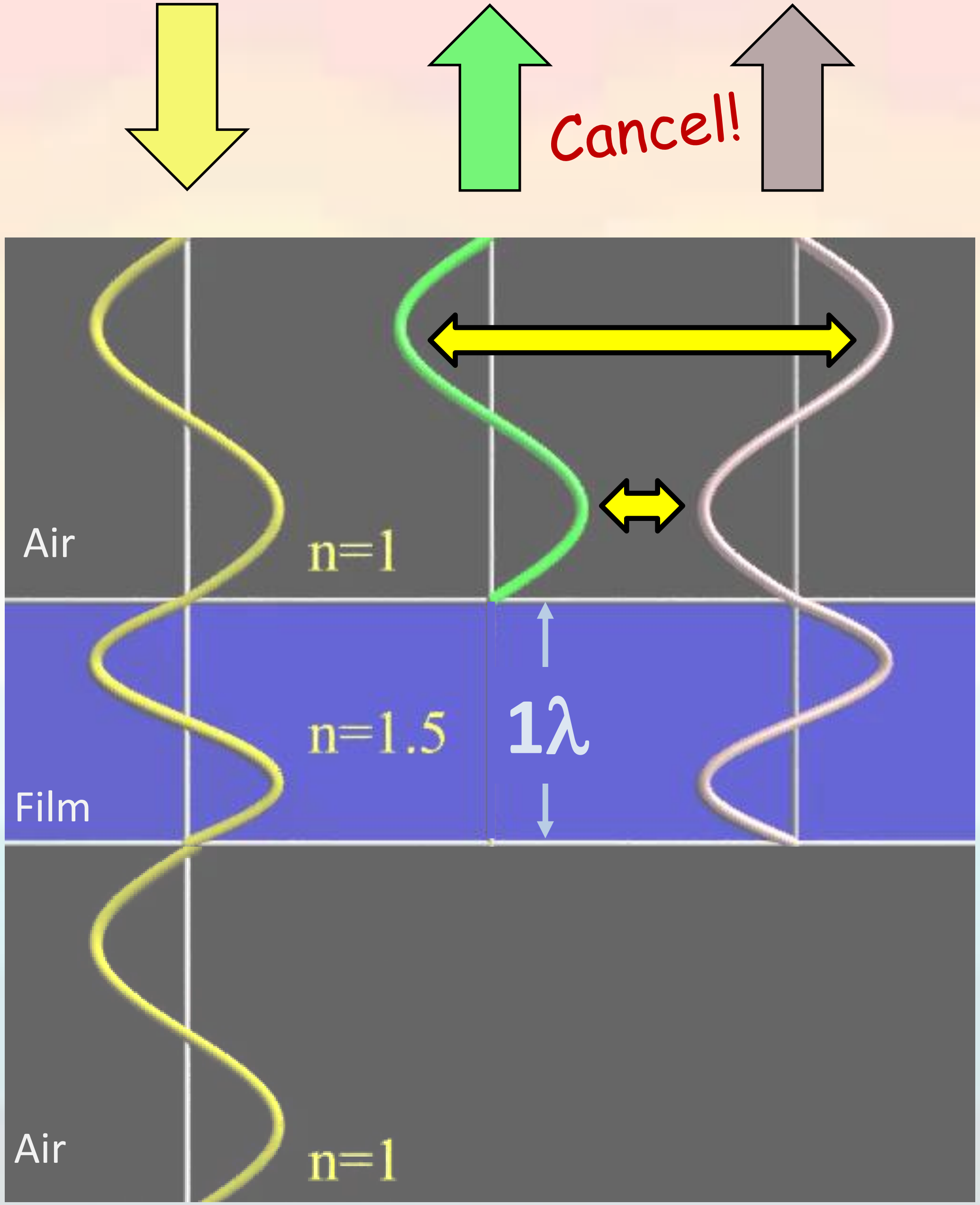
Brocken Inaglory 2007

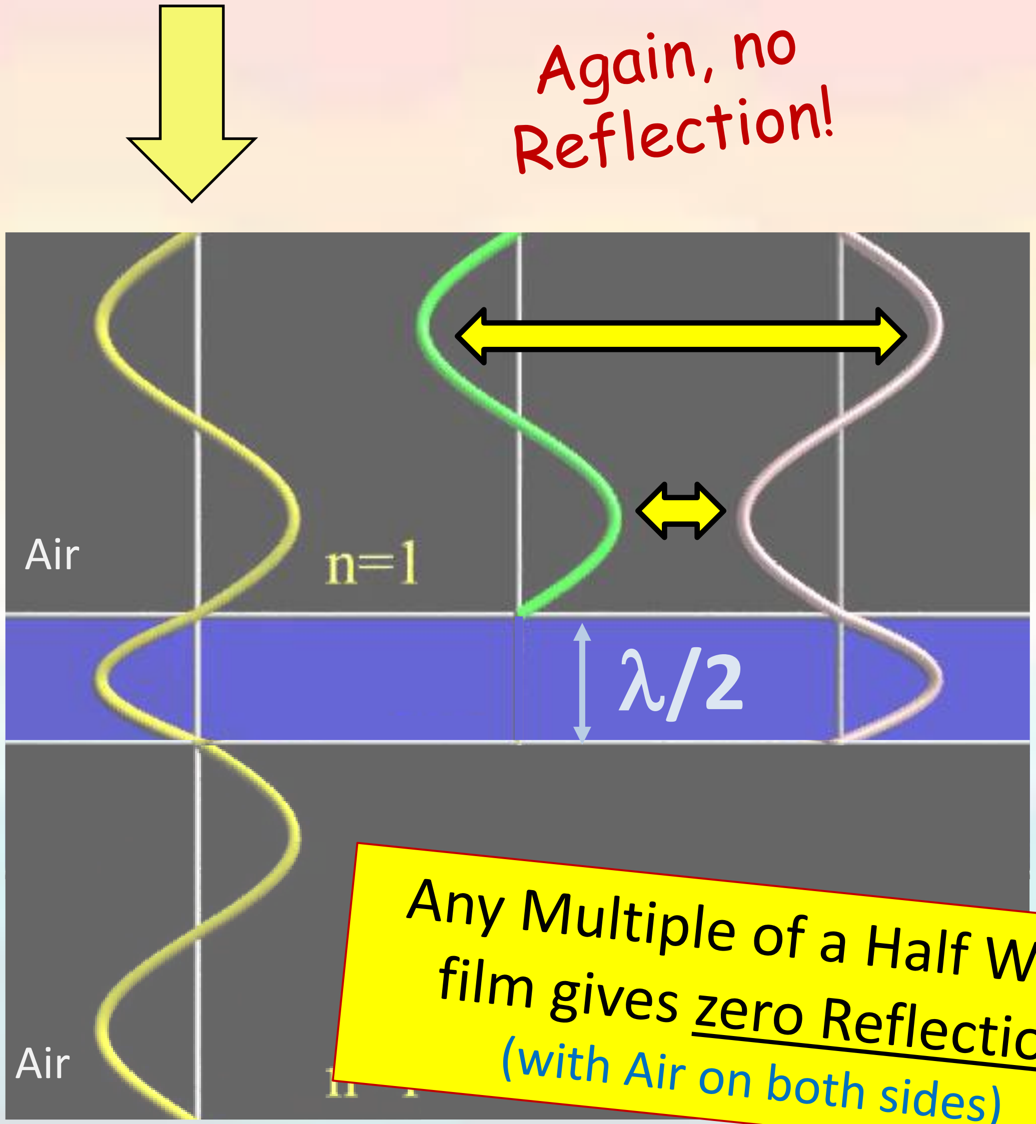


Thin Film Interference

What if we reduced the film to half a wavelength?

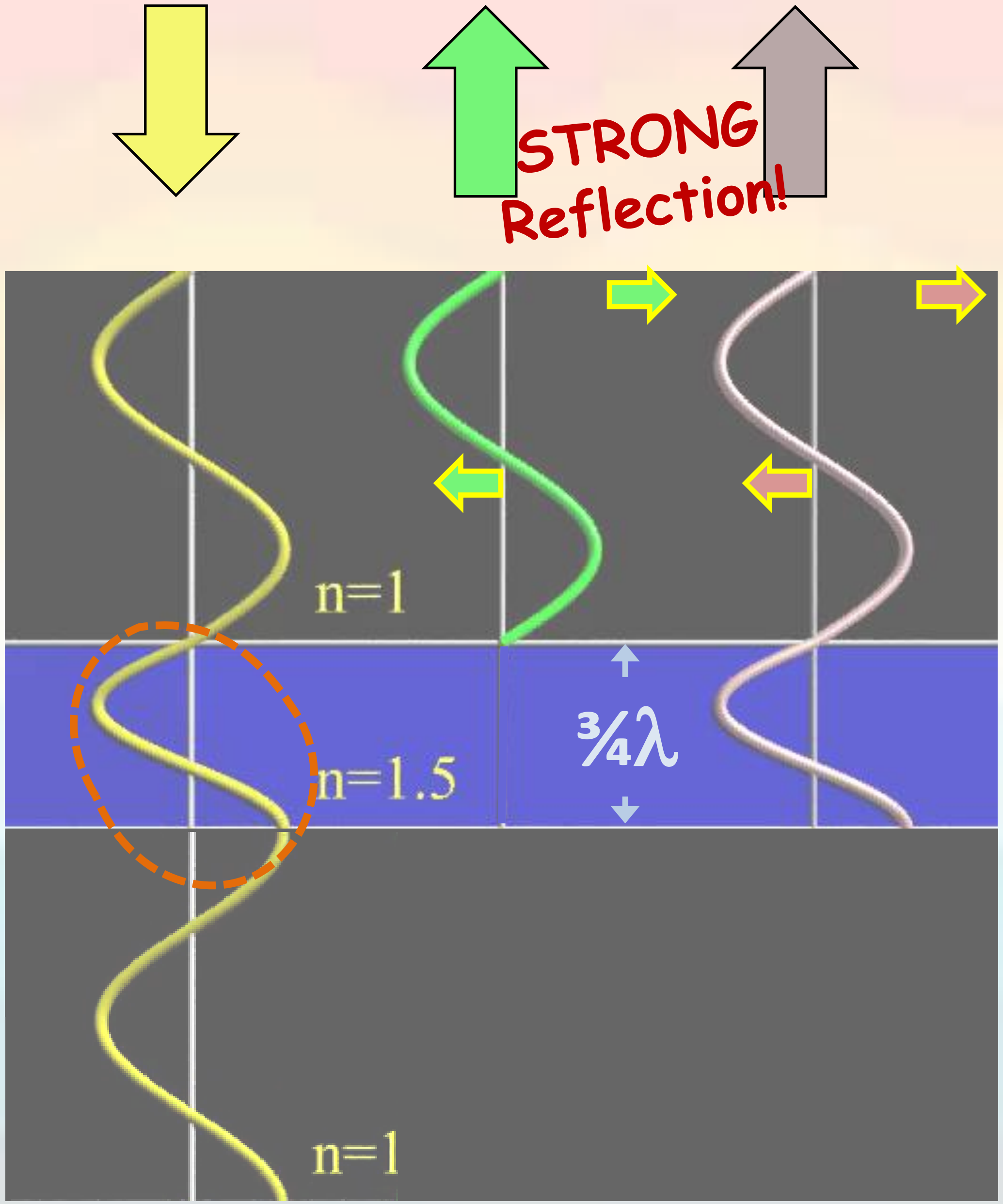
Thin Film Interference





Any Multiple of a Half Wave film gives zero Reflection
(with Air on both sides)

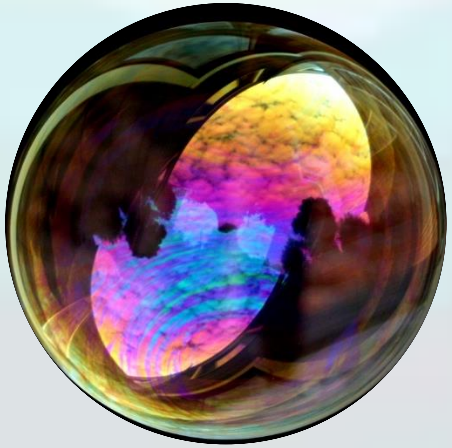
What about a 3/4 Wave Film?



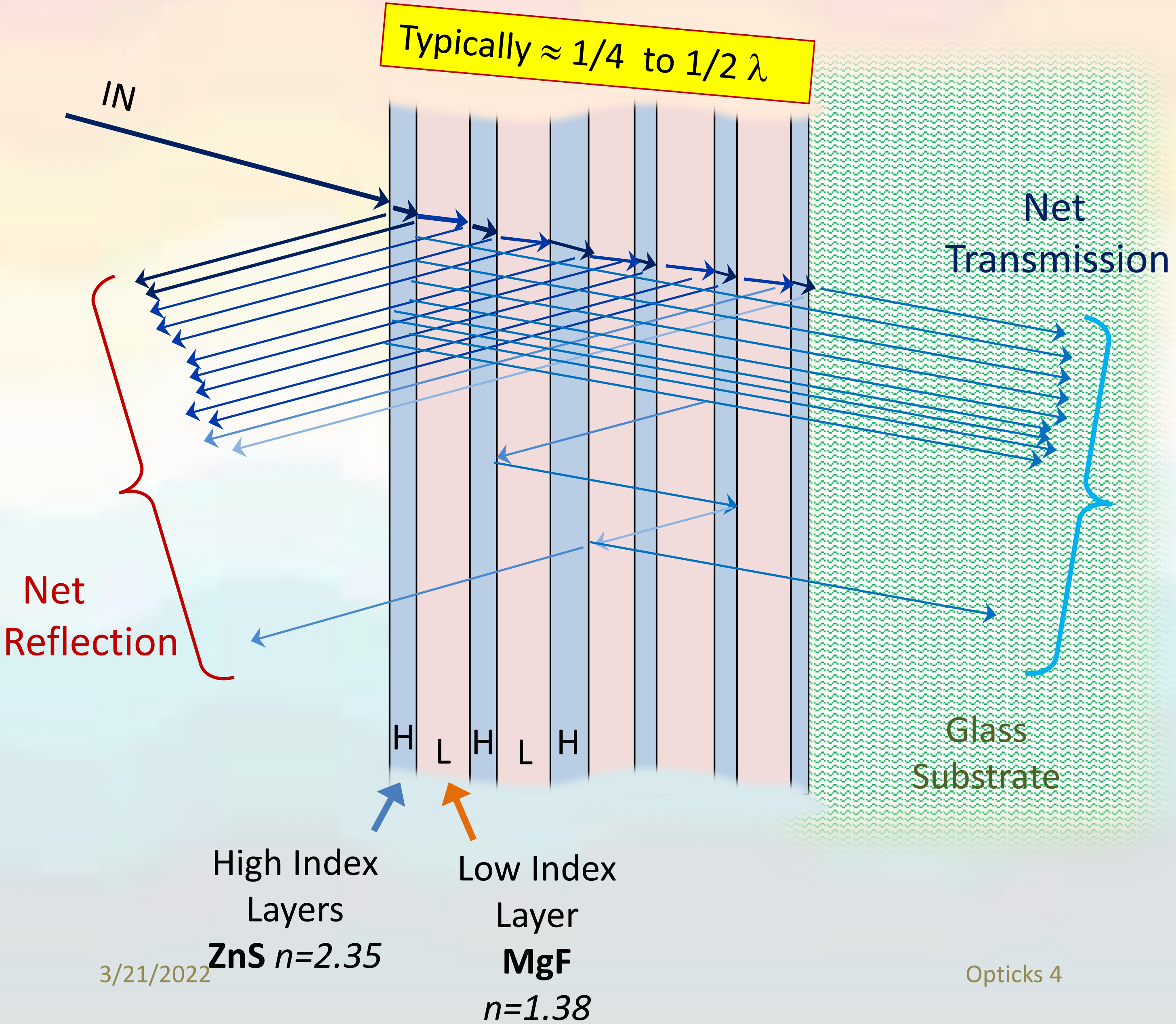
Maximum Reflection for
¼ λ, ¾ λ, 1¼ λ *etc.*
(with Air on both sides)

Result depends on

- Physical film thickness
- Wavelength of light
- Angle of incidence



Multilayer Coatings Can Perform Wonders



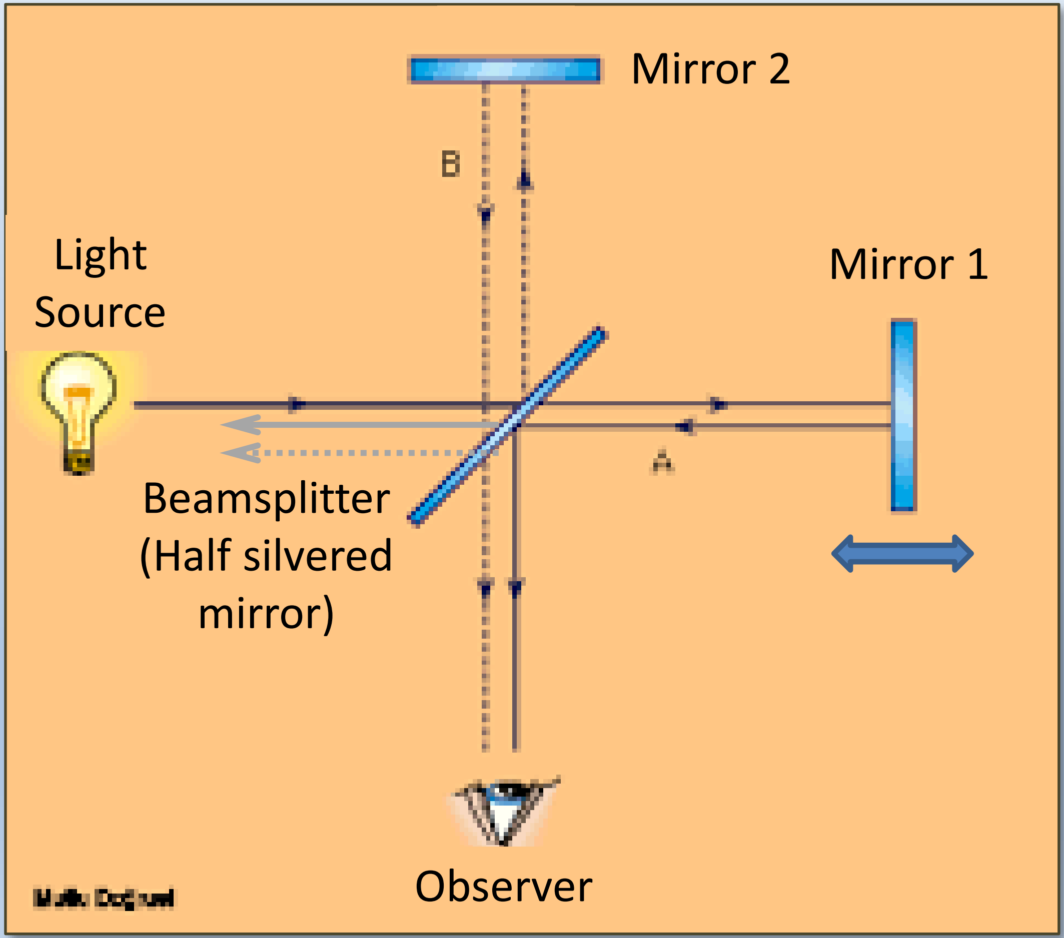
- Anti-Reflection Coatings

- High Reflection Coatings
    - 90% to 99.999%
- Dichroic Mirrors

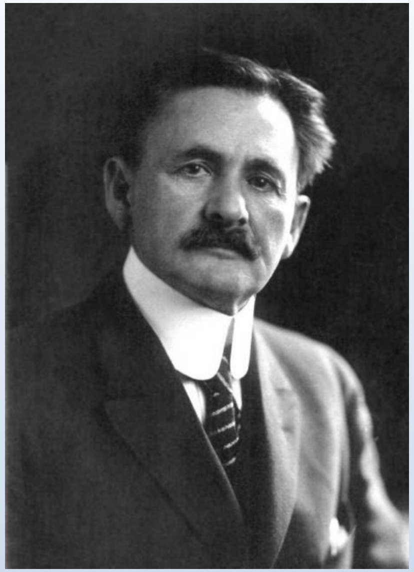
  e.g. Reflect Red, Transmit Blue
- Narrow Band Interference Filters

Interference: Clash of Two Waves

Michelson Interferometer



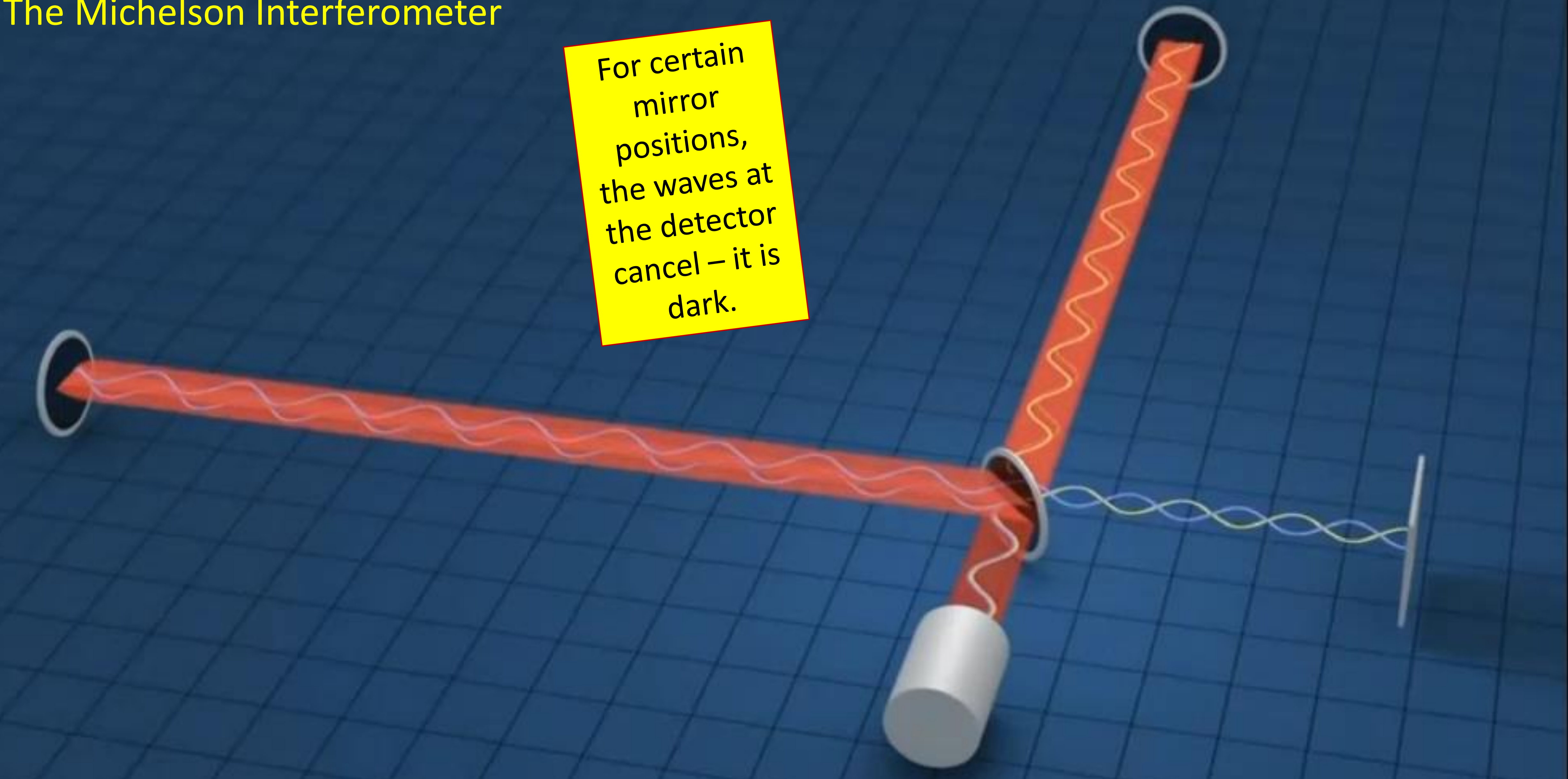
Uses:
- Precision Length Measurements
- Versions can be used to test optical surfaces
- Can measure Spectra of light sources via the Fourier Transform



Albert Michelson
1852 – 1931
German-American
Physicist

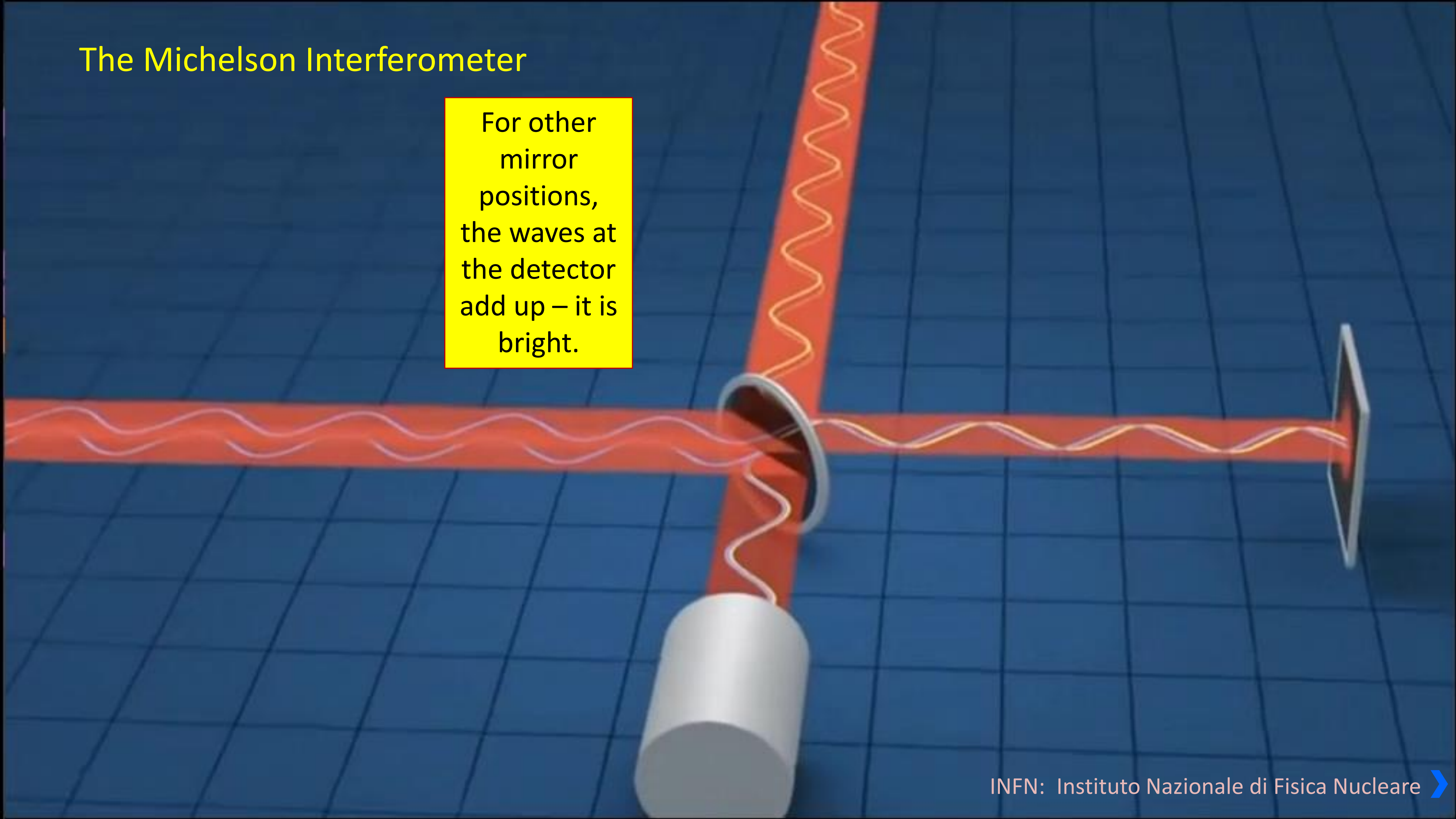
Gfycat

The Michelson Interferometer



For certain mirror positions, the waves at the detector cancel – it is dark.

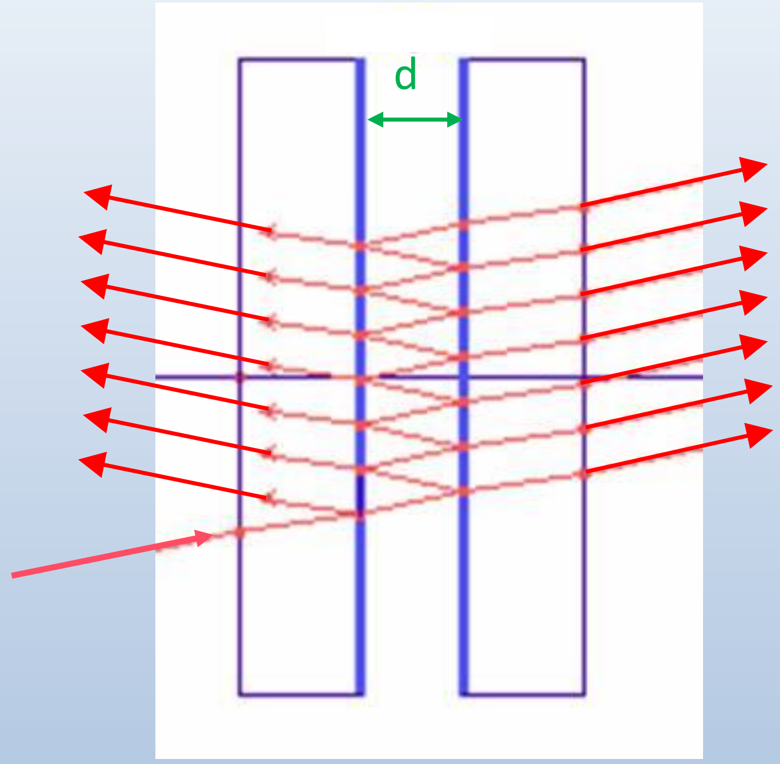
The Michelson Interferometer



For other mirror positions, the waves at the detector add up – it is bright.

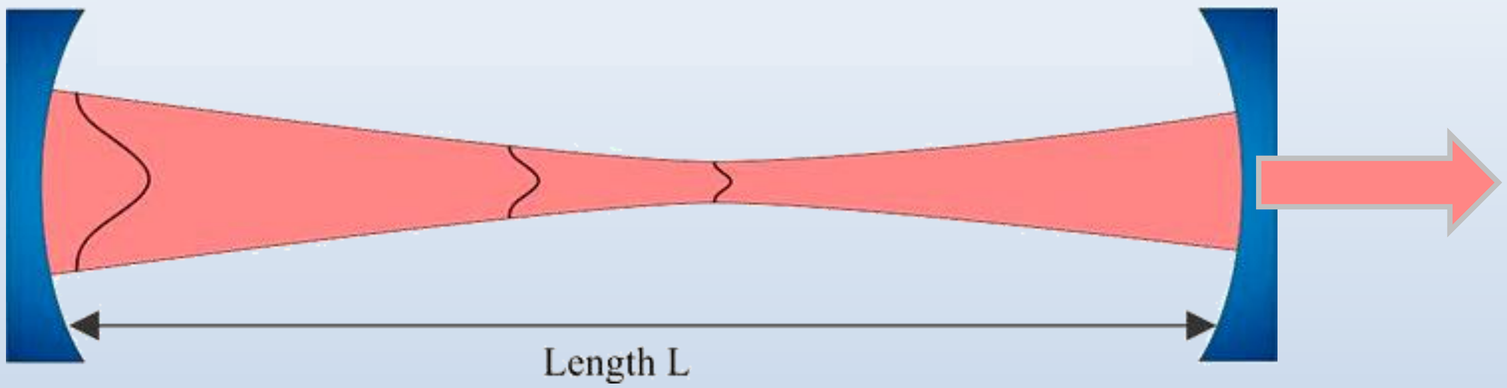
INFN: Instituto Nazionale di Fisica Nucleare

Multibeam Interference: The Fabry Perot Interferometer Cavity

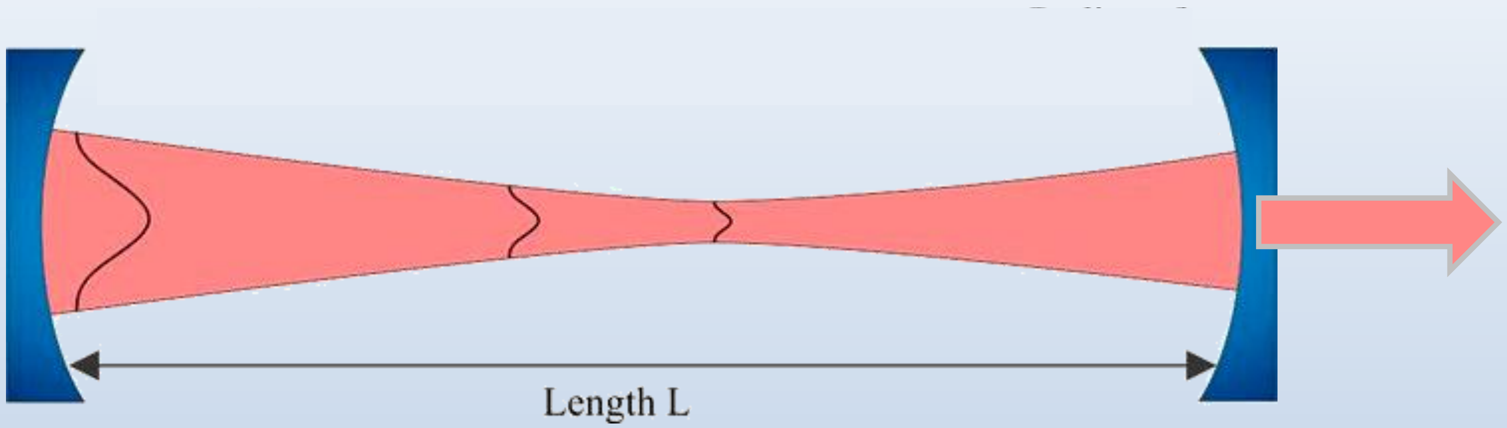


Two parallel highly reflecting mirrors

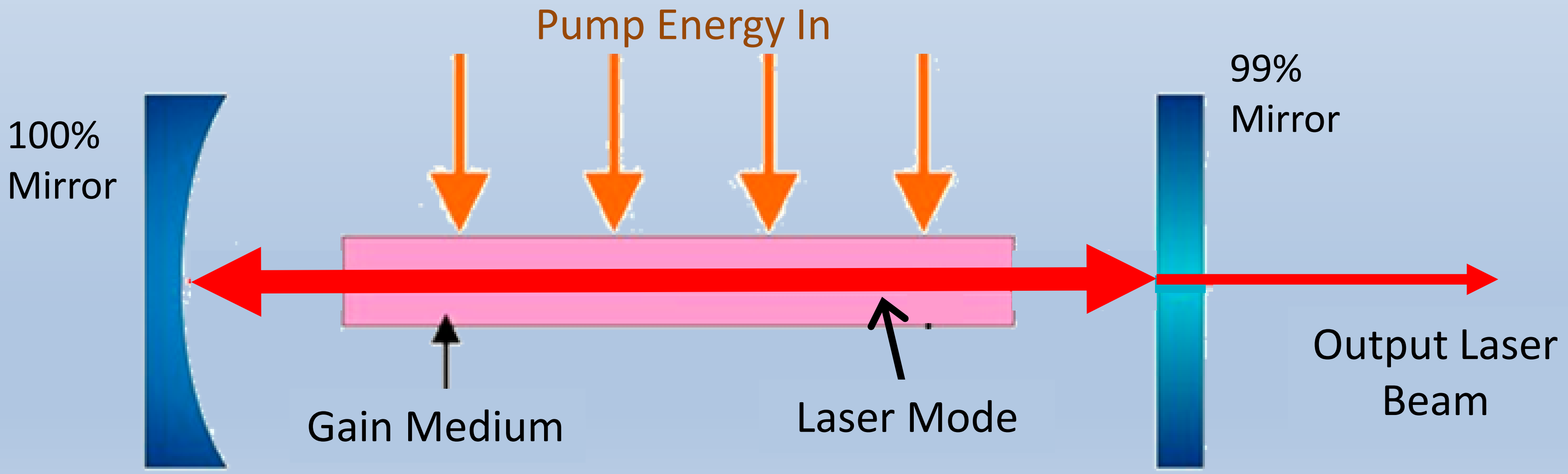
Multibeam Interference: Spherical Fabry Perot Resonator and Lasers



Multibeam Interference: Spherical Fabry Perot Resonator and Lasers



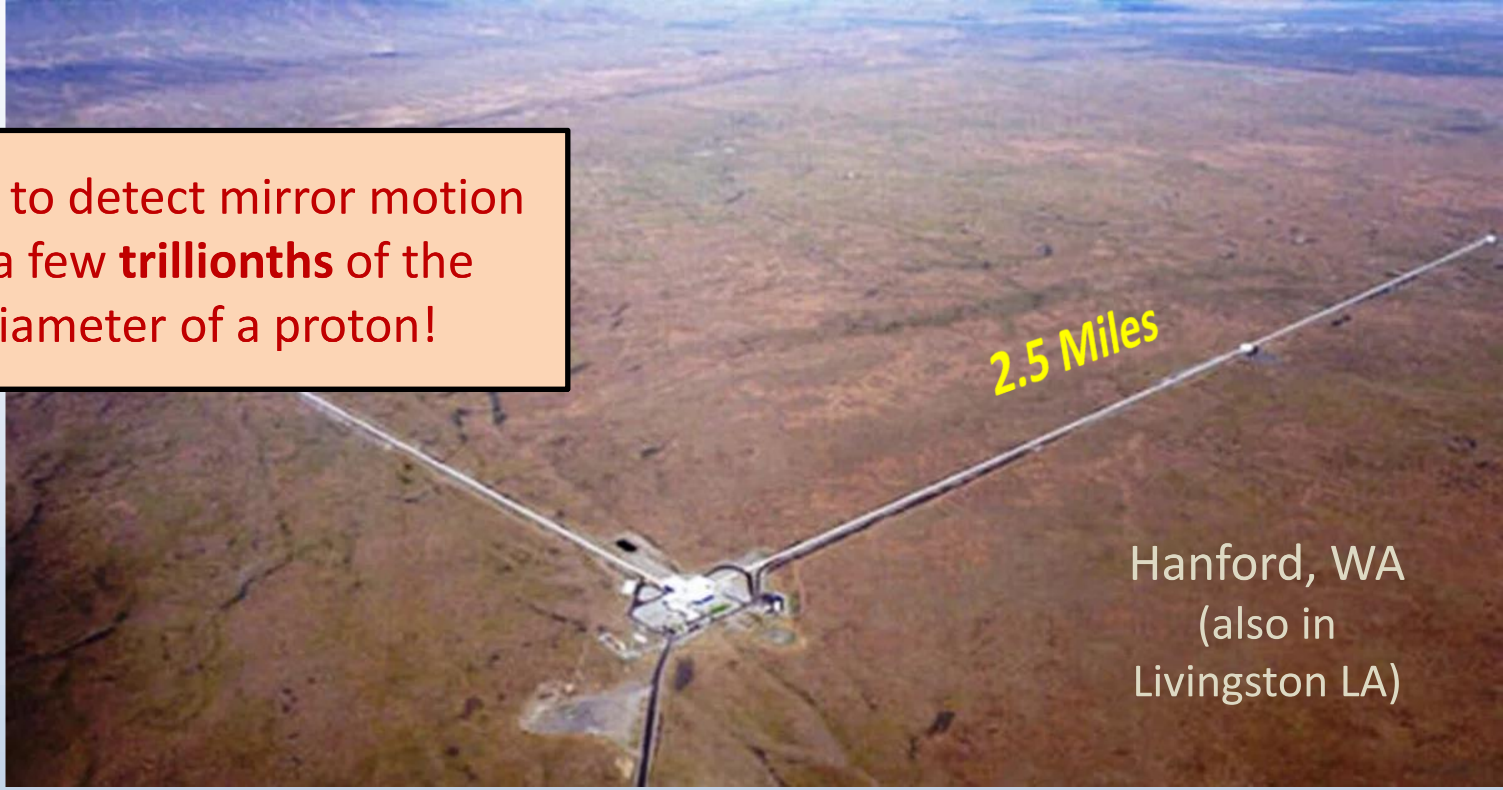
Laser

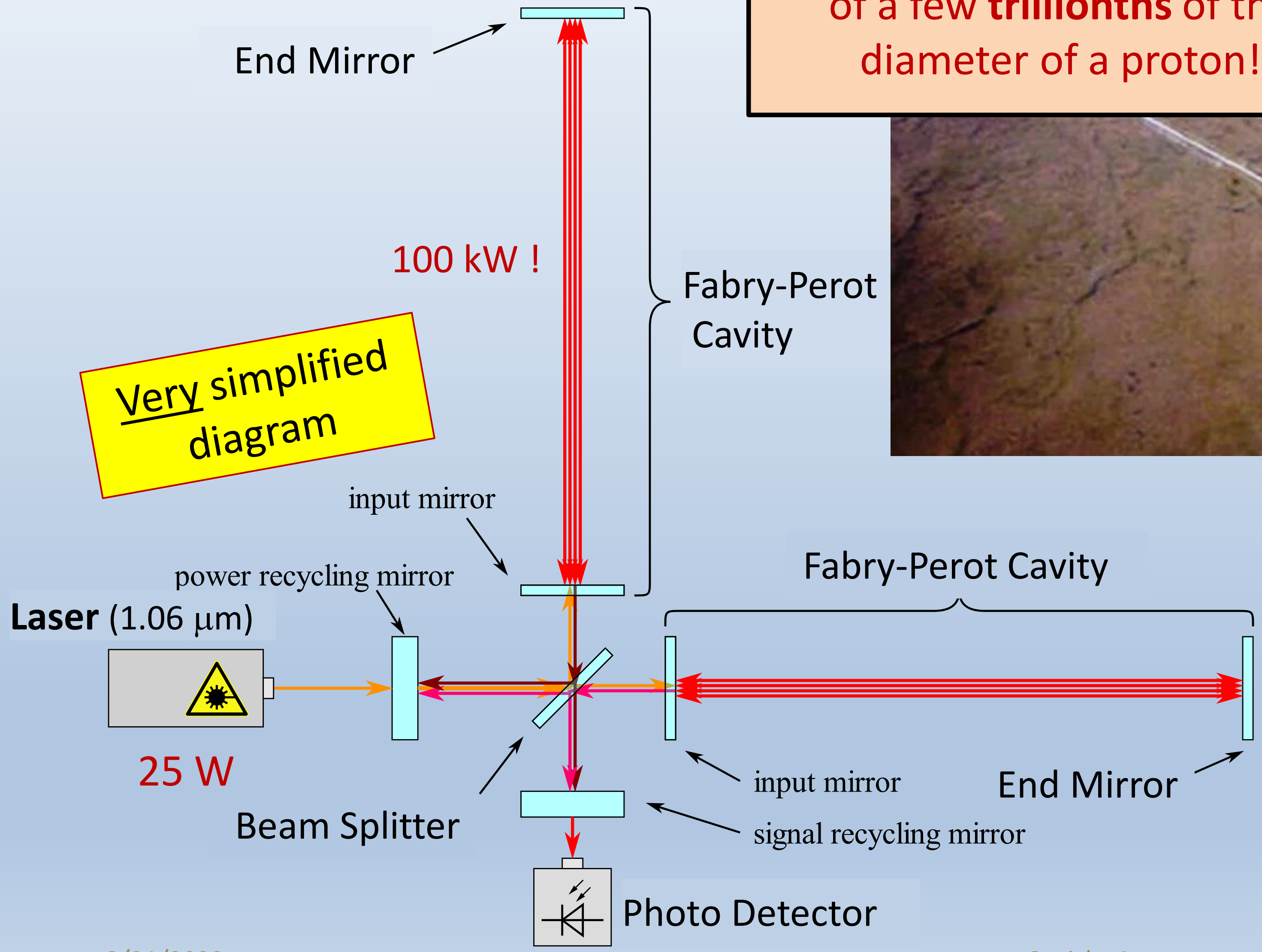



Two massive Black Holes
merging in a death spiral
(Computer Simulation)
Caltech/SXS

LIGO Gravitational Wave Detectors

Need to detect mirror motion of a few **trillionths** of the diameter of a proton!





LIGO Gravitational Wave Detectors

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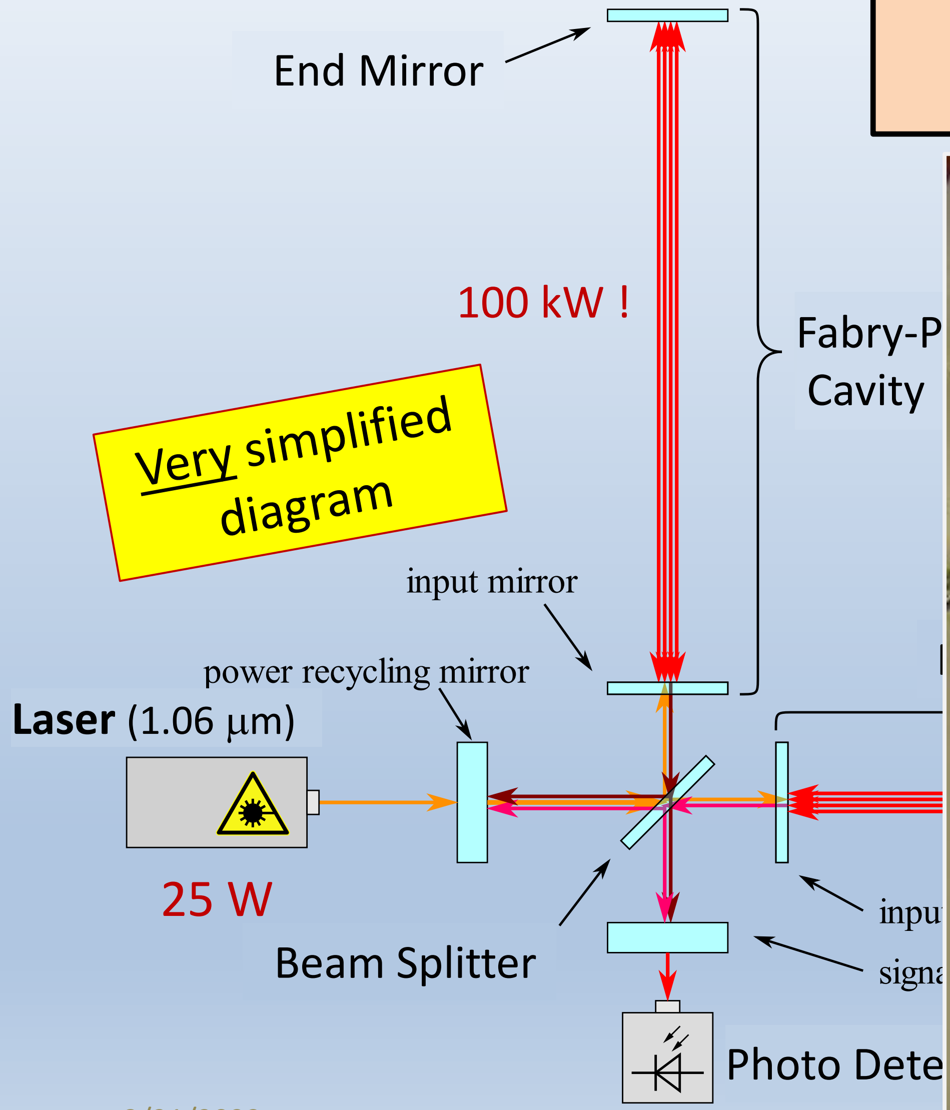
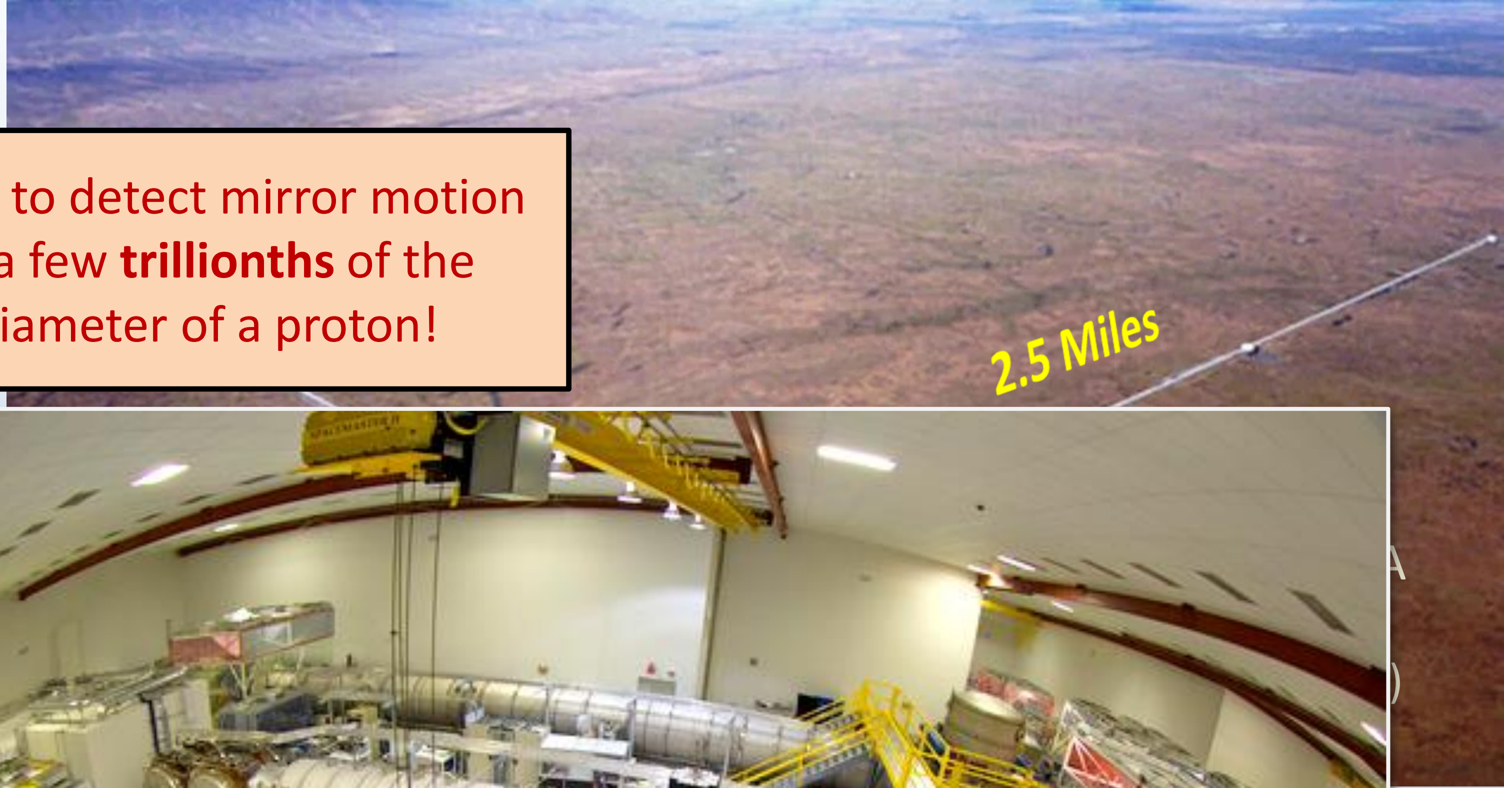
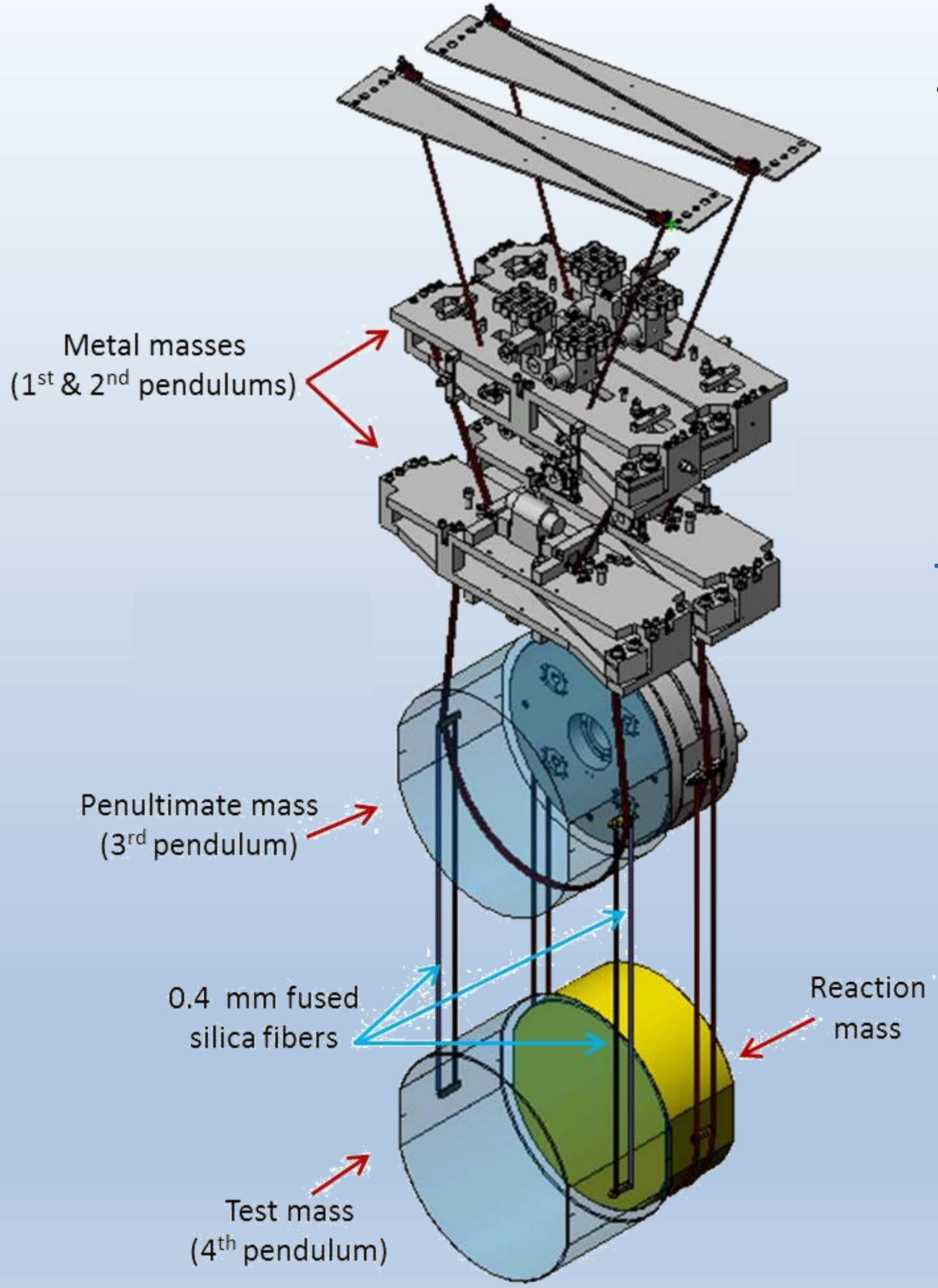


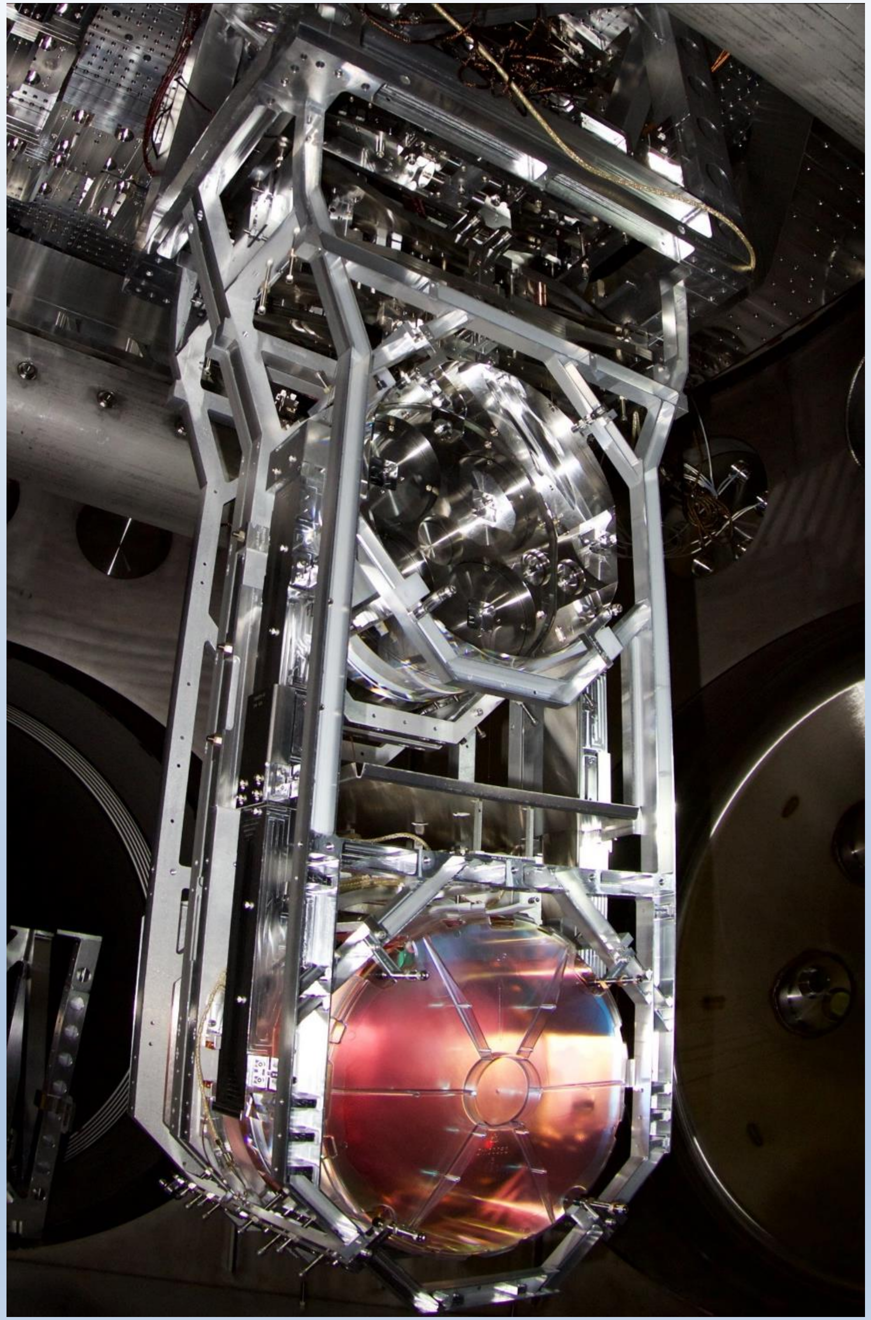




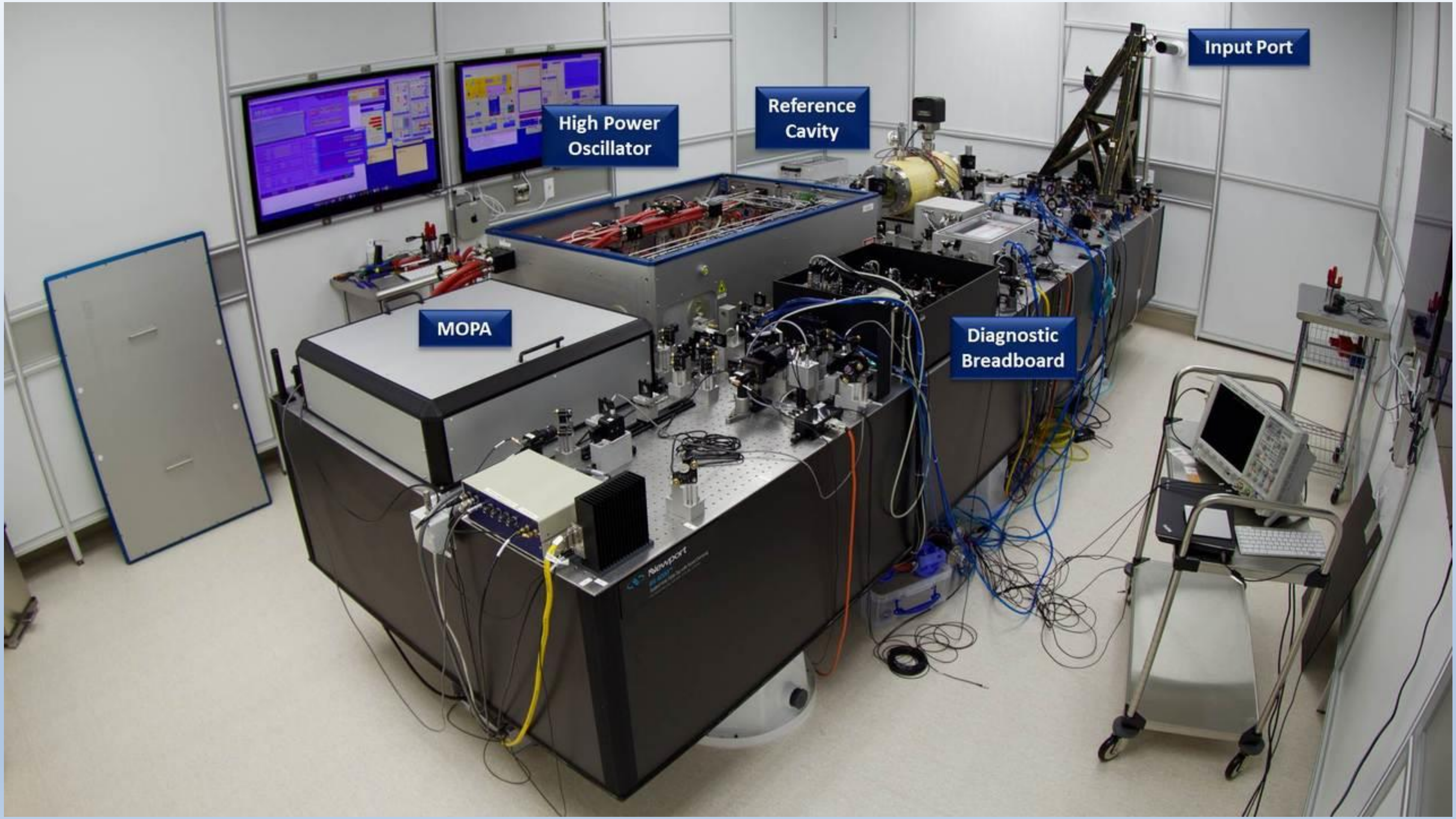
40 kG Cavity Mirrors
are Suspended by
4 tiny Glass Fibers

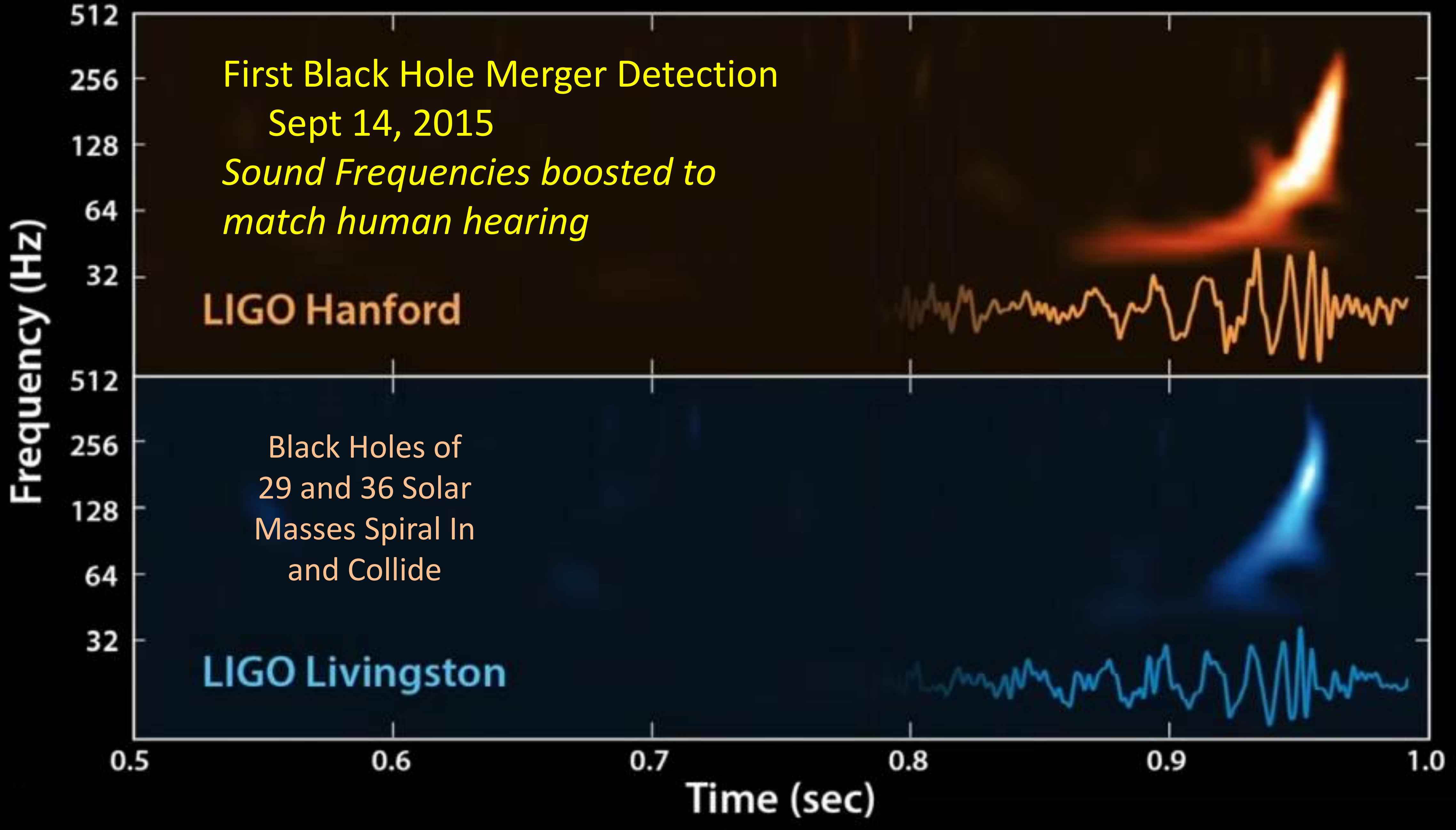
Extreme isolation
from environmental
vibrations is vital

The entire optical path
and mirrors are under
ultrahigh vacuum



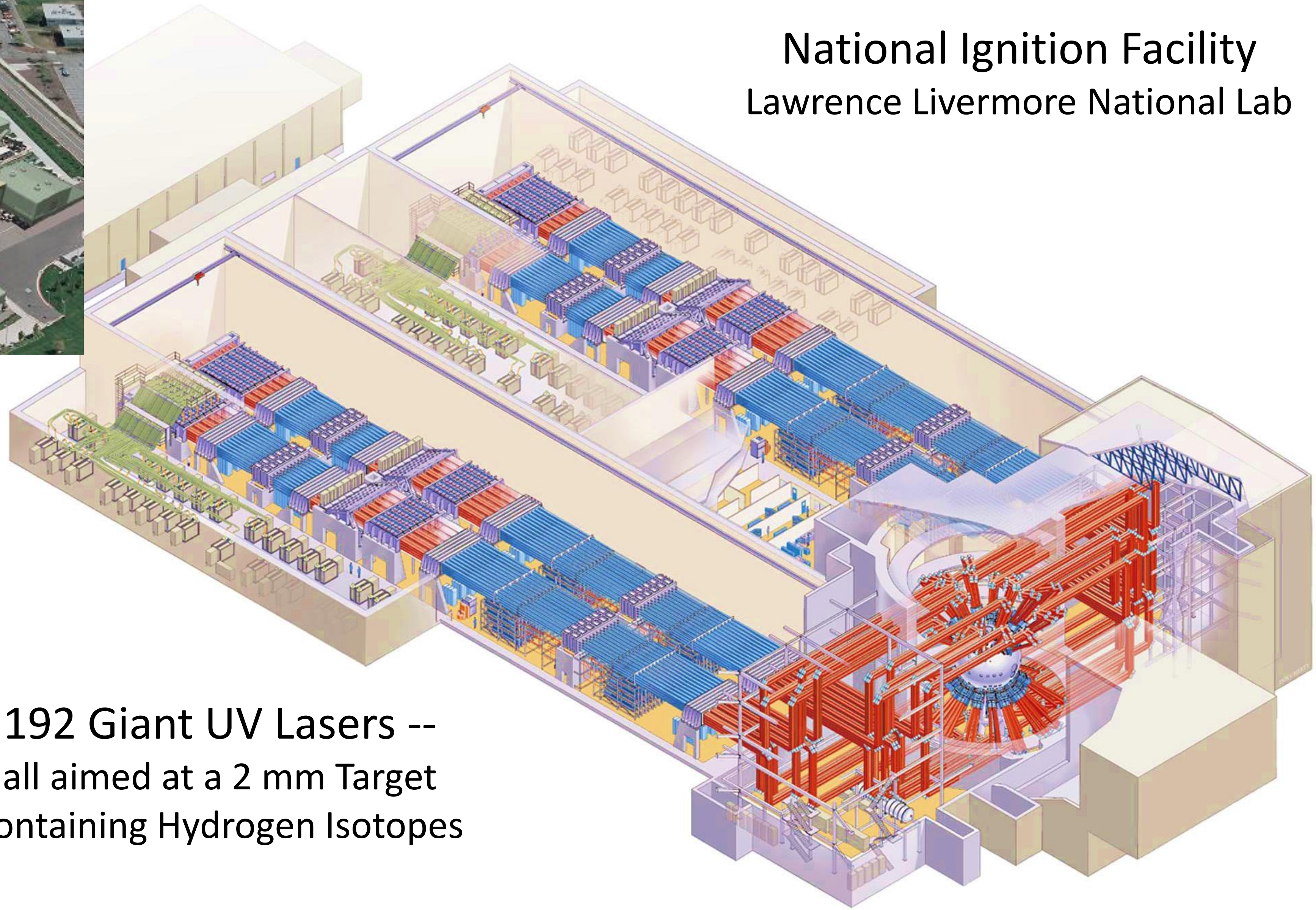
The 25W Laser




First Black Hole Merger Detection
Sept 14, 2015
Sound Frequencies boosted to
match human hearing
LIGO Hanford
Black Holes of
29 and 36 Solar
Masses Spiral In
and Collide
LIGO Livingston
Frequency (Hz)
512
256
128
64
32
512
256
128
64
32
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

National Ignition Facility

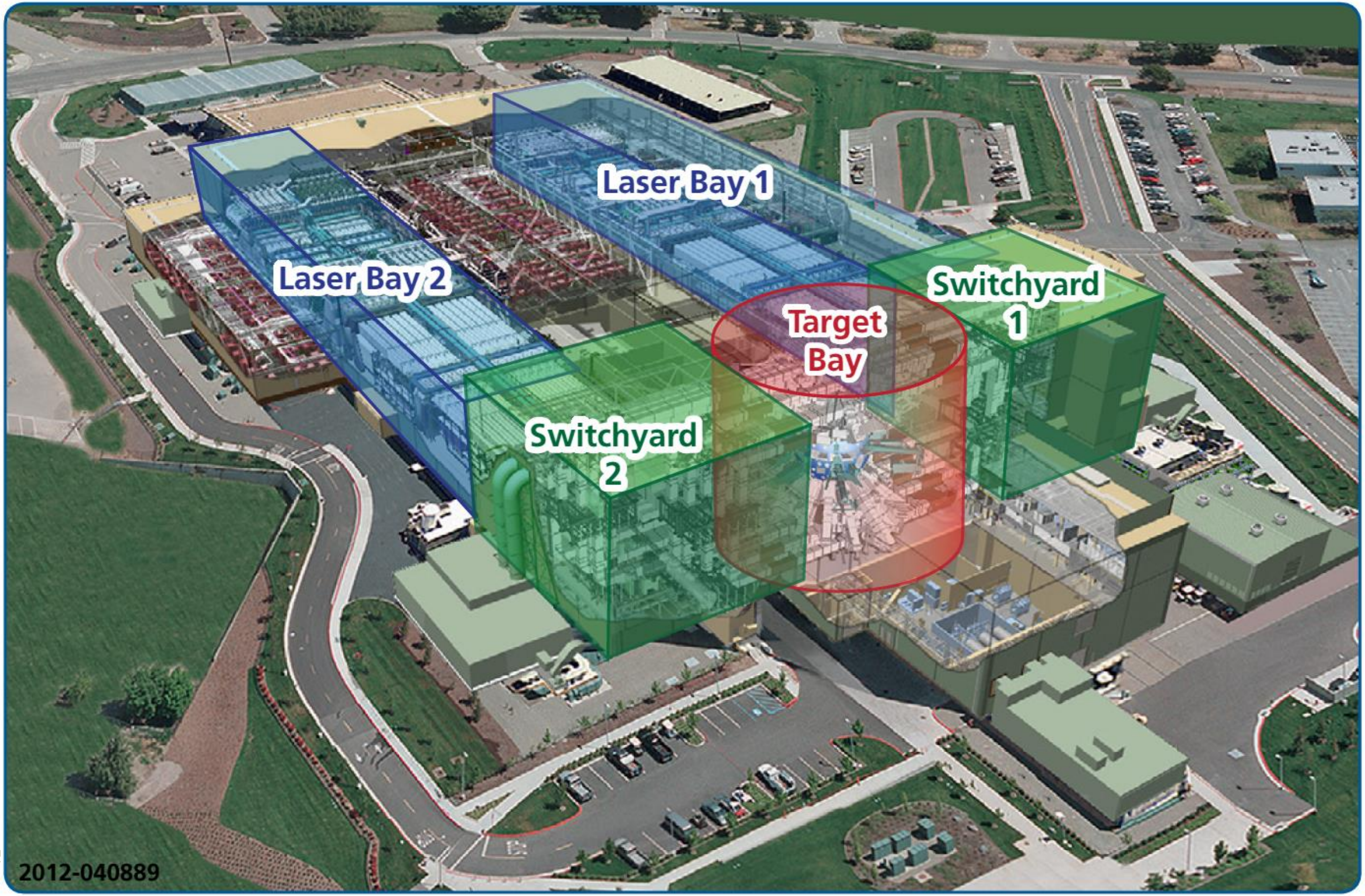
Lawrence Livermore National Lab



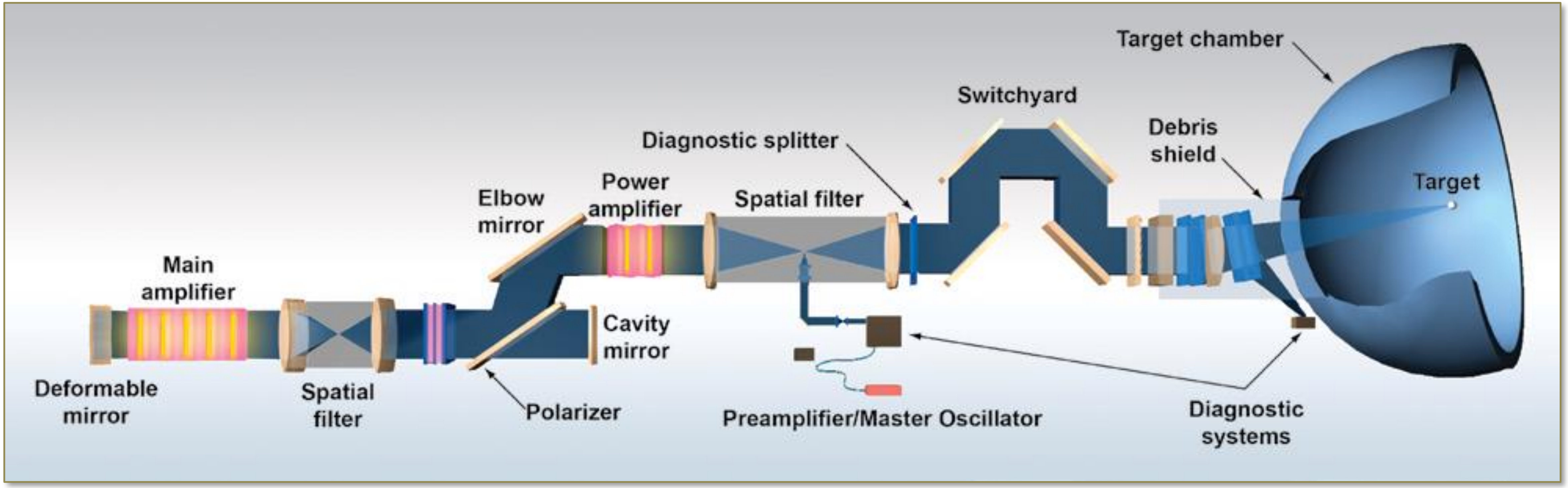
Goal:
Ignite a Fusion Reaction and Emulate the Sun

192 Giant UV Lasers --

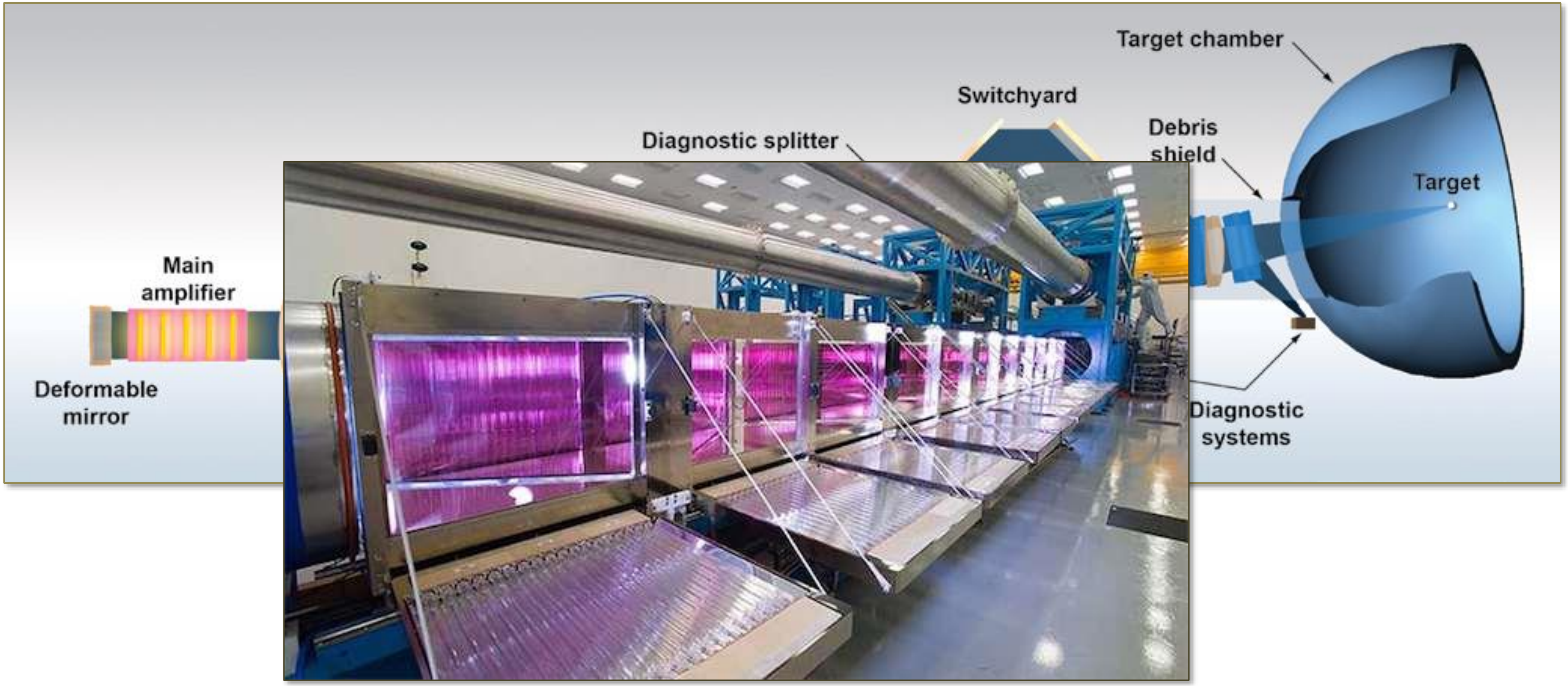
all aimed at a 2 mm Target containing Hydrogen Isotopes


Laser Bay 1
Laser Bay 2
Switchyard 1
Switchyard 2
Target Bay
2012-040889

National Ignition Facility
Lawrence Livermore National Lab



National Ignition Facility
Lawrence Livermore National Lab



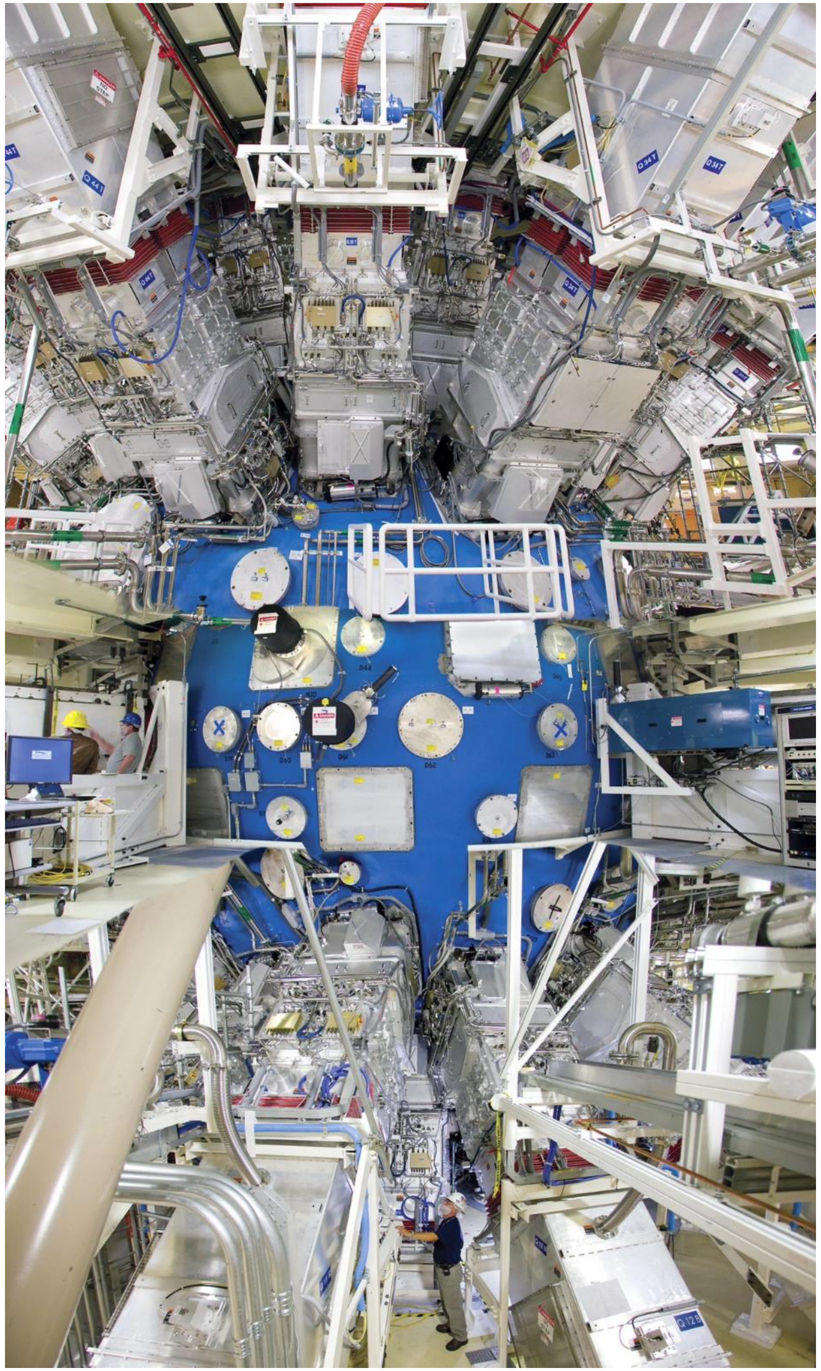
Some of the ~3000 doped glass laser amplifier slabs

Na
Lawre

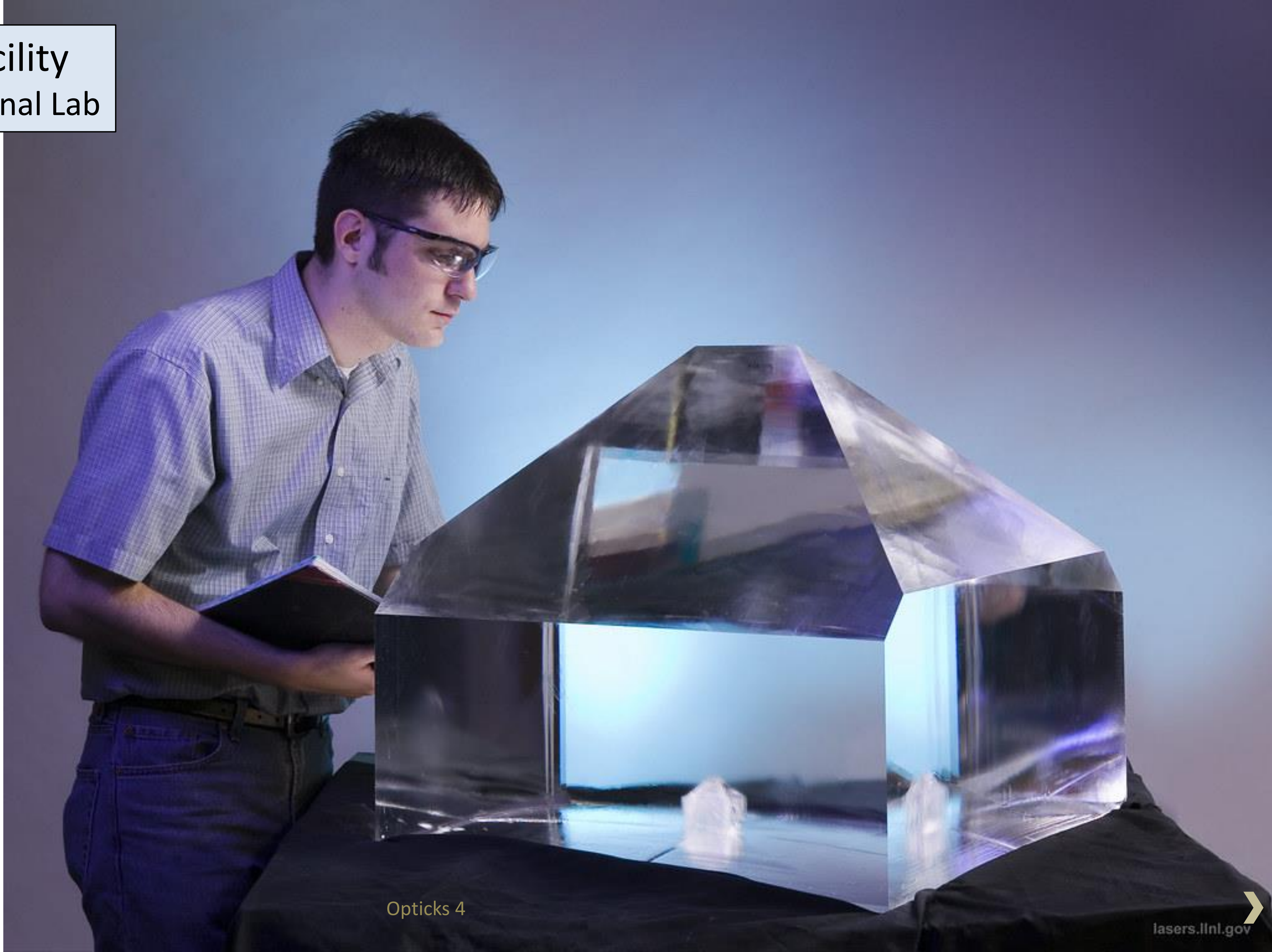
National Ignition Facility

Lawrence Livermore National Lab

30 ft target sphere with holes for 192 laser beams



National Ignition Facility
Lawrence Livermore National Lab

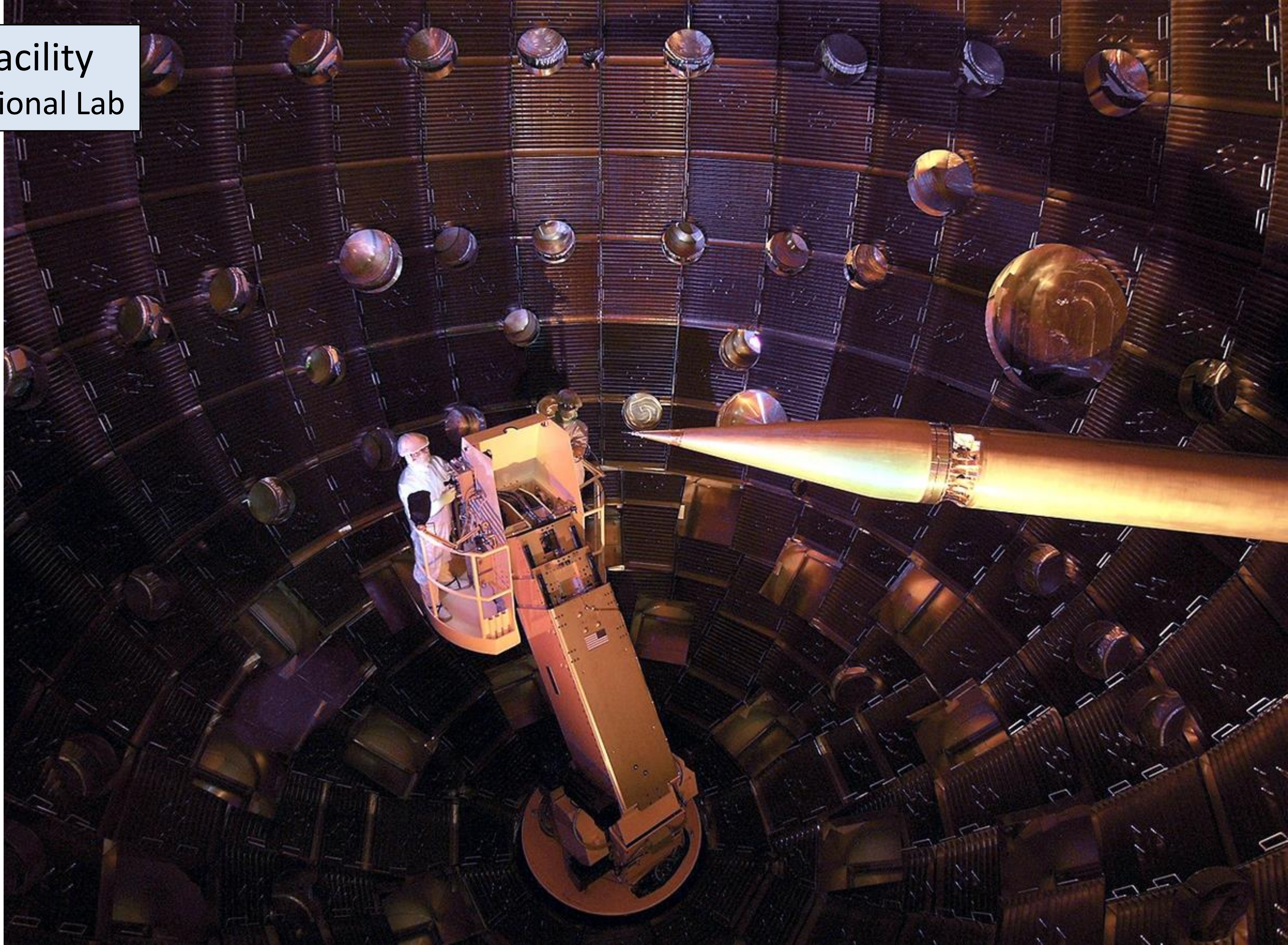


800 Lb Crystal of KDP
(Potassium Dihydrogen Phosphate)

Used to Convert Infrared Lasers (1053nm) to Ultraviolet (351nm)

300 of these crystals were needed

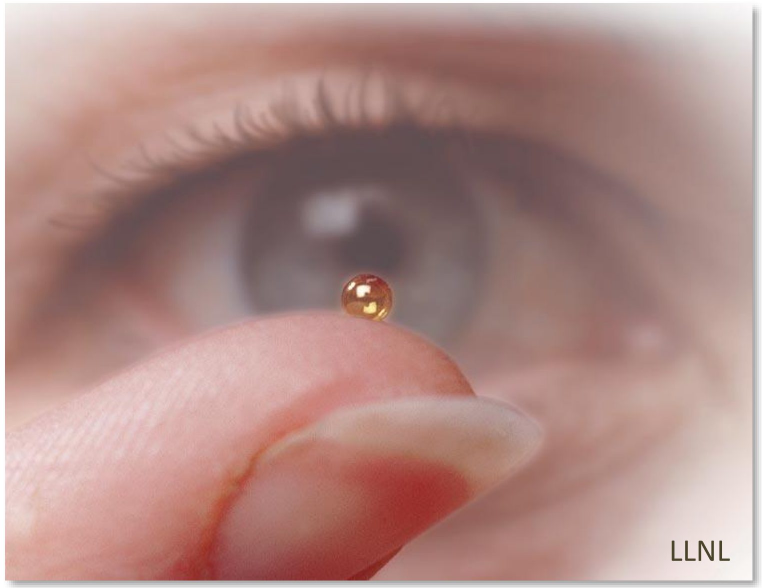
National Ignition Facility
Lawrence Livermore National Lab



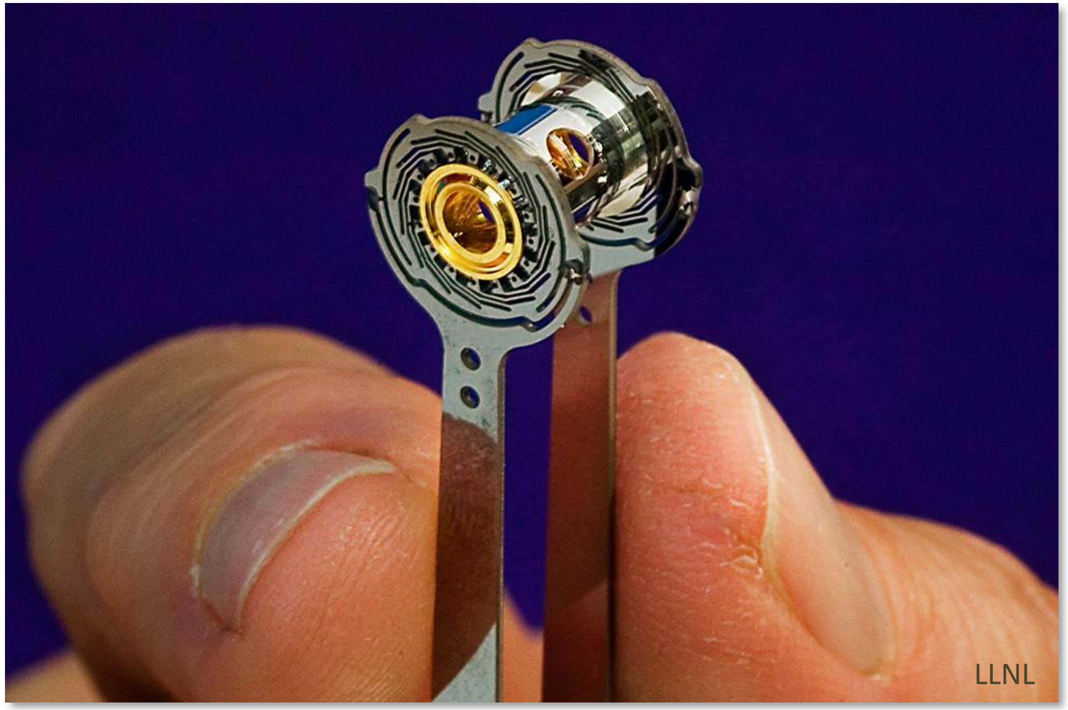
The Hydrogen Target is held at the center of the sphere on this arm

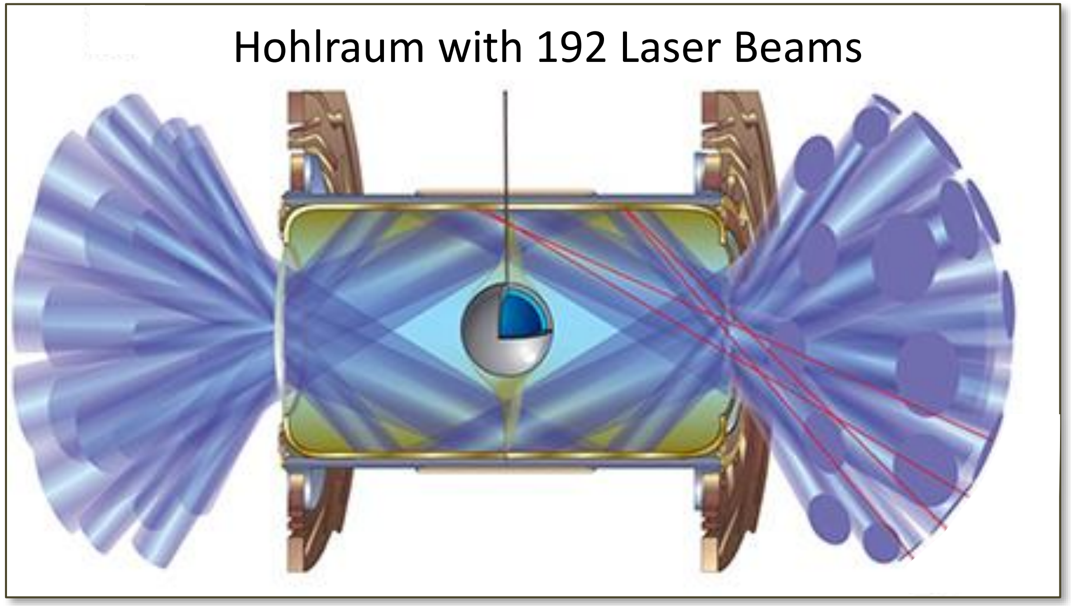
National Ignition Facility
Lawrence Livermore National Lab

The 2mm Hydrogen Fuel ball is in the center of the Hohlraum



The Gold Hohlraum Cylinder





National Ignition Facility
Lawrence Livermore National Lab

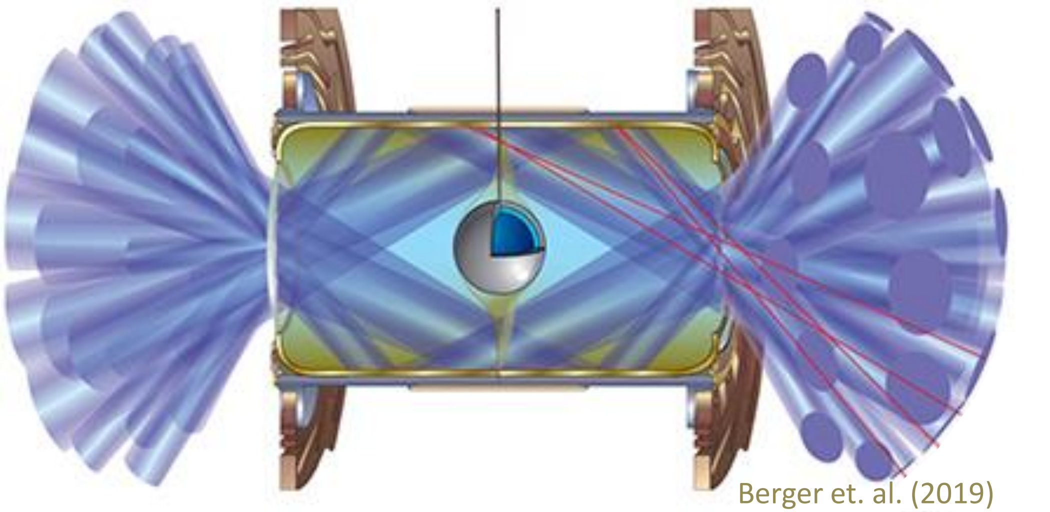
Encouraging experiment of Aug 8, 2021:

1.9 MJ of laser energy IN
1.35 MJ of fusion energy OUT (70% of “break-even”)

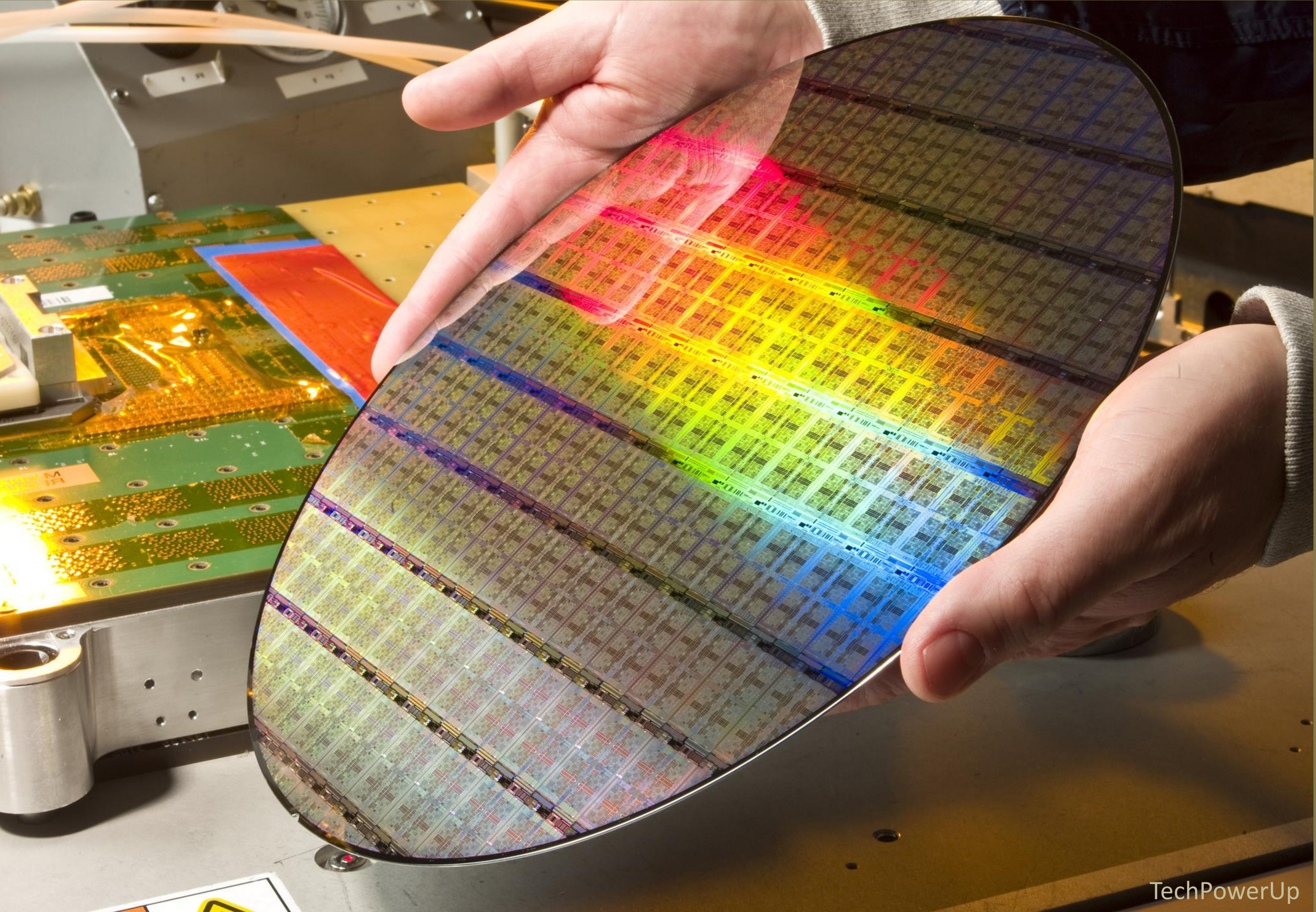
1.35 MJ would roughly bring a gallon of water to a boil!

70% is a fusion record

Hohlraum with 192 Laser Beams

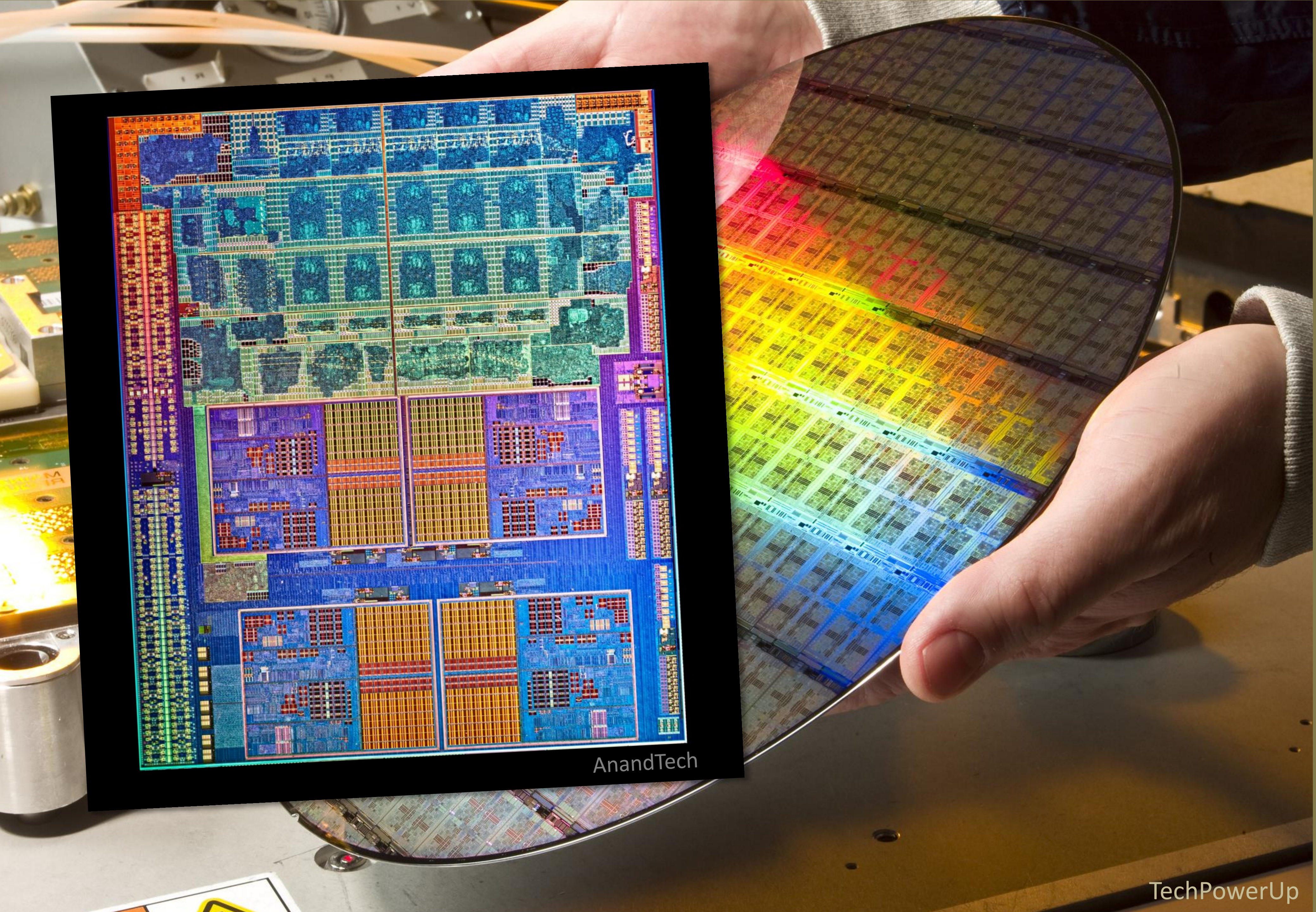


Berger et. al. (2019)



Silicon Wafers with many “chips”, each with billions of transistors.

The necessary tiny features are patterned using **Optical Lithography**



Silicon Wafers with many “chips”, each with billions of transistors.

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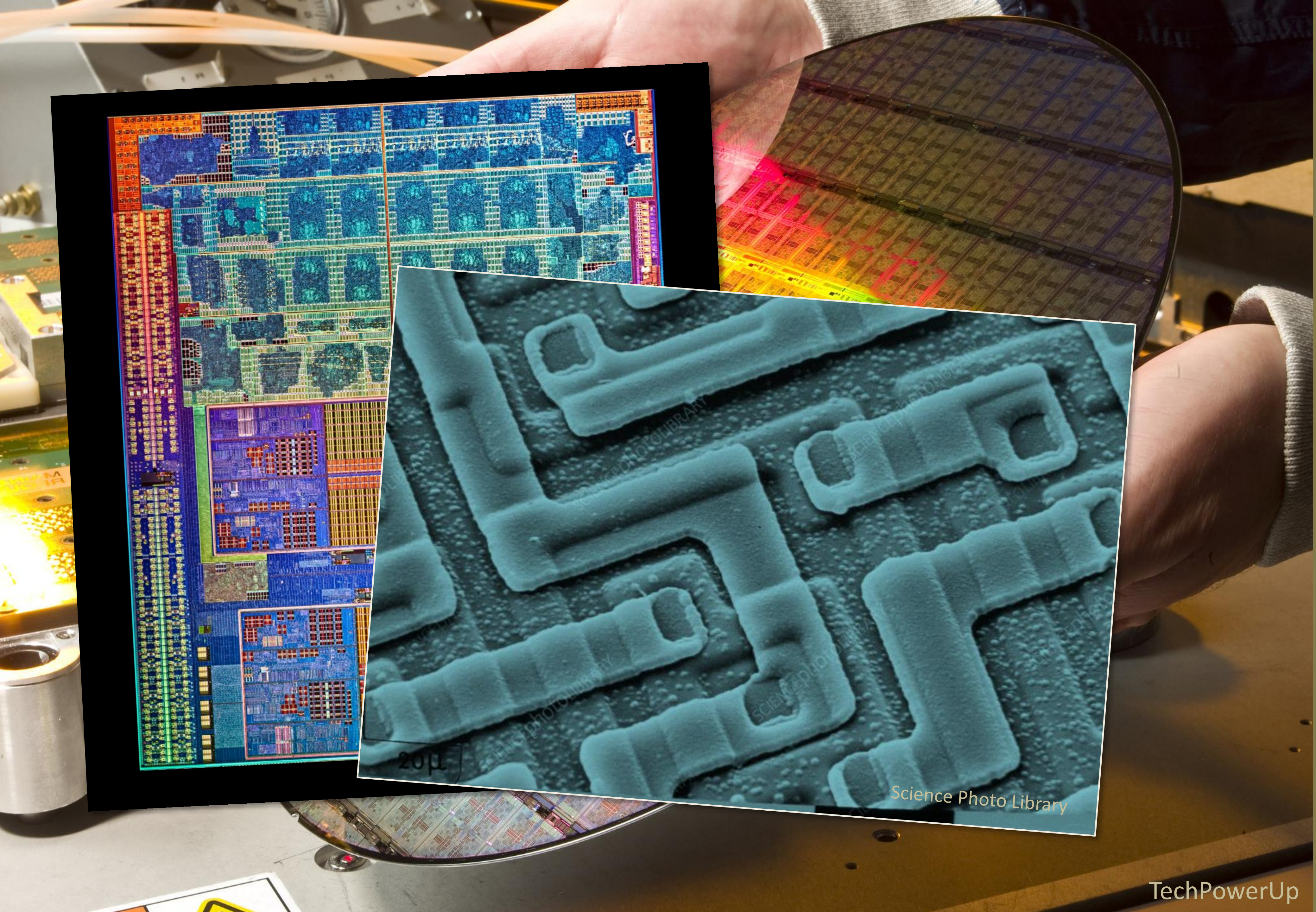

Silicon Wafers with many “chips”, each with billions of transistors.

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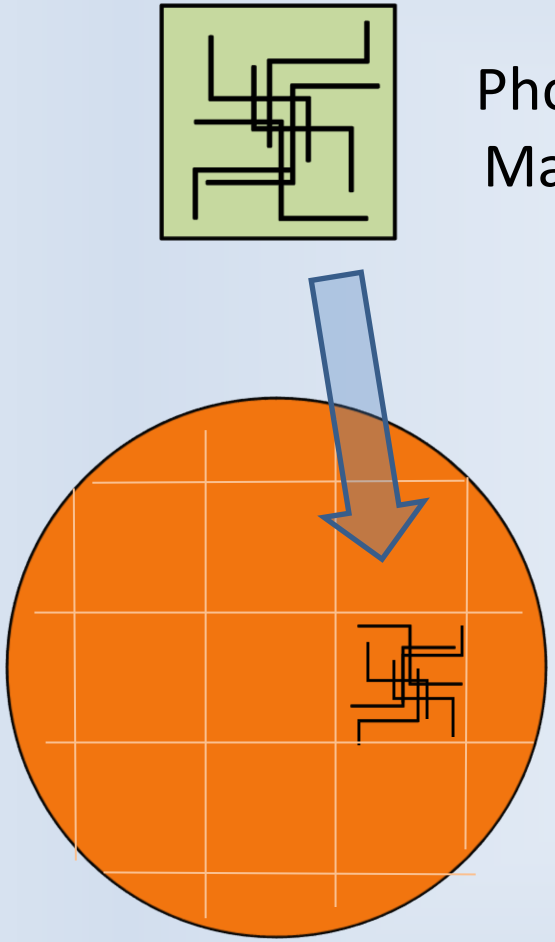
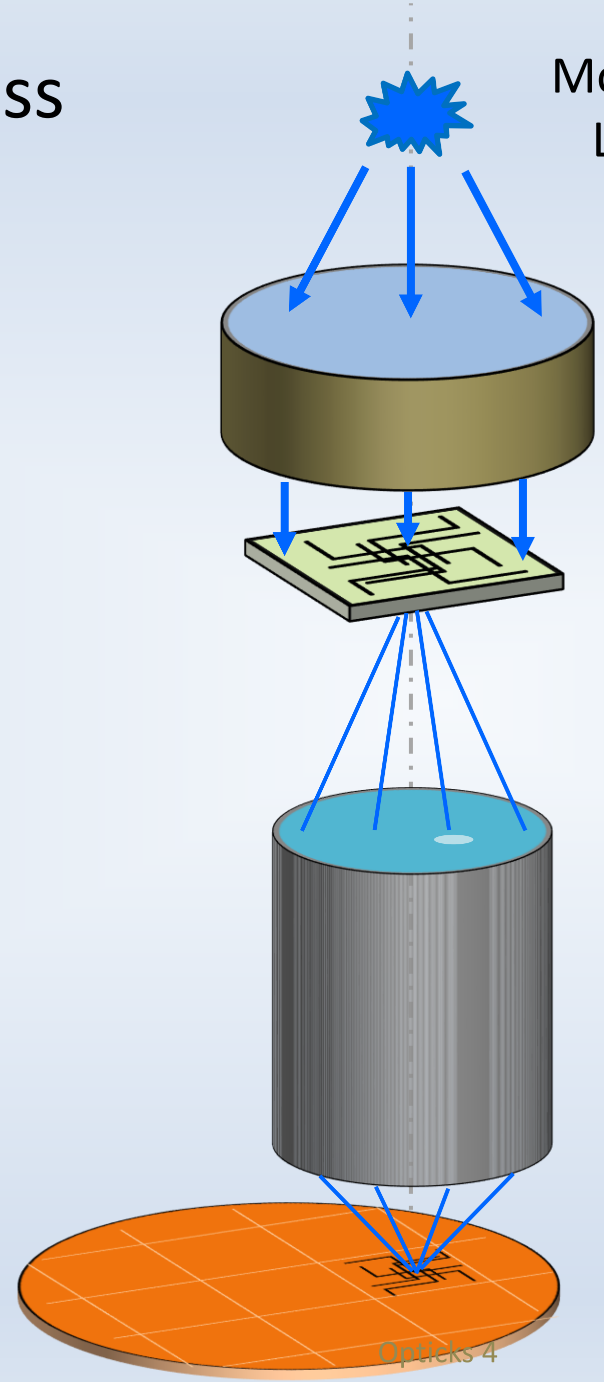
Photolithography Process





Mercury Lamps, Lasers, Plasmas

Illumination is Critical – Often very complex

Usually 4x Larger than circuit on chip

Refractive Lens *or* Mirror System

Wafer is Patterned up to dozens of times

Photolithography Process

Monochromatic Light Source

Mercury Lamps, Lasers, Plasmas

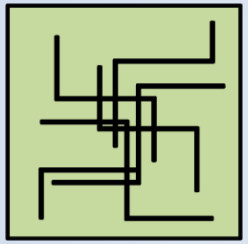
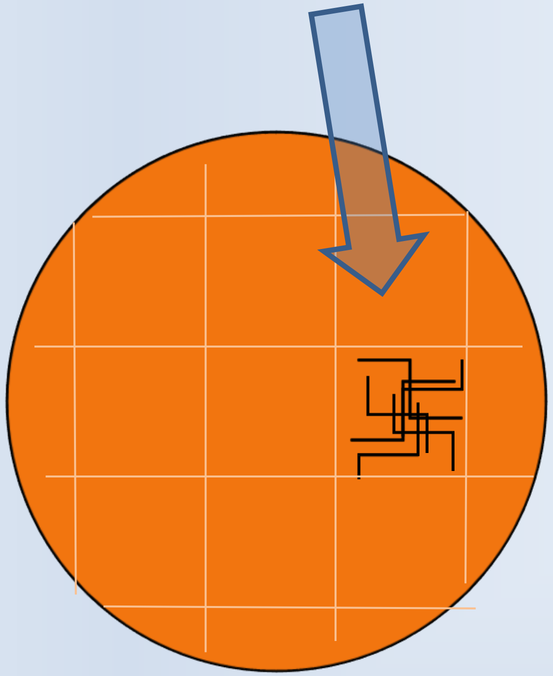
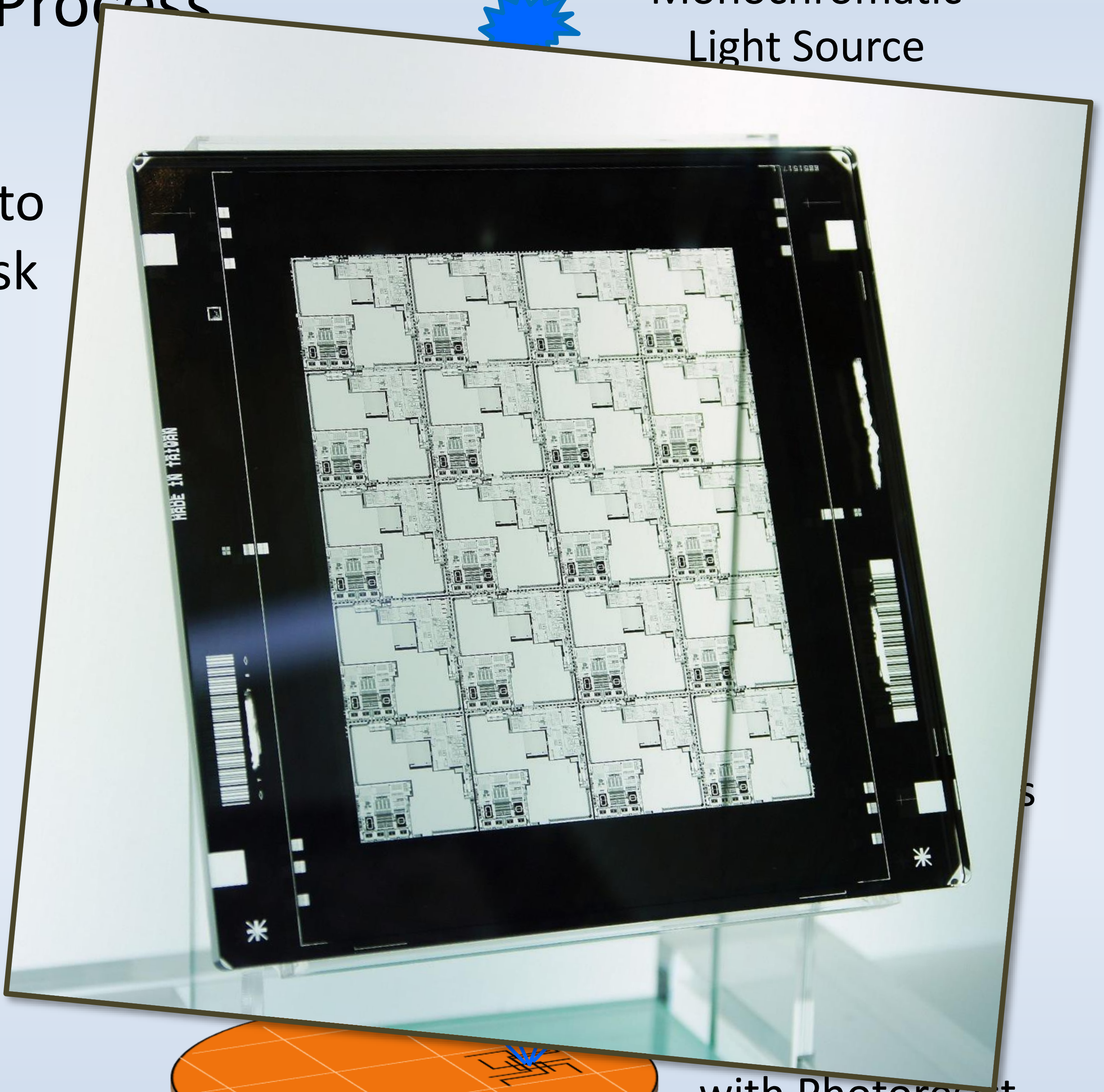


Photo Mask

Illumination is Critical – Often very complex

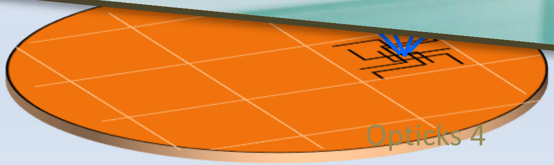
Usually 4x Larger than circuit on chip





Refractive Lens *or* Mirror System

Silicon Wafer



with Photoresist

Wafer is Patterned up to dozens of times

Photolithography Process

Monochromatic Light Source

Merc... mps

x

ger

chip

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n

ed up

mes

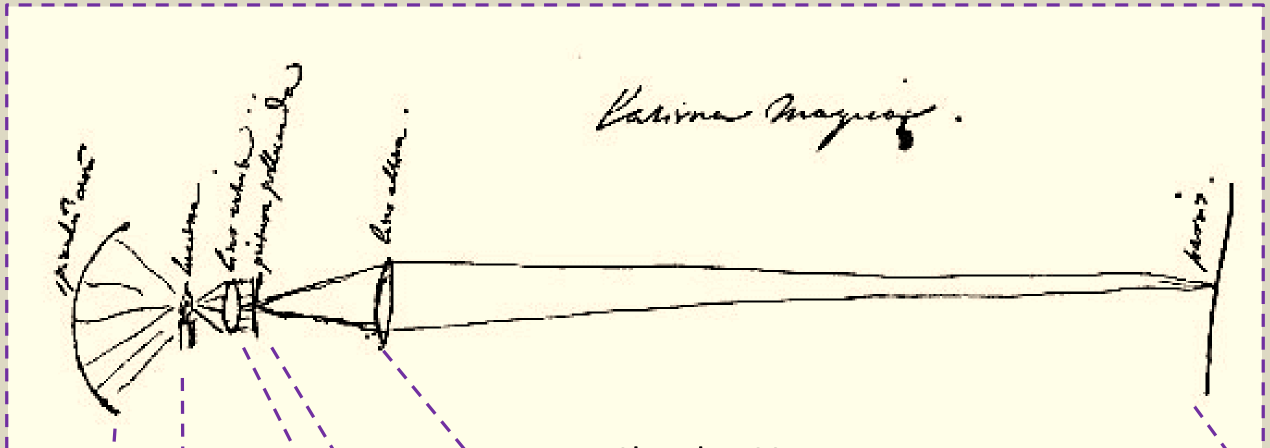
Silicon Wafer

with Photoresist

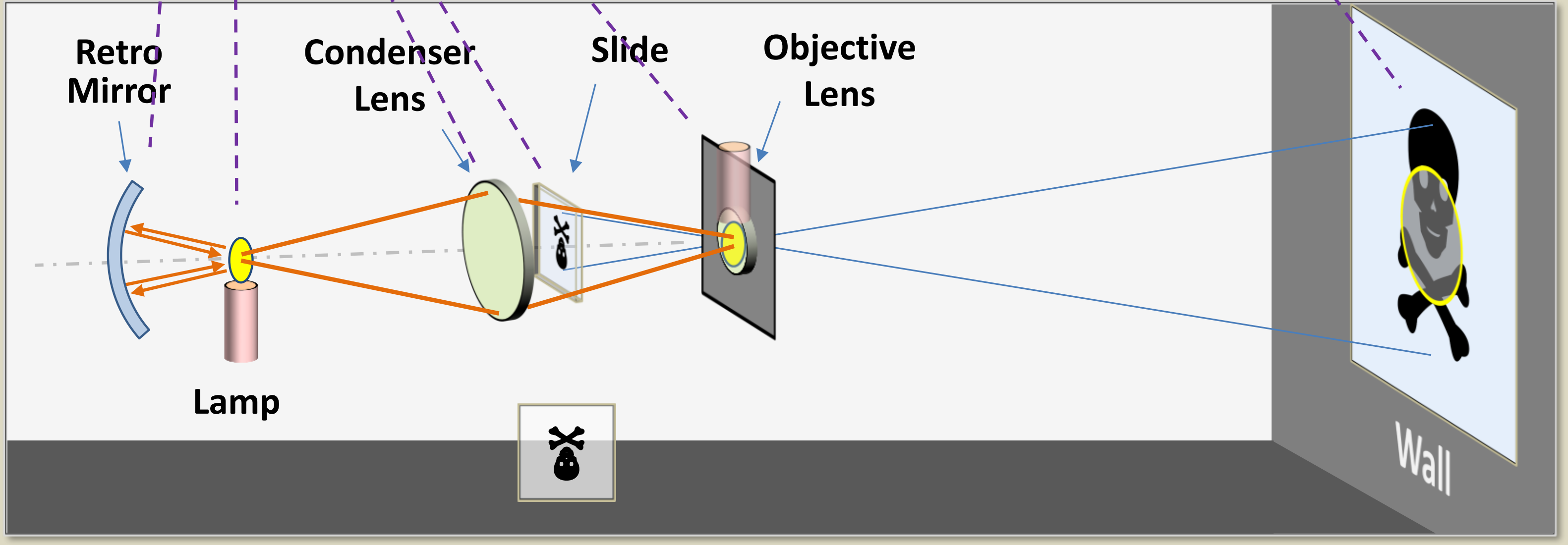
MAGIC LANTERN

Christiaan Huygens
1629-1695
Dutch Physicist

Built and demonstrated a Magic Lantern *ca* 1659

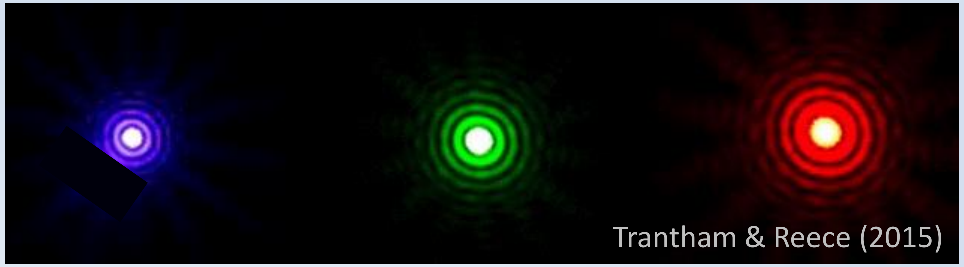


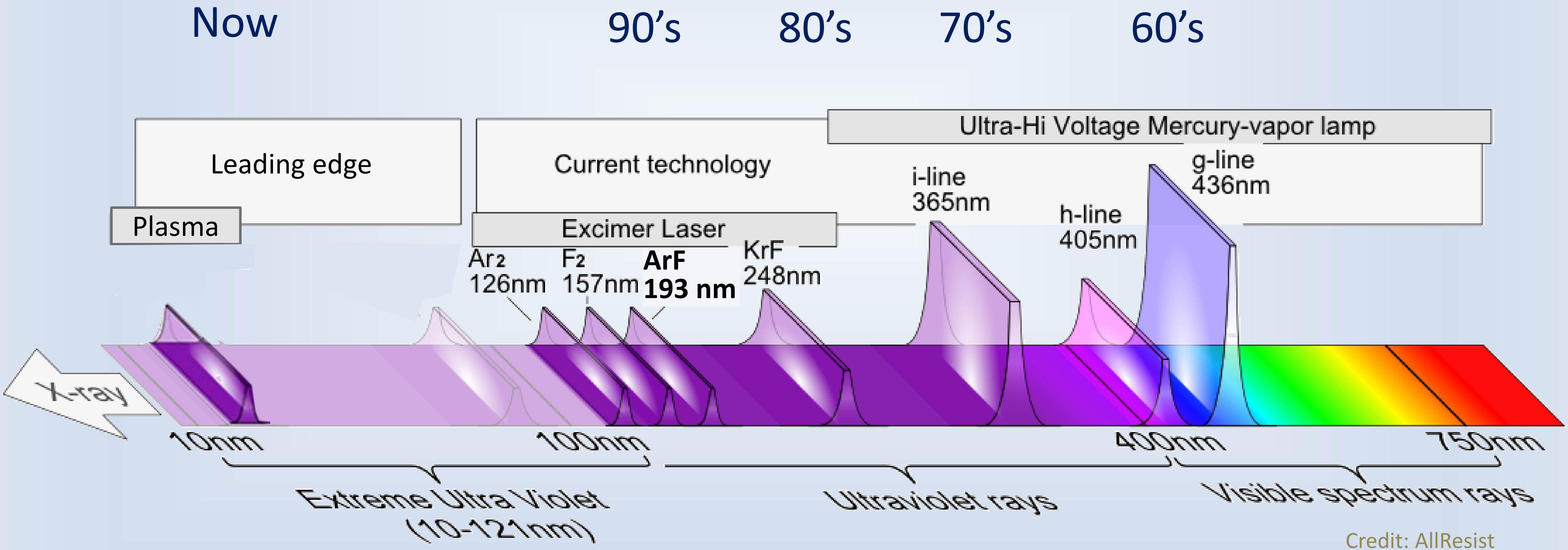
Huygens Sketch 1695



Remember Huygens? The optics are basically the same…

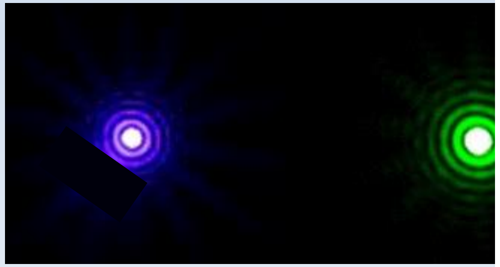
Semiconductor Lithography: The March to Shorter Wavelengths

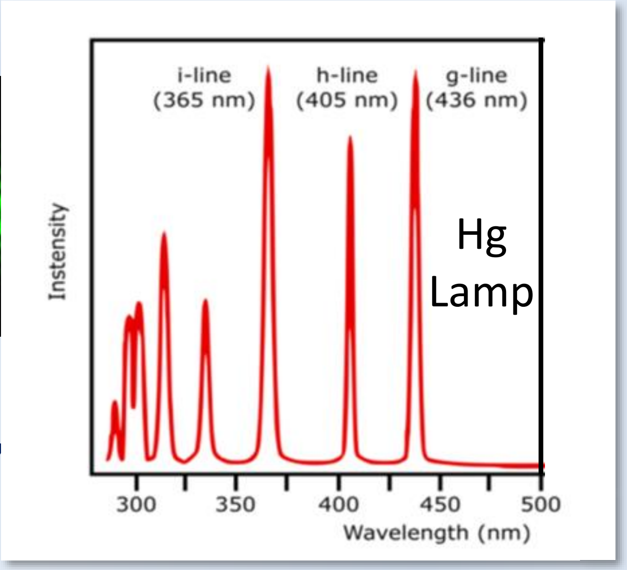




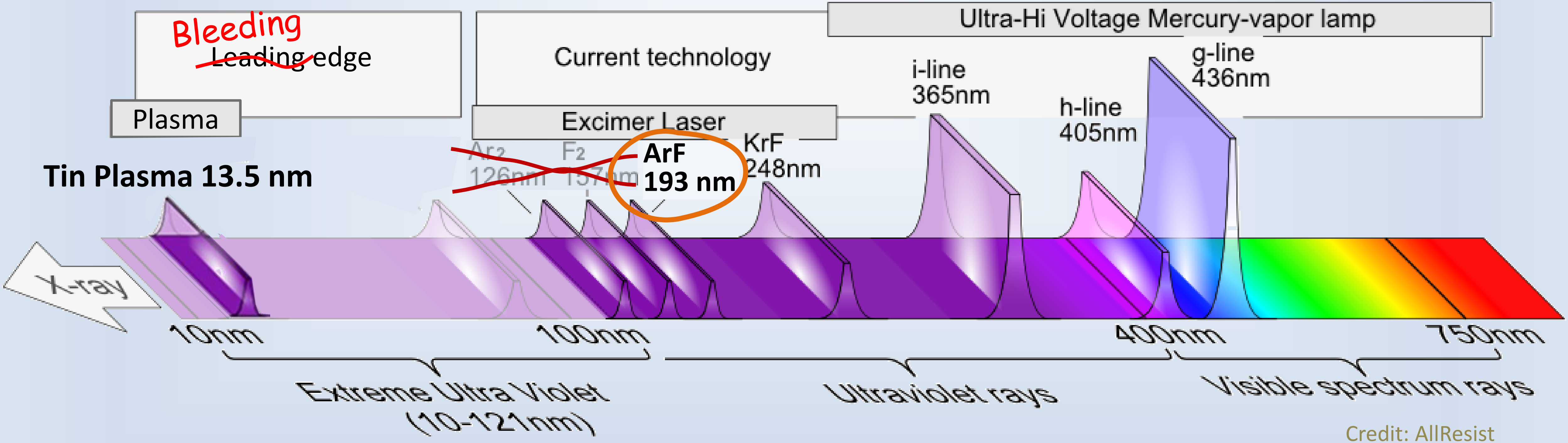
Credit: AllResist

Semiconductor Lithography:
The March to Shorter Wavelengths





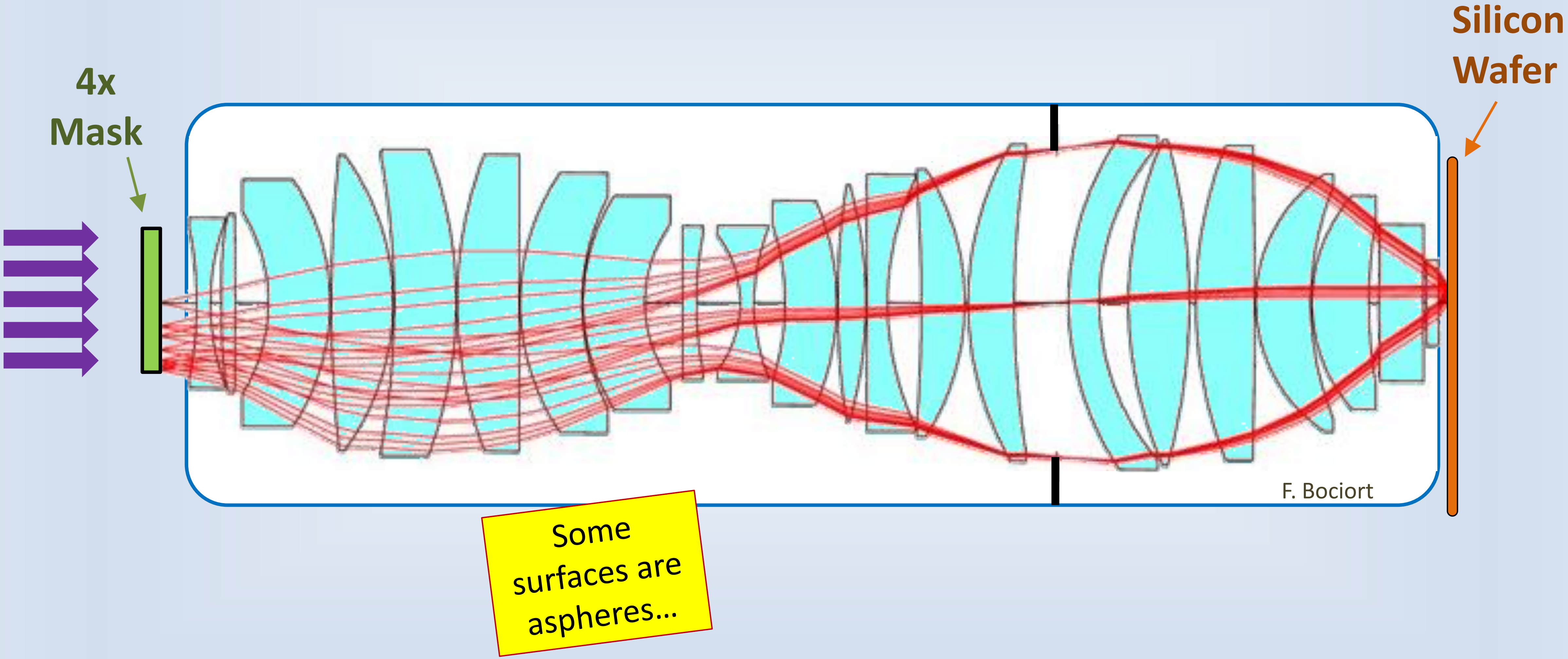
Now 90's 80's 70's 60'



Credit: AllResist

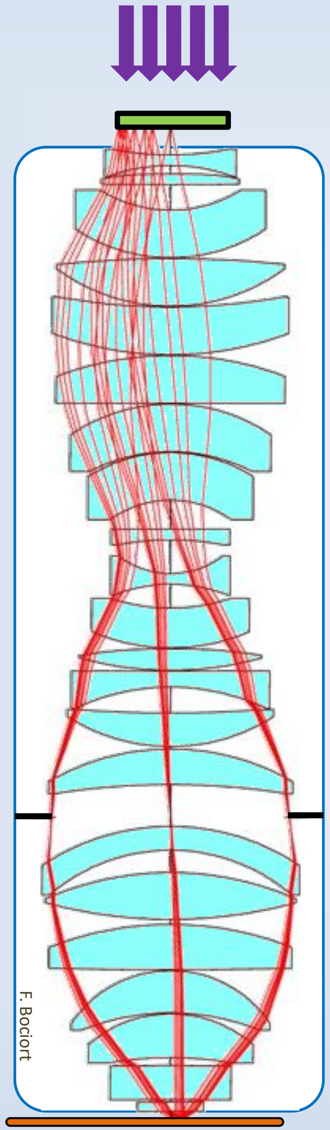
Example of a High Performance 4:1 Reduction Photolithographic Lens

(used with a 193nm Ultraviolet Laser Light Source)



What do these Photolithographic Lenses actually look like?

Photolithographic
'Stepper' Lens
4:1 Reduction
27mm Field
0.85NA
λ 193nm

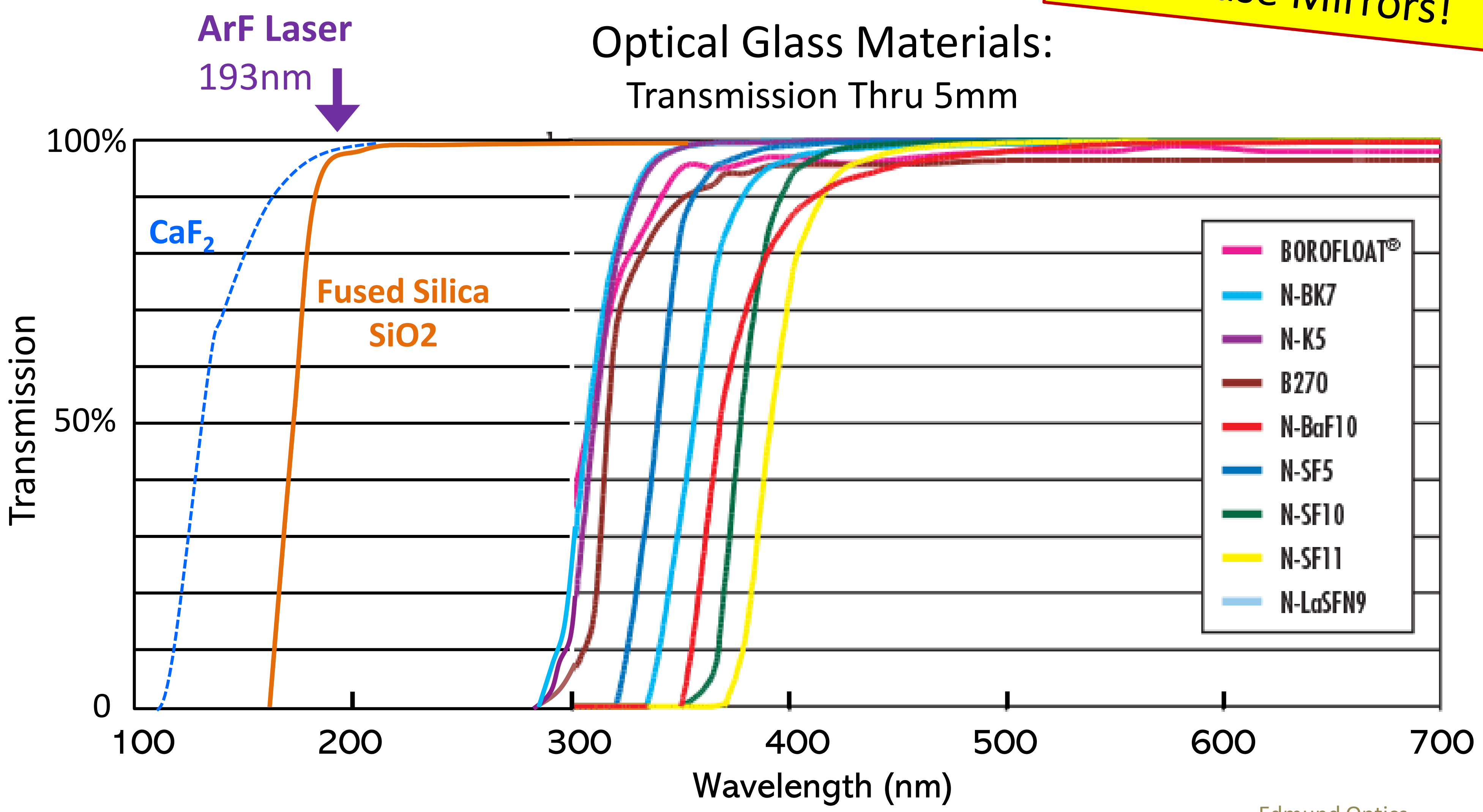


Zeiss Stepper Lens
4:1 Reduction
λ 193nm

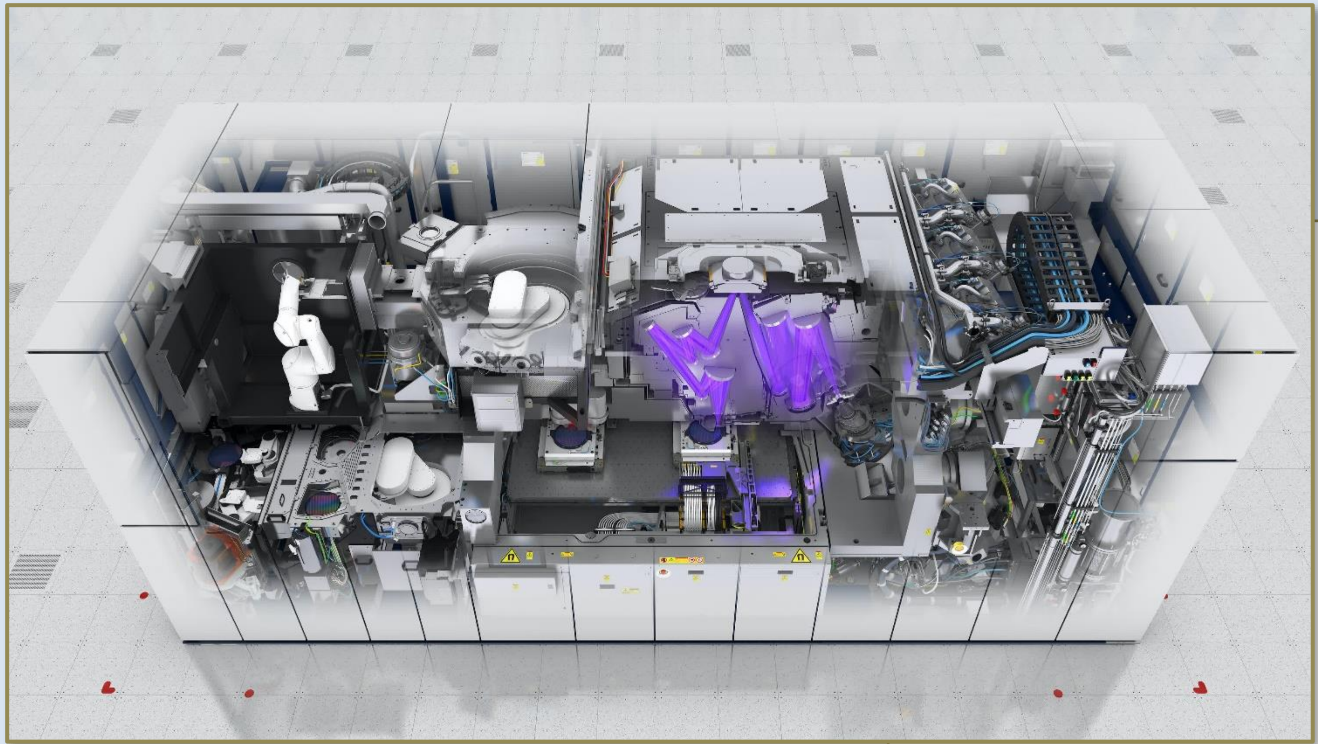
Price:
$ Millions

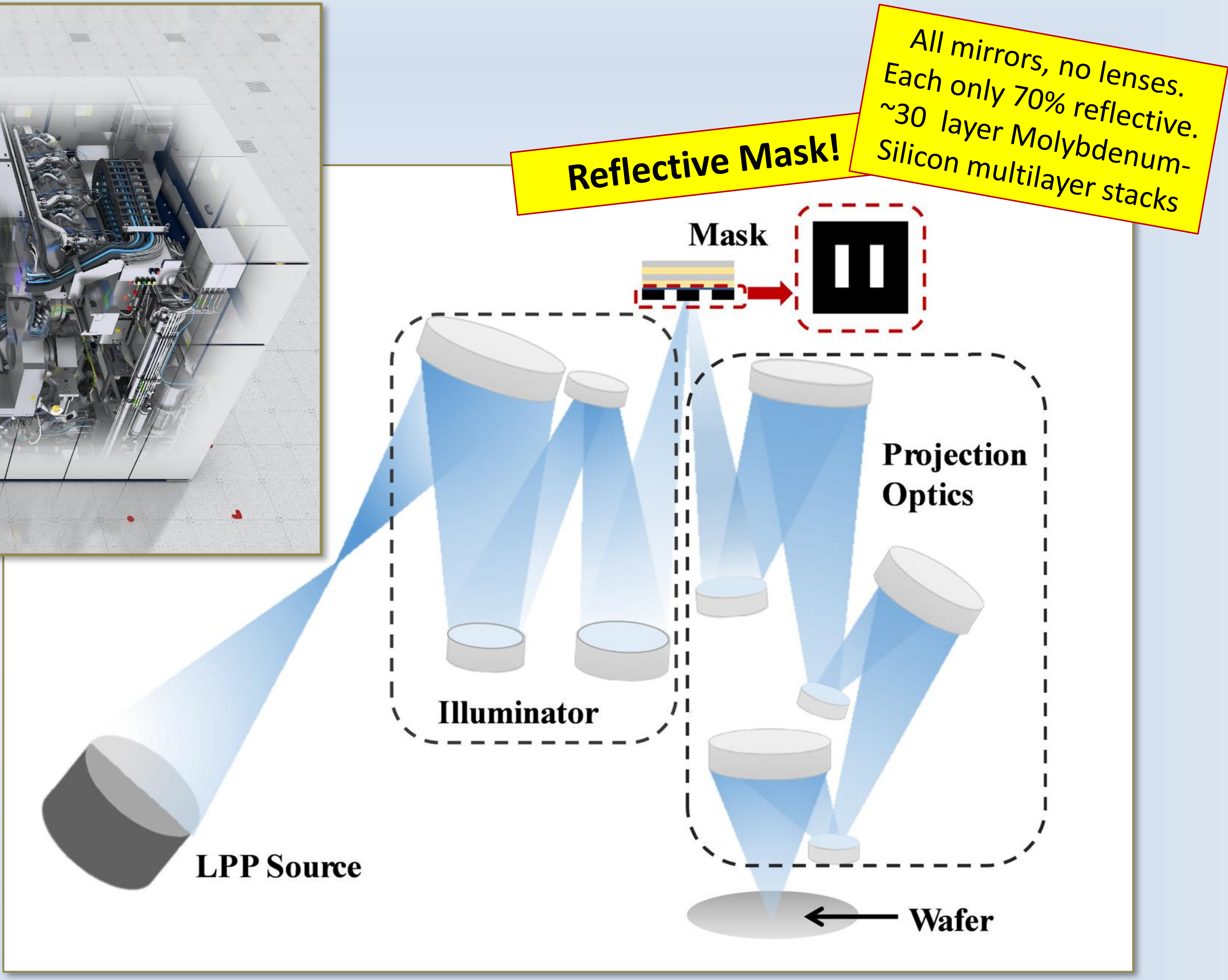
Lenses Conk Out Below 200 nm

Below 193nm we'll need to use Mirrors!



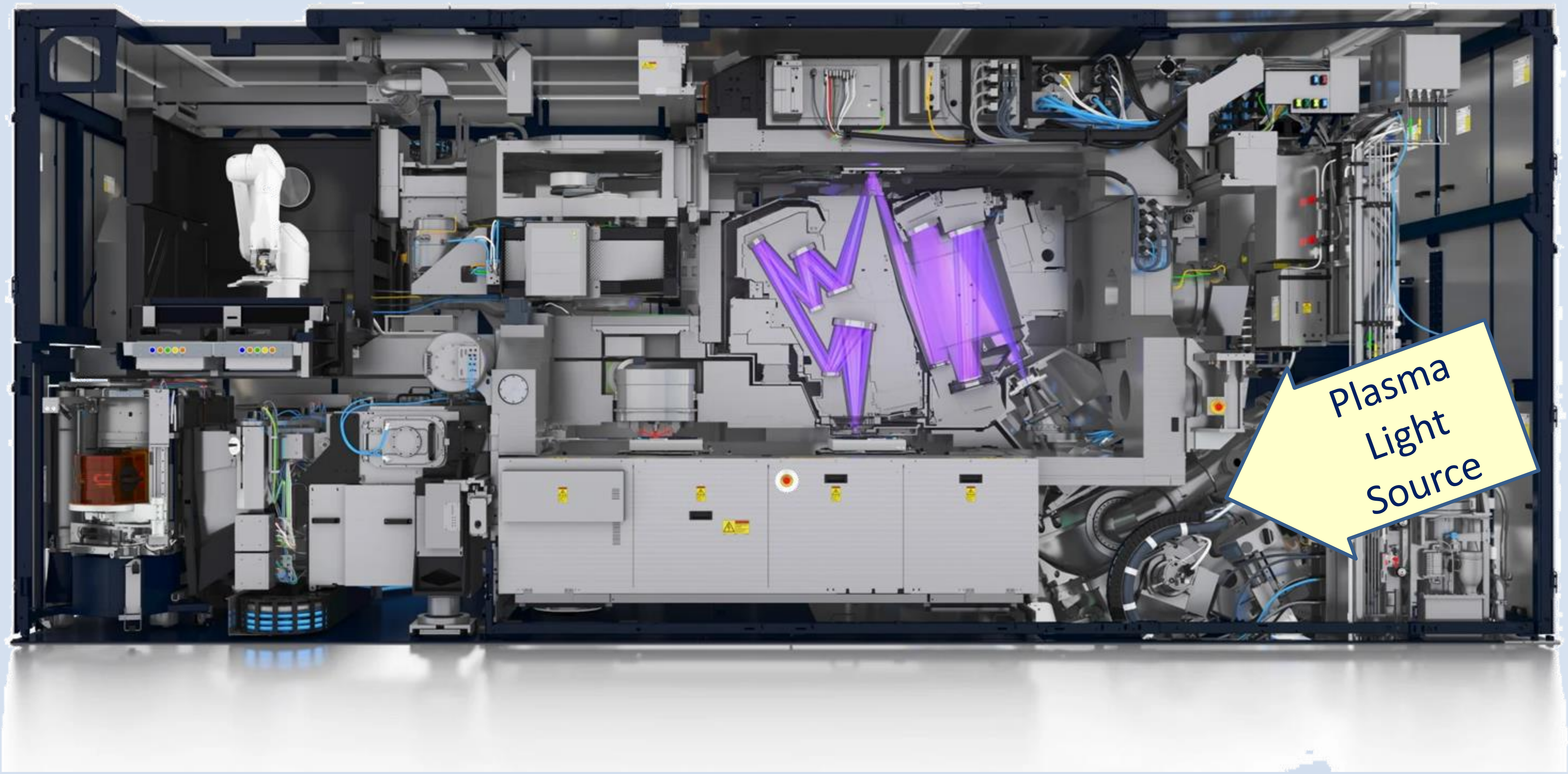
Edmund Optics





State of the Art
λ 13.5nm EUV
Lithography Tool
Recently Introduced
(ASML)

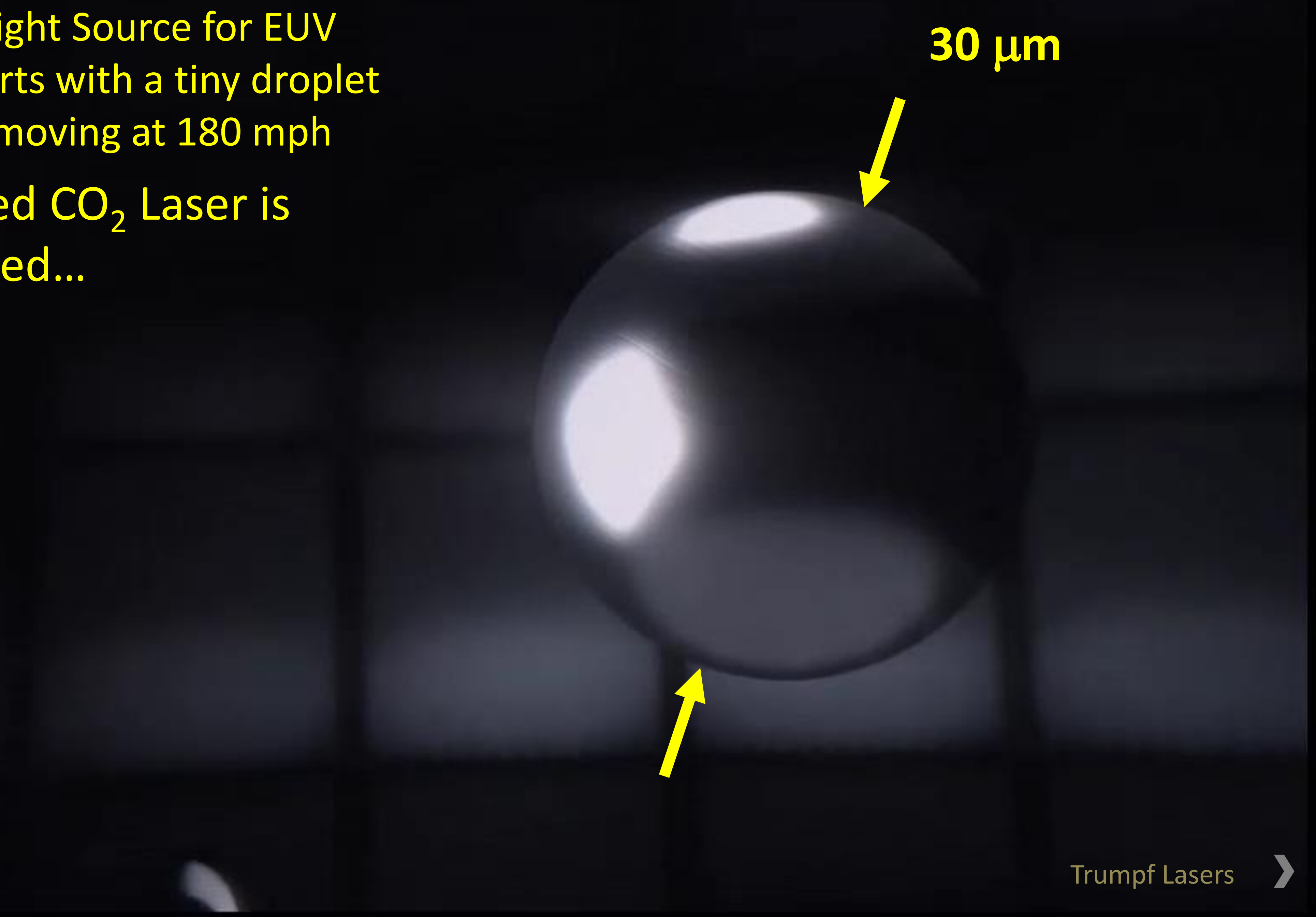
The Tool Contains *much more* than just the Optics…



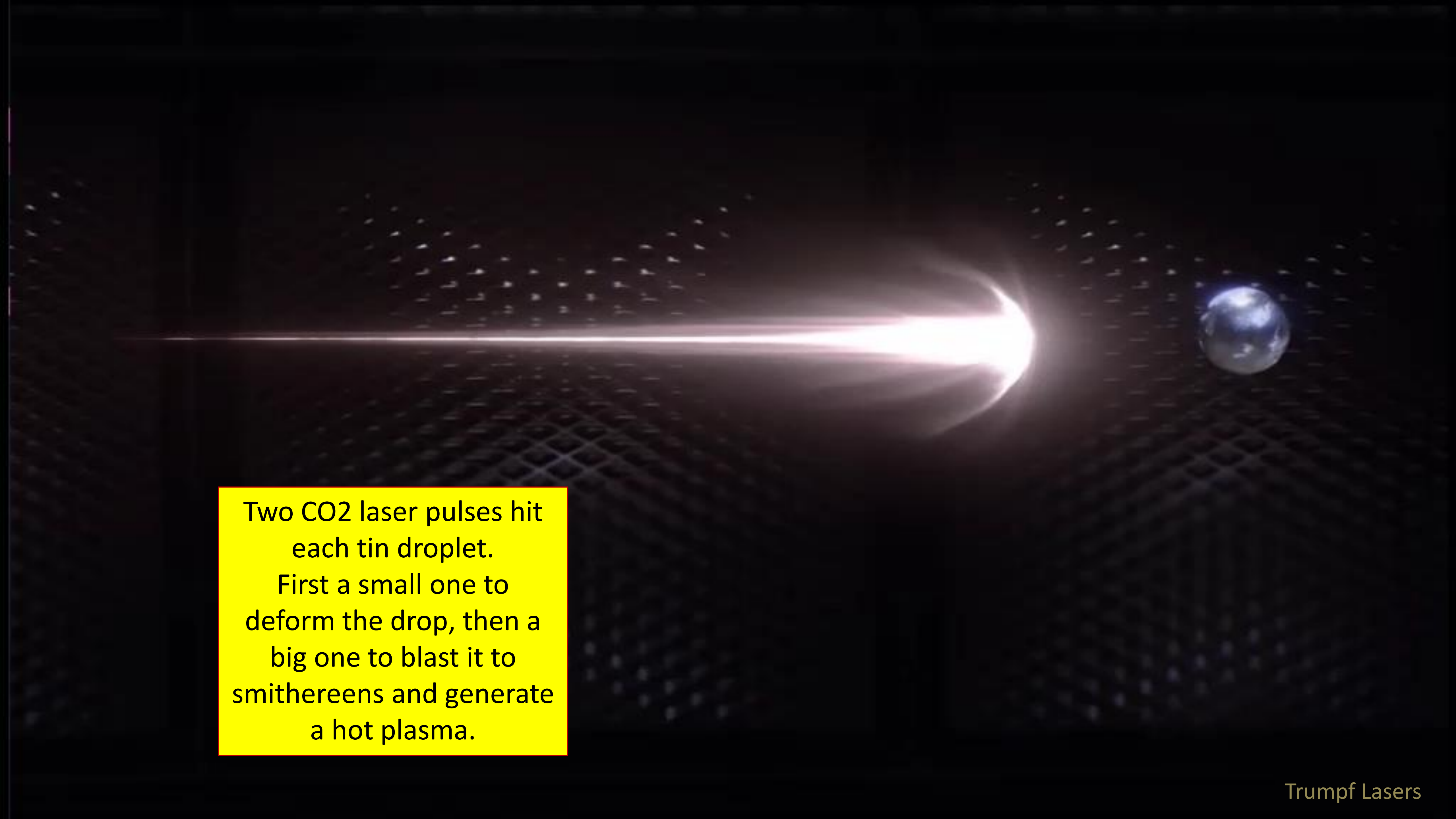

All of this is in a Vacuum Chamber!

The Bizarre Light Source for EUV Lithography Starts with a tiny droplet of liquid Tin moving at 180 mph

First, a pulsed CO_2 Laser is fired…



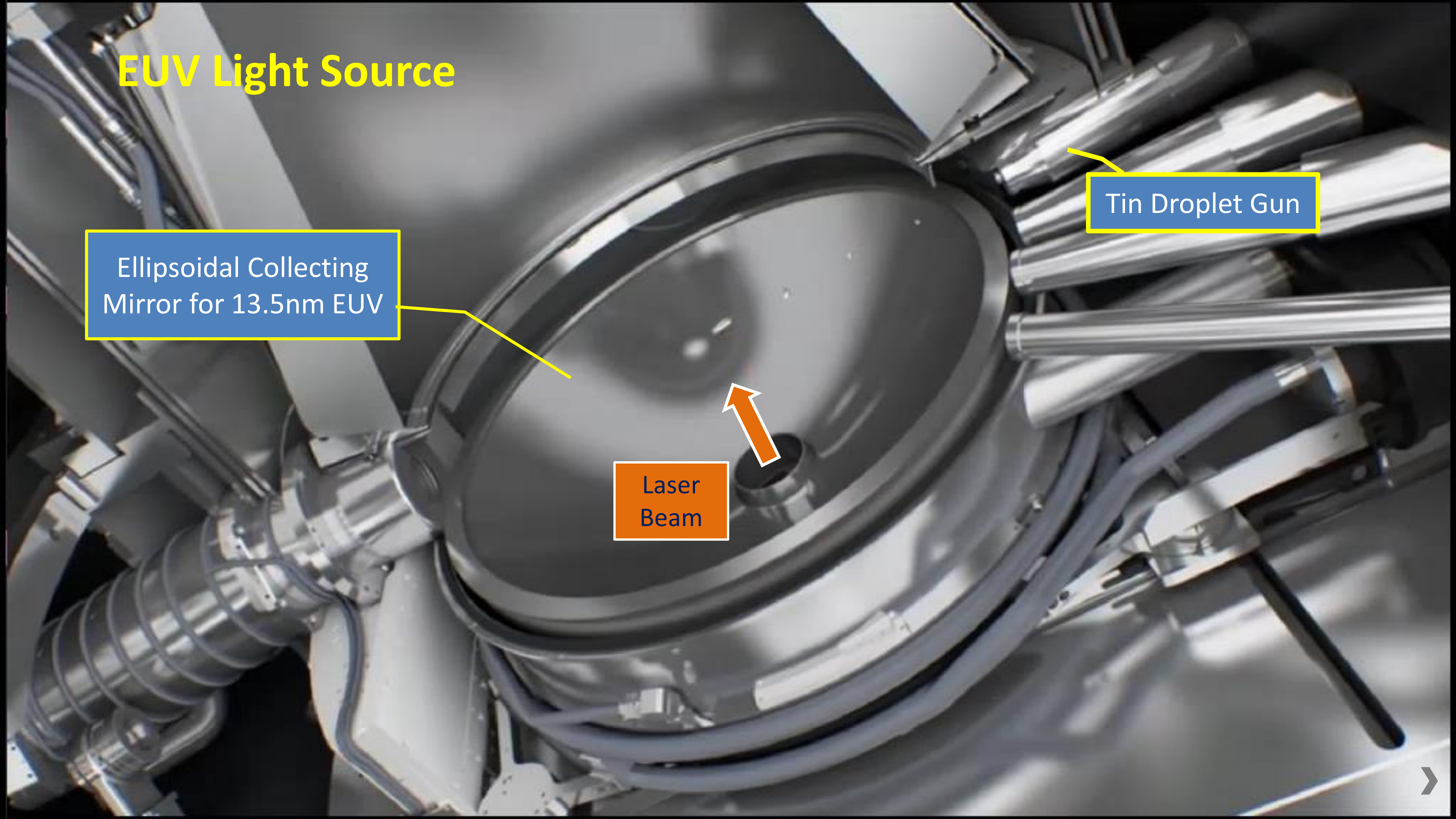
Trumpf Lasers

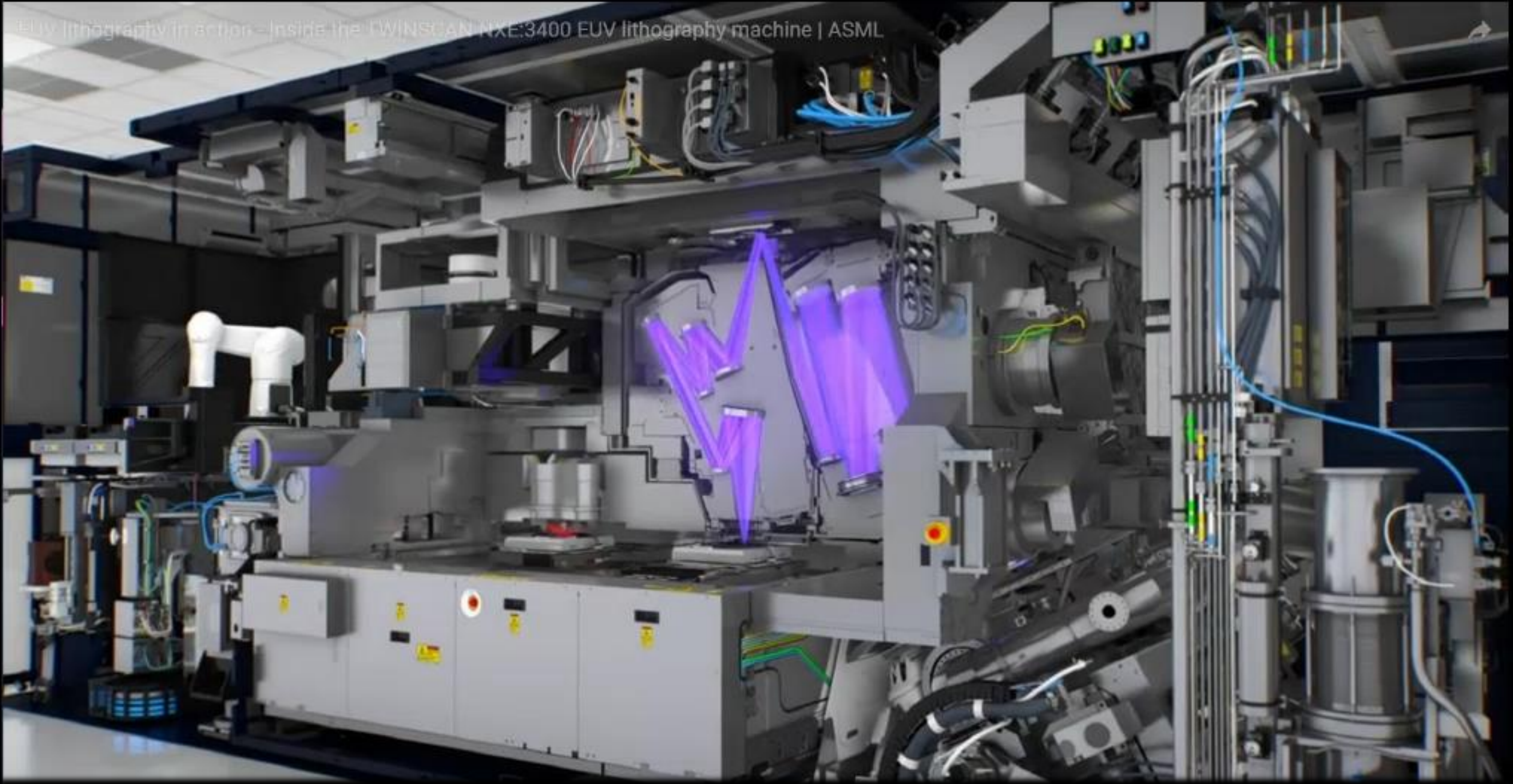


Two CO2 laser pulses hit each tin droplet.
First a small one to deform the drop, then a big one to blast it to smithereens and generate a hot plasma.

Trumpf Lasers

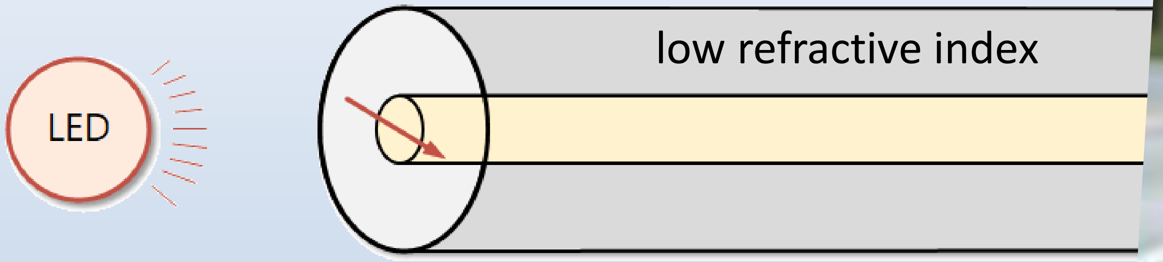
50,000 Tin drops per second are blasted, producing an incredible average power of 250 watts of EUV light


EUV Light Source
Ellipsoidal Collecting Mirror for 13.5nm EUV
Tin Droplet Gun
Laser Beam


EUV lithography in action - Inside the TWINSCAN NXE:3400 EUV lithography machine | ASML

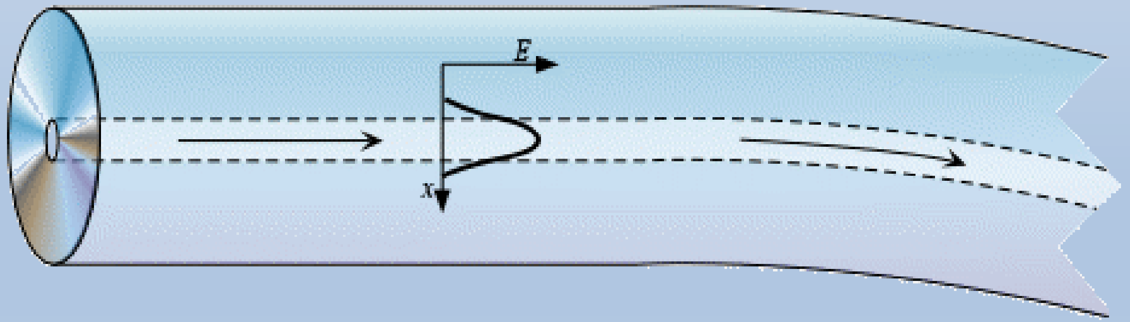

ASML
$150 Million
180 tons
(Including CO_2 Laser on floor below)

Fiber Optics



Network Academy.io

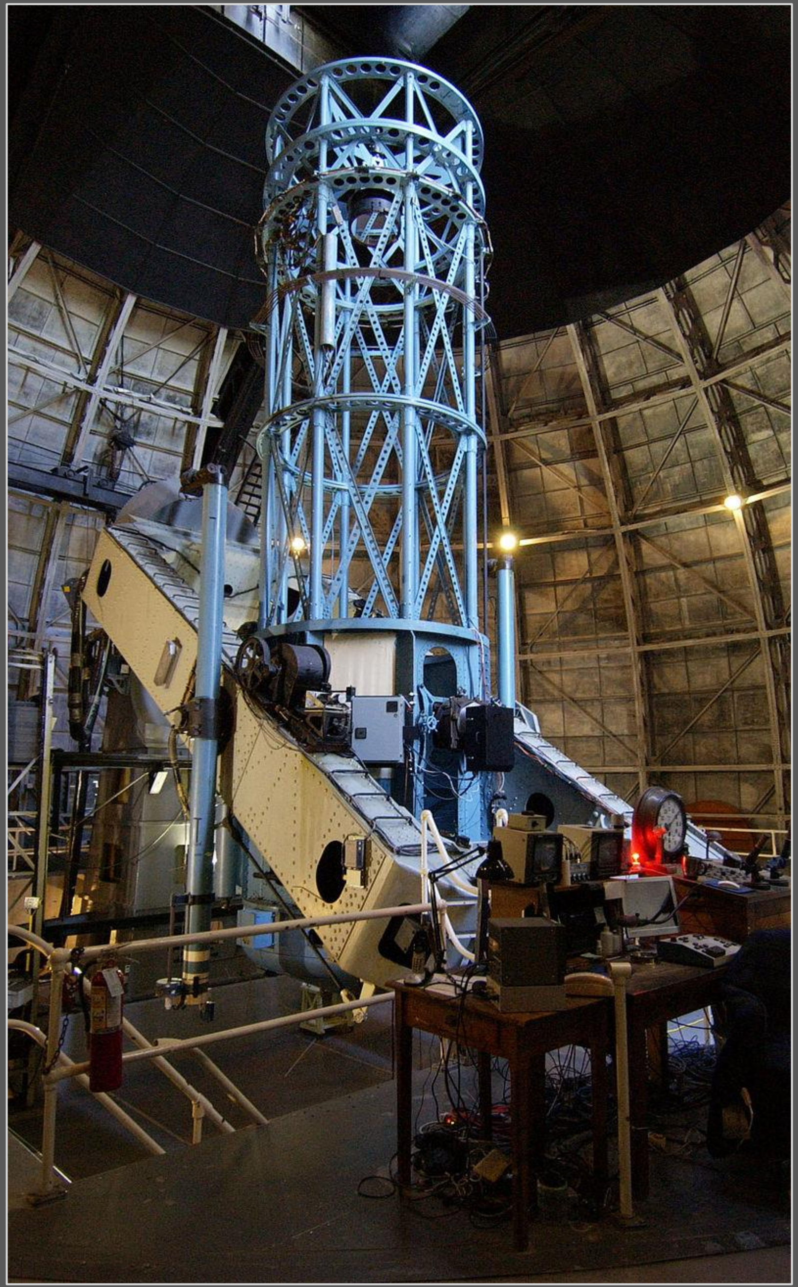
Single Mode Fibers



giphy.com Physics Stack Exchange

Charismatic Telescopes

Mount Wilson
Hooker Telescope
100 Inch (2.5m)
1917
Cassegrain
Equatorial Mount

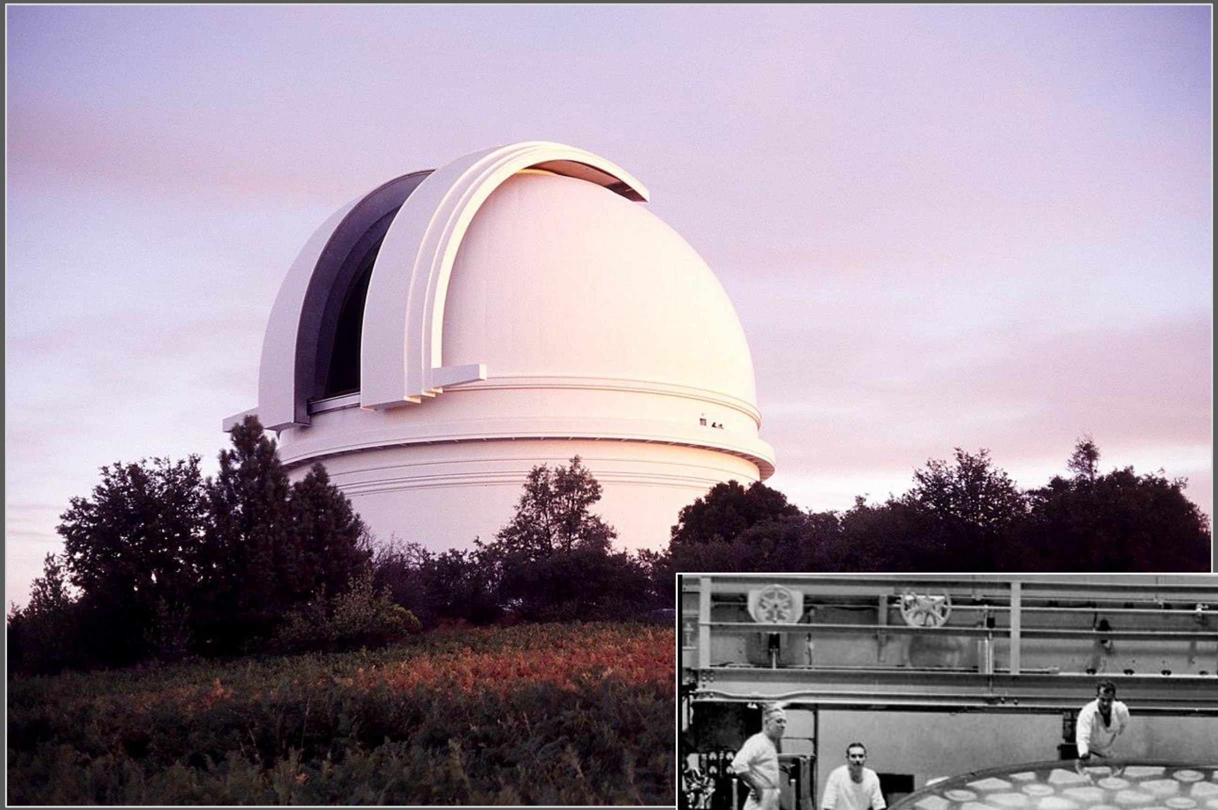


- Used by Edwin Hubble for his famous observations 1920's
- World's largest until 1948
- Mirror cast by Saint-Gobain
- Now used for public viewing

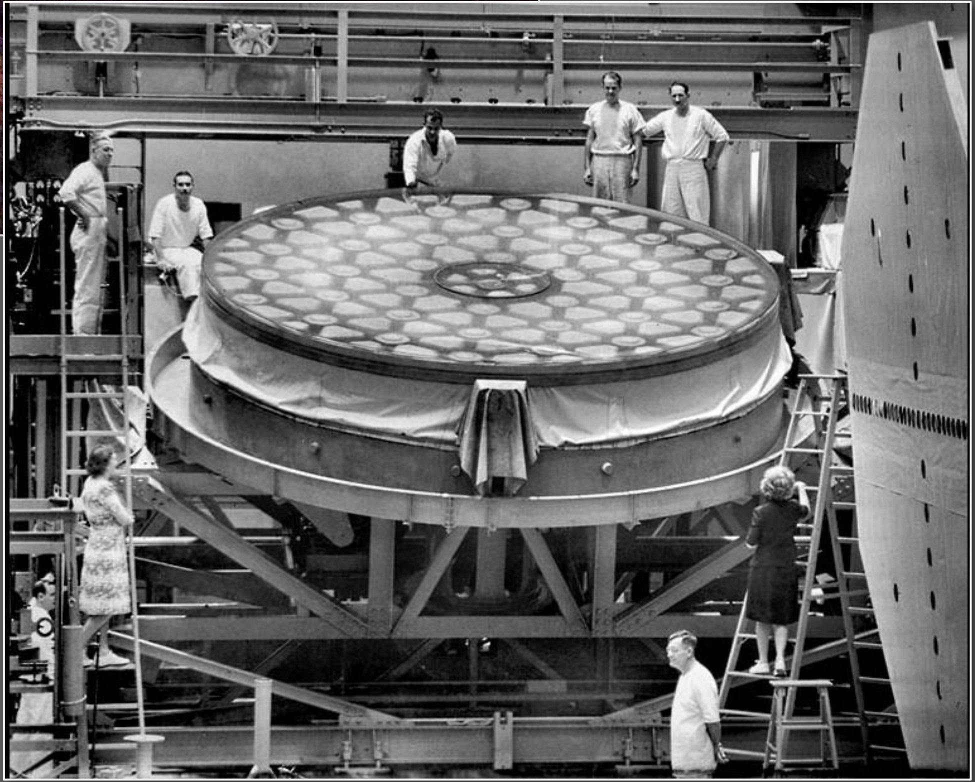
Mount Palomar
Hale Telescope
200 Inch (5.1 m)
1949
Parabolic Primary
Prime Focus *or*
Cassegrain

Equatorial Mount

- Pyrex Mirror
  (Corning Glass)
- World's largest until 1976
- Still a research instrument



Mirror blank:
20 tons
(15 tons after grinding)



Mount Palomar Hale Telescope 200 Inch (5.1 m) 1949

Parabolic Primary
Prime Focus *or* Cassegrain

Equatorial Mount

- Pyrex Mirror (Corning Glass)
- World's largest until 1976
- Still a research instrument

Hale Observatories

Mount Palomar Hale Telescope 200 Inch (5.1 m) 1949

Parabolic Primary
Prime Focus *or* Cassegrain

Equatorial Mount

- Pyrex Mirror (Corning Glass)
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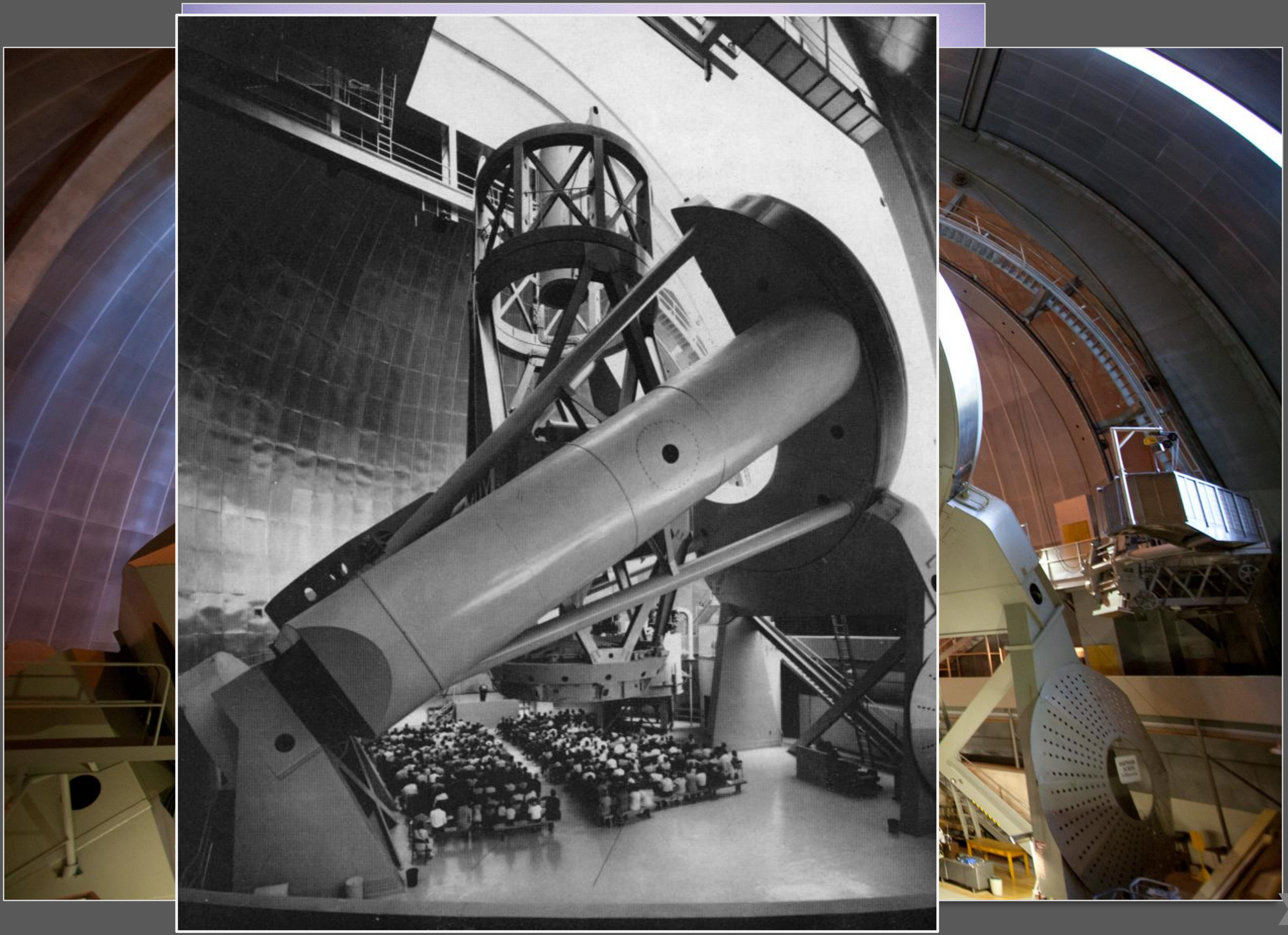

Mount Palomar Hale Telescope 200 Inch (5.1 m) 1949

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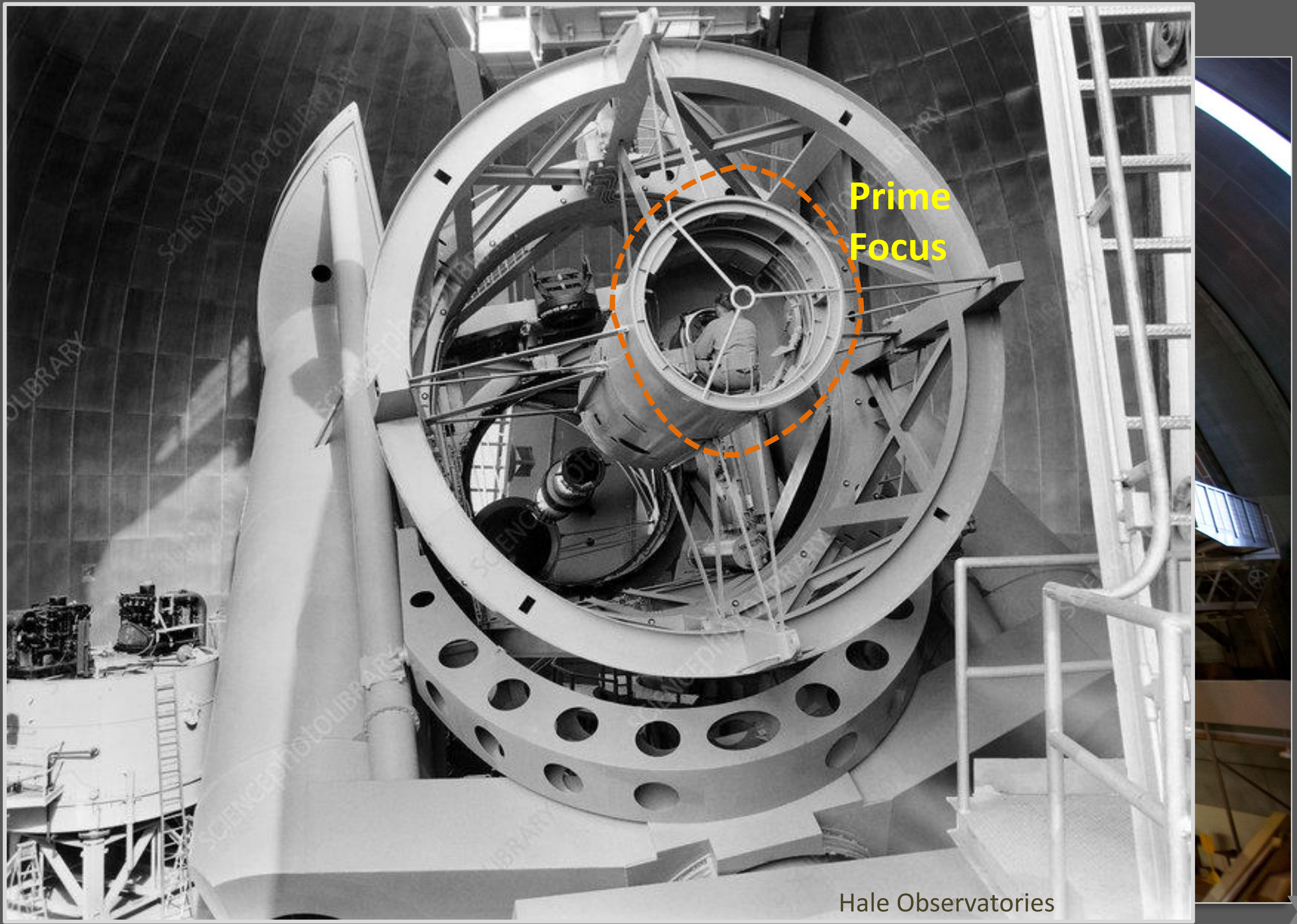


Hale Observatories

Keck Telescopes

Mauna Kea

10 meter

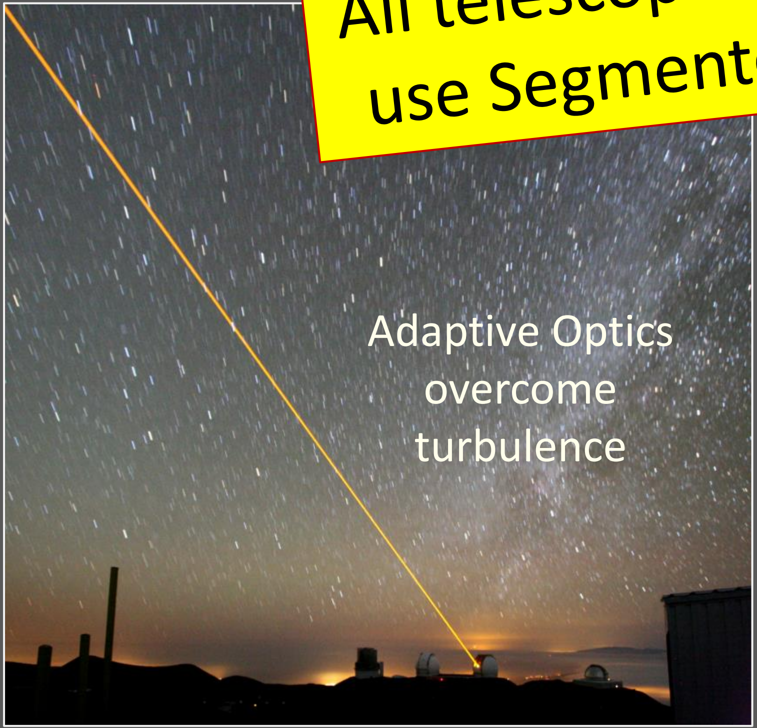
1993-96

Cassegrain

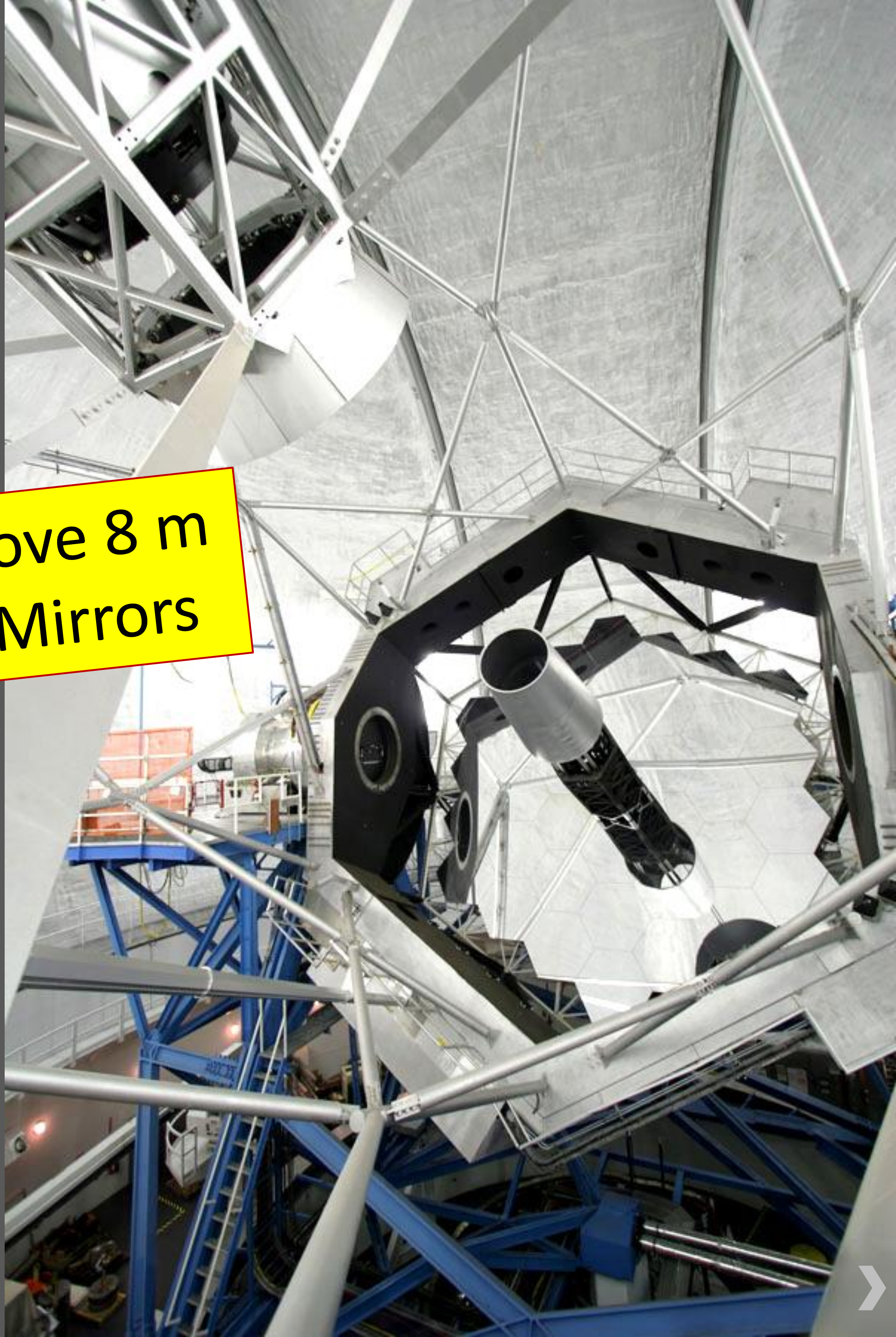
36 Segment Mirror

Altazimuth Mount

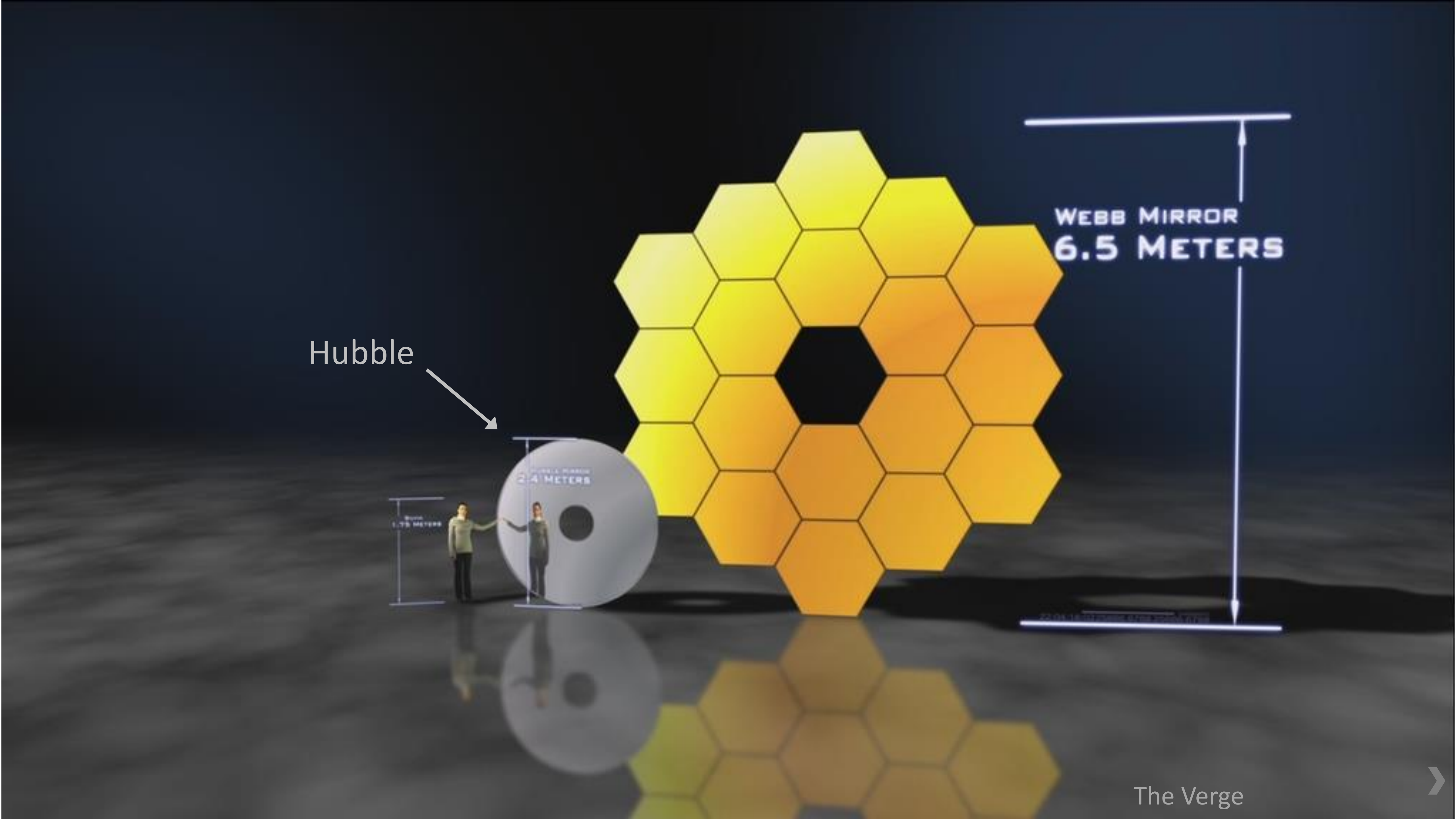
- Zerodur glass hexagonal segments actively controlled
- Still among World's largest
- But 30 m and 39 m telescopes are coming!



All telescopes above 8 m use Segmented Mirrors

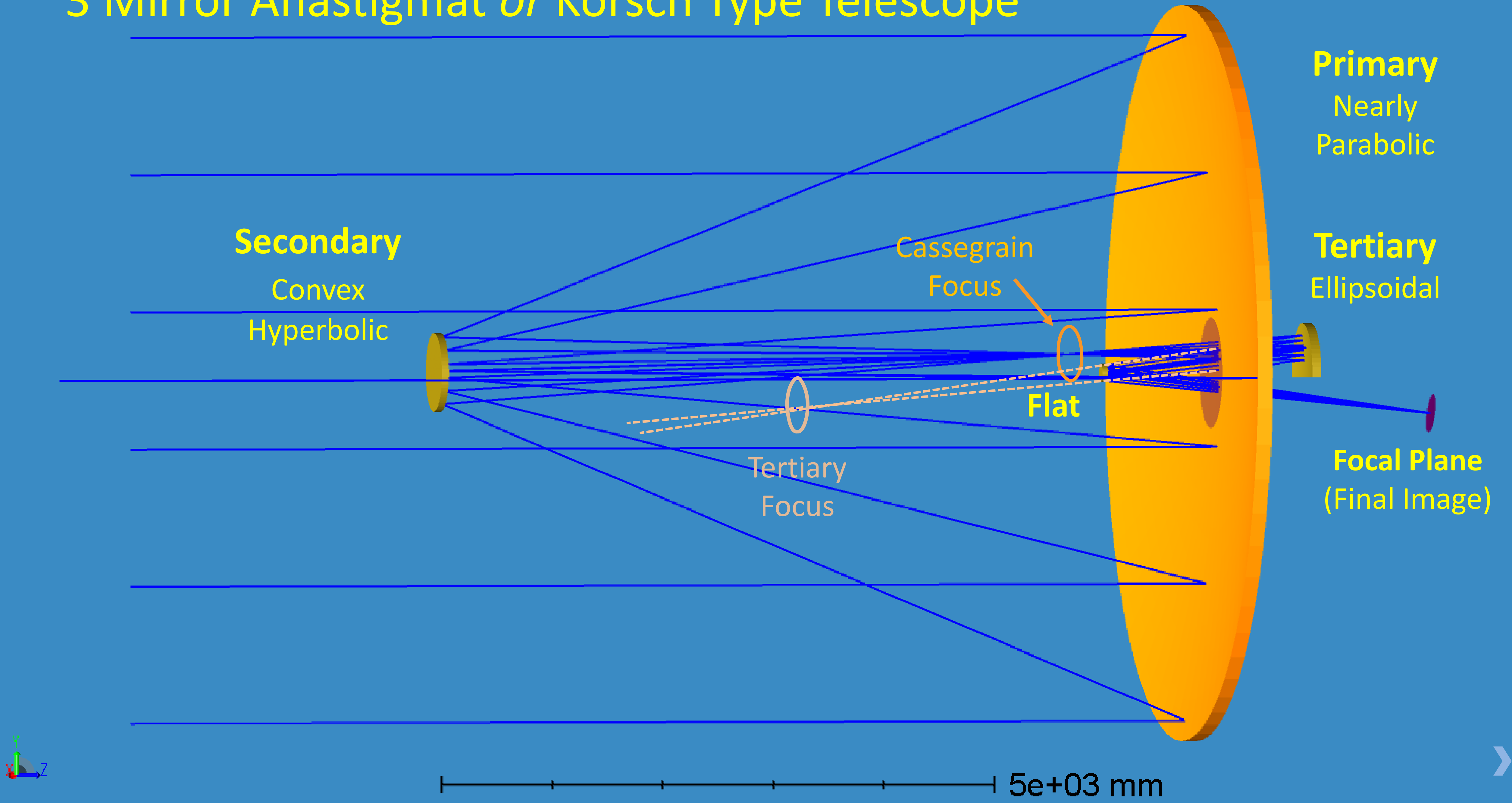


WEBB
SPACE TELESCOPE

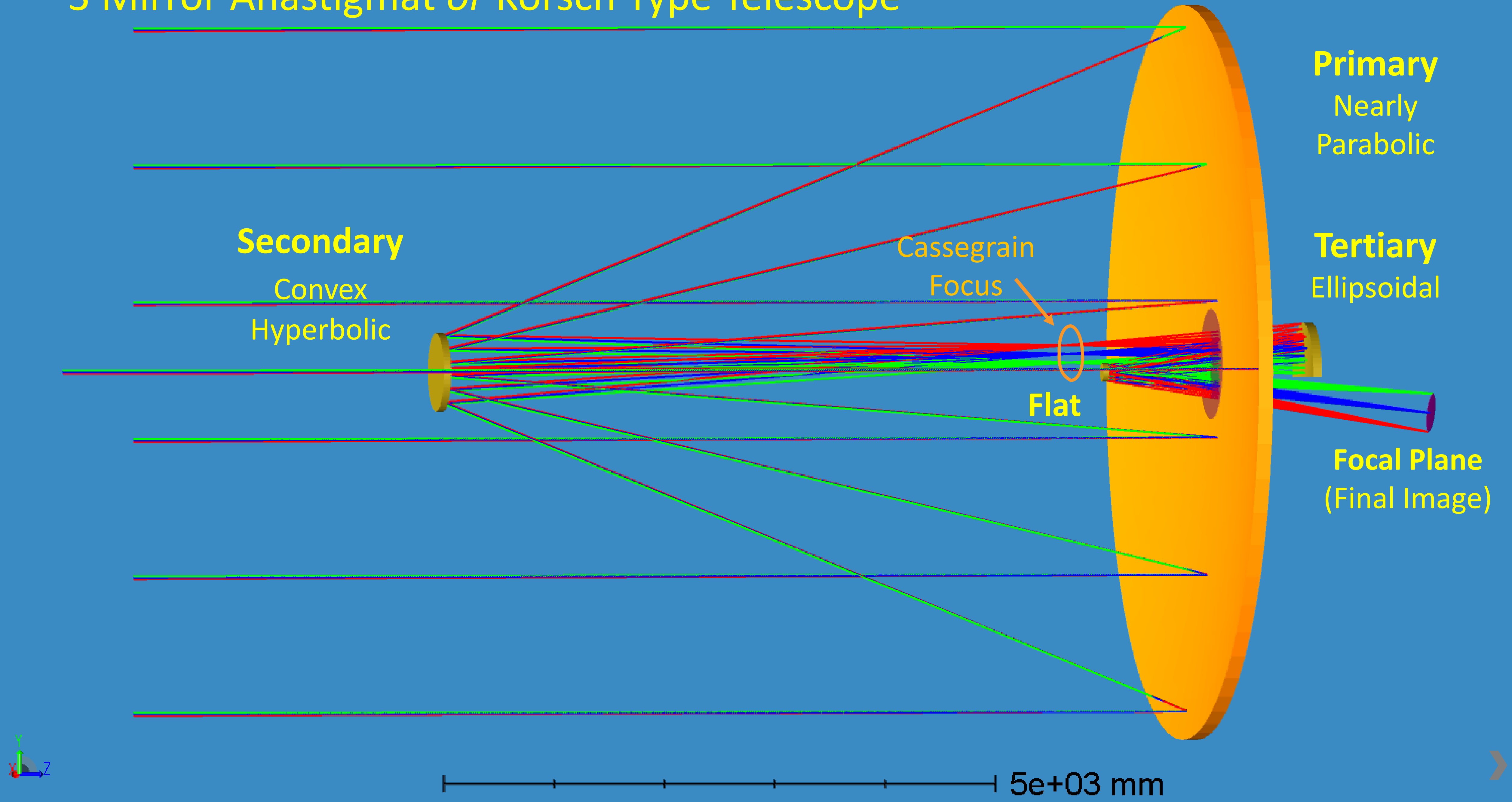


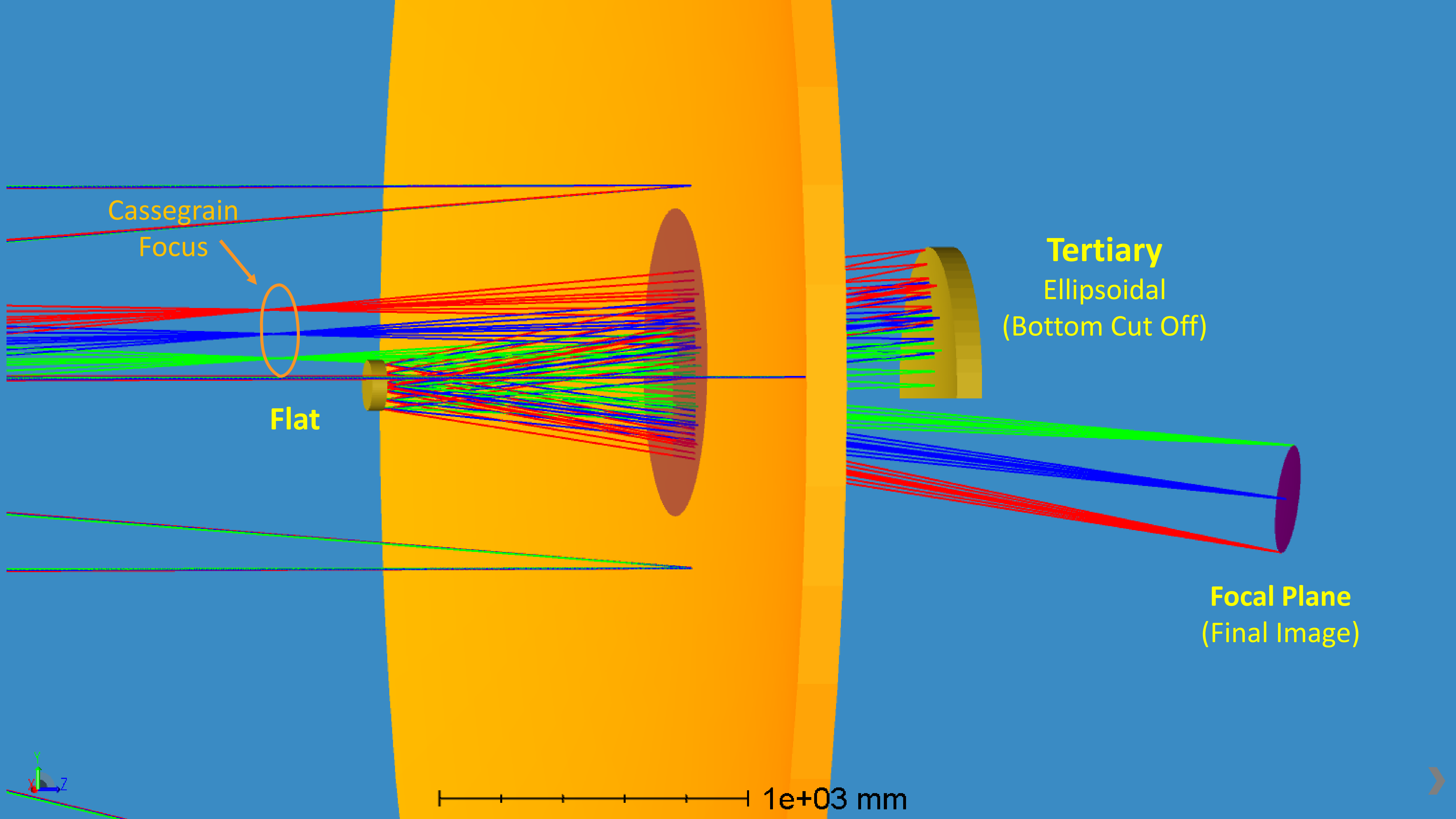
The Verge

3 Mirror Anastigmat *or* Korsch Type Telescope



3 Mirror Anastigmat *or* Korsch Type Telescope




Cassegrain
Focus
Flat
Tertiary
Ellipsoidal
(Bottom Cut Off)
Focal Plane
(Final Image)
1e+03 mm

The Webb Telescope Recipe

131 meter effective focal length

6 meter aperture

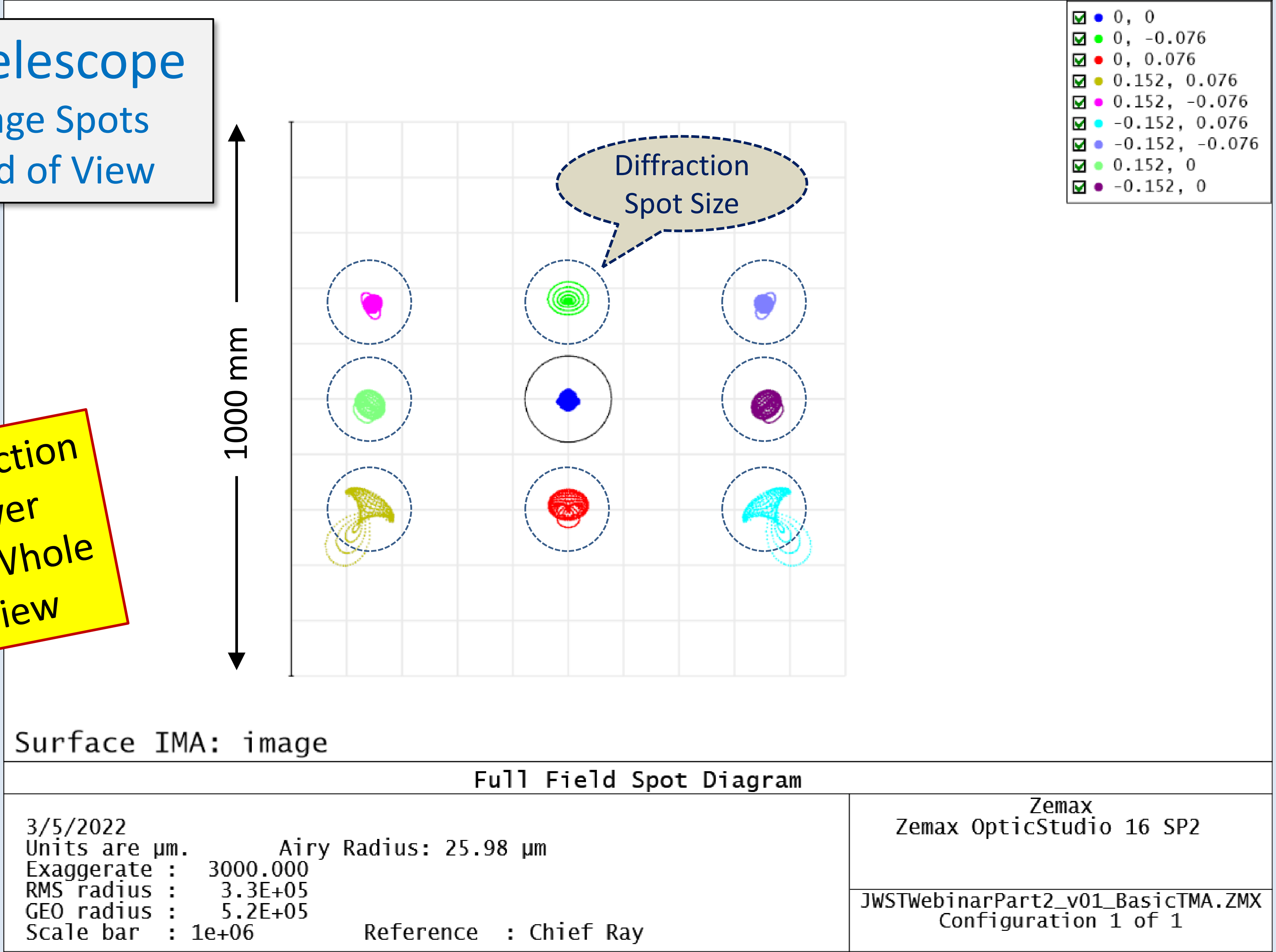
f/20

This is all there is to it. A few numbers fully specify the design

	Surf:Type		Comment	Radius	Thickness	Material	Semi-Diameter	Conic
0	OBJECT	Standard		Infinity	Infinity		Infinity	0.000
1		Standard	plot begin	Infinity	1.000E+04		3332.260	0.000
2	STOP	Standard	primary mirror	-1.588E+04	-7169.000	MIRROR	3303.619	-0.997
3		Standard	secondary mirror	-1778.900	7965.300	MIRROR	344.537	-1.660
4		Standard	tertiary mirror	-3016.200	-1844.100	MIRROR	356.997	-0.659
5		Standard	fine steering mirror	Infinity	0.000	MIRROR	78.997	0.000
6		Coordinate Break			3027.612	-	0.000	
7	IMAGE	Standard	image	-3040.463	-		391.753	0.000

The Webb Telescope

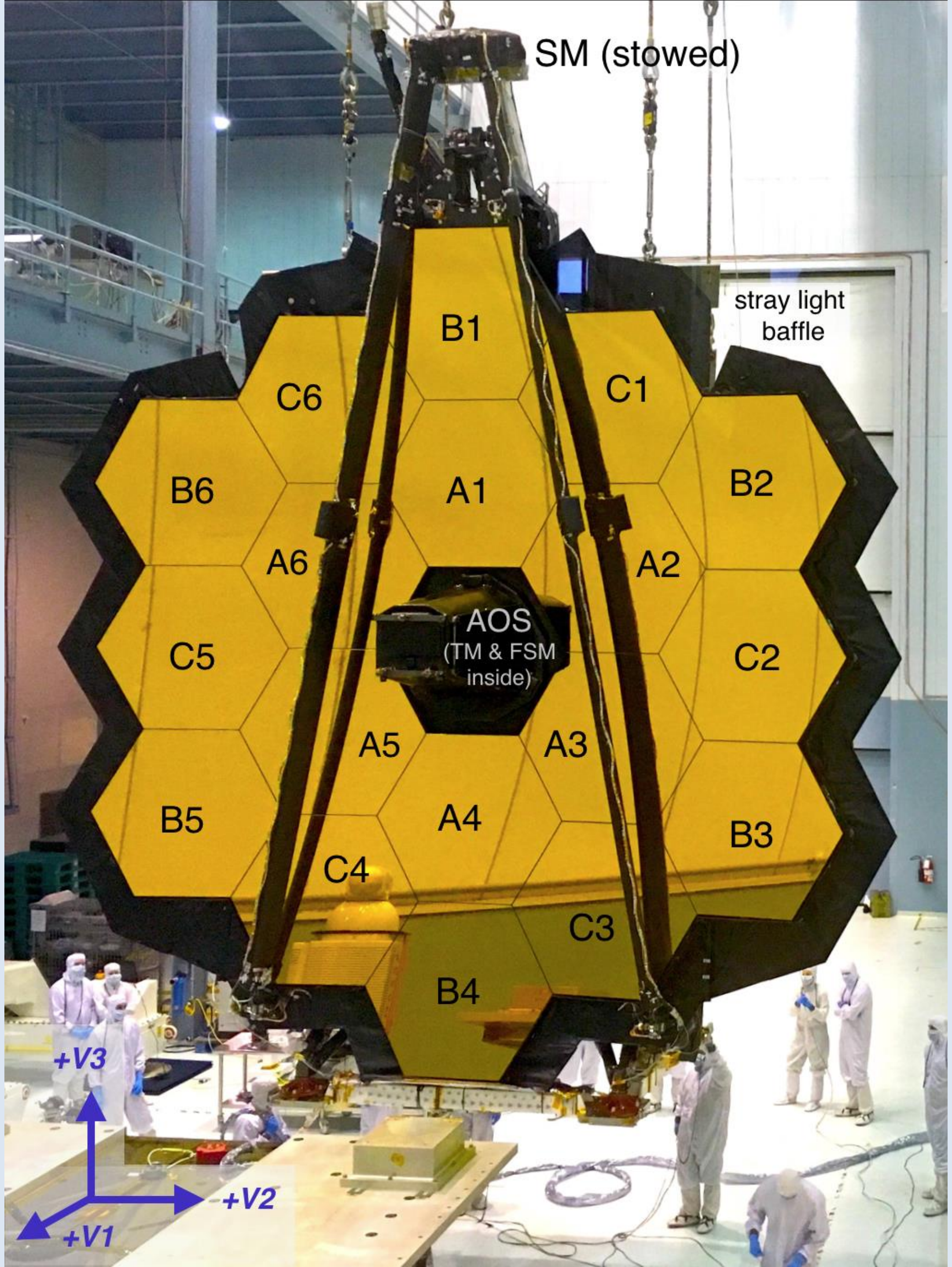
Calculated Image Spots Across the Field of View



JWST is Diffraction Limited Over Almost the Whole Field of View

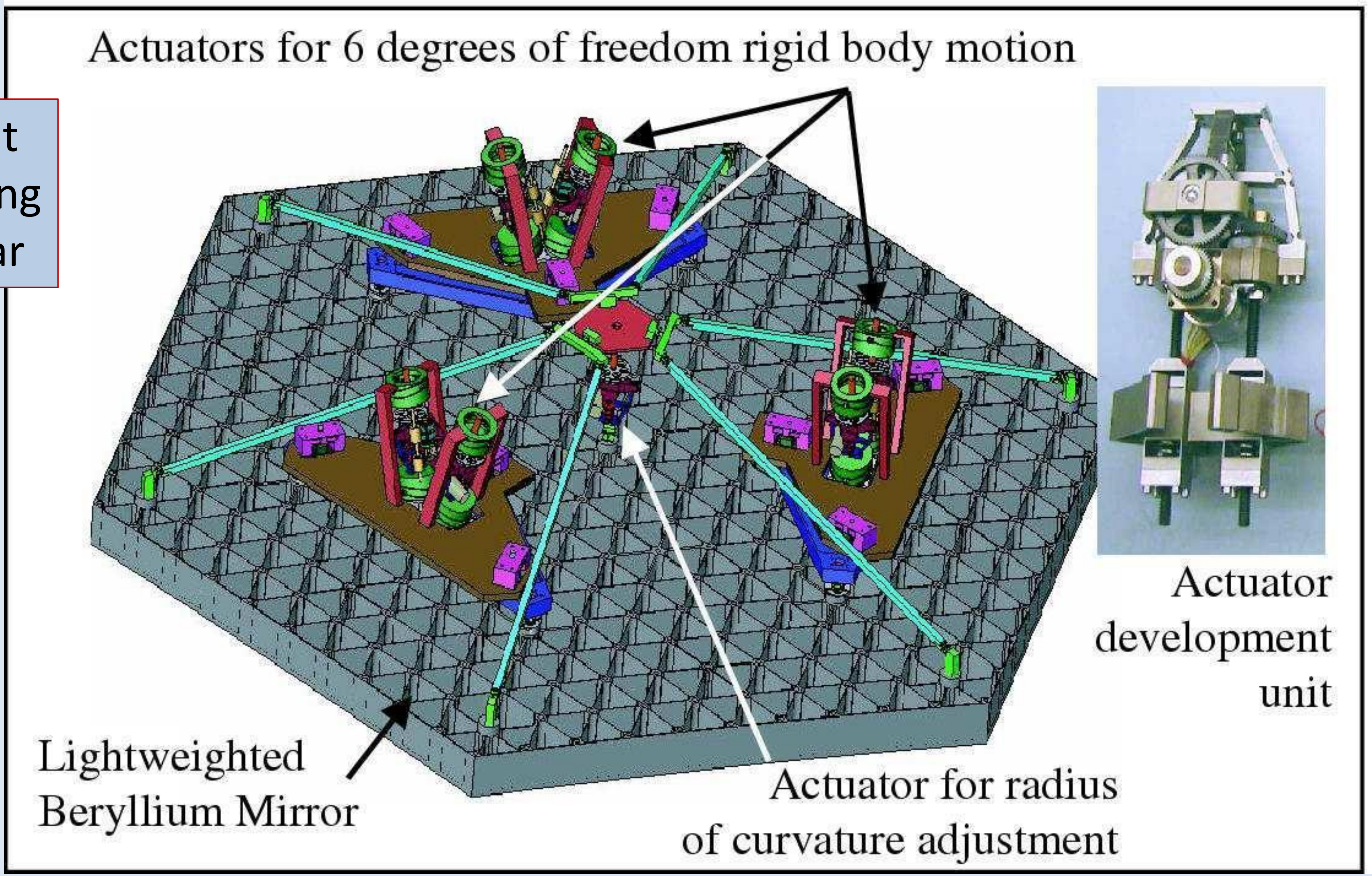
There are 3 different shapes of mirror segments: A, B, and C

All the B's are interchangeable, etc.



NASA

Each Mirror Segment has 7 Nano- Positioning Actuators on the Rear



Gardner *et al*, Space Science Rev (2006)

Science Instruments at the Focal Plane

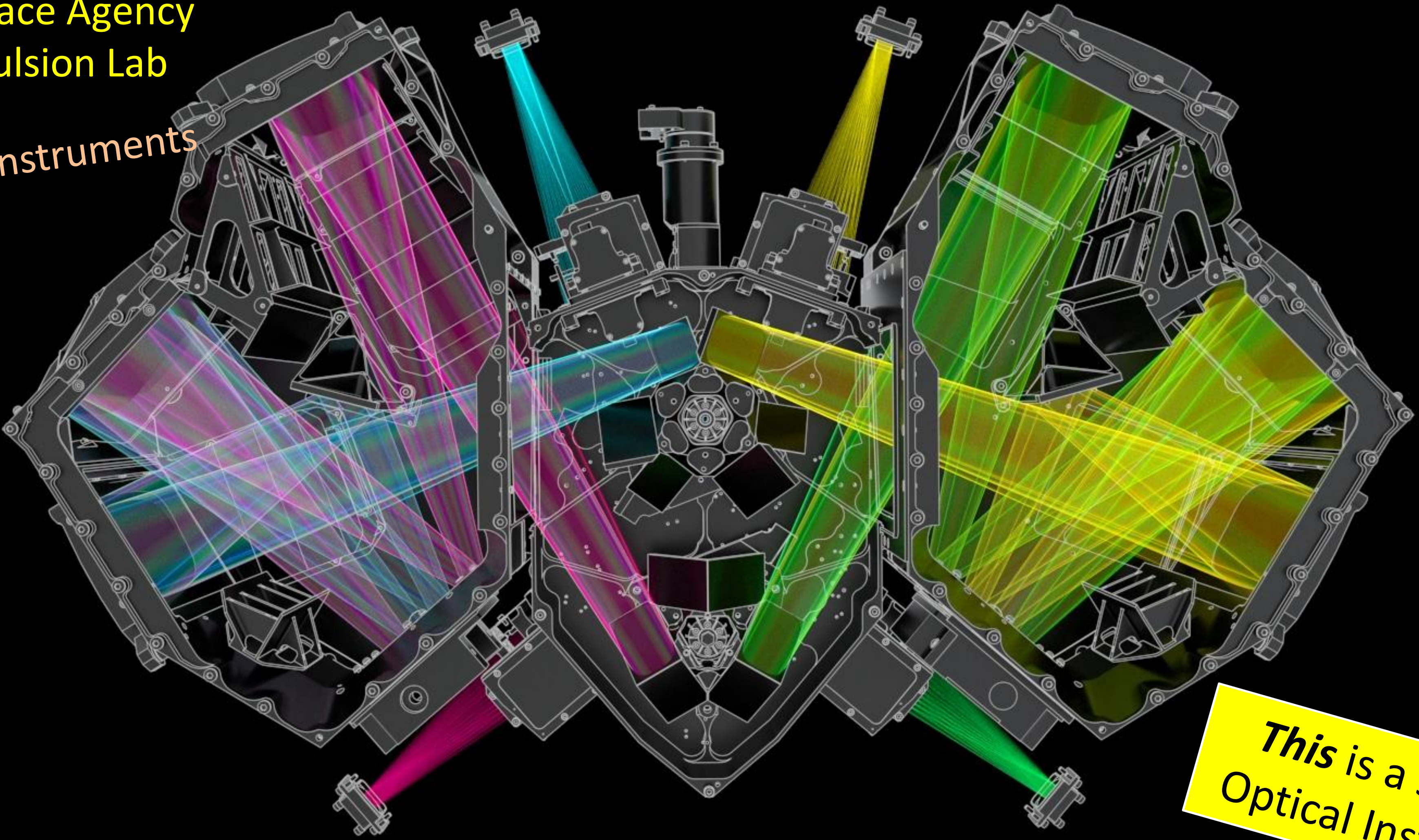
- Near Infrared Camera (U of Arizona)
- 2 Near Infrared Spectrographs (European Space Agency)
  - Can simultaneously observe over 100 sources
- Mid-Infrared (5-29 um) Instrument (ESA & JPL)
  - Camera
  - Spectrograph
- Fine Guidance Sensor/Near InfraRed Imager (Canadian Space Agency)

Integrated Science Module and Team

Mid-Infrared Instrument

European Space Agency
& Jet Propulsion Lab

One of the 5 Instruments



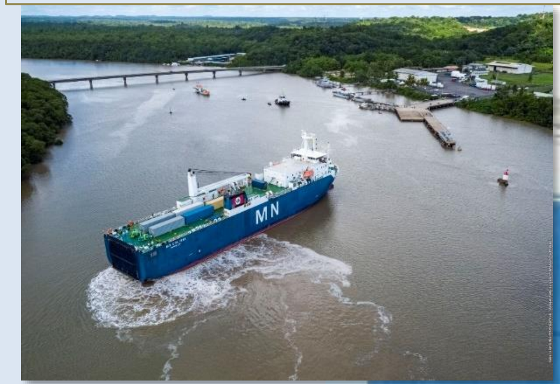
This is a serious Optical Instrument

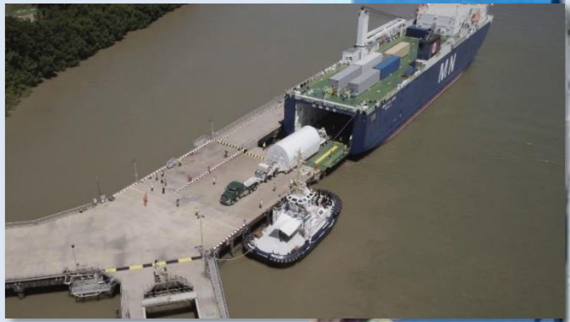
Delivery to the European Spaceport in French Guiana

Delivery to the European Spaceport in French Guiana

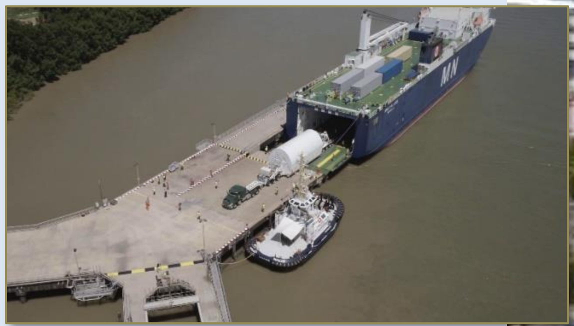
NASA/ESA

Delivery to the European Spaceport in French Guiana





Delivery to the European Spaceport in French Guiana



NASA/ESA

Our Excellent Trip to French Guiana 2010

Setup and Launch on Ariane 5

NASA/ESA

Setup and Launch on Ariane 5

Setup and Launch on Ariane 5

NASA/ESA

Setup and Launch on Ariane 5

Setup and Launch on Ariane 5

Setup and Launch on Ariane 5

Setup and Launch on Ariane 5

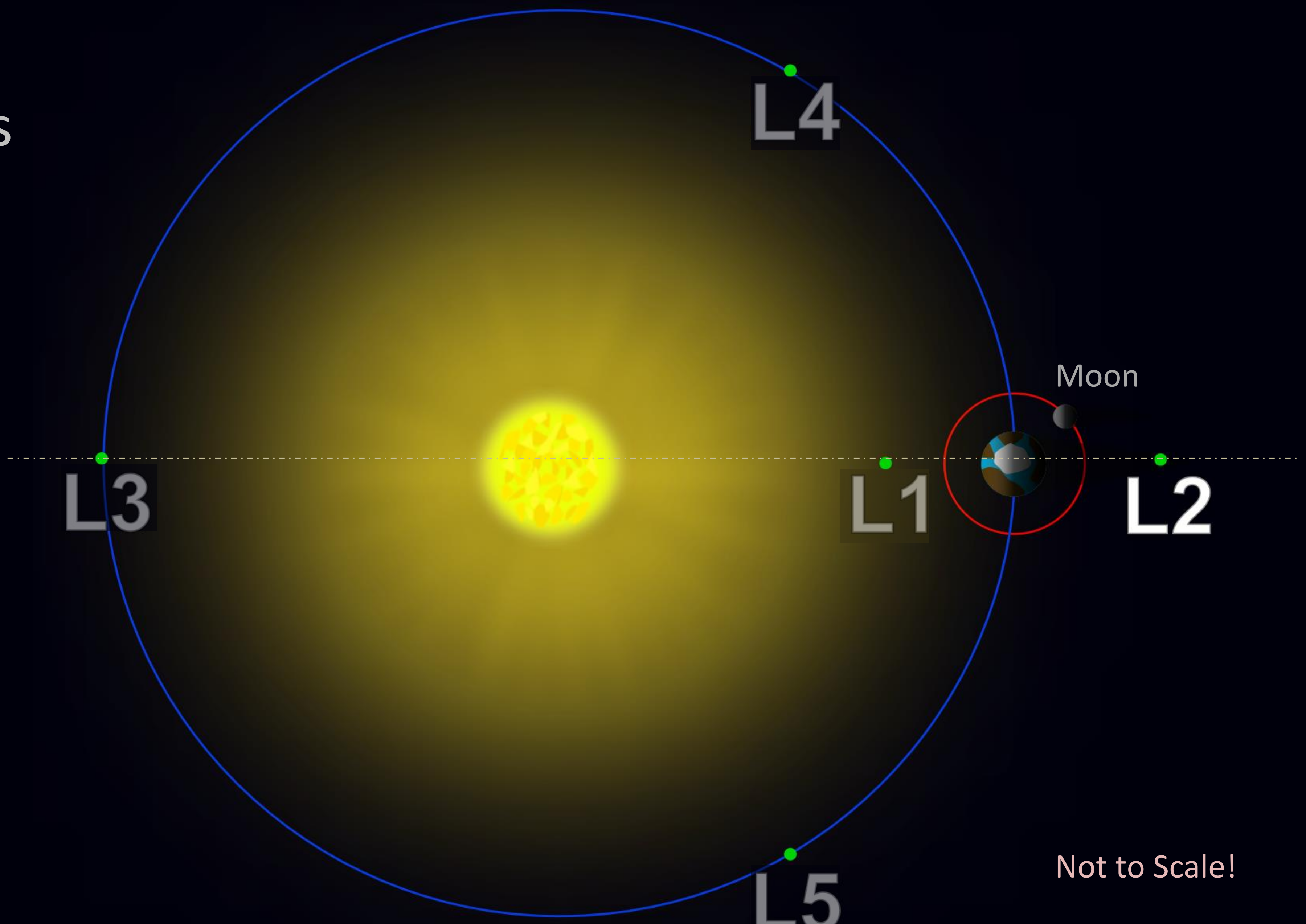
JAMES WEBB SPACE TELESCOPE

NOMINAL DEPLOYMENT SEQUENCE

Lagrange Points

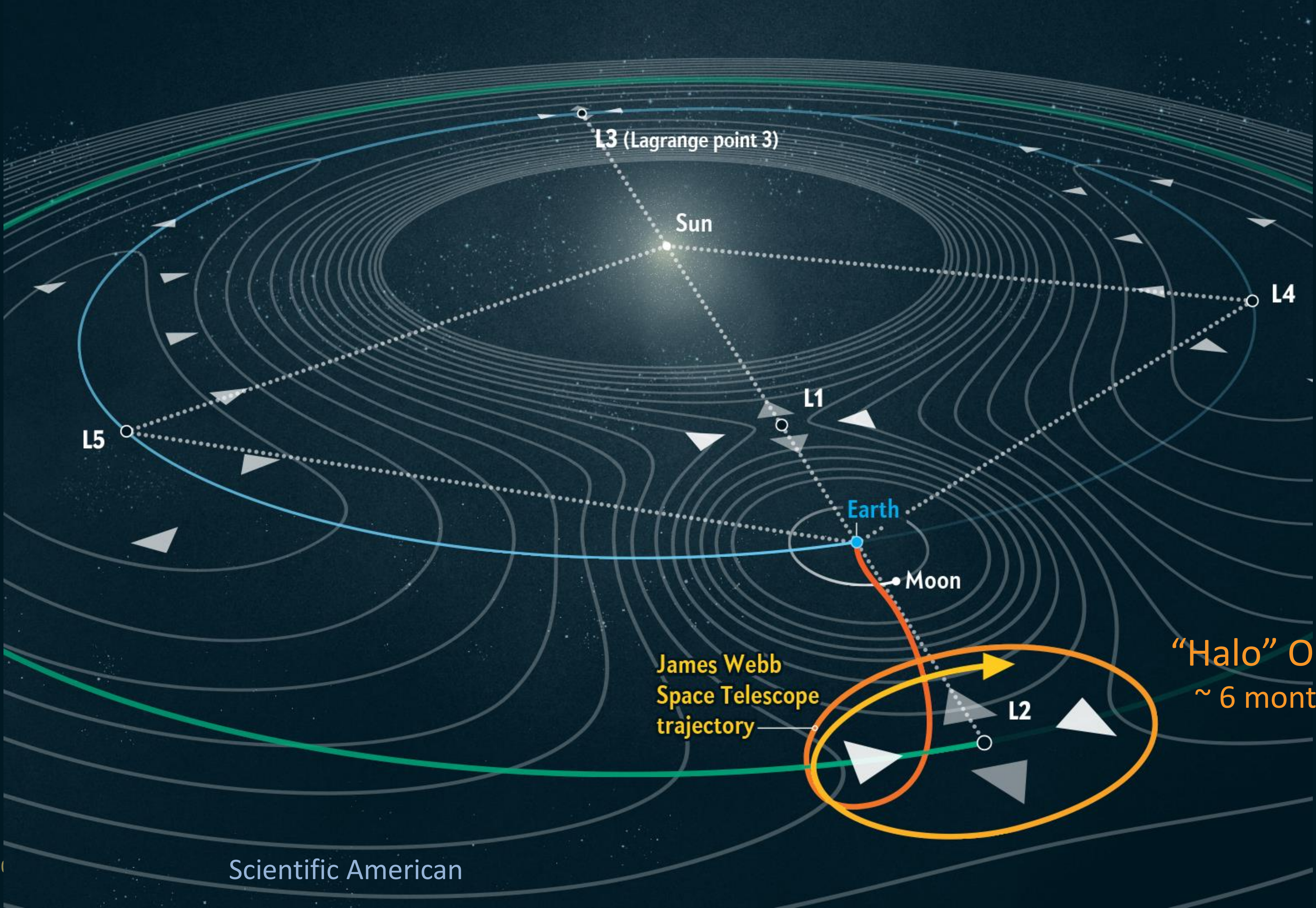
Semi-stable parking spots in space fixed relative to earth

L1, L2, L3 discovered by Leonhard Euler 1750



Not to Scale!

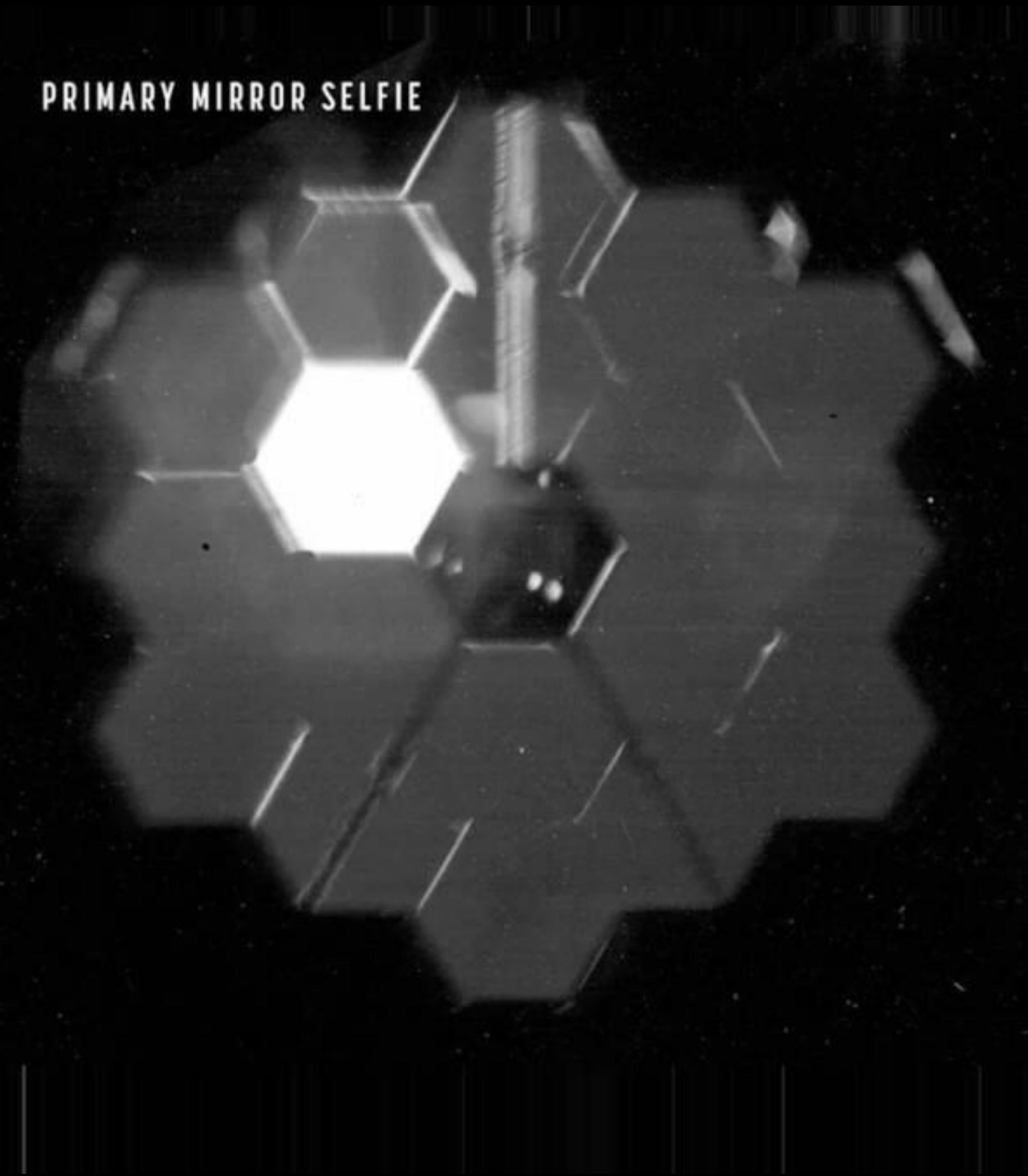
Wikipedia



Scientific American

The Webb Halo Orbit

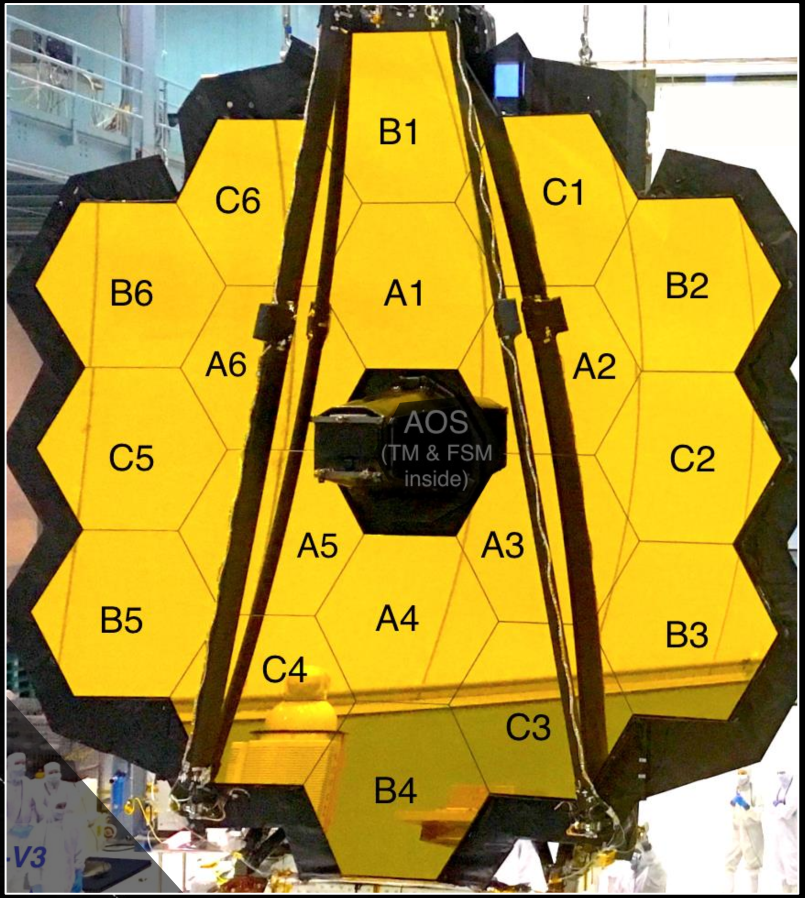
Goddard Space Flight Center



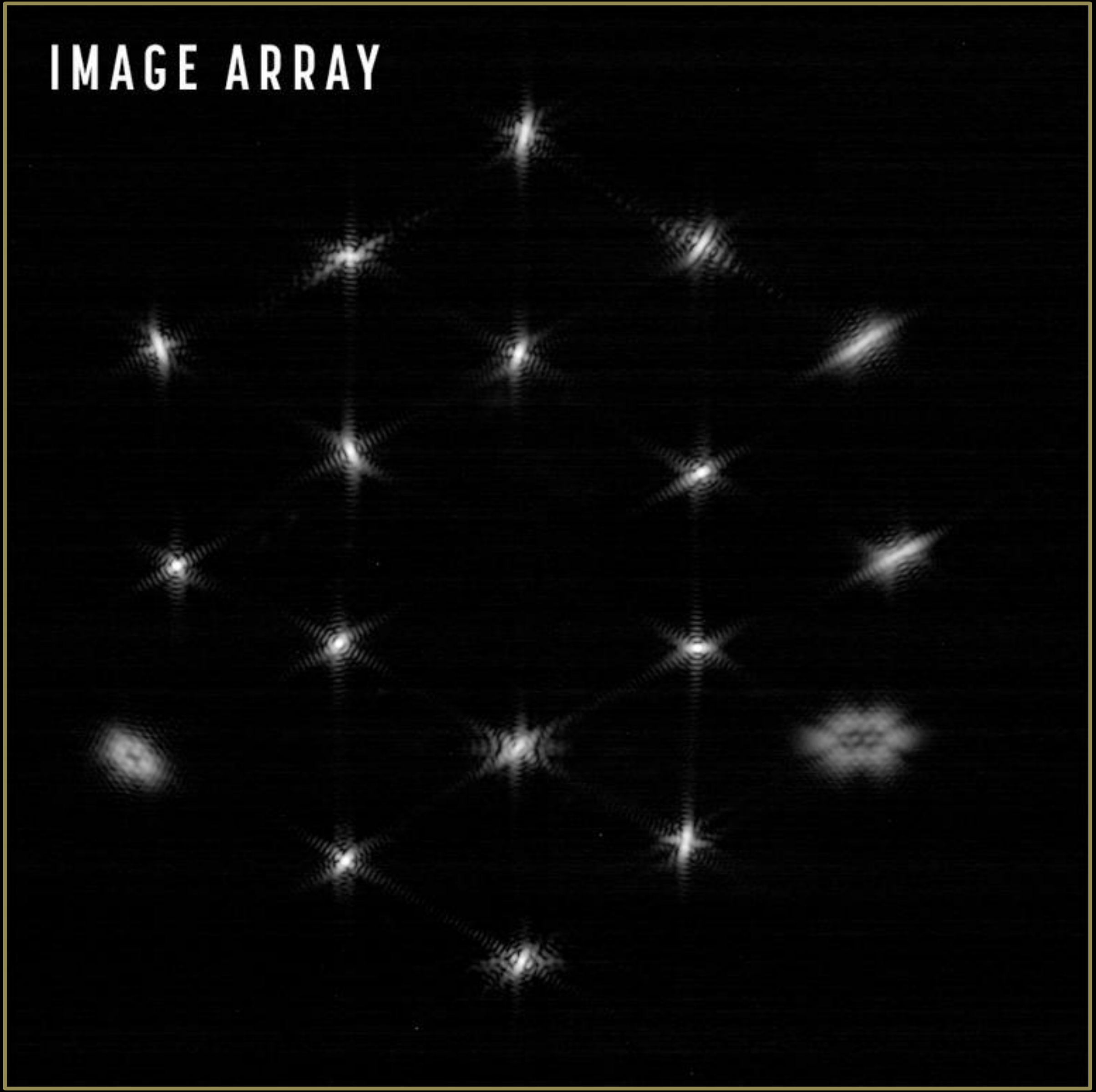
Near Infrared Camera with special pupil imaging lens used for engineering only

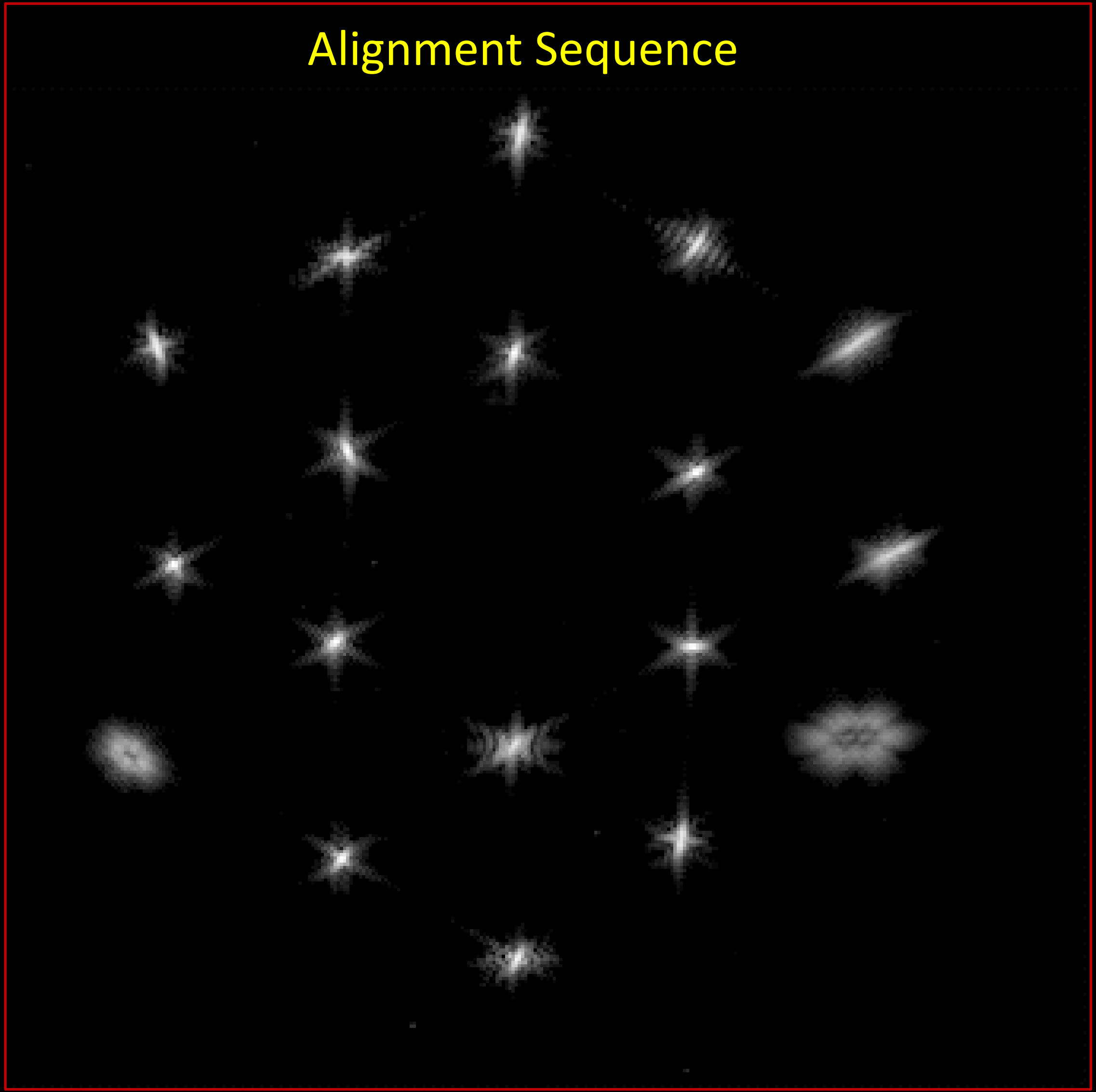
NASA Blog

SEGMENT IDENTIFICATION MOSAIC

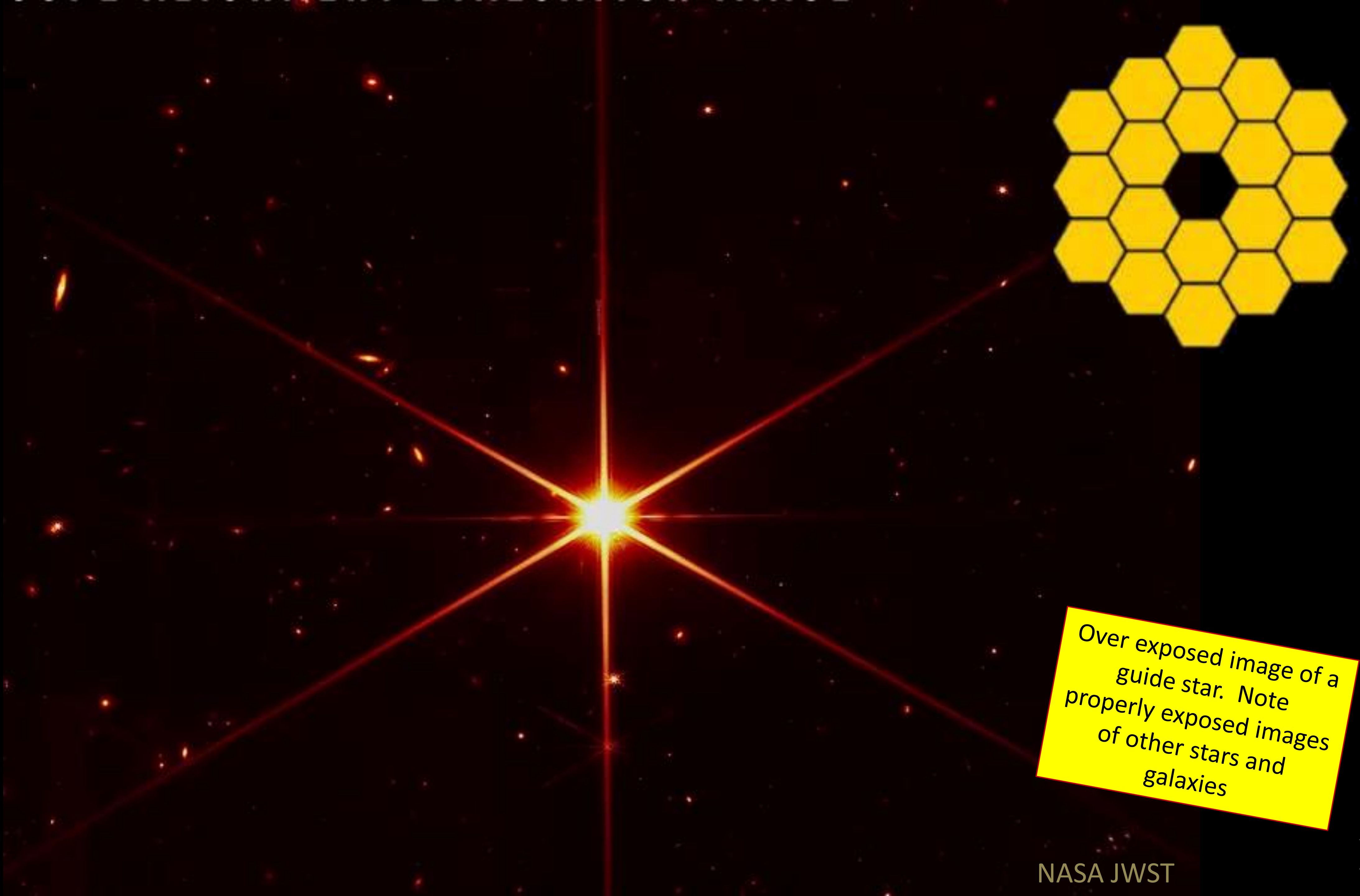


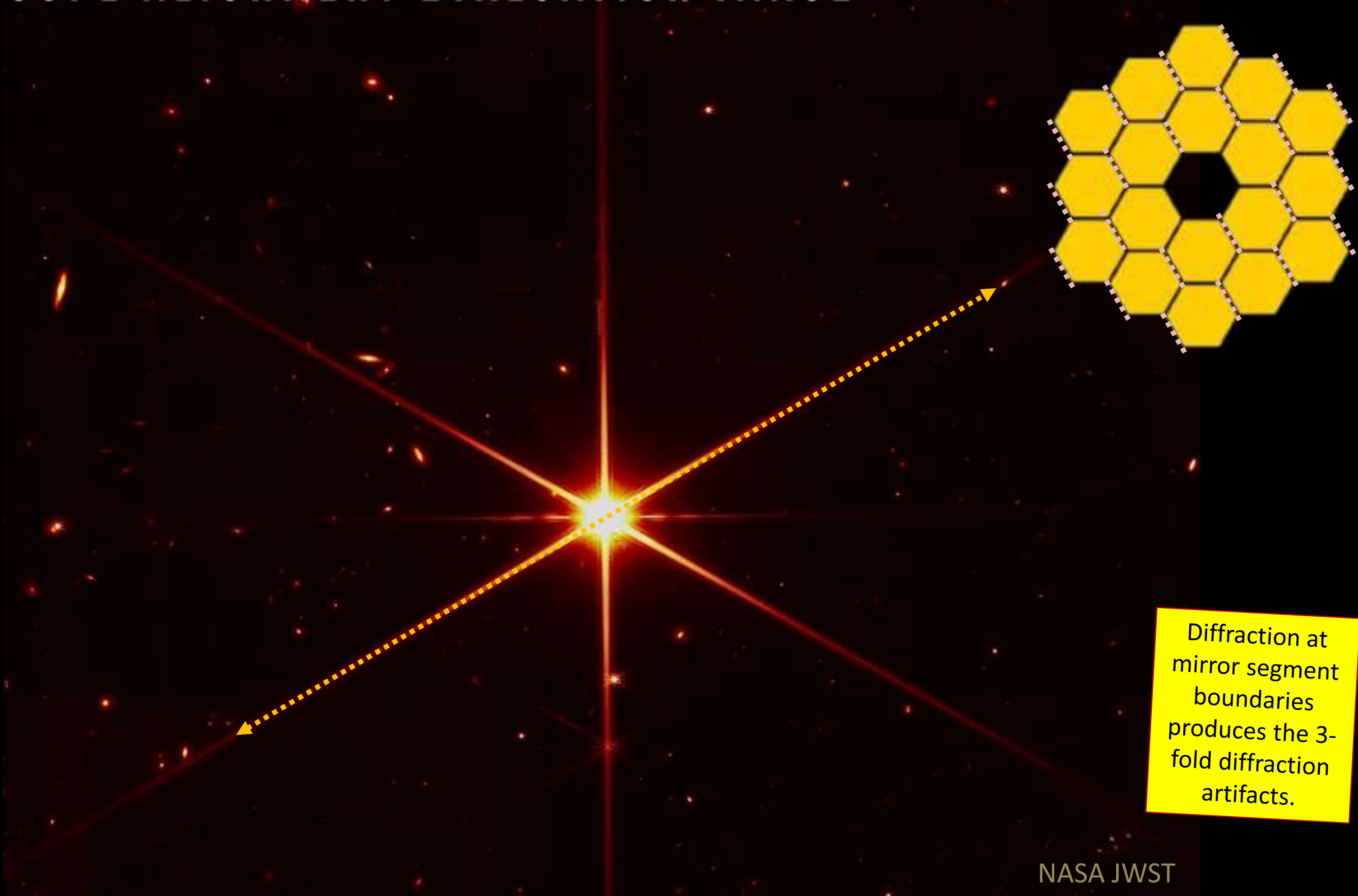
NASA Blog





NASA Blog


Over exposed image of a guide star. Note properly exposed images of other stars and galaxies



Diffraction at mirror segment boundaries produces the 3-fold diffraction artifacts.

NASA JWST


Thank you!