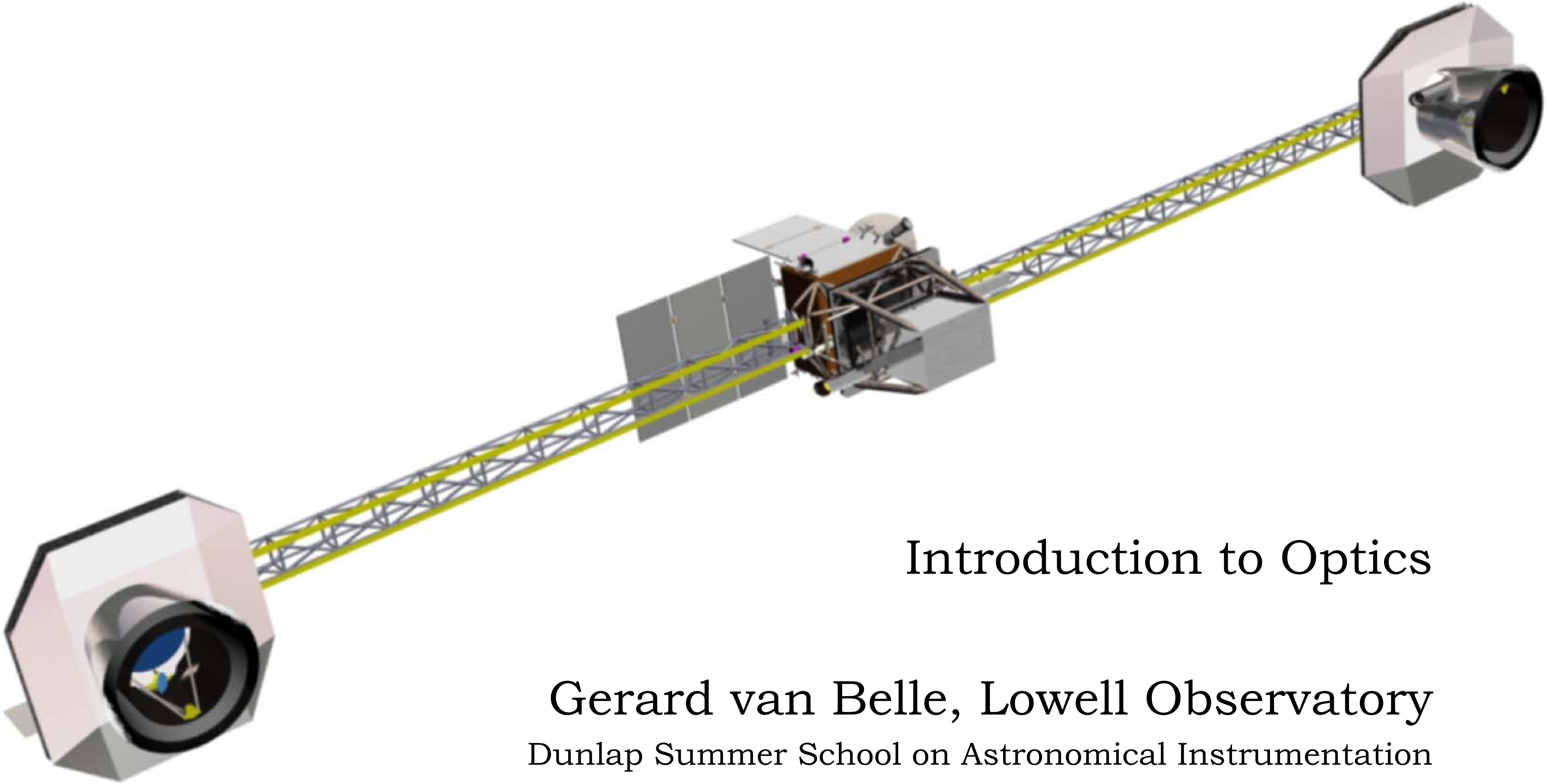


NASA

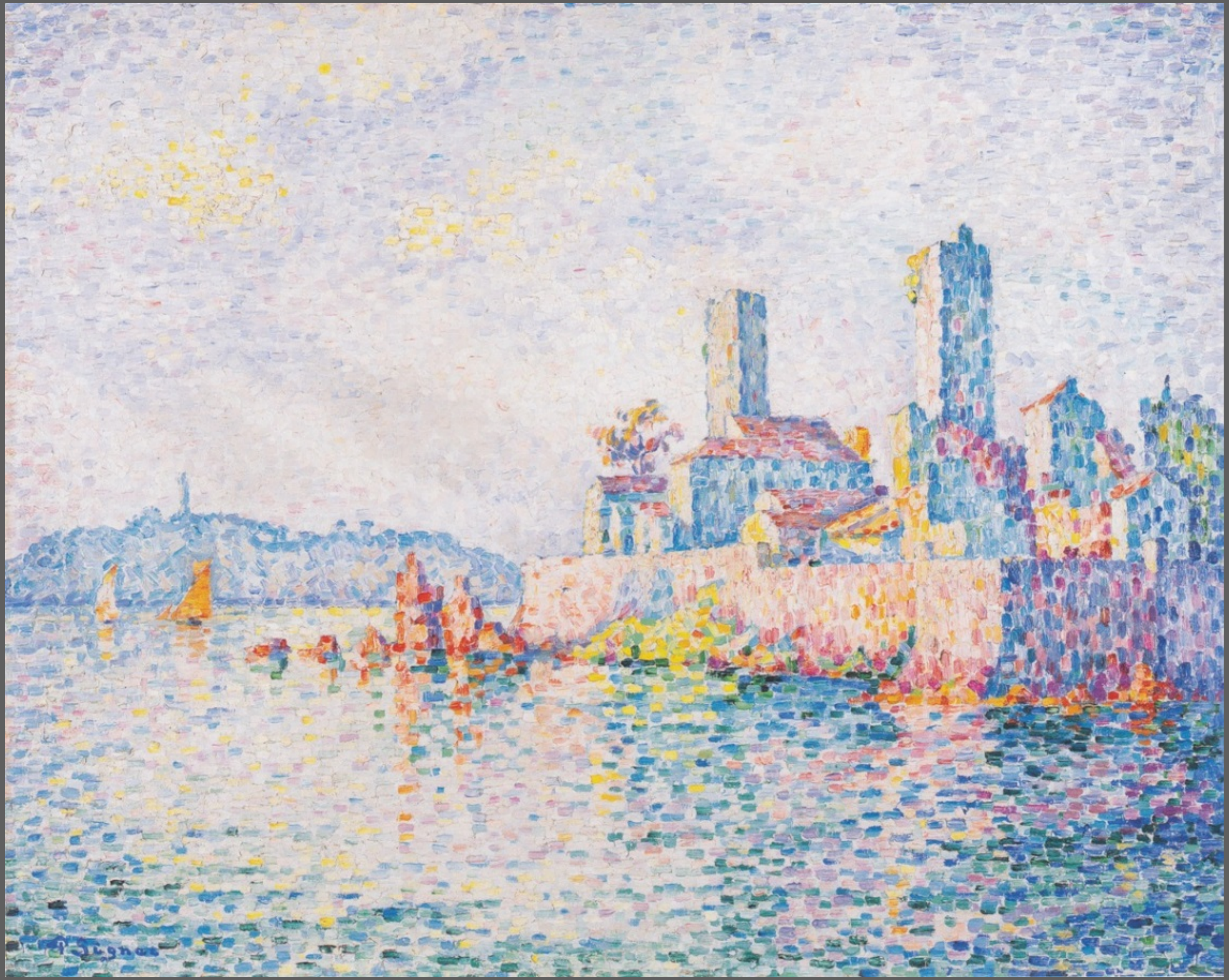
SPIRIT concept:
NASA Goddard Space Flight Center

Introduction to Optics

Gerard van Belle, Lowell Observatory

Dunlap Summer School on Astronomical Instrumentation

Optics



Paul Signac, “Antibes, die Türme”, 1911

What is ‘Optics’?

- The study of electromagnetic (EM) radiation,
- its interactions with matter,
- and instruments that gather information due to those interactions

What is 'Optics'?

- The study of electromagnetic (EM) radiation,
- its interactions with matter,
- and instruments that gather information due to those interactions

← **AKA 'LIGHT'**

Can apply to the whole EM spectrum, from radio to gamma

Basic Properties of Light

- Reflects and refracts
- Rectilinear (straight-line) propagation
- Finite speed
- Carries energy
- Can be broken into a spectrum
- Wave-particle duality

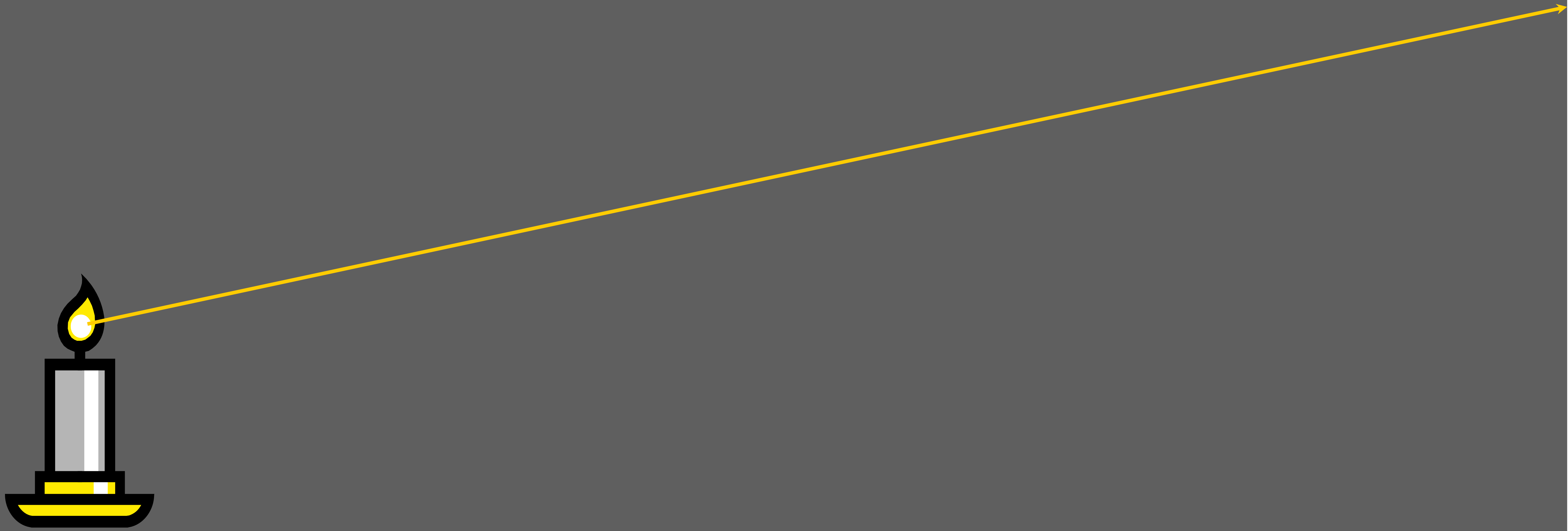
Manipulation of Light

- Reflection

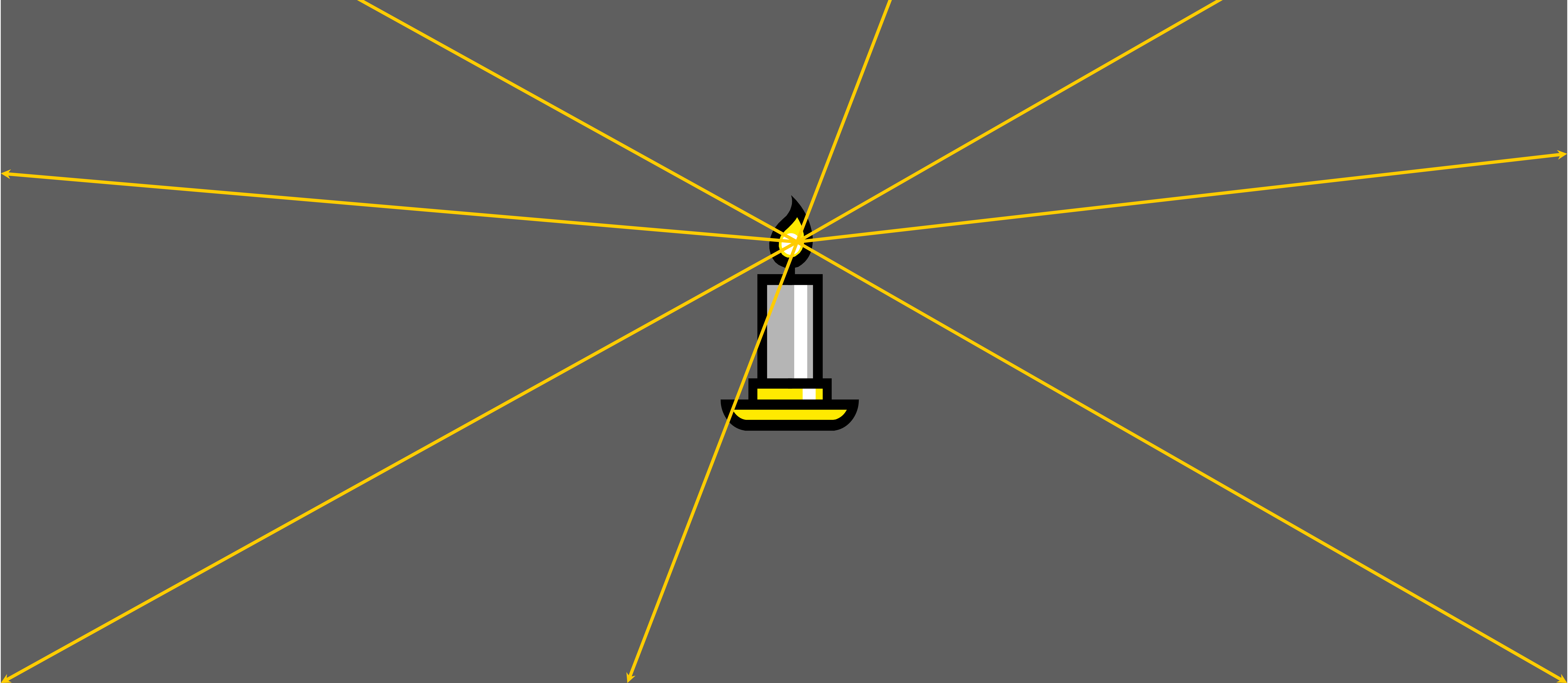
    and

- Refraction

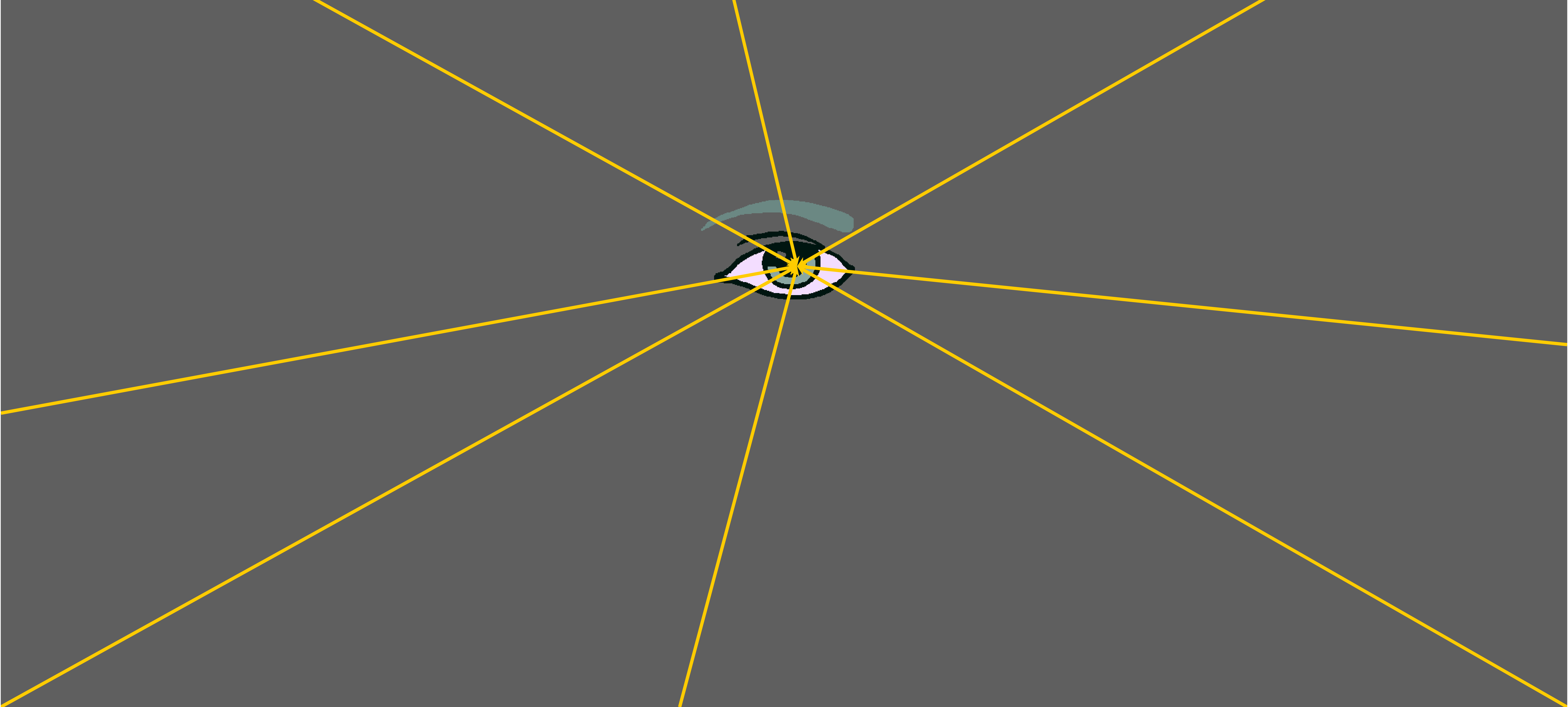
A **ray of light** is an extremely narrow beam of light.

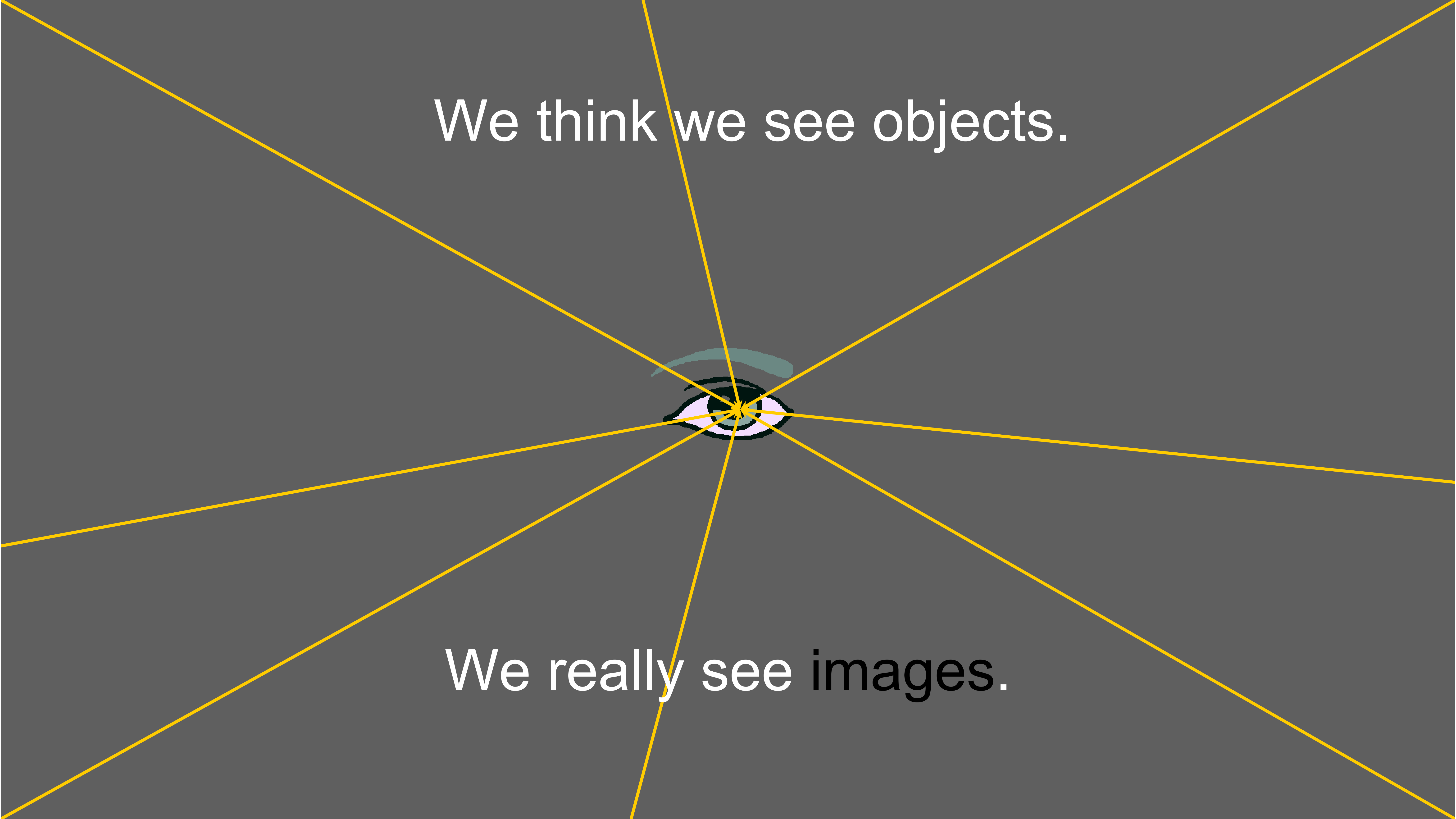


All visible objects emit or reflect **light rays** in all directions.

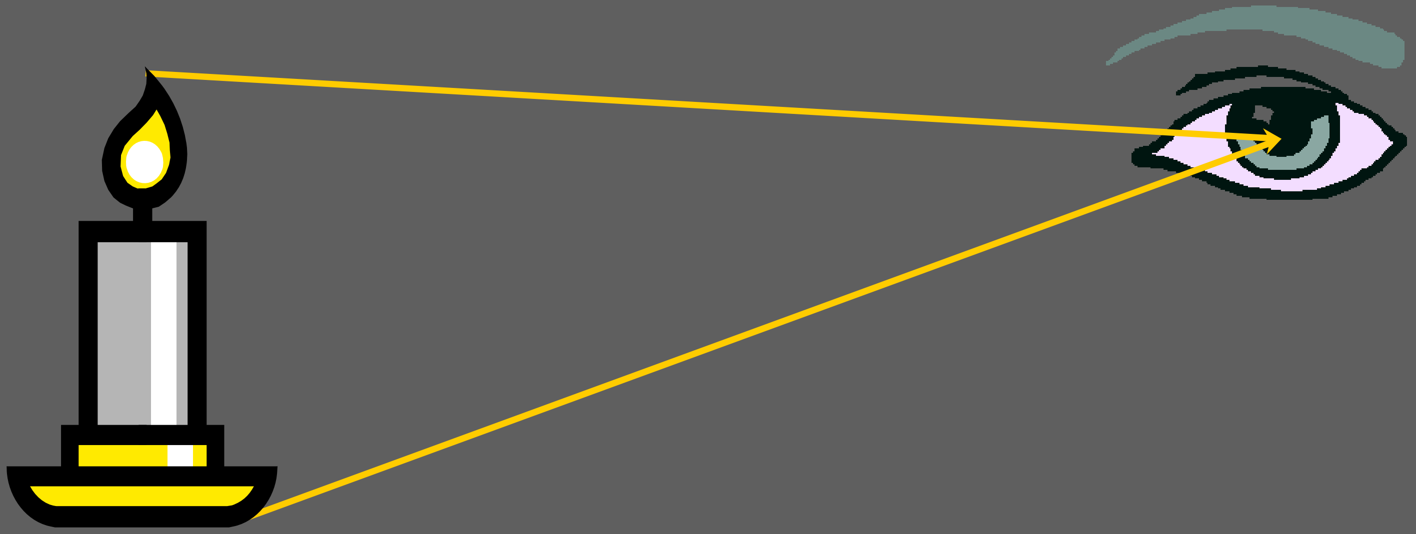


Our eyes detect **light rays**.



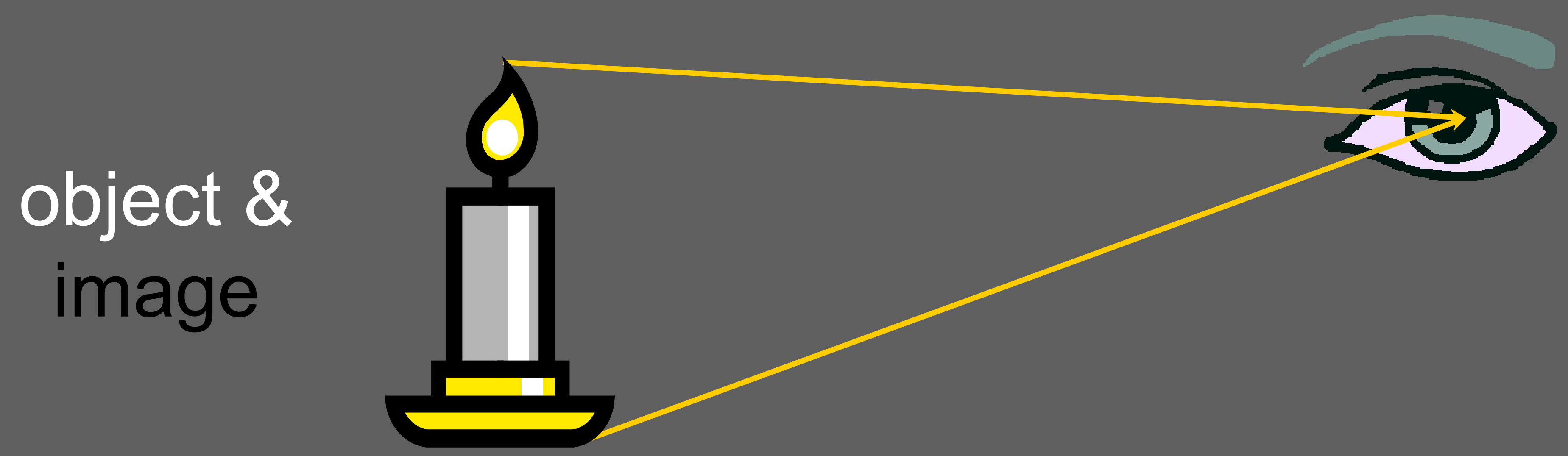

We think we see objects.
We really see images.

Images are formed when **light rays** converge.

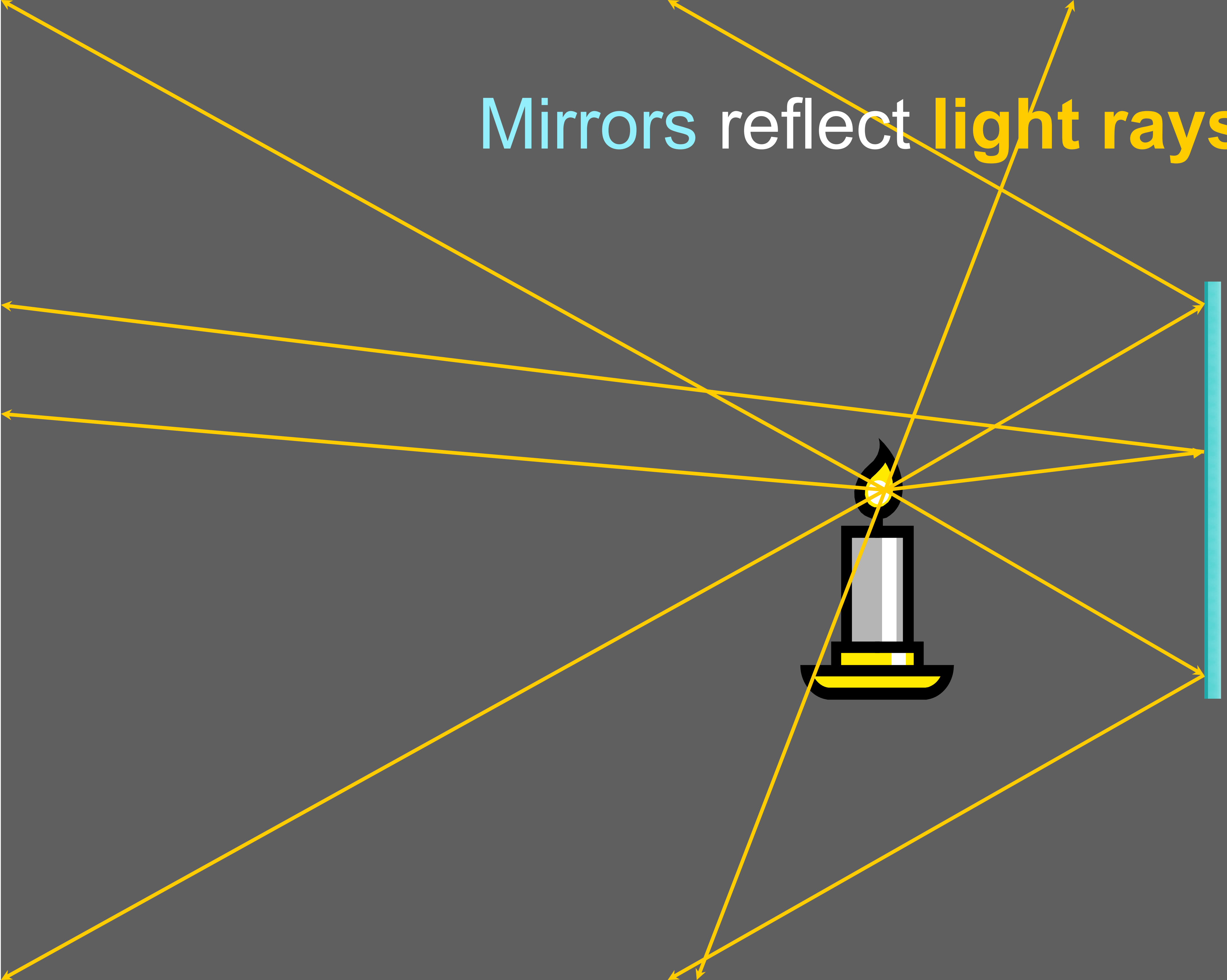


converge: come together

When **light rays** go straight into our eyes,
we see an image in the same spot as the object.



Mirrors reflect **light rays**.



Mirrors

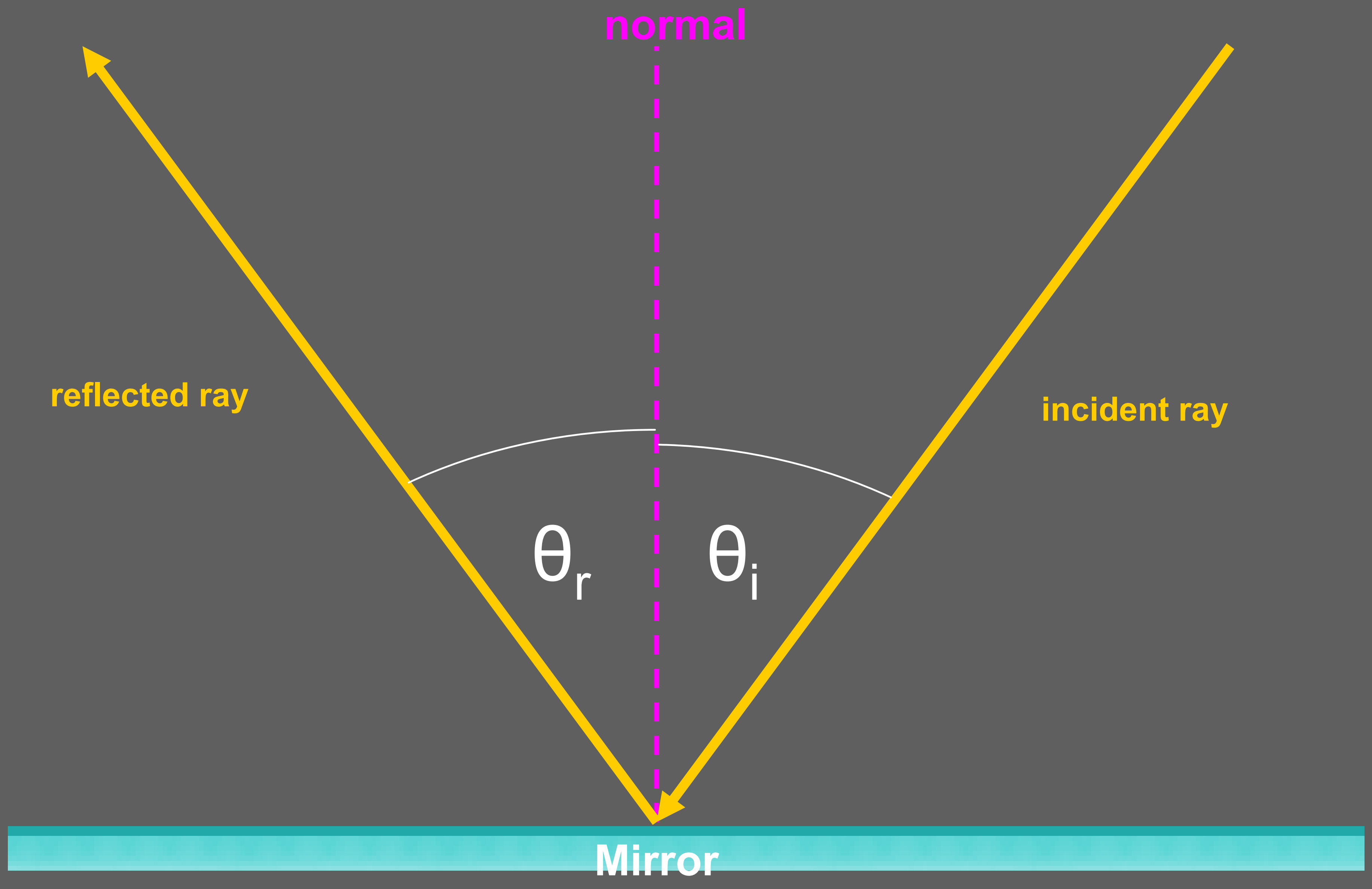
It is possible to see images when converging light rays reflect off of mirrors.

Reflection
(bouncing light)

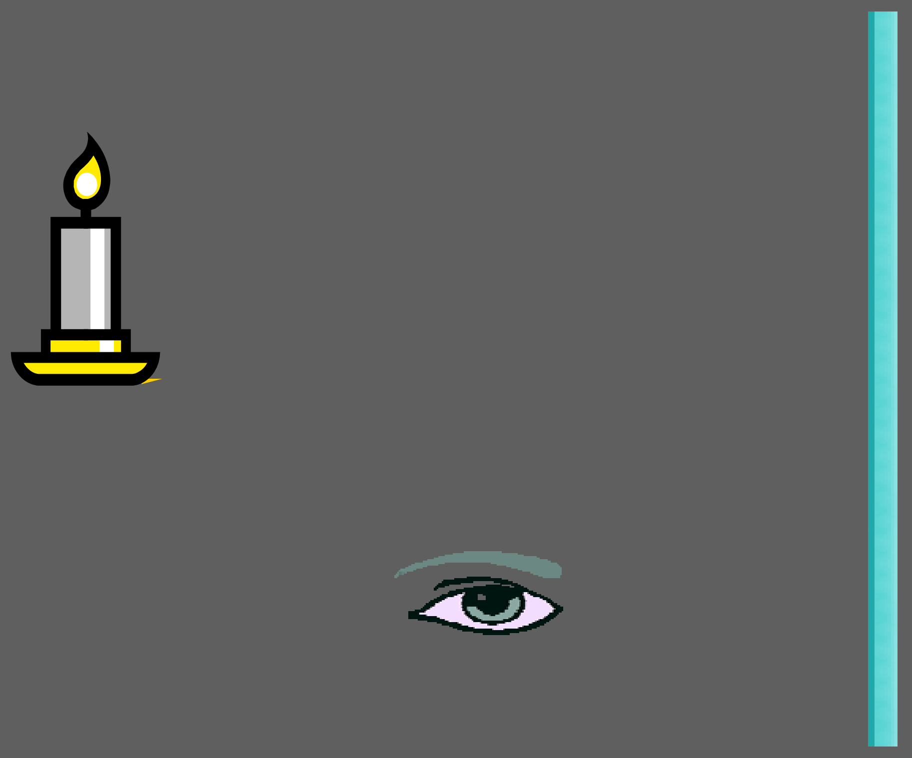
Reflection is when light changes direction by bouncing off a surface.

When light is **reflected** off a mirror, it hits the mirror at the same angle (θ_i, the incidence angle) as it **reflects** off the mirror (θ_r, the reflection angle).

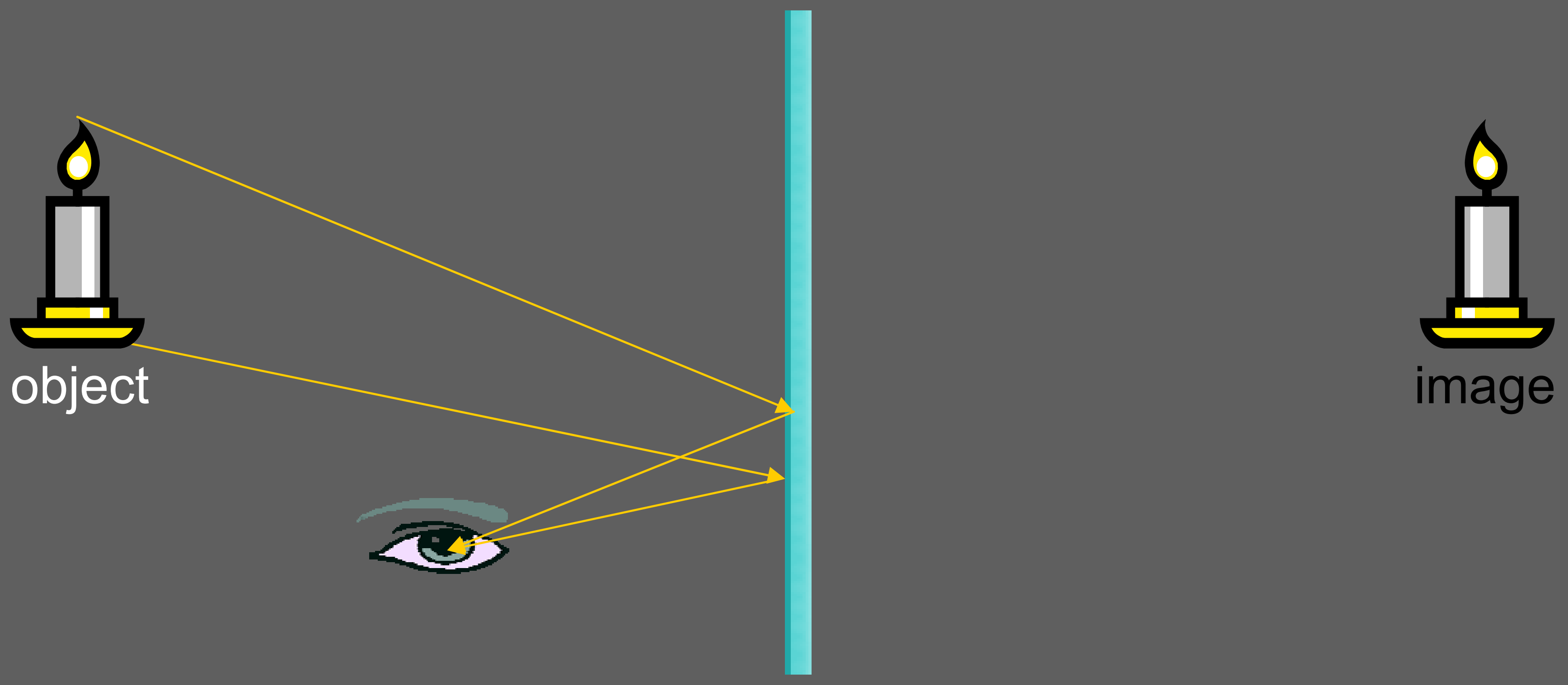
The normal is an imaginary line which lies at right angles to the mirror where the ray hits it.



How do we see images in mirrors?



How do we see images in mirrors?

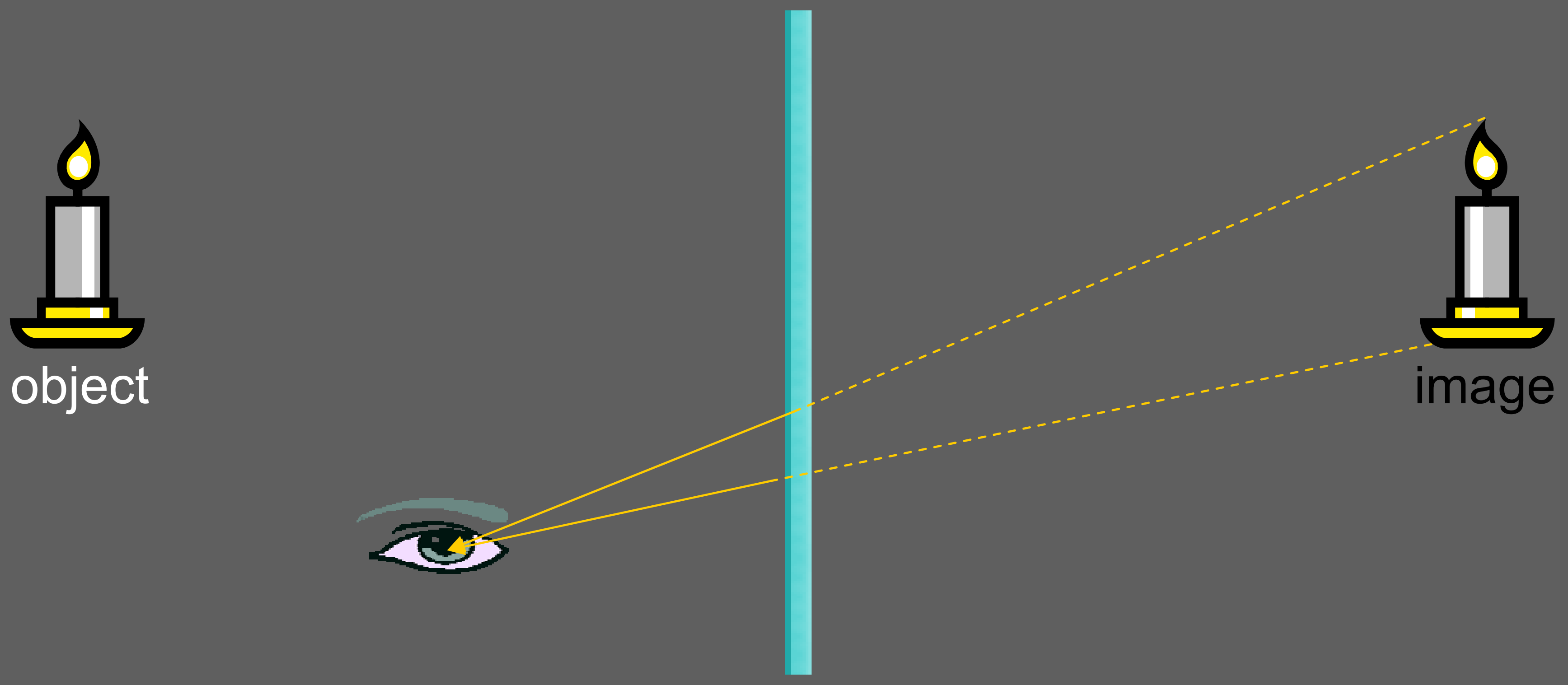


Light from the object

reflects off the mirror

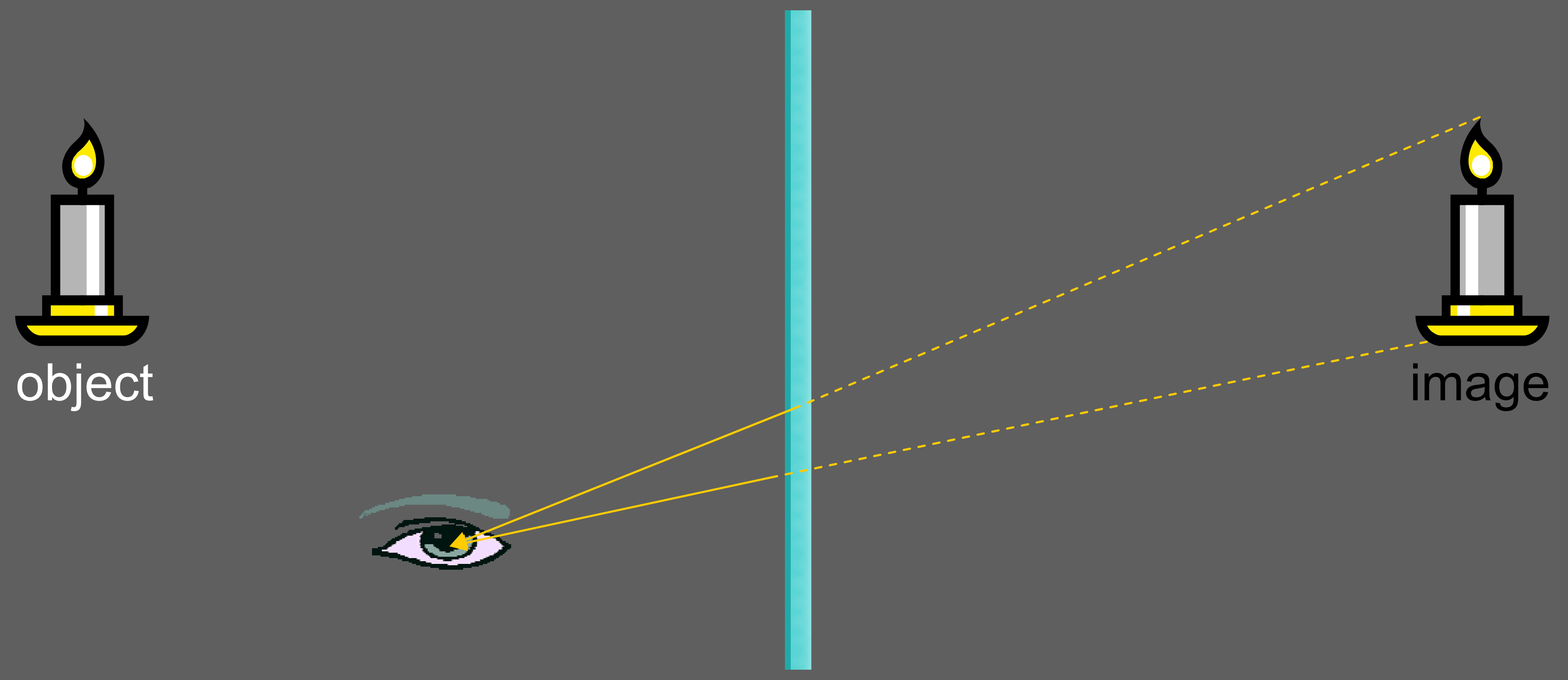
and converges to form an image.

Sight Lines



We perceive all light rays as if they come straight from an object.

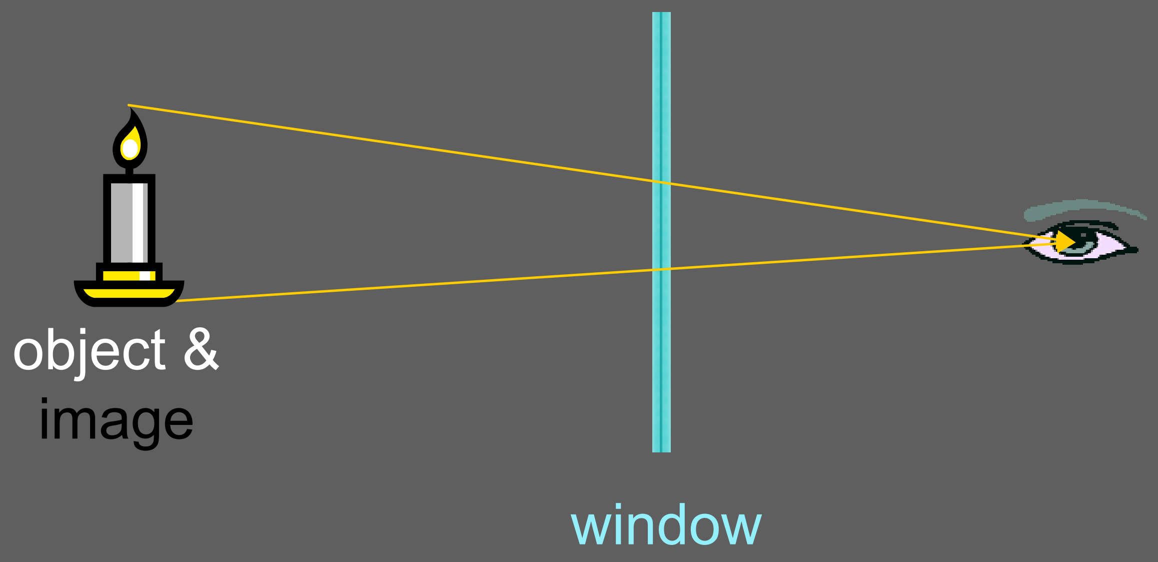
Sight Lines

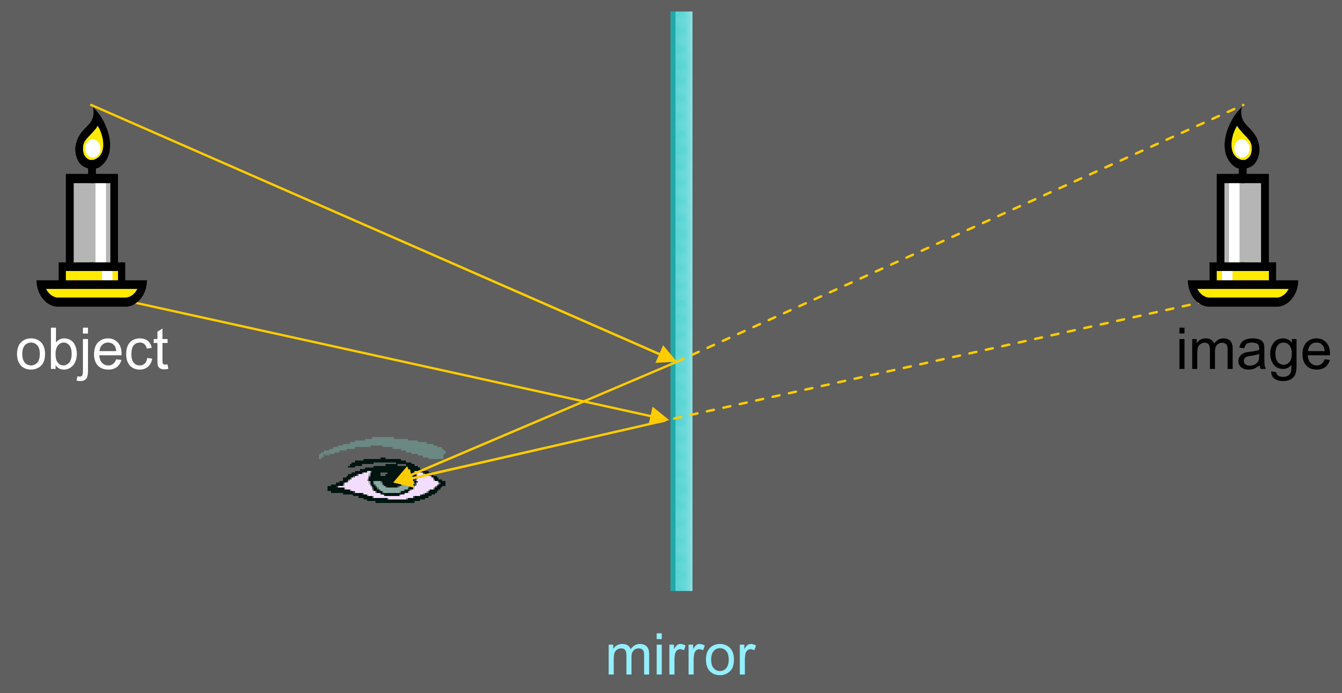


We perceive all light rays as if they come straight from an object.

The imaginary light rays that we think we see are called *sight lines*.

Image Types

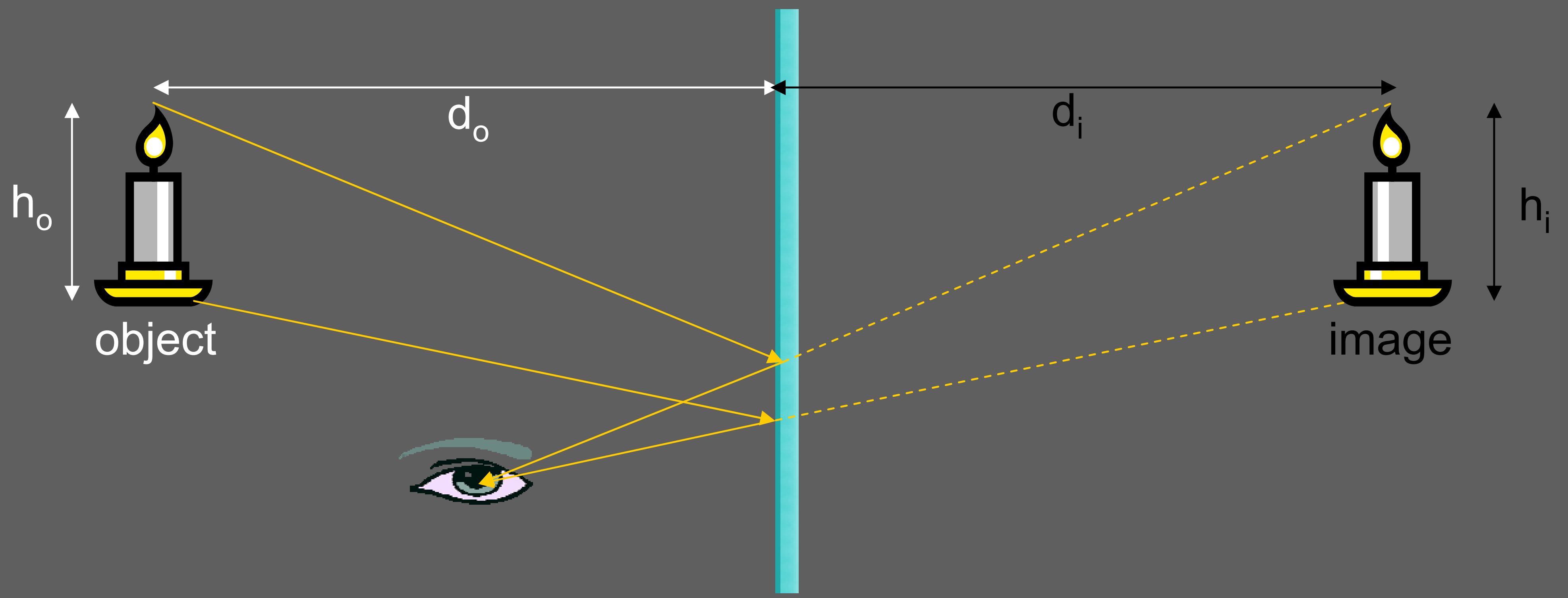




Real images are formed by light rays.

Virtual images are formed by *sight lines*.

Plane (flat) Mirrors



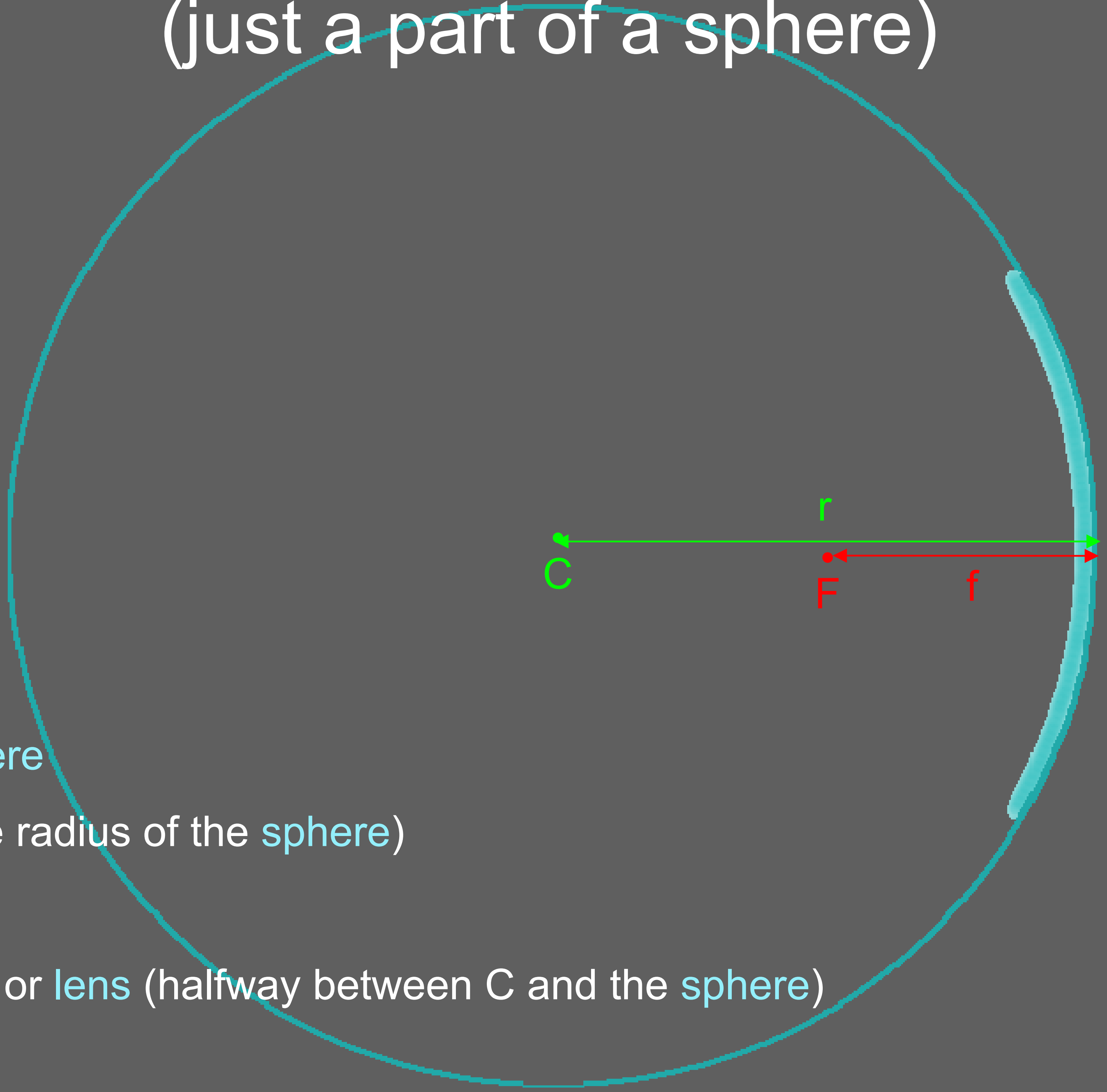
Images are virtual (formed by *sight lines*) and upright

Objects are not magnified: object height (h_o) equals image height (h_i).

Object distance (d_o) equals image distance (d_i).

Spherical Mirrors
(concave & convex)

Concave & Convex
(just a part of a sphere)



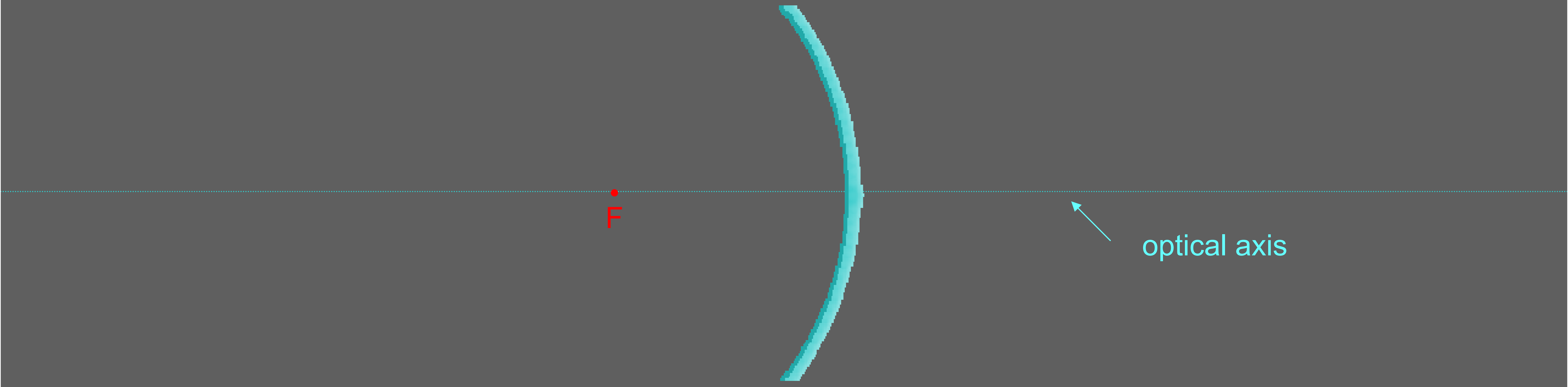
C: the center point of the sphere

r: radius of curvature (just the radius of the sphere)

F: the focal point of the mirror or lens (halfway between C and the sphere)

f: the focal distance, f = r/2

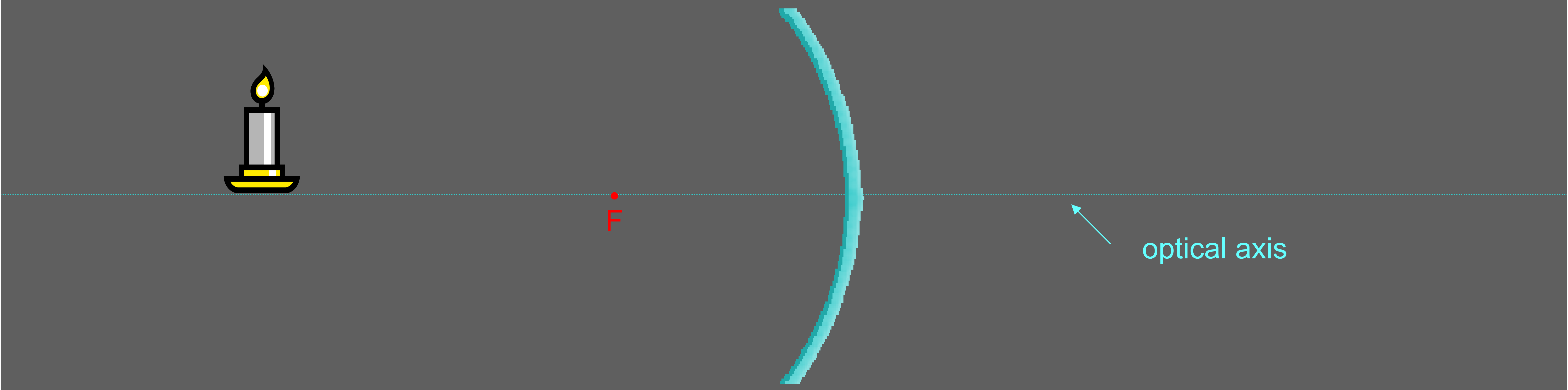
Concave Mirrors
(caved in)



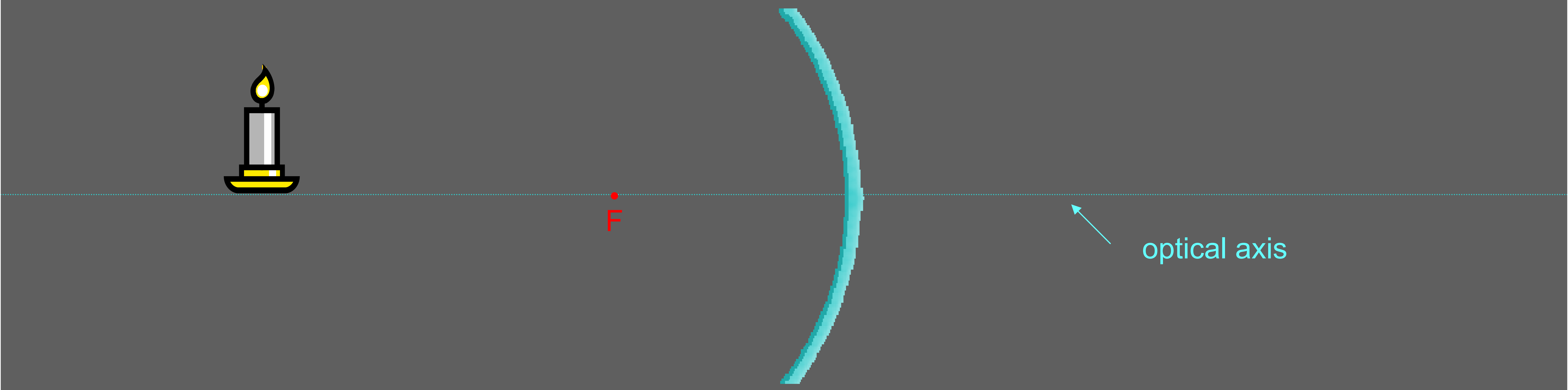
Light rays that come in parallel to the optical axis reflect through the focal point.

Concave Mirror

(example)

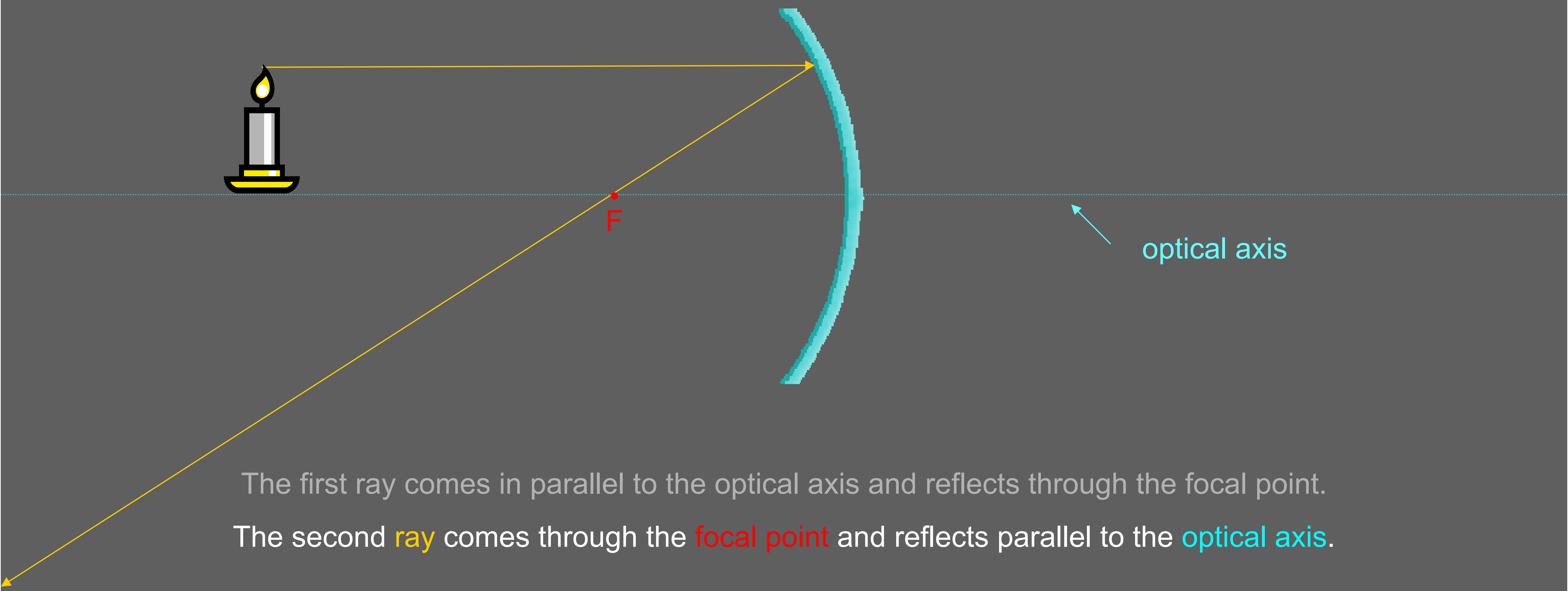


Concave Mirror
(example)



The first ray comes in parallel to the optical axis and reflects through the focal point.

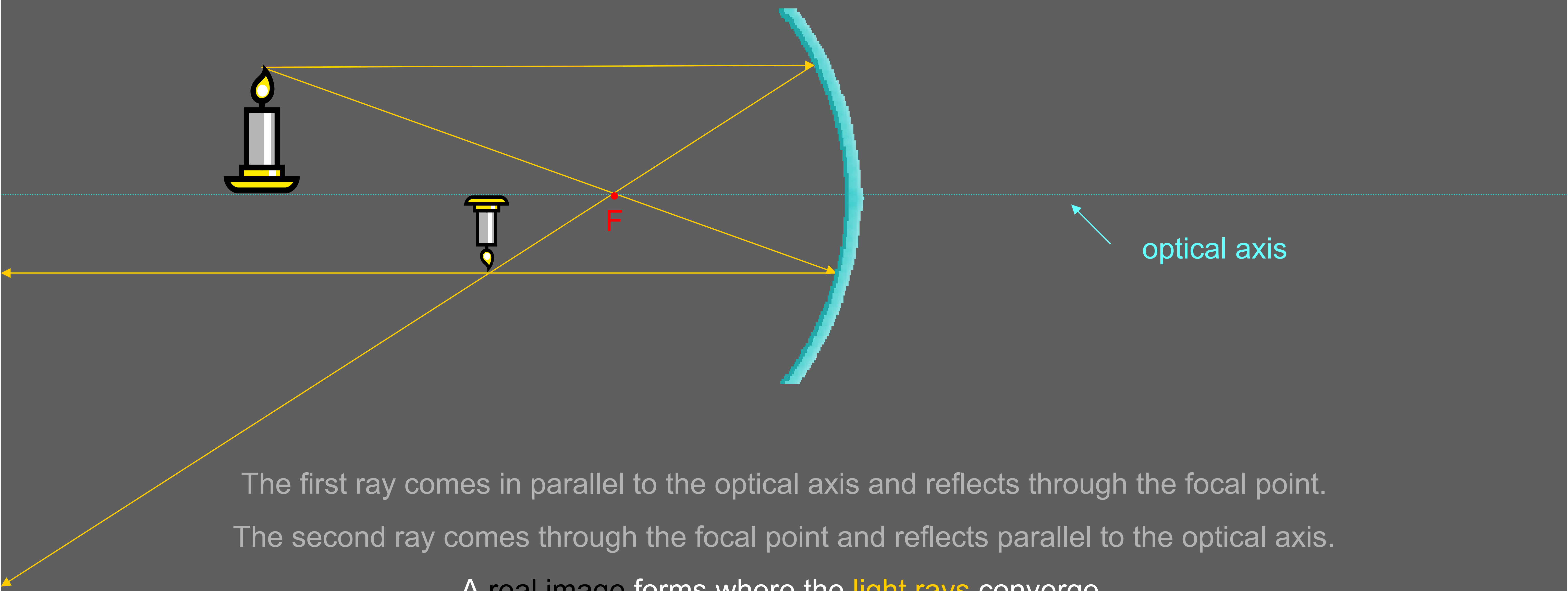
Concave Mirror
(example)



The first ray comes in parallel to the optical axis and reflects through the focal point.

The second ray comes through the focal point and reflects parallel to the optical axis.

Concave Mirror
(example)



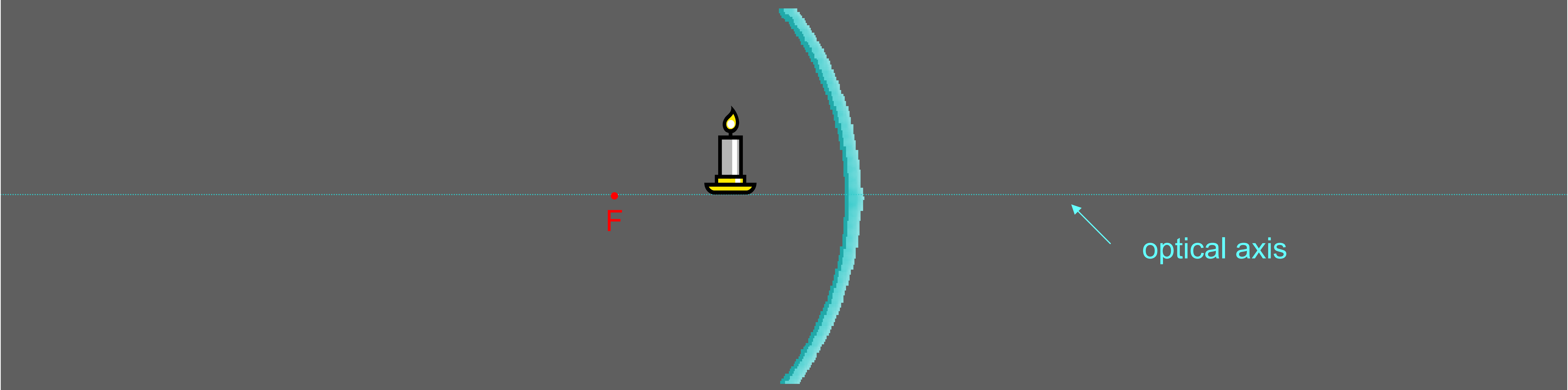
The first ray comes in parallel to the optical axis and reflects through the focal point.

The second ray comes through the focal point and reflects parallel to the optical axis.

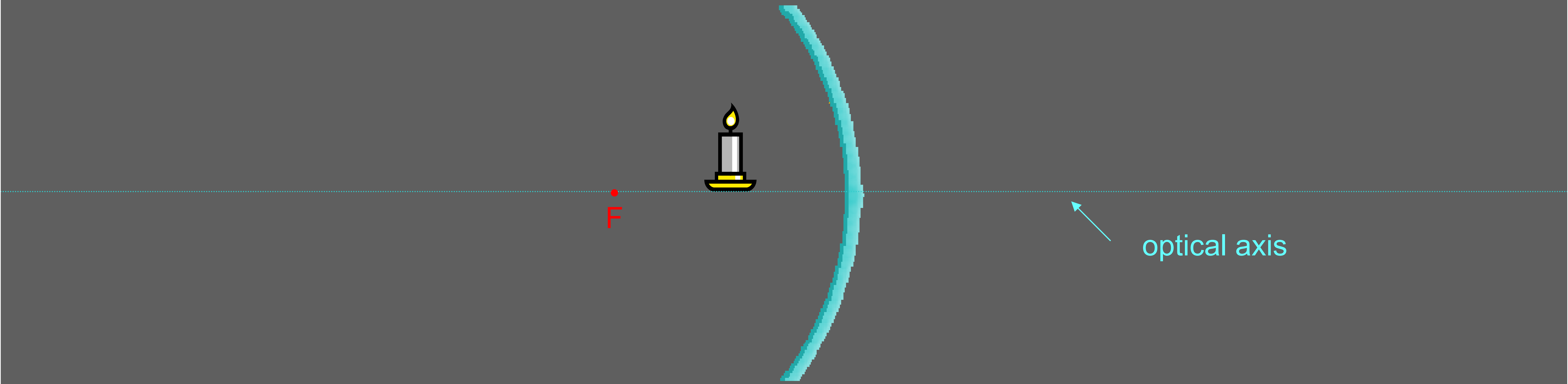
A real image forms where the light rays converge.

Concave Mirror

(example 2)

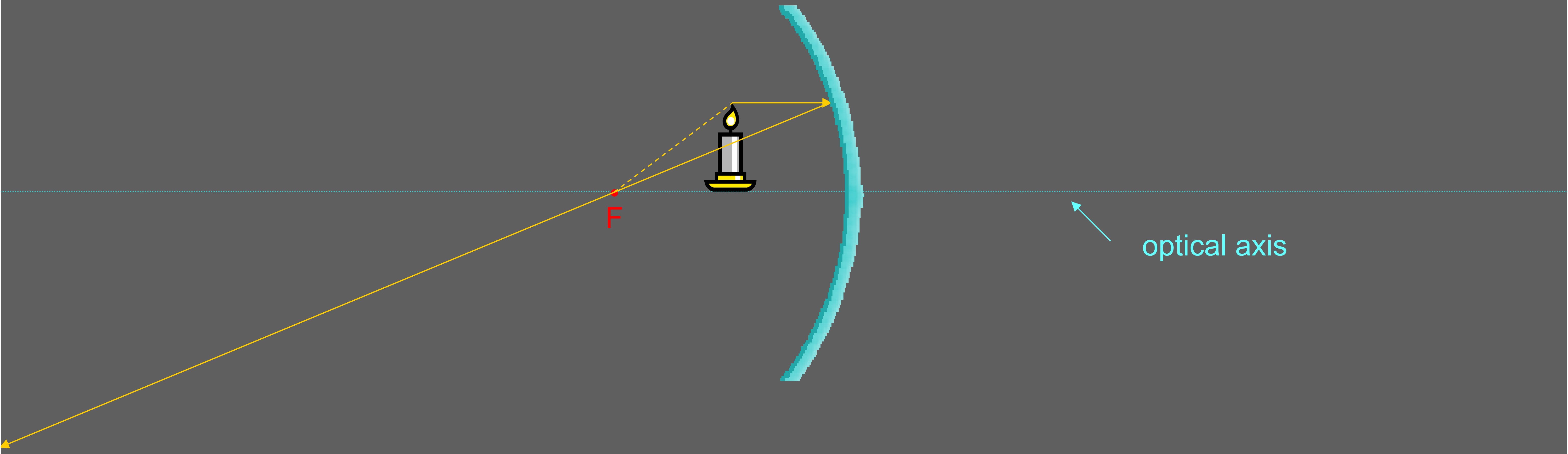


Concave Mirror
(example 2)



The first ray comes in parallel to the optical axis and reflects through the focal point.

Concave Mirror
(example 2)

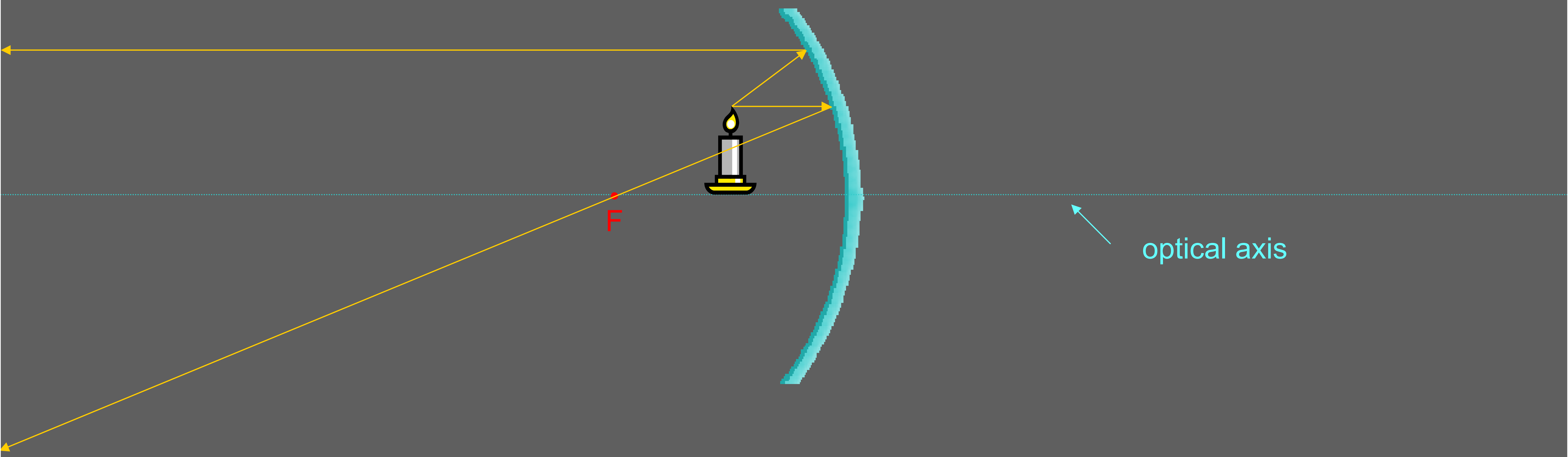


The first ray comes in parallel to the optical axis and reflects through the focal point.

The second ray comes through the focal point and reflects parallel to the optical axis.

Concave Mirror

(example 2)

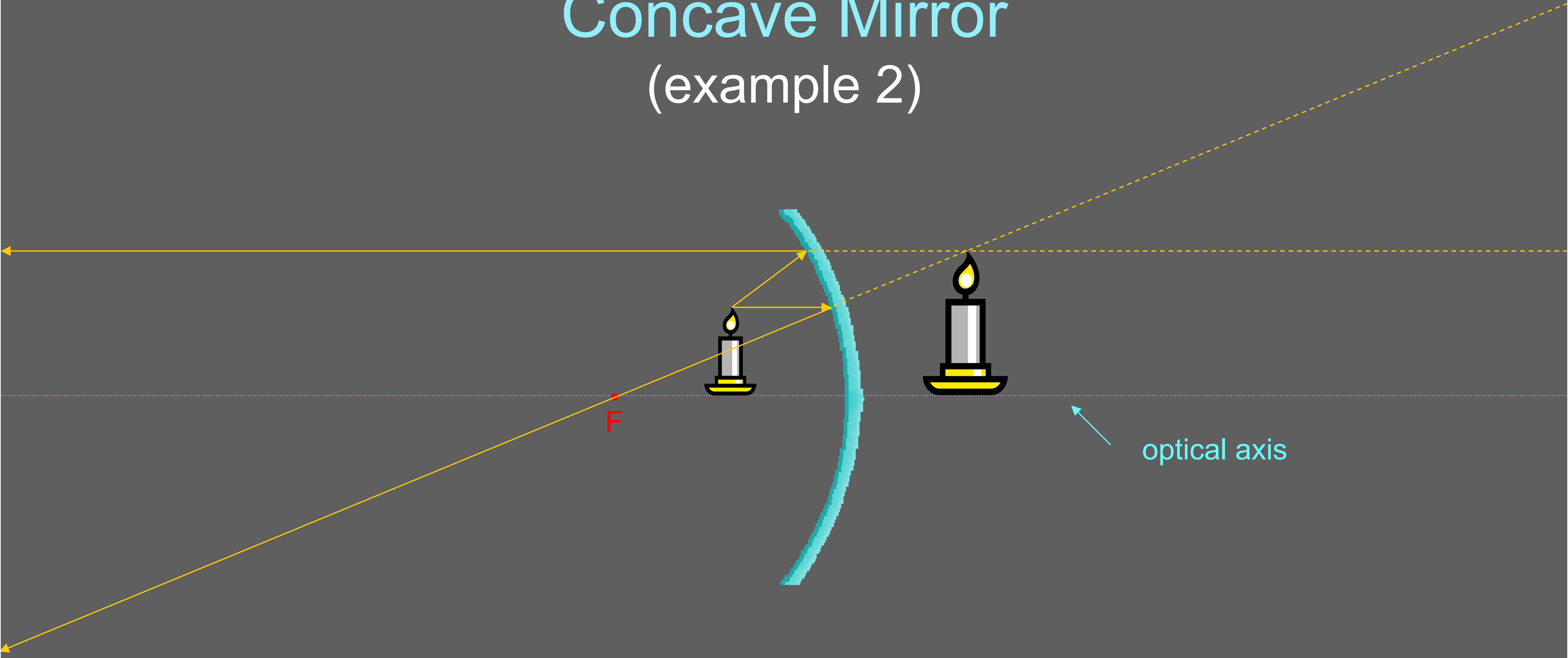


The first ray comes in parallel to the optical axis and reflects through the focal point.

The second ray comes through the focal point and reflects parallel to the optical axis.

The image forms where the rays converge. But they don't seem to converge.

Concave Mirror
(example 2)

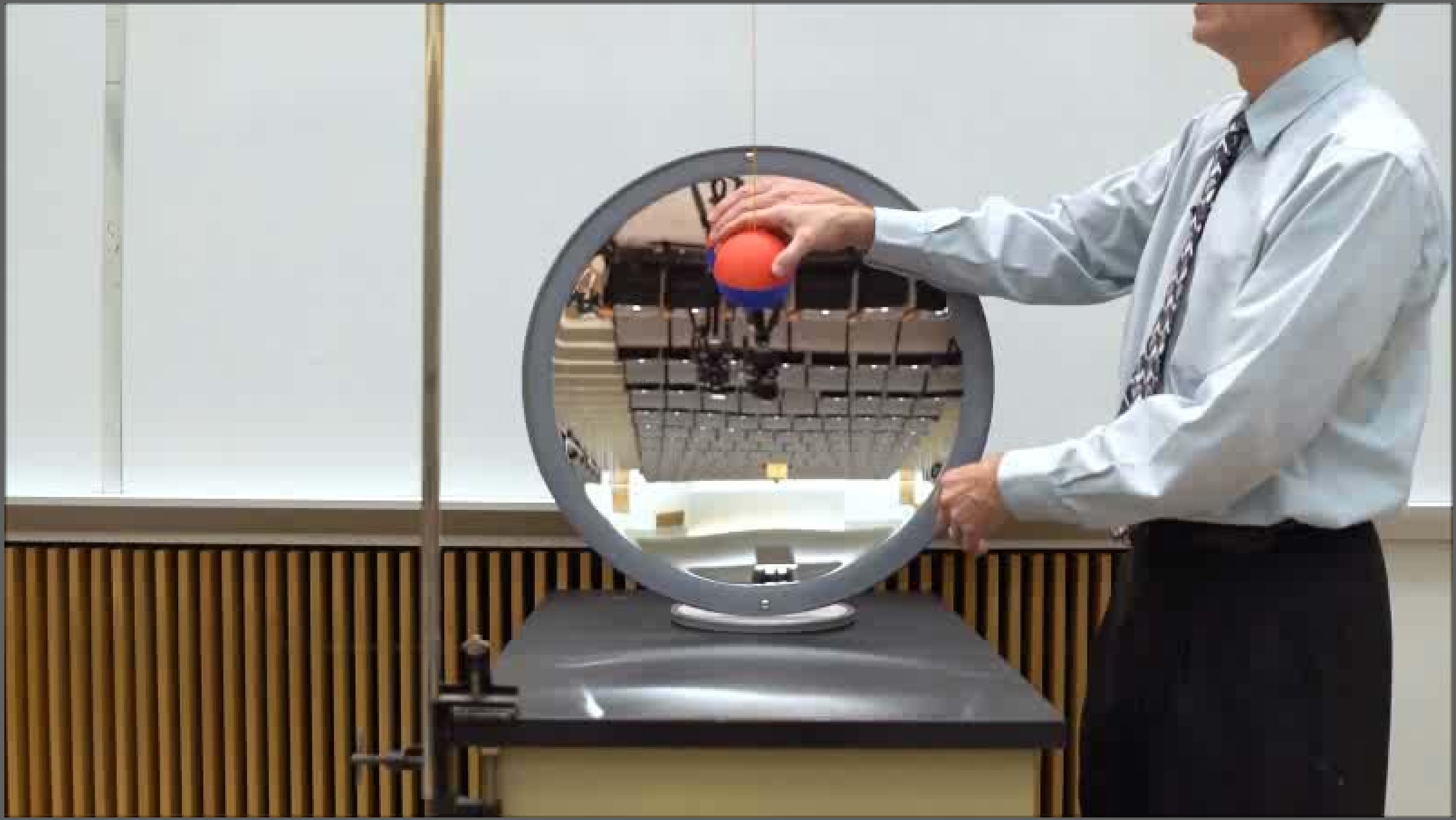


The first ray comes in parallel to the optical axis and reflects through the focal point.

The second ray comes through the focal point and reflects parallel to the optical axis.

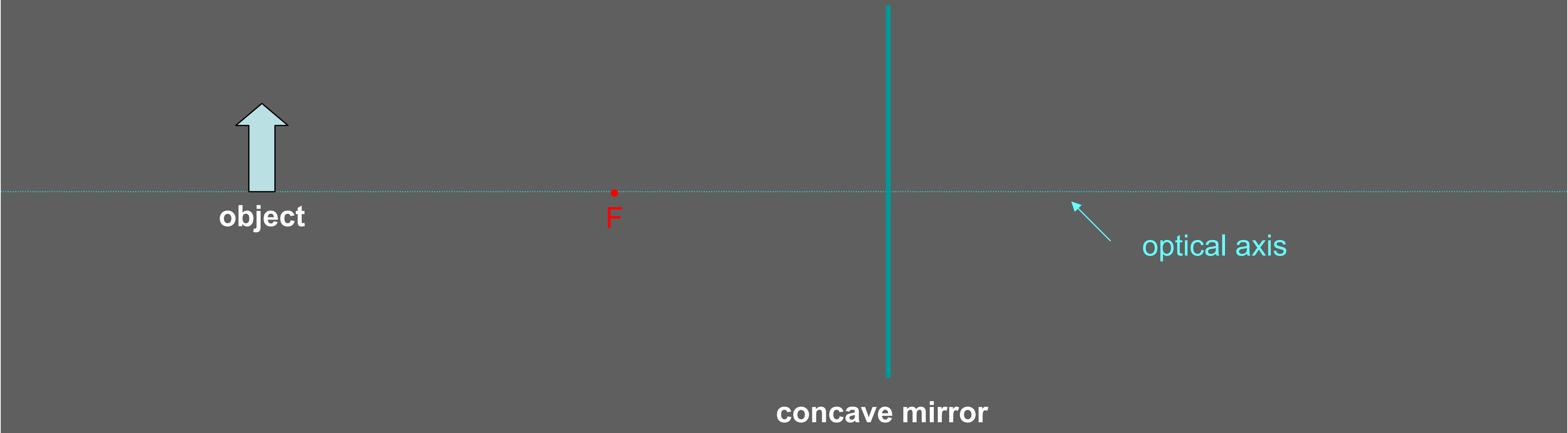
A virtual image forms where the *sight rays* converge.

Pendulum, concave mirror



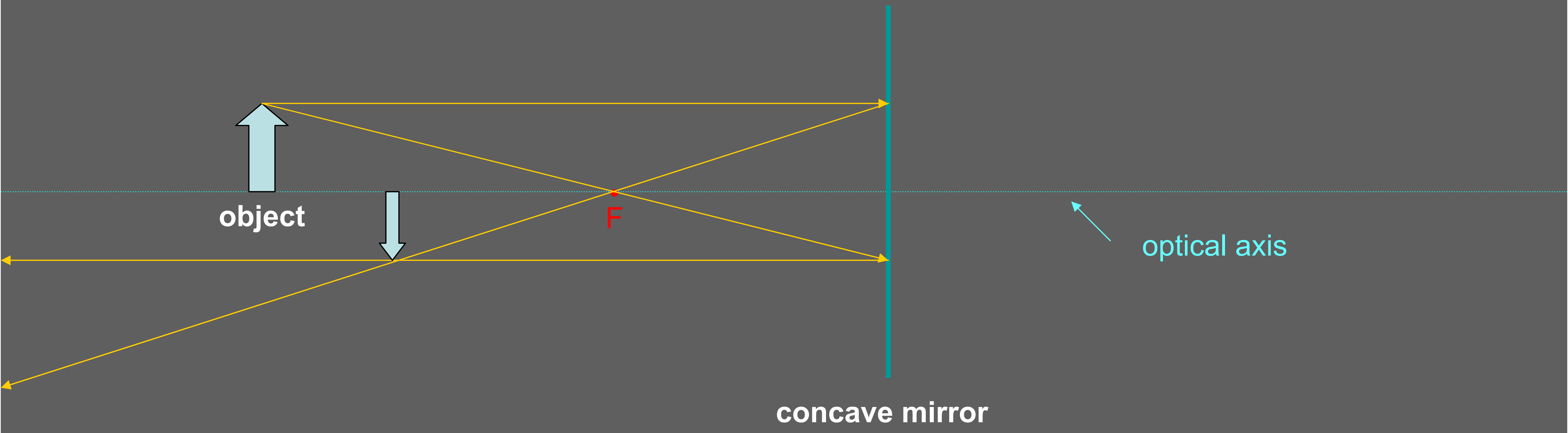
Video courtesy Boyd F. Edwards, USU

Your Turn
(Concave Mirror)



- Note: mirrors are thin enough that you just draw a line to represent the mirror
- **Locate the image of the arrow**

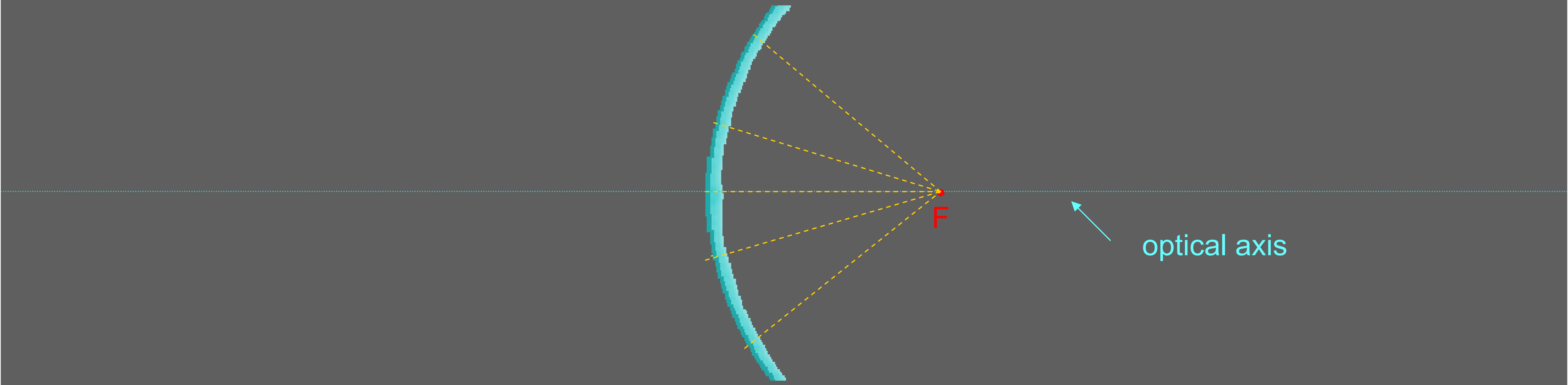
Your Turn
(Concave Mirror)



- Note: the mirrors and lenses we use are thin enough that you can just draw a line to represent the mirror or lens
- **Locate the image of the arrow**

Convex Mirrors

(curved out)

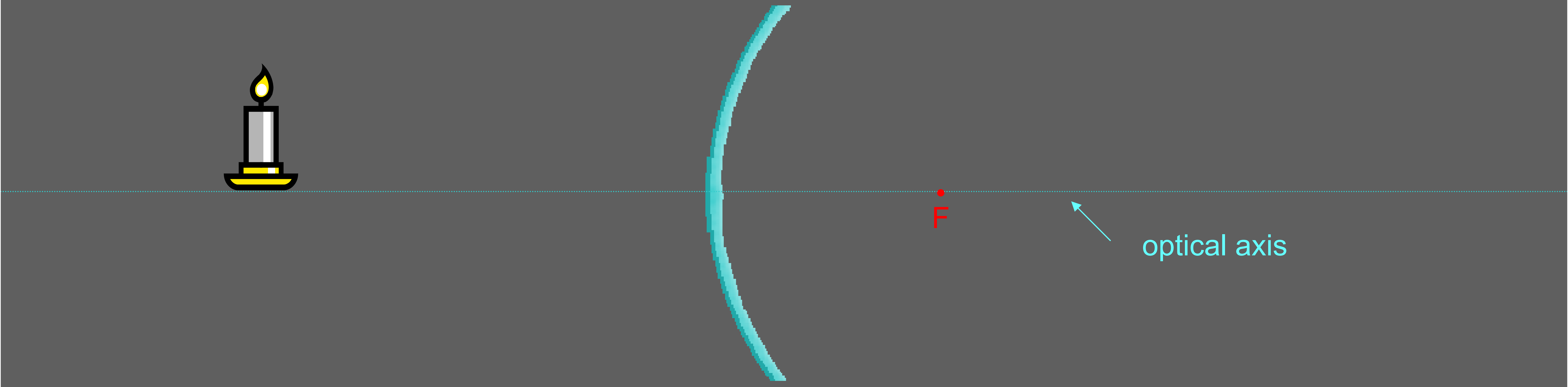


Light rays that come in parallel to the optical axis reflect from the focal point.

The focal point is considered virtual since *sight lines*, not light rays, go through it.

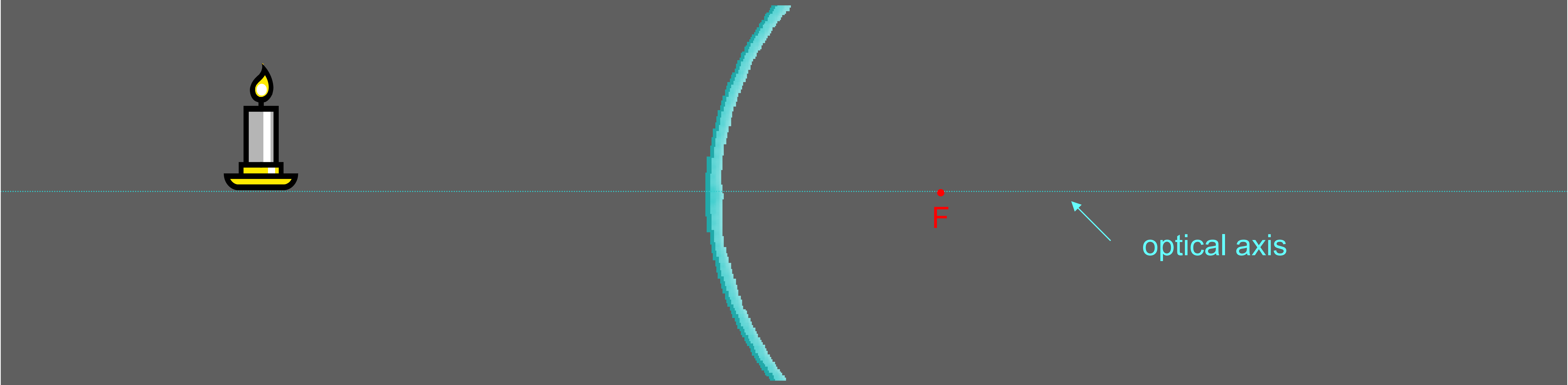
Convex Mirror

(example)



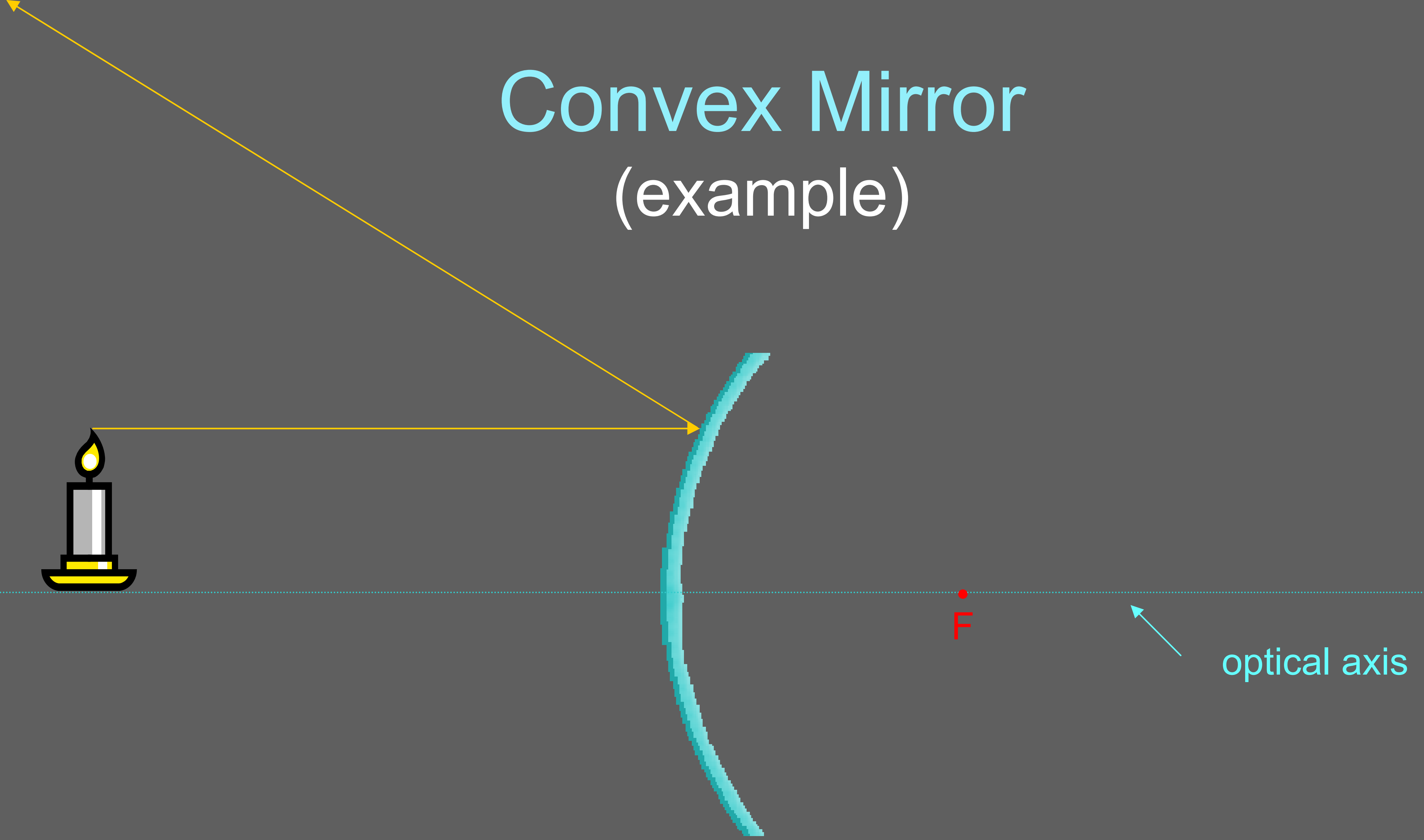
Convex Mirror

(example)



The first ray comes in parallel to the optical axis and reflects through the focal point.

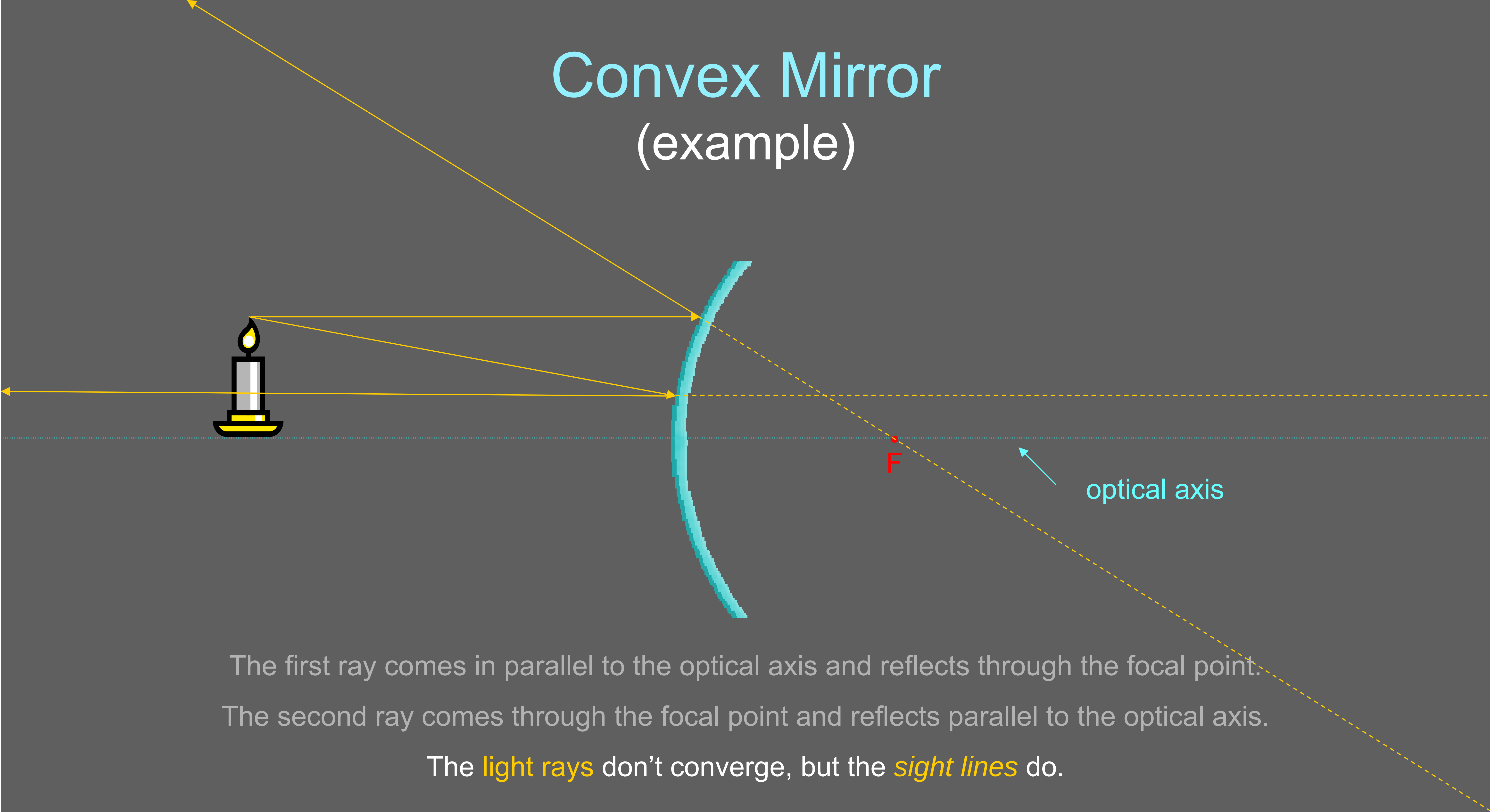
Convex Mirror
(example)



The first ray comes in parallel to the optical axis and reflects through the focal point.

The second ray comes through the focal point and reflects parallel to the optical axis.

Convex Mirror
(example)

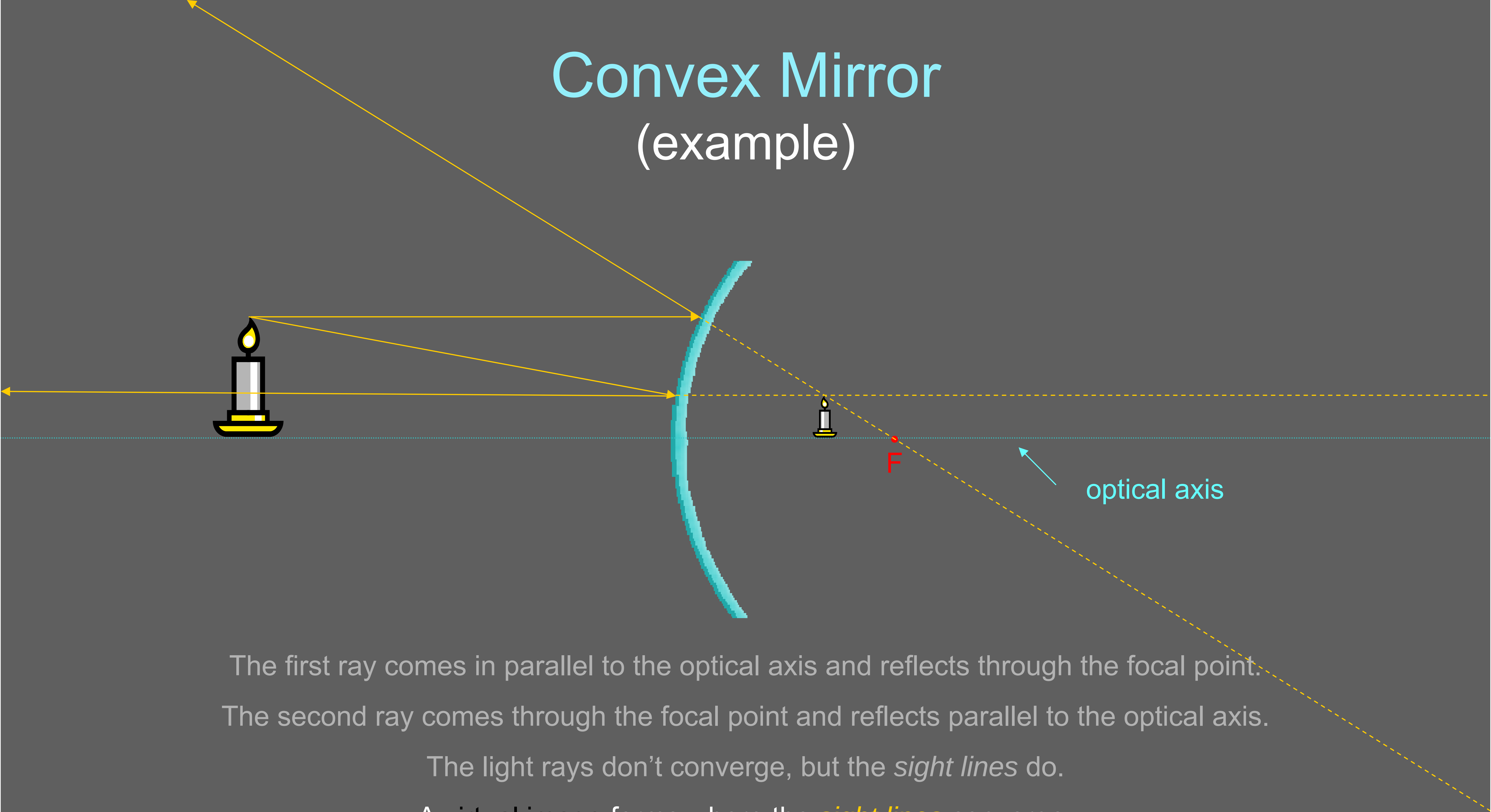


The first ray comes in parallel to the optical axis and reflects through the focal point.

The second ray comes through the focal point and reflects parallel to the optical axis.

The light rays don’t converge, but the *sight lines* do.

Convex Mirror
(example)



The first ray comes in parallel to the optical axis and reflects through the focal point.

The second ray comes through the focal point and reflects parallel to the optical axis.

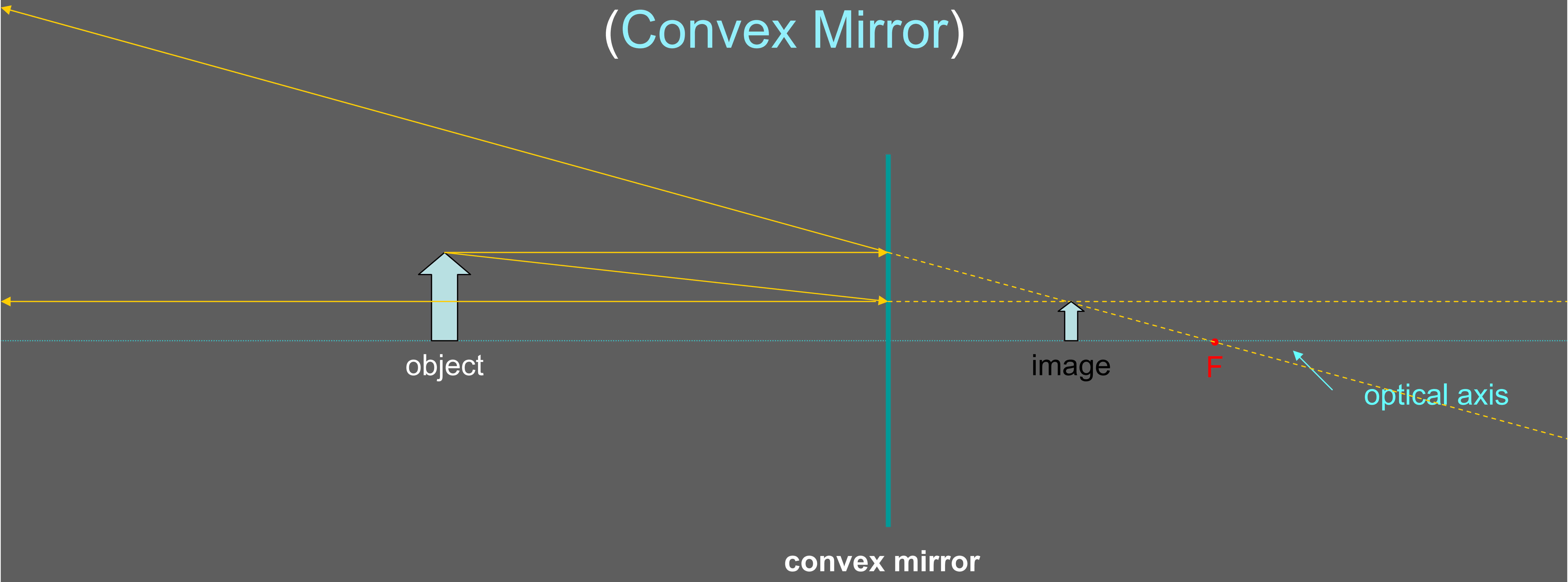
The light rays don't converge, but the *sight lines* do.

A virtual image forms where the *sight lines* converge.

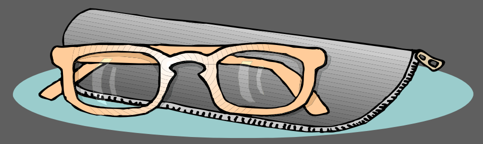
Your Turn
(Convex Mirror)

- Note: you just draw a line to represent thin mirrors
- **Locate the image of the arrow**

Your Turn
(Convex Mirror)



- Note: you just draw a line to represent thin mirrors
- **Locate the image of the arrow**



Lens & Mirror Equation

$$\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$$

f = focal length
d_o = object distance
d_i = image distance

f is negative for diverging mirrors and lenses
d_i is negative when the image is behind the lens or mirror

Magnification Equation

$$m = \frac{h_i}{h_o} = \frac{-d_i}{d_o}$$

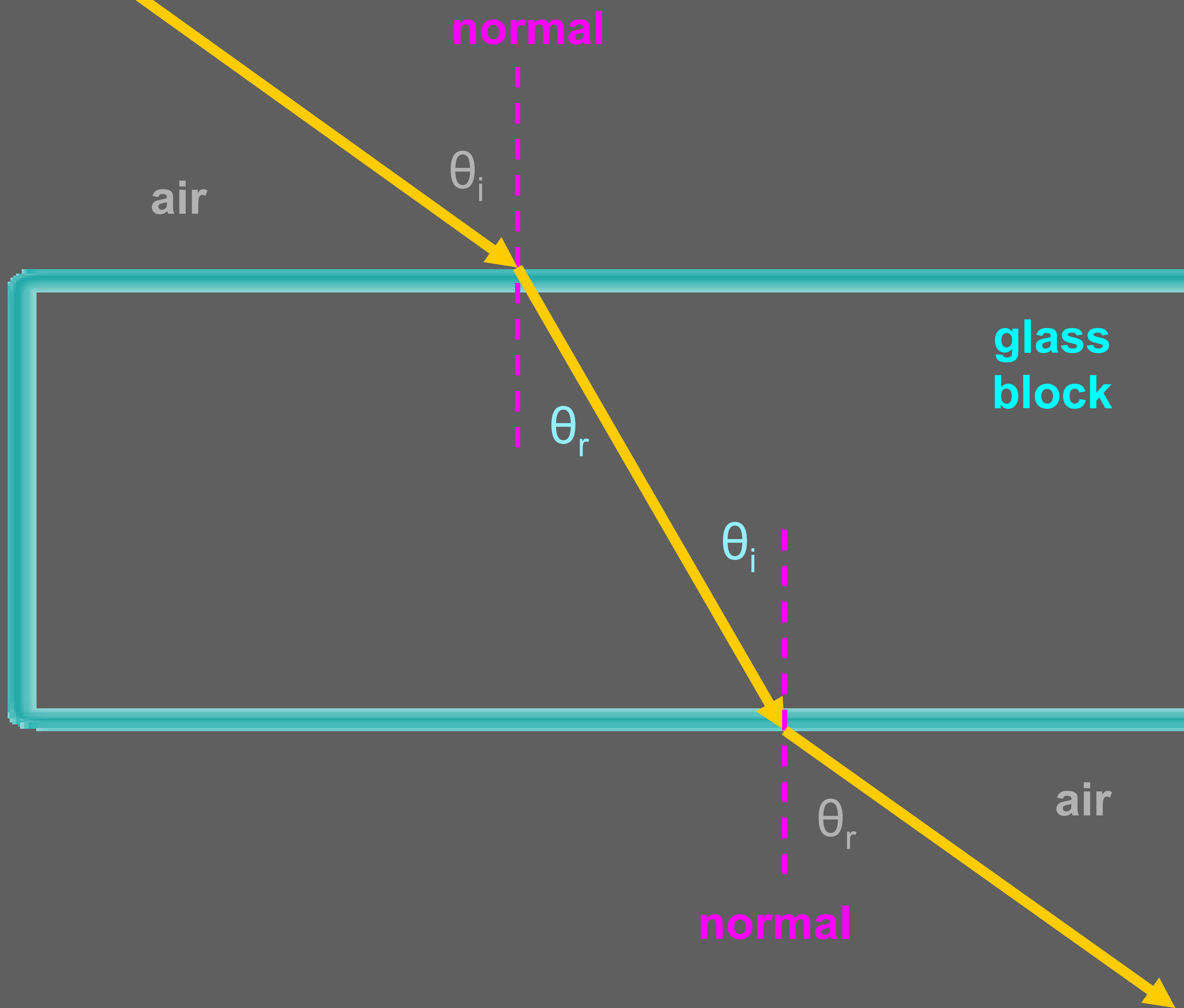
m = magnification
h_i = image height
h_o = object height

If height is negative the image is upside down

if the magnification is negative
the image is inverted (upside down)

Refraction
(bending light)

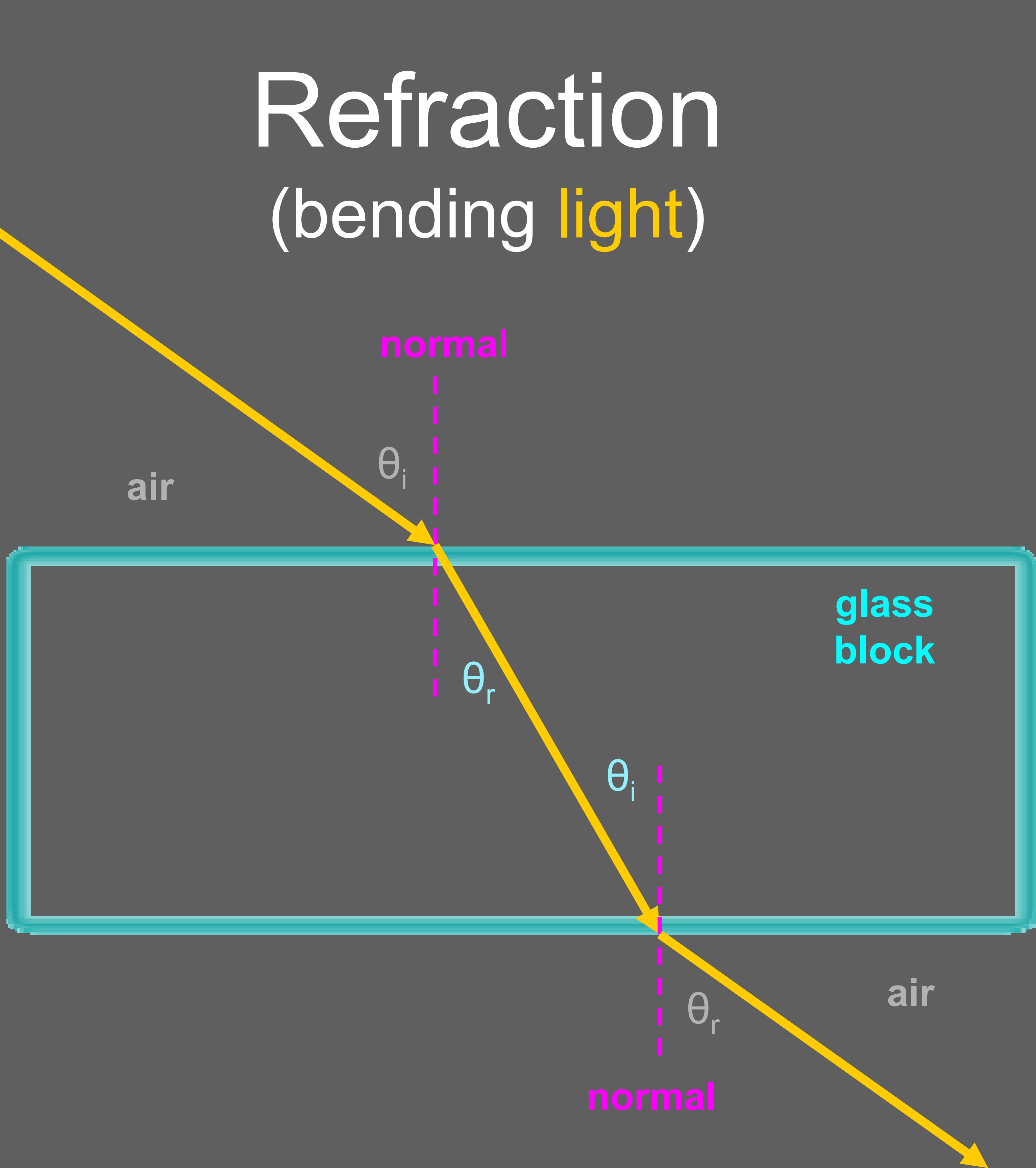
Refraction is when light **bends** as it passes from one medium into another.



Refraction
(bending light)

Refraction is when light **bends** as it passes from one medium into another.

When light traveling through air passes into the glass block it is **refracted** towards the normal.

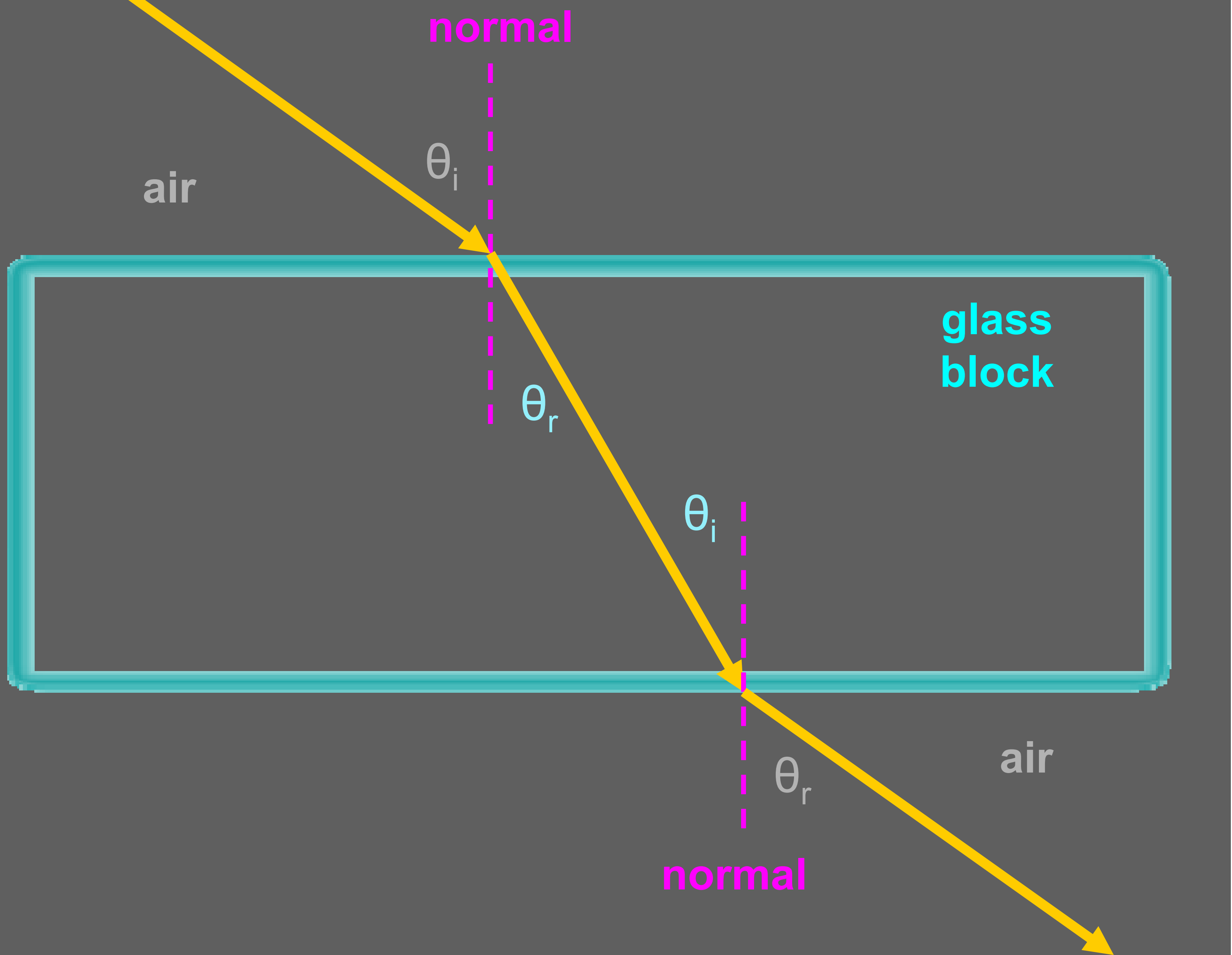


Refraction
(bending light)

Refraction is when light **bends** as it passes from one medium into another.

When light traveling through air passes into the glass block it is **refracted** towards the normal.

When light passes back out of the glass into the air, it is **refracted** away from the normal.



Refraction

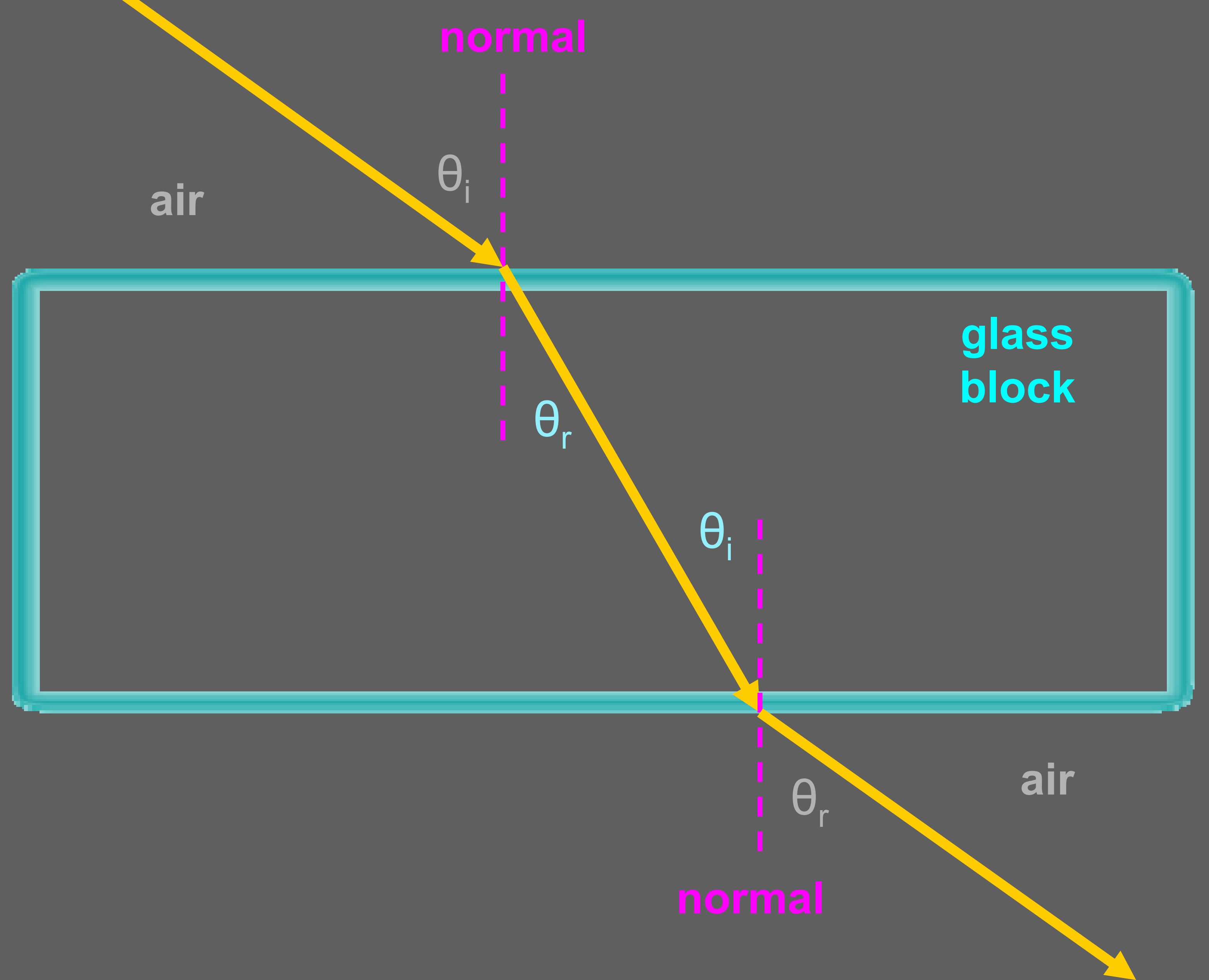
(bending light)

Refraction is when light **bends** as it passes from one medium into another.

When light traveling through air passes into the glass block it is **refracted** towards the normal.

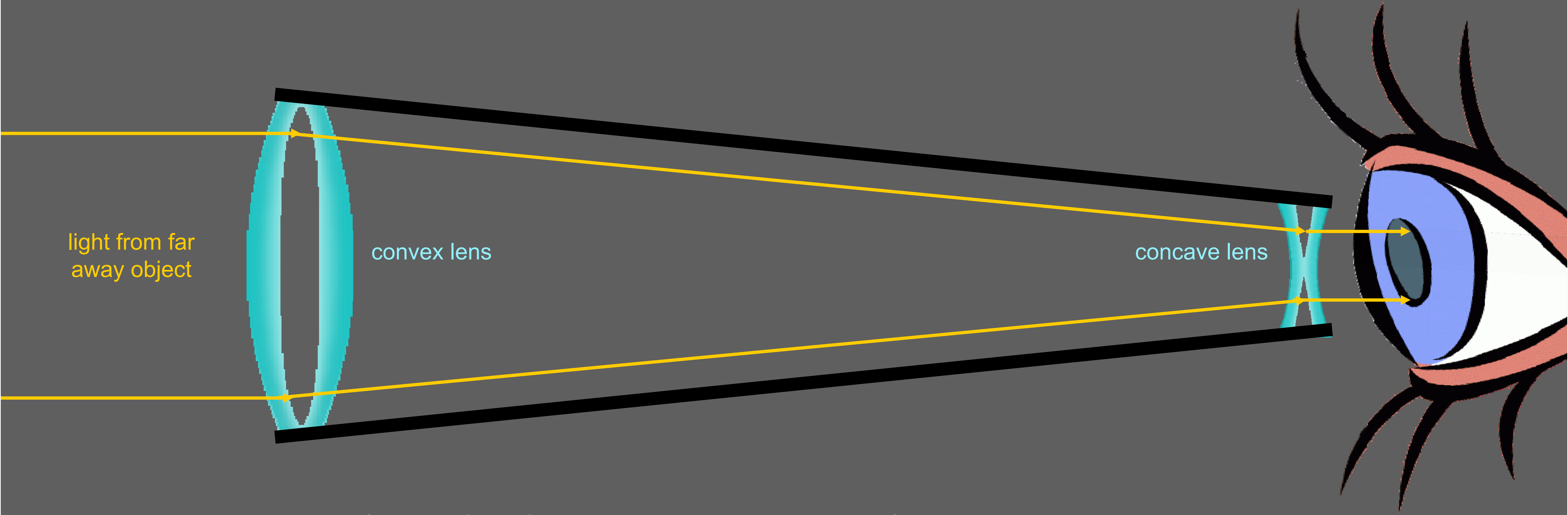
When light passes back out of the glass into the air, it is **refracted** away from the normal.

Since light **refracts** when it changes mediums it can be aimed. Lenses are shaped so light is aimed at a focal point.



Lenses

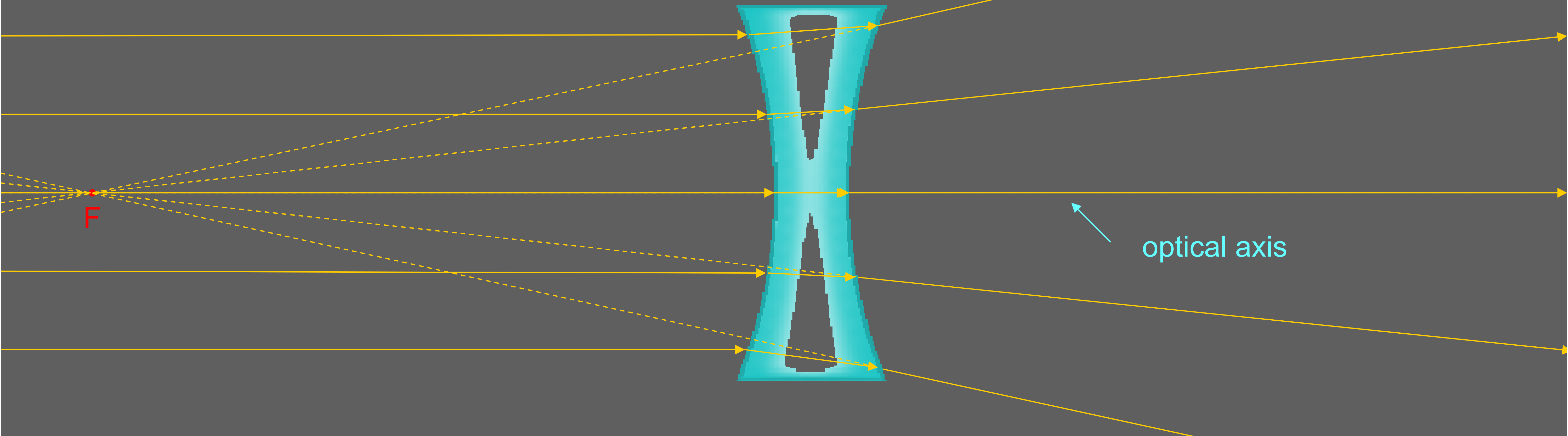
The first telescope, designed and built by Galileo, used lenses to focus light from faraway objects, into Galileo's eye. His telescope consisted of a concave lens and a convex lens.



Light rays are always refracted (bent) towards the thickest part of the lens.

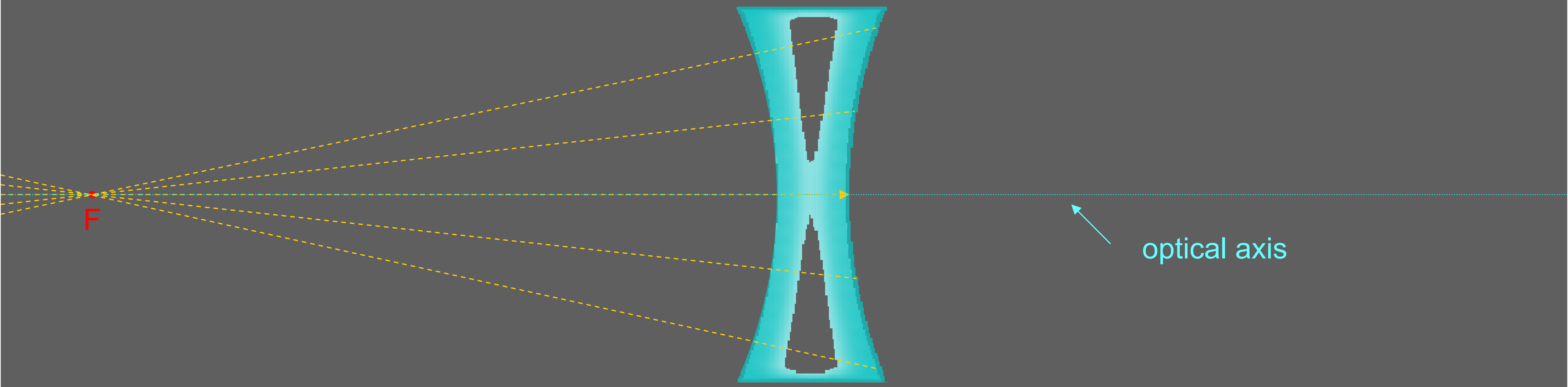
Concave Lenses

Concave lenses are thin in the middle and make light rays diverge (spread out).



If the rays of light are traced back (*dotted sight lines*), they all intersect at the focal point (F) behind the lens.

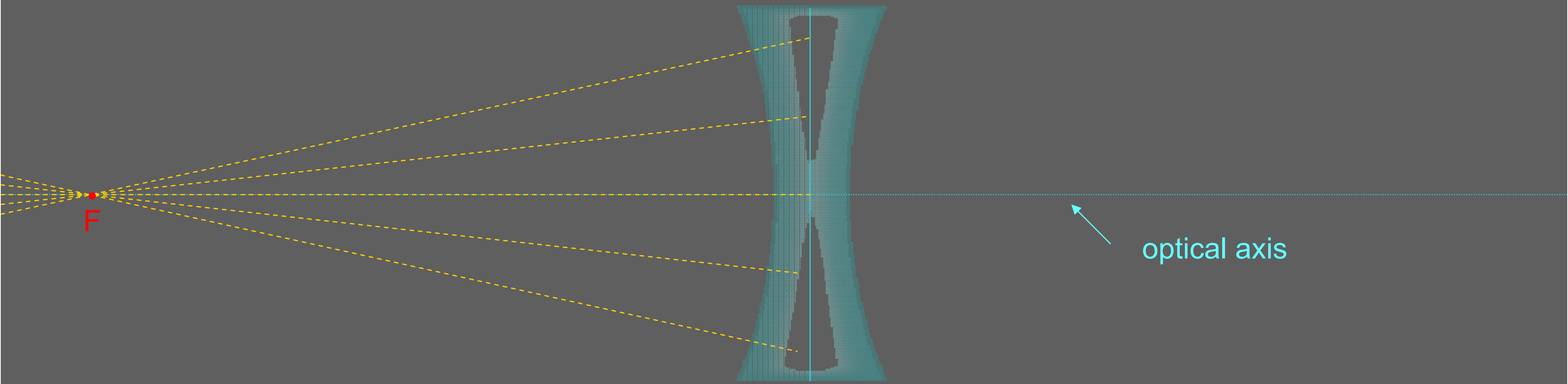
Concave Lenses



Light rays that come in parallel to the optical axis diverge from the focal point.

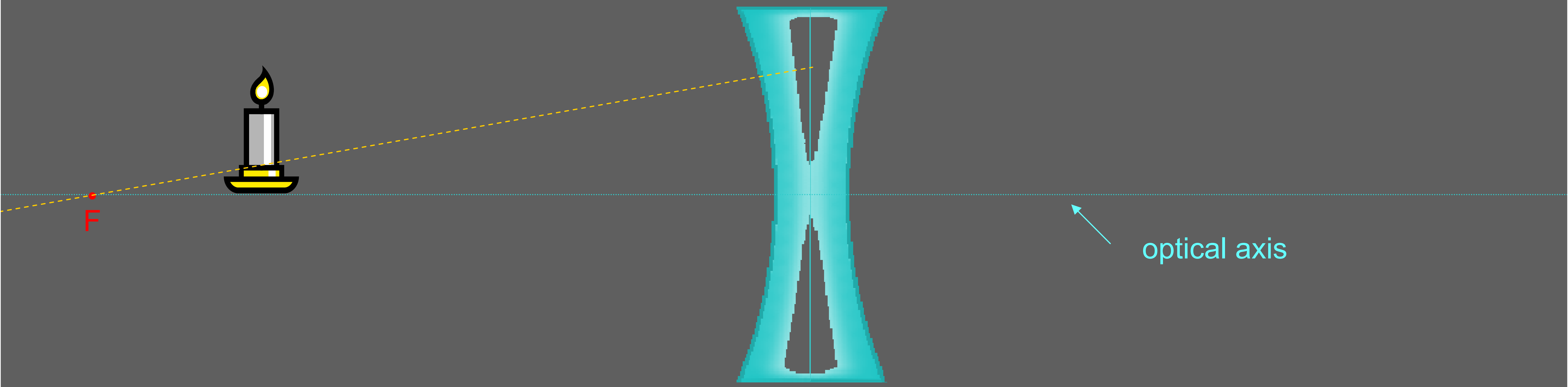
The light rays behave the same way if we ignore the thickness of the lens.

Concave Lenses



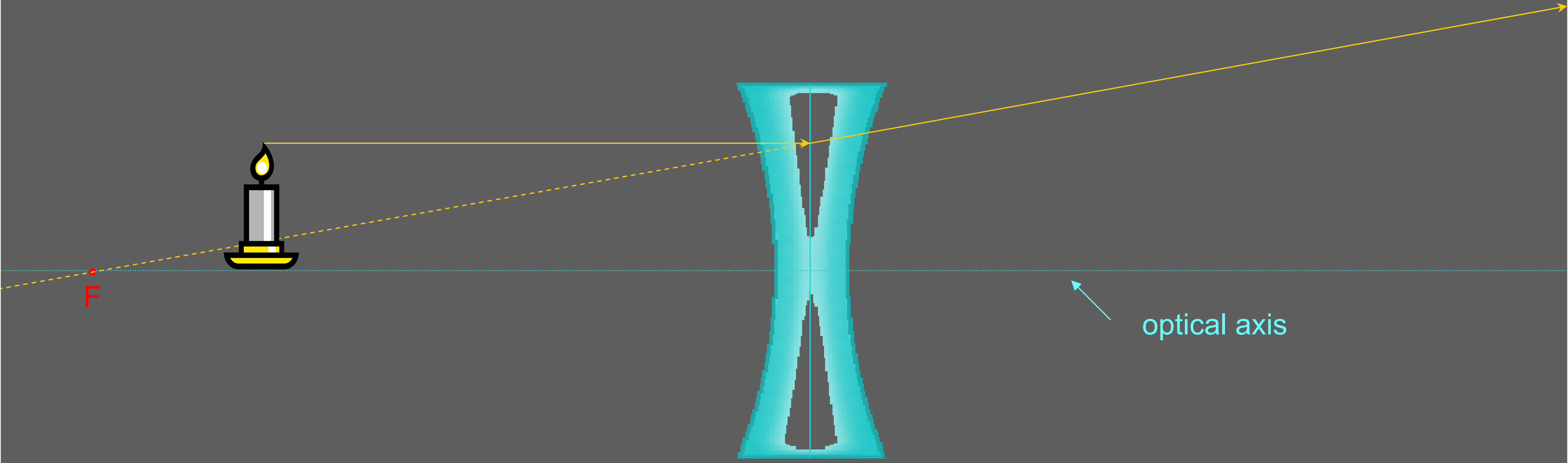
Light rays that come in parallel to the optical axis still diverge from the focal point.

Concave Lens
(example)



The first ray comes in parallel to the optical axis and refracts from the focal point.

Concave Lens
(example)

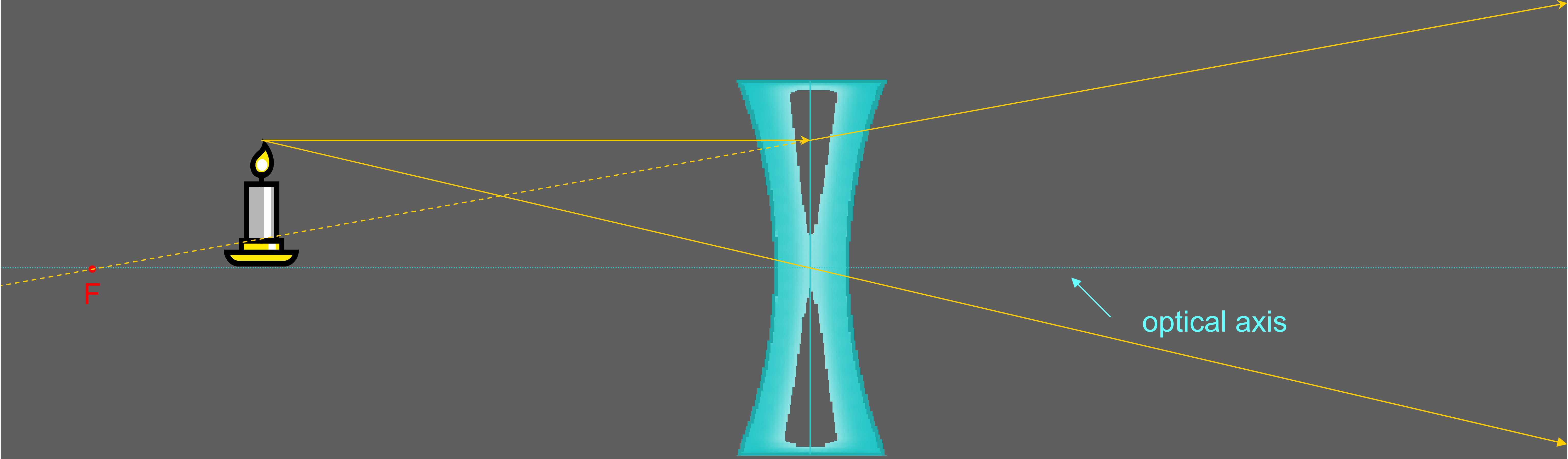


The first ray comes in parallel to the optical axis and refracts from the focal point.

The second ray goes straight through the center of the lens.

Concave Lens

(example)



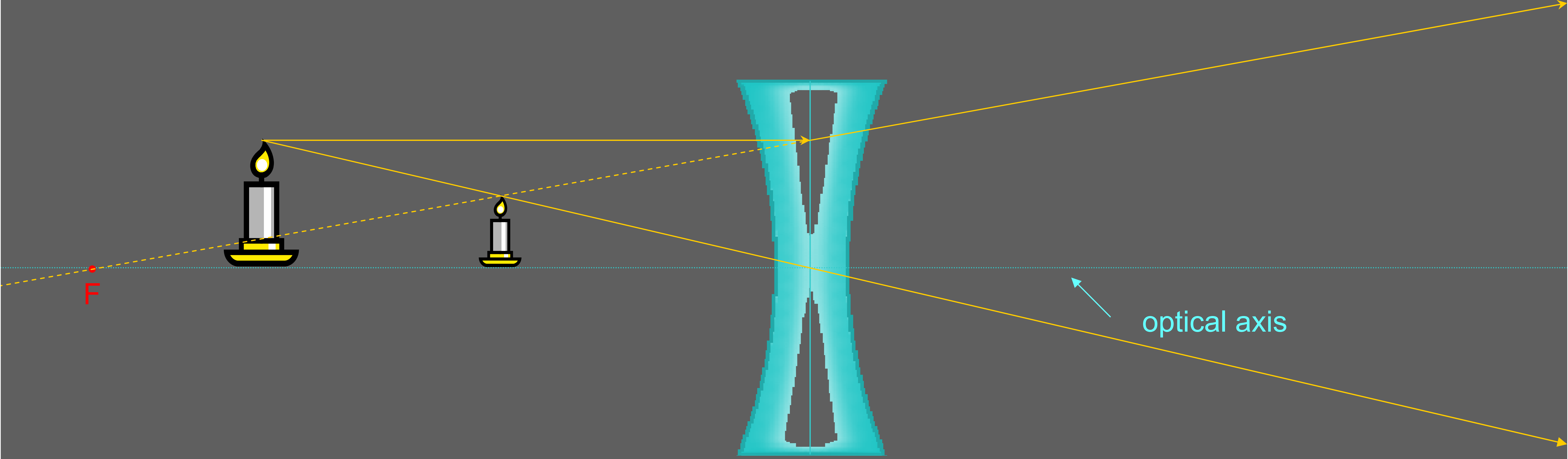
The first ray comes in parallel to the optical axis and refracts from the focal point.

The second ray goes straight through the center of the lens.

The light rays don't converge, but the *sight lines* do.

Concave Lens

(example)



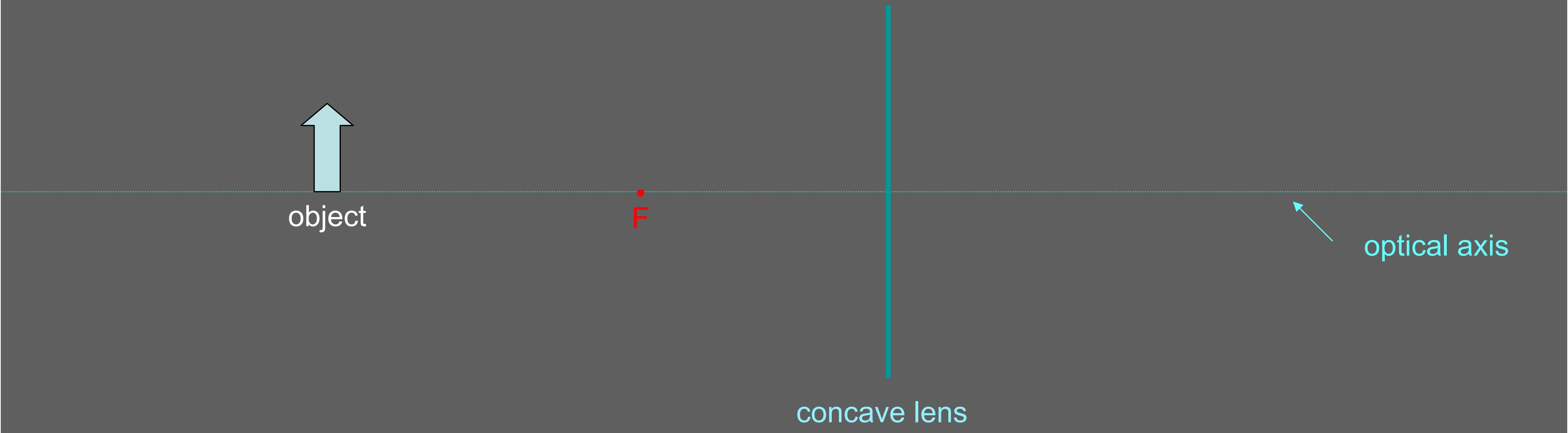
The first ray comes in parallel to the optical axis and refracts from the focal point.

The second ray goes straight through the center of the lens.

The light rays don't converge, but the *sight lines* do.

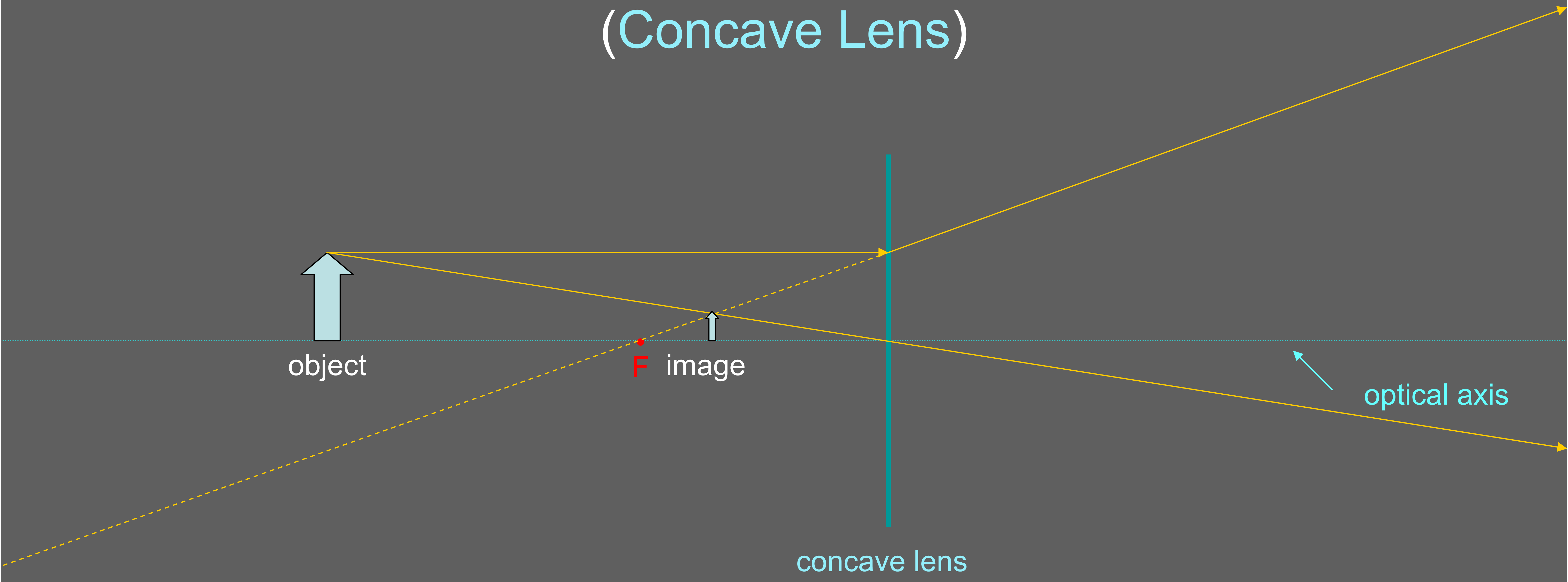
A virtual image forms where the *sight lines* converge.

Your Turn
(Concave Lens)



- Note: lenses are thin enough that you just draw a line to represent the lens.
- **Locate the image of the arrow.**

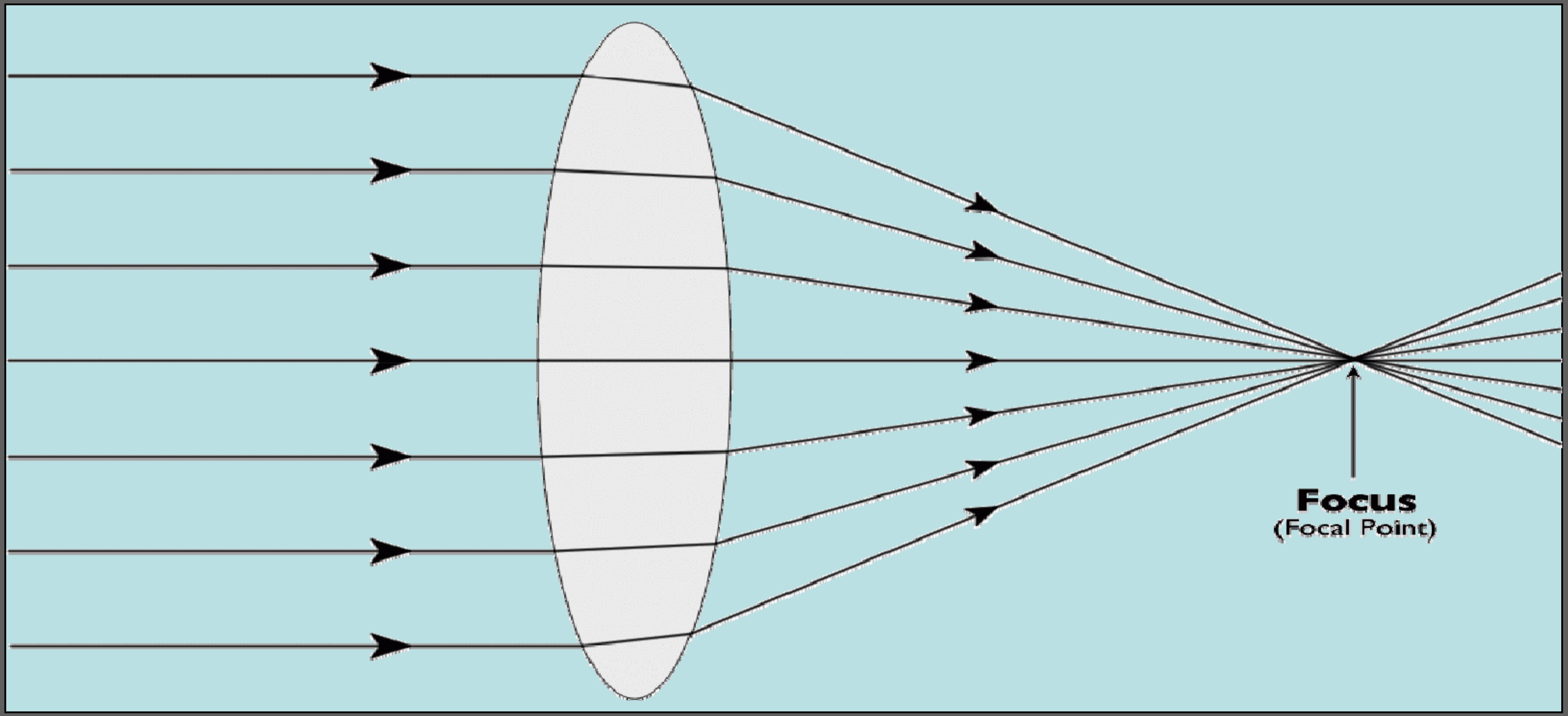
Your Turn
(Concave Lens)



- Note: lenses are thin enough that you just draw a line to represent the lens.
- **Locate the image of the arrow.**

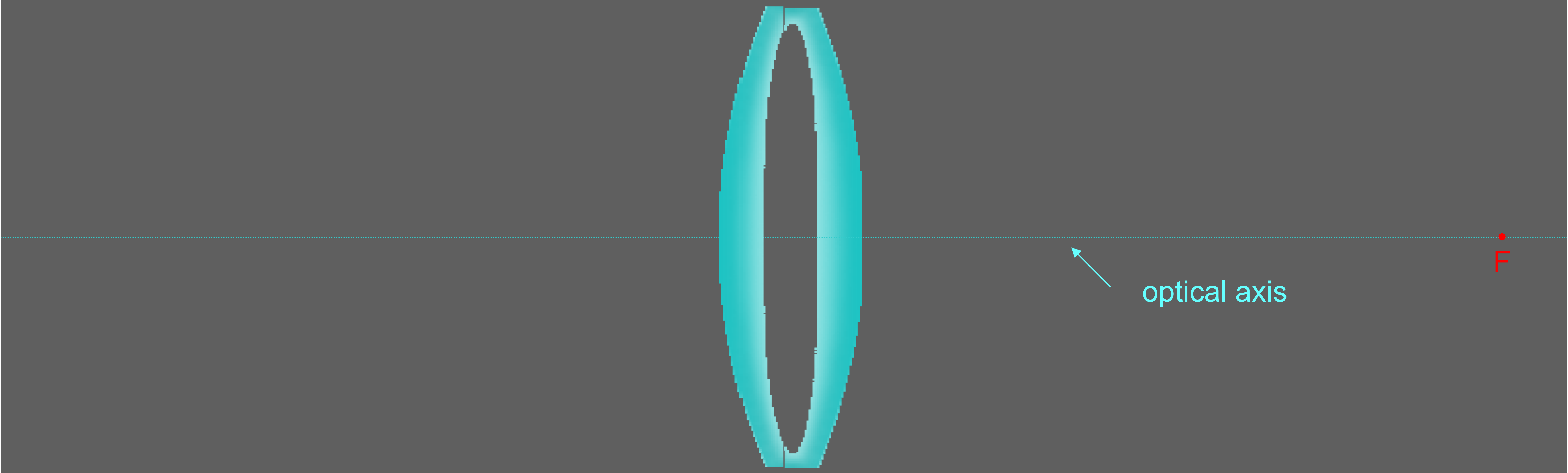
Convex Lenses

Convex lenses are thicker in the middle and focus light rays to a focal point in front of the lens.

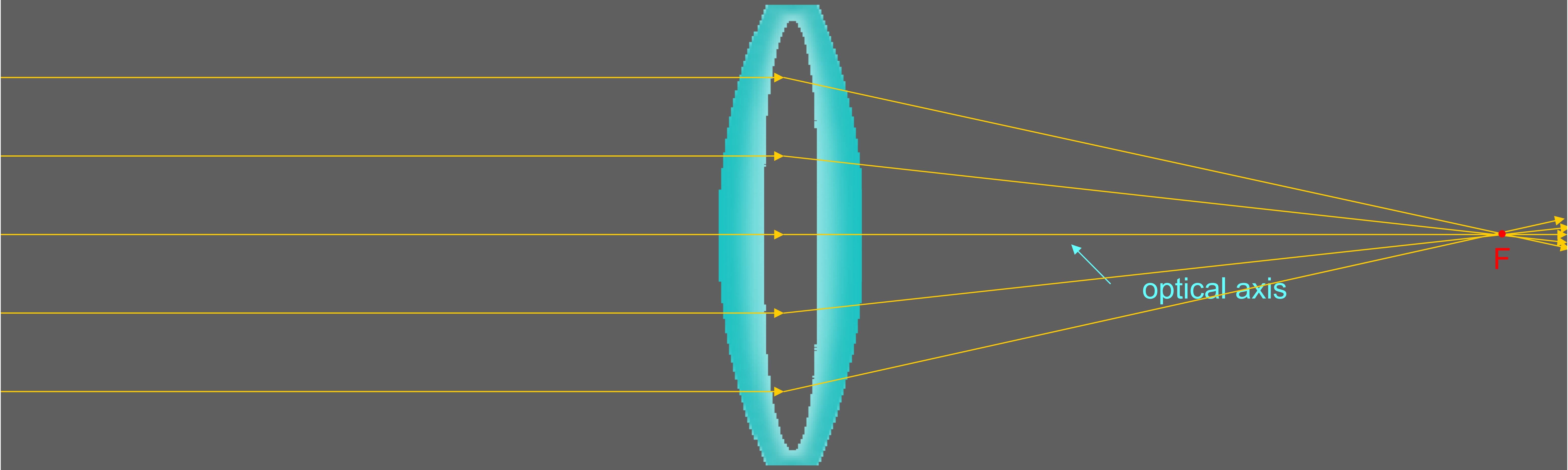


The focal length of the lens is the distance between the center of the lens and the point where the light rays are focused.

Convex Lenses



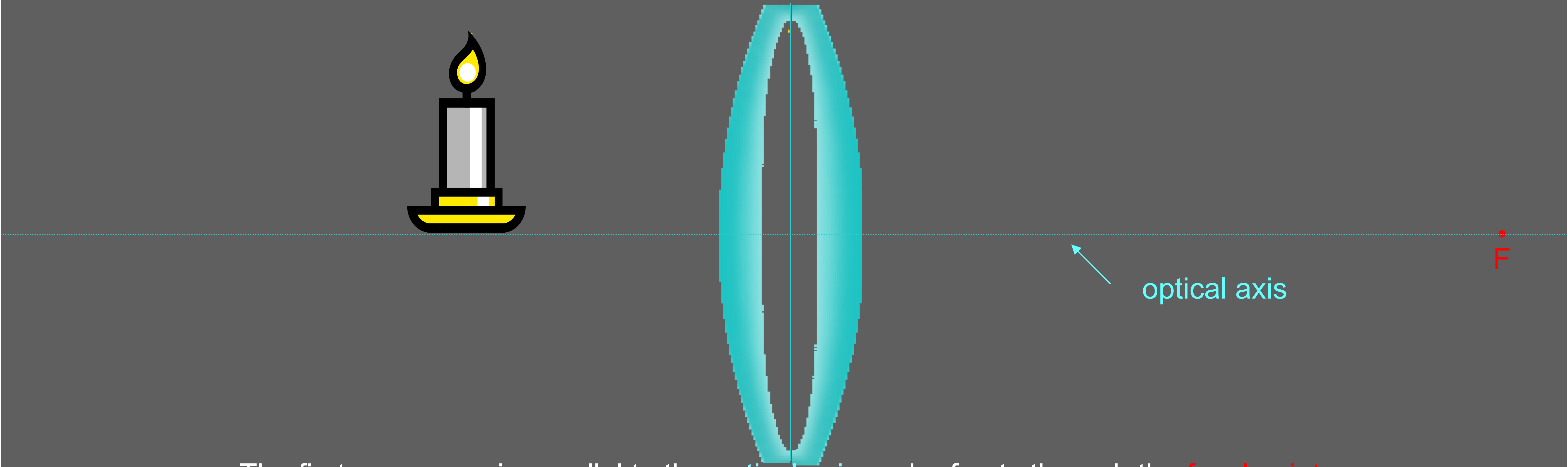
Convex Lenses



Light rays that come in parallel to the optical axis converge at the focal point.

Convex Lens

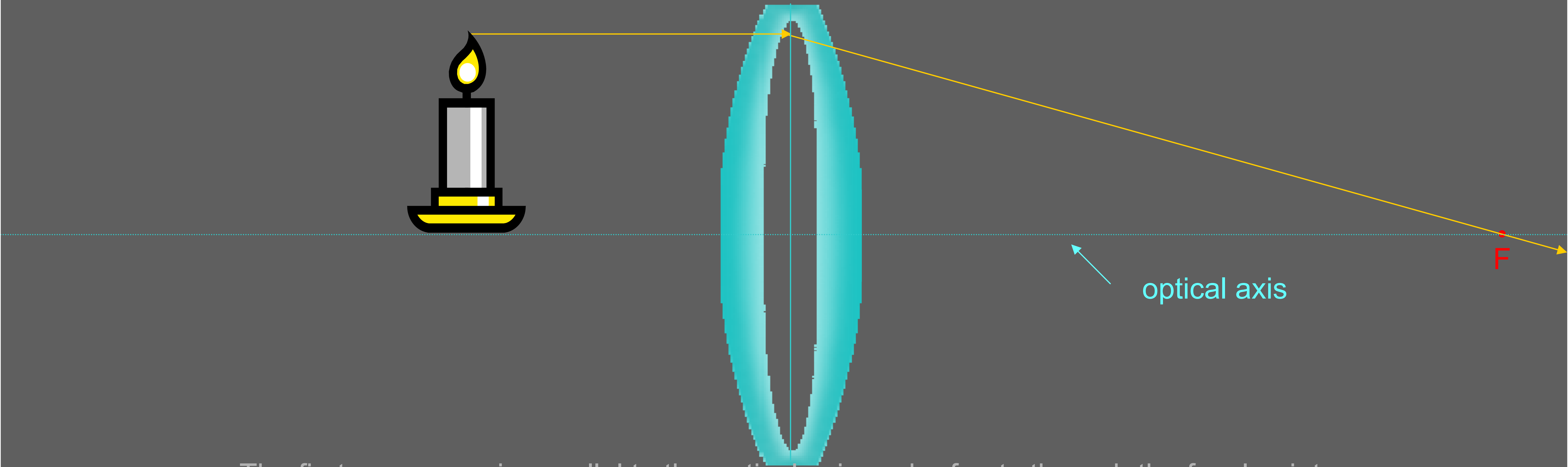
(example)



The first ray comes in parallel to the optical axis and refracts through the focal point.

Convex Lens

(example)

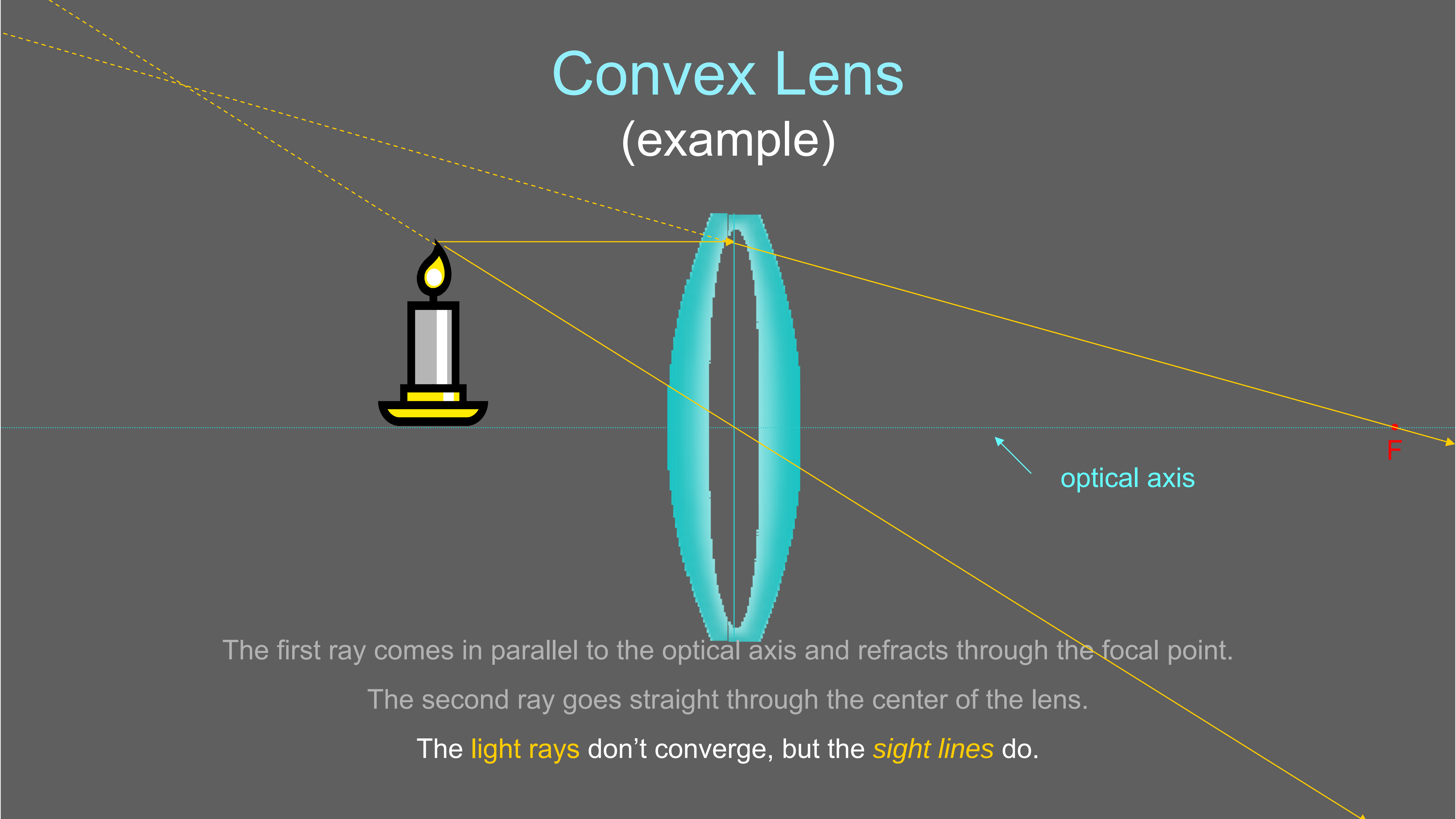


The first ray comes in parallel to the optical axis and refracts through the focal point.

The second ray goes straight through the center of the lens.

Convex Lens

(example)

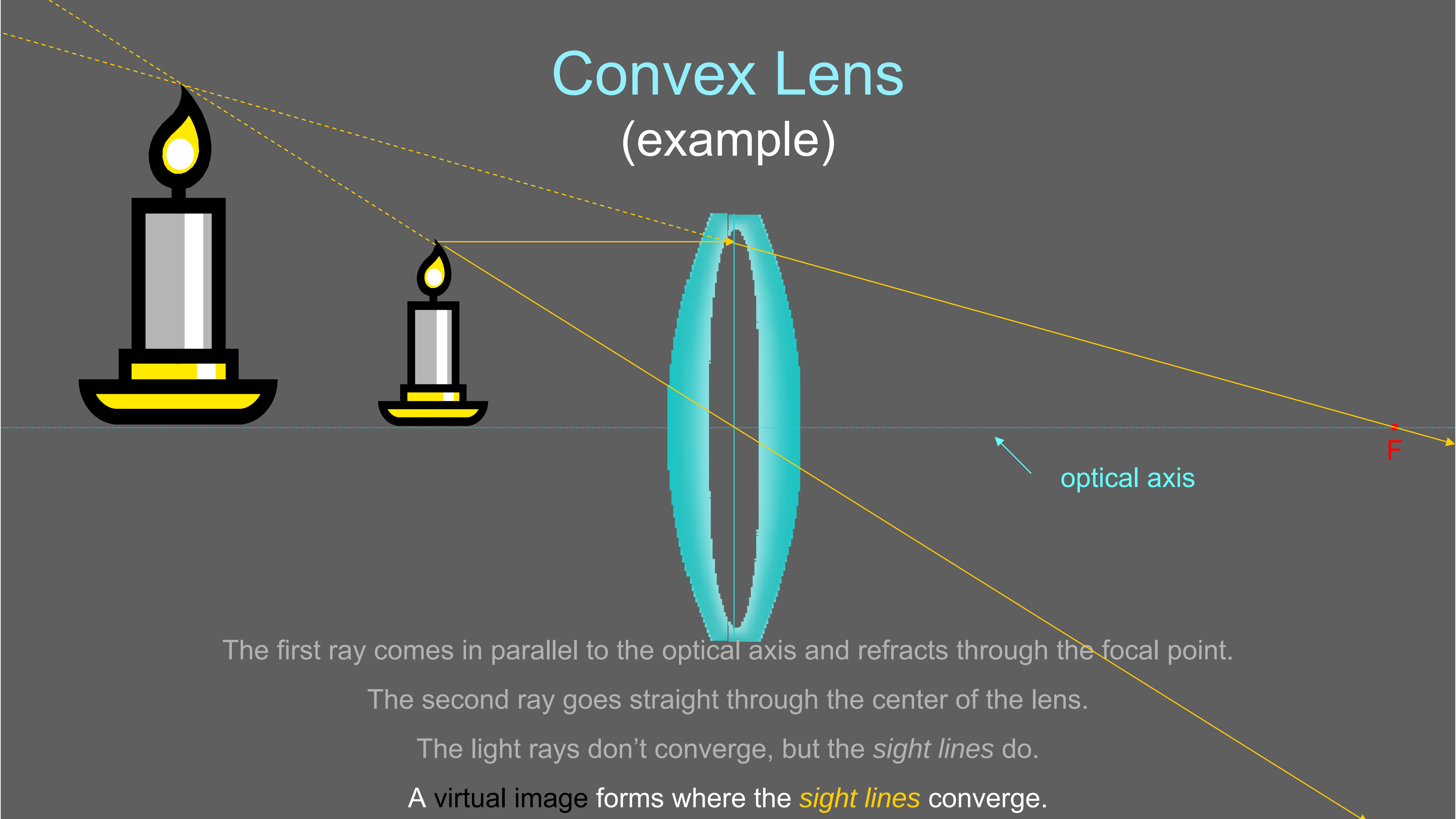


The first ray comes in parallel to the optical axis and refracts through the focal point.

The second ray goes straight through the center of the lens.

The light rays don’t converge, but the *sight lines* do.

Convex Lens
(example)



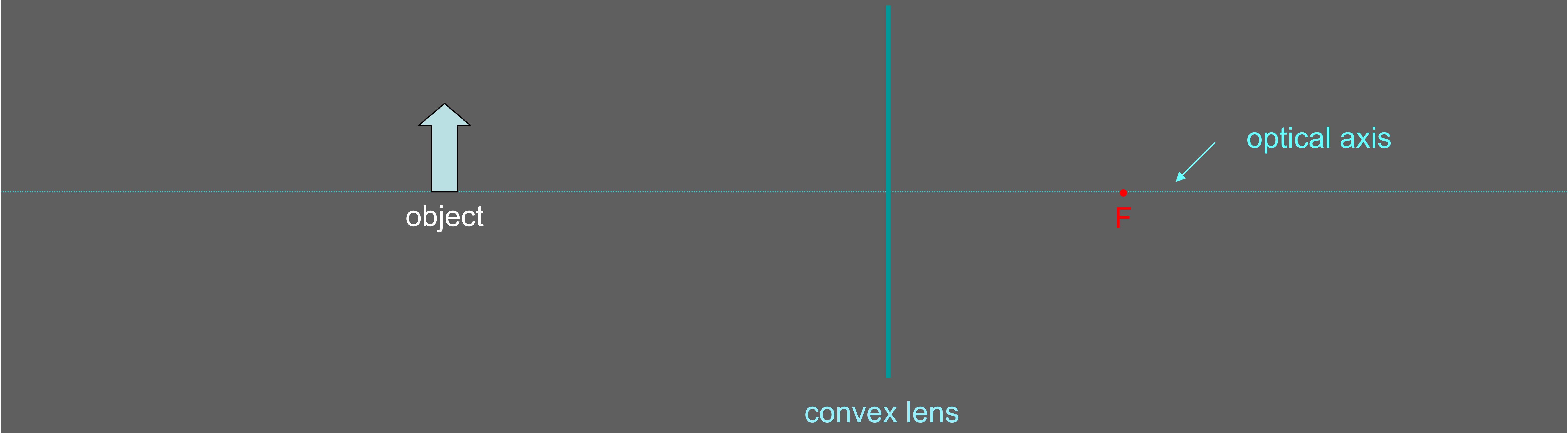
The first ray comes in parallel to the optical axis and refracts through the focal point.

The second ray goes straight through the center of the lens.

The light rays don't converge, but the *sight lines* do.

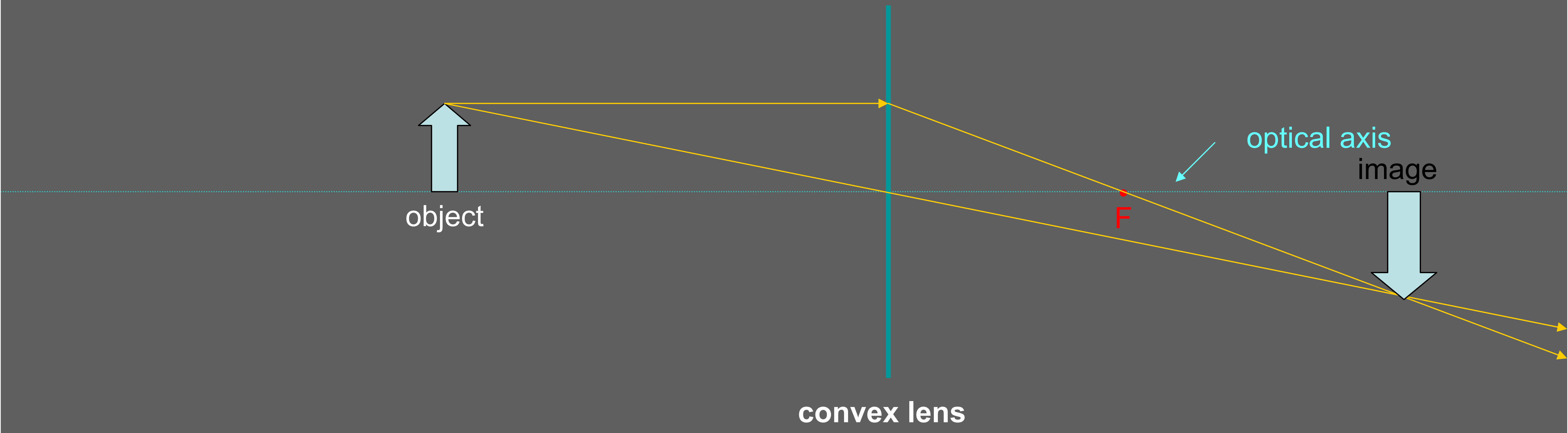
A virtual image forms where the *sight lines* converge.

Your Turn
(Convex Lens)



- Note: lenses are thin enough that you just draw a line to represent the lens.
- **Locate the image of the arrow.**

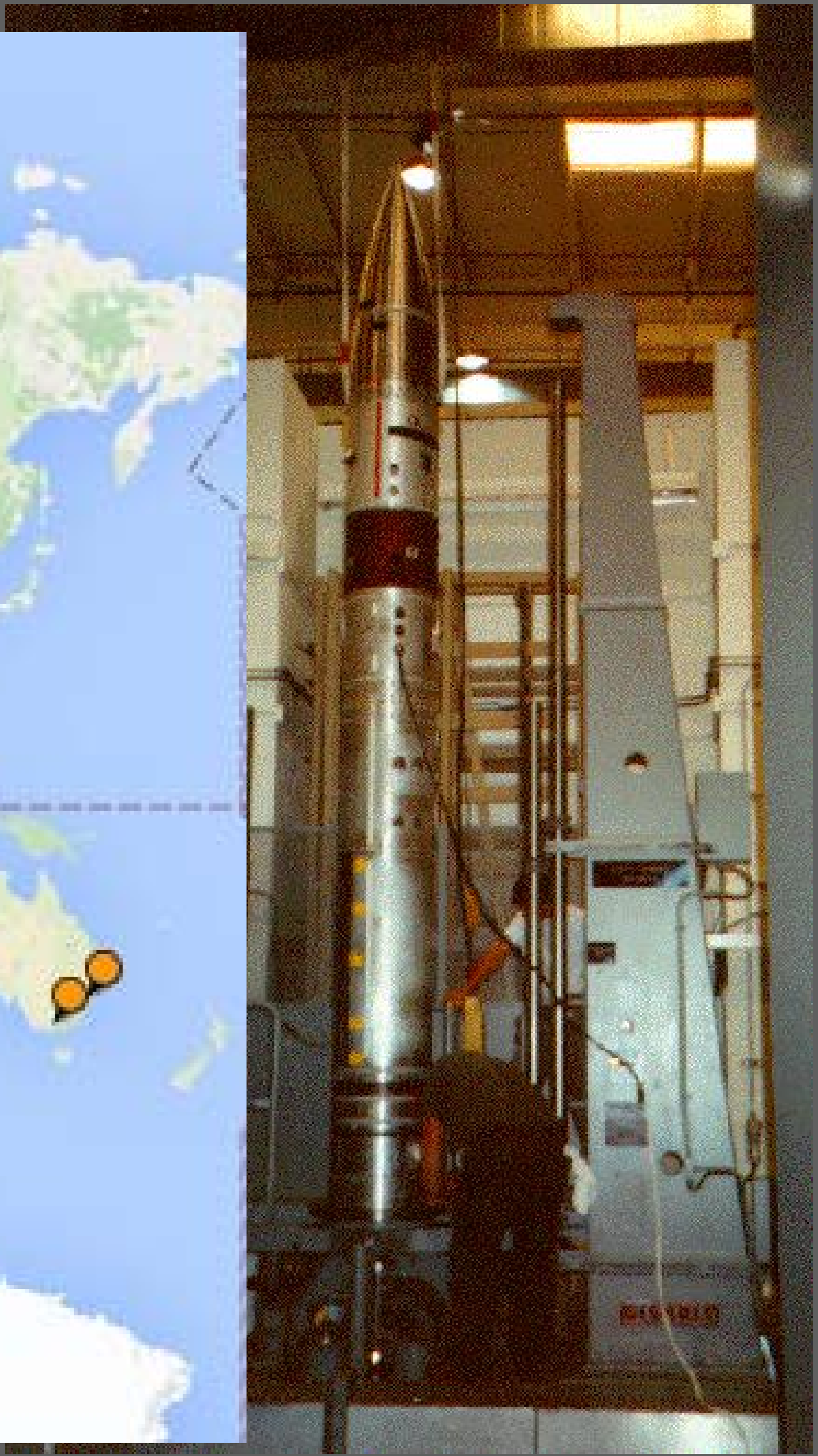
Your Turn
(Convex Lens)



- Note: lenses are thin enough that you just draw a line to represent the lens.
- **Locate the image of the arrow.**

A Reflection on History

Ferdinand Du Puigaudeau, “The Customs Cabin”, 1878


ASIA
Atlantic Ocean
AFRICA
SOUTH AMERICA
Pacific Ocean
Indian Ocean


Optics in Ancient History

A mirror was discovered in workers' quarters near the tomb of Pharaoh Sesostris II (1900 BCE).

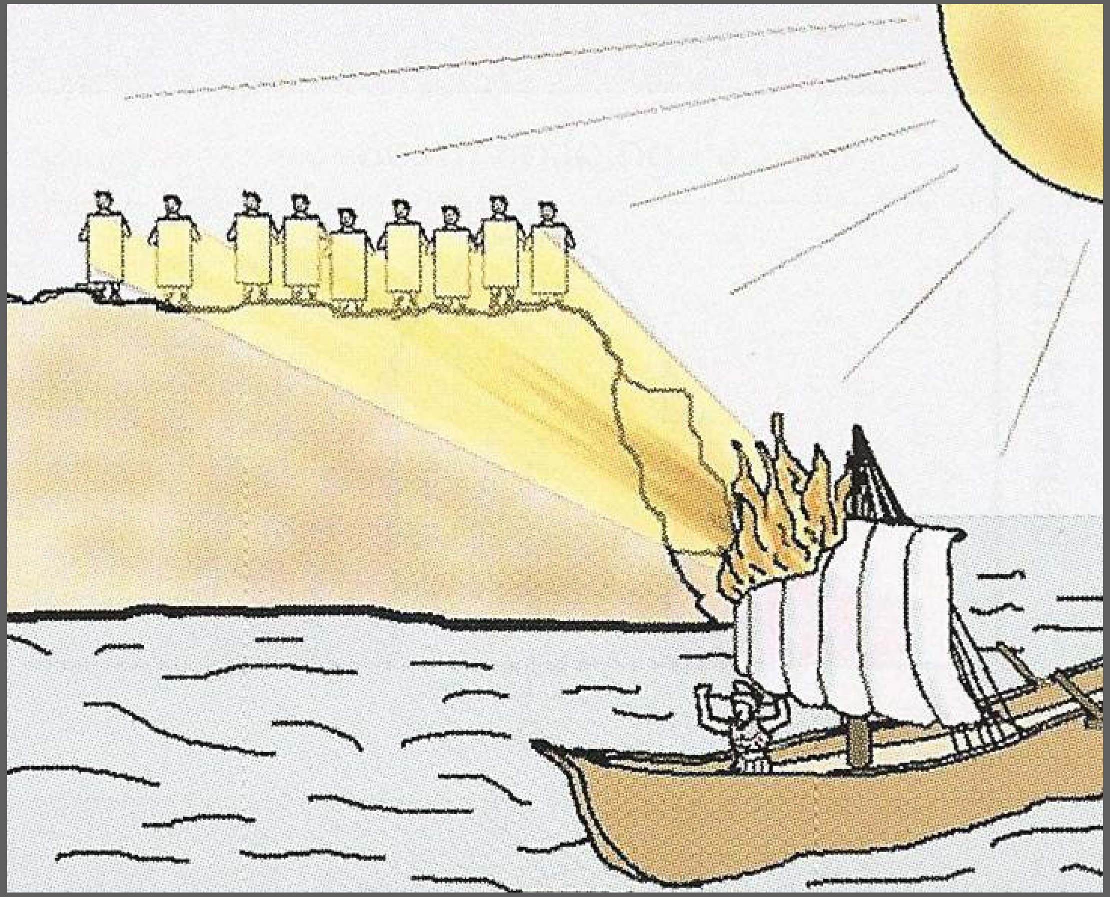
Pyramid of Sesostris II
(also known as Senusret II)

Ancient Greeks (500-300 BCE)

- Burning glass mentioned by Aristophanes (424 BCE)
- Law of reflection: “Catoptrics” by Euclid (300 BCE)
- Refraction in water mentioned by Plato in “The Republic”
- But they thought that the eye emits rays that reflect off objects.

Ancient Greeks: Ancient light weapons

Early Greek and Roman historians report that Archimedes equipped several hundred people with metal mirrors to focus sunlight onto Roman warships in the battle of Syracuse (213 -211 BCE).



This story is probably apocryphal.

Optics in the Middle Ages: Alhazen

Alhazen (~1000 AD) studied spherical and parabolic mirrors.

Alhazen correctly proposed that the eyes passively receive light reflected from objects, rather than emanating light rays themselves.

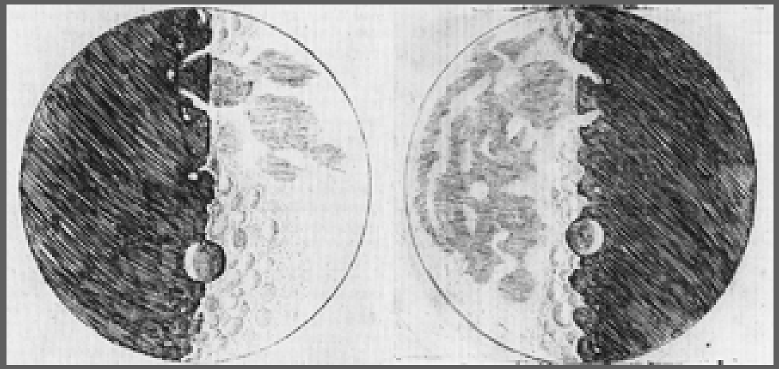
He also explained the laws of reflection and refraction by the slower movement of light through denser substances.

Alhazen
(965-1040)

Optics in early 17th-century Europe

Hans Lippershey applied for a patent on the Galilean telescope in 1608.

Galileo (1564-1642) used one to look at our moon, Jupiter and its moons, and the sun.



Galileo's drawings of the moon

Two of Galileo's telescopes

Johannes Kepler

Discovered total internal reflection

Showed why telescopes work

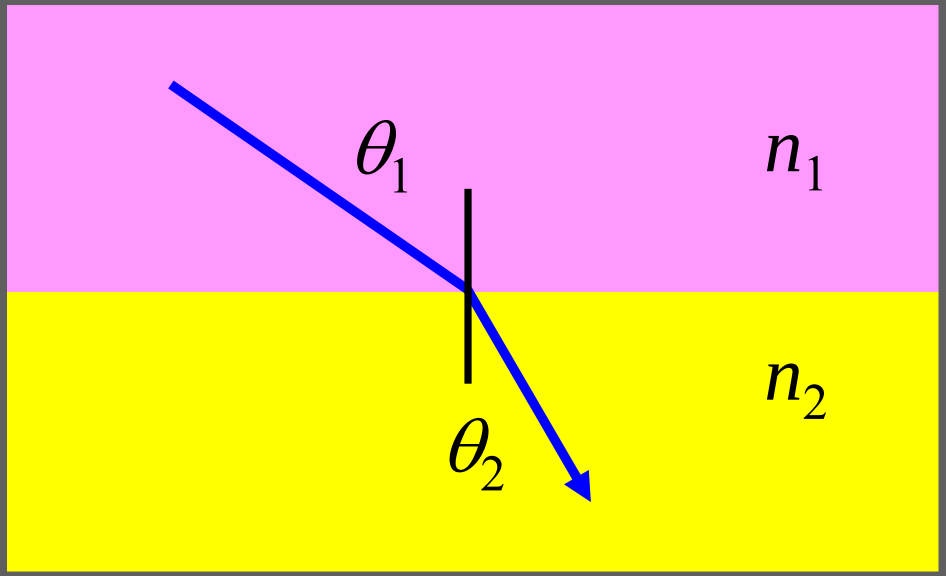
Developed a first-order theory of geometrical optics

Discovered the small-angle approximation to the law of refraction

Johannes Kepler
(1571–1630)

Willibrord Snell

Willibrord Snell discovered the Law of Refraction, now named after him.



n_i is the refractive index of each medium.

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

Willibrord Snell (1591-1626)

17th-century Optics

Descartes reasoned that light must be like sound. So he modeled light as pressure variations in a medium (aether).

Robert Hooke (1635-1703) studied colored interference between thin films and developed the first wave theory of light.

Rene Descartes (1596-1659)

Christiaan Huygens

Huygens extended the wave theory of optics.

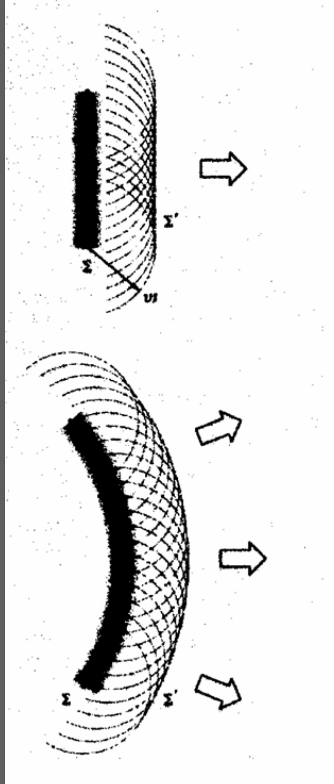
He realized that light slowed down on entering dense media.

He explained polarization and double refraction.

Christiaan Huygens (1629-1695)

Double refraction

Huygens' principle says that a wave propagates as if the wave-front were composed of an array of point sources each emitting a spherical wave.



Isaac Newton

"I procured me a triangular glass prism to try therewith the celebrated phenomena of colours." (Newton, 1665)

A prism is an example of a *dispersive element:*

$$n \sim n(\lambda)$$

Isaac Newton (1642-1727)

After remaining ambivalent for many years, he eventually concluded that it was evidence for a particle theory of light.

18th and 19th century Optics: Euler, Young, and Fresnel

Leonhard Euler (1707-1783) further developed the wave theory and designed achromatic lenses by combining lenses of different materials.

Thomas Young (1773-1829) explained interference and colored fringes and showed that light was a transverse wave.

Augustin Fresnel (1788-1827) did experiments to establish the wave theory and derived expressions for reflected and transmitted waves.

Augustin Fresnel

James Clerk Maxwell

Maxwell unified electricity and magnetism with his now famous equations and showed that light is an electromagnetic wave.

$$\vec{\nabla} \cdot \vec{E} = 0 \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

where $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, and c is the velocity of light.

James Clerk Maxwell (1831-1879)

Maxwell's equations simplify to the wave equation for the electric field.

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

which has a simple sine-wave solution:

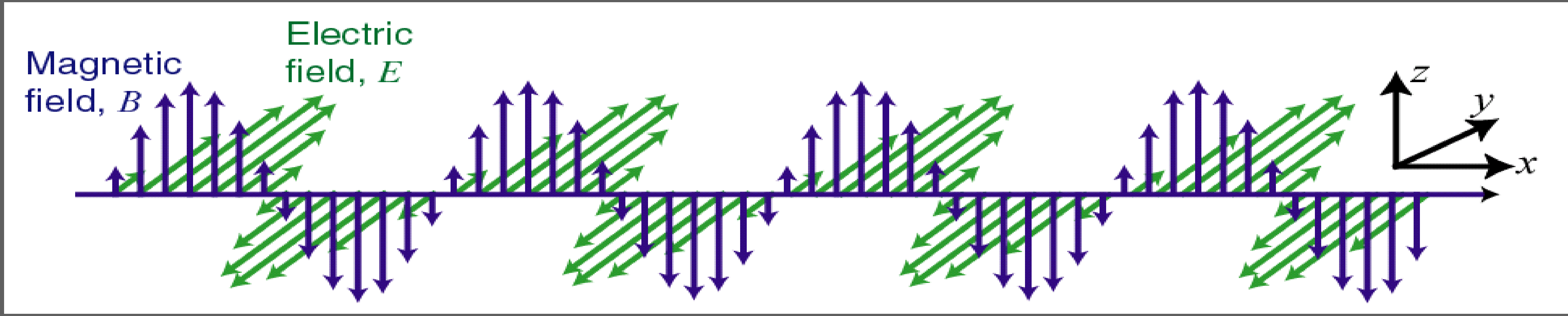
$$\vec{E}(\vec{r},t) \propto \cos(\omega t \pm \vec{k}\cdot\vec{r})$$

where $c = \omega / \left|\vec{k}\right|$

The same is true for the magnetic field.

Light is an electromagnetic wave.

The electric (E) and magnetic (B) fields are in phase.



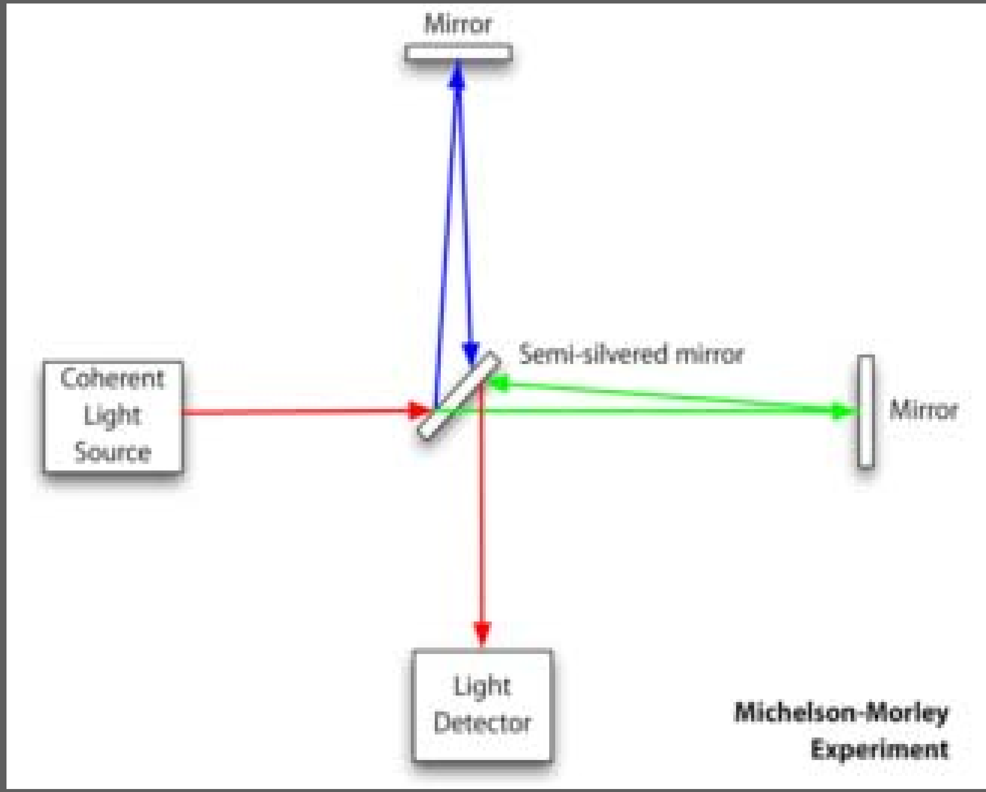
The electric field, the magnetic field, and the propagation direction are all perpendicular.

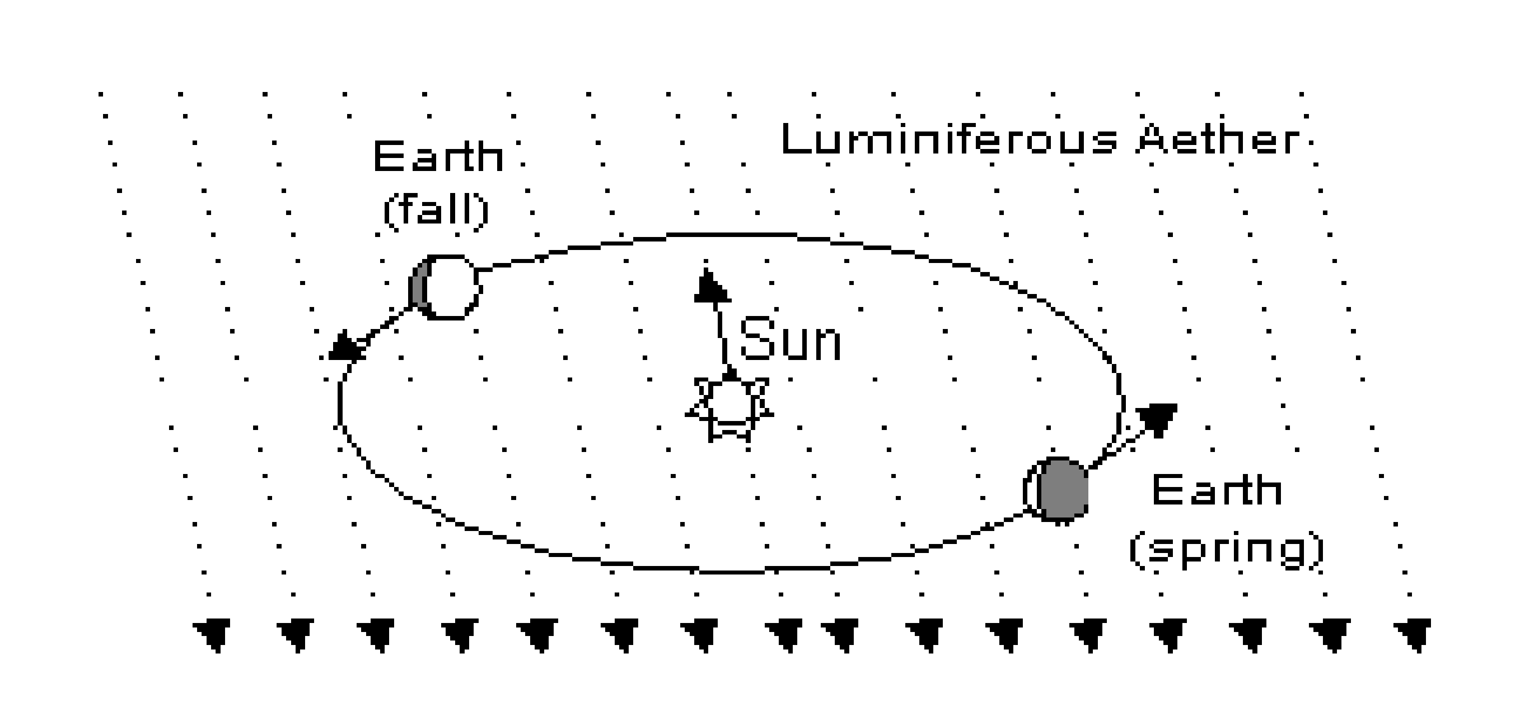
Michelson & Morley

Michelson and Morley then attempted to measure the earth's velocity with respect to the aether and found it to be zero, effectively disproving the existence of the aether.

Albert Michelson
(1852-1931)

Edward Morley
(1838-1923)





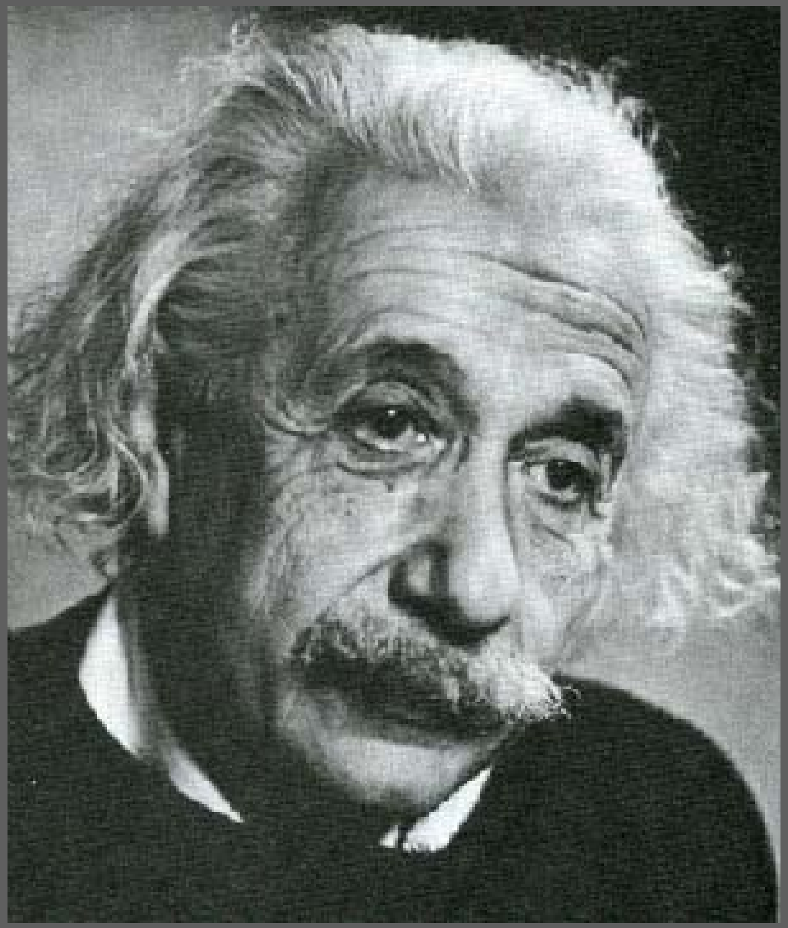
Albert Einstein

Einstein showed that light:

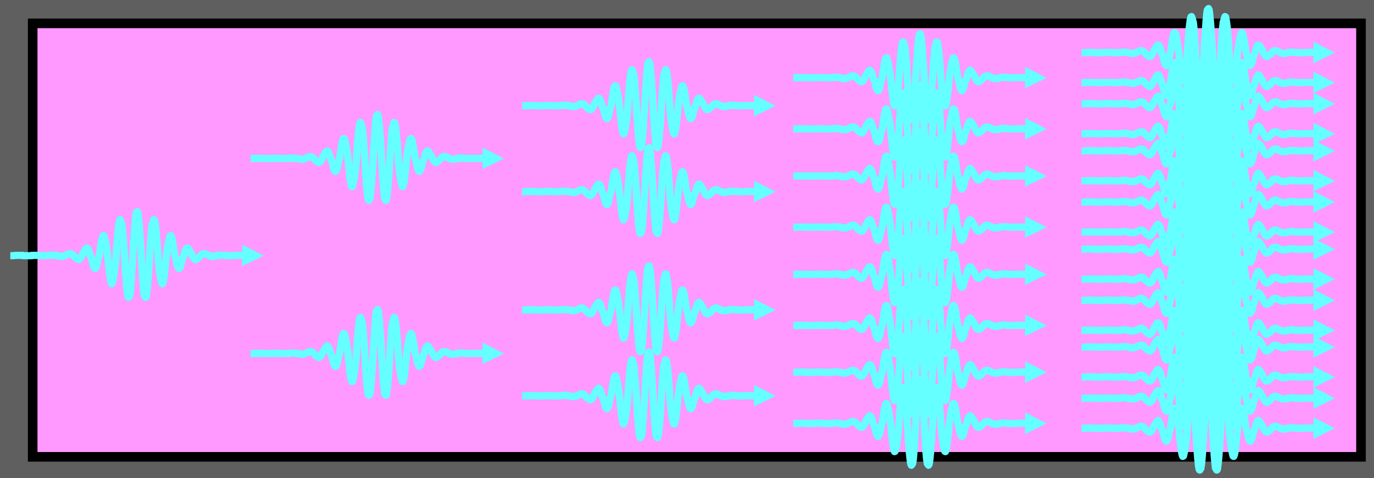
is a phenomenon of empty space;

has a velocity that's constant, independent of observer velocity;

is both a wave and a particle;



Albert Einstein (1879-1955)



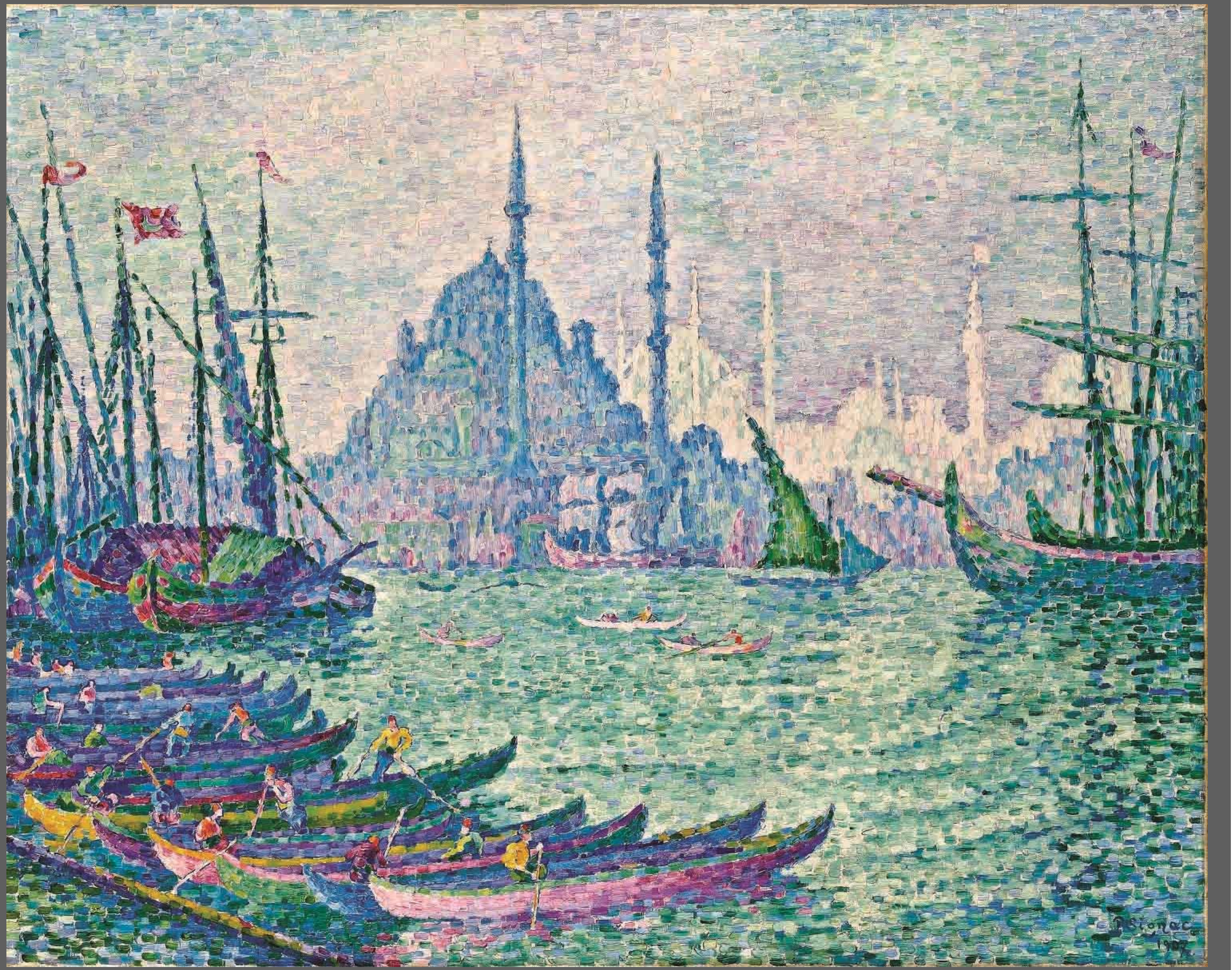
and undergoes **stimulated emission**, the basis of the laser.

Quiz: What did Einstein receive his Nobel Prize for? and, When did Einstein receive the Nobel Prize?

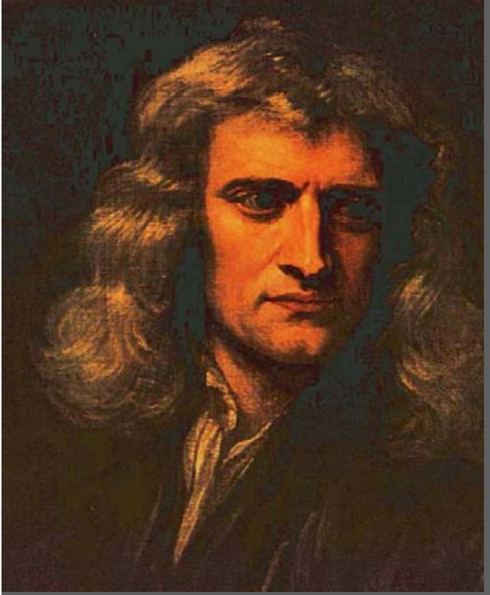
Wave-Particle Duality

and

Fourier Optics



Paul Signac, “La Corne D'or, Les Minarets”, 190



The Wave-Particle Debate

Newton

- light consists of small “massy” particles or corpuscles that travel in straight lines
- are subject to forces as one would expect of particles
- but also have additional vibratory properties
  - can be used to explain dispersion, color produced by oil slicks and so on.

Huygens

- light propagates as a wave disturbance through the ether - an unseen, elastic medium pervading all of space.
- Light will add, cancel and share properties common to all waves.

Huygen’s Principle

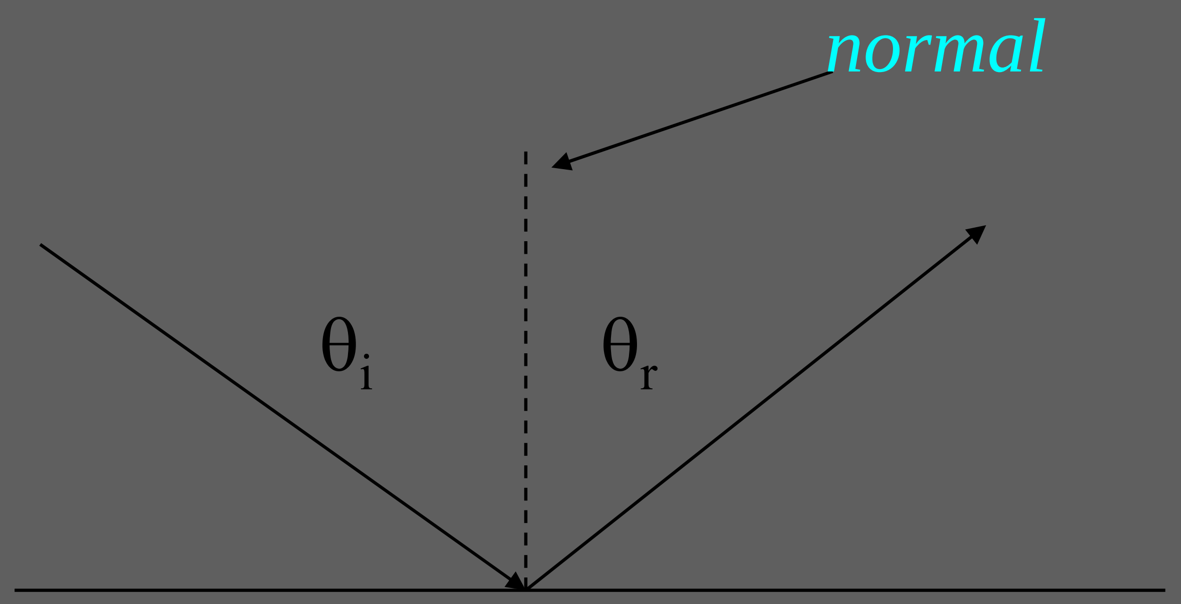
... every point on a primary wavefront serves as the source of spherical secondary wavelets propagating in the forward direction such that the primary wavefront at some later time is the envelope of these wavelets. Further, the wavelets advance with a speed and frequency equal to the primary wave at each point in space.

Explaining Reflection and Refraction

Law of Reflection….

- Newton…
  - conservation of momentum and simple application of physics of forces
- Huygens…
  - wave superposition and interference

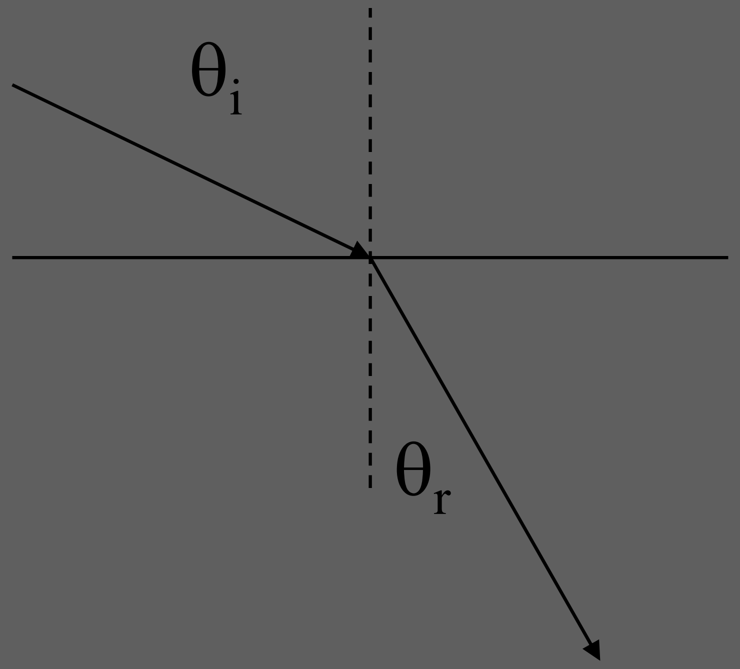
$$\theta_{incident} = \theta_{reflected}$$



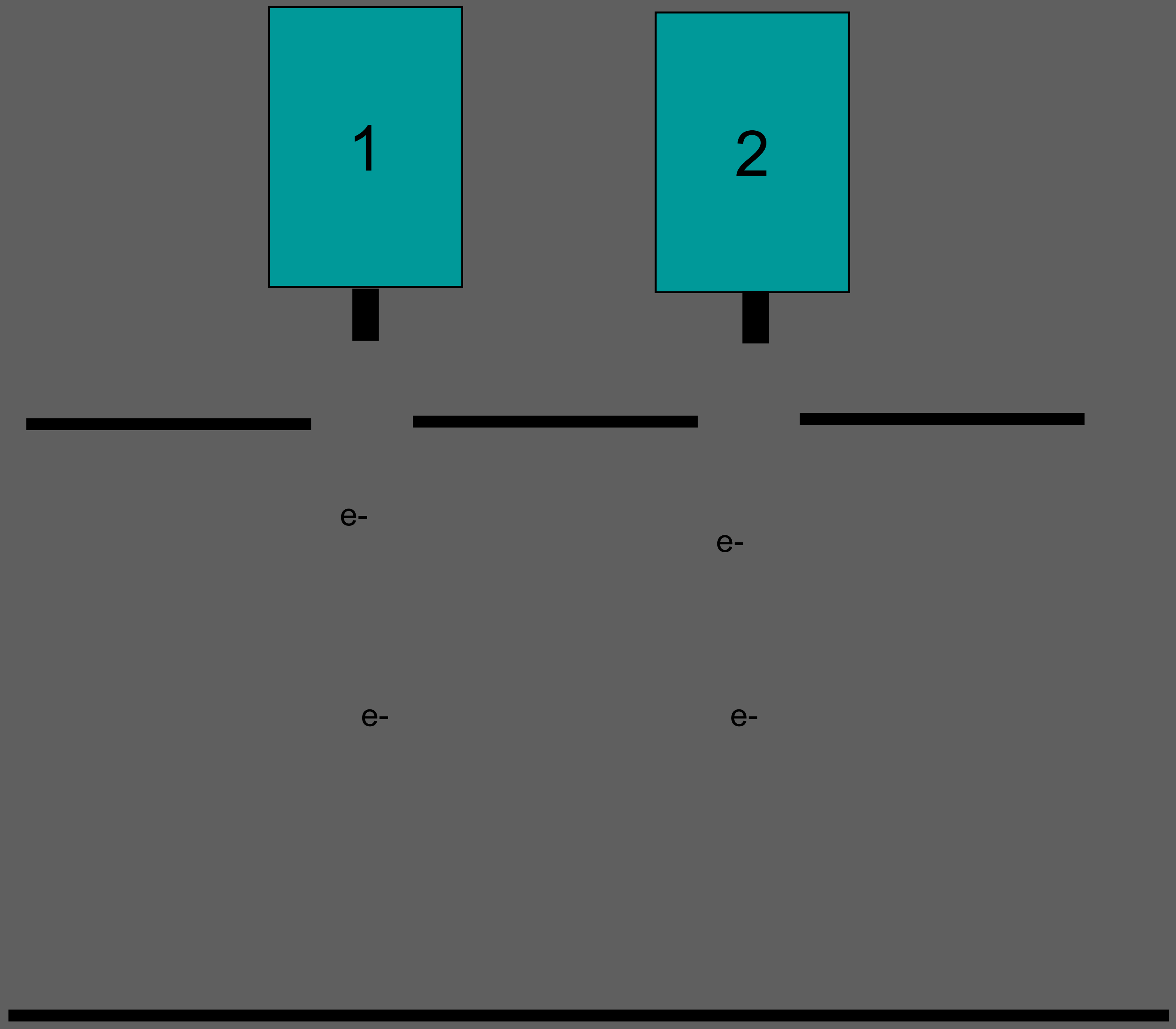
Law of Refraction (Snell's Law)

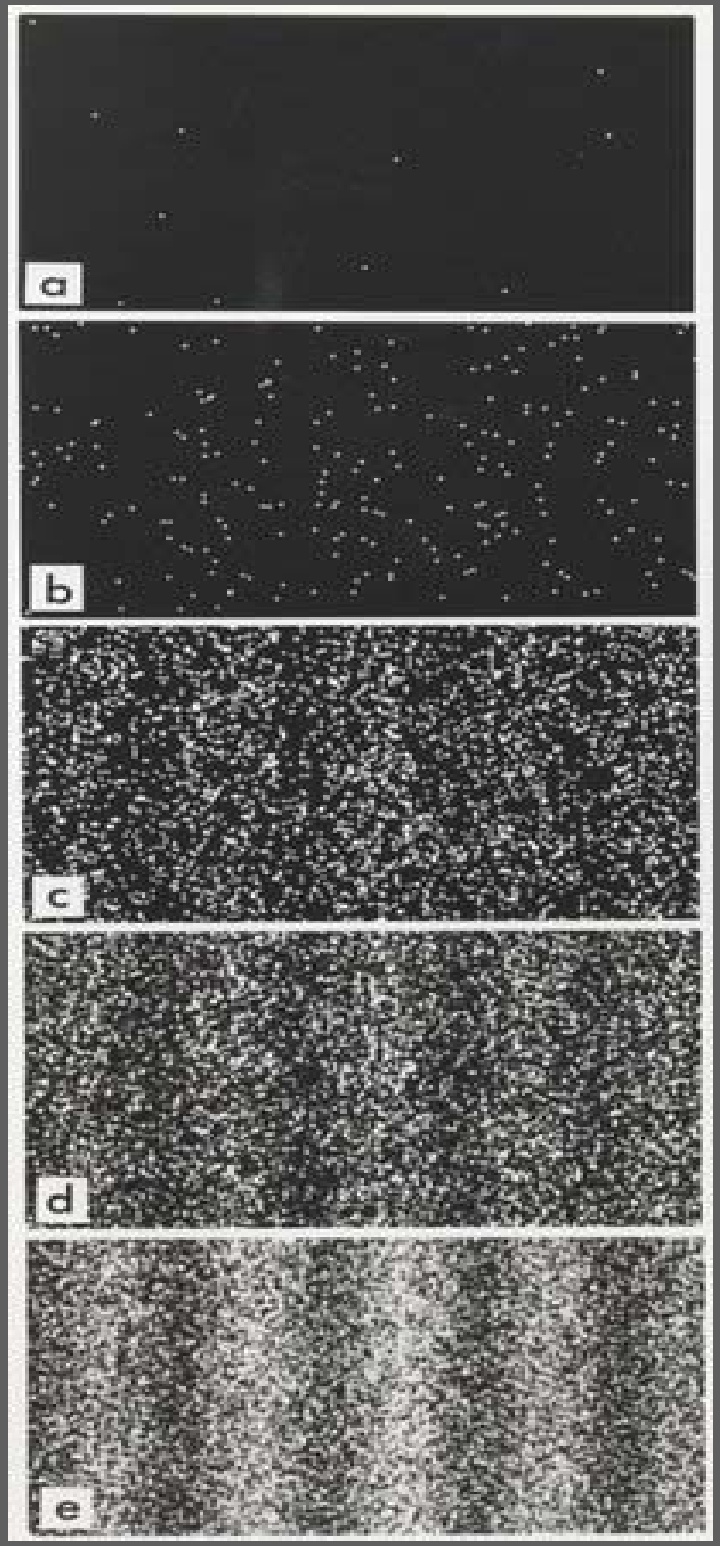
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

- Newton
  - attractive forces
- Huygens
  - wave interference

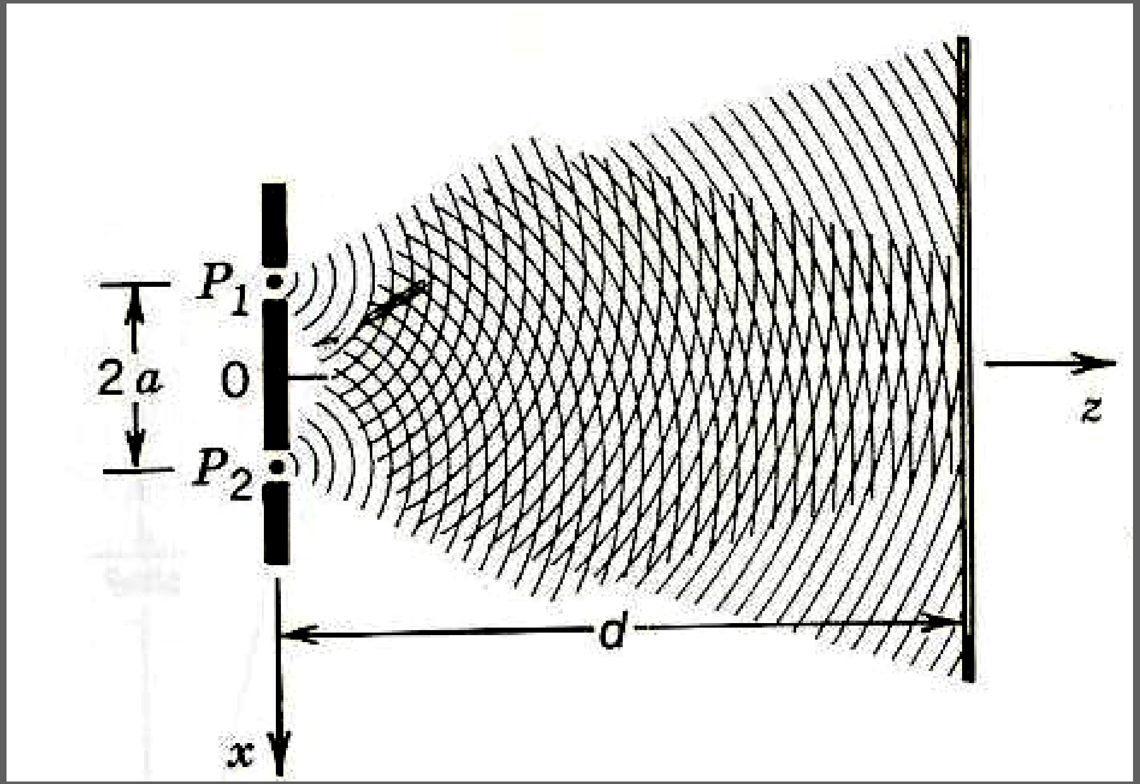


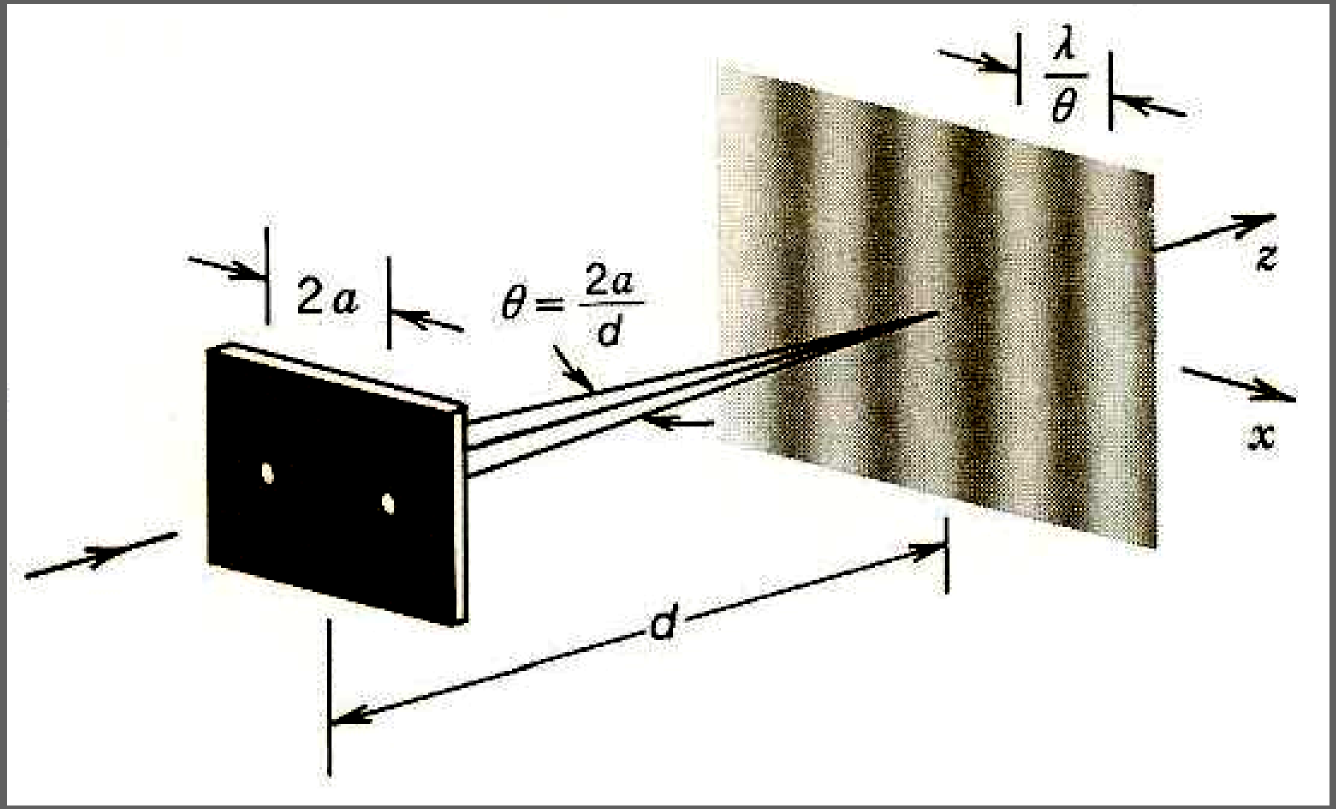
Single Photon Sources



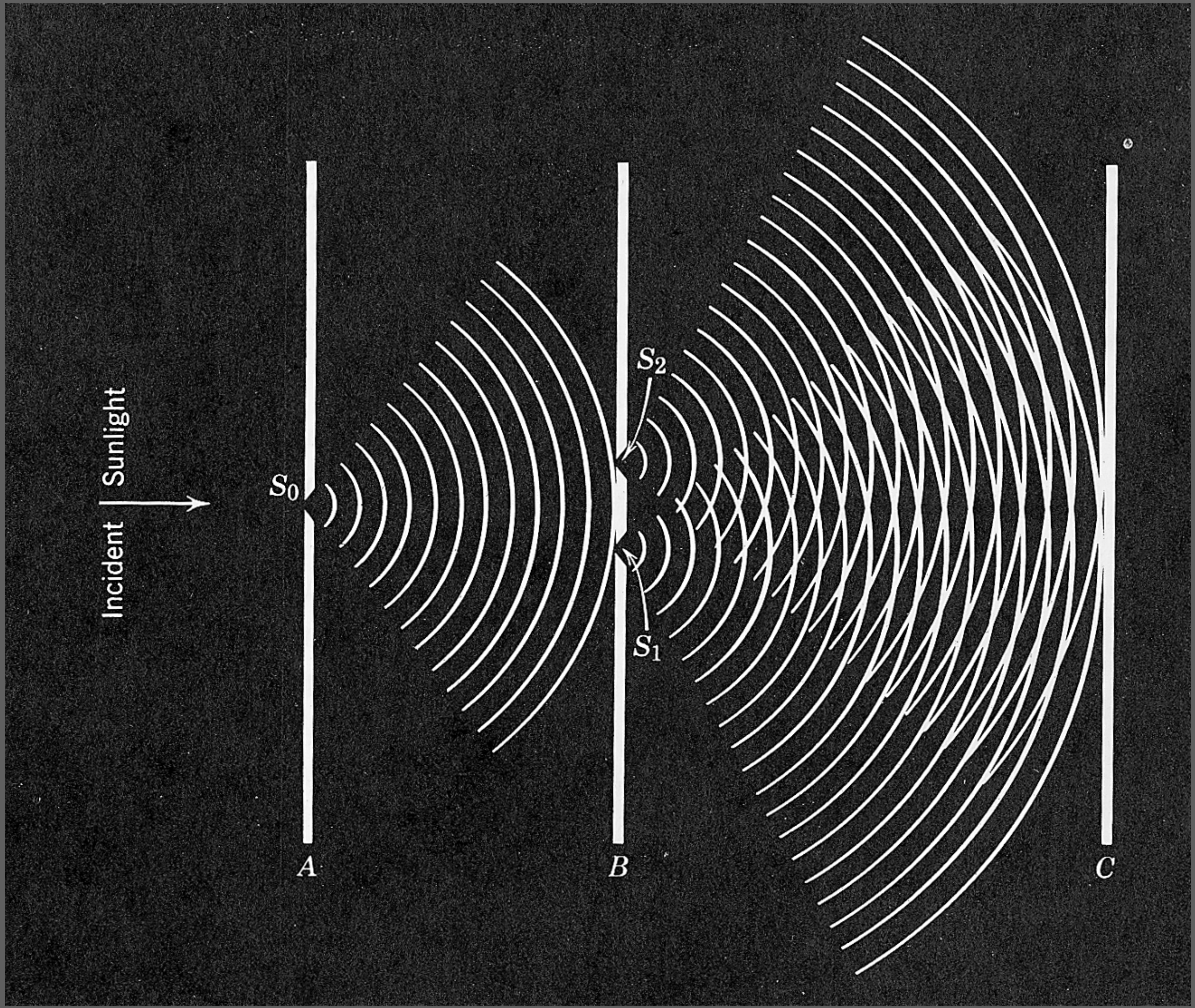


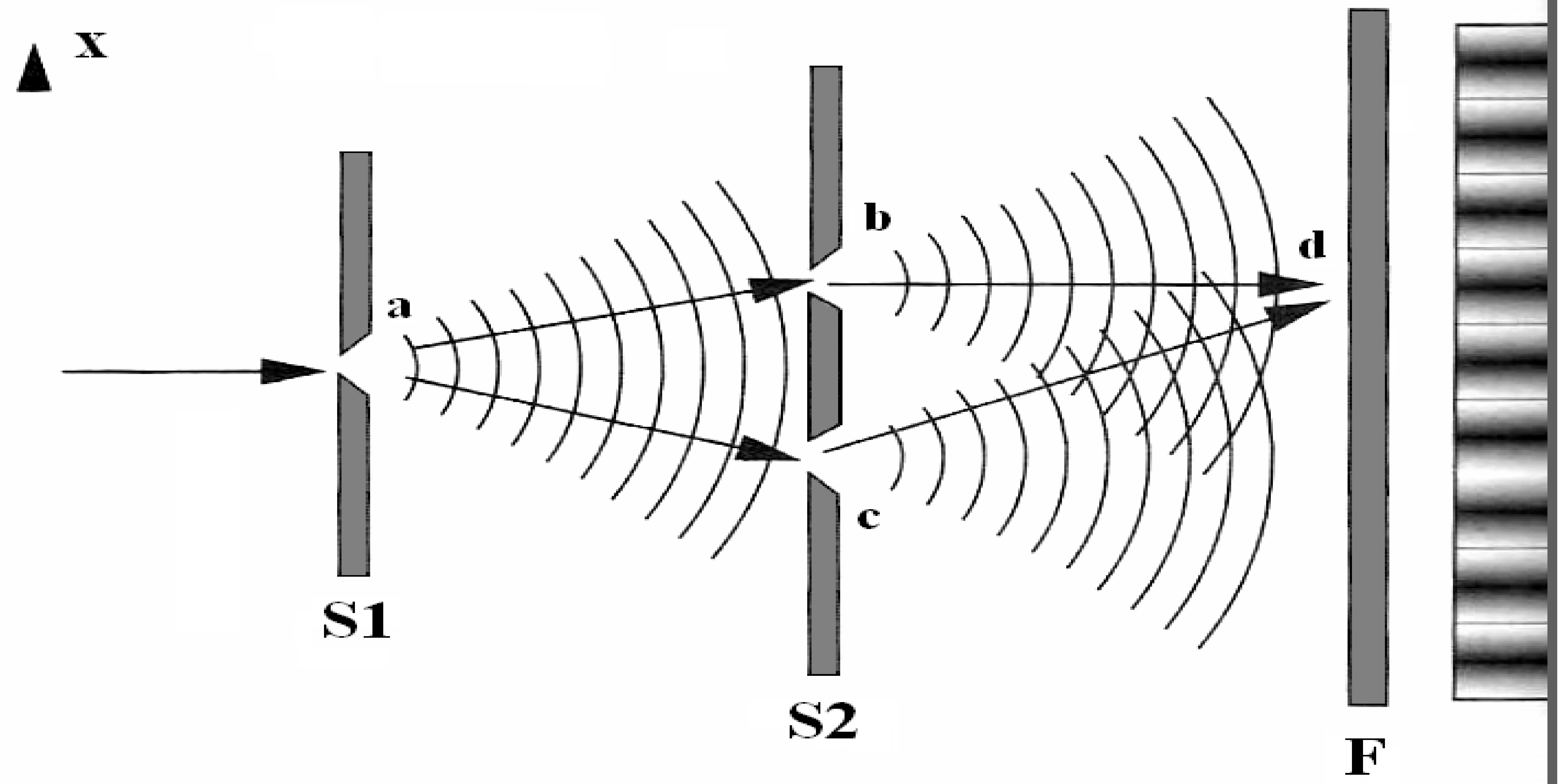
Thomas Young
(1773 - 1829)



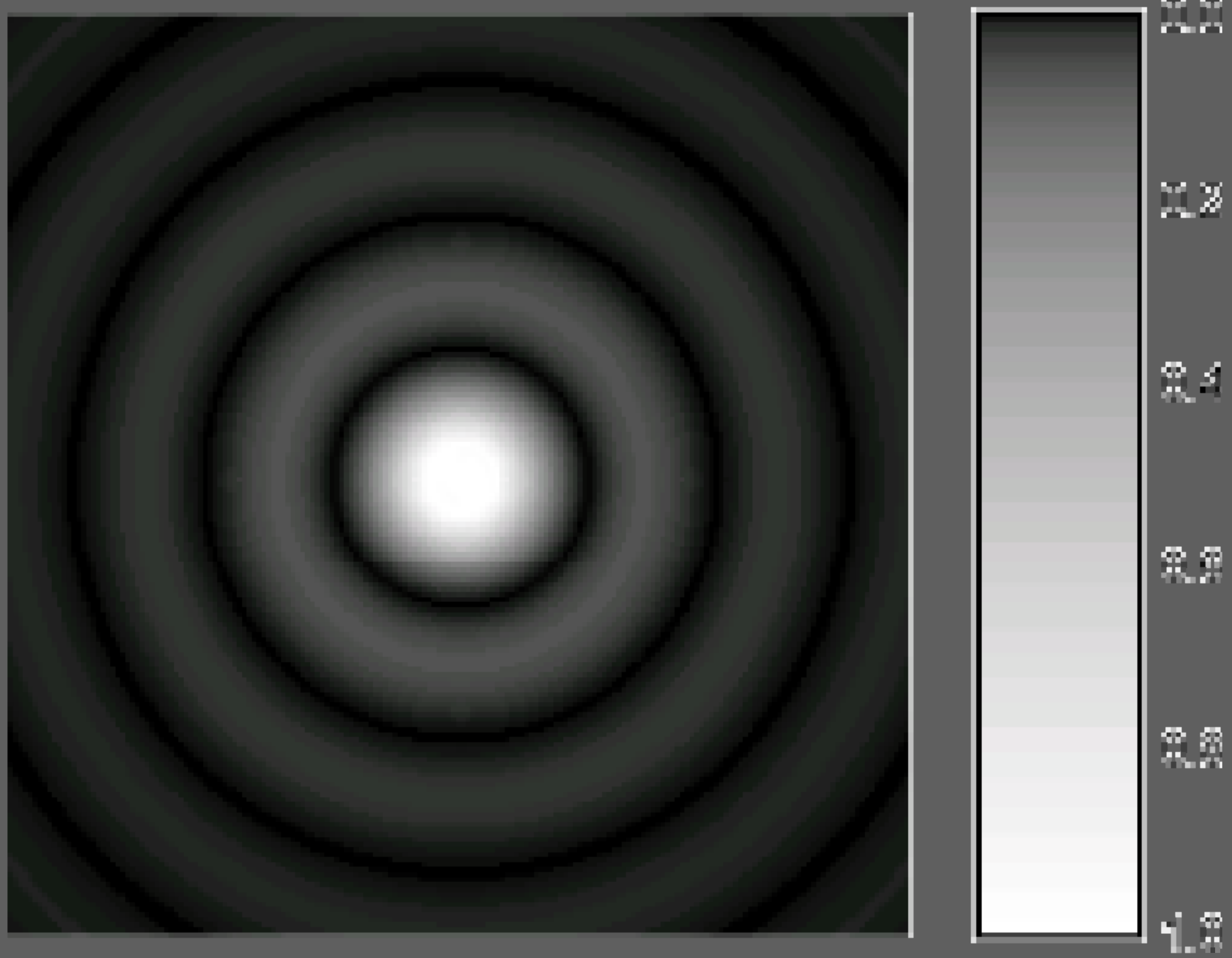


Interference



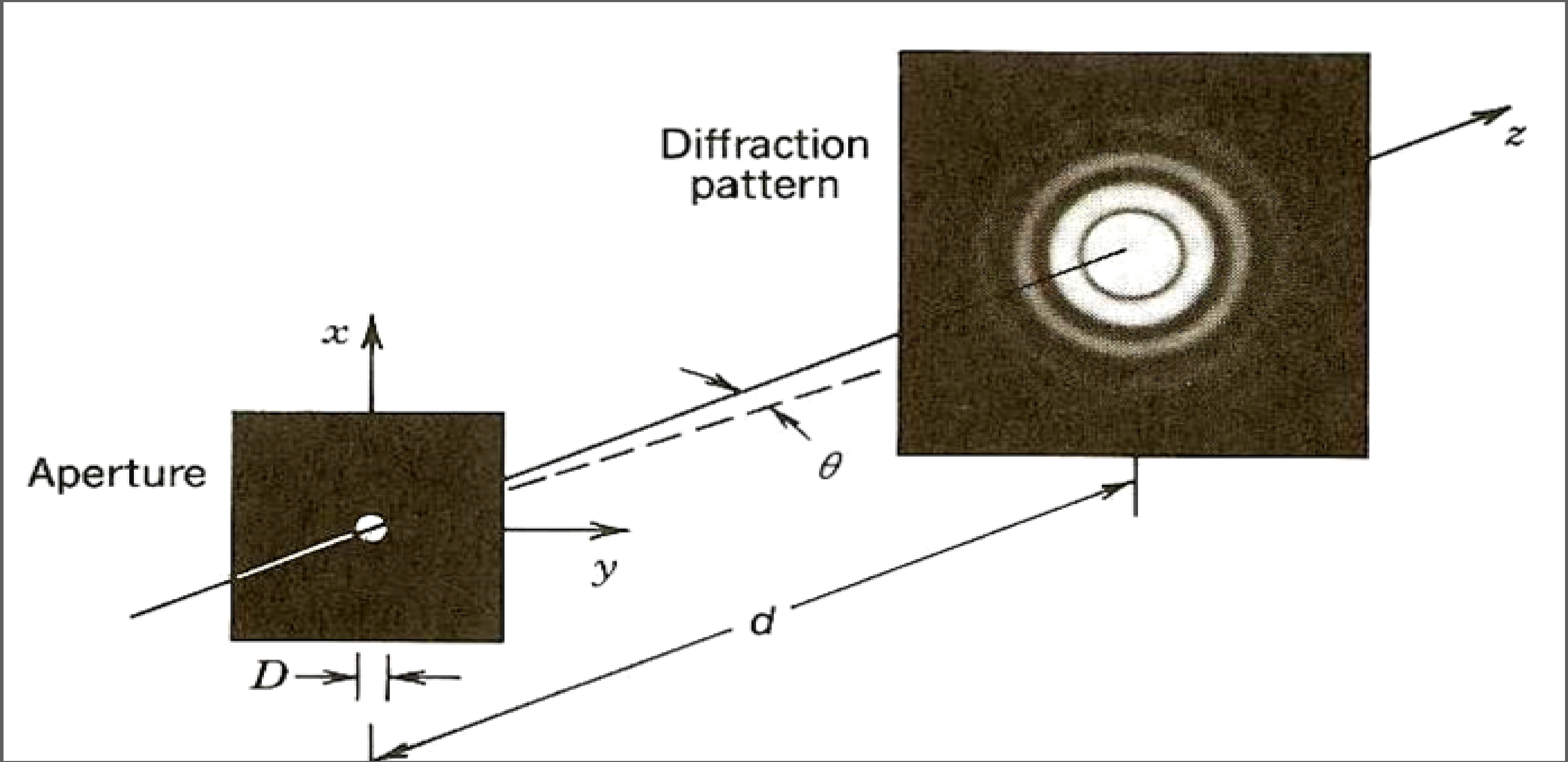

x
a
b
c
d
S1
S2
F

George Biddell Airy



Airy Disk

“Airy Disk” Diffraction Pattern

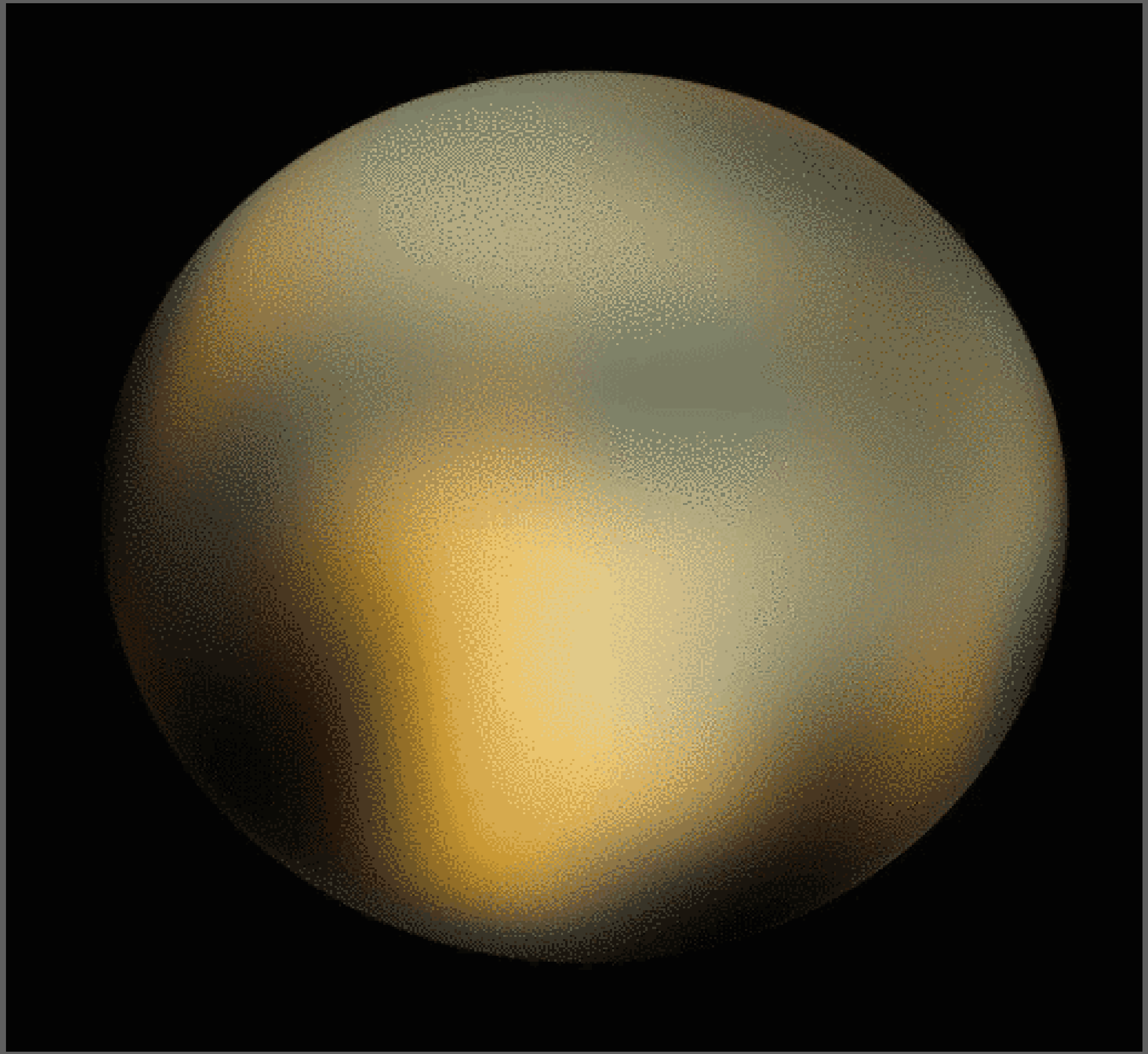


Design Case: NPOI

Paul Signac, "Port St. Tropez", 1899

Spatial Resolution Advances Science

- Example: Planetary science
- Is the surface old or new?
  - Implications for population & dynamics of Kuiper Belt
- Variations in surface morphology
  - Chemical composition
  - Seasonal variations in the surface?
- Evidence for plate tectonics?

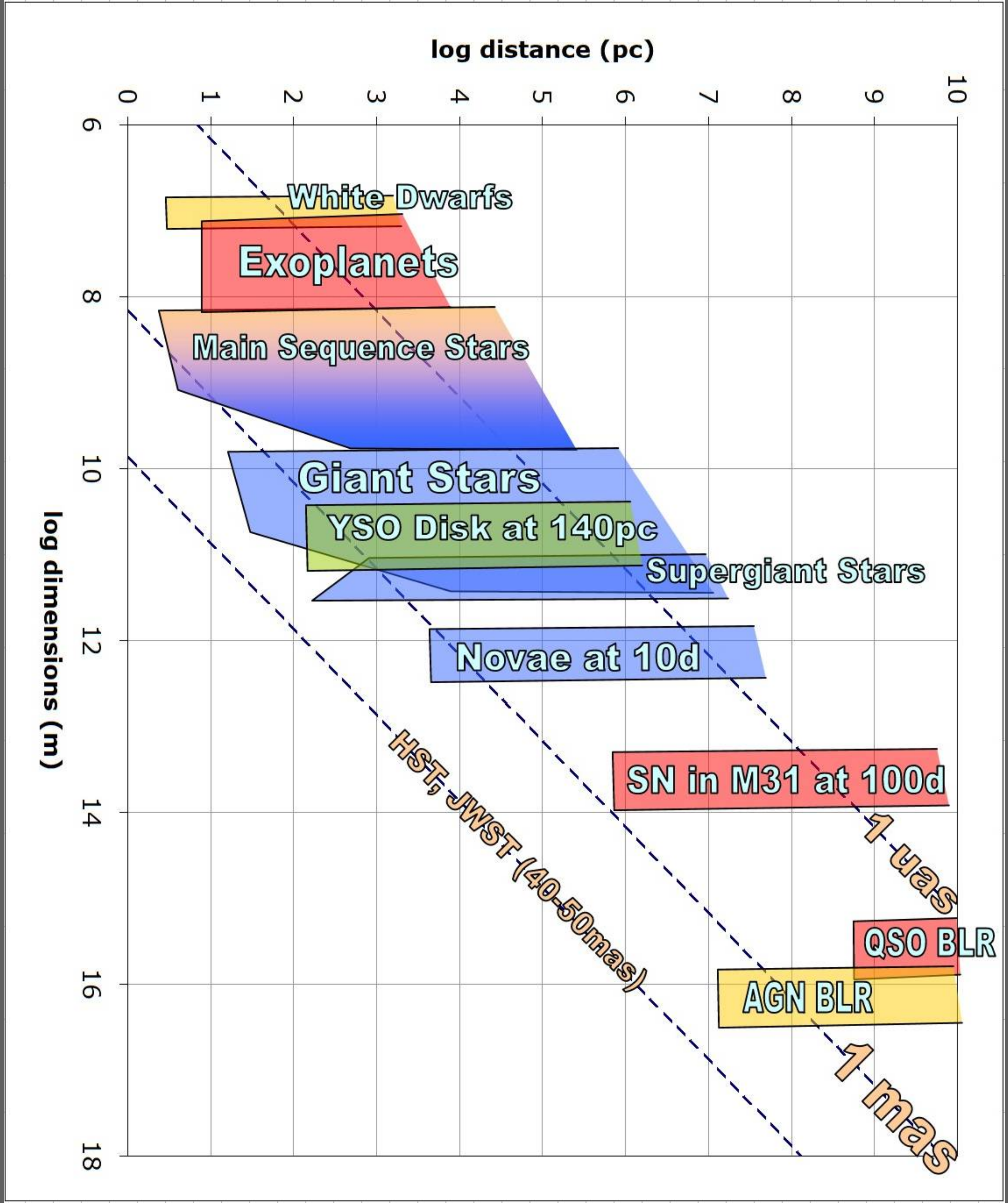


Our Science Menu

- From the near to the distant

Blue = bright

Red = faint



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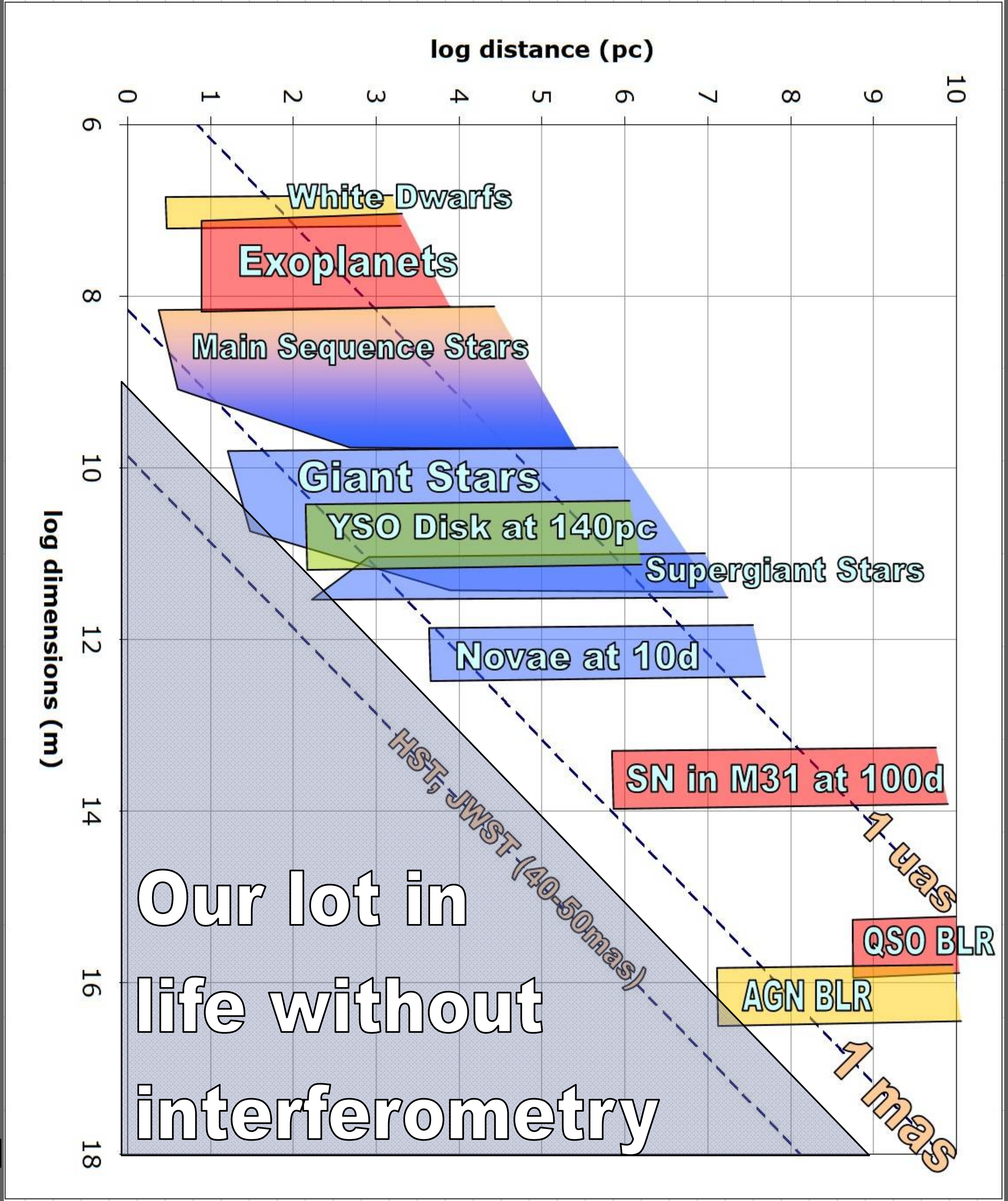
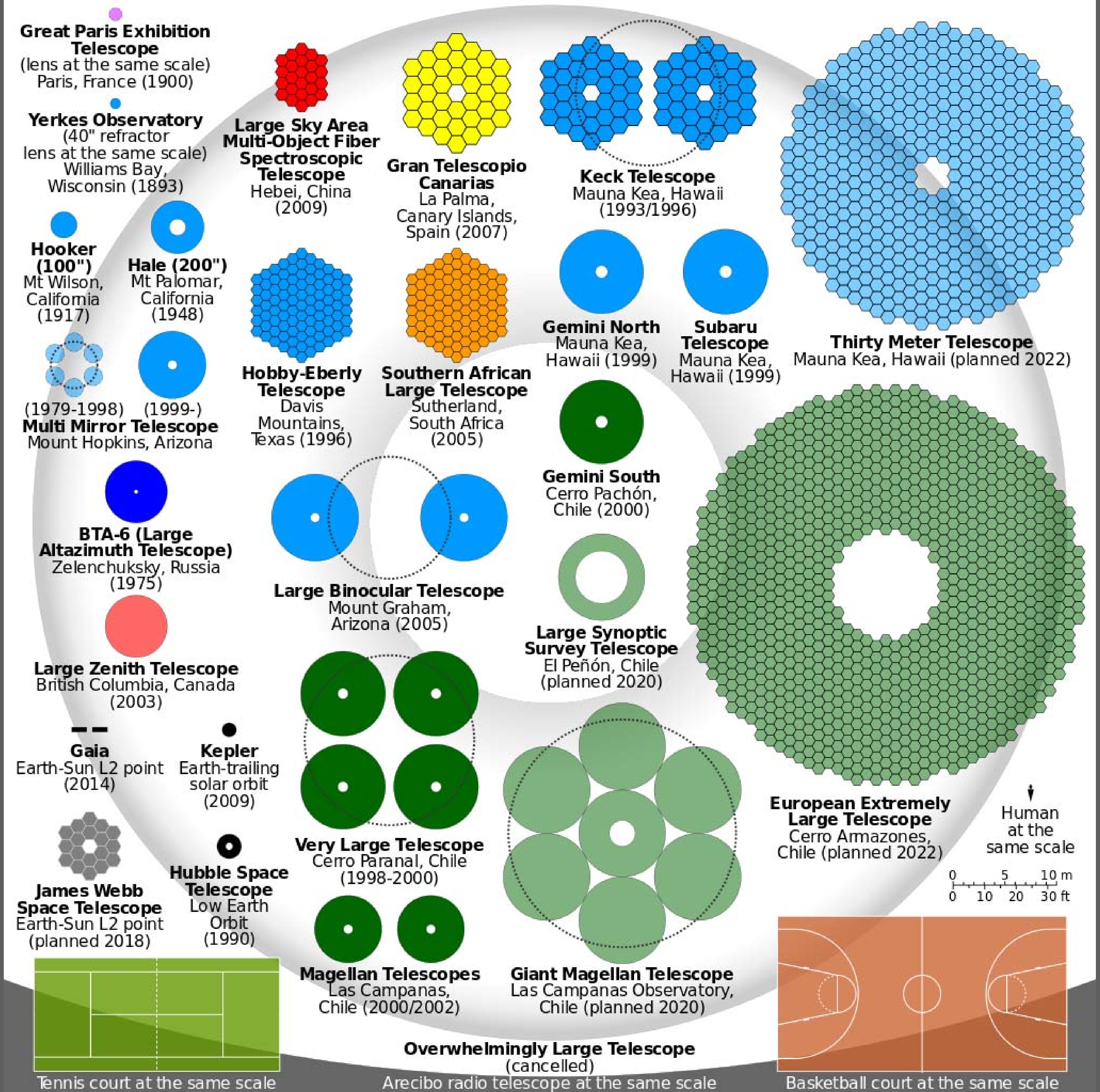
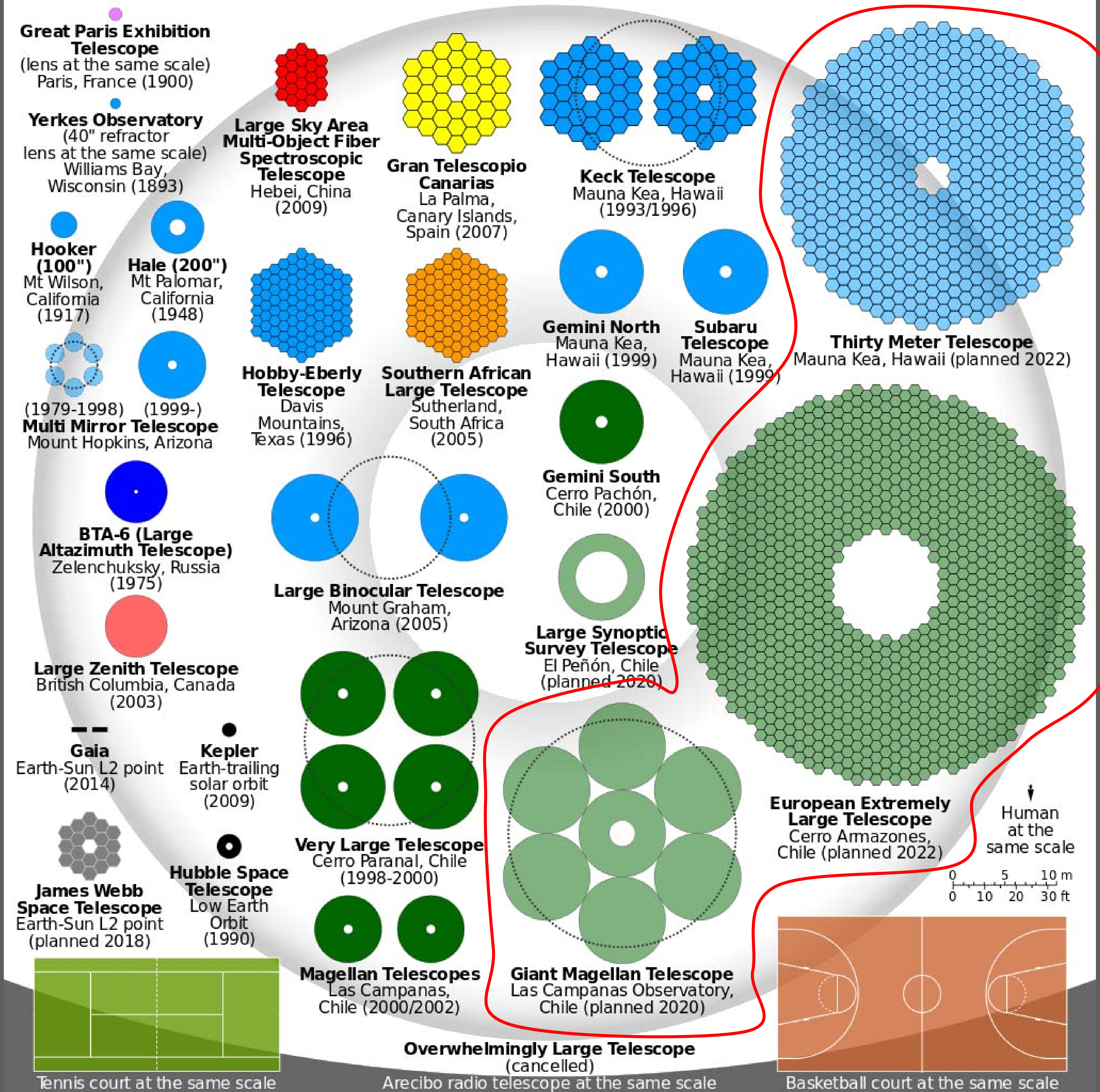




Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
Gemini South
Cerro Pachón, Chile (2000)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale



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Tennis court at the same scale
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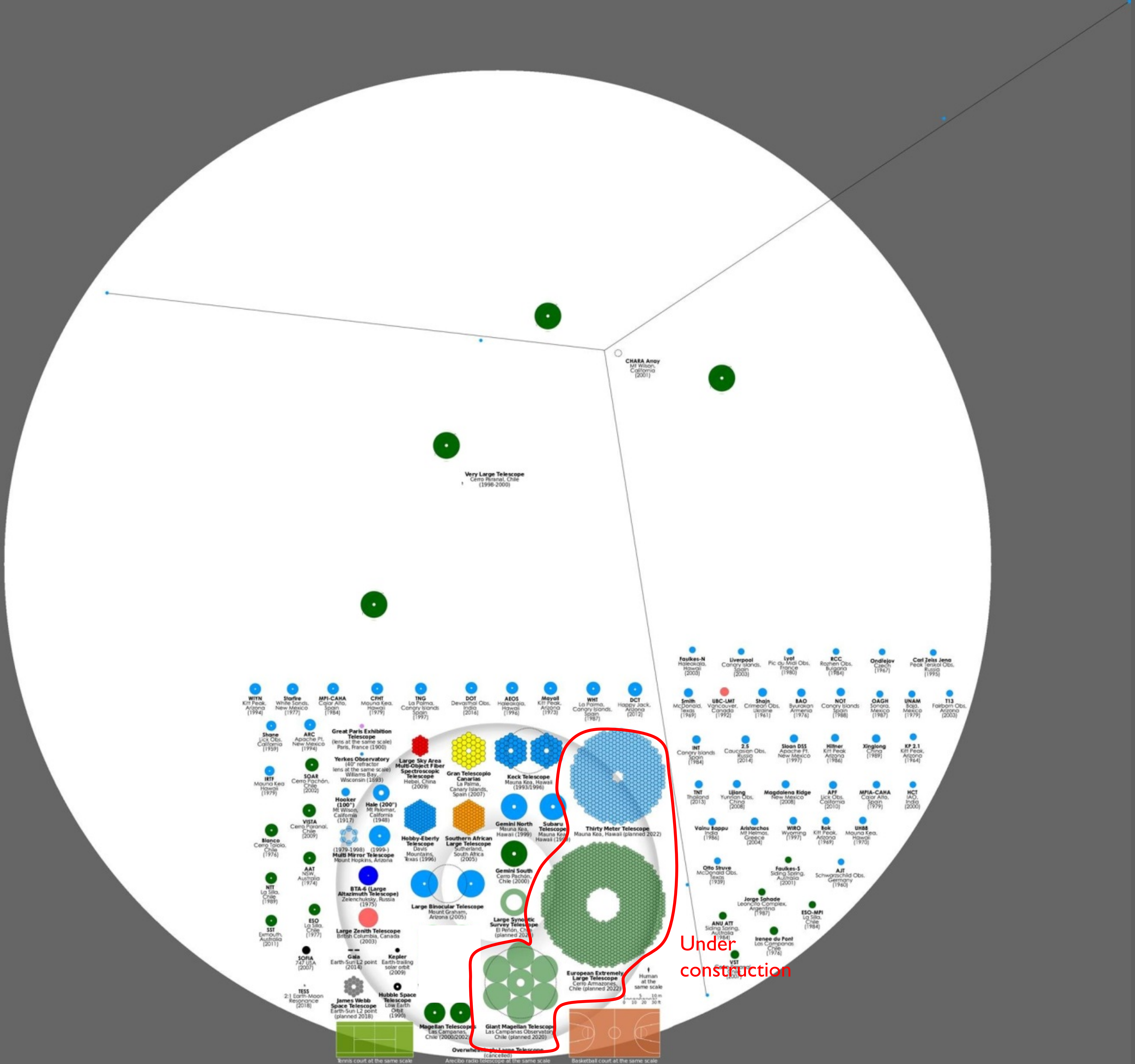
Basketball court at the same scale
Under construction



Very Large Telescope
Cerro Paranal, Chile
(1998-2000)
CHARA Array
Mt Wilson, California
(2001)
Keck Telescope
Mauna Kea, Hawaii
(1993/1996)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Southern African Large Telescope
Sutherland, South Africa (2005)
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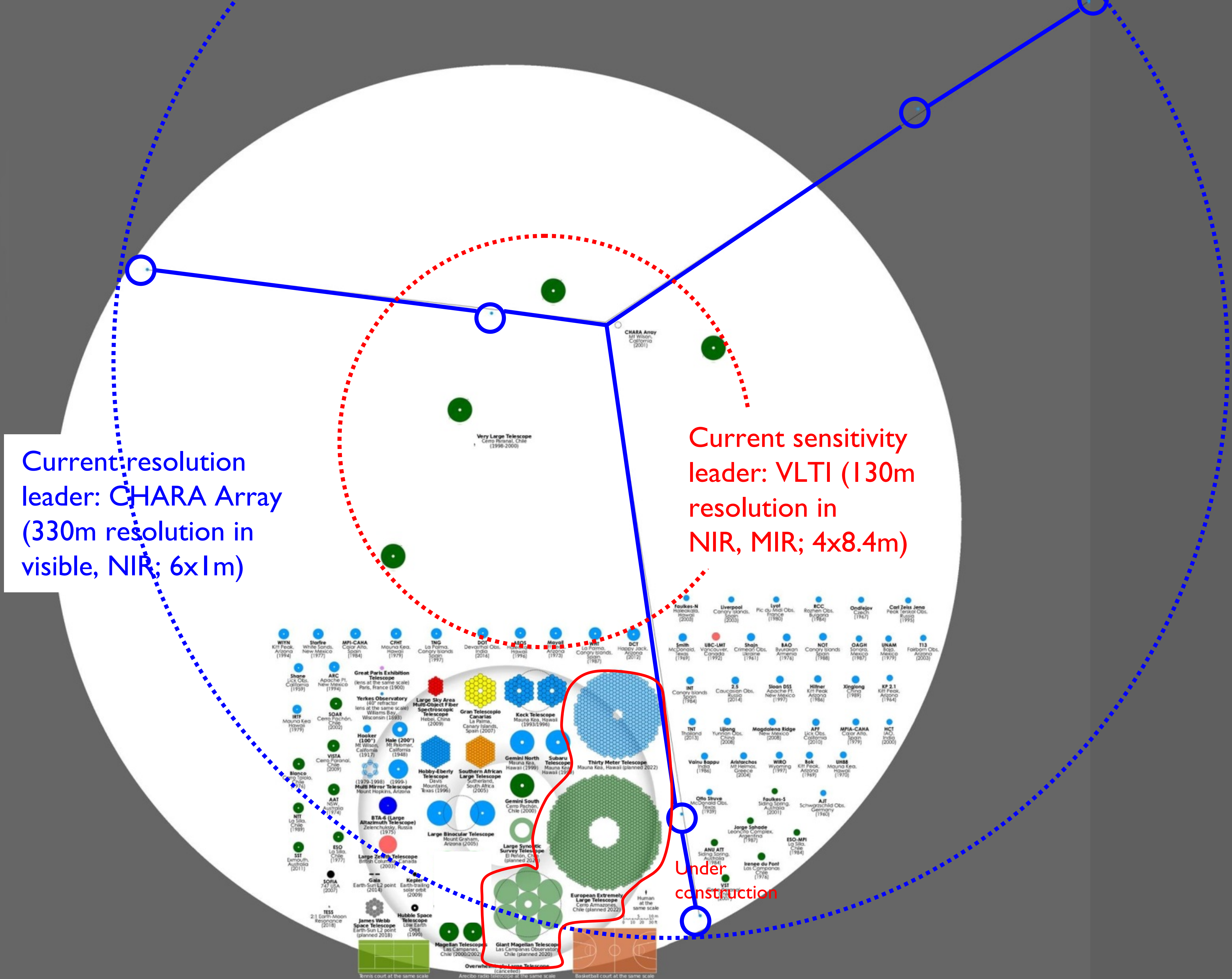
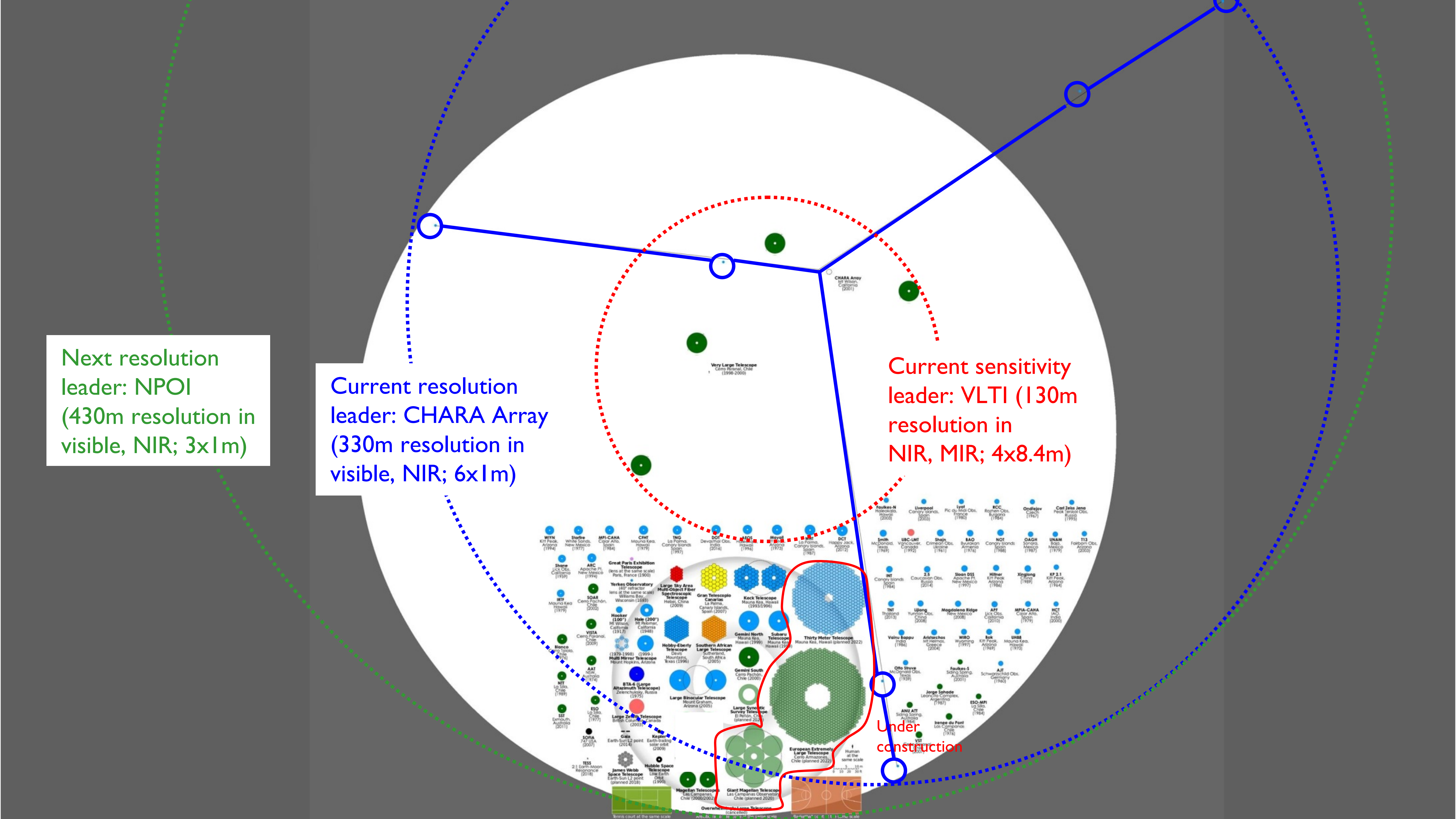
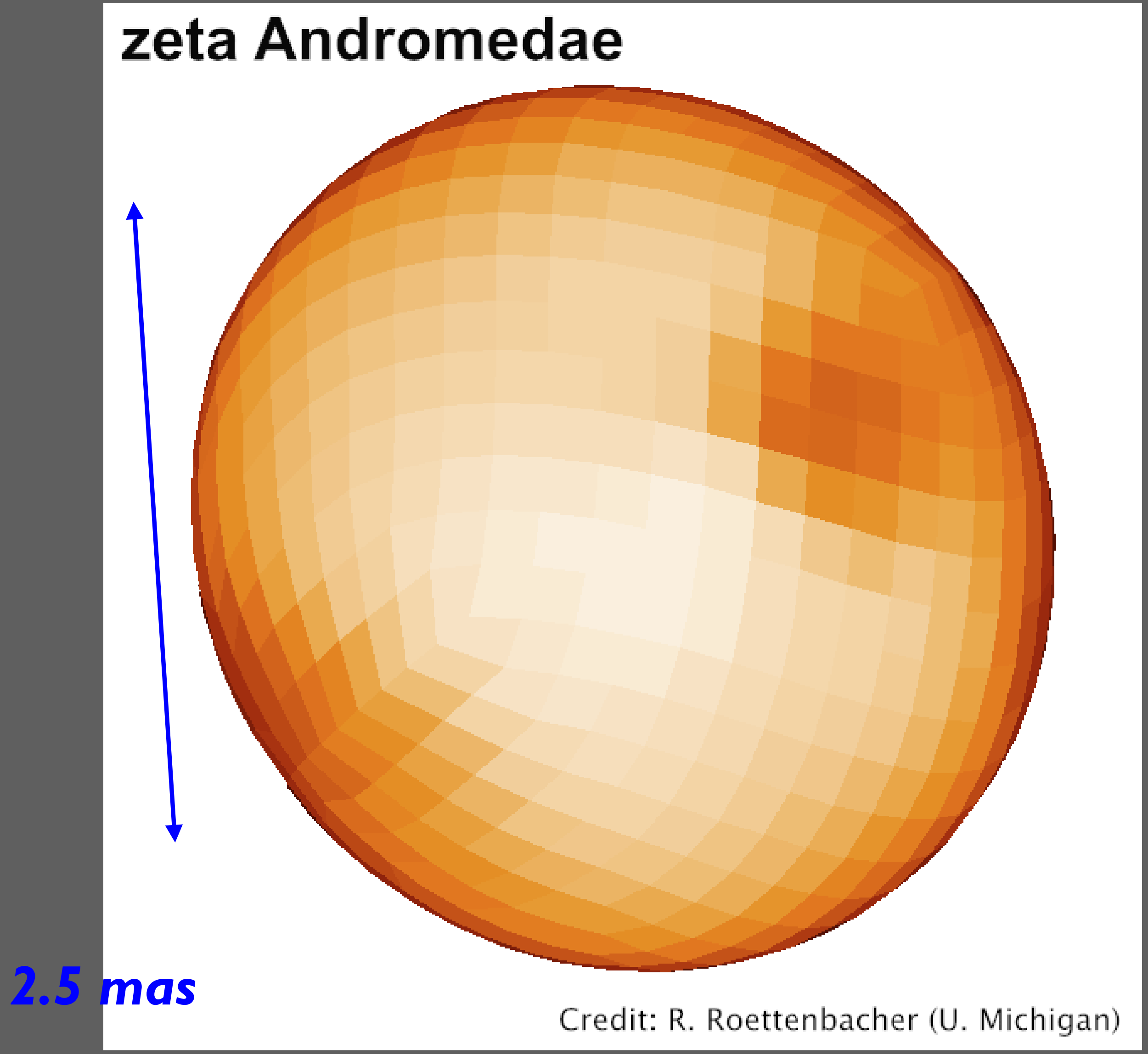

Current resolution leader: CHARA Array (330m resolution in visible, NIR; 6x1m)
Current sensitivity leader: VLTI (130m resolution in NIR, MIR; 4x8.4m)
Under construction


Next resolution leader: NPOI (430m resolution in visible, NIR; 3x1m)
Current resolution leader: CHARA Array (330m resolution in visible, NIR; 6x1m)
Current sensitivity leader: VLTI (130m resolution in NIR, MIR; 4x8.4m)
Under construction
CHARA Array
Very Large Telescope
Thirty Meter Telescope
European Extremely Large Telescope
Giant Magellan Telescope
Keck Telescope
Large Binocular Telescope

Science Enabled by Extreme Resolution

- Still interesting things to learn about *bright* objects
- Stellar surface imaging
- Limb darkening: upper stellar structure
- Spot mapping: convection physics, magnetic field strength and persistence



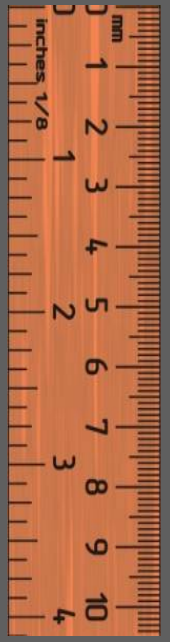
Dr. van Belle's Patented Six-Slide Crash Course in Interferometry

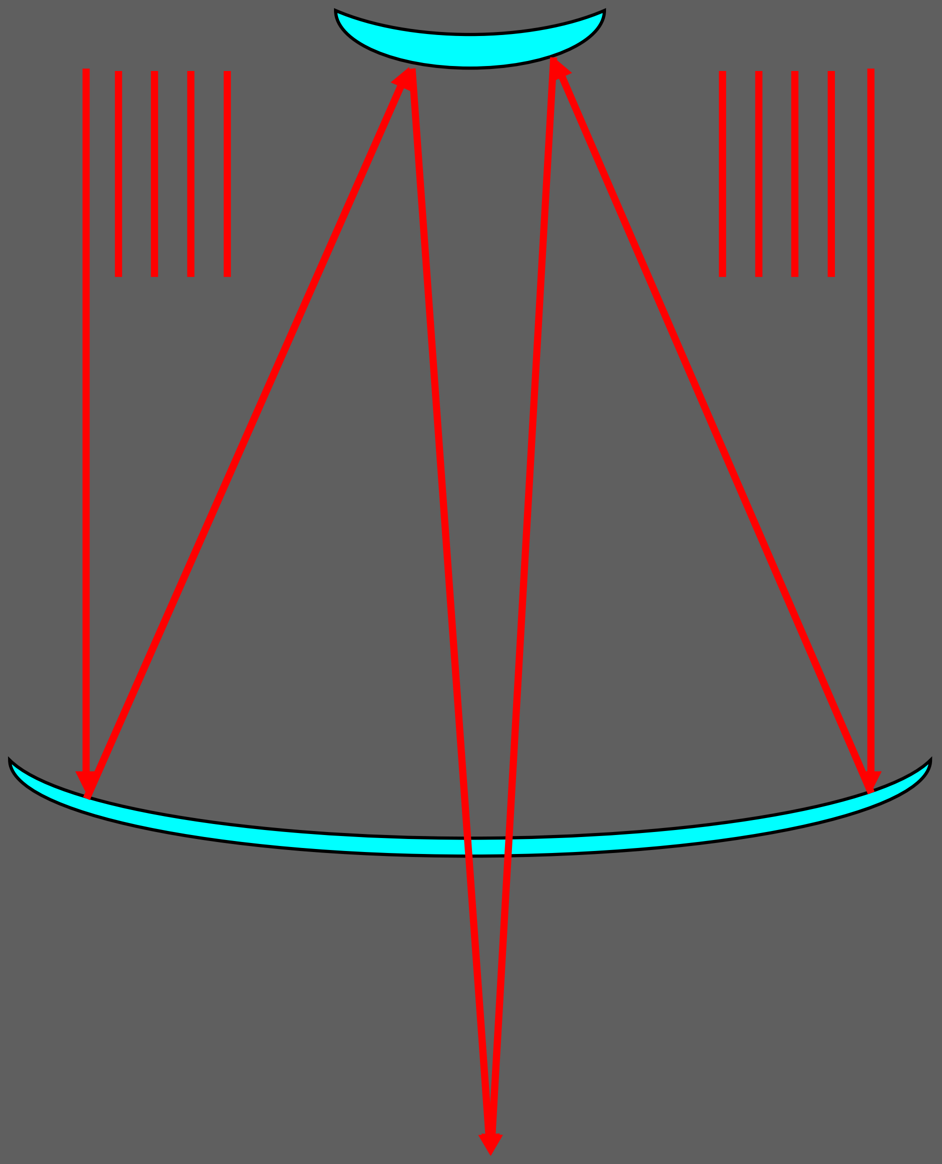
You too will be an expert in 180 seconds

The Telescope: What's Happening Inside?

- Our parallel rays enter and bounce around – **in a very special way**

- Every path of every ray from the star traces the **same pathlength** through the telescope

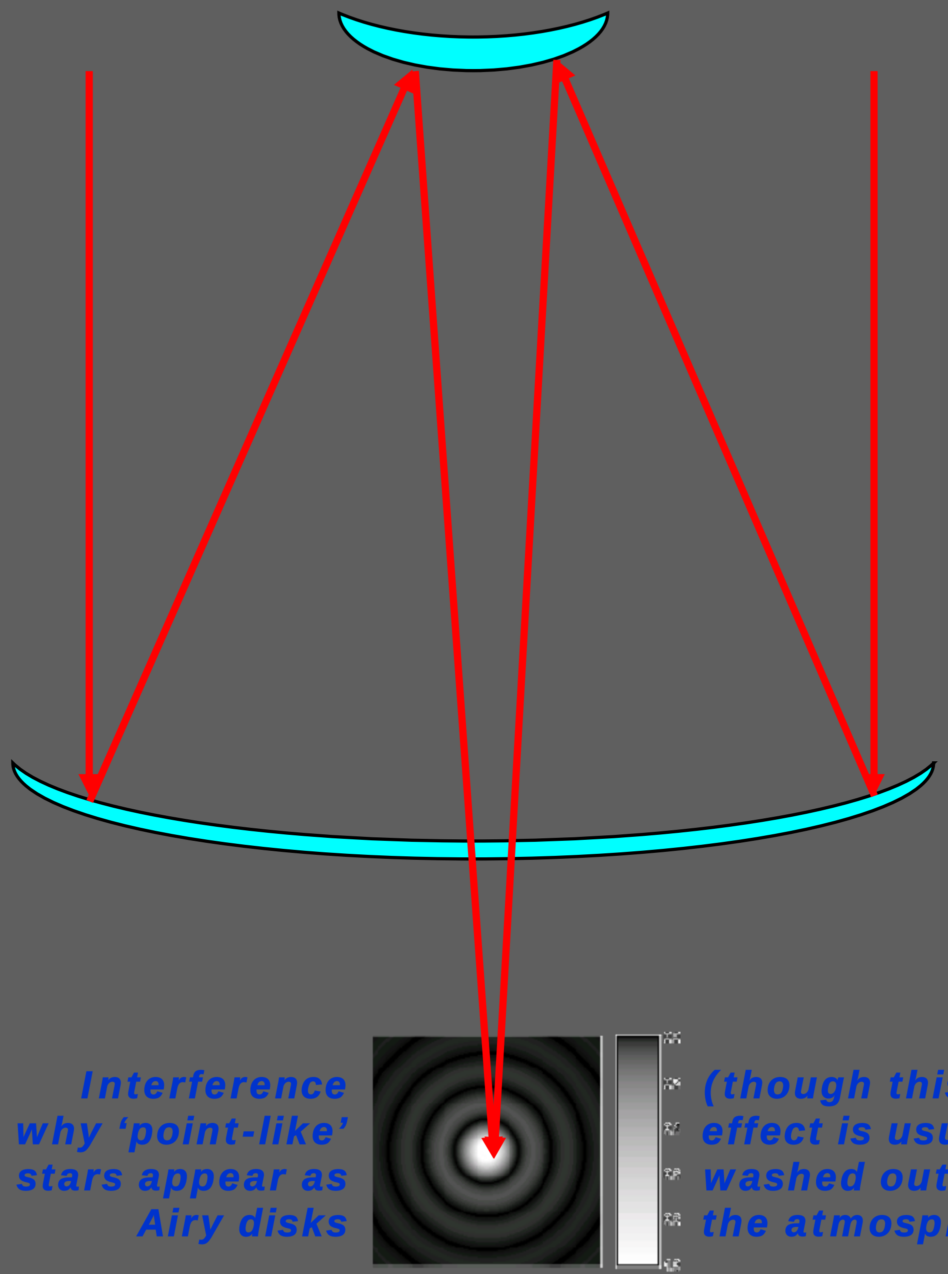




The Telescope: What's Happening Inside?

- When light rays from a source satisfy this pathlength condition, the can form an image
  - This is an 'interference phenomenon'

- Special secret: **all telescopes are interferometers**



Interference is why 'point-like' stars appear as Airy disks

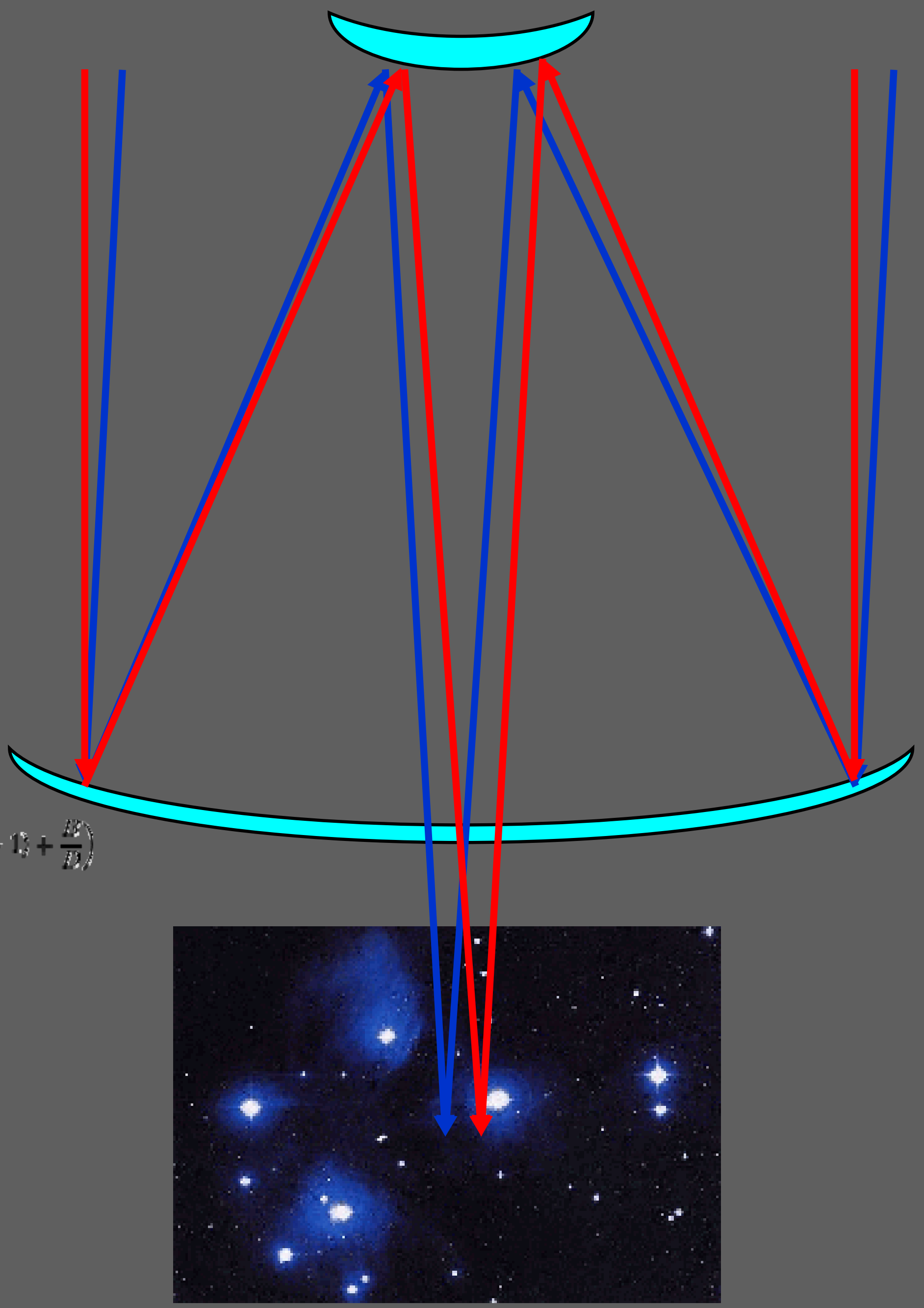
(though this effect is usually washed out by the atmosphere)

The Telescope: What's Happening Inside?

- This **pathlength condition** is true for other nearby stars in the field of view of the telescope, at slightly different angles

- This dictates the very special shape of the mirrors

$$K_1 = -1 - \frac{2}{M^3} \cdot \frac{B}{D}$$



$$K_2 = -1 - \frac{2}{(M-1)^3}\left(M(2M-1) + \frac{B}{D}\right)$$

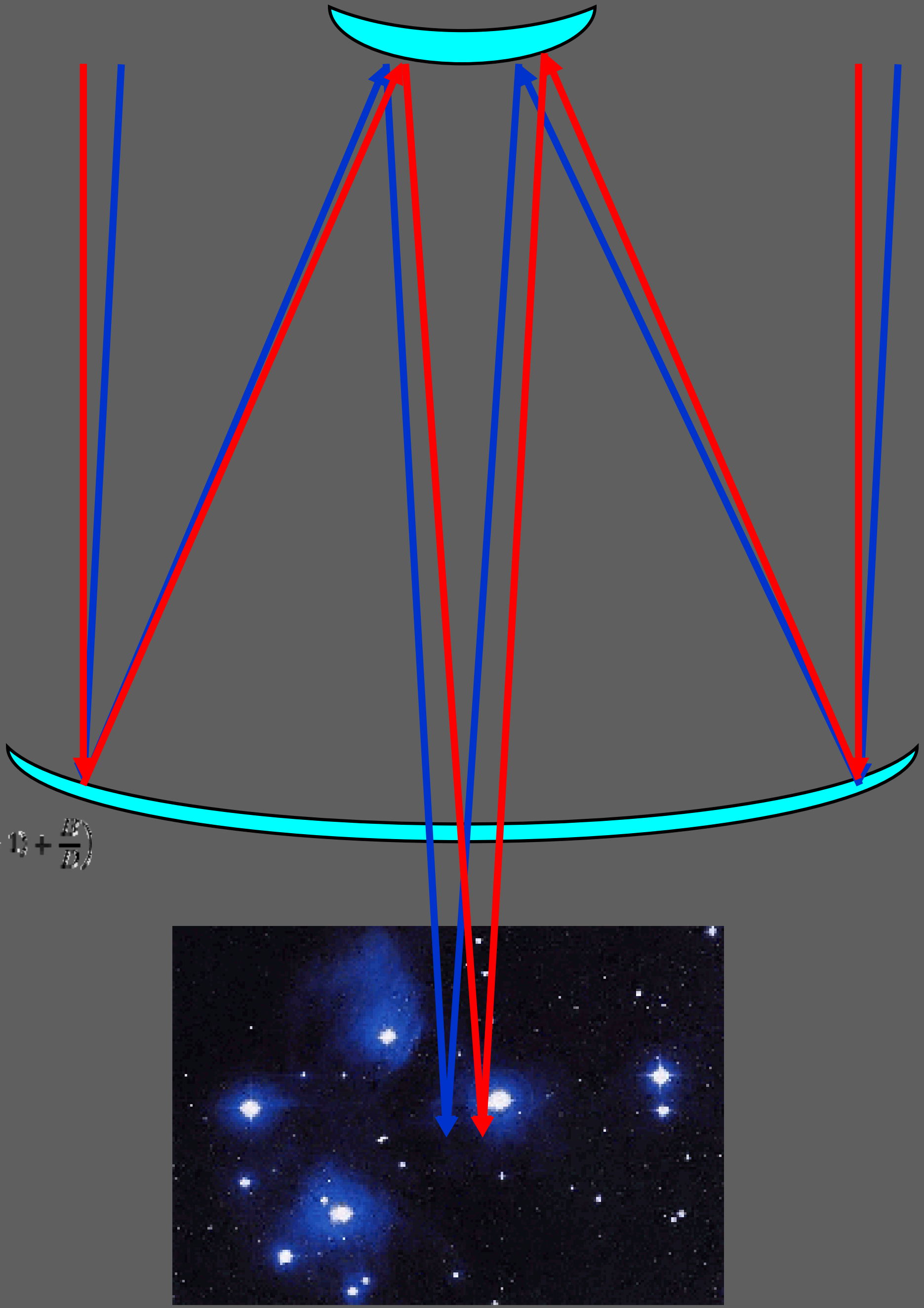
The Telescope: What's Happening Inside?

- Screw this up?

You get Hubble:

Mirror missed spec by 2000×

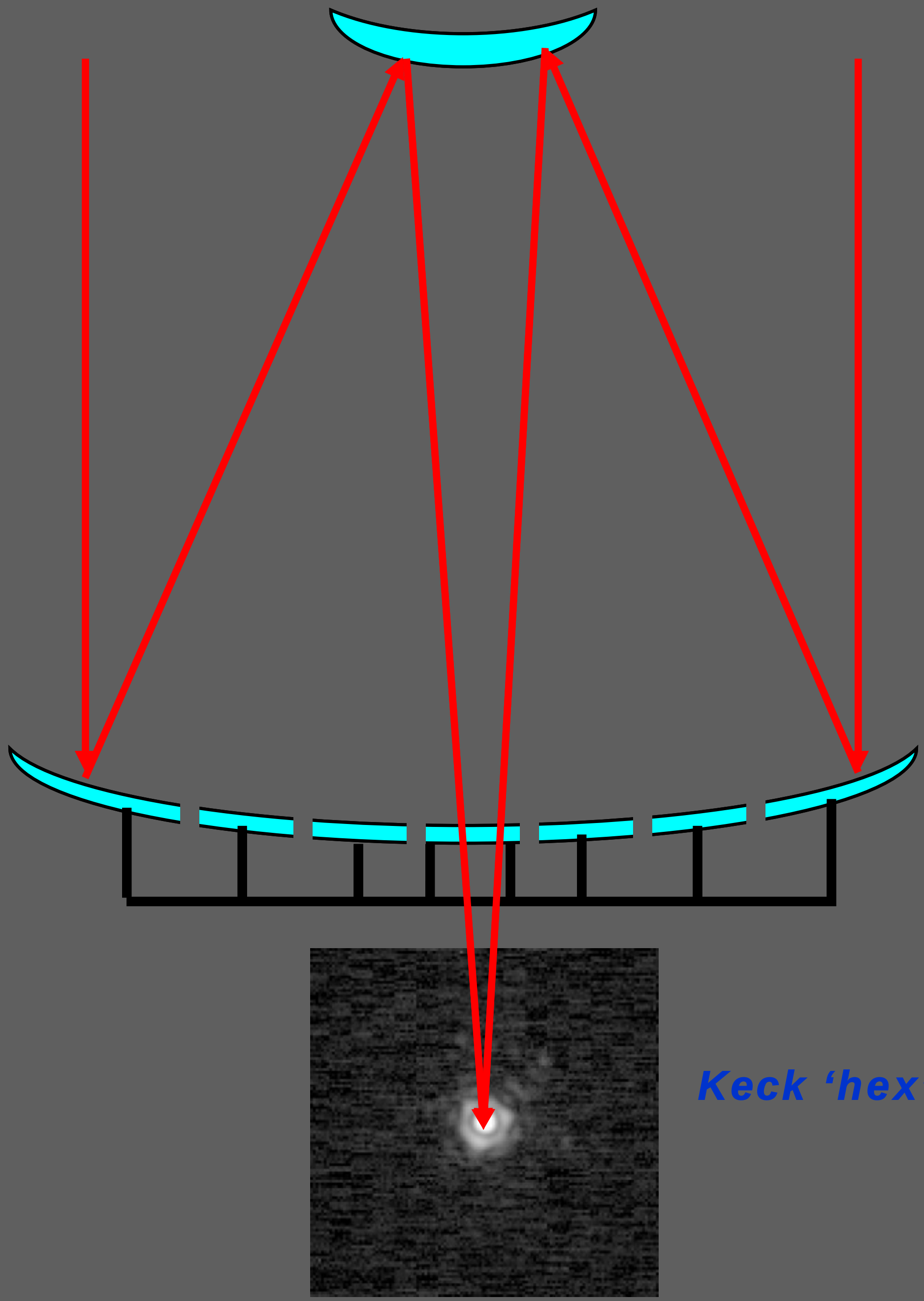
$$K_1 = -1 - \frac{2}{M^3} \cdot \frac{B}{D}$$



$$K_2 = -1 - \frac{2}{(M-1)^3}\left(M(2M-1) + \frac{B}{D}\right)$$

In the Pursuit of Clever (at the risk of Stupid)

- Here's a neat trick: satisfy the pathlength condition with separate pieces of glass for your primary mirror
- Examples: Keck, GTC, E-ELT, TMT, GMT

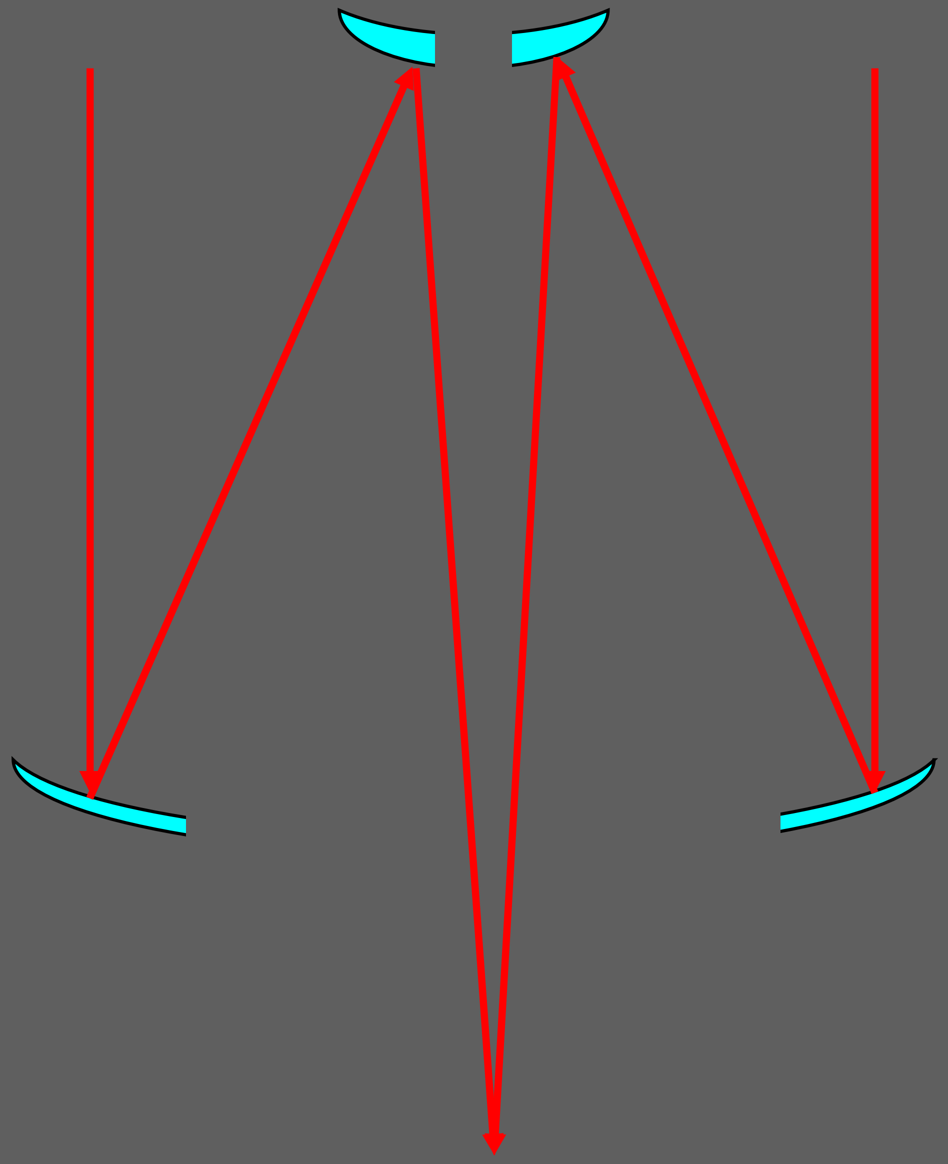


Keck 'hex' PSF

Cracking the Resolution Problem

- Taking the neat trick even further: really chop up your telescope into a **long baseline interferometer**

- This works as long as *some* light is getting to the back end, and if the pathlength condition is met
- Can make the 'diameter' very big

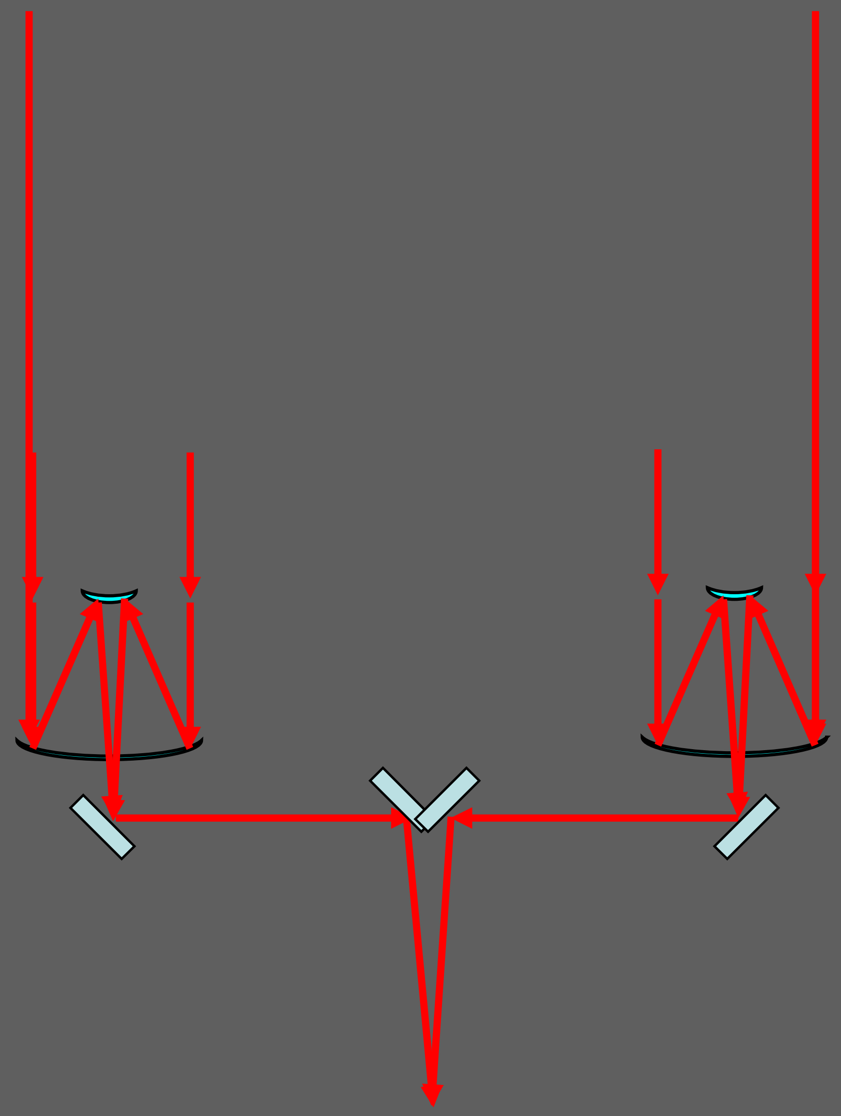


Cracking the Resolution Problem

- Taking the neat trick even further: really chop up your telescope by making it **many telescopes**
  - (Still have to satisfy the pathlength condition)

- Viola! High spatial resolution

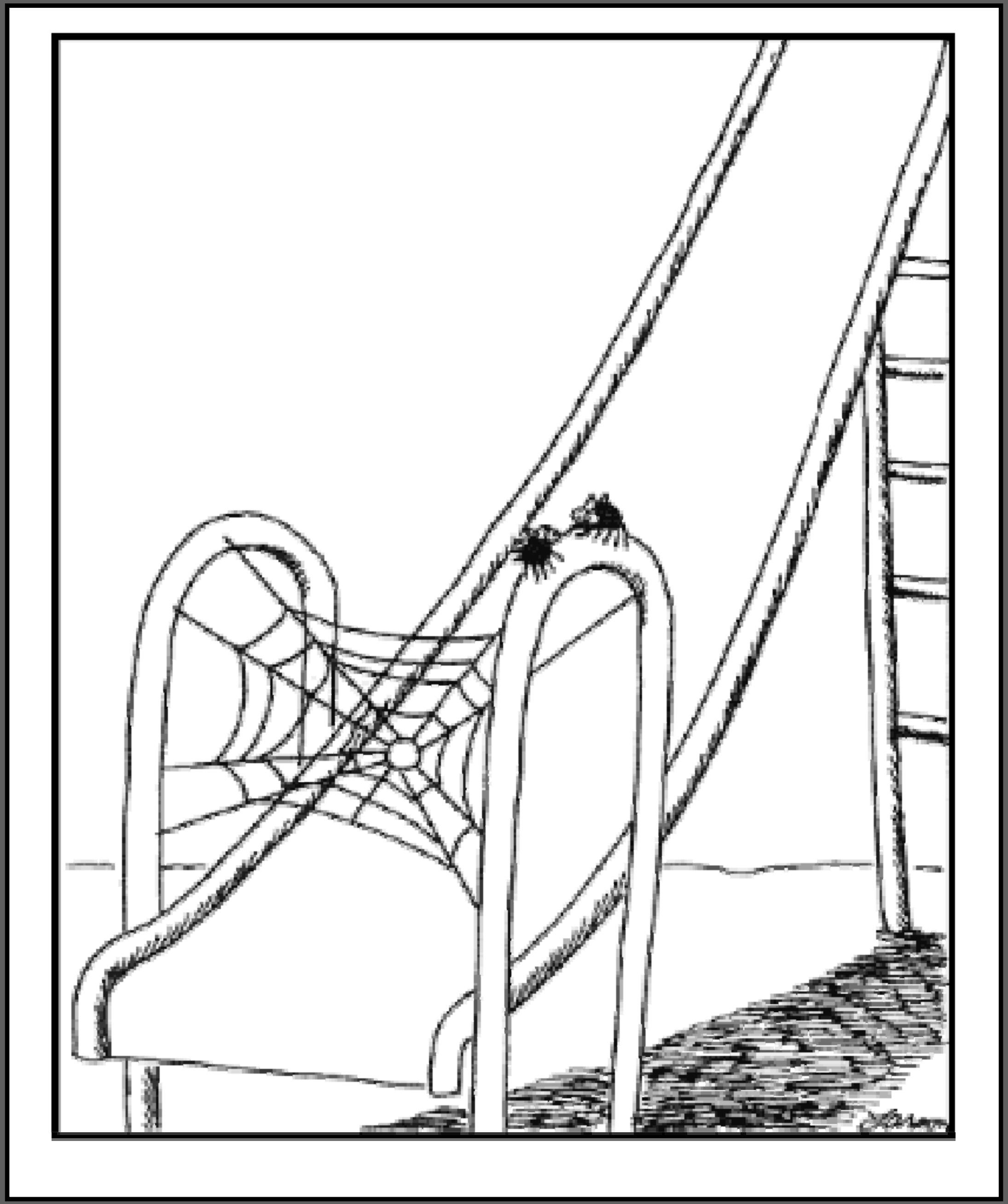
NB. for greatest sensitivity in the optical, one must mix-then-detect; for radio, detect-then-mix is OK



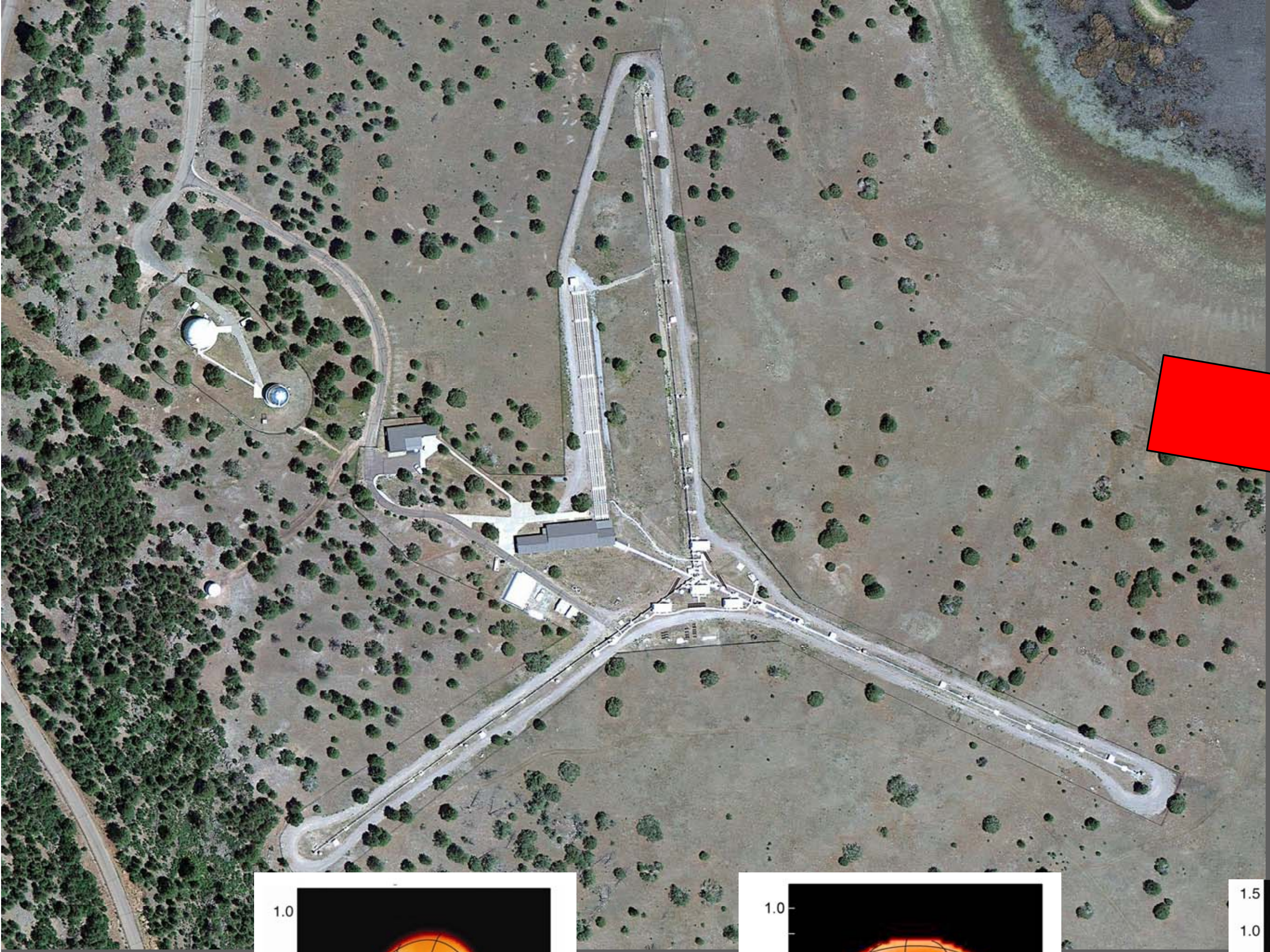
~ Thus Concludes the Lesson ~

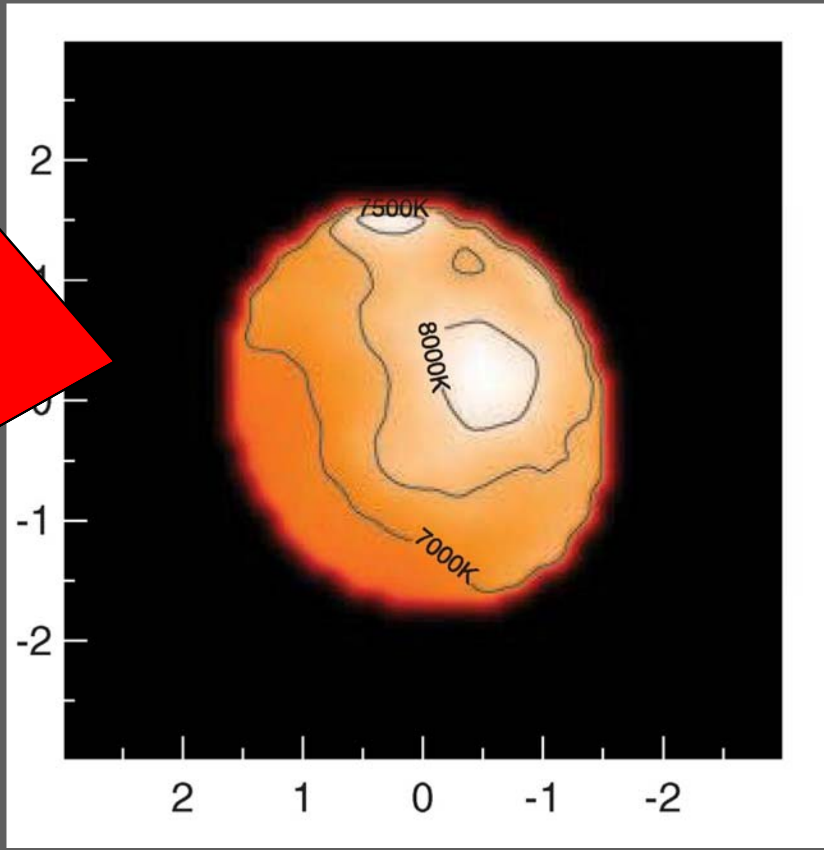
What Interferometers Really Look Like

"If we pull this off, we'll eat like kings."

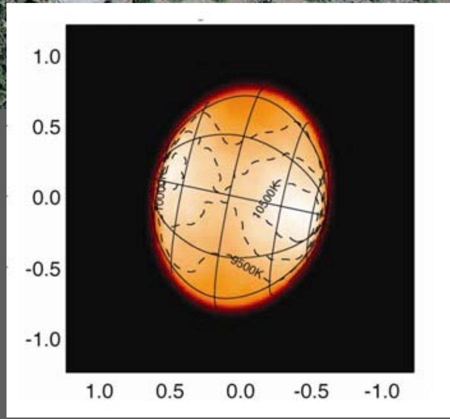


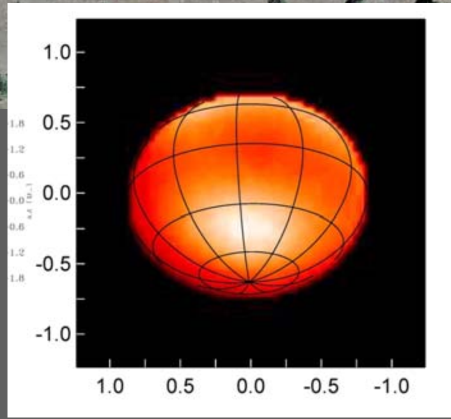
The Short Version

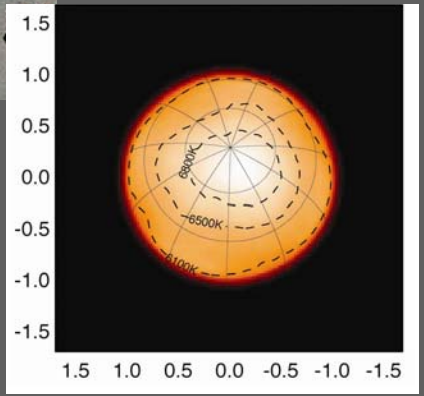


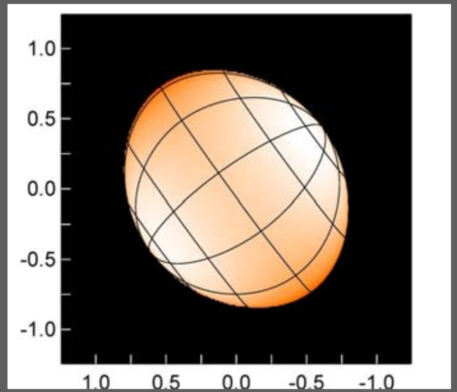


A Miracle Occurs





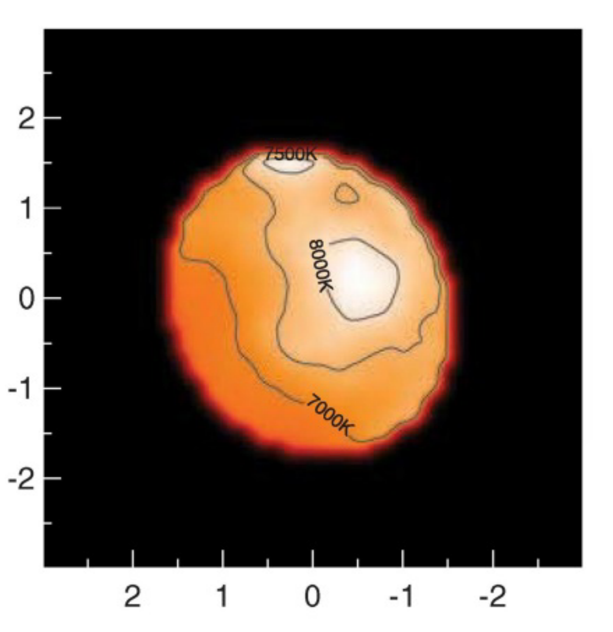


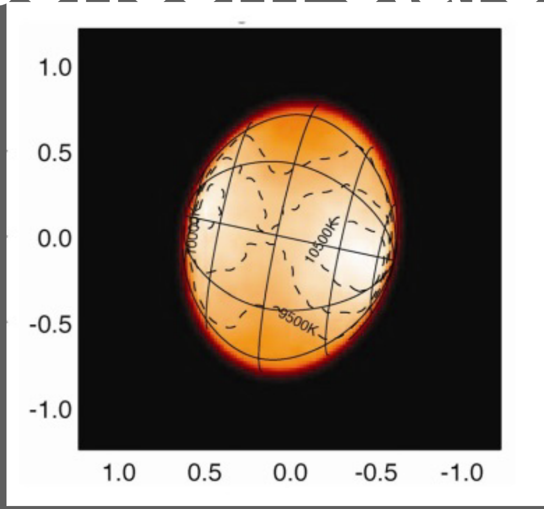


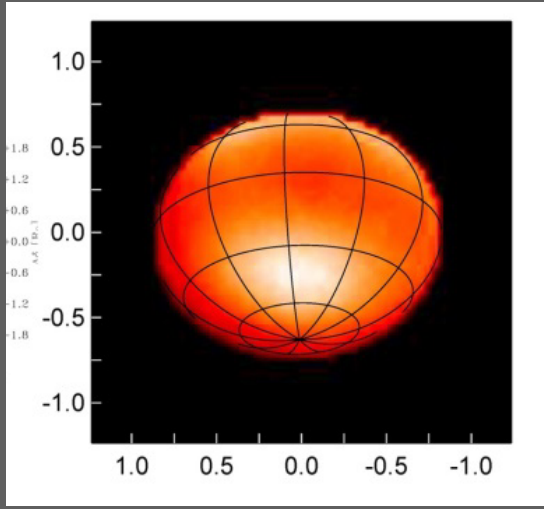
CHARA-MIRC Surface Images of Rapid Rotators

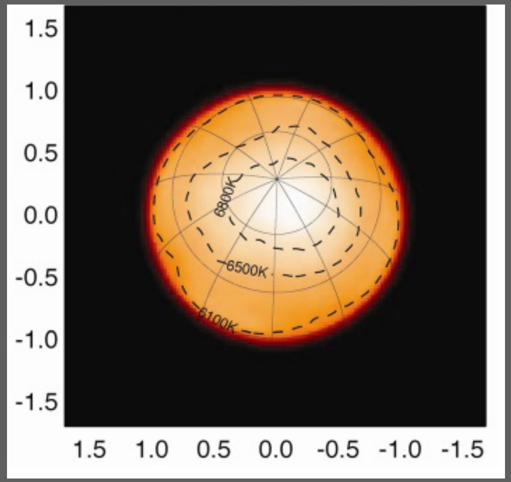
Imaging: Stars are Photogenic

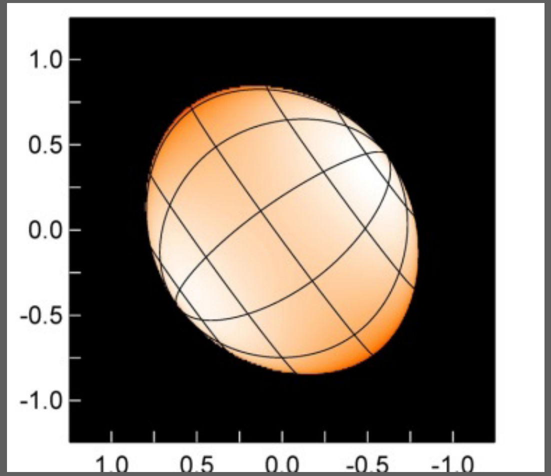
- The past 10 years
  - **Parametric modeling** at first,
  - and nowadays **Direct imaging**
- Already starting to see some surprises
  - Stellar structure not as expected from simple models, particularly gravity darkening
- Nearly 1/6 of all Astro2020 Science WPs concern stars







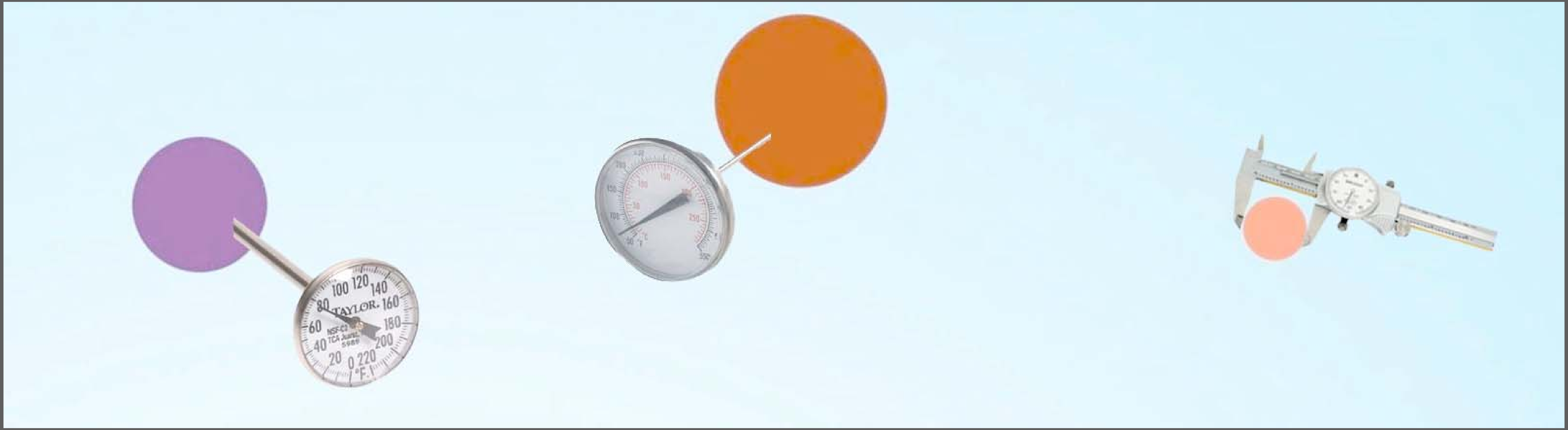




CHARA-MIRC Images of Rapid Rotators: Monnier+ 2007, Zhao+ 2009, Che+ 2011

Angular Sizes: How are they Useful?

- Spoiler alert:
  - *By themselves, they're not*



The Key: Ancillary Data

- By measuring the contrast of fringes, we directly measure the angular size of a star
  - If we know the **distance** to a star, we get its **linear size** (R)
  - If we know the **brightness** of a star, we get its **temperature** (T)
- Interestingly enough, these ancillary data are often *very hard* to directly measure
- The key here is ‘**directly**’
  - Astronomers often guess their way to R and T
  - But the guesses needed to be tested, calibrated

Fundamental Parameters from Angular Sizes

- **Linear Size**

$$R = \pi\theta$$

(the real trick here is determination of π)

- **Effective Temperature** – from definition of luminosity

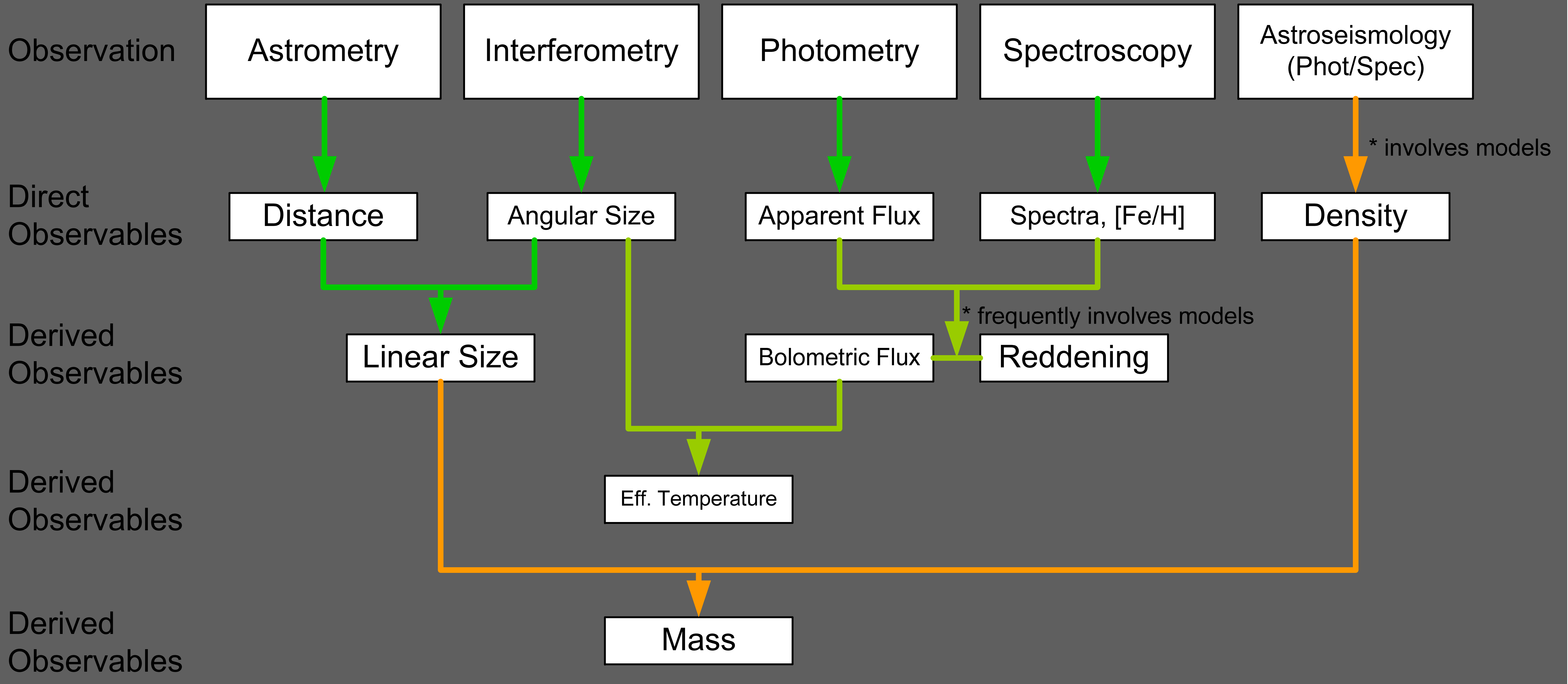
$$L = 4\pi\sigma R^2 T_{\mathrm{EFF}}^4$$

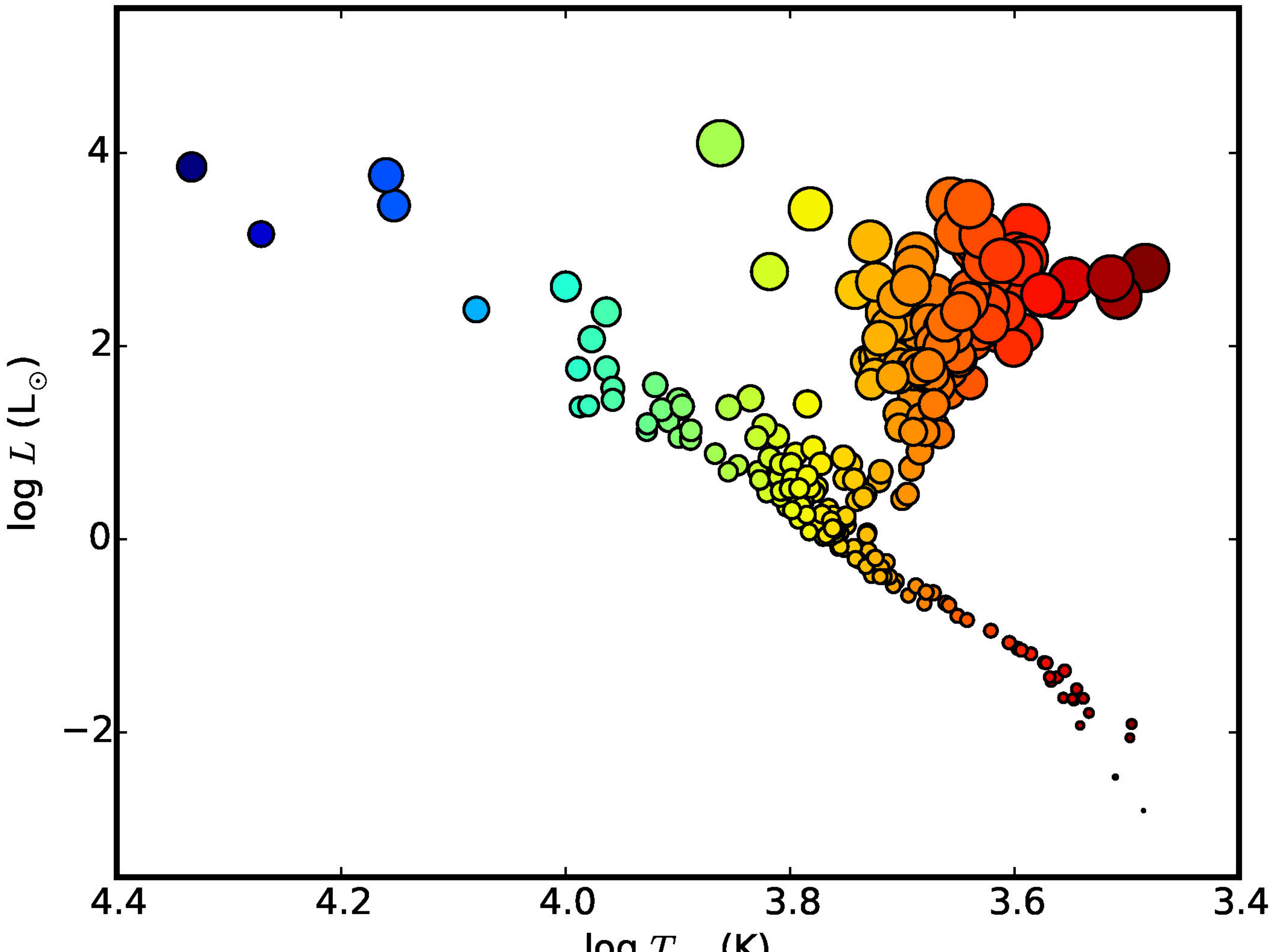
we can divide out distance and get

$$T_{\mathrm{EFF}} \propto \left(\frac{F_{\mathrm{BOL}}}{\theta^2}\right)^{1/4}$$

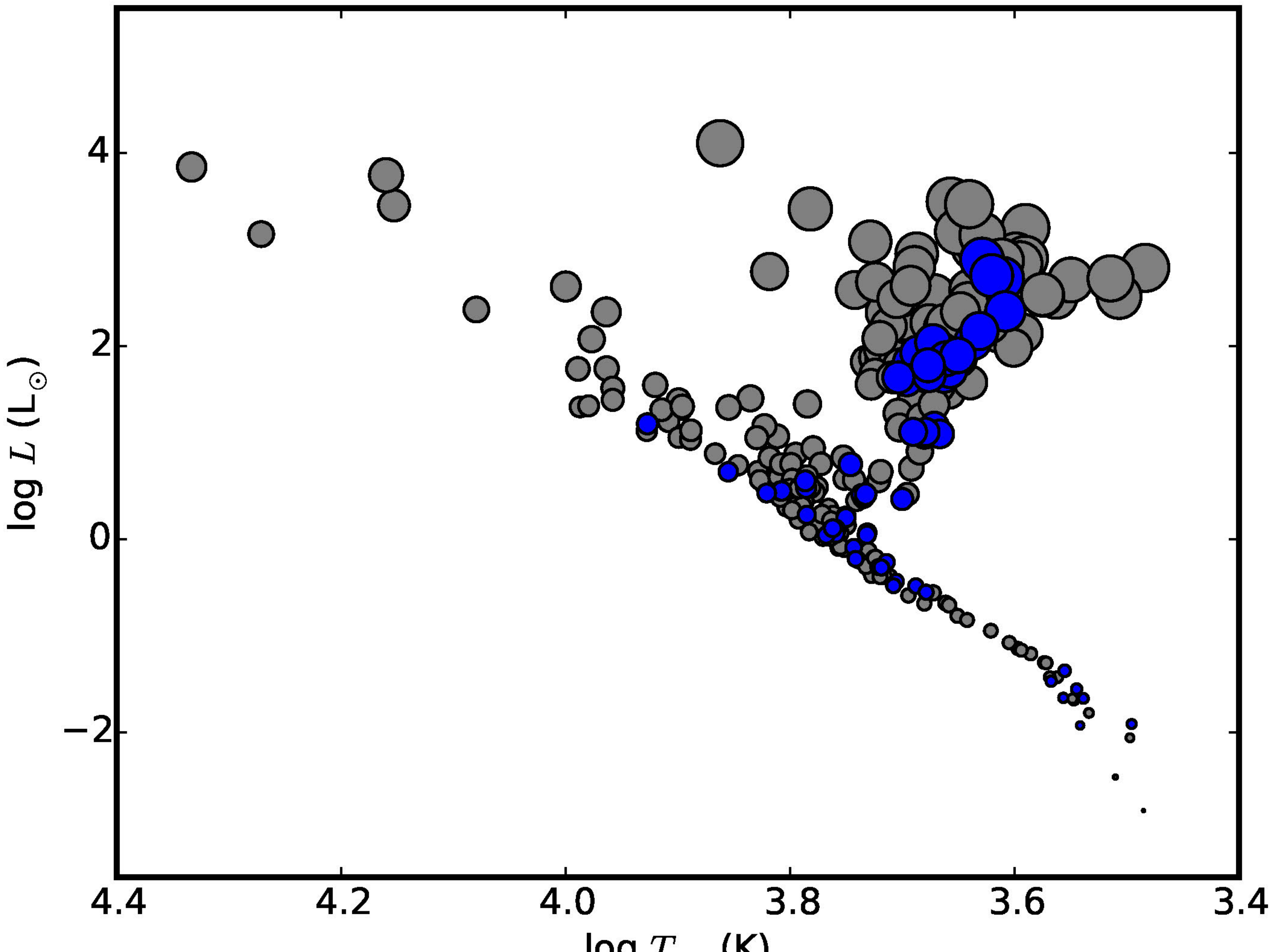
(the real trick here is determination of F_{BOL})

Tree of Fundamental Parameters: Single Stars





4
2
0
−2
log L (L$_\odot$)
4.4
4.2
4.0
3.8
3.6
3.4

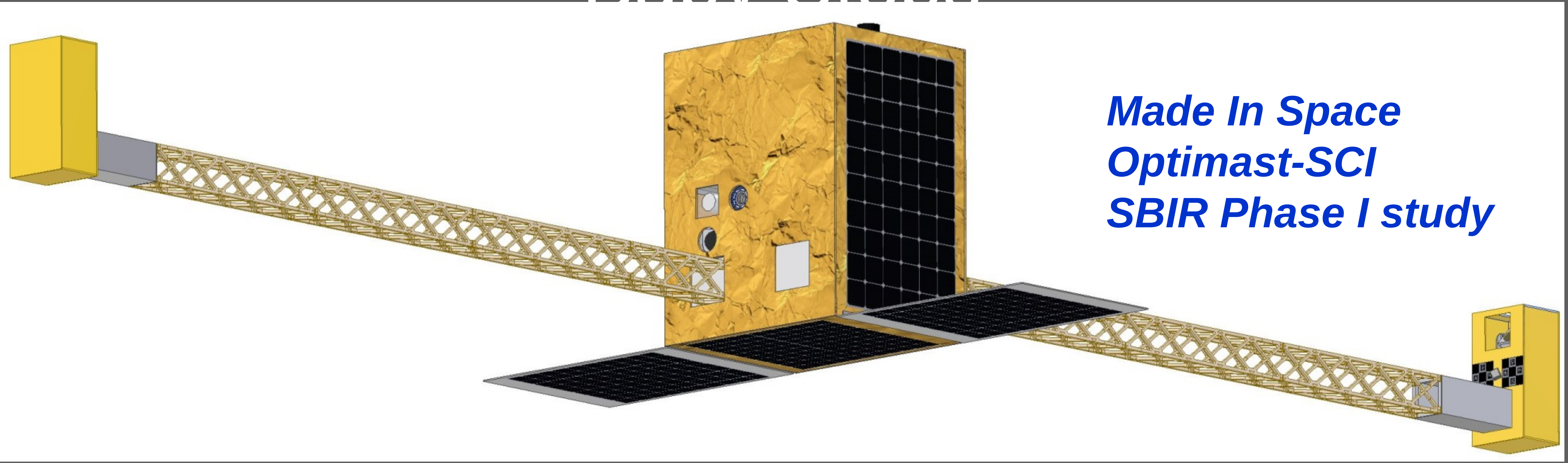


4
2
0
−2
log L (L$_\odot$)
4.4
4.2
4.0
3.8
3.6
3.4

The Frontier: Interferometry from Space

Paul Signac, “La Corne D'or, Les Minarets”, 190

Baby Steps



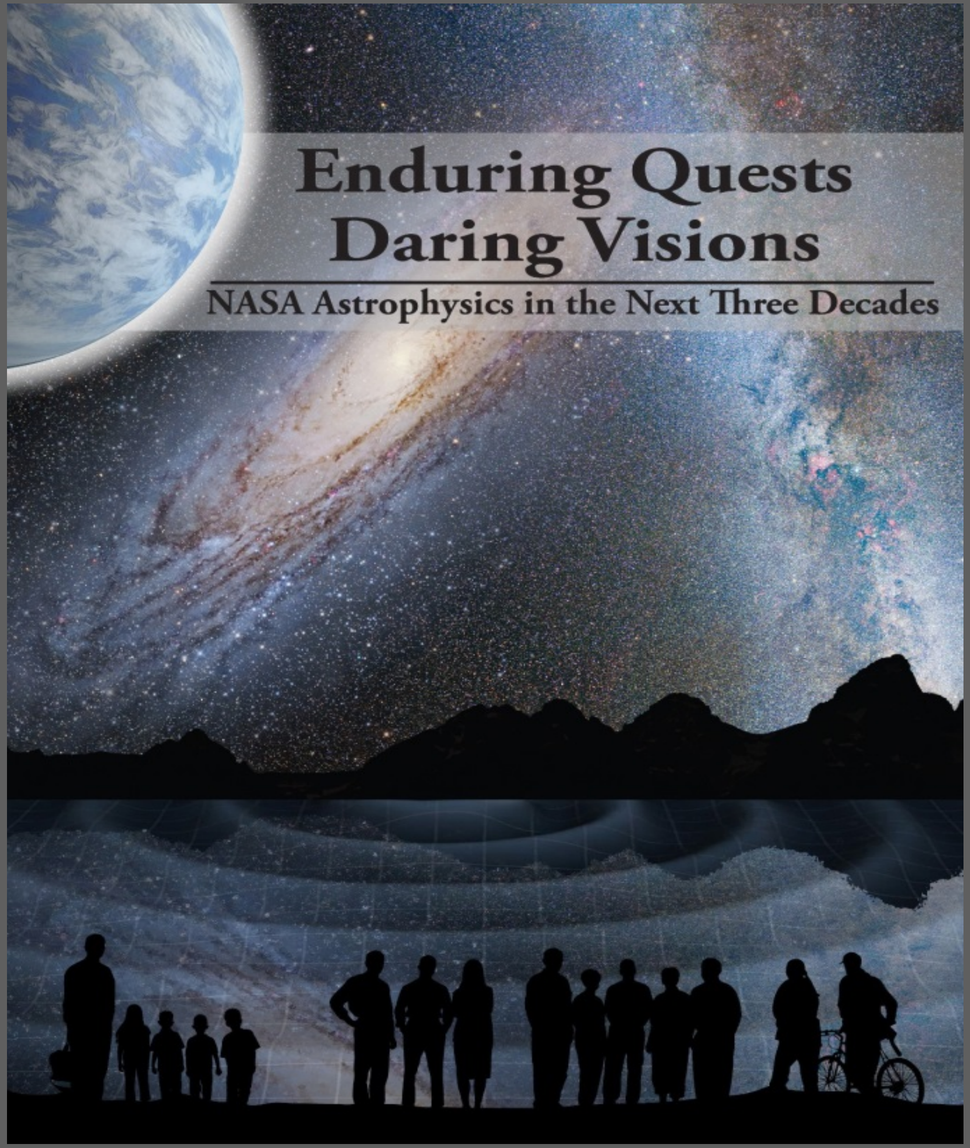
- *Simple* space interferometer
  - Based on 2×10m manufactured booms, visible operations (non-cryogenic)
- Small apertures (2”) *easily* more sensitive than CHARA, NPOI (1 meter!)

ISS Additive Manufacturing

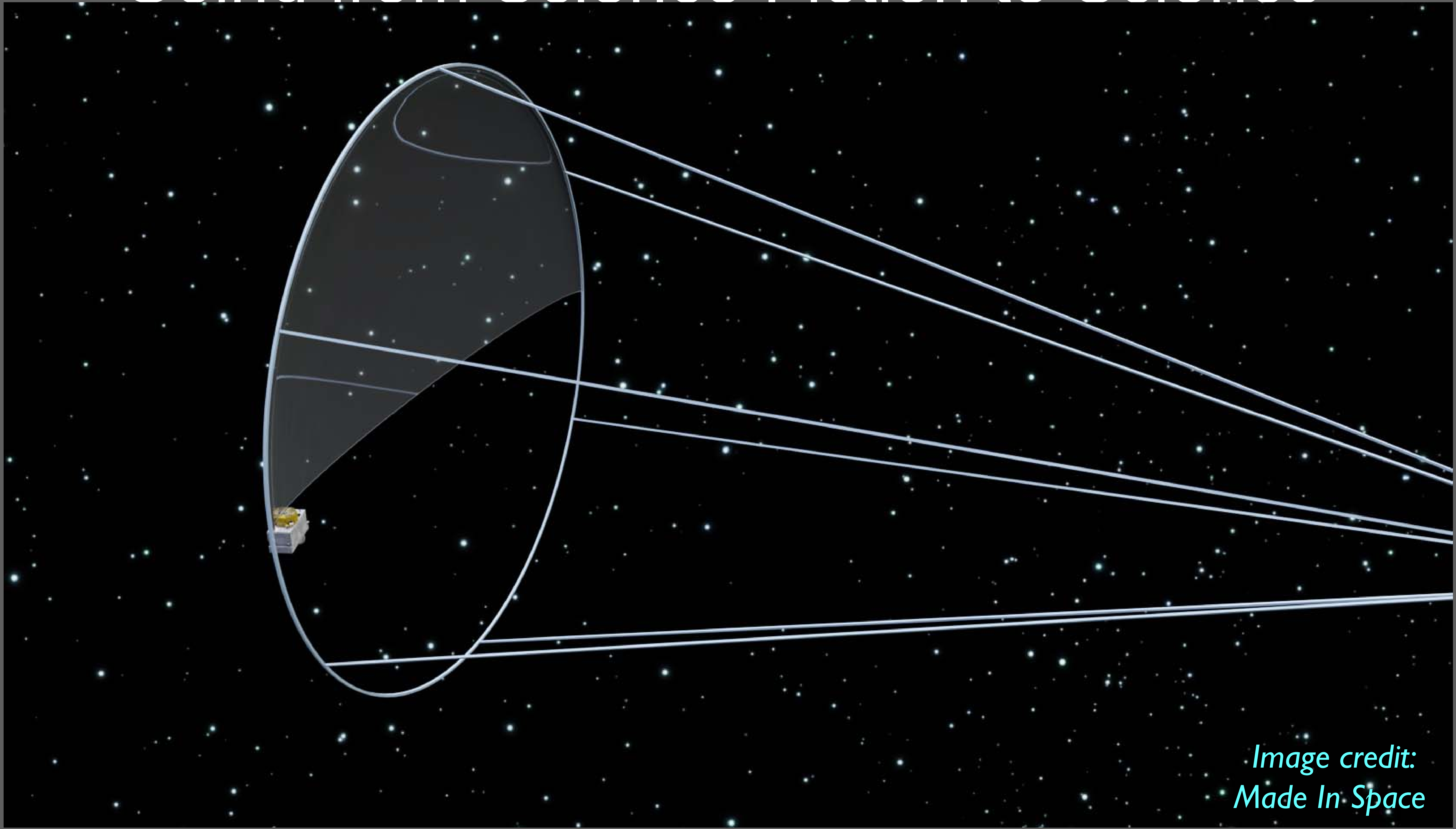
- First, second generation of additive manufacturing printers are aboard ISS
- Commercial fiber manufacturing experiment also on-board
- Further developments
  - ‘Extended structure’ manufacturing
  - Thermal/vac demonstrated

Why Do You Care?

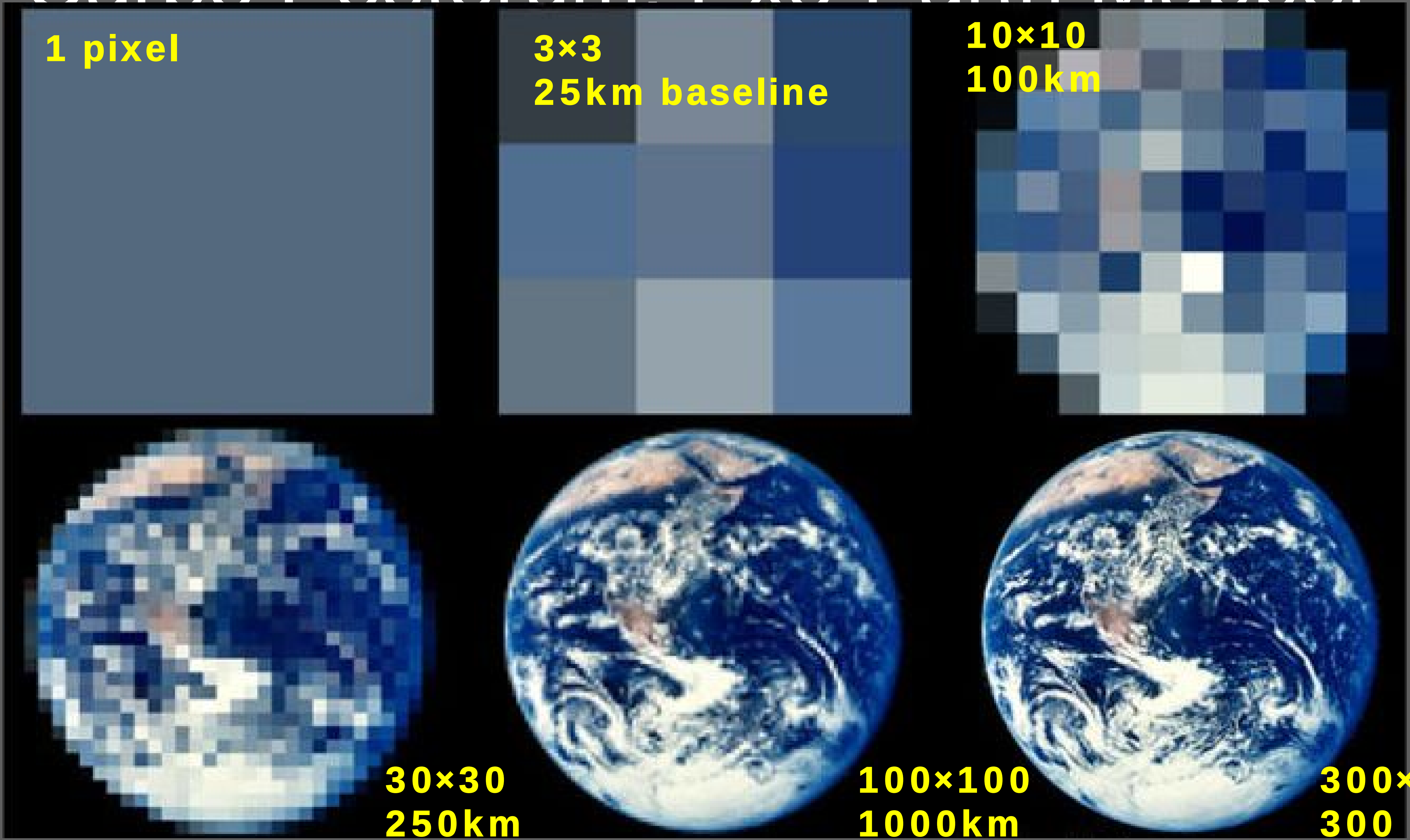
- Virtually all missions discussed in NASA's 2015 'Enduring Quests Daring Visions' report are interferometric in nature
- These tools are needed to establish the fundamental nature of the cosmos
- Astro community will need a workforce that can plan, design, implement, and use these facilities



Going from Science Fiction to Science



Carpe Posterum: Exo-Earth Mapper



Summary

- Reflection, refraction
- Diffraction
- Can be broken into a spectrum
- Wave-particle duality
- Basic tools: mirrors, lenses, prisms (dispersers)