# Optical astronomy

Optics, telescopes, and detectors

*Matt Bothwell*

# Optical astronomy

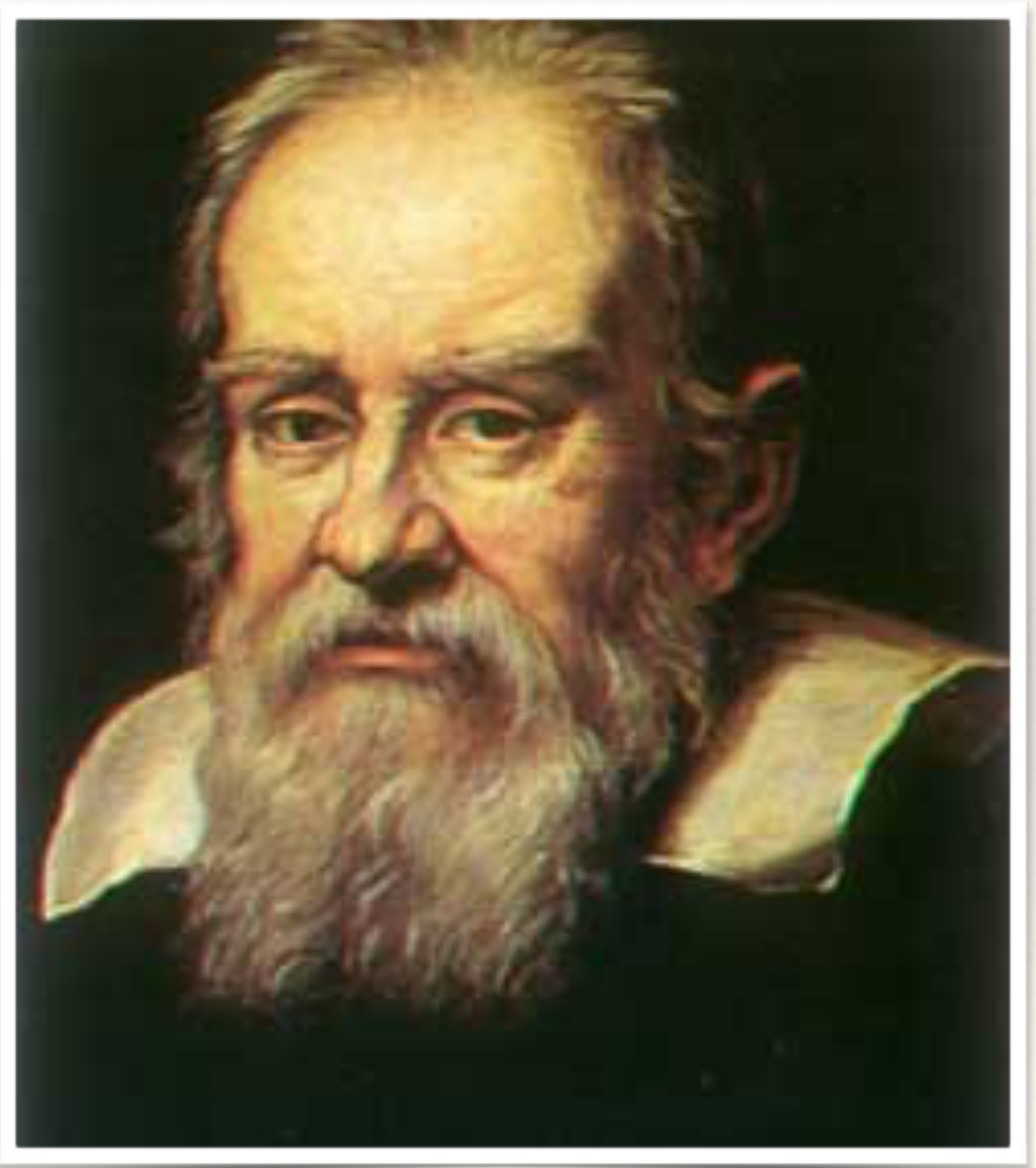
- Quick introduction to optical astronomy
- Optics
- Telescope resolution and adaptive optics
- Photometry and spectroscopy

# The telescope…

- First telescope was probably designed by Johann Lippershey (NOT Galileo!)
- Lippershey was a spectacle-maker, and in 1608 applied for a patent "for seeing things far away as if they were nearby"
- Patent never actually issued… many other people claimed to have invented it first.

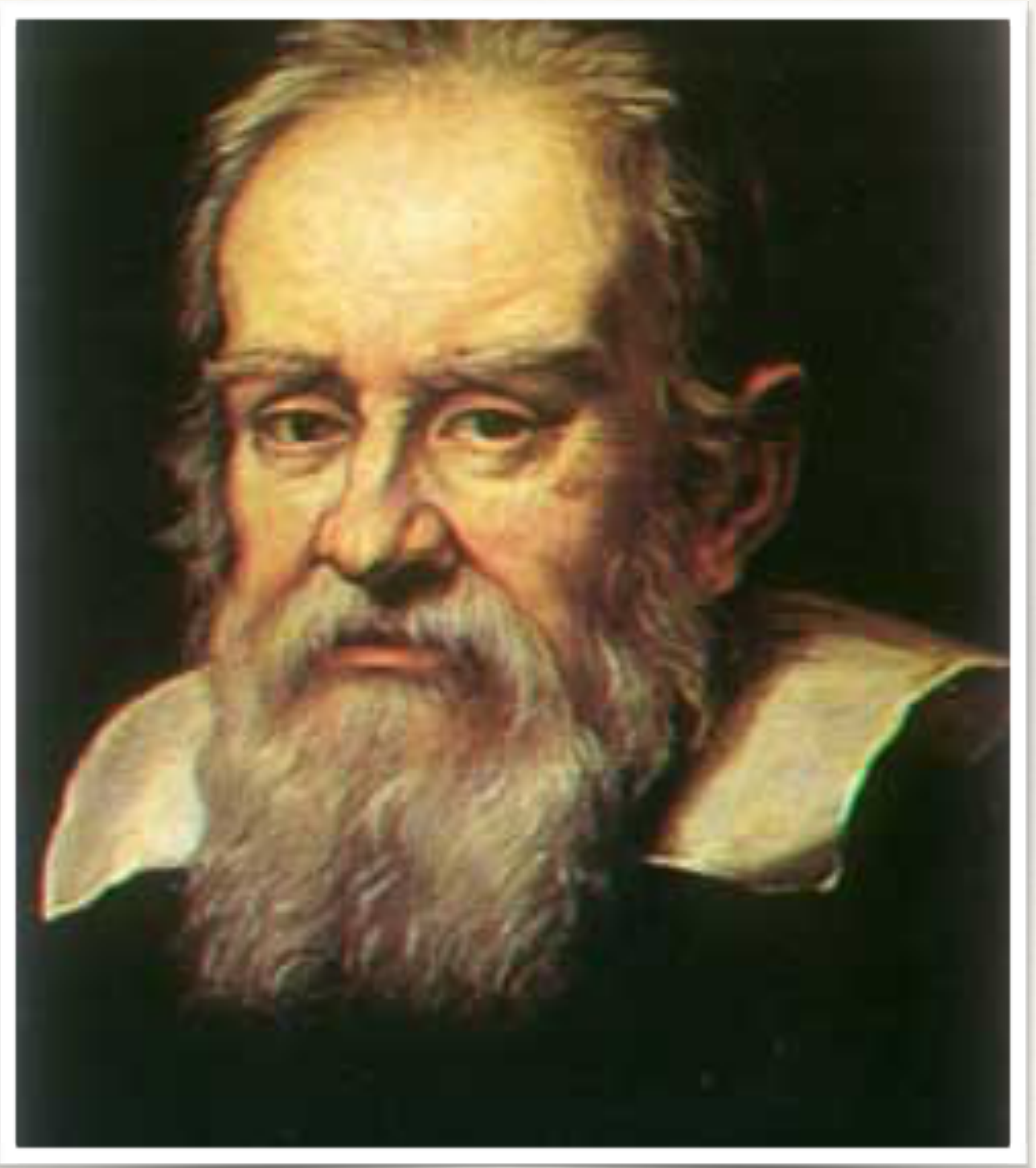
# Enter Galileo

- Galileo heard of the 'Dutch Perspective Glass', and built his own (without seeing one).
- Built it in a day, and immediately demonstrated it to Leonardo Donato (the Doge of Venice)



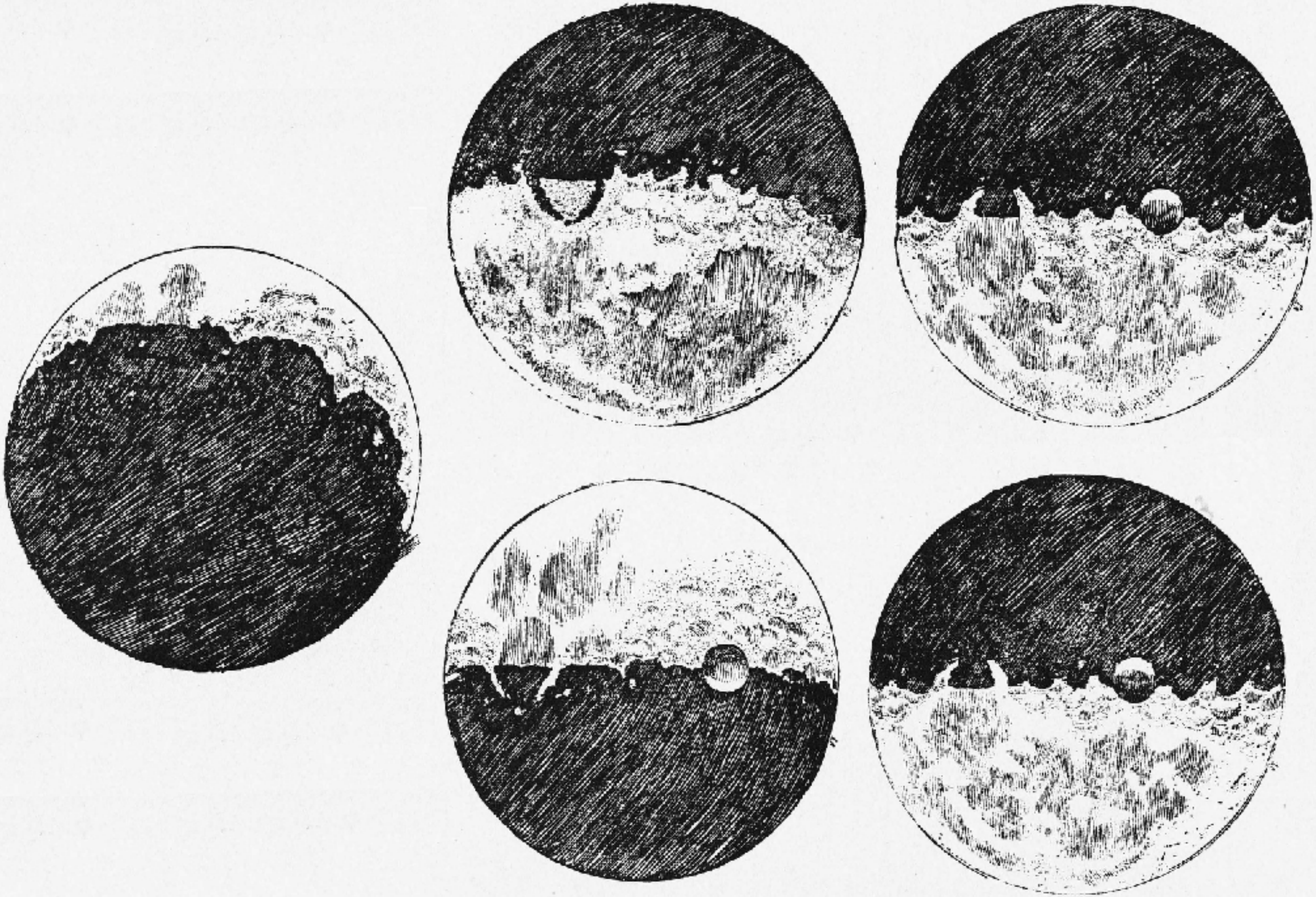
# Enter Galileo

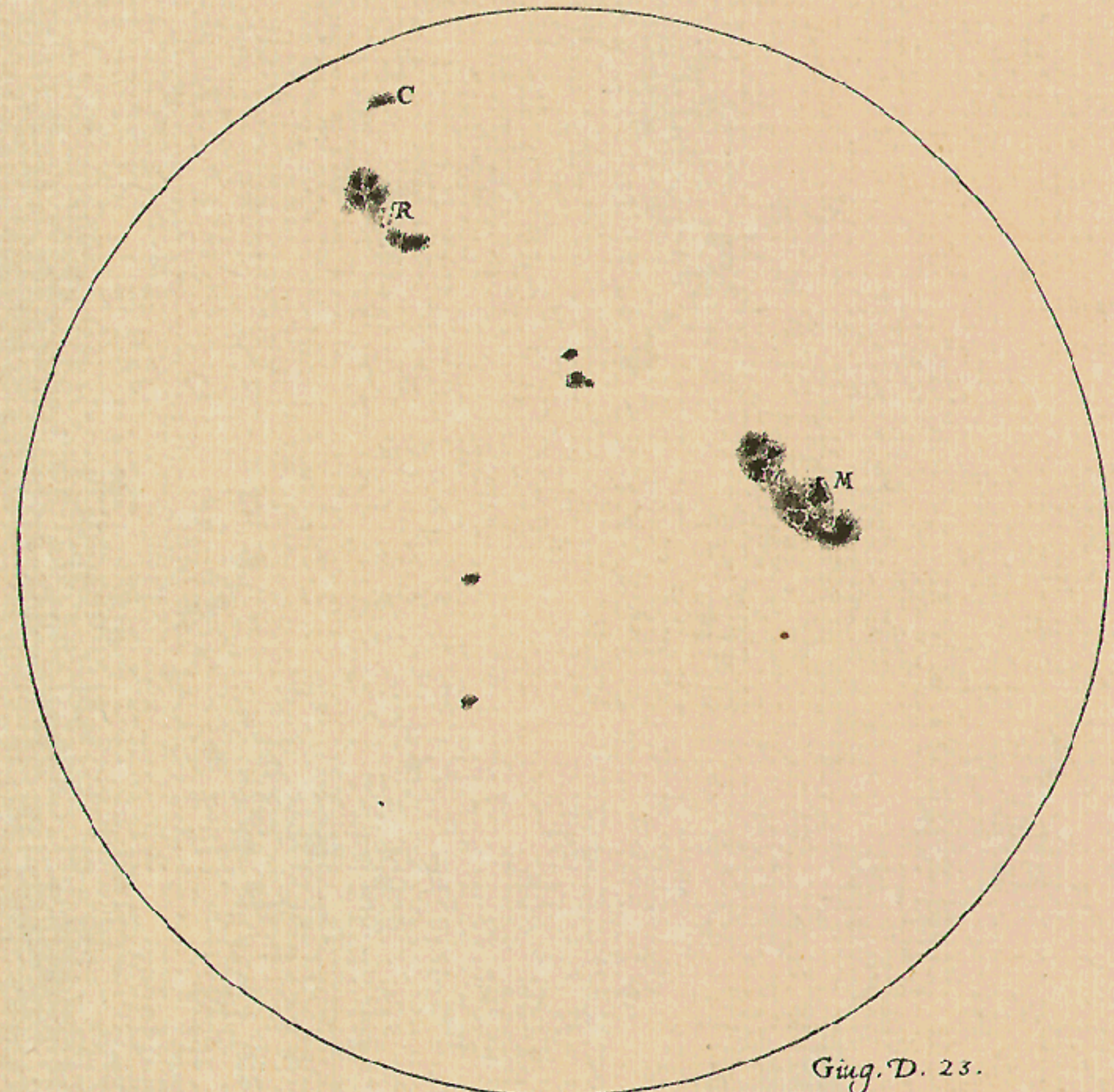
- Galileo heard of the 'Dutch Perspective Glass', and built his own (without seeing one).
- Built it in a day, and immediately demonstrated it to Leonardo Donato (the Doge of Venice)
- He was immediately awarded tenure for life, and had his salary doubled…



# Turning telescopes skywards

- Whoever actually invented the telescope, Galileo improved the design, and (importantly), was the first person to use one to look at the sky.



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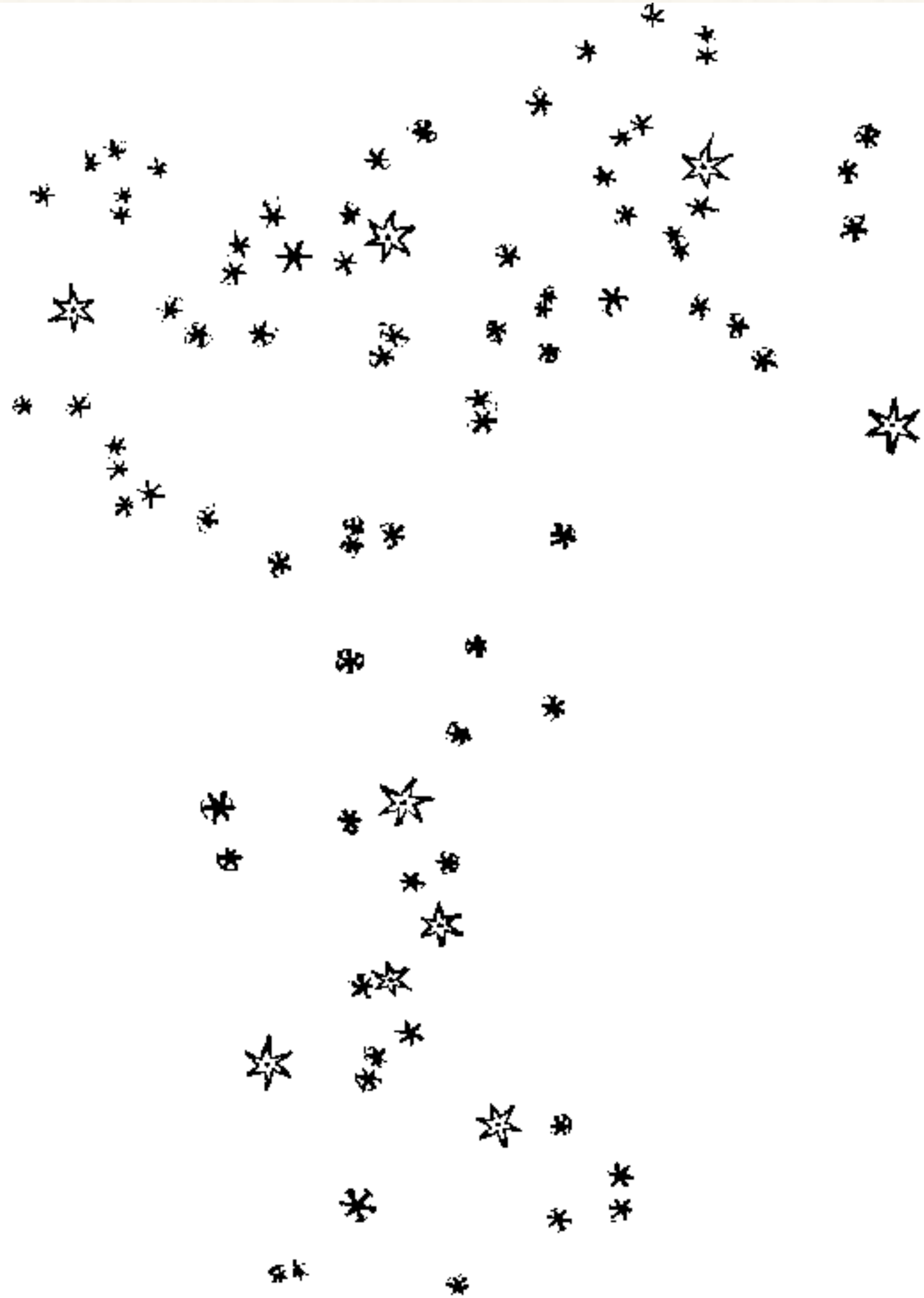

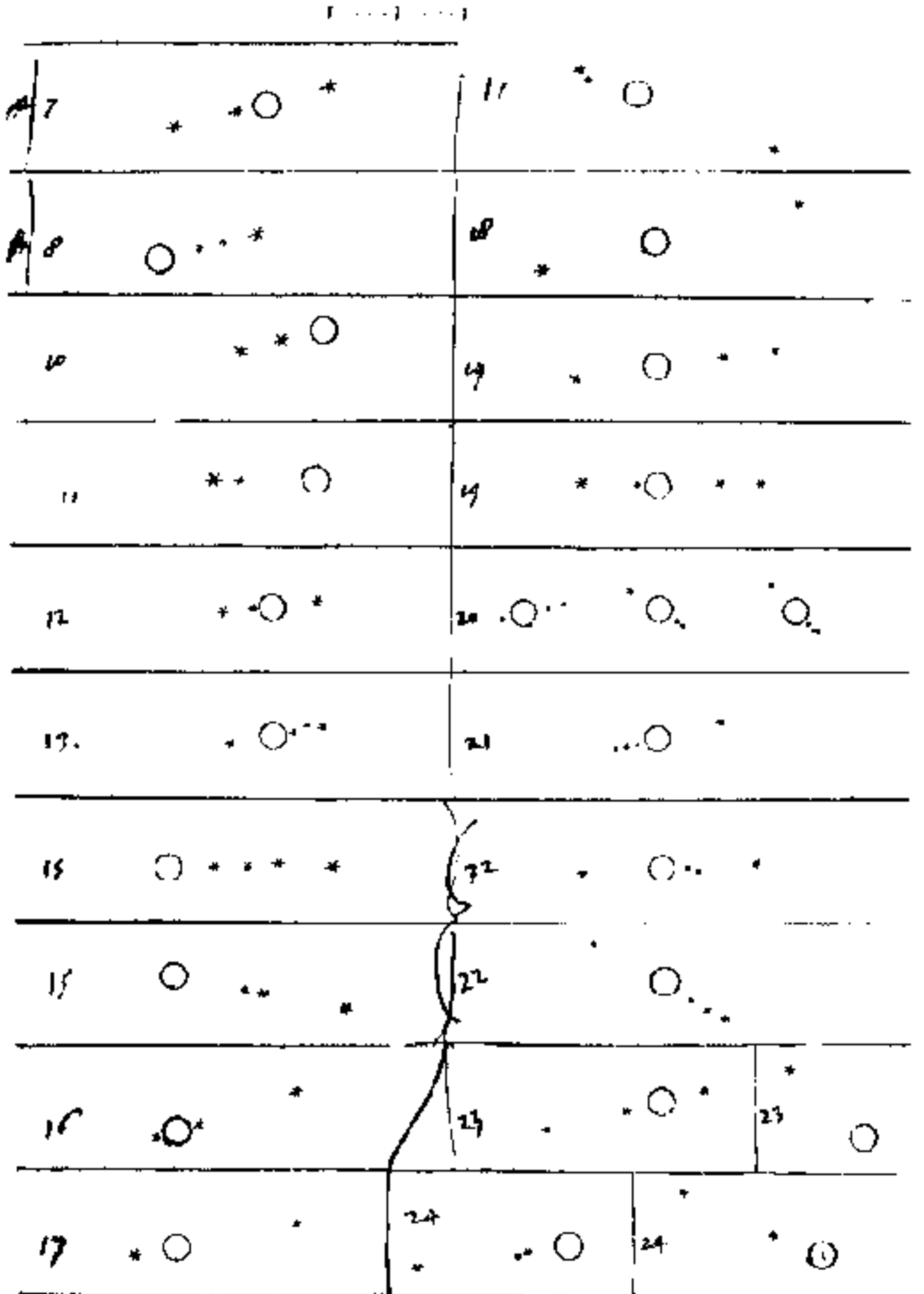
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# Reflections and refractions

- Early telescopes were *refracting* telescopes (relied on lenses to form image)… they have many problems:
- Chromatic aberration
- Size!

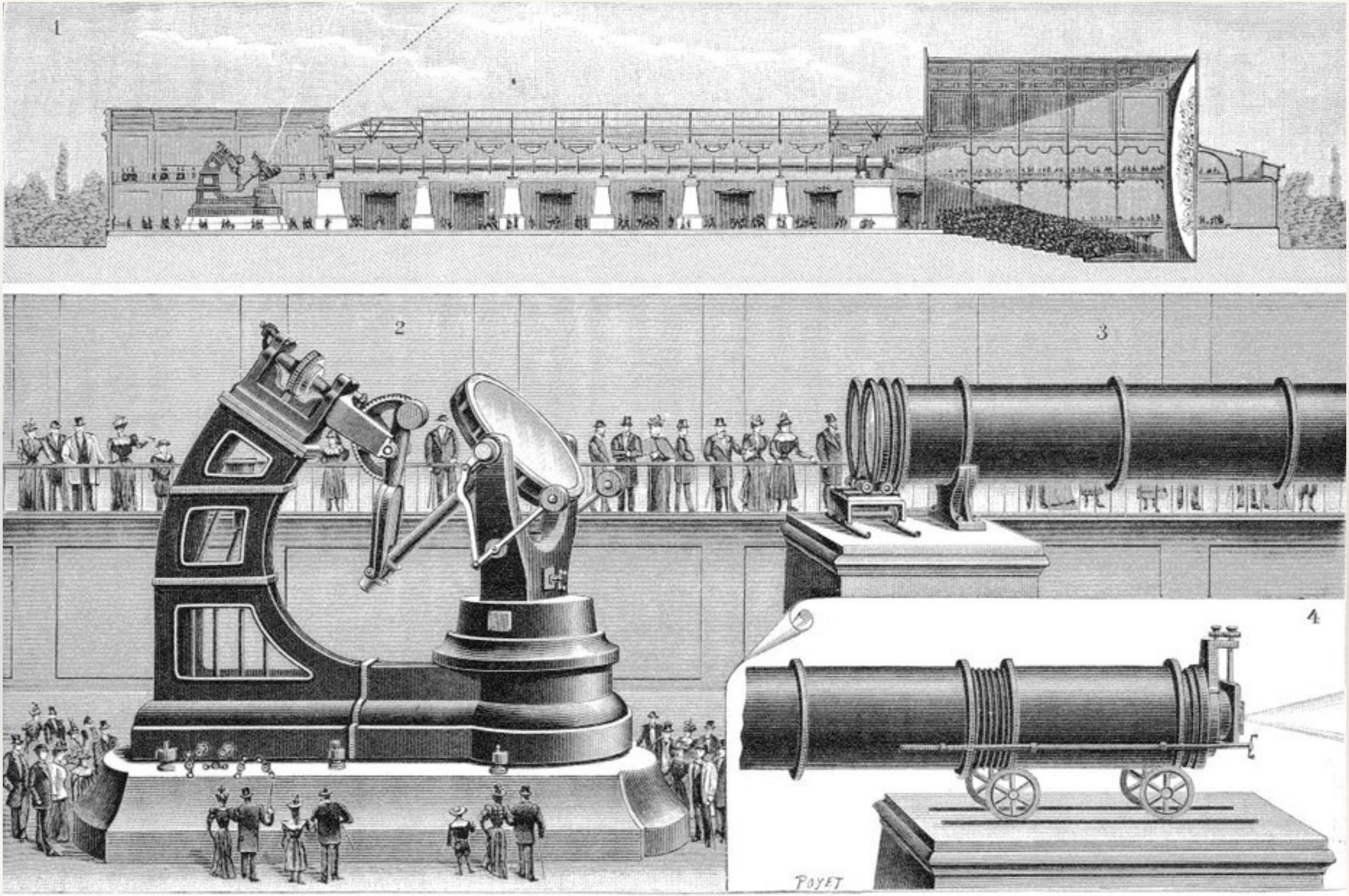
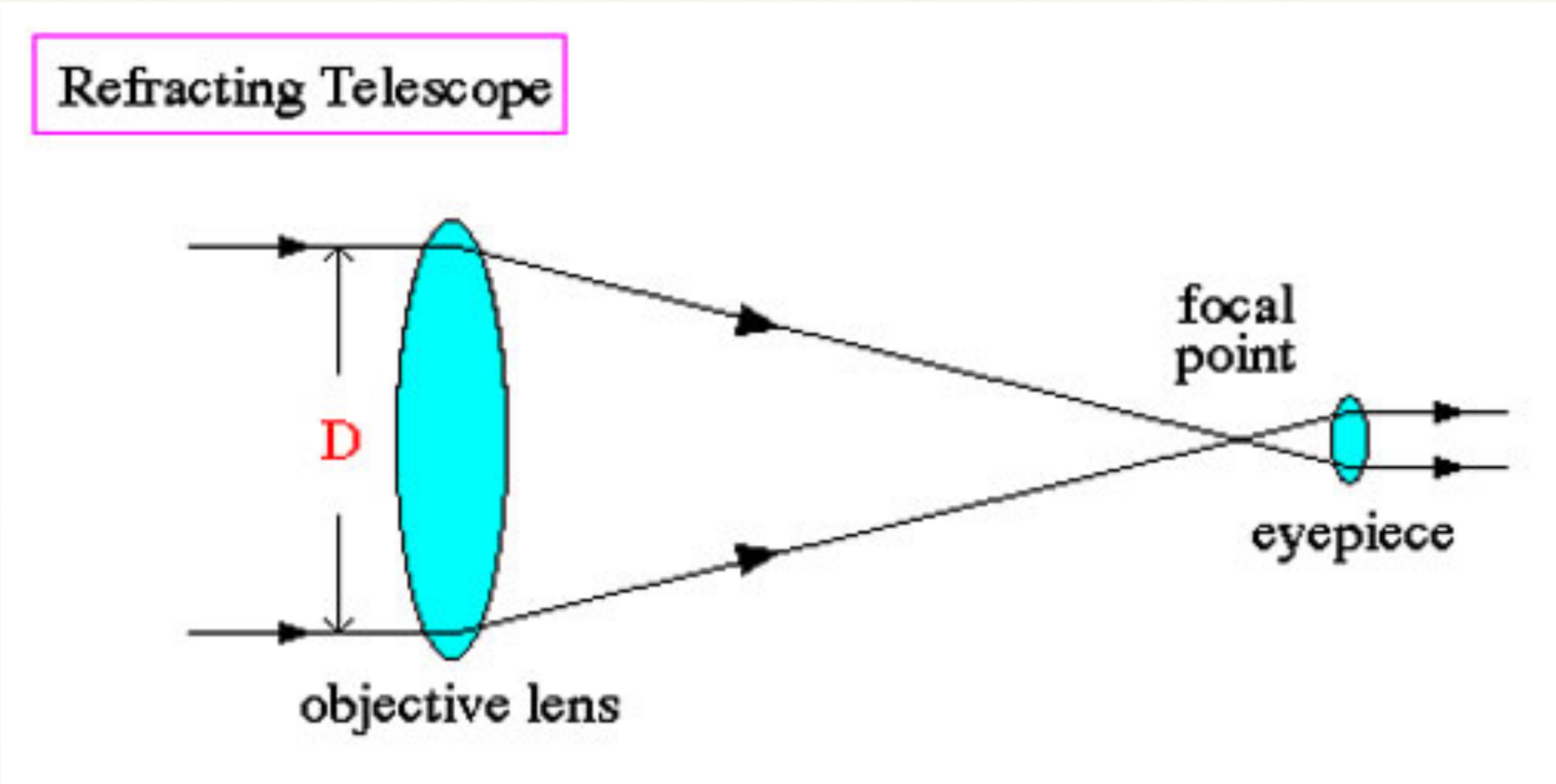



Fig. 3. — Détails de la grande lunette. — 1. Vue d'ensemble. — 2. Le sidérostat. — 3. La lunette. — 4. L'oculaire.

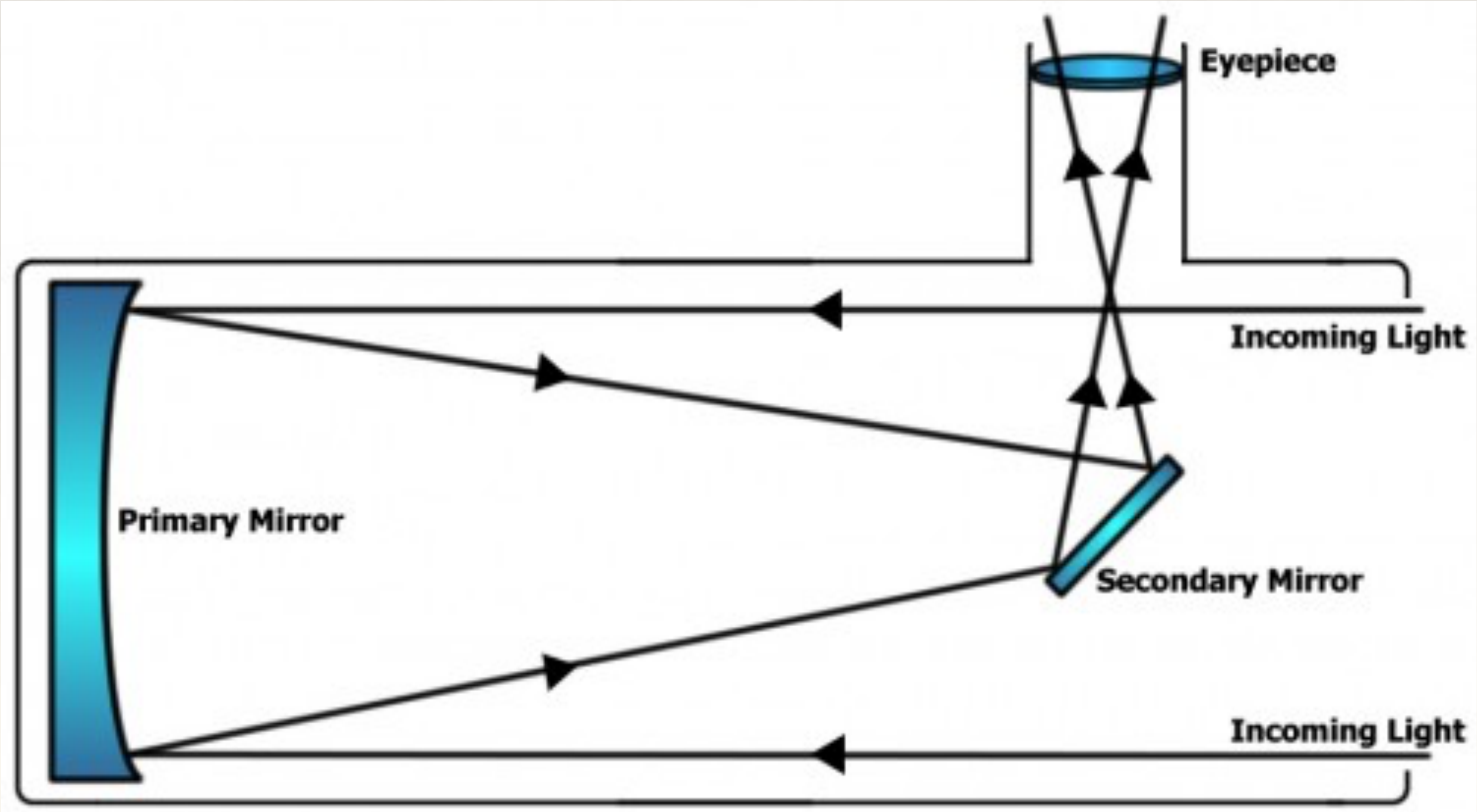
# Reflections and refractions

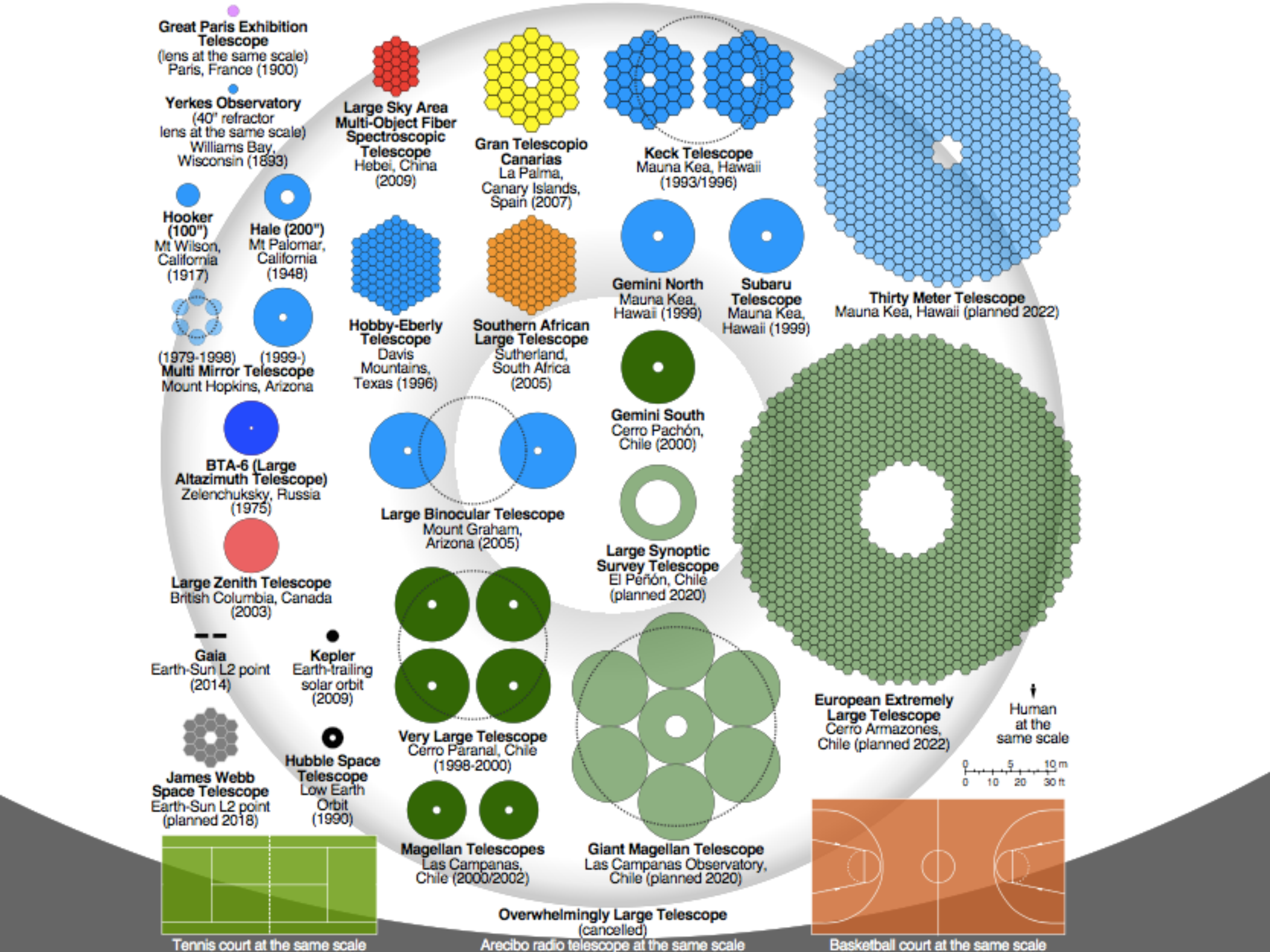
- Early telescopes were *refracting* telescopes (relied on lenses to form image)… they have many problems:
- Chromatic aberration
- Size!
- Since 1734, the world's largest telescope has always been a *reflector*

Refractor




Reflector




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)
Tennis court at the same scale
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)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, 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
Overwhelmingly Large Telescope
(cancelled)
Arecibo radio telescope at the same scale
Basketball court at the same scale

# Optical astronomy

- Quick introduction to optical astronomy
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- Telescope design and adaptive optics
- Detector technology

# Fermat's principle

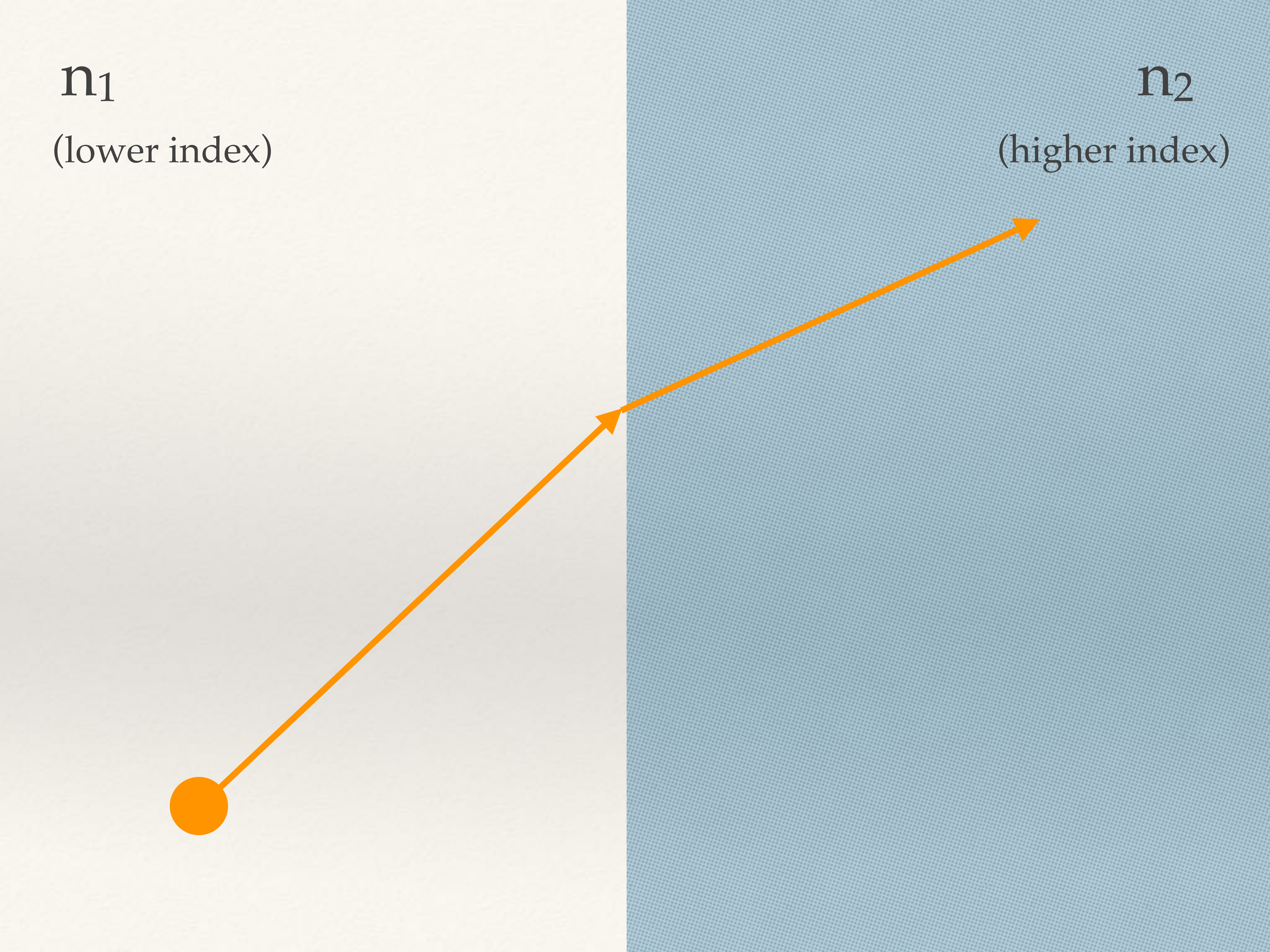
- Fermat's principle of *least time:*
- **"Light travels through the path in which it can reach the destination in least time"**
- This basic idea can be used to derive all laws of reflection and refraction

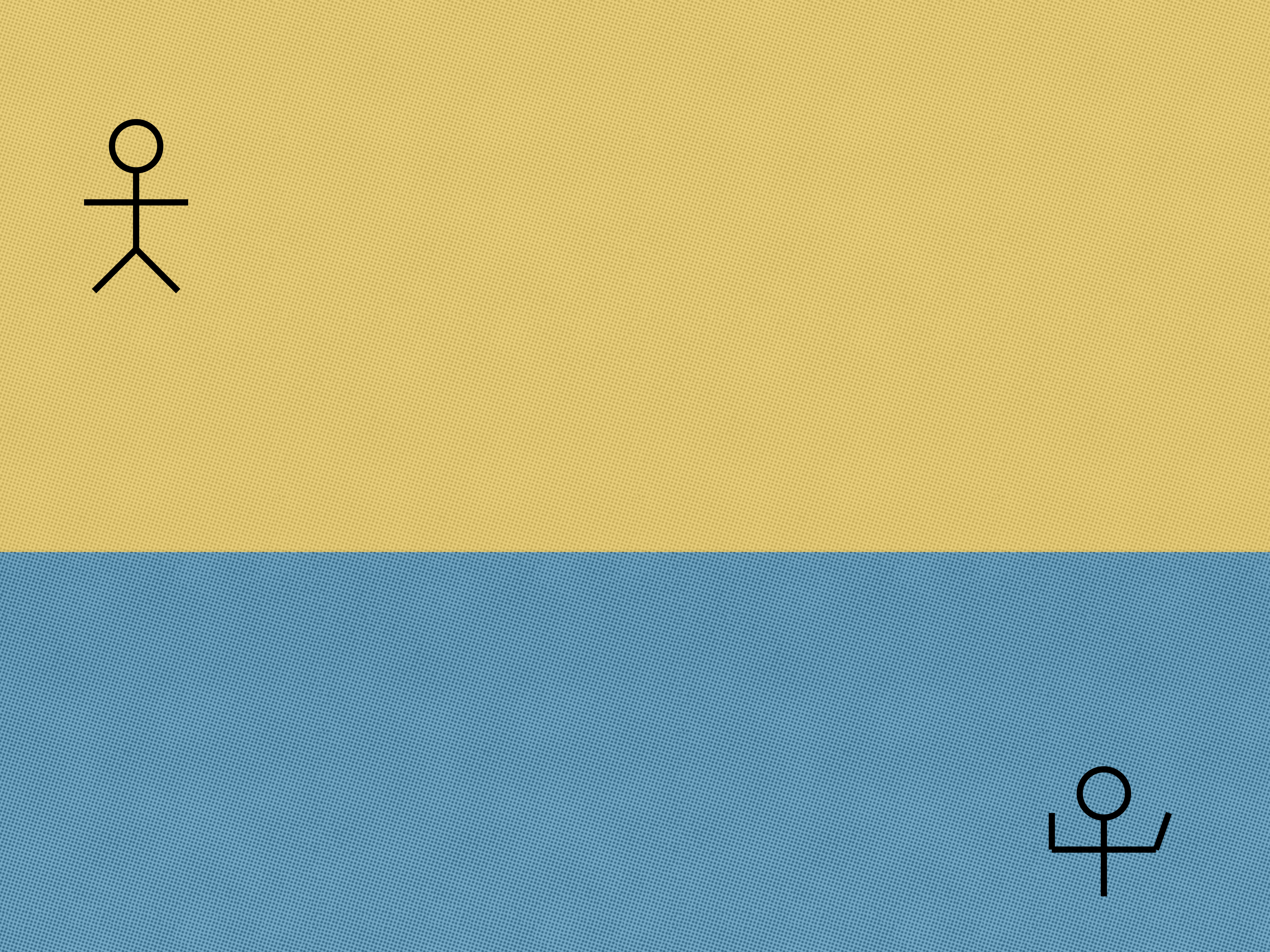
# Index of refraction

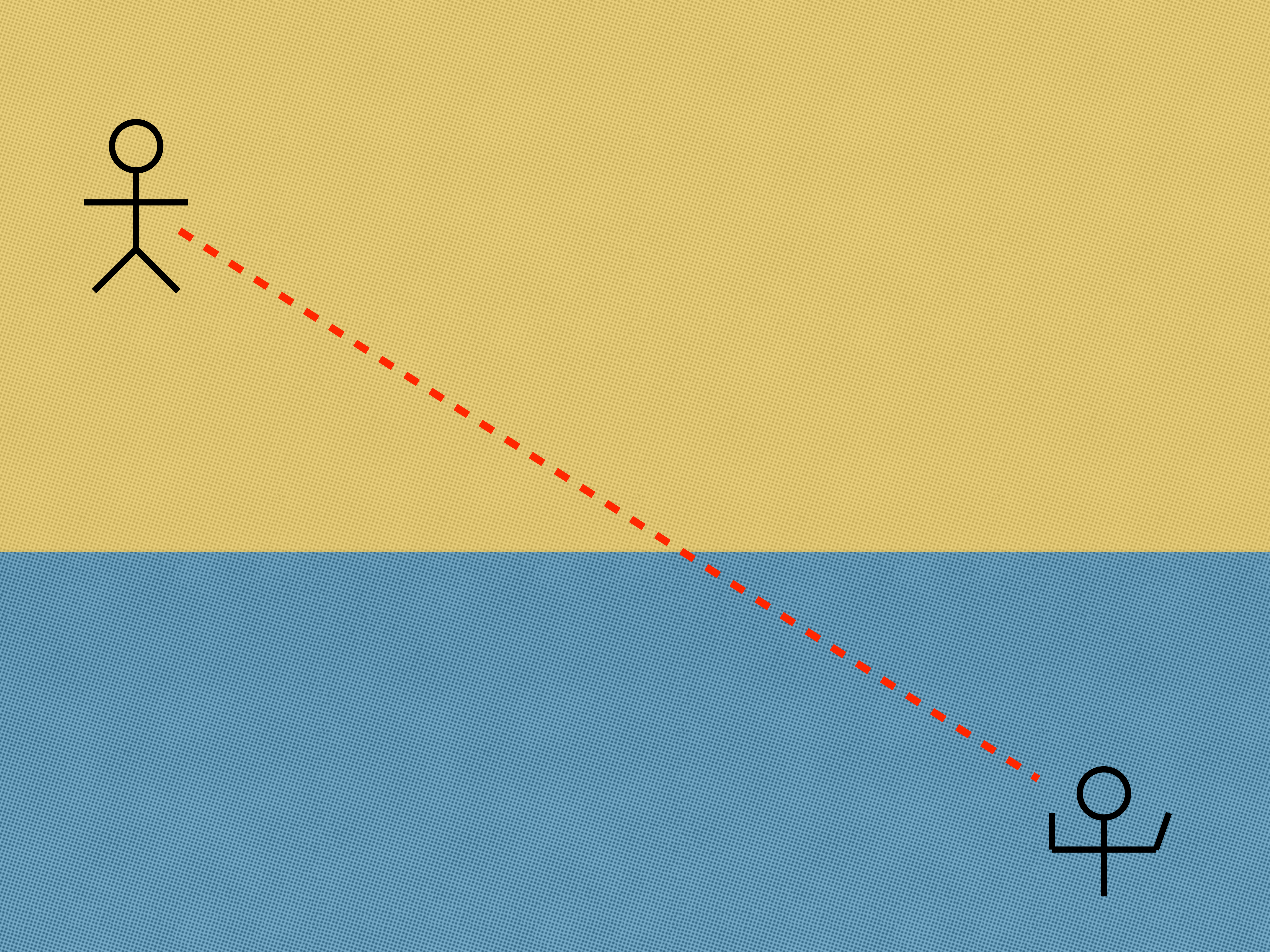
- The index of refraction of a material, *n*, describes the reduction in the speed of light when propagating through a material.

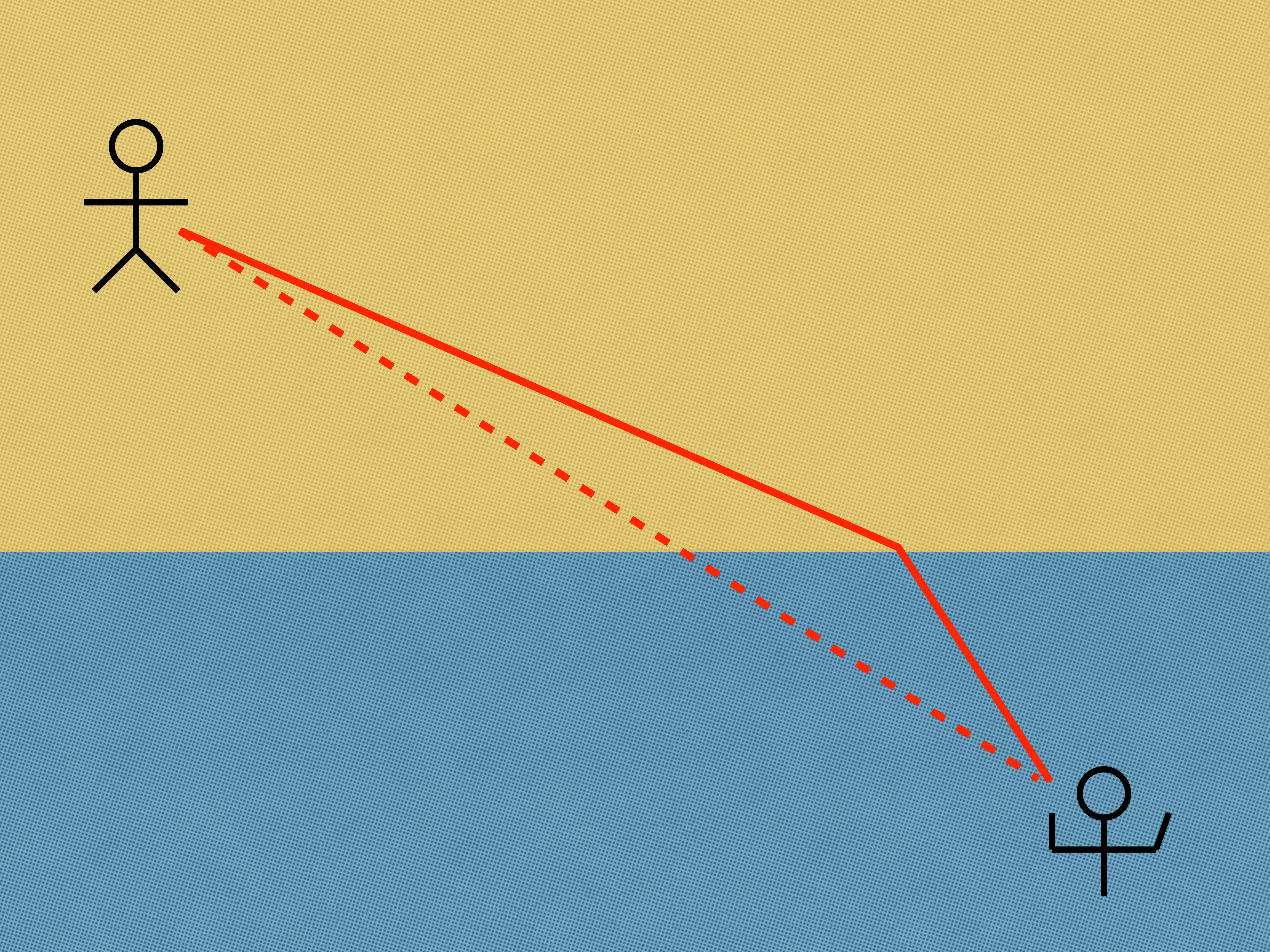
$$v = \frac{c}{n}$$

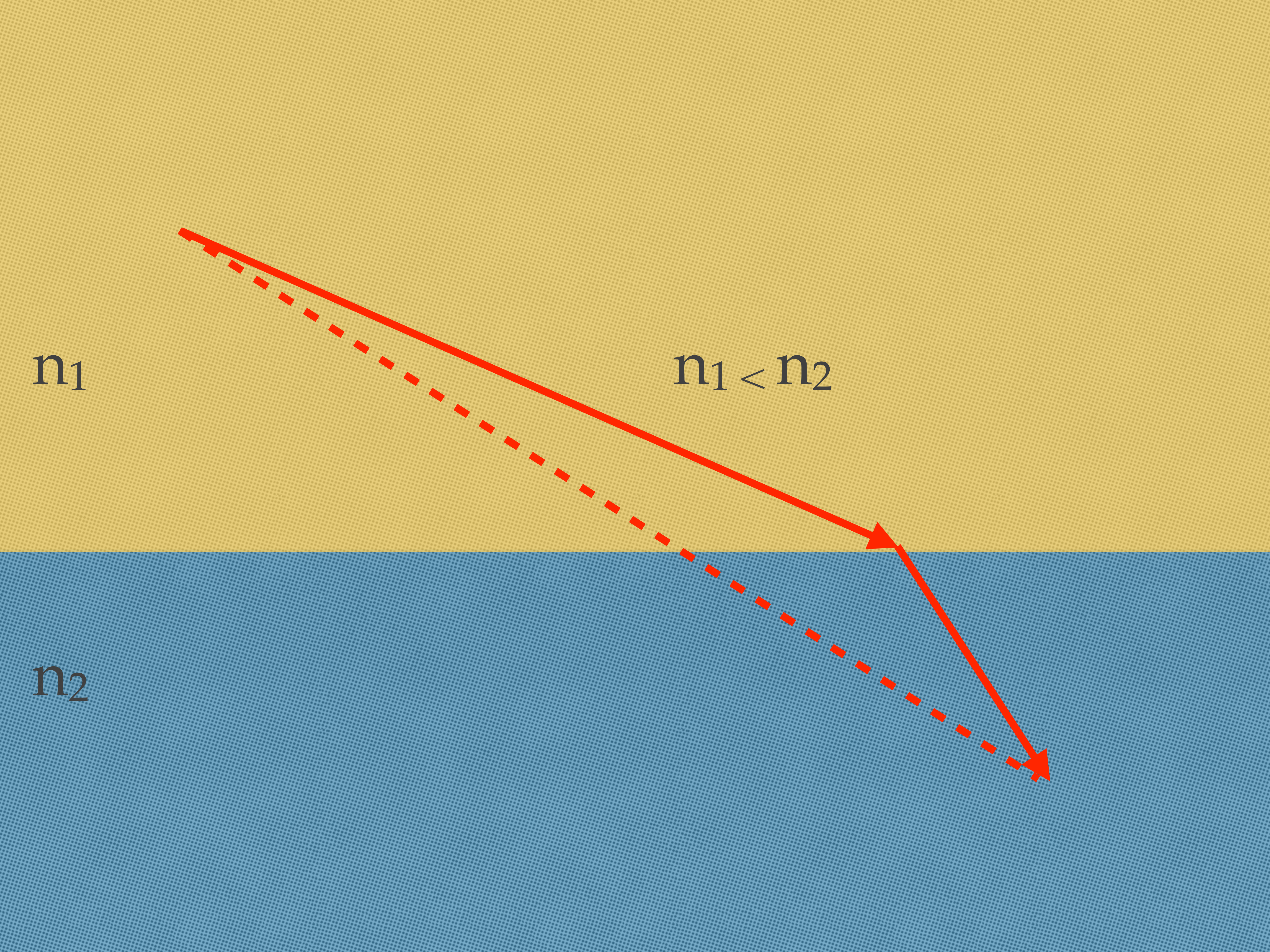
- Using Fermat's principle of least time, we can see that this causes light to change direction at optical interfaces


$n_1$
(lower index)
$n_2$
(higher index)

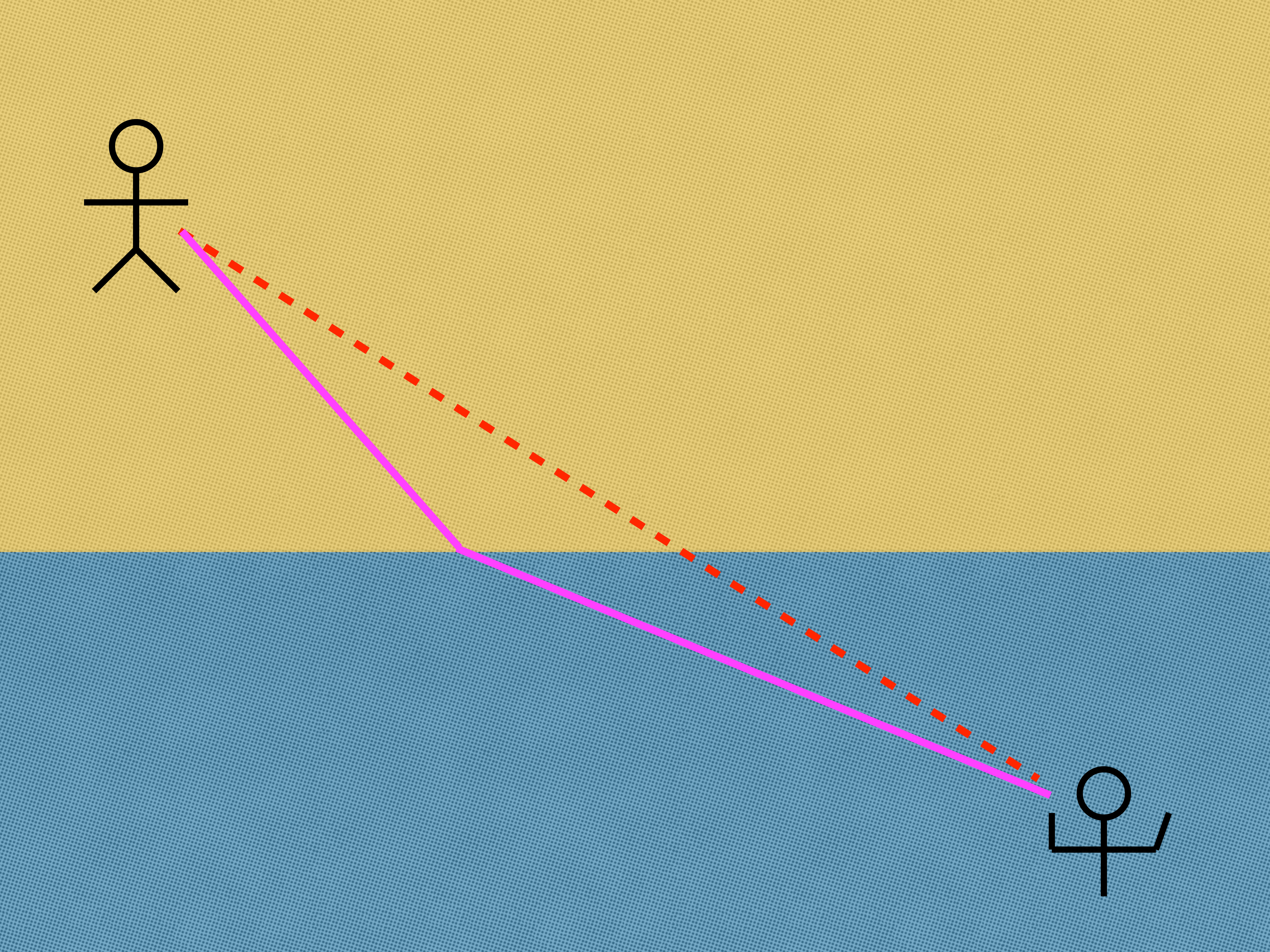


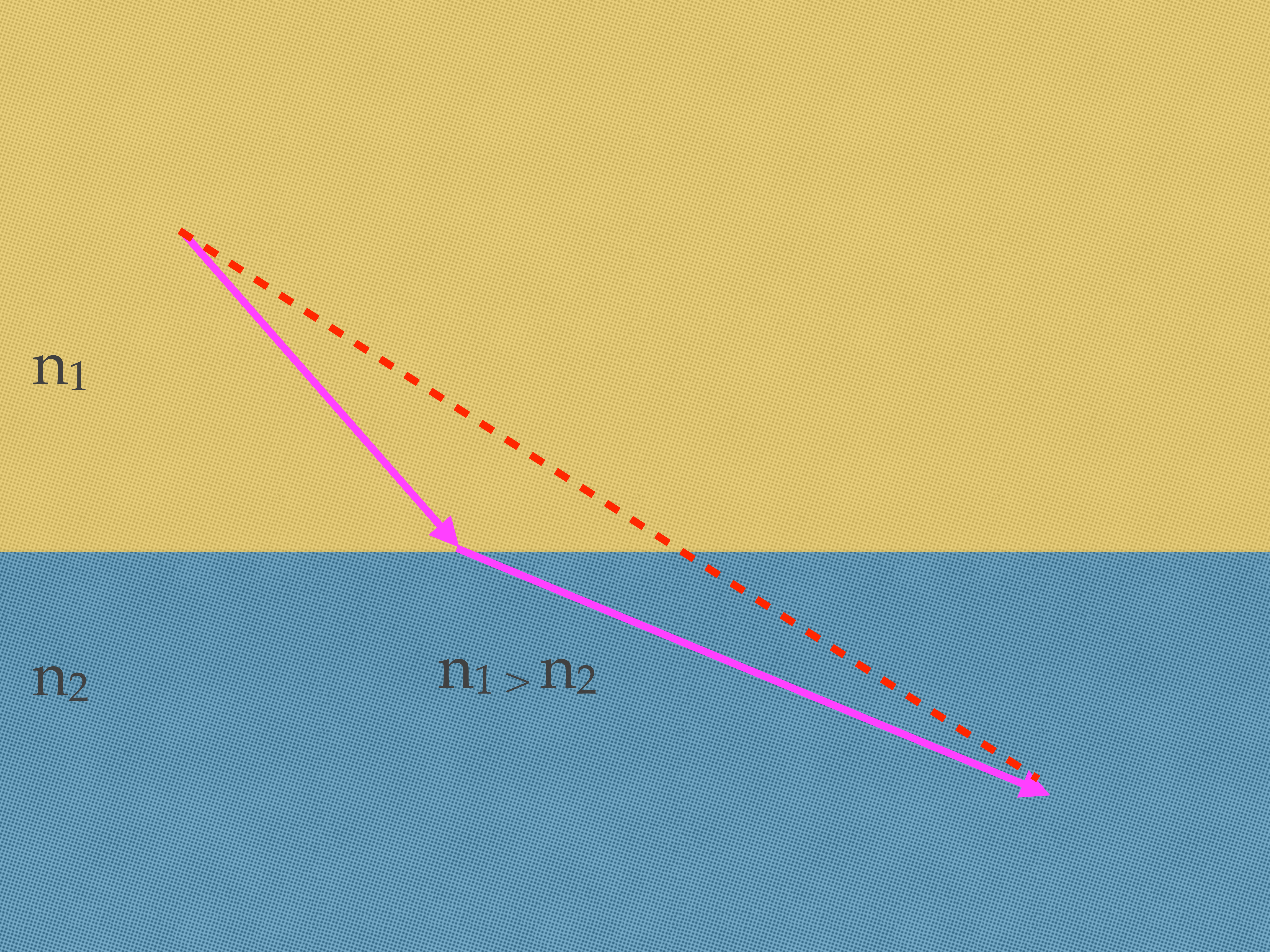






$n_1$
$n_1 < n_2$
$n_2$




$n_1$
$n_2$
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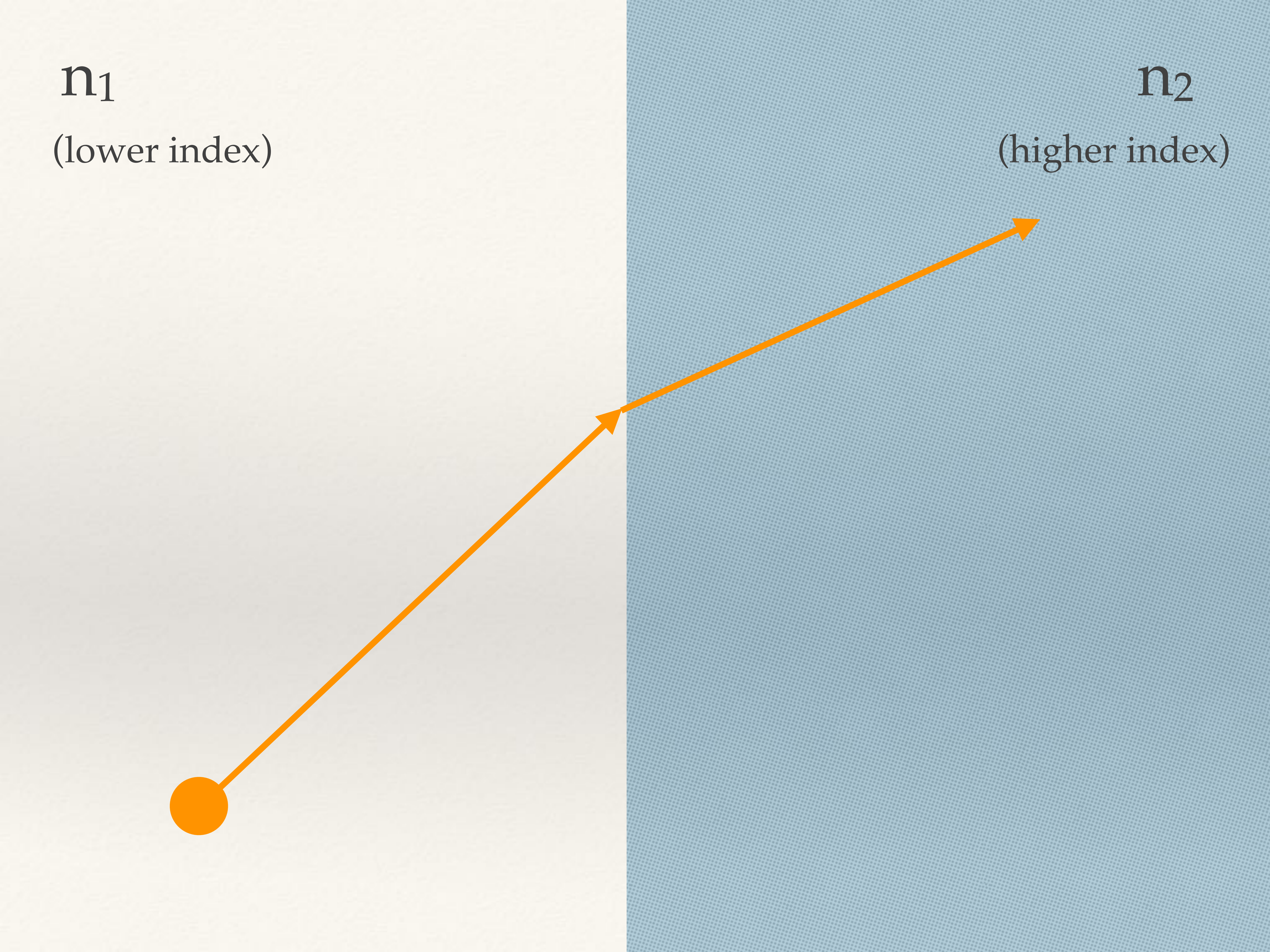
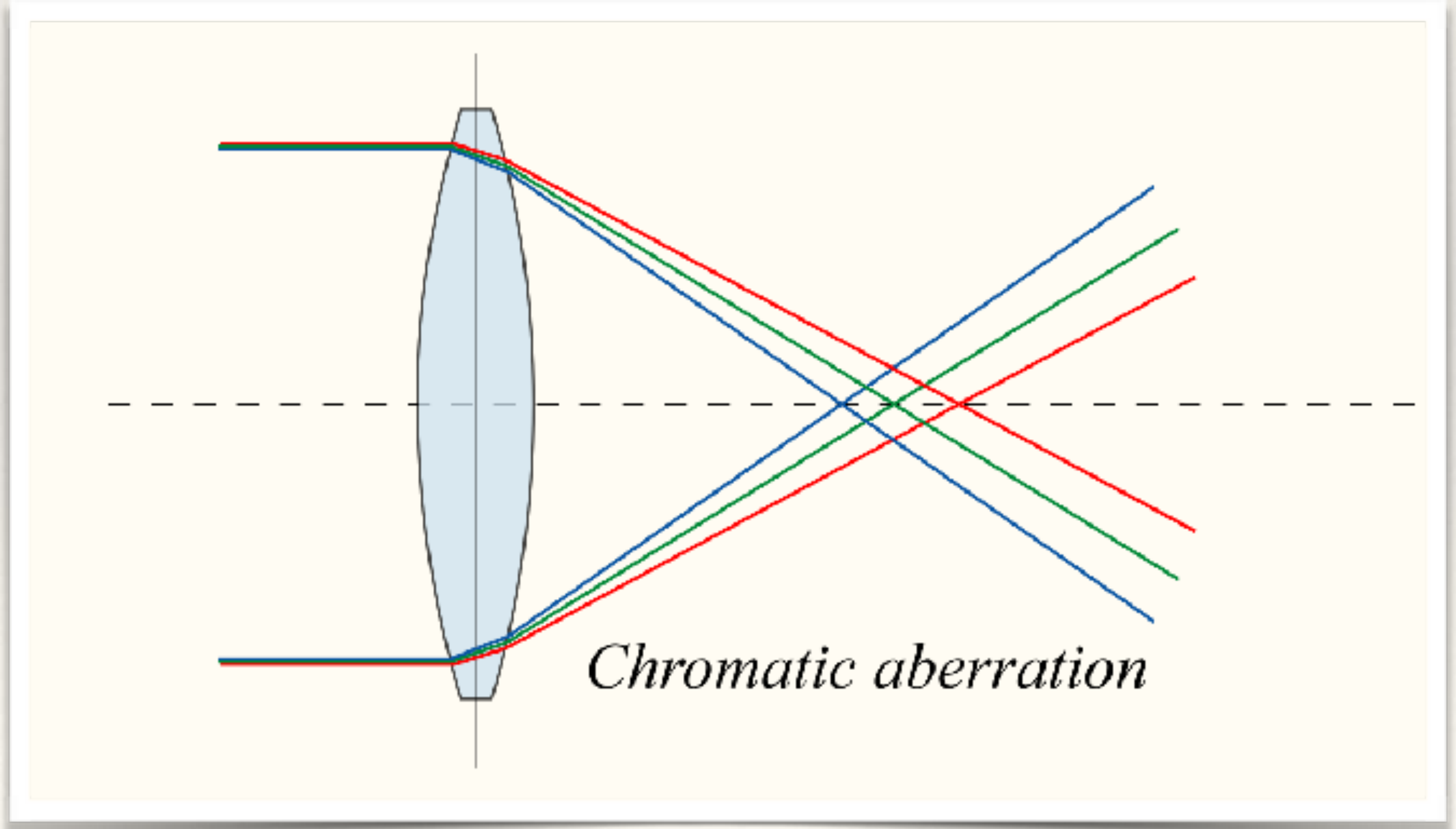


$n_1$
(lower index)
$n_2$
(higher index)

# Chromatic aberration

Materials don't have a fixed refractive index, $n$…

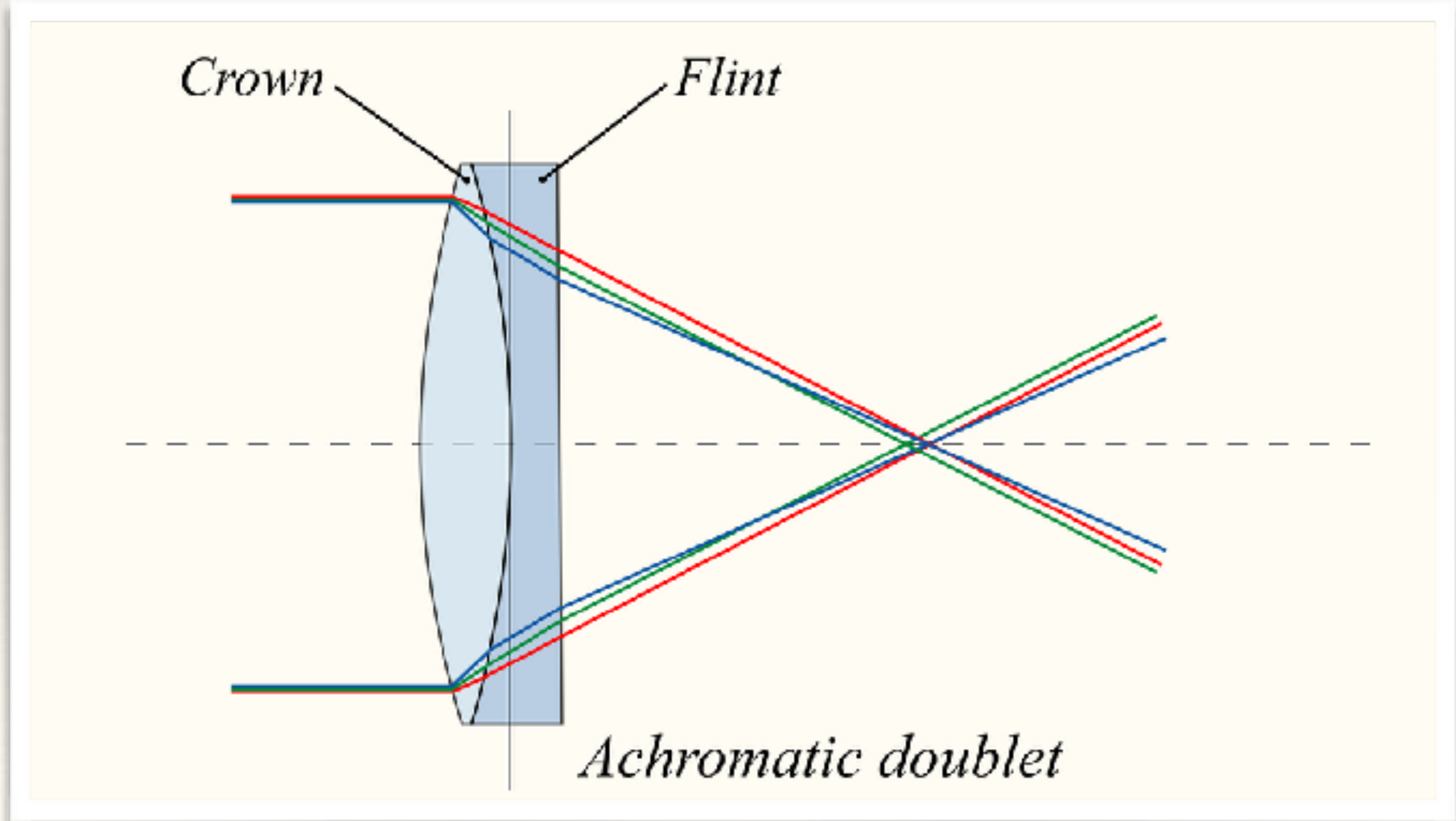
Instead, their refractive index varies with wavelength, $n(\lambda)$



# Chromatic aberration

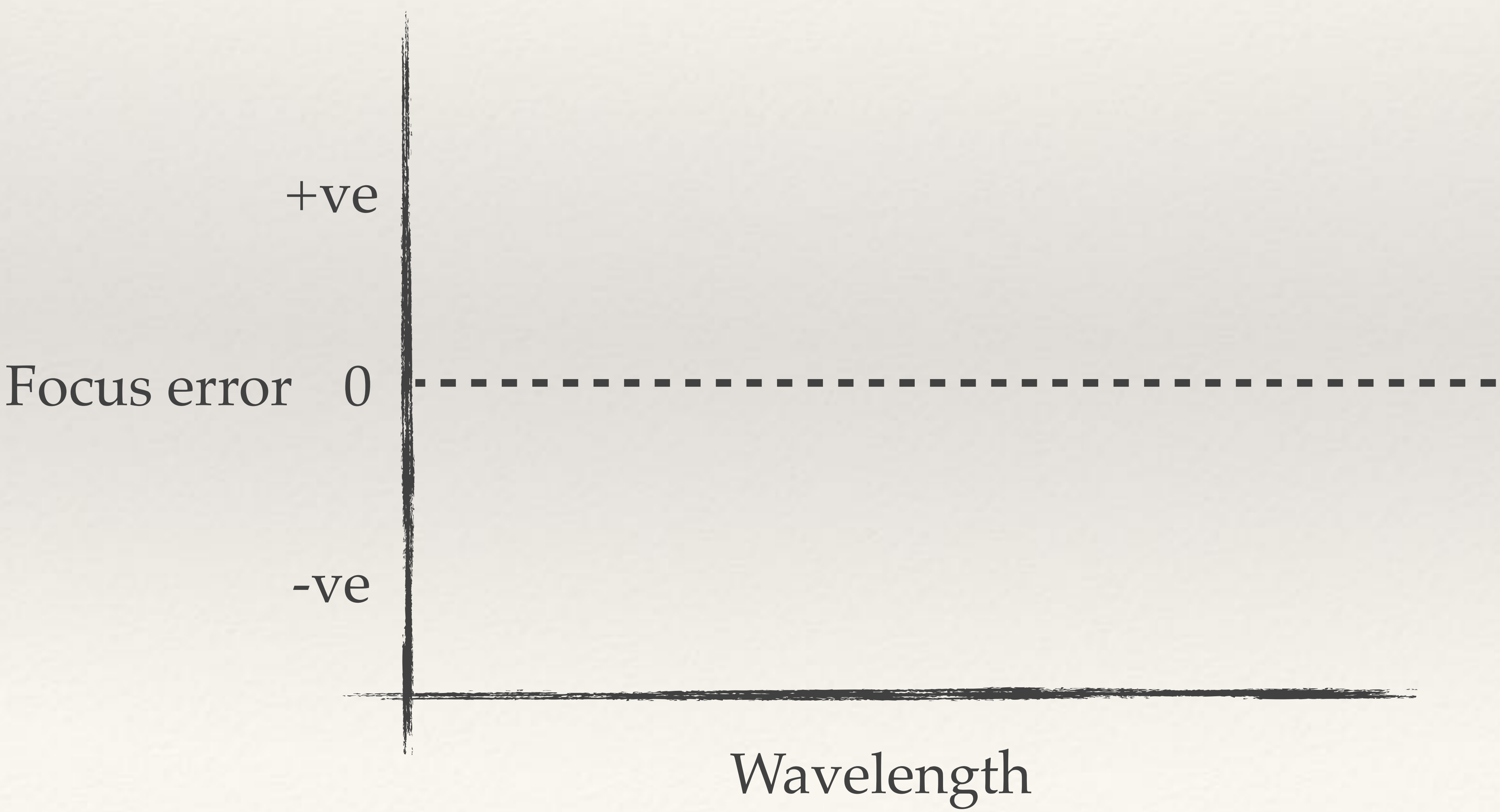
(Partial) solution: achromatic doublet (declared impossible by Newton!)

By combining materials, simultaneously focus two wavelengths…



# Chromatic aberration

Apochromats and superapochromats focus 3 and 4 wavelengths



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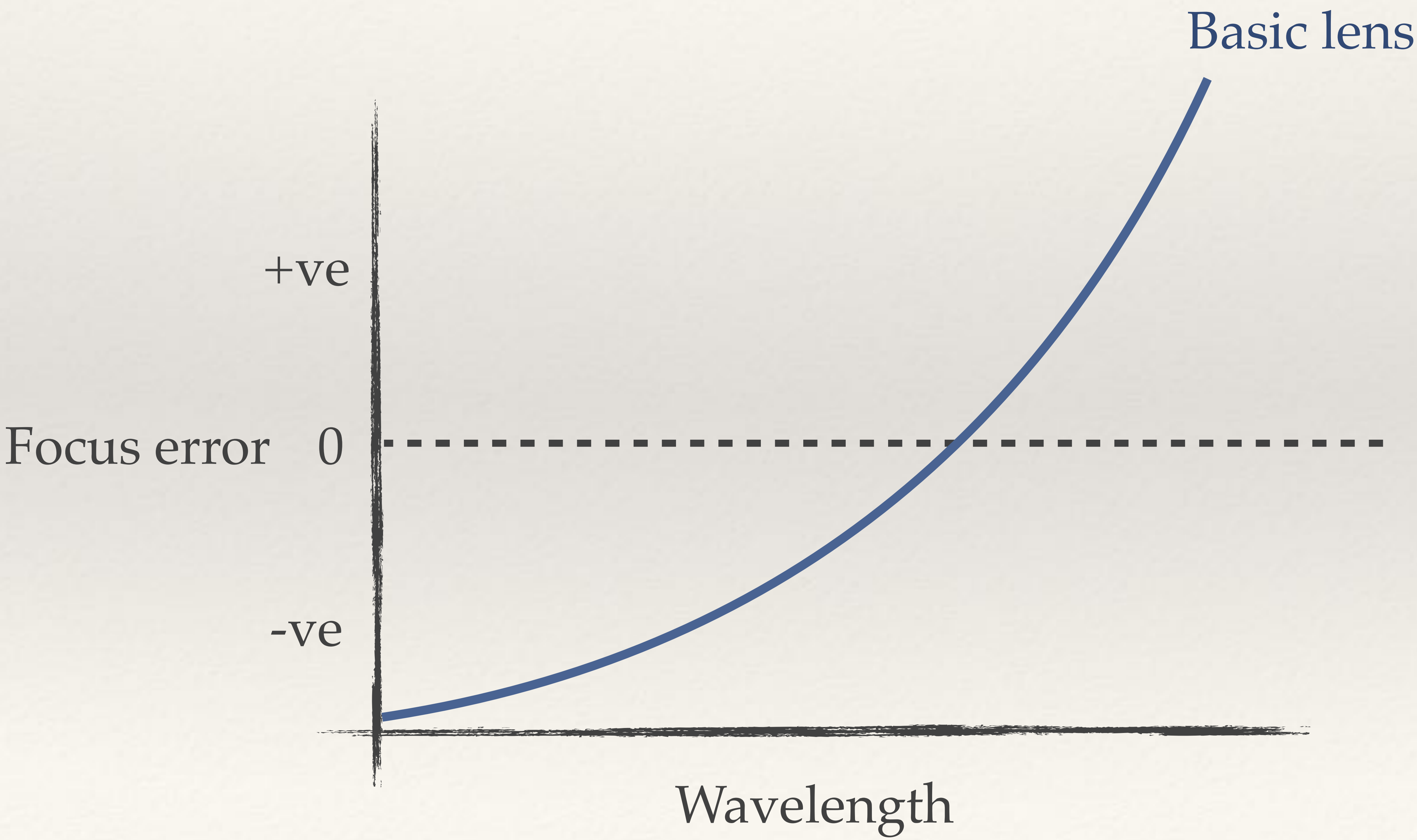

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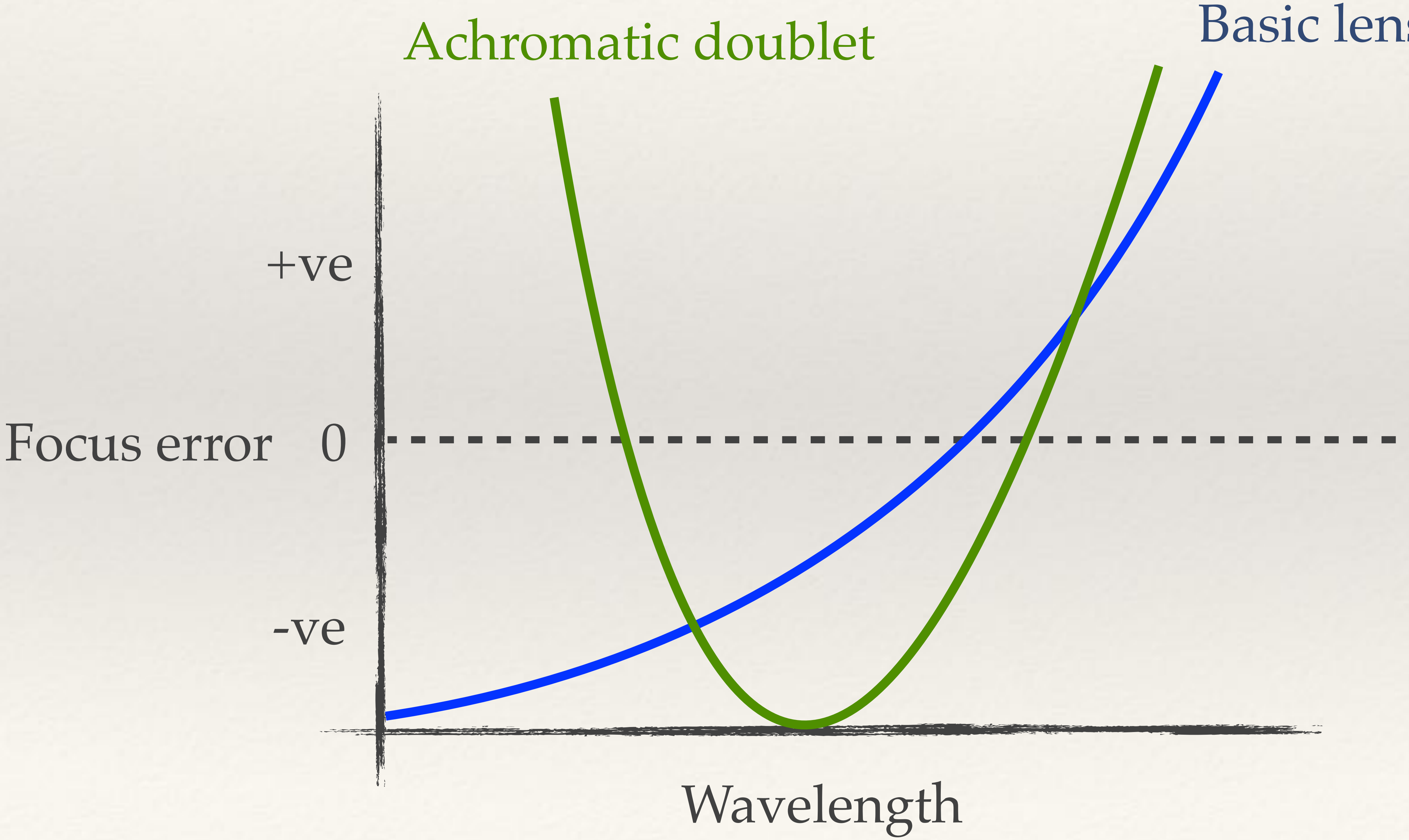

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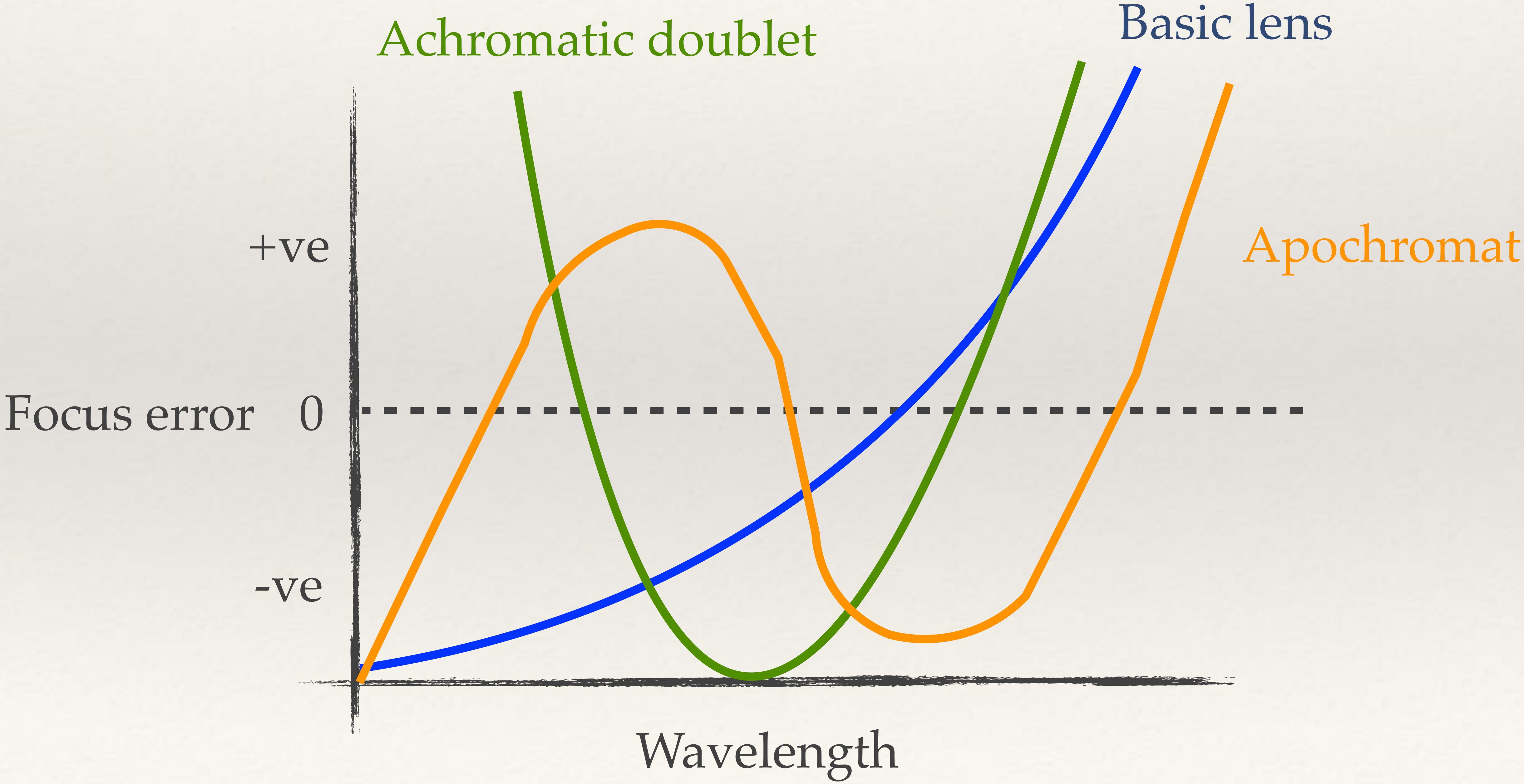
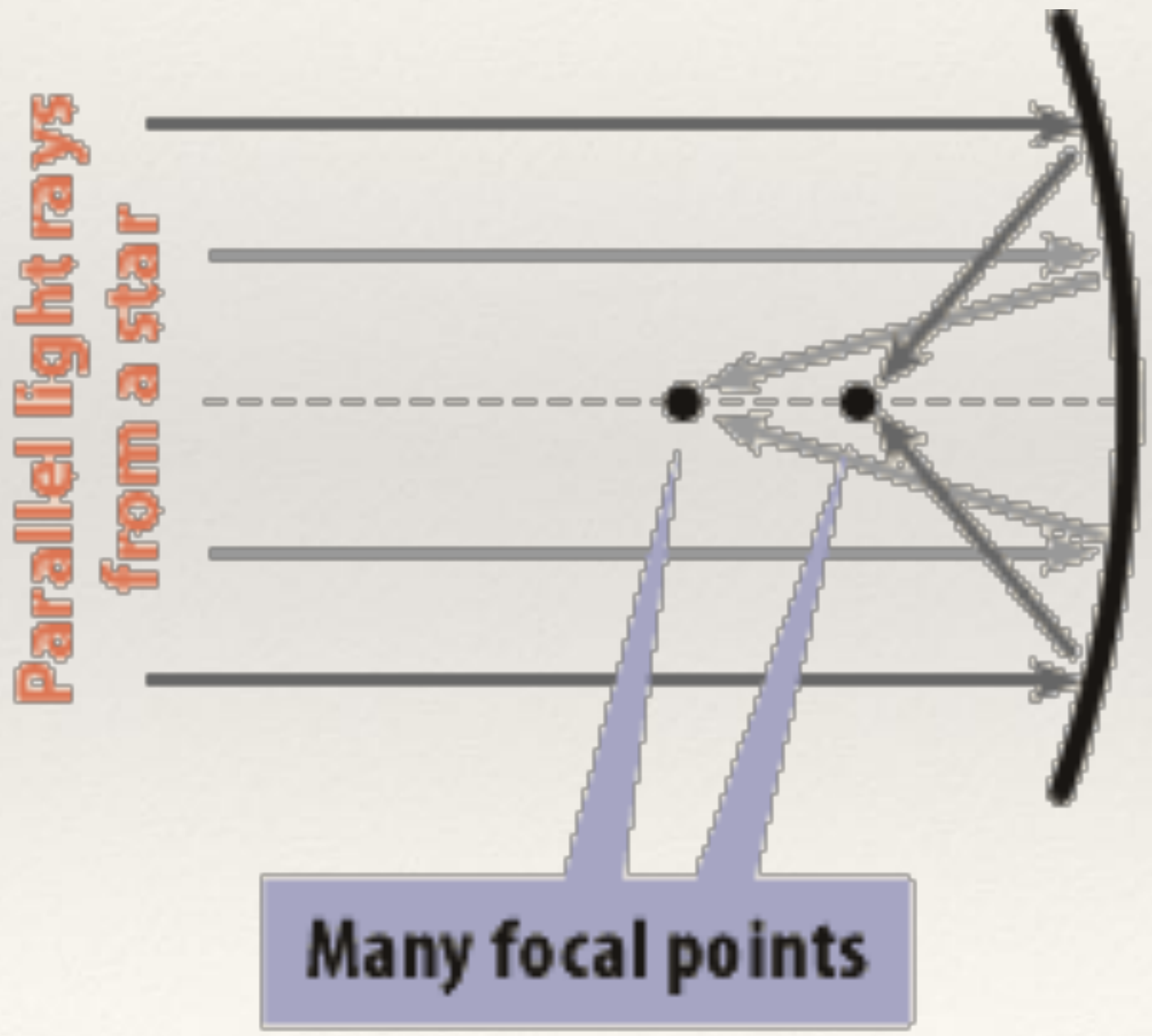


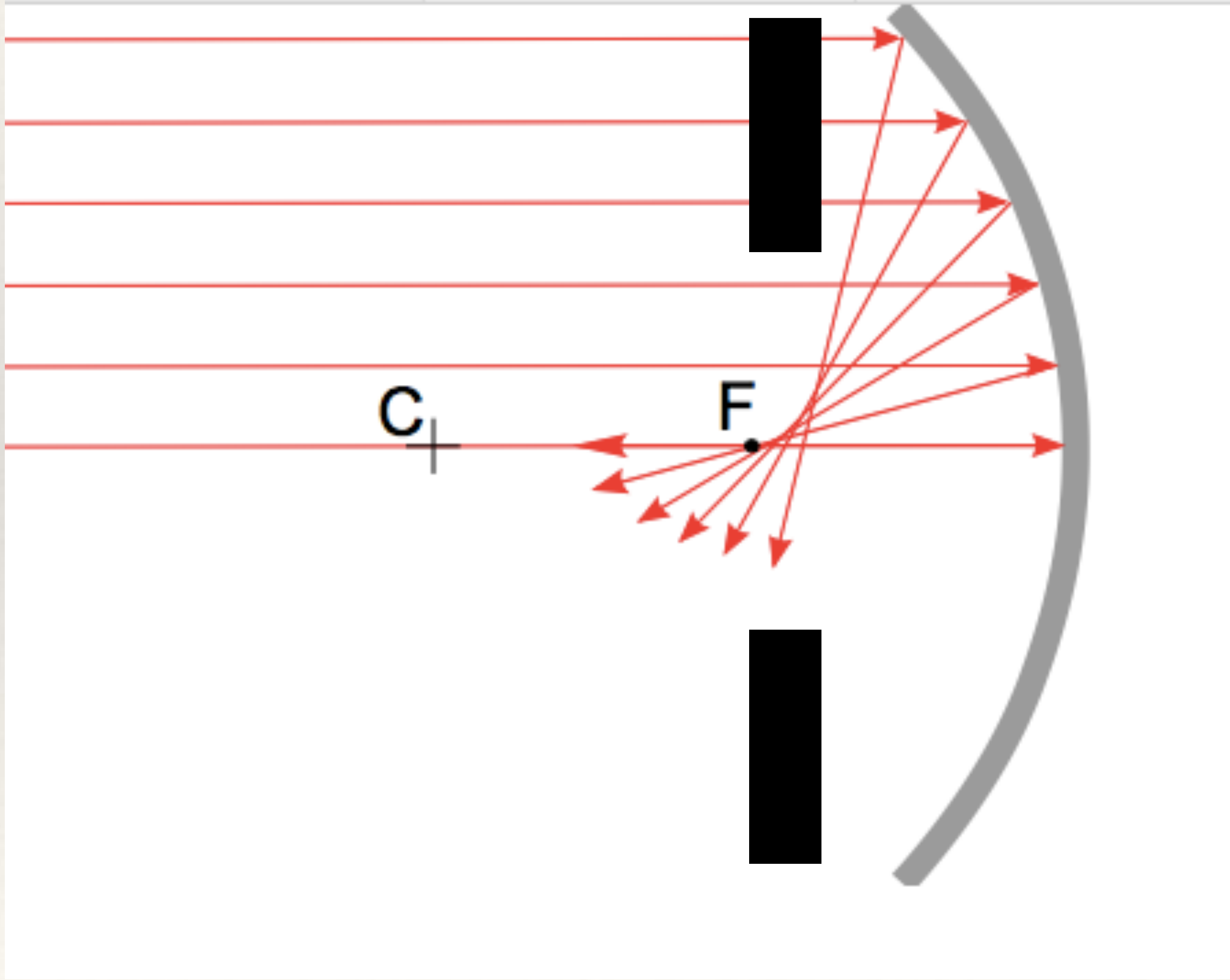
# Spherical aberration

Similar problem for spherical mirrors (reflecting telescopes)…



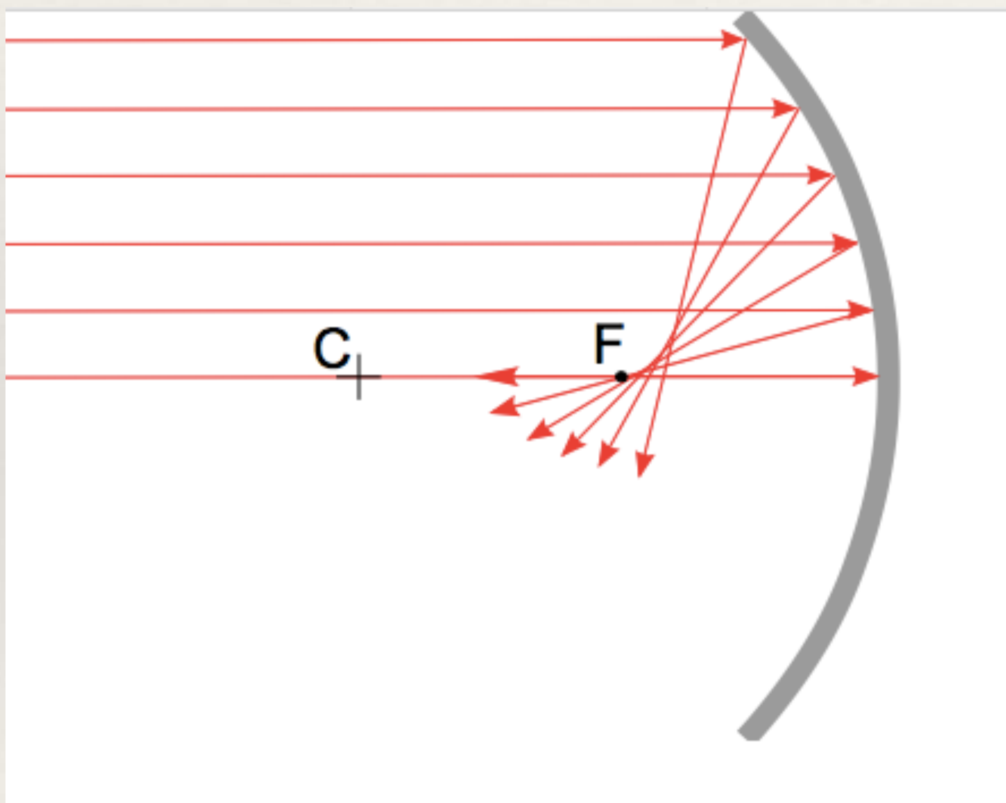
# Spherical aberration

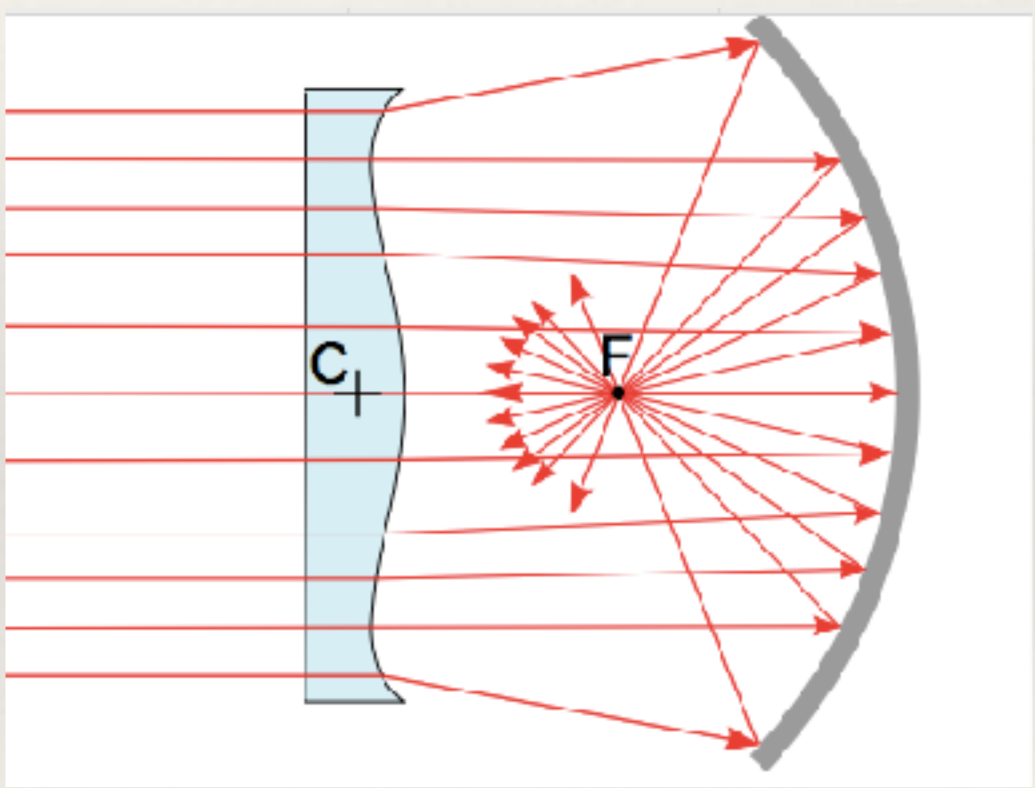
Solution (1): Block the outer edges of mirror



# Spherical aberration

Solution (2): Use a ‘corrector plate’

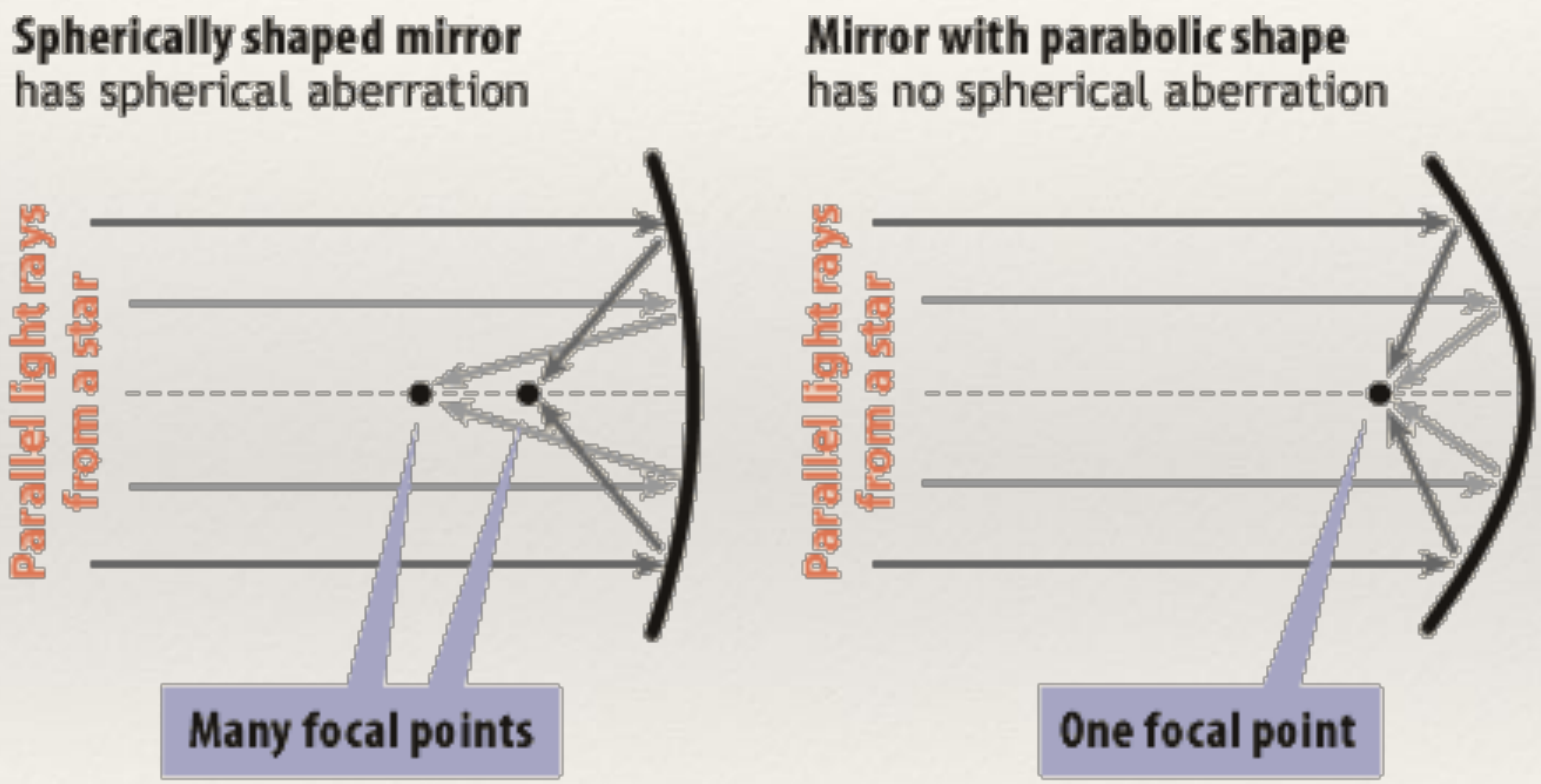



This is used in Schmidt telescopes (i.e., Schmidt–Cassegrain)

# Spherical aberration

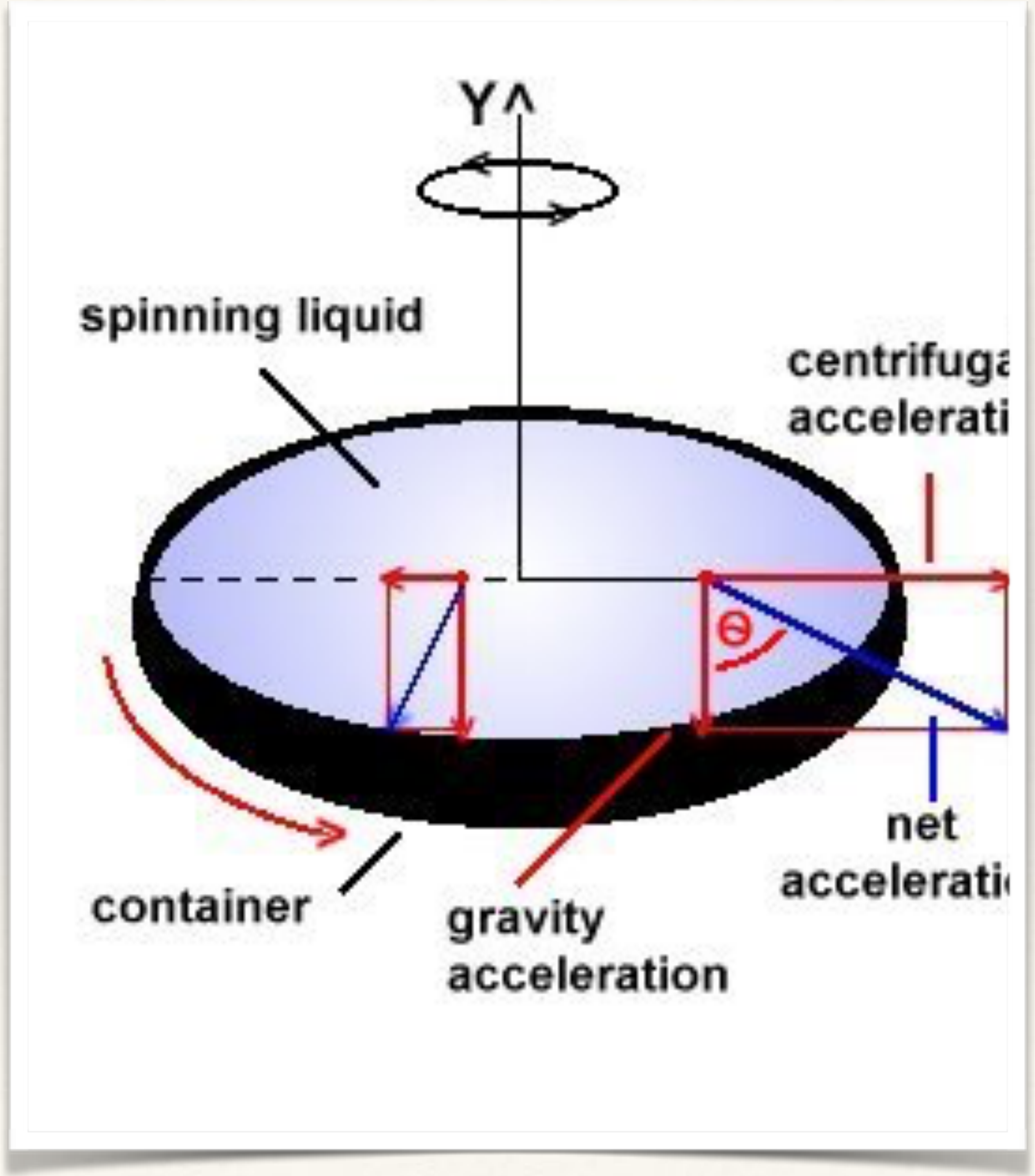
Solution (3): Aspherical mirrors (parabolic reflector)




Aspherical mirrors are expensive, but ubiquitous among world-class telescopes

# Liquid mirror telescopes

- Spinning liquid forms parabolic surface due to centrifugal force
- If liquid is reflective (i.e., mercury), you can make a perfect (+ cheap) parabolic reflector



**Water in a rotating container forms a parabolic shape**

(due to the centrifugal force).

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# Diffraction limit

Wave properties of light set fundamental limit on resolution of telescope

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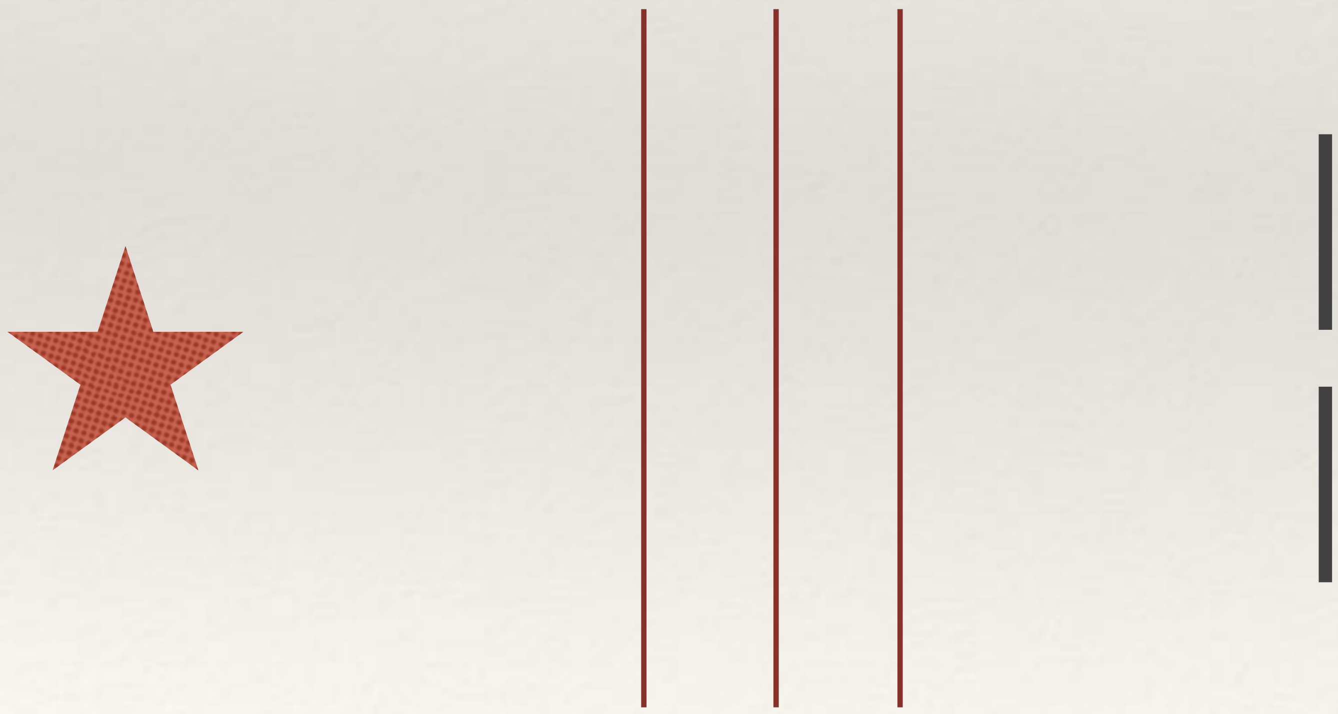

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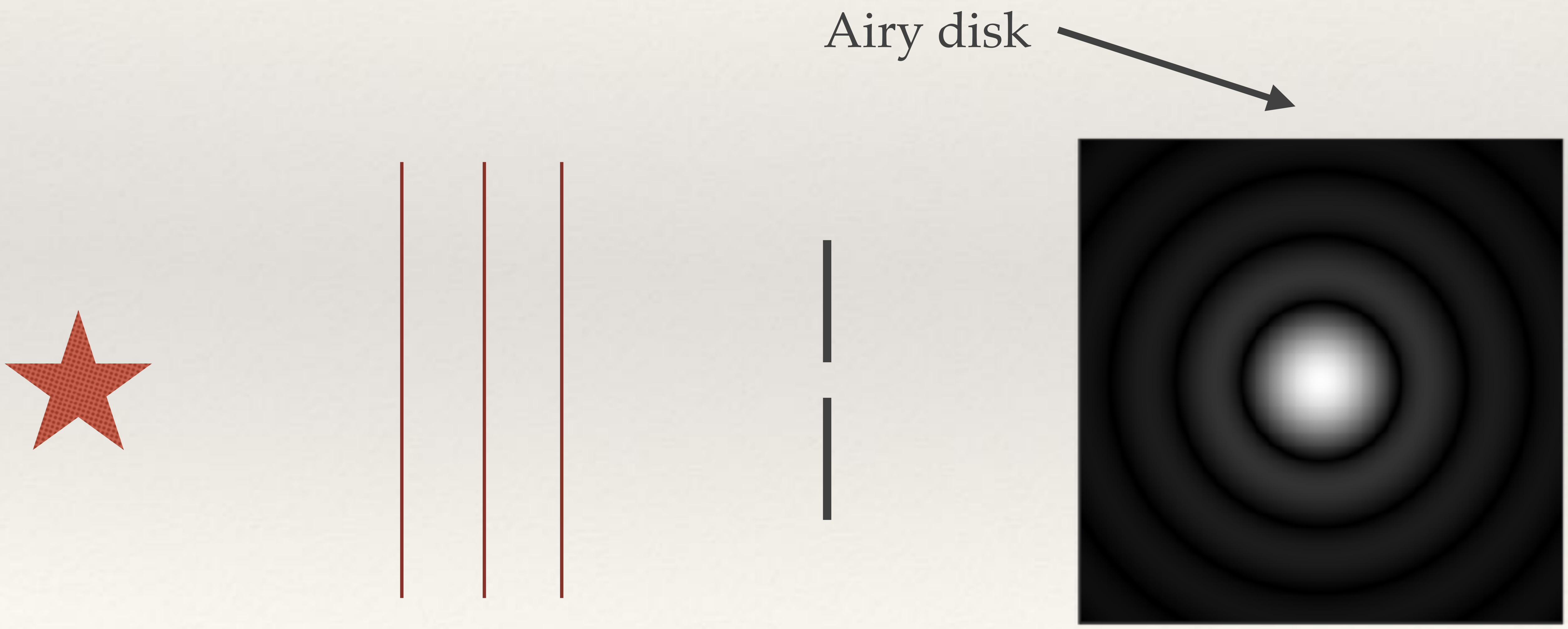
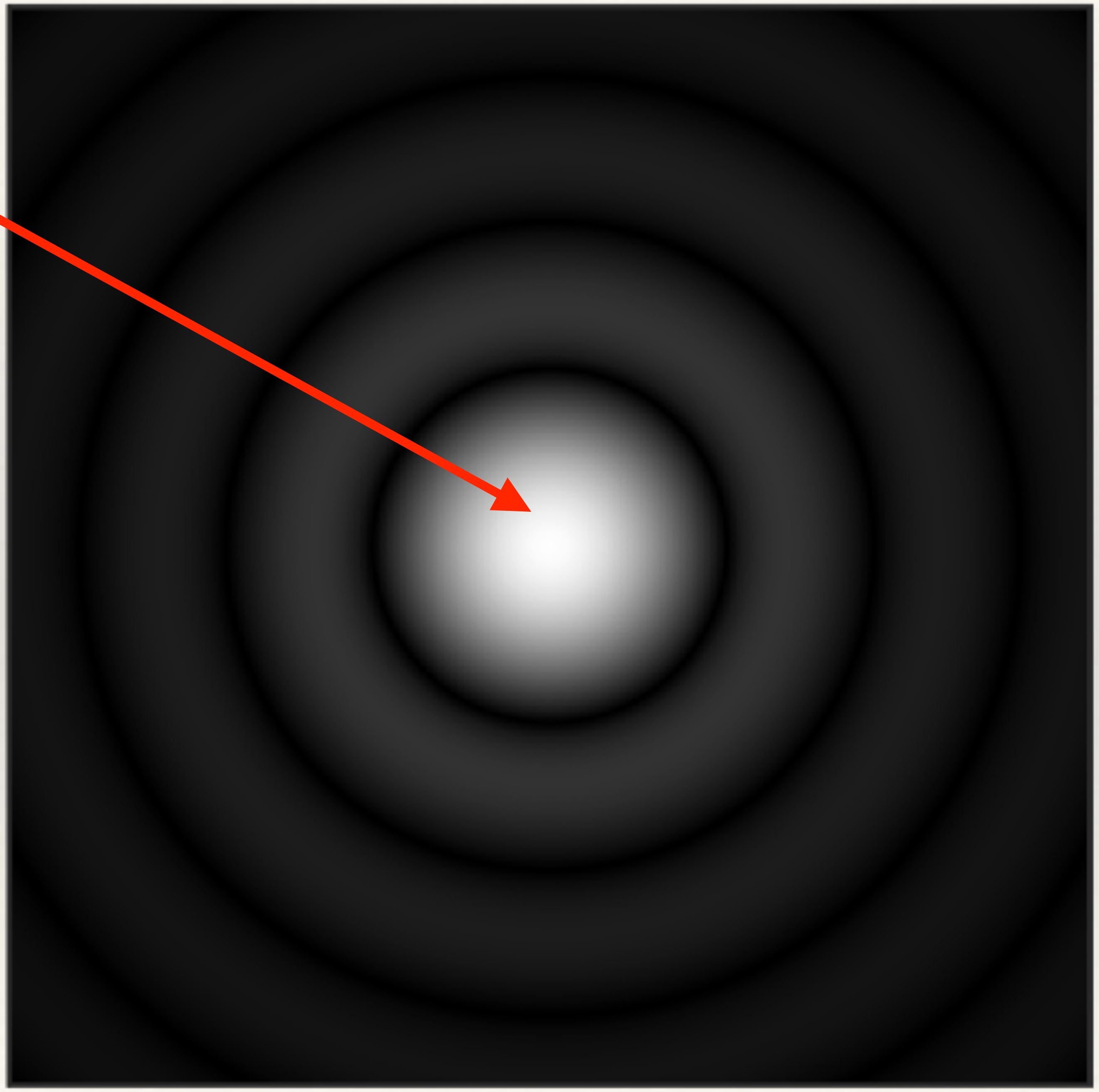


# Airy disk

84% of light in central spot



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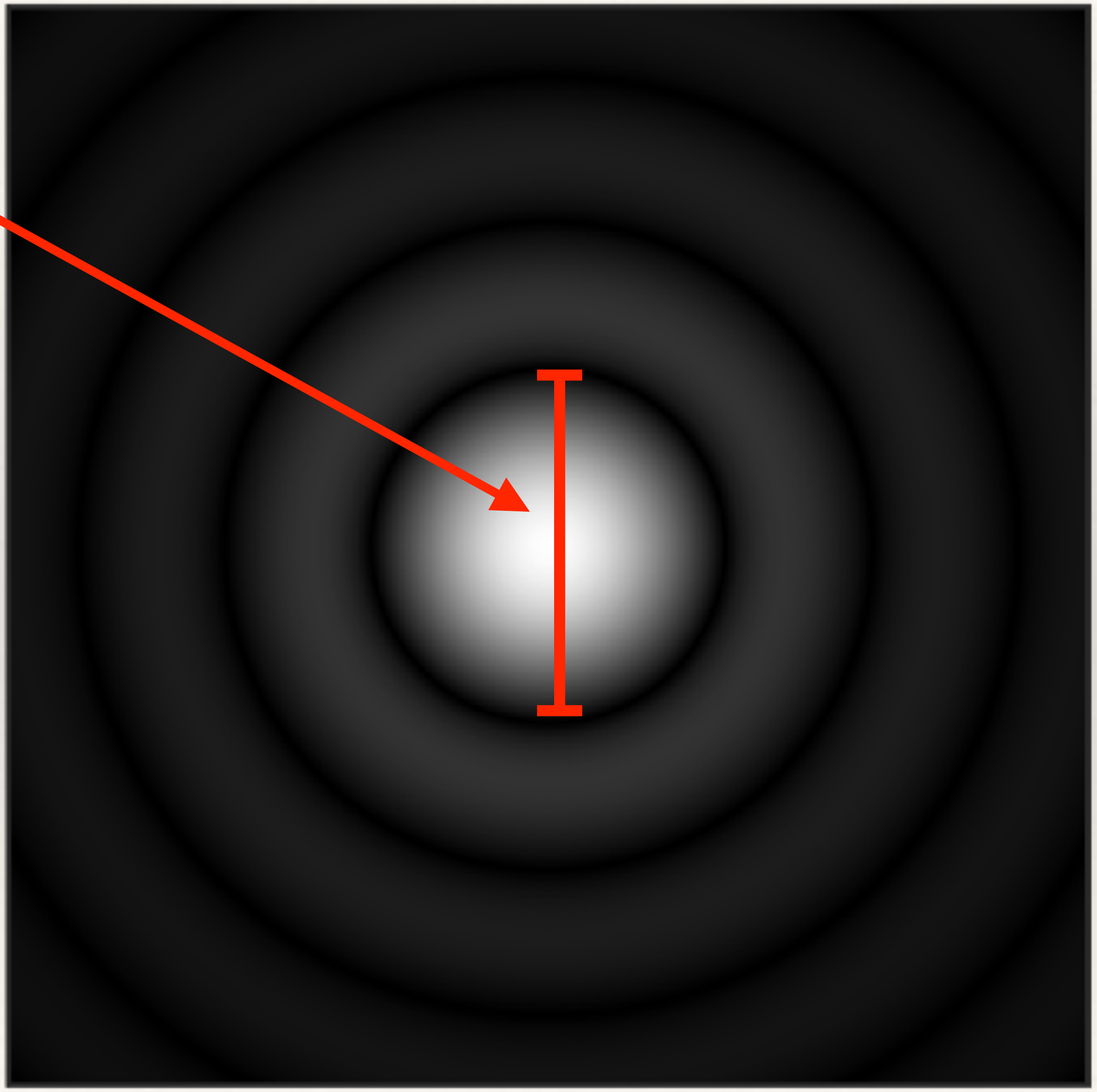
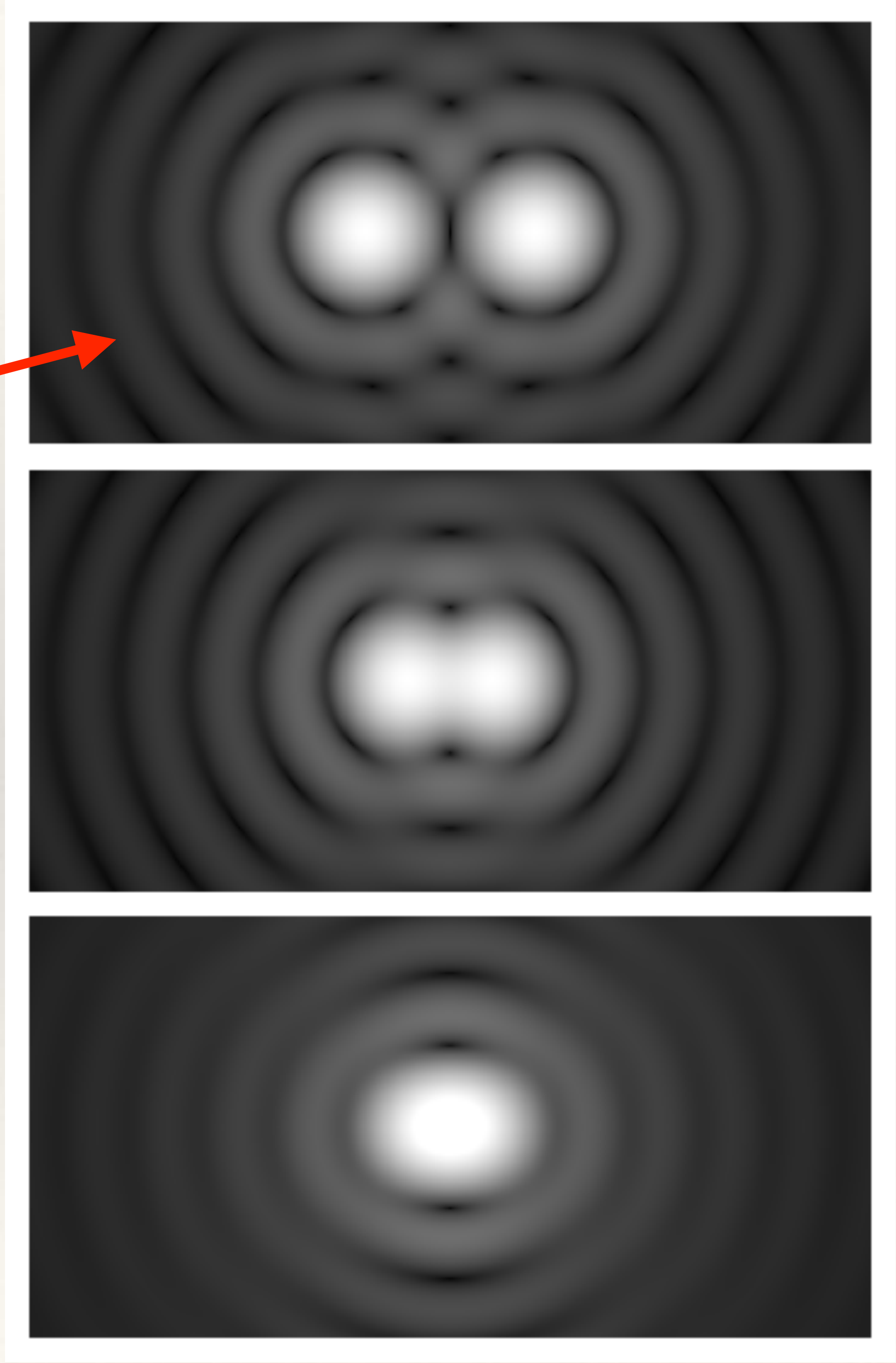


$$\frac{2.44\ \lambda}{D}$$

# Airy disk



Rayleigh criterion: two objects can be resolved if the centre of the Airy disk of first object is at first minimum of second

$$\frac{1.22\ \lambda}{D}$$

# Astronomical 'seeing'

This is only a theoretical maximum… atmospheric turbulence reduced this further ('seeing')

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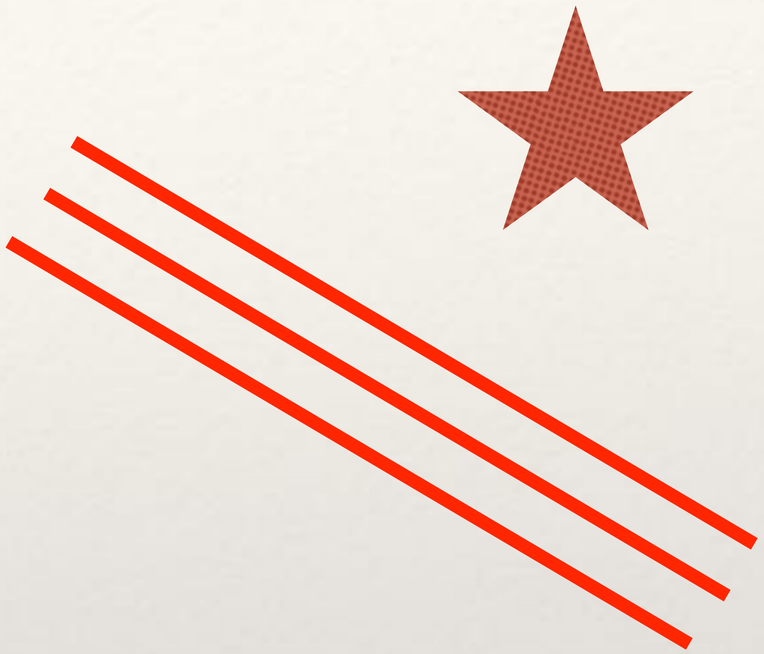

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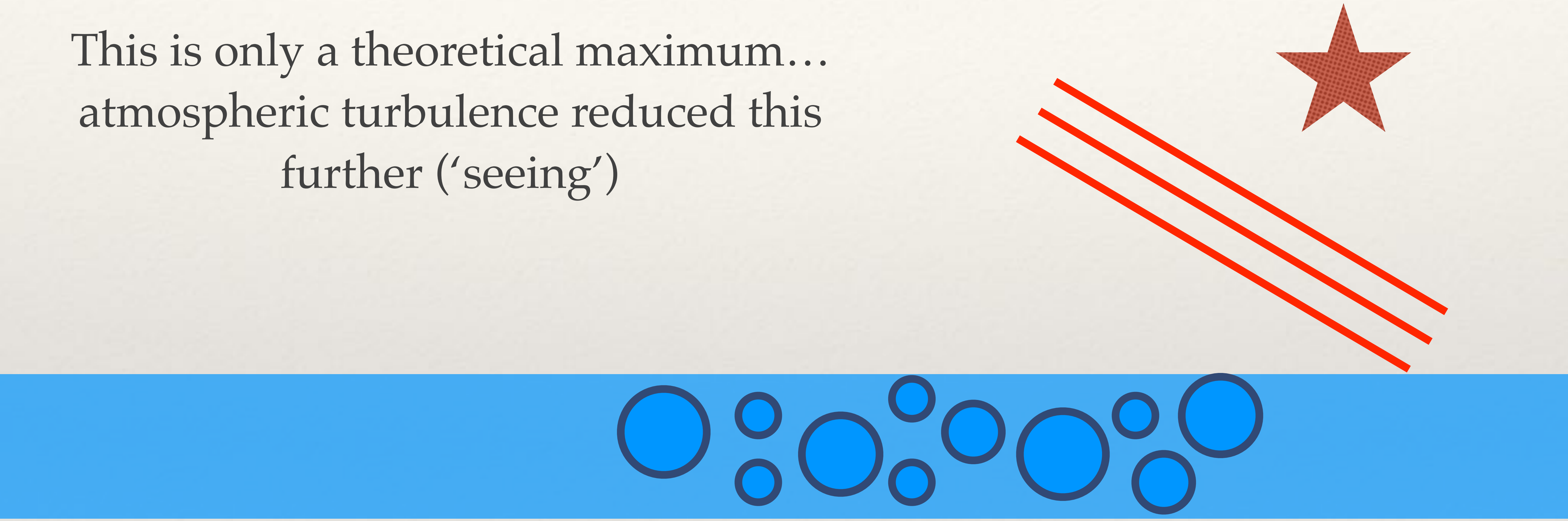

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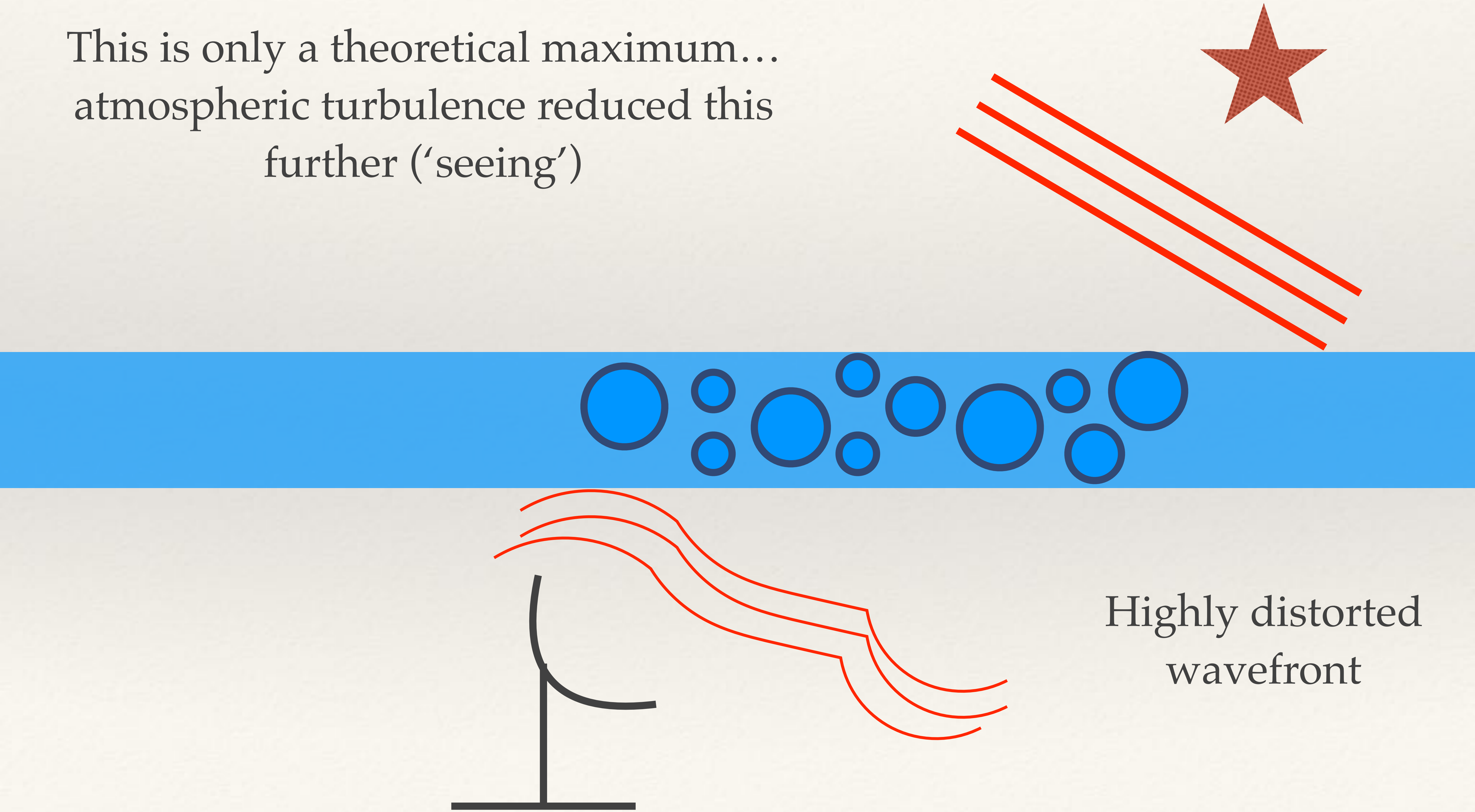
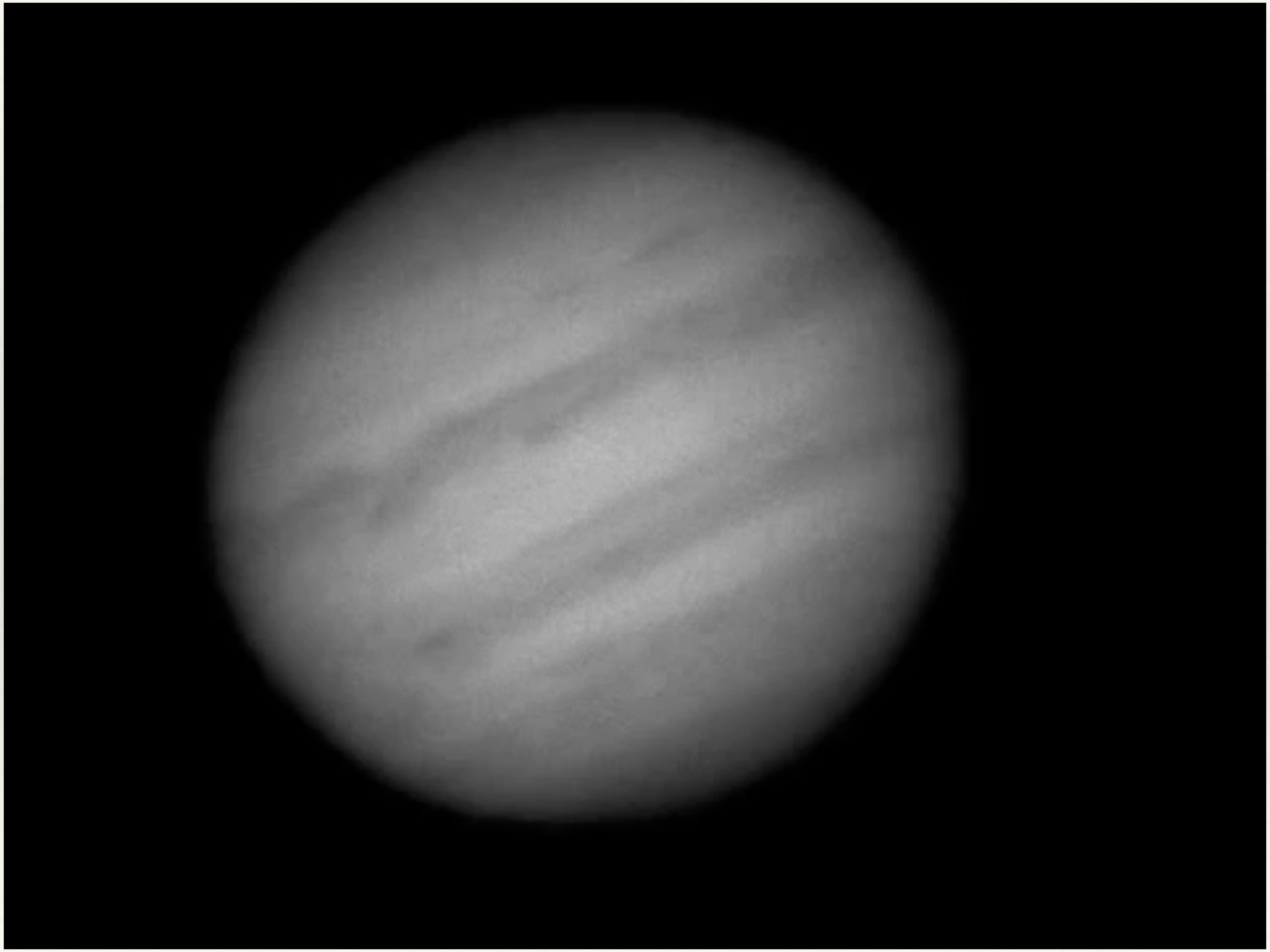


Highly distorted wavefront

# Astronomical ‘seeing’



# Astronomical ‘seeing’

Solution 1: sensible telescope placement

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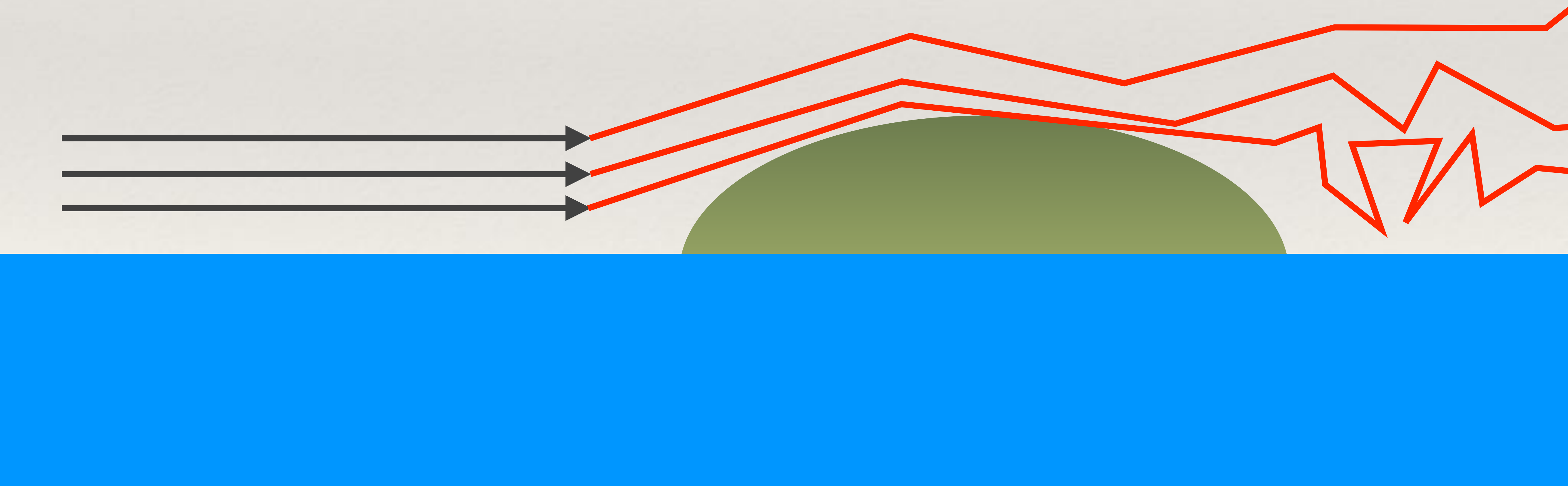

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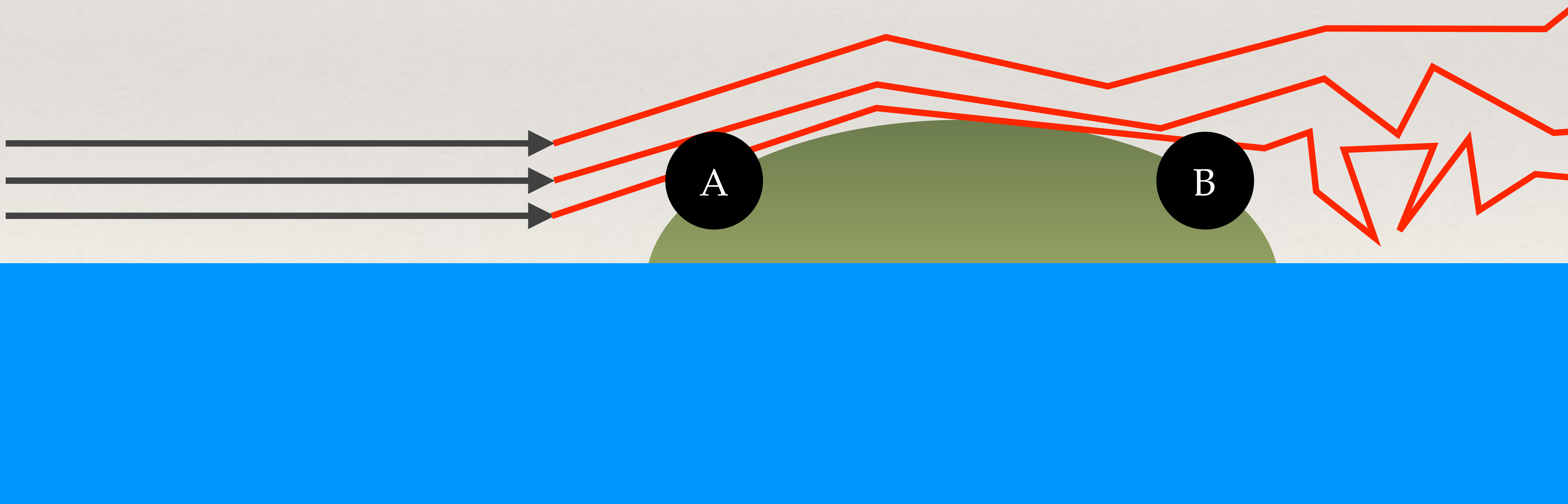
Solution 1: sensible telescope placement

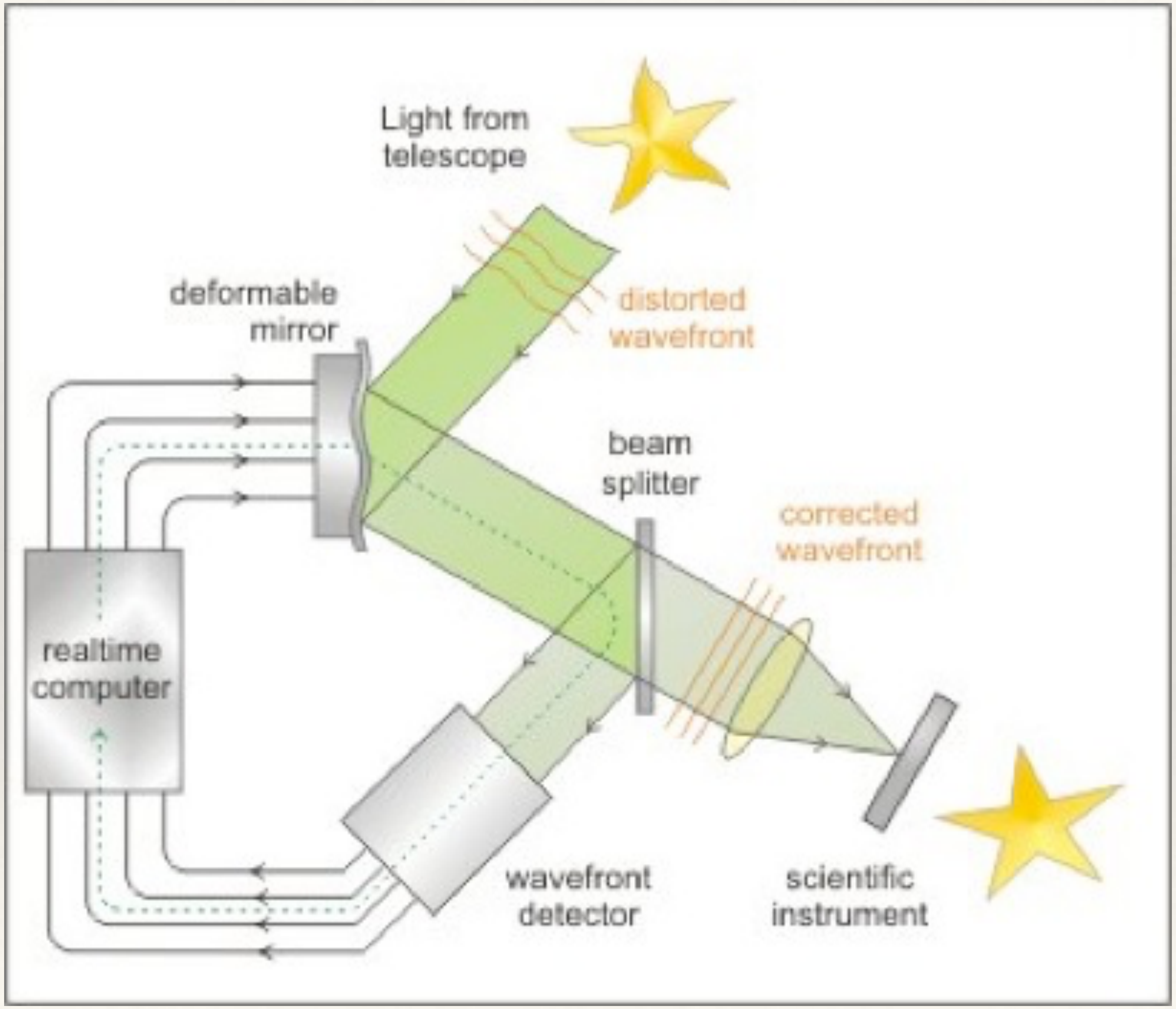


Solution 2: space!

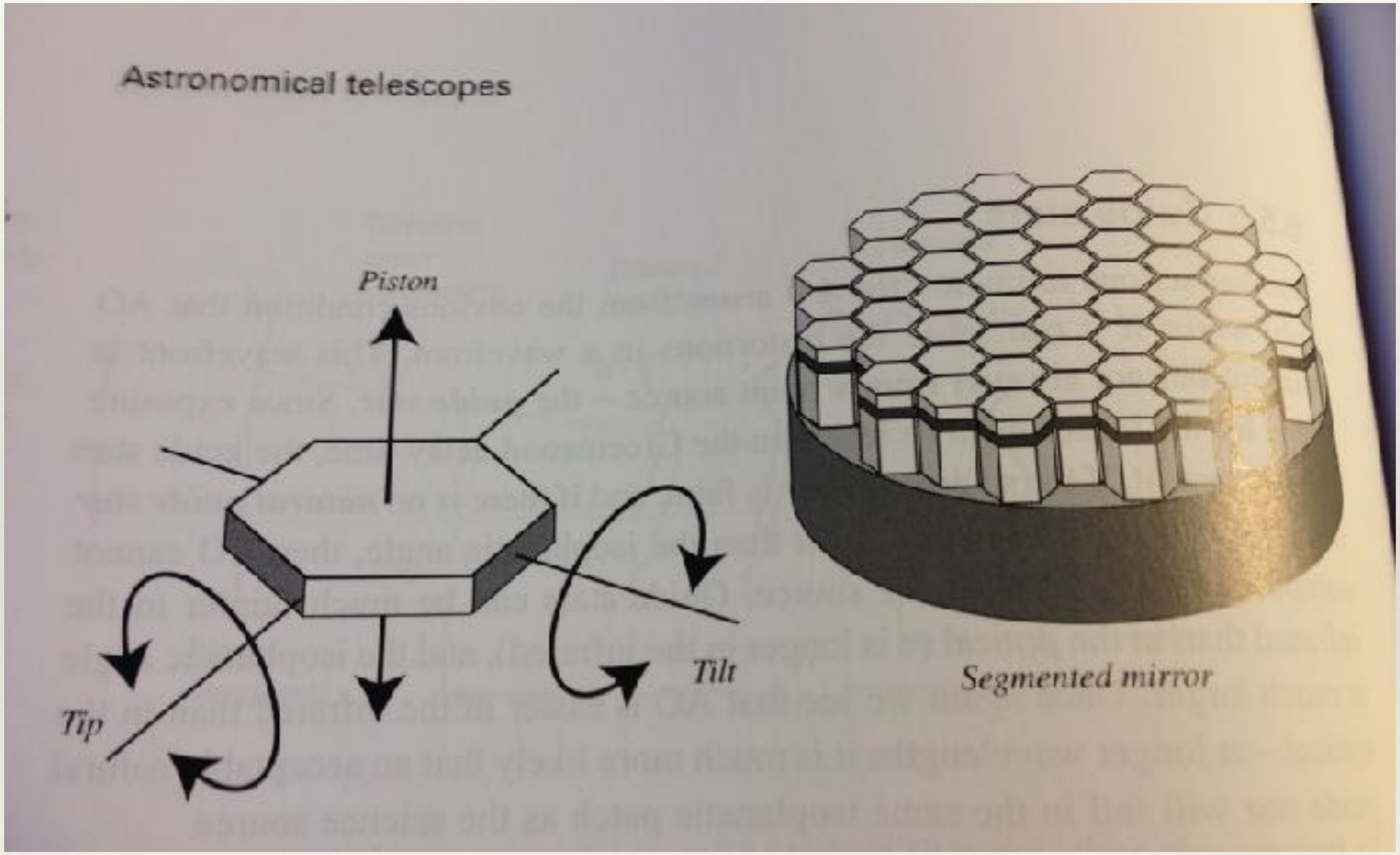
# Adaptive optics

- Remove wavefront distortions using adjustable optical elements
- Normally, a distortable reflective surface in the telescope

# Adaptive optics

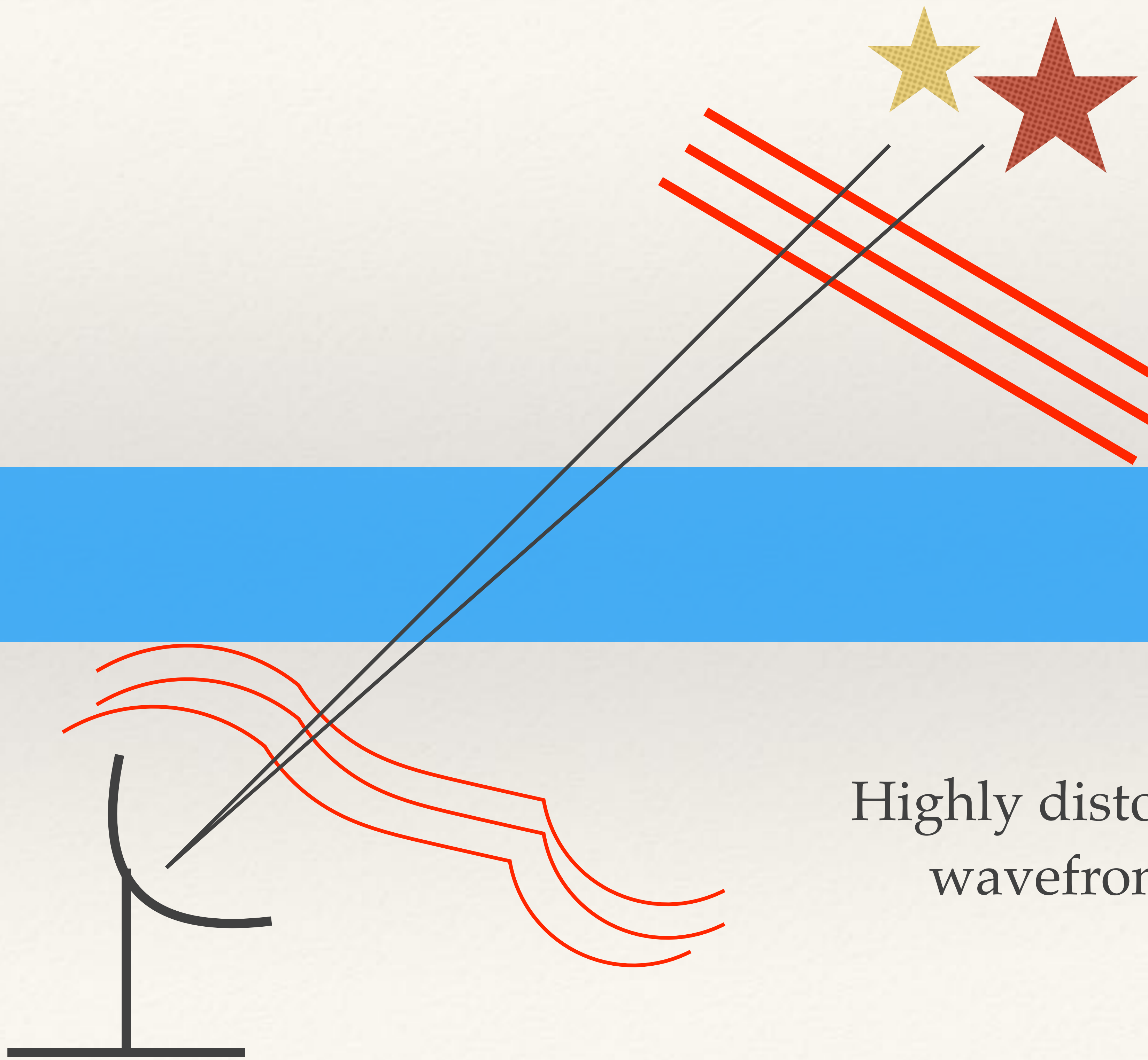


# Adaptive optics




Greenwood time delay $\quad \tau \sim 0.559 \dfrac{\lambda^{6/5}}{v_{\rm turb}}$ (few milliseconds)

# Guide stars



Highly distorted
wavefront

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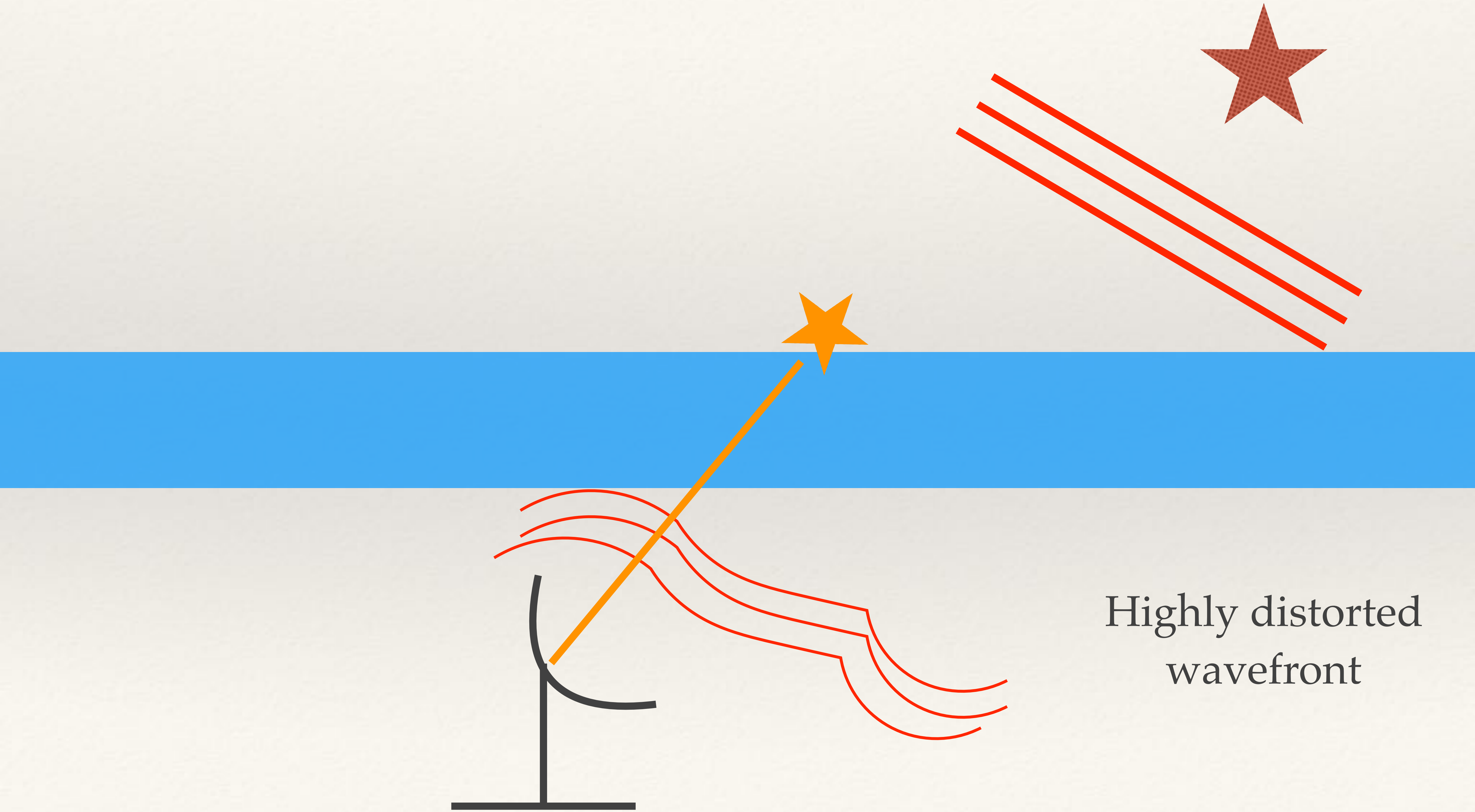
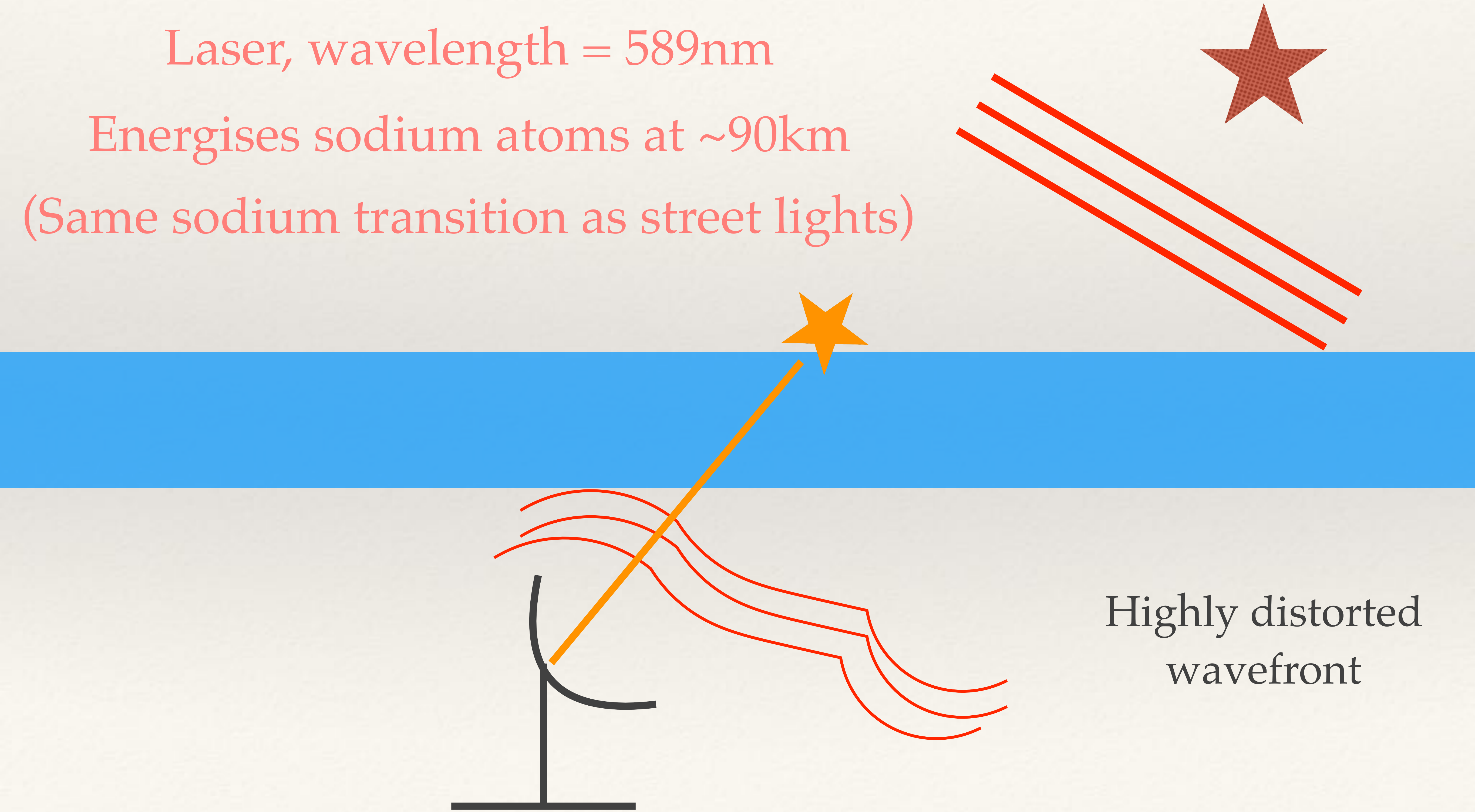


# Guide stars

Laser, wavelength = 589nm

Energises sodium atoms at ~90km

(Same sodium transition as street lights)



Highly distorted wavefront

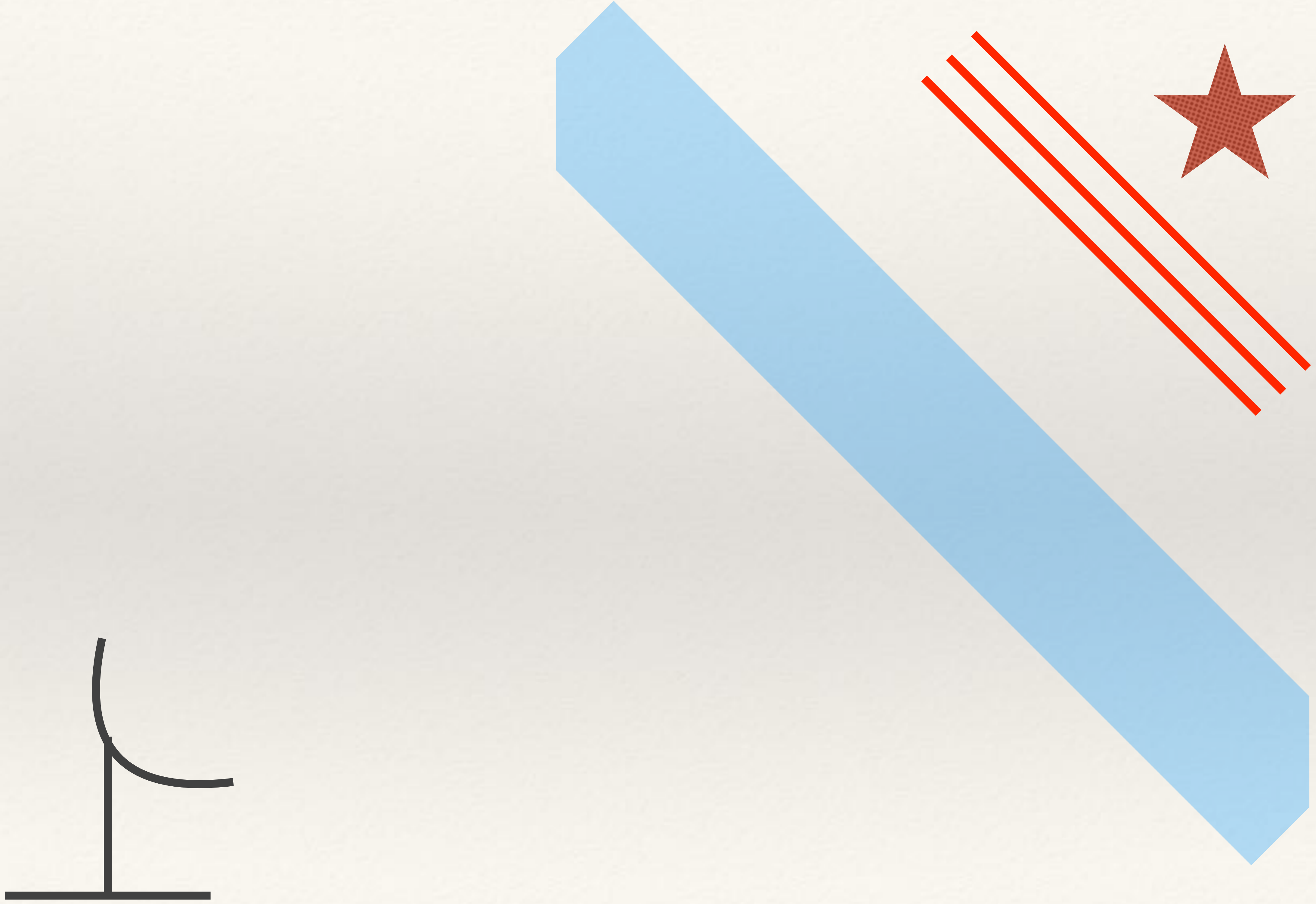
# Lucky imaging

Cheap + easy alternative to adaptive optics

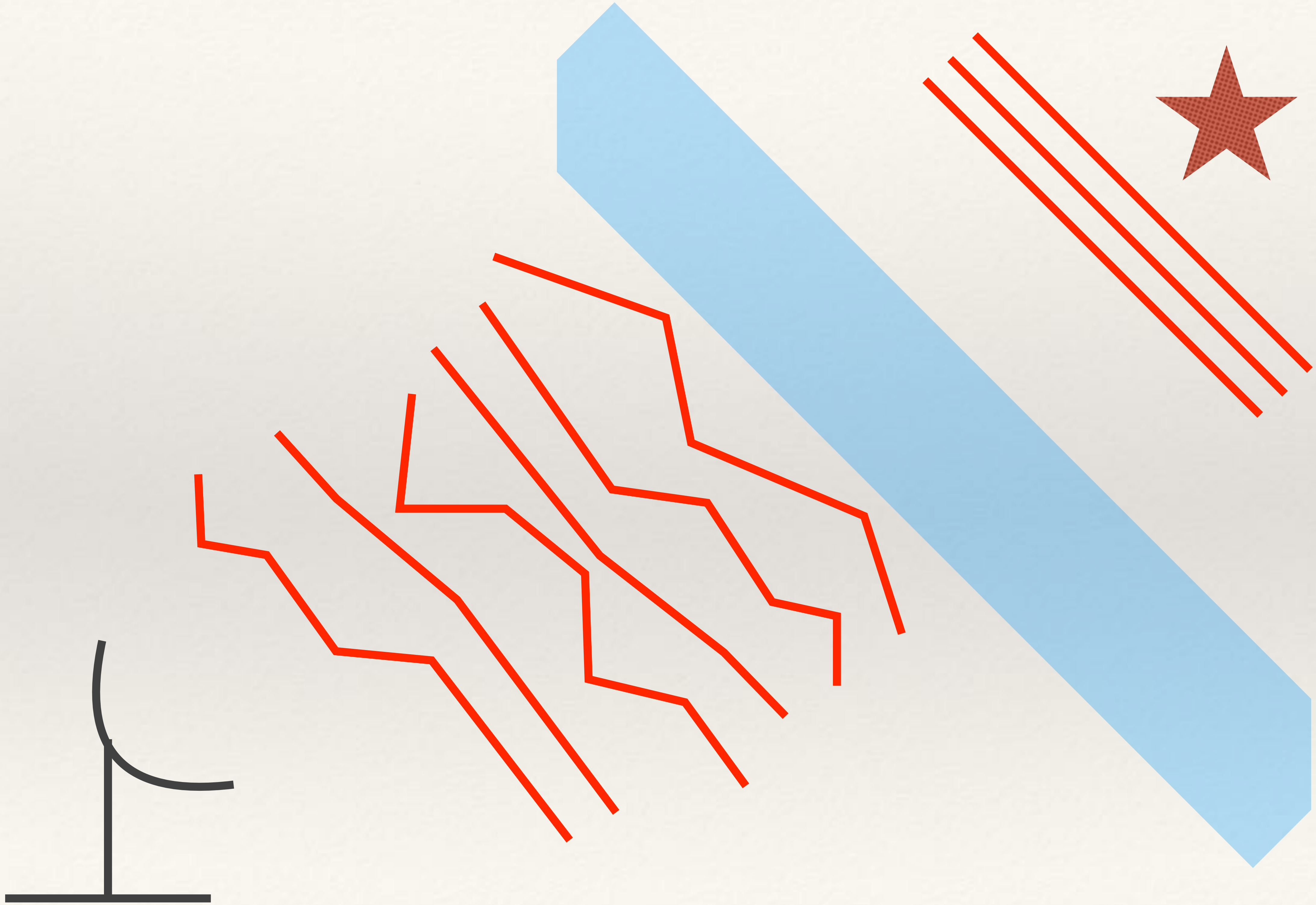
Developed here in Cambridge, in 2007

Now popular worldwide (and with amateur astronomers)

# Lucky imaging

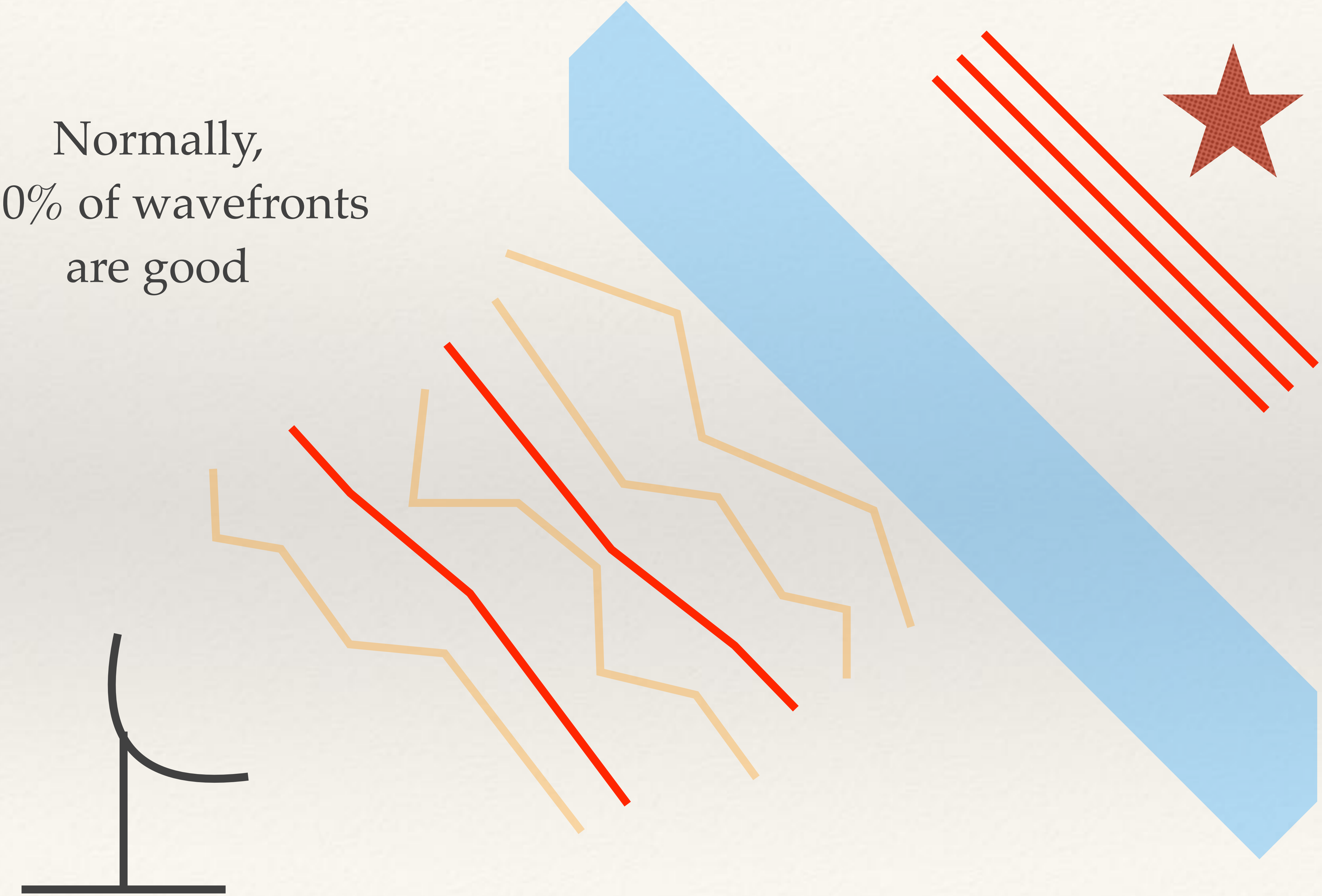


# Lucky imaging



# Lucky imaging

Normally,
~10% of wavefronts
are good



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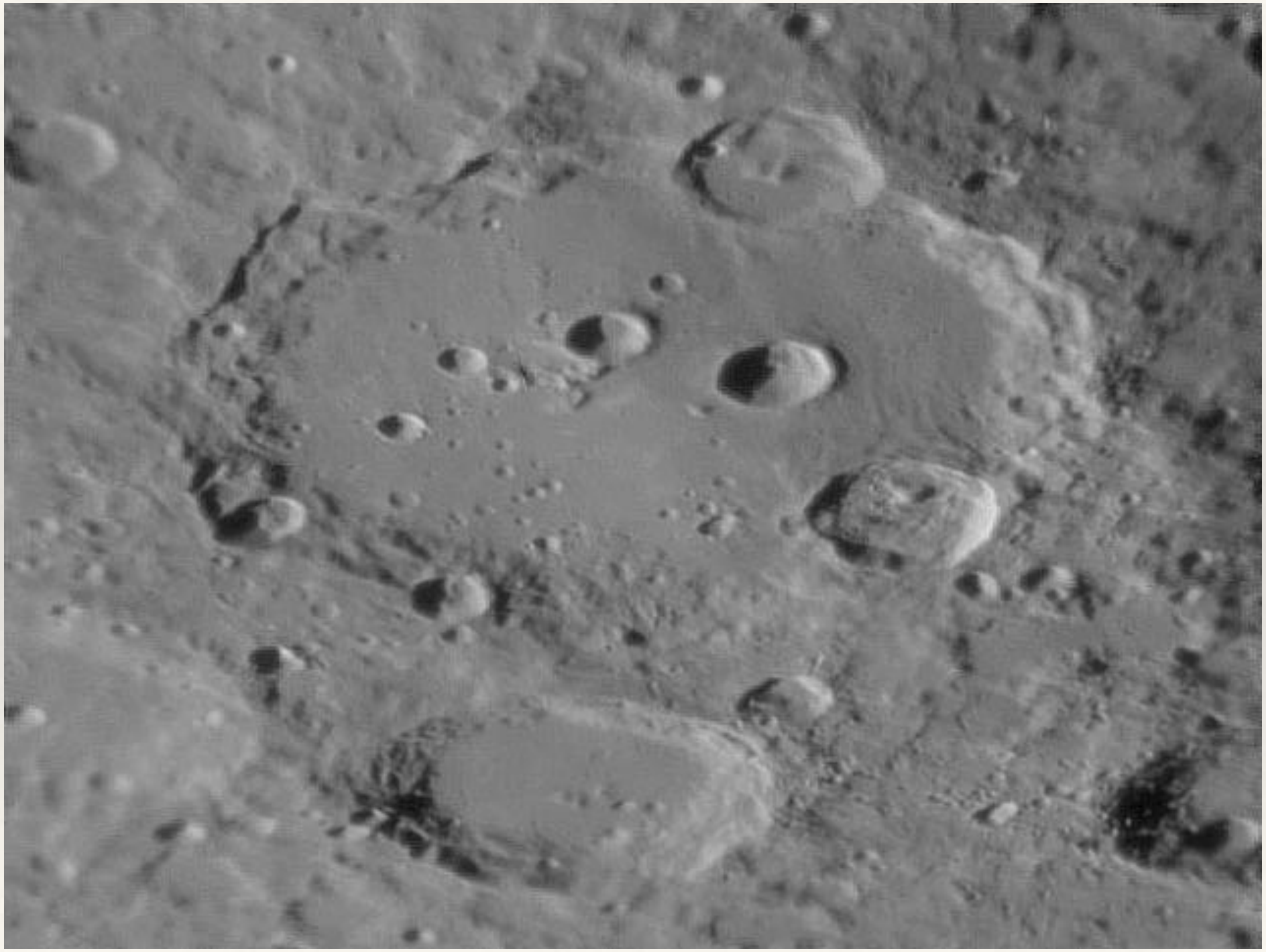

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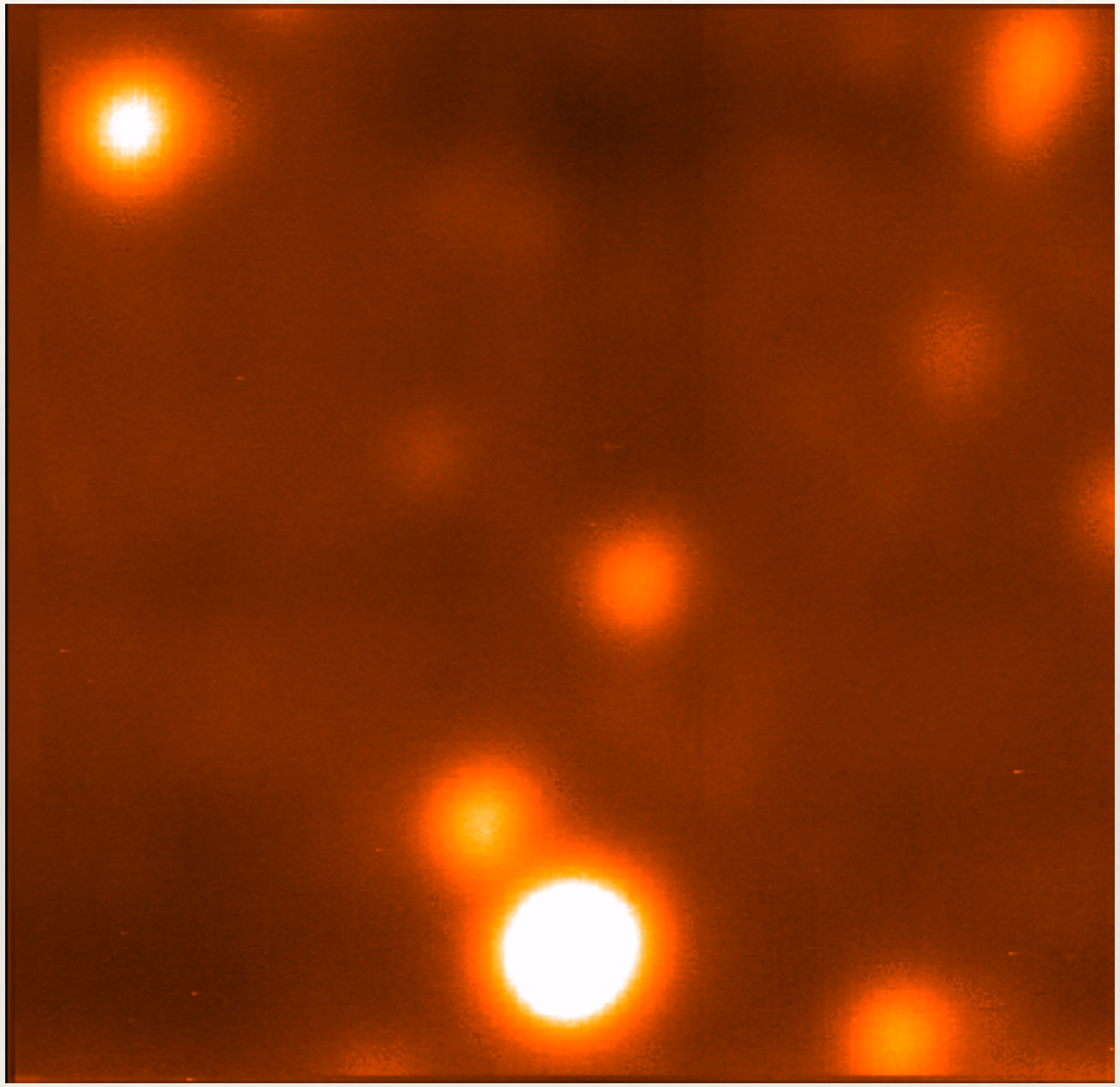
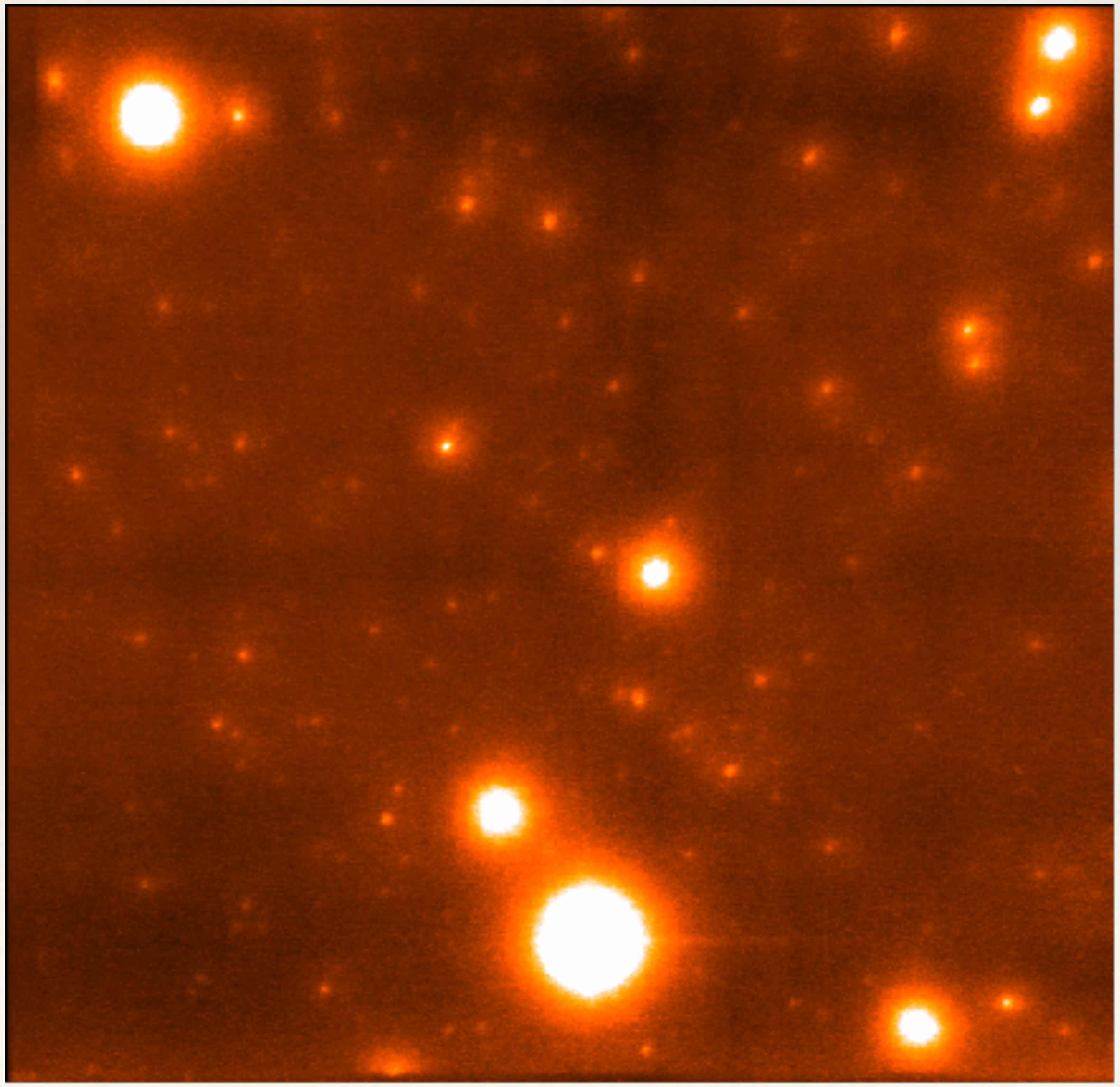




# Optical astronomy (II)

- Photometry
- Spectroscopy

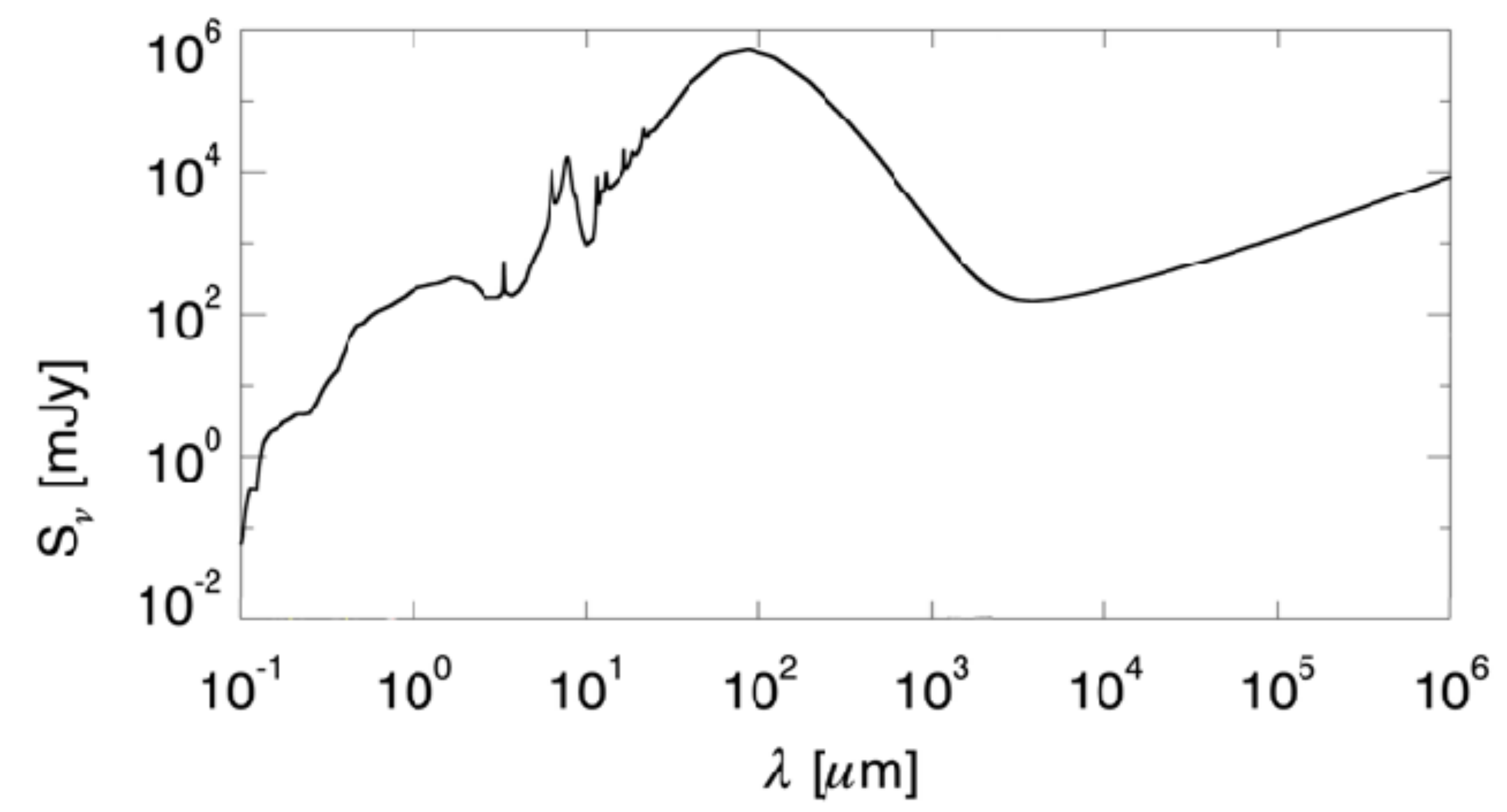
# Photometry vs. Spectroscopy

Photometry measures brightness of an object at a certain wavelength

Spectroscopy measures brightness of an object at across a range of wavelengths

# Photometry vs. Spectroscopy

The ideal situation is to have *full spectral information* for an object



# Photometry vs. Spectroscopy

The ideal situation is to have *full spectral information* for an object

… but, this is very time consuming (and may be difficult for fainter sources)

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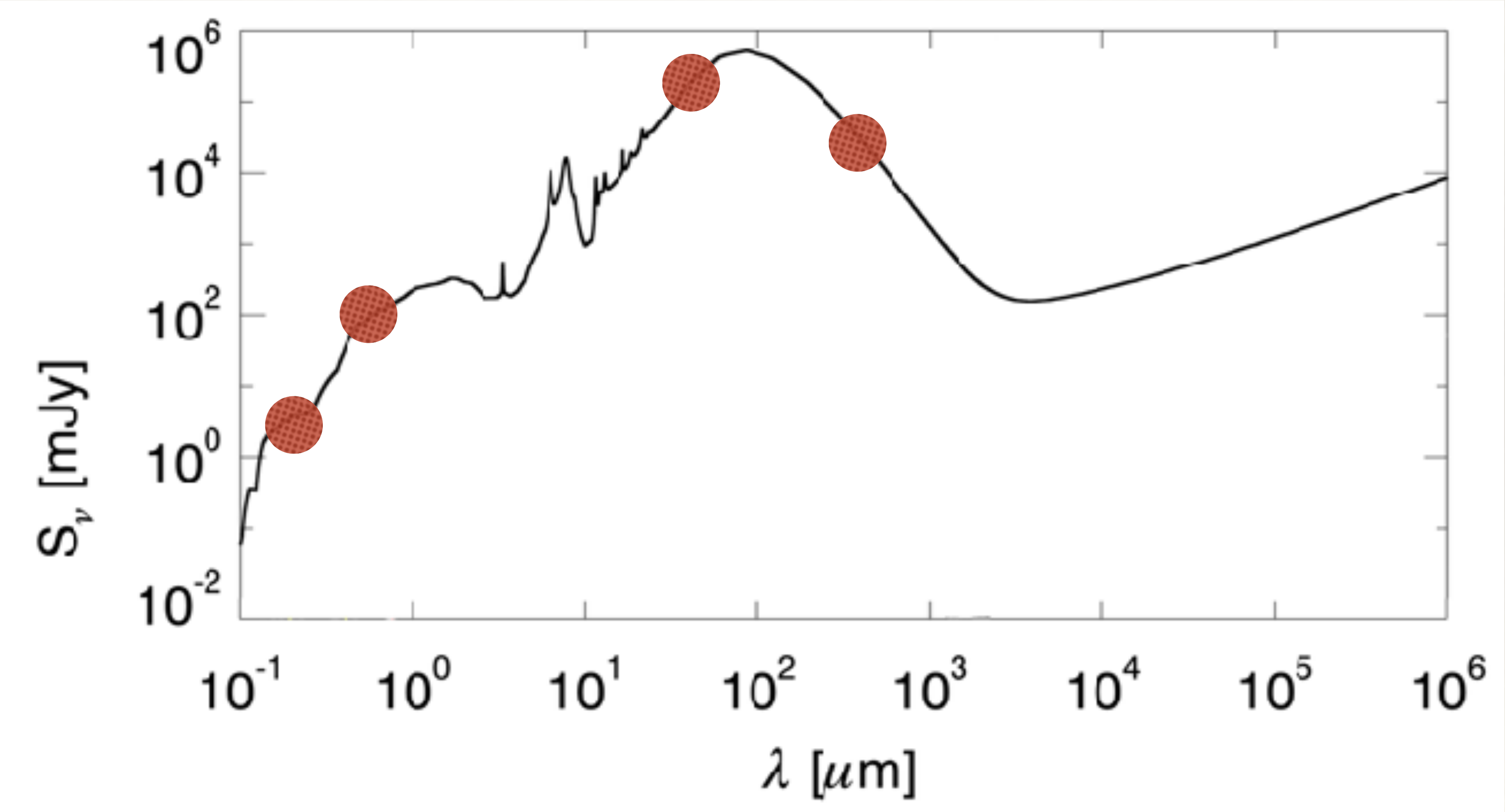
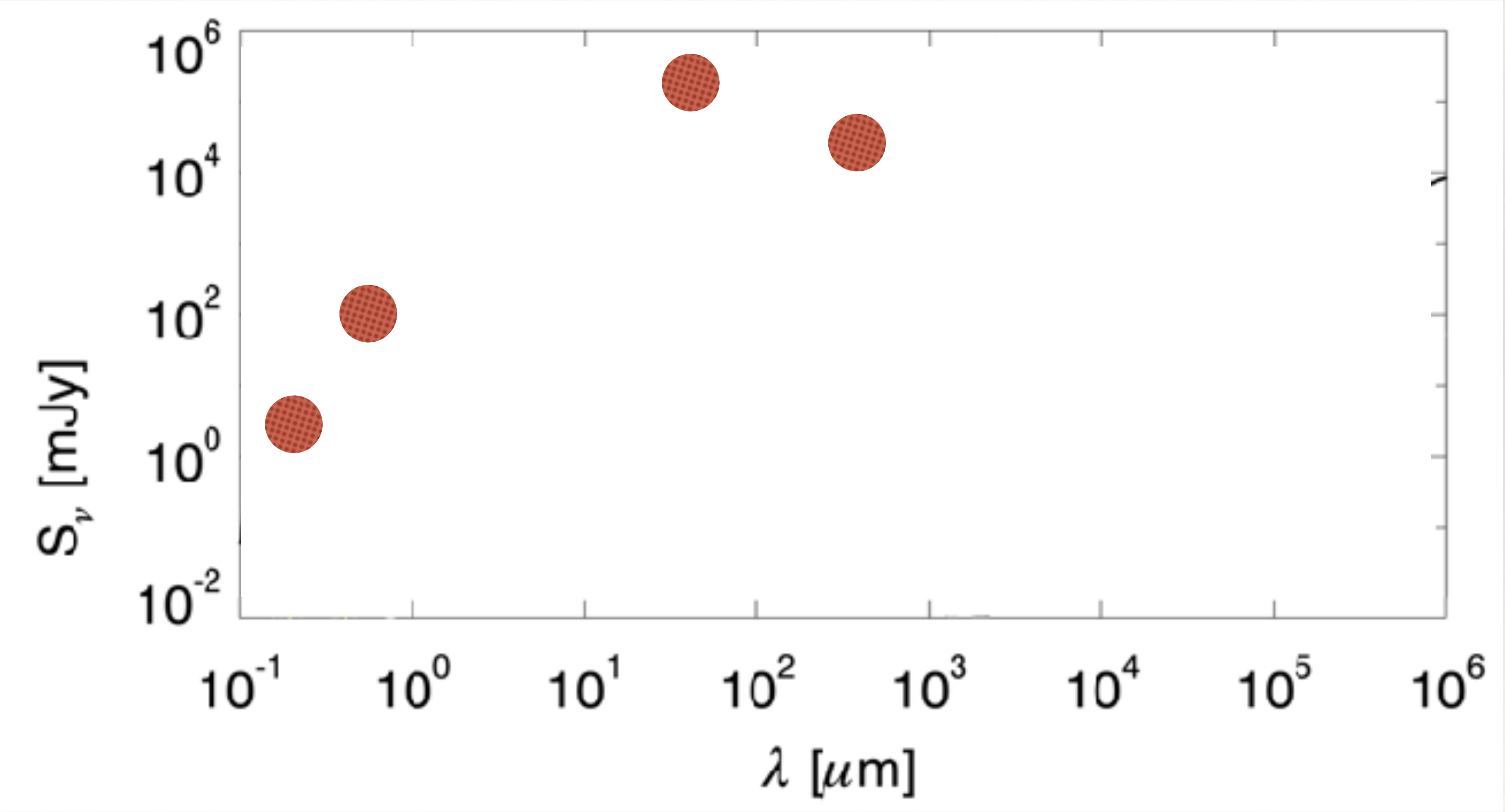


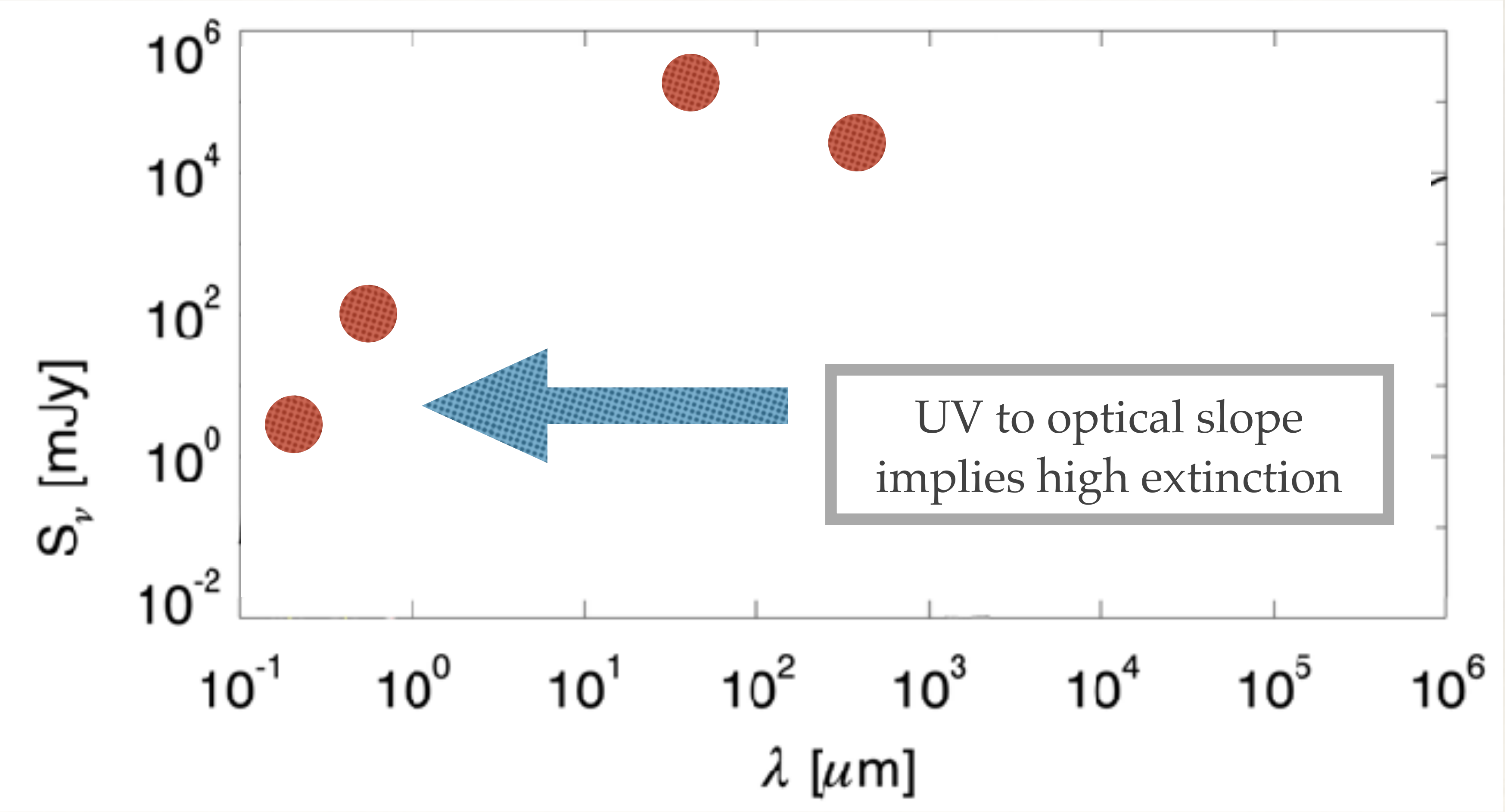
# Photometry vs. Spectroscopy

But, photometry can provide a quick approximation



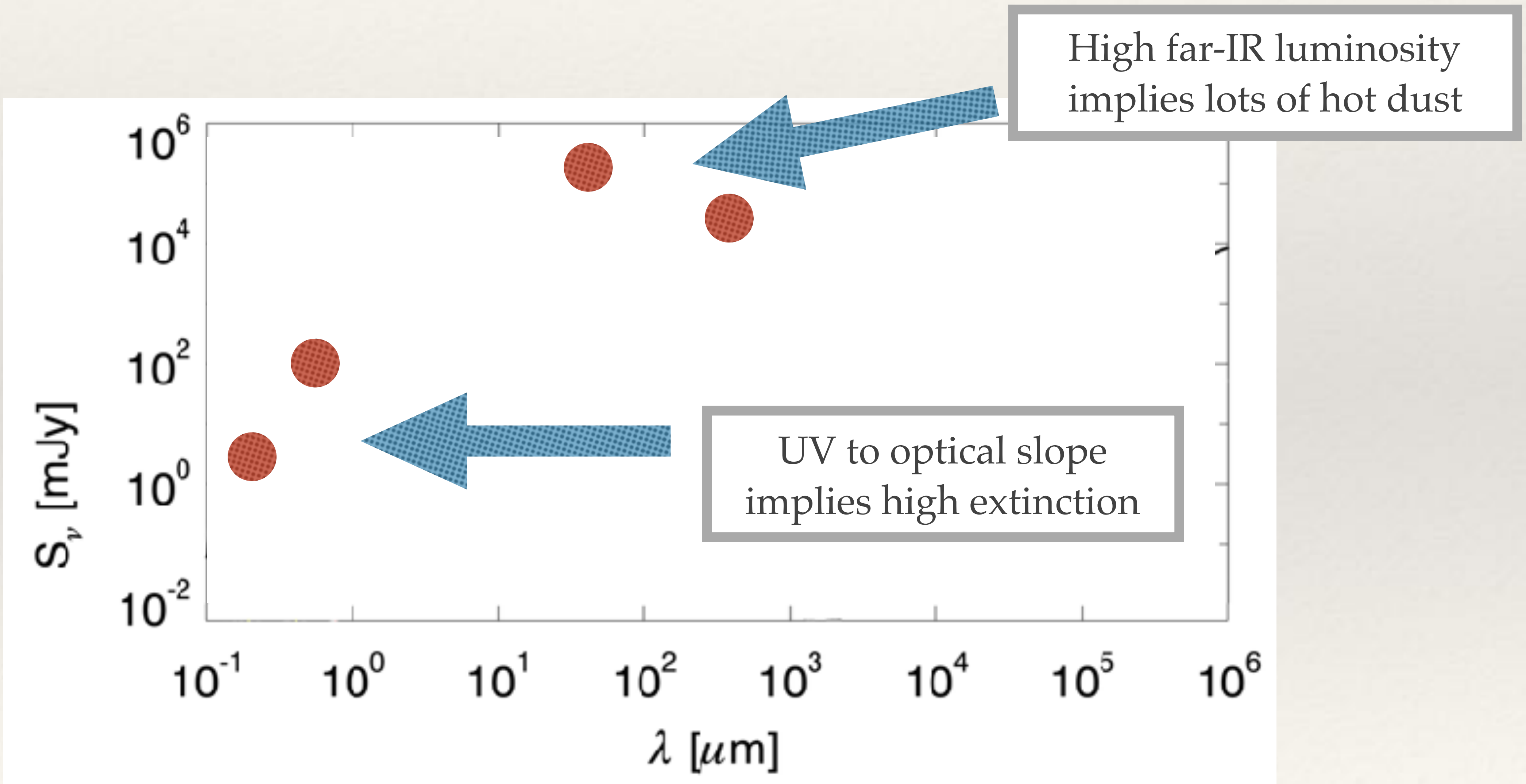
# Photometry vs. Spectroscopy

But, photometry can provide a quick approximation



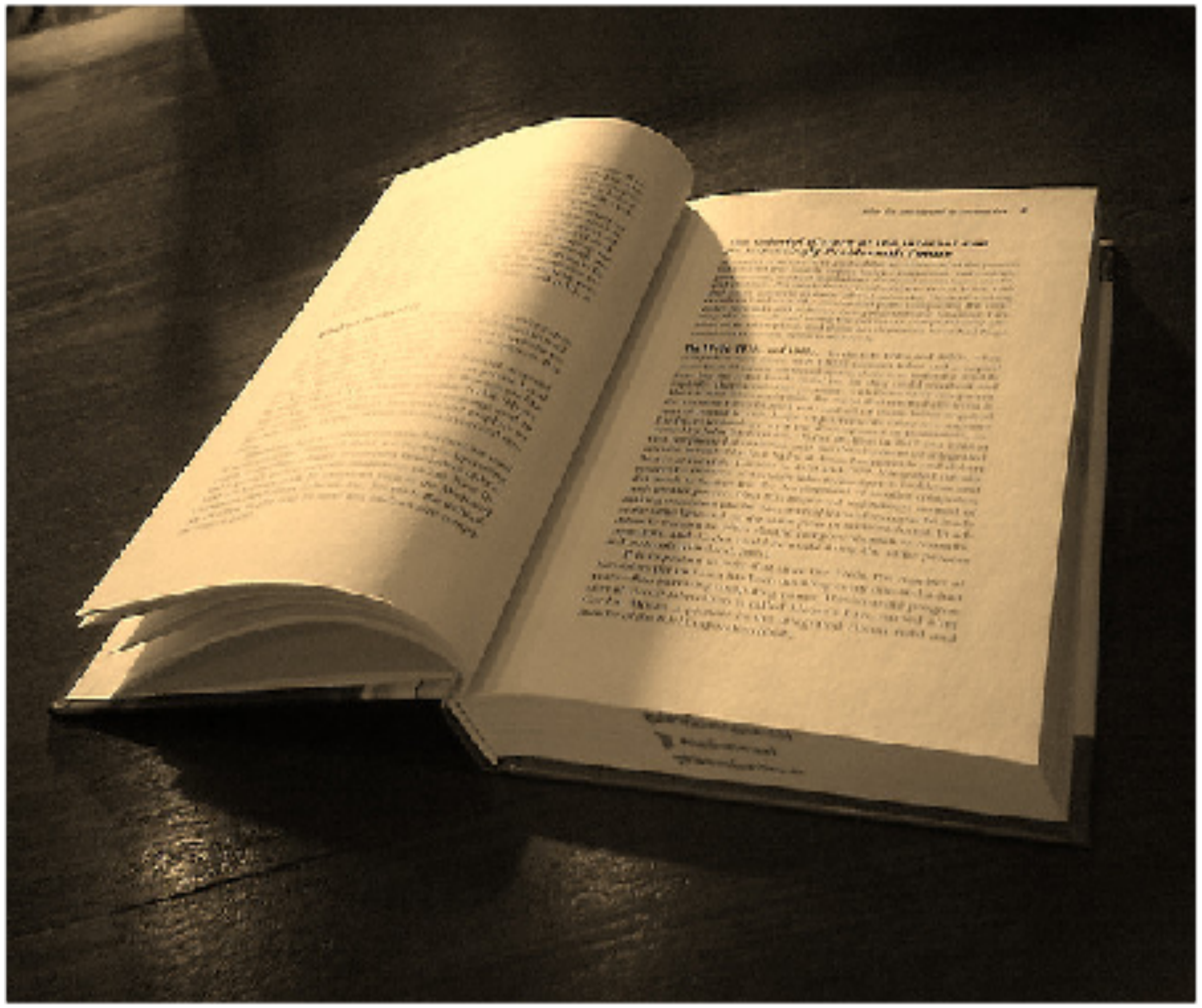
# Photometry vs. Spectroscopy

But, photometry can provide a quick approximation



# Photometry vs. Spectroscopy

- Metaphor: if total light emitted by an object is a book…
- *Spectroscopy* is reading the book cover-to-cover
- *Photometry* is just looking at chapter titles (less information, but much faster)

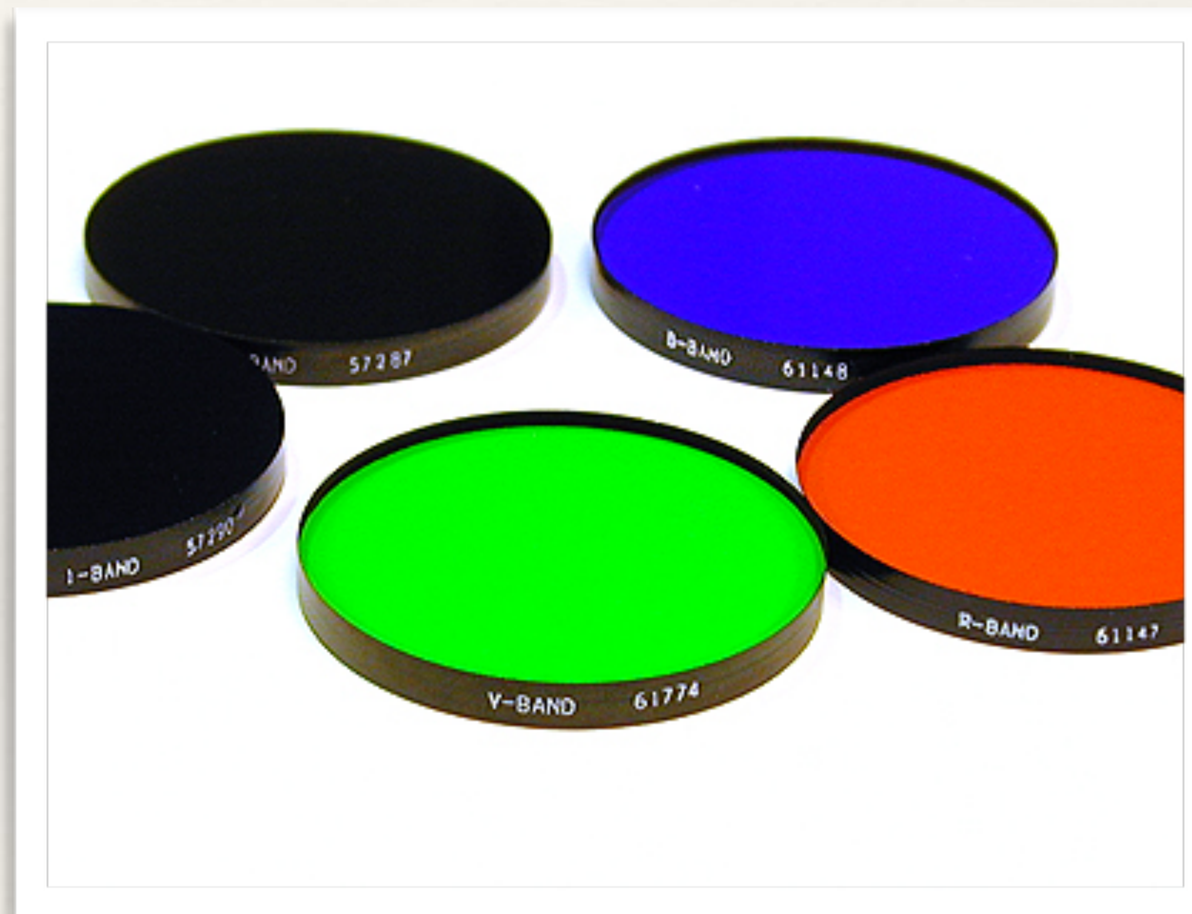


# Optical astronomy (II)

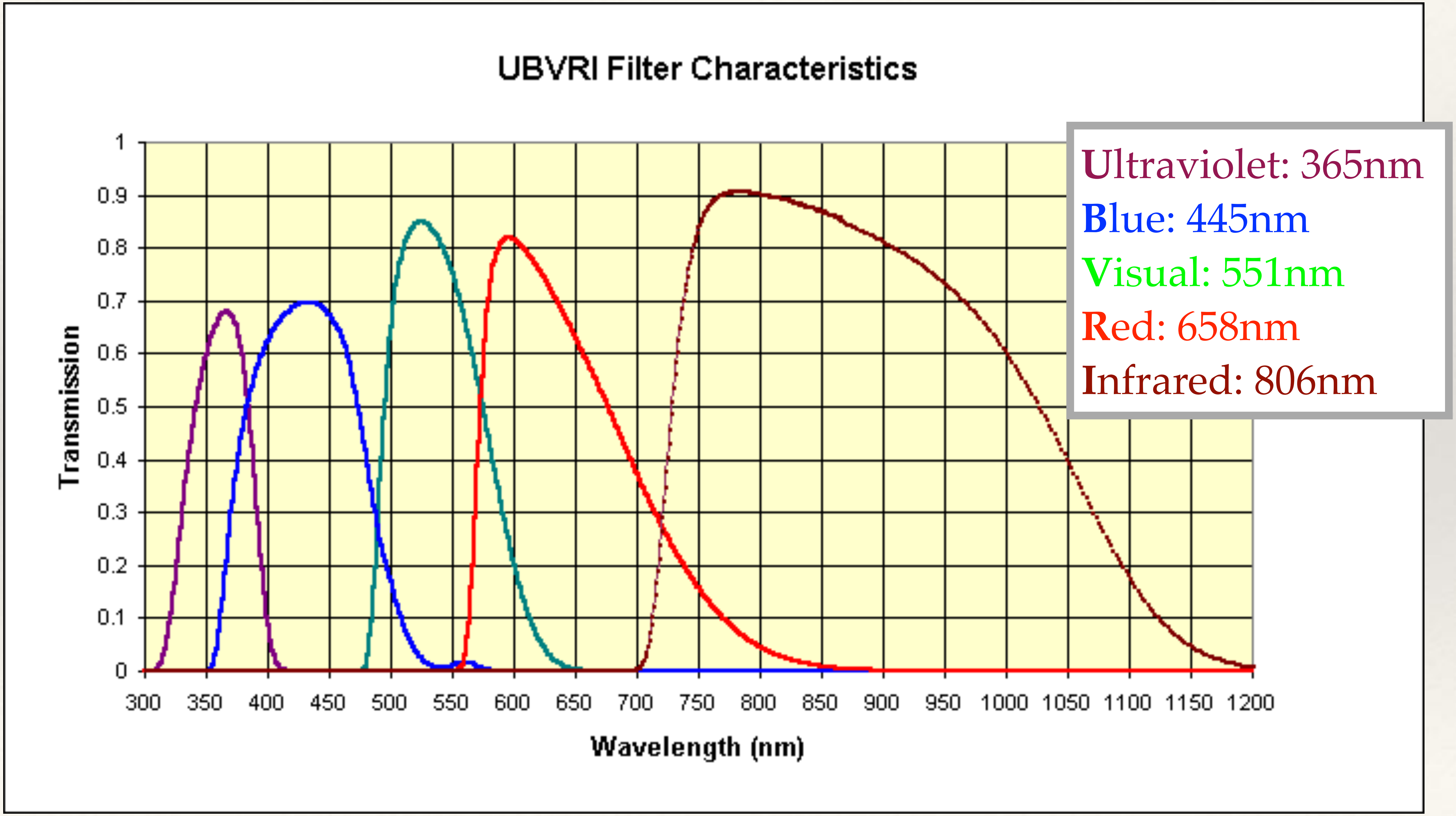
- Photometry
- Spectroscopy
- `Reduction' of astronomical data

# Photometric filters

- Photometric system is based on some defined filters
- Original standard system developed by Harold Johnson in 1953
- Called the ‘UBV’ system (later, extended to ‘UBVRI’



# Photometric filters



# Photometric filters

- UBVRI system useful because atmospheric transmission is essentially featureless across BVRI (U-band is shortest useful transmission band)
- Johnson defined zero points of the UBVRI system relative to Vega (setting Vega to $V = 0.03$, and all colours $= 0$)
- Magnitudes are often now measured relative to Vega ('Vega magnitudes')

# Alternate systems

UBVRI was defined relative to the original photometer owned by Johnson

Every time a detector failed there was a crisis to find another detector with similar spectral properties (and then to re-establish the photometric system)

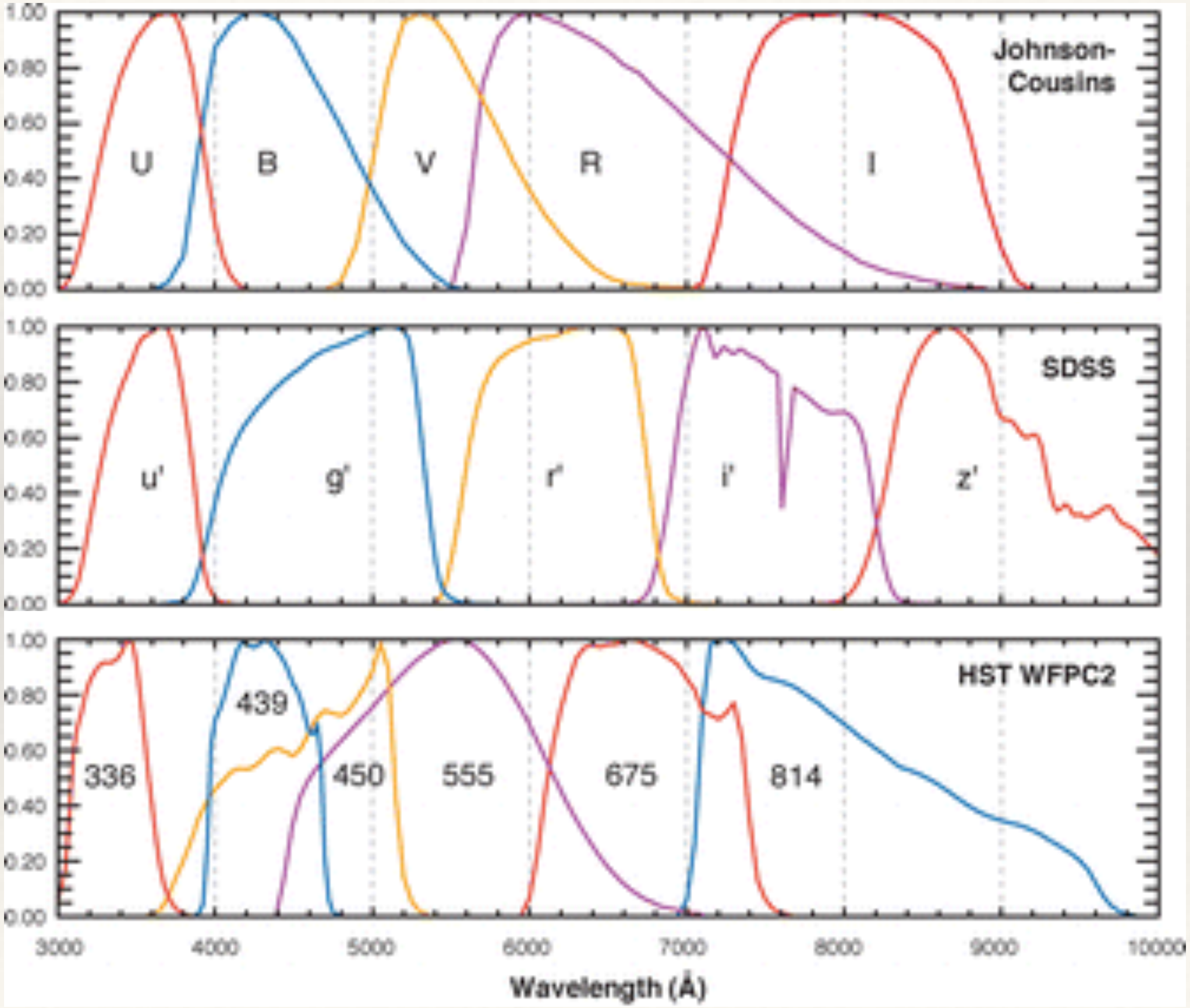
Now, we have dropped the idea of a single defining photometer. So, magnitude systems can differ!

# Alternate systems

Classic

SDSS

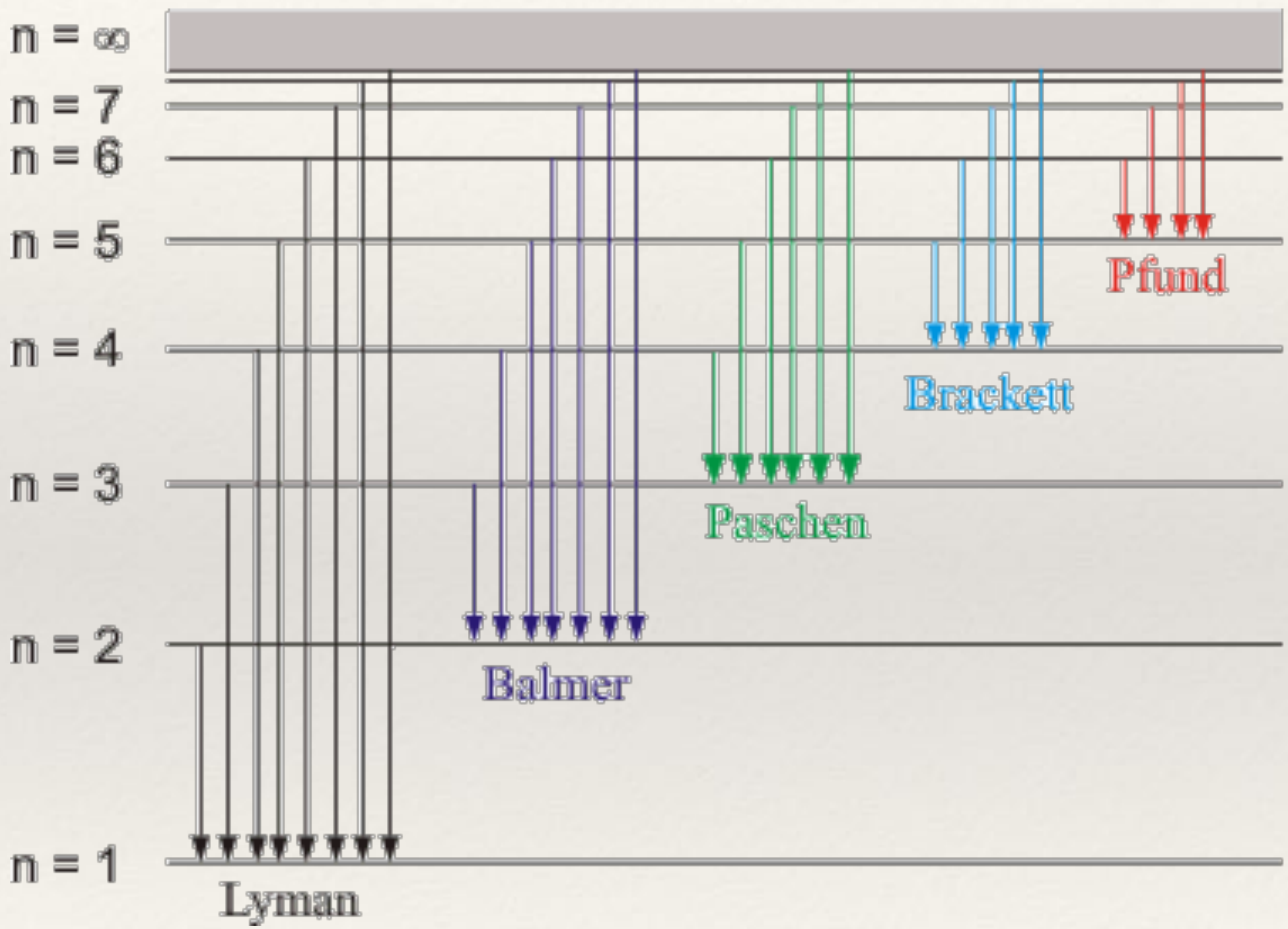
Hubble



# Uses of photometry

- `Photometric dropout' technique (searching for the most distant galaxies)
- Stellar light curves (eclipses of planets)

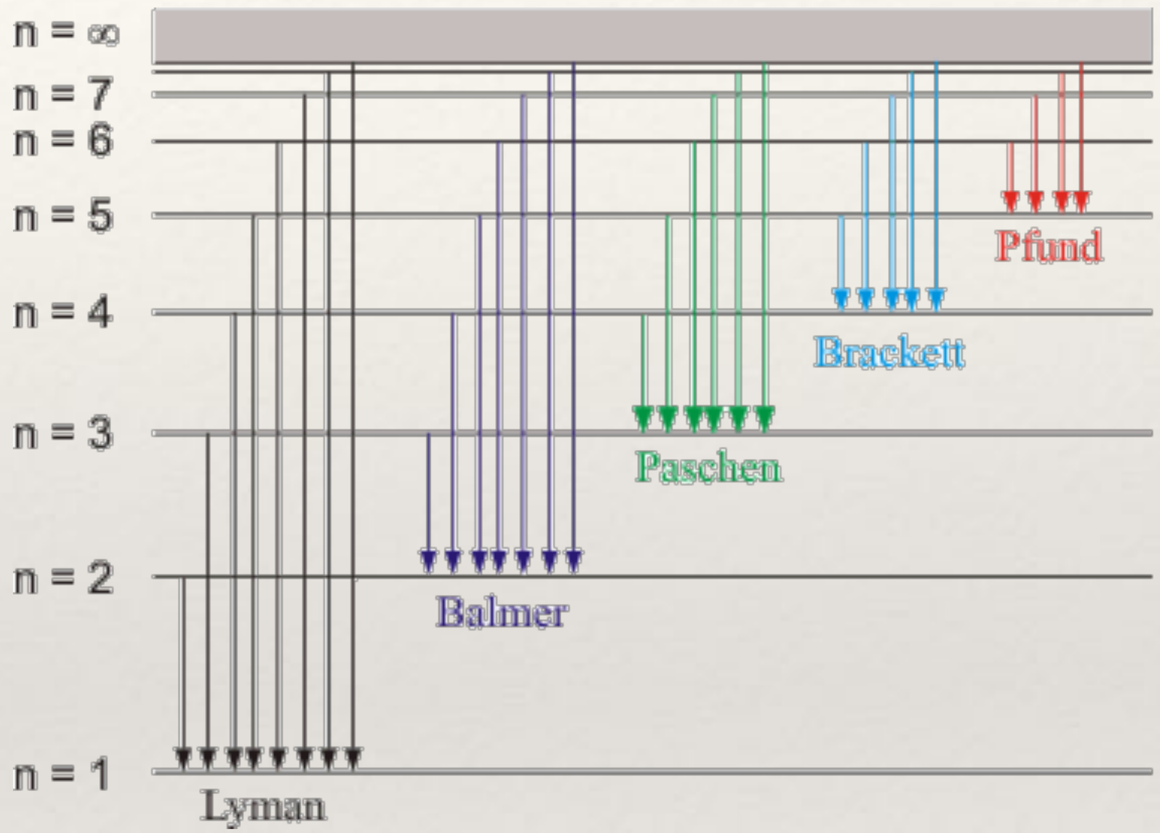
# Photometric dropouts



# Photometric dropouts

- Wavelength given by Rydberg formula:

$$1/\lambda = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$




For full ionisation, $n_1$=1, $n_2$=infinity

# Photometric dropouts

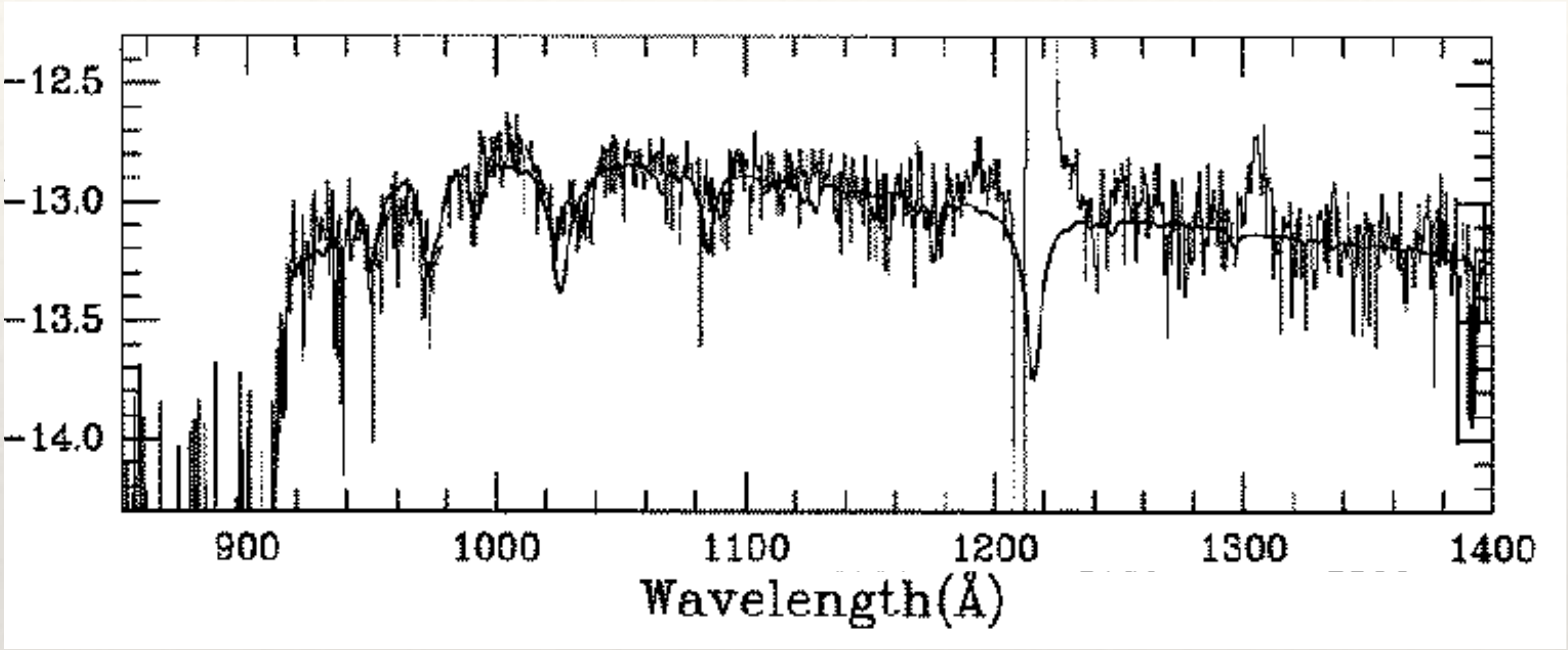
$$1/\lambda = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

$$1/\lambda = R$$

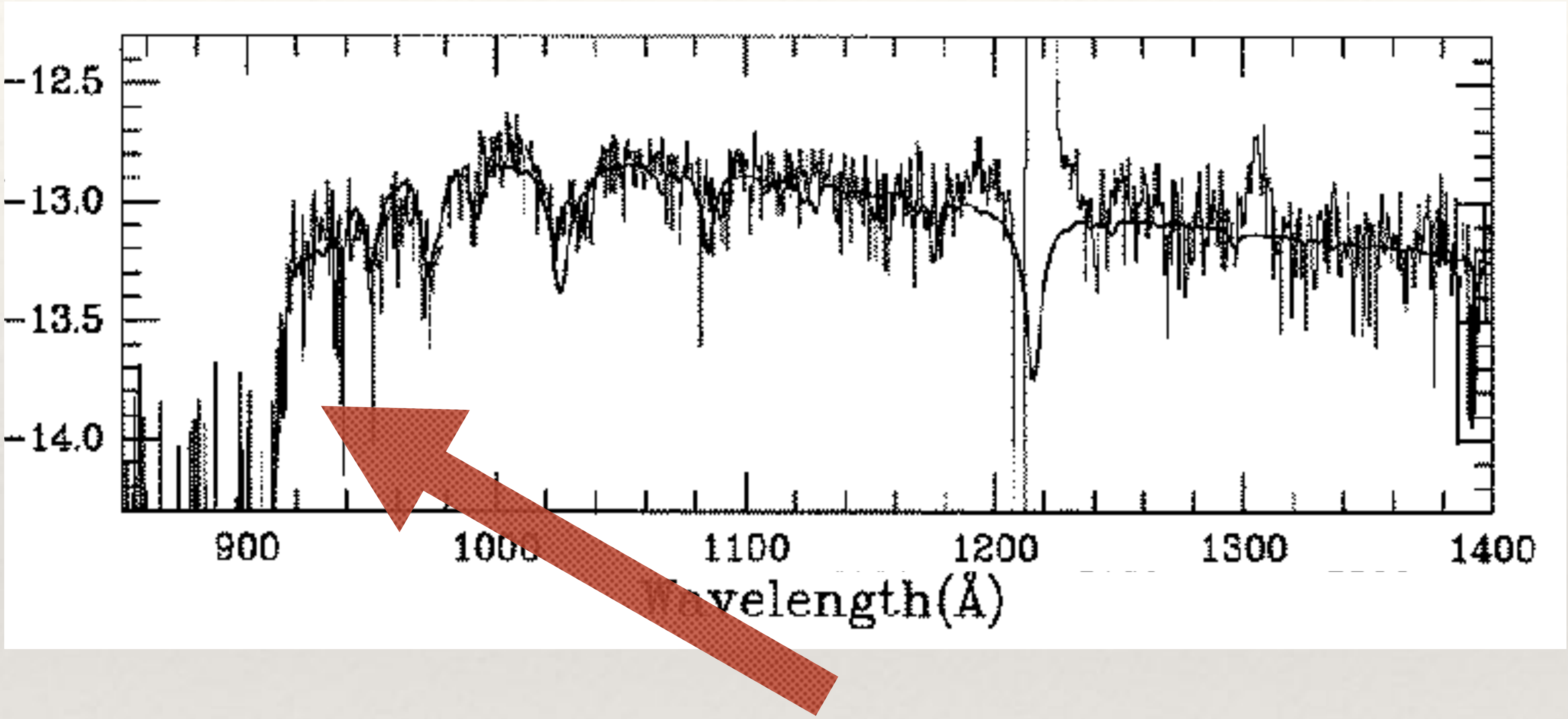
$$\lambda = 91.1\mathrm{nm}$$

Photons of wavelength 91.1nm (and above) are absorbed by hydrogen: the Universe is very opaque to these photons

# Photometric dropouts



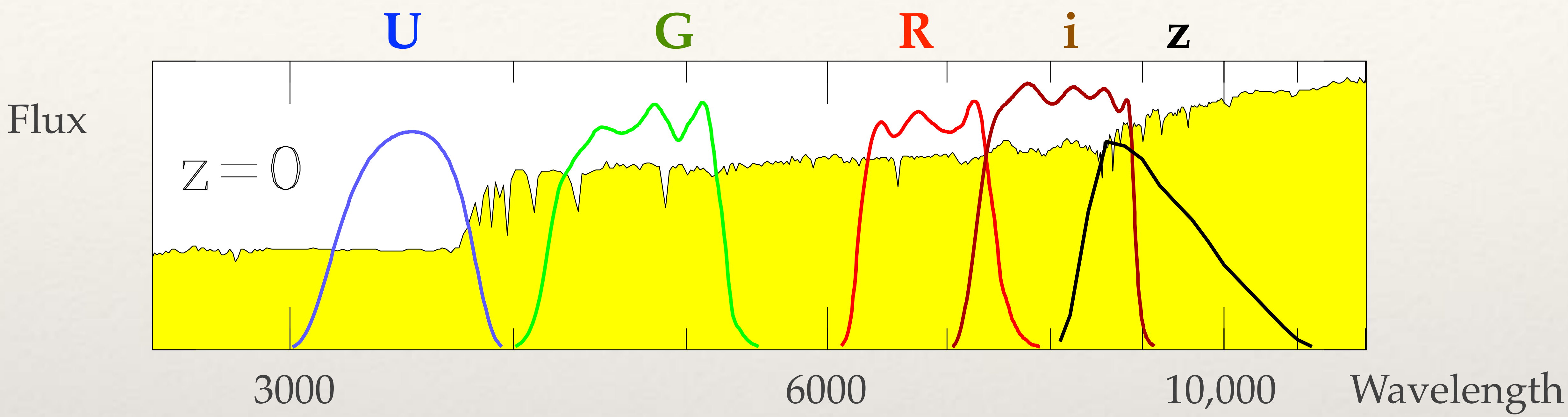
# Photometric dropouts



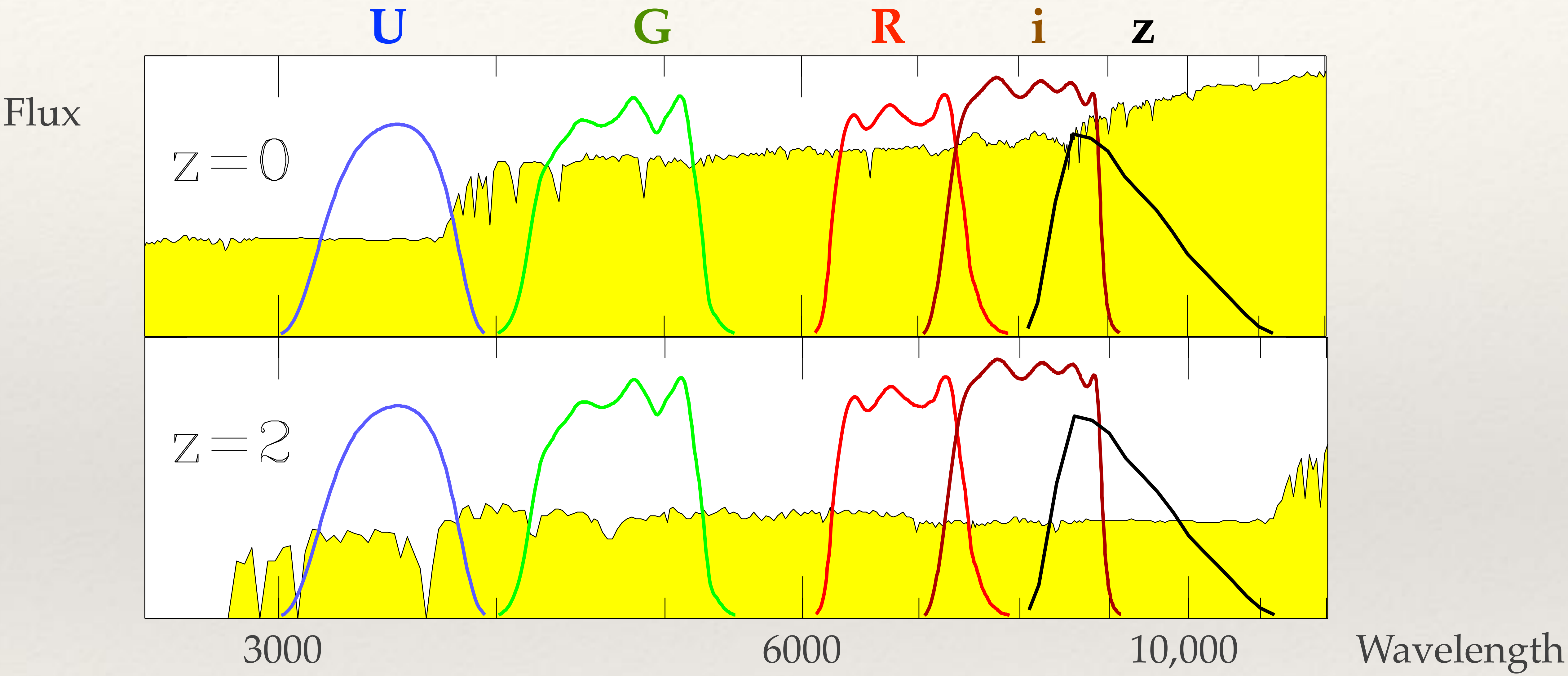

Spectral drop-off after 'Lyman Limit'

**This feature is in the rest-frame UV, but can be redshifted into the optical bands**

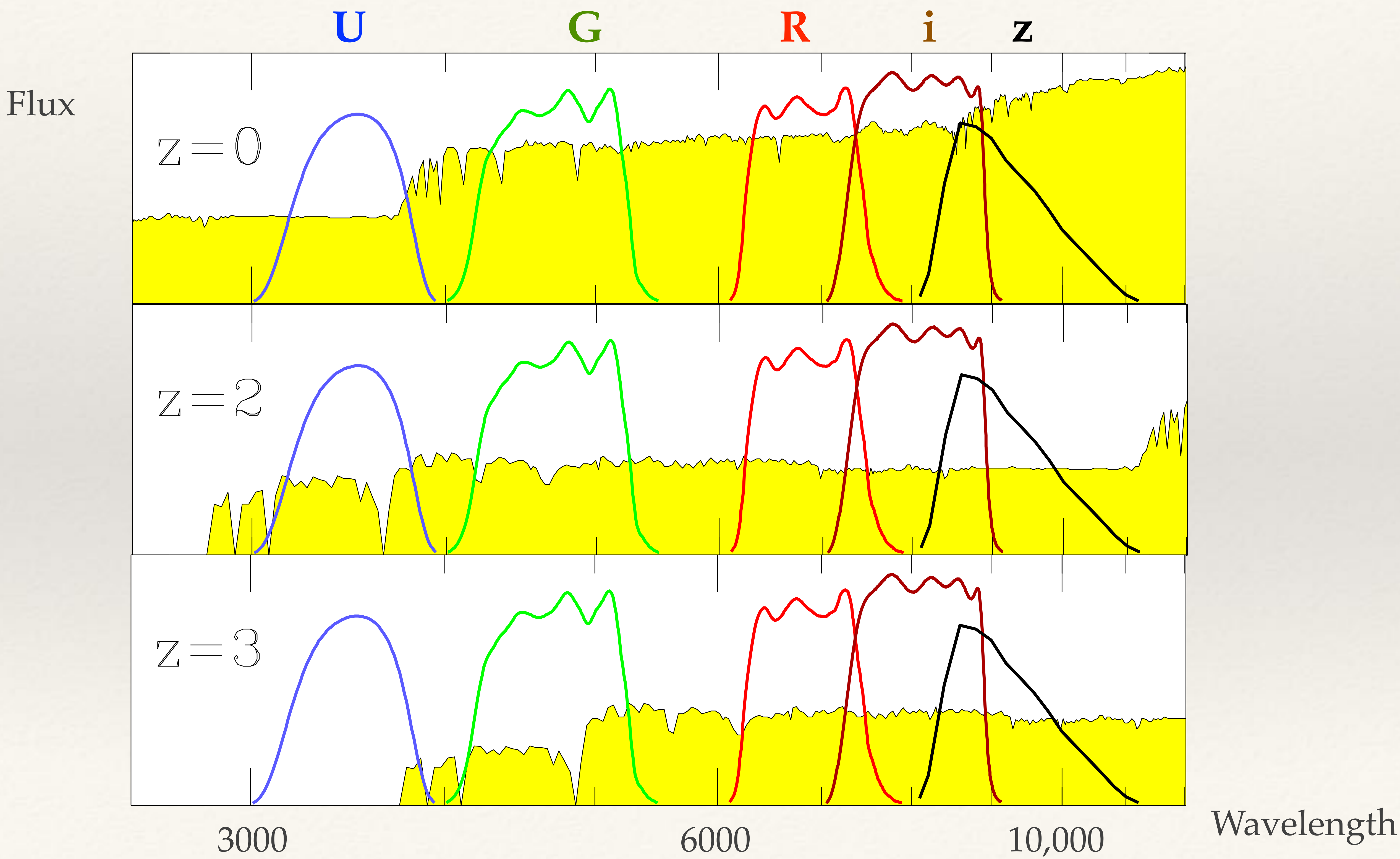
# Photometric dropouts



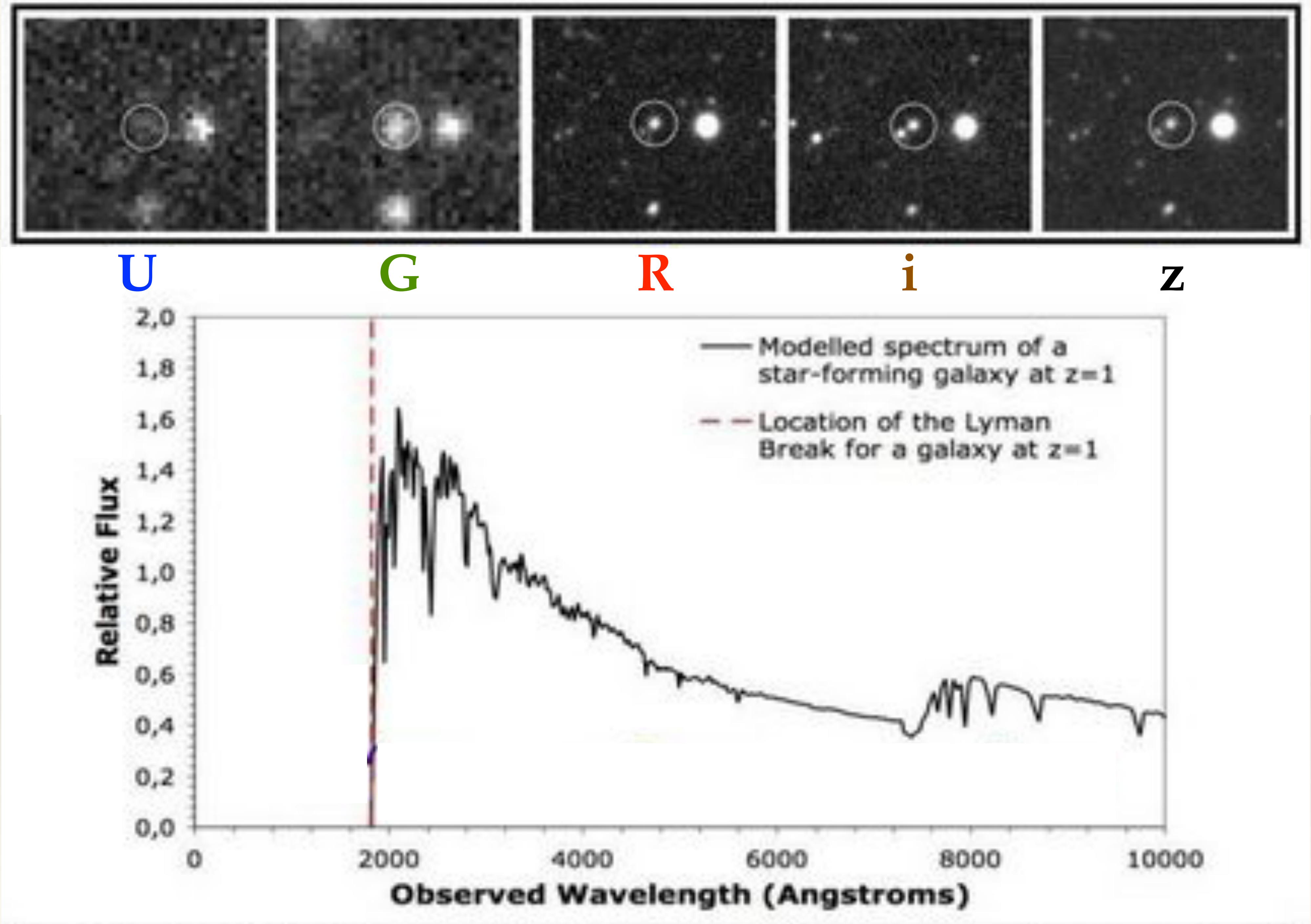
# Photometric dropouts



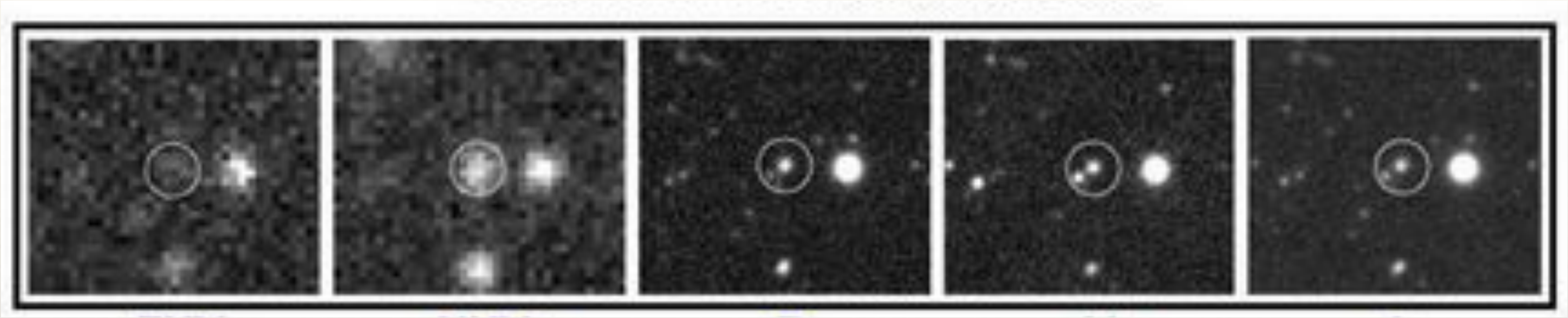
# Photometric dropouts



# Photometric dropouts



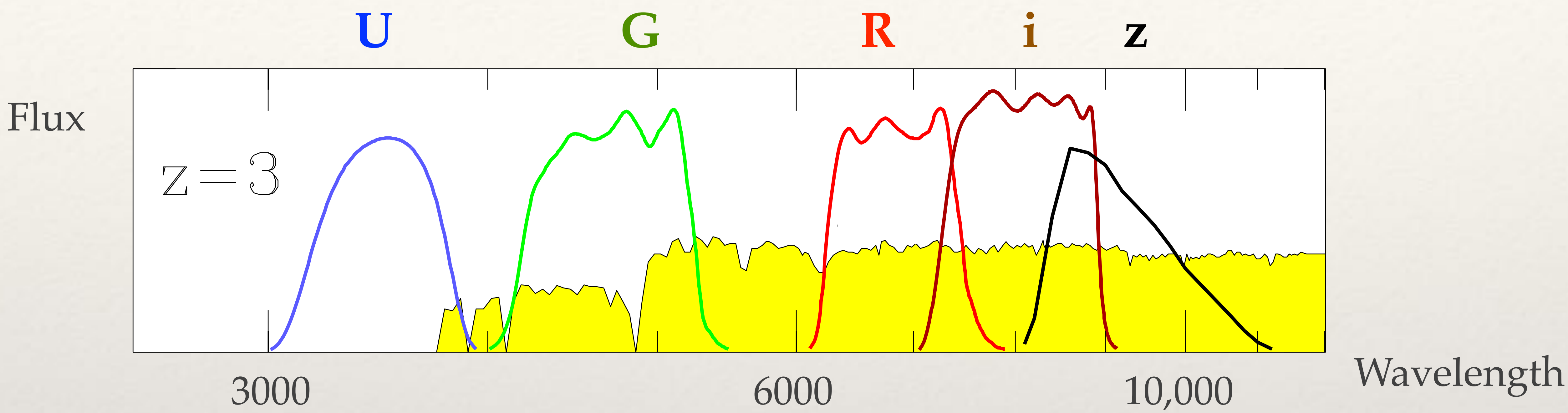
# Photometric dropouts




Even in the absence of spectral data, these photometric datapoints indicate a star-forming galaxy at z~3

The galaxy is a *U-dropout*

# Photometric dropouts




U-band dropouts are at z~3

Can extend this technique to higher redshifts:

G-band dropouts are at z~4

R-band dropouts are at z~5

# Lyman-Break Galaxies (LBGs)

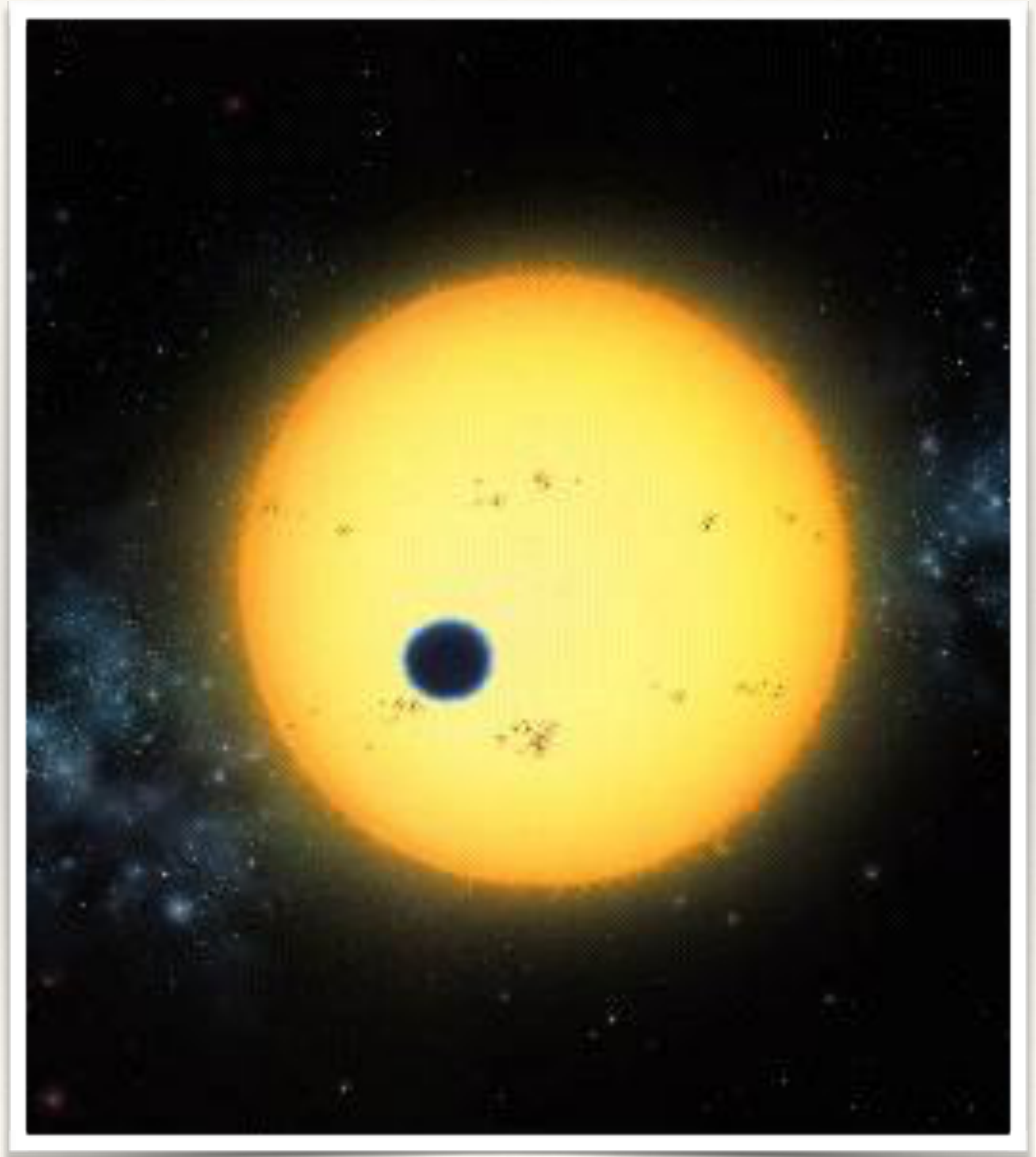
Galaxies found using this method are called 'Lyman-Break' Galaxies (LBGs)

At $z \sim 3$, LBGs are star-forming galaxies that would generally be too small to be found using other ways (they are 'normal' galaxies)

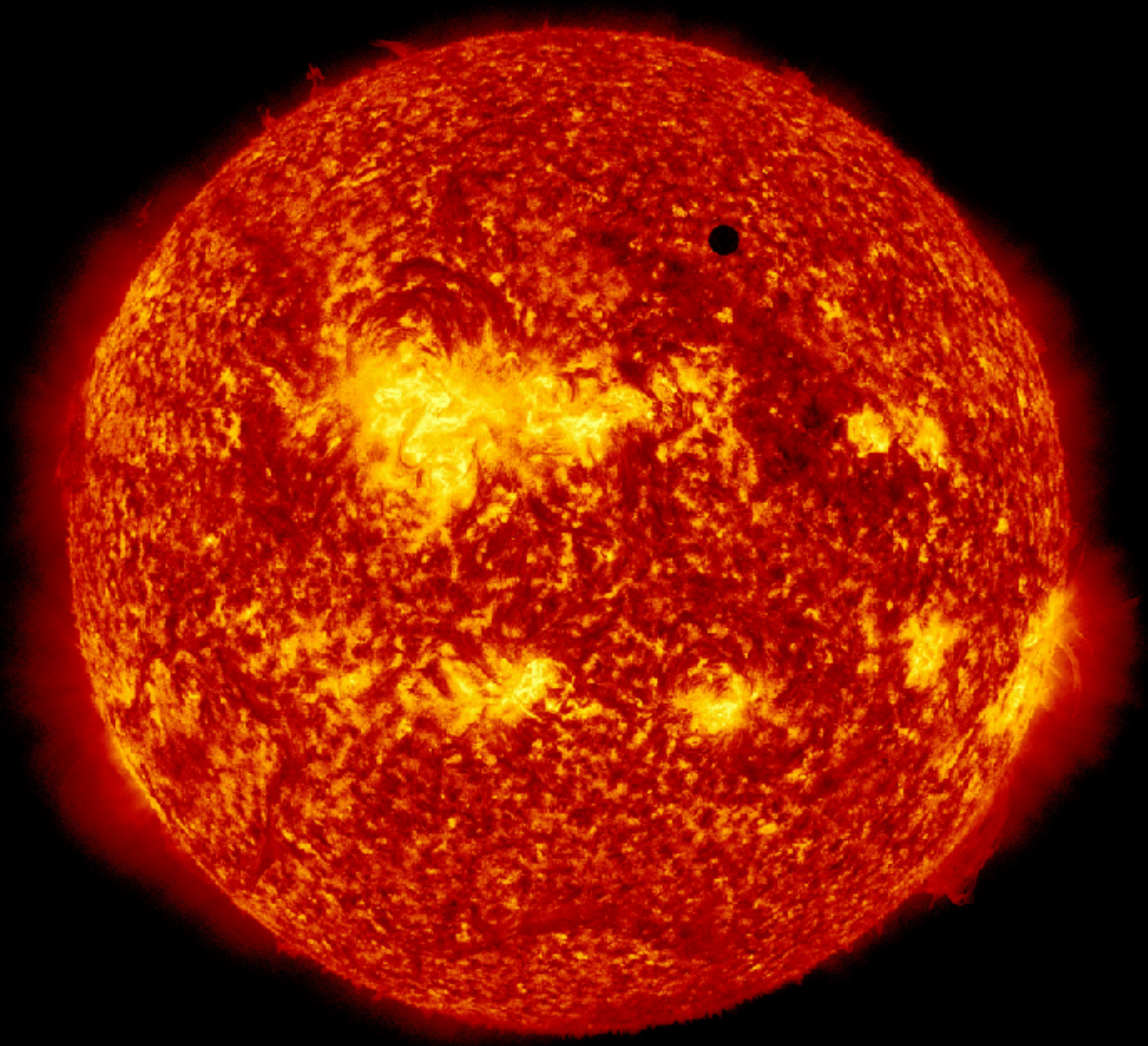
At the highest redshifts (dropouts in very red bands), galaxies are too faint for spectroscopy

# Detecting transiting exoplanets

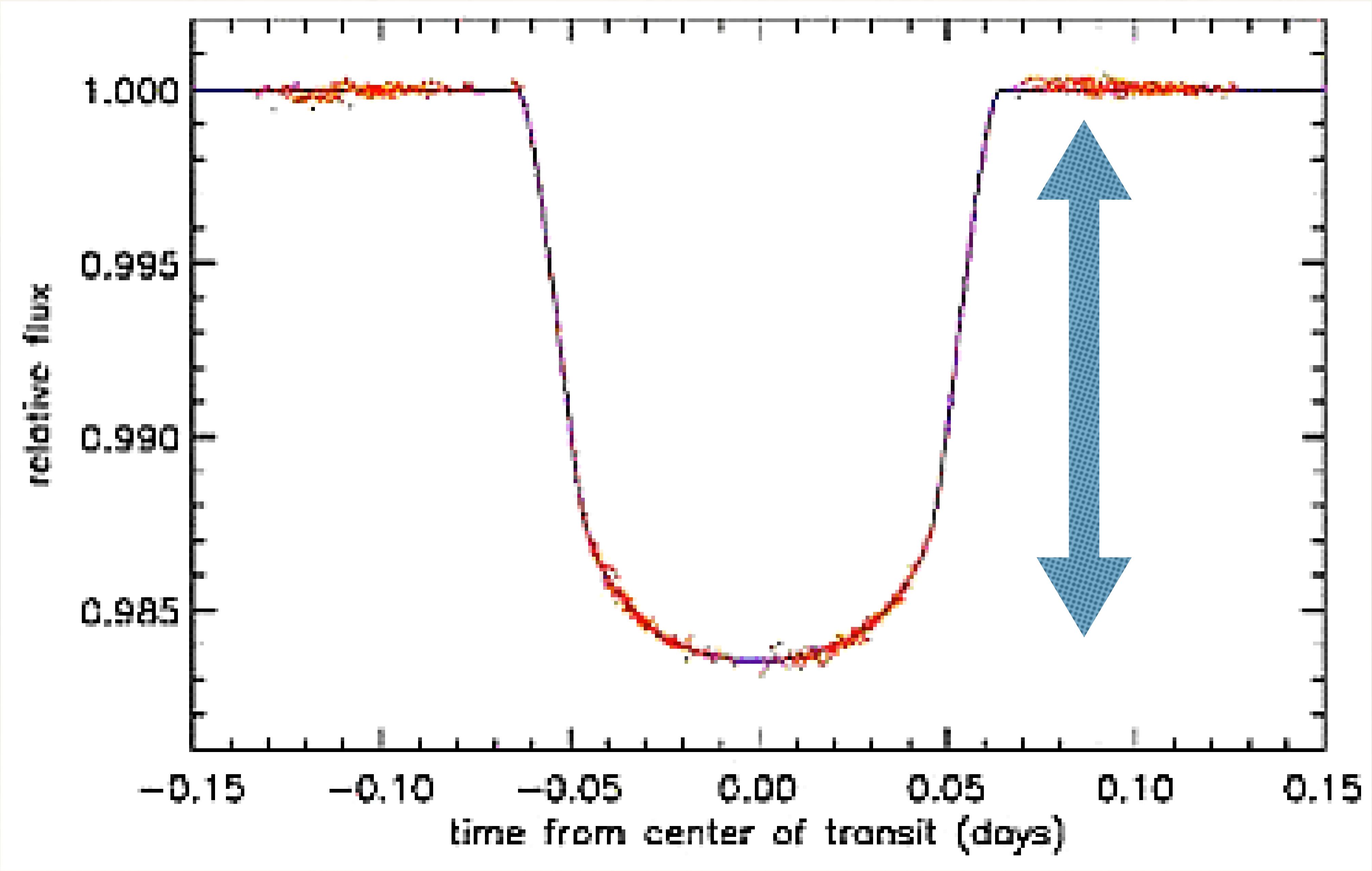
- Using very high precision photometry, it's possible to detect transiting exoplanets
- Method relies on detecting a drop in stellar flux as the exoplanet transits the star
- Drop in flux depends on star/planet radius ratio, and is typically tiny: $(R\_jupiter/R\_sun)^2 = 1\%$



Transit of Venus



# Detecting transiting exoplanets




Flux drop
=1.6%

# Detecting transiting exoplanets

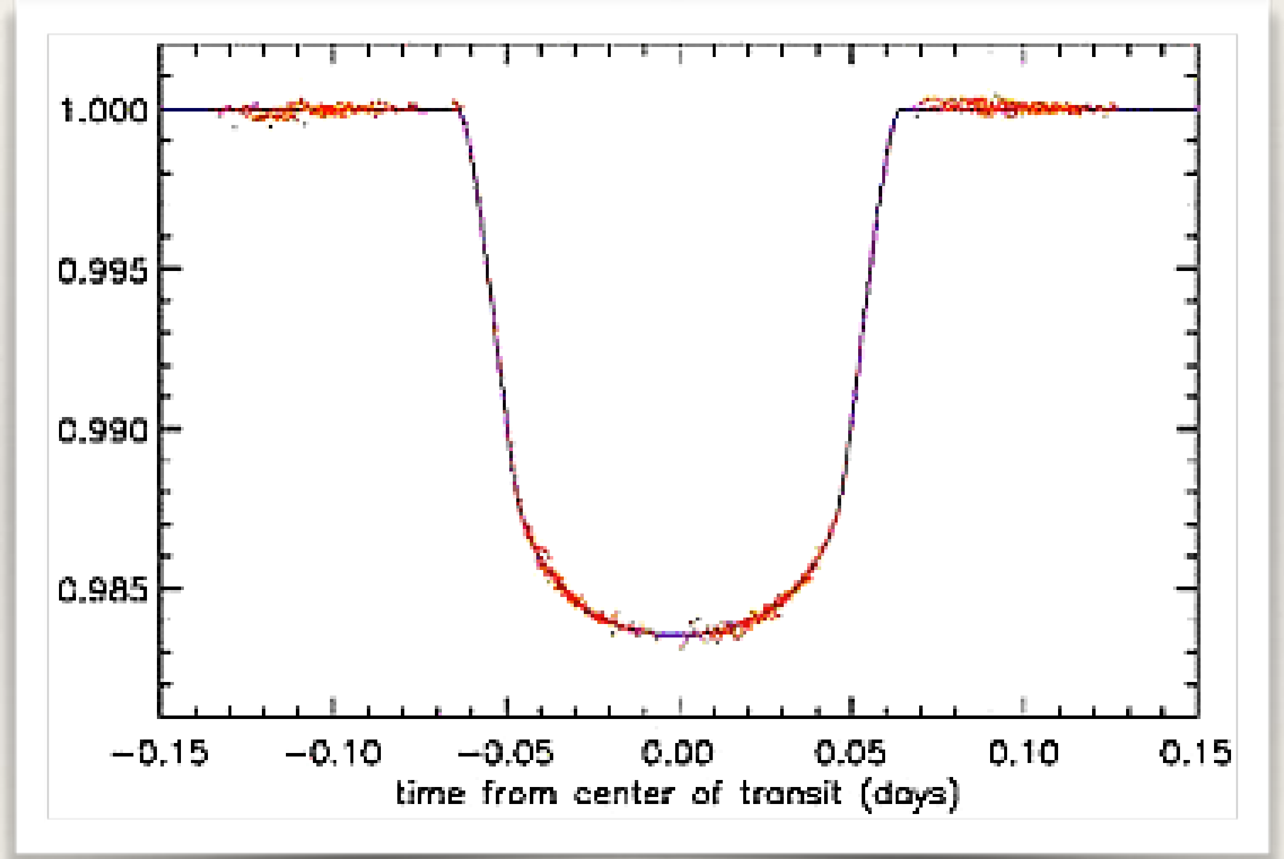
Flux drop depends on ratio of star/ planet radii

$$\left(\frac{R_P}{R_S}\right)^2 = 0.016$$

$$R_P = 0.13\ R_S$$

Star is G0V, R ~ 1.15 R_sun

$$R_P = 0.16\ R_\odot$$



# Also… pretty pictures

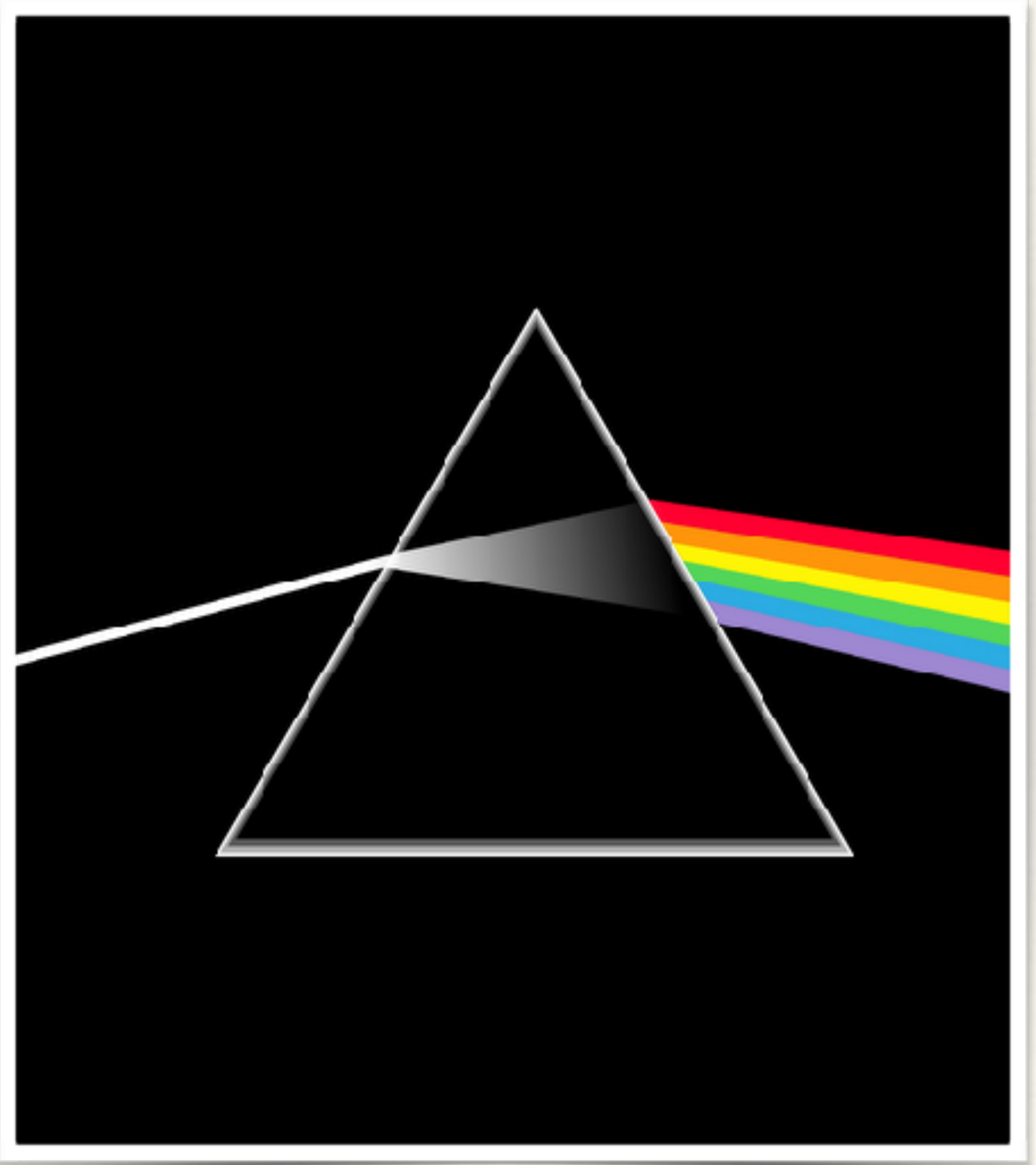

© Stanislav Volskiy

# Optical astronomy (II)

- Photometry
- Spectroscopy
- `Reduction' of astronomical data

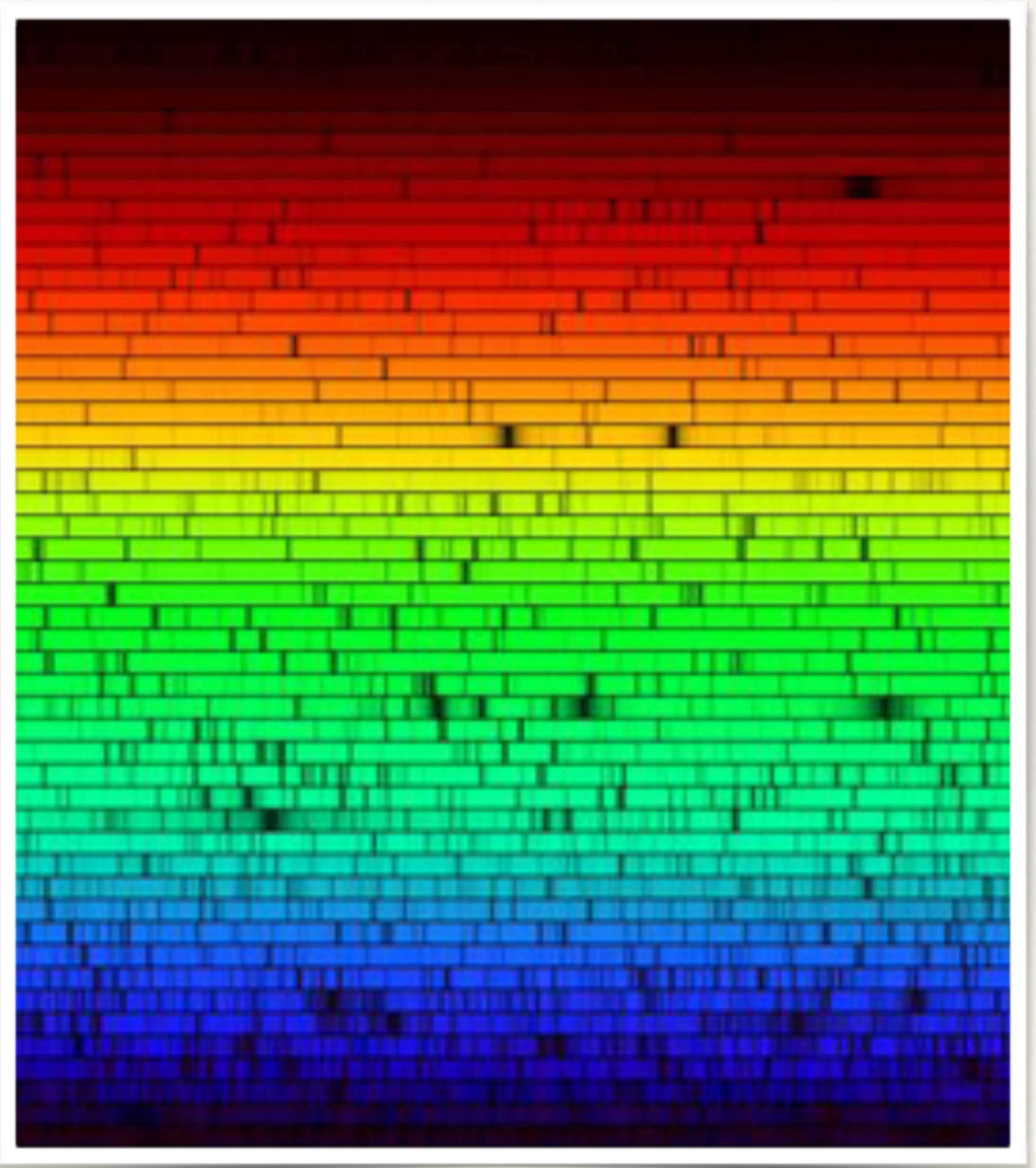
# Spectroscopy

- Spectroscopy involves splitting light at wavelength $\lambda$ into smaller chunks, $\Delta\lambda$
- *Spectral resolution* $R = \Delta\lambda/\lambda$
- If R>10, then information can be gained that is different to photometric observations



# Uses of spectroscopy

- Too many to count: could be entire lecture course on spectroscopy alone!
- Velocity measurements of all kinds (exoplanets, stars, galaxies, outflows…)
- Spectral lines (astrophysical chemistry, physical conditions)

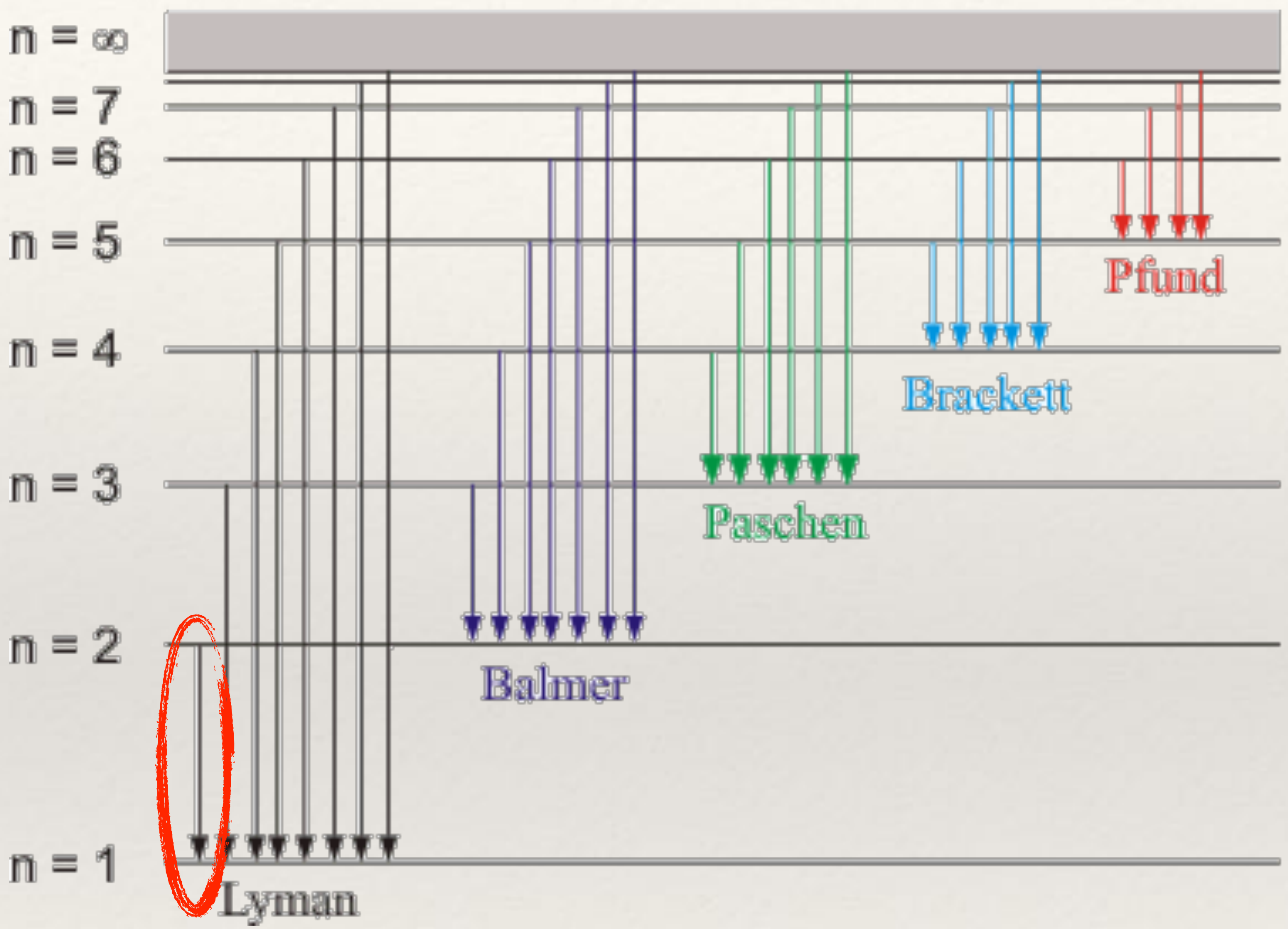


# The ‘Lyman-alpha forest’

Using spectroscopic observations of Lyman-alpha absorption, it is possible to map the structure of the IGM (Inter Galactic Medium)

Intergalactic medium is hard to detect, but contains majority of all the baryons in the Universe

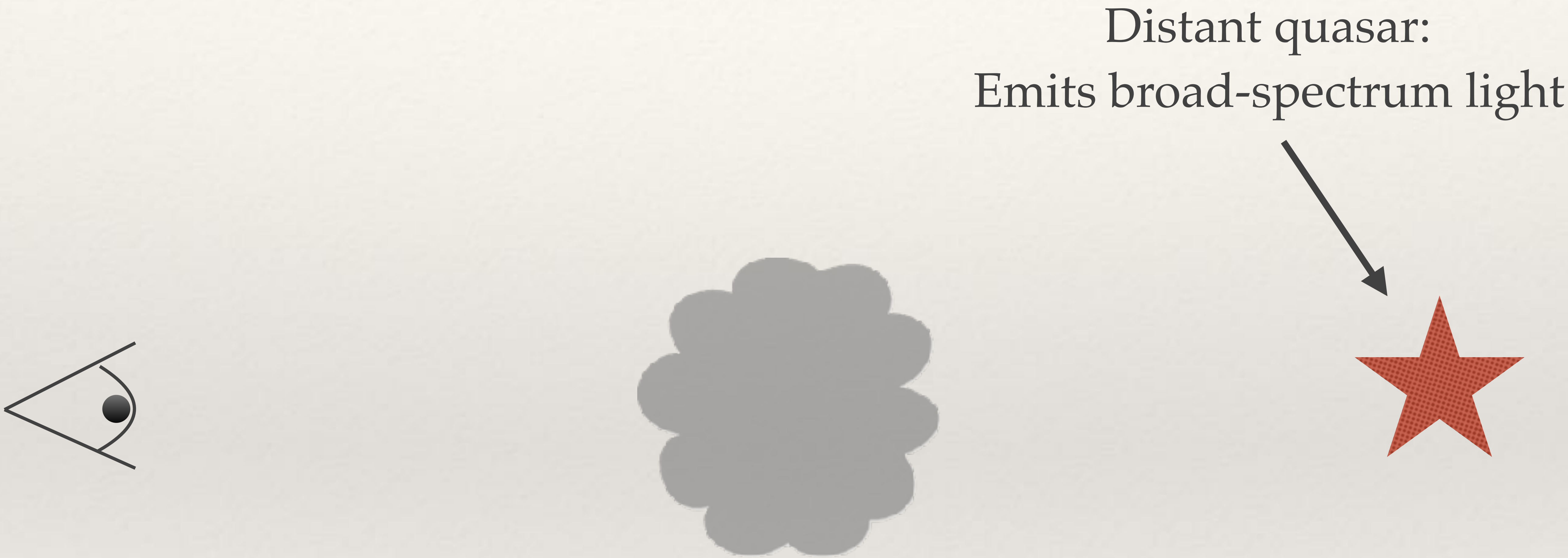
# The ‘Lyman-alpha forest’




Lyman alpha: n=2-1

Wavelength = 1215.67 A

# The ‘Lyman-alpha forest’

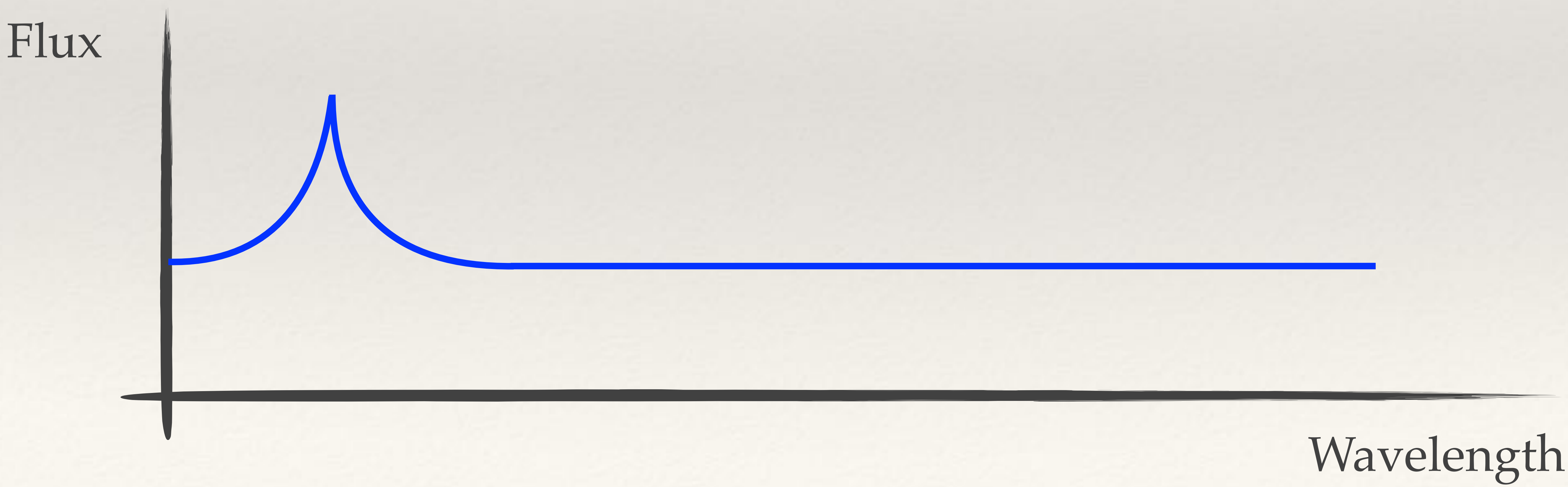


# The ‘Lyman-alpha forest’

Distant quasar:
Emits broad-spectrum light

Intervening gas cloud contains
hydrogen, and will absorb at 1215.67 A

# The ‘Lyman-alpha forest’



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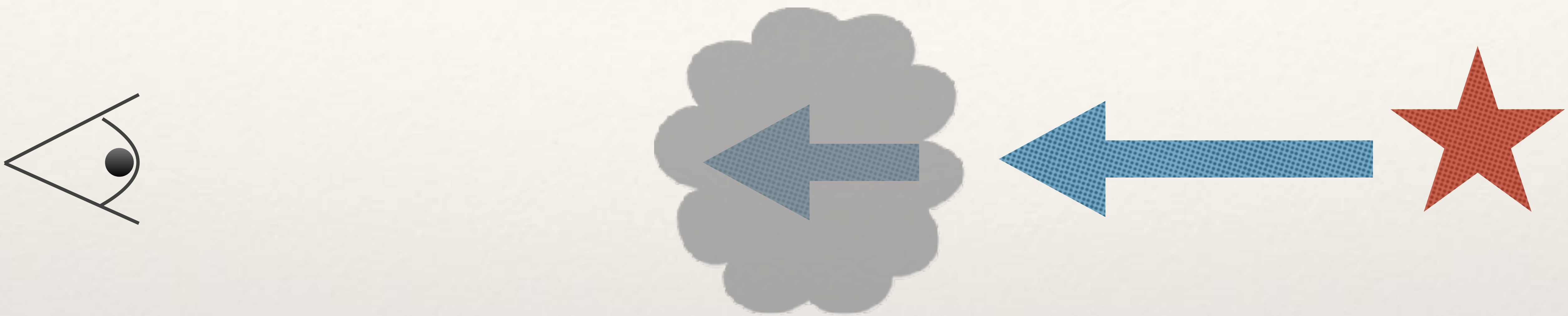

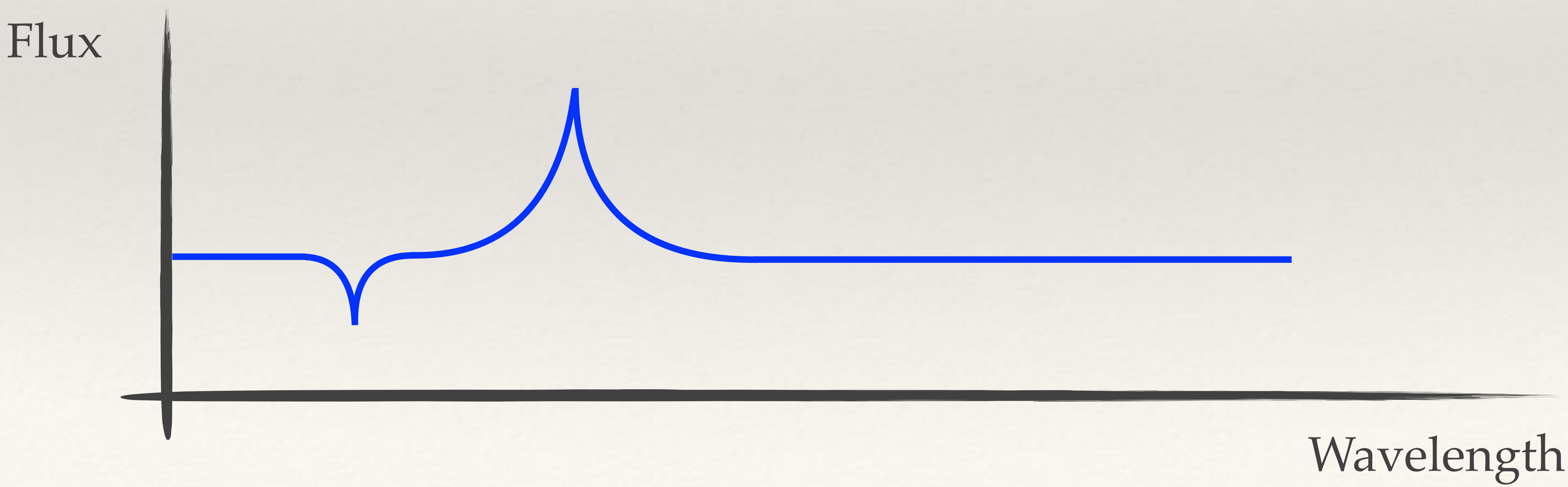

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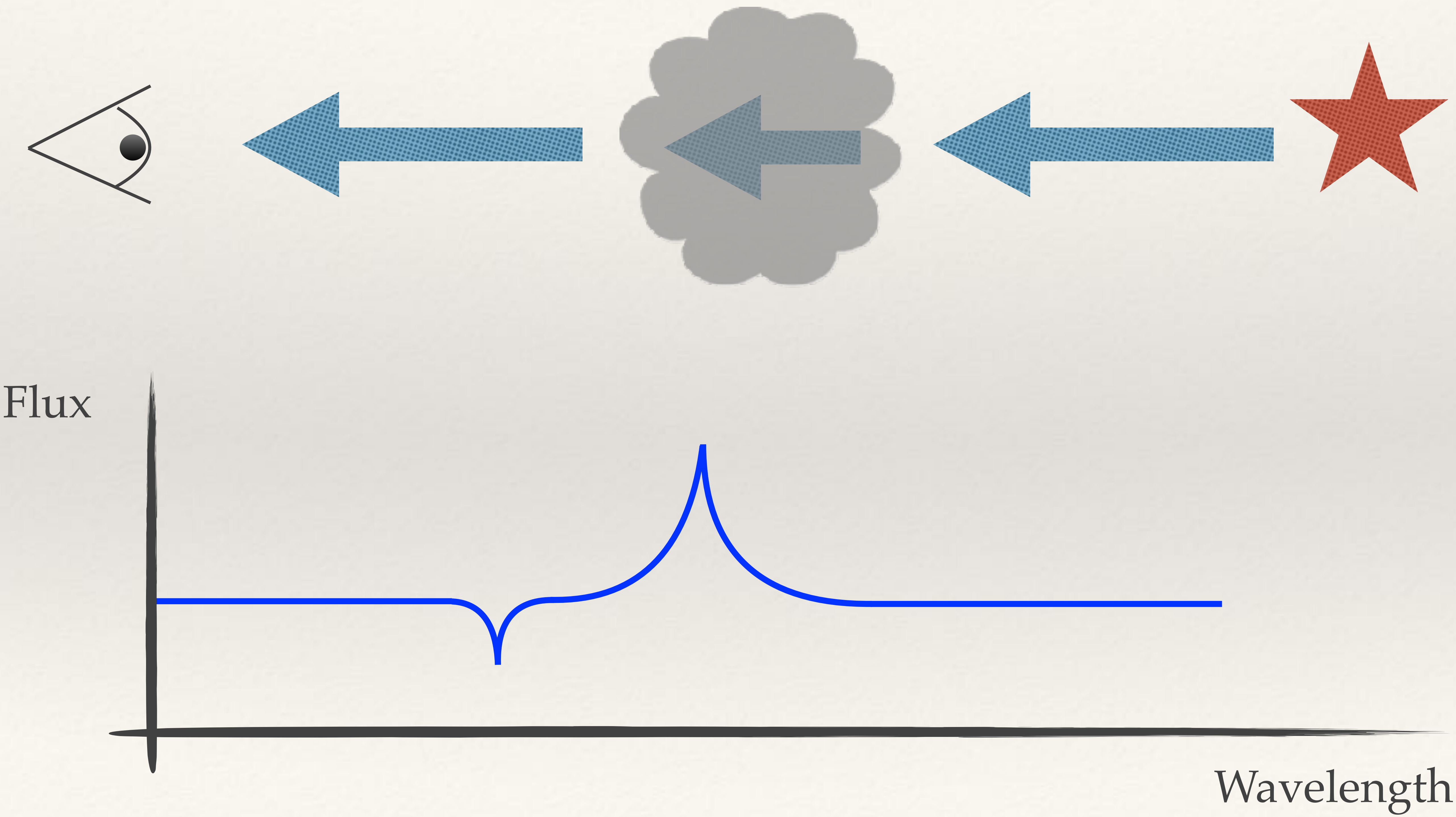

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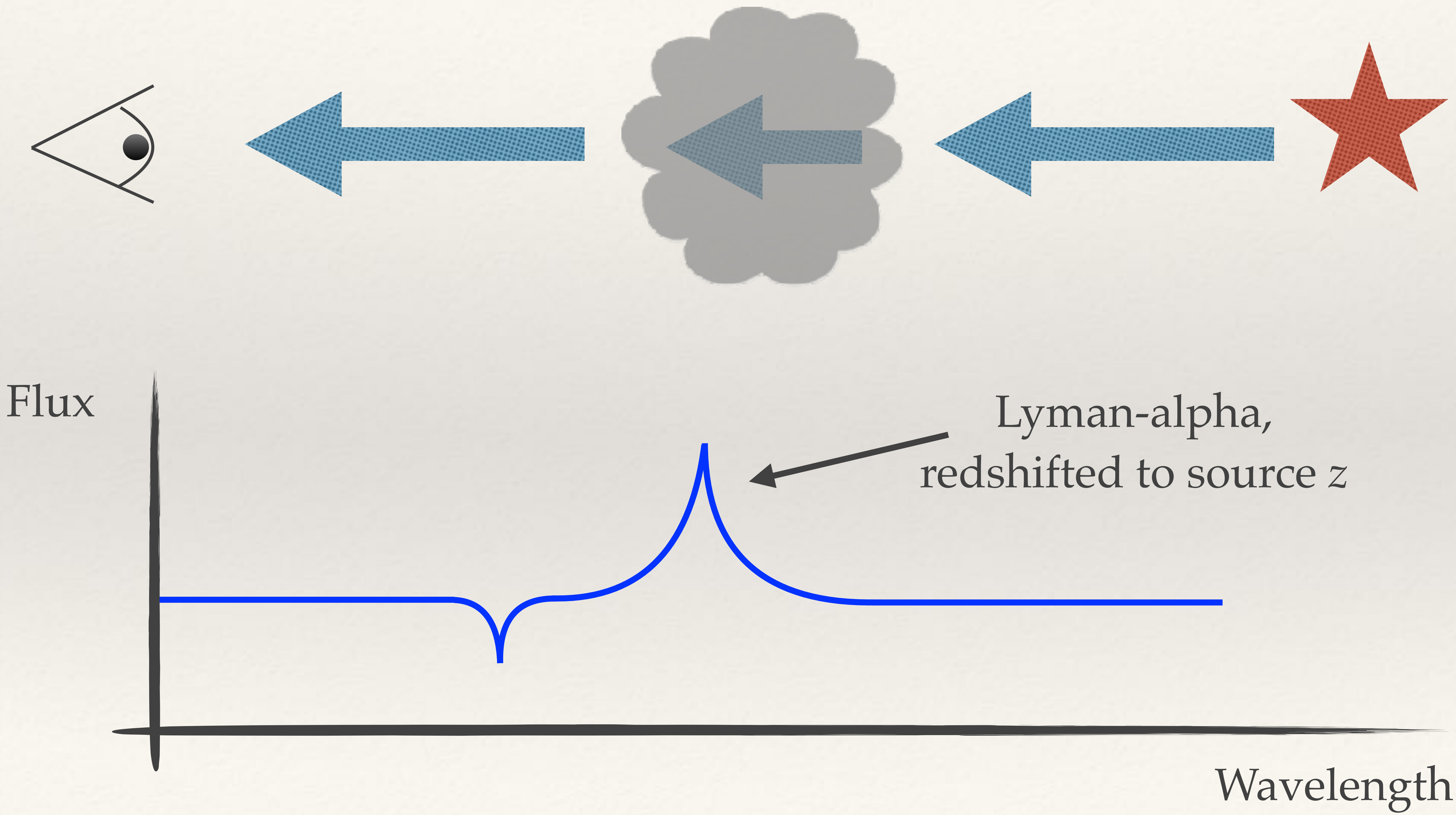

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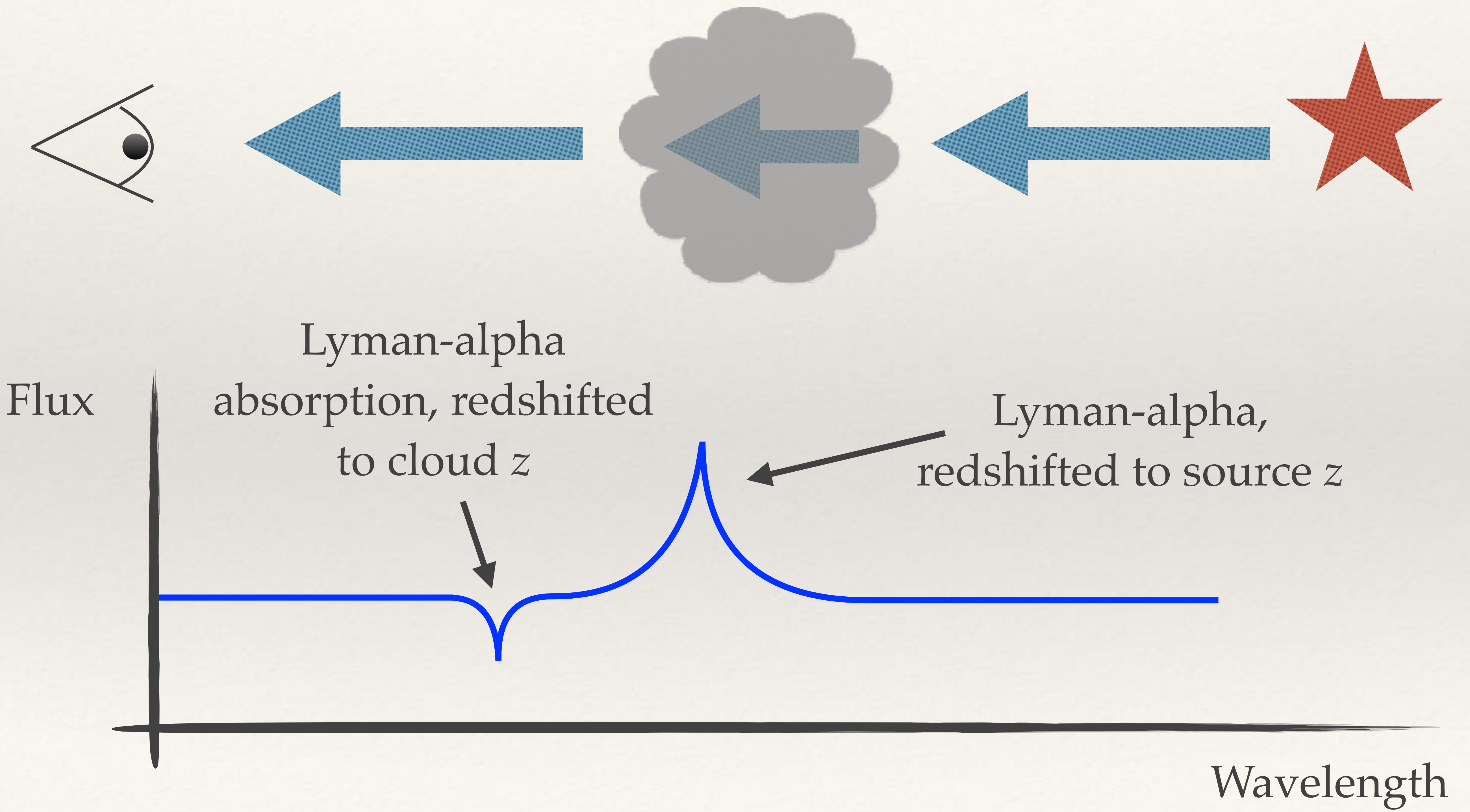

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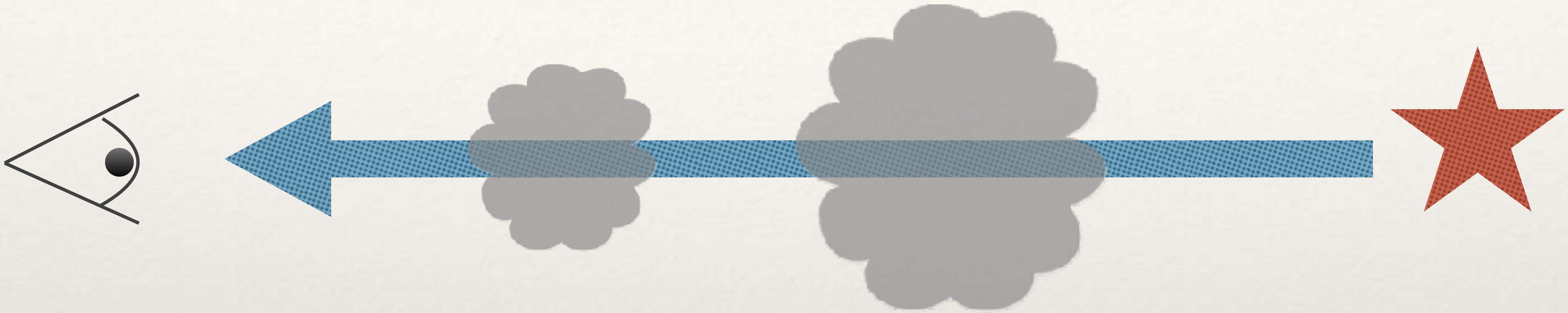

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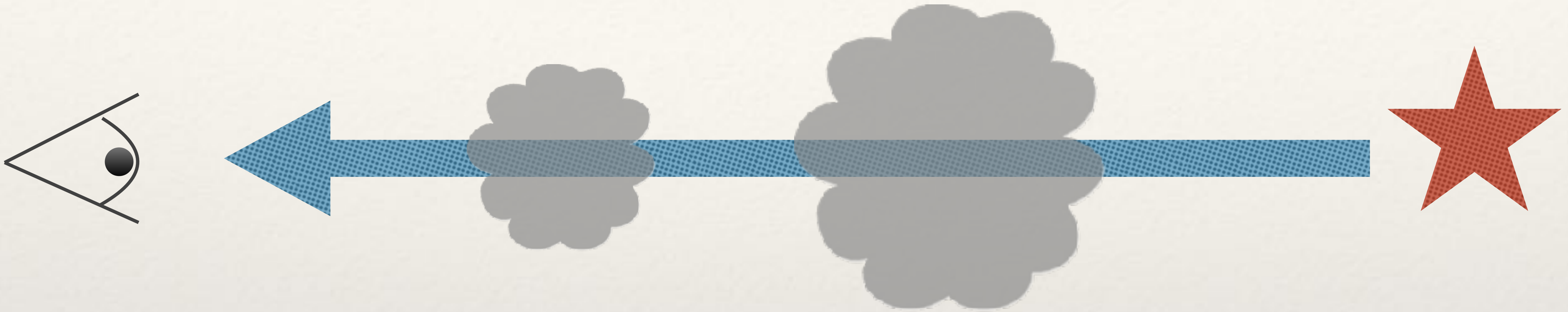

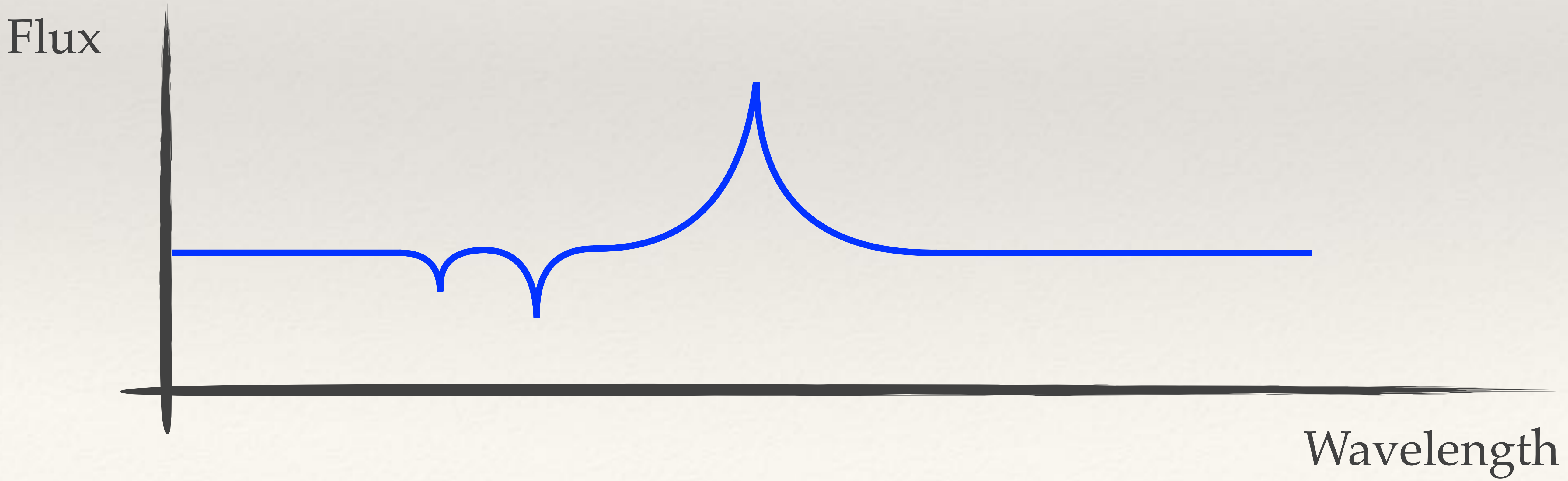

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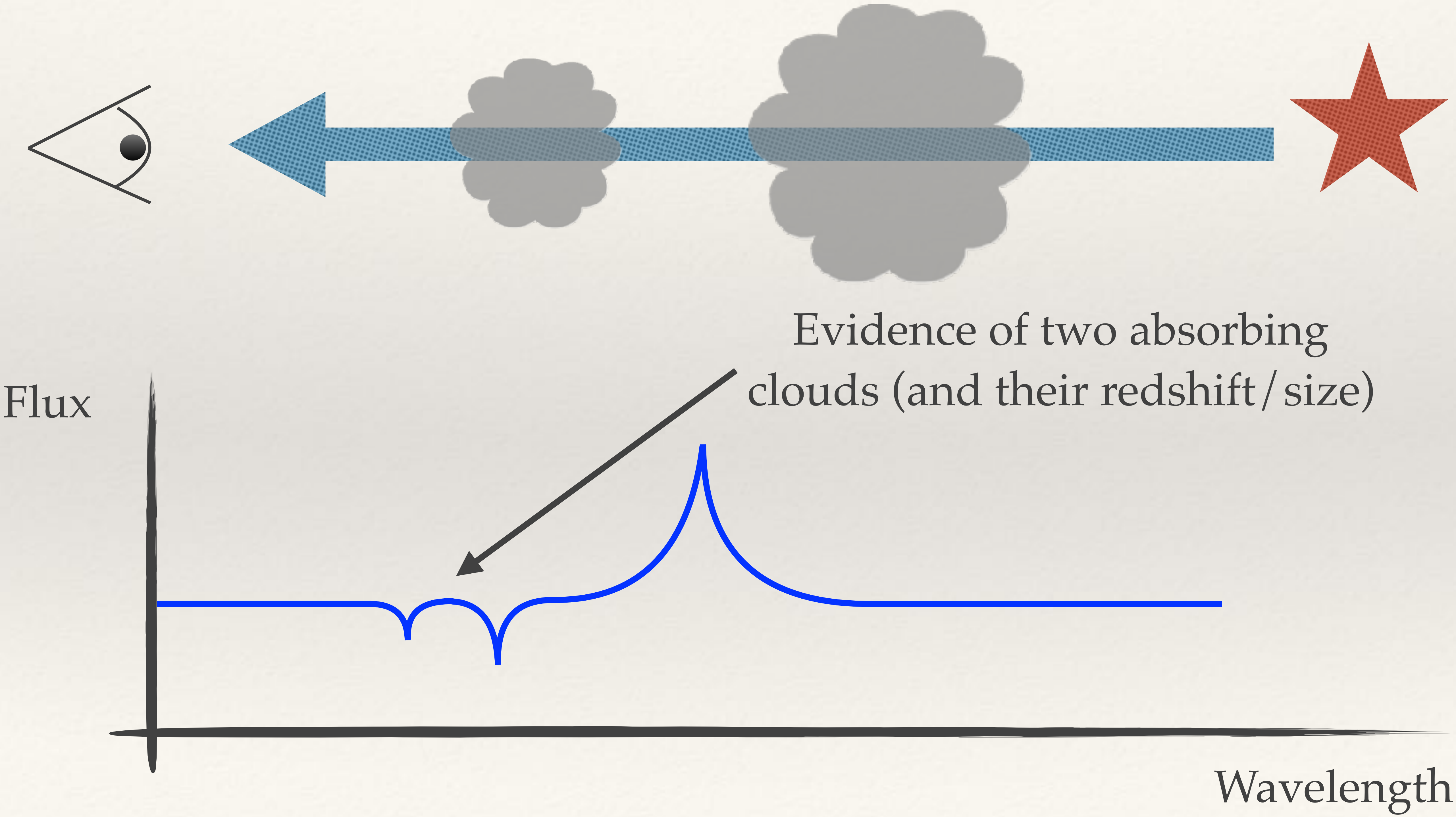
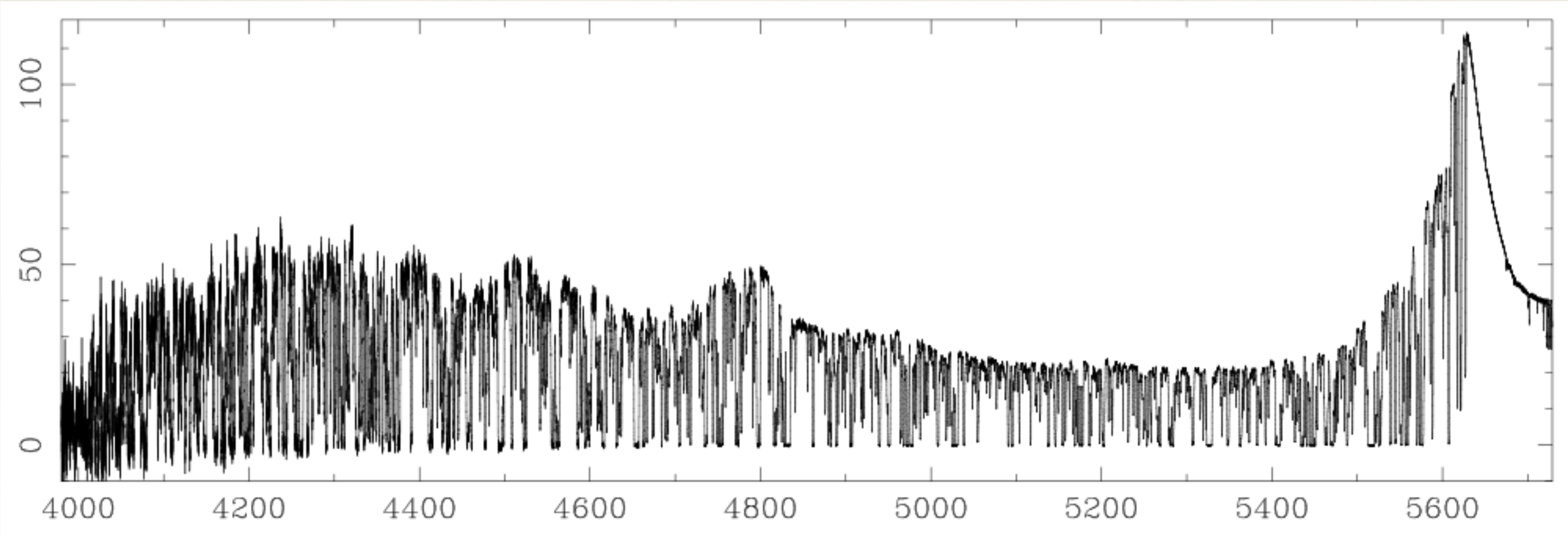


# The 'Lyman-alpha forest'

In reality there aren't one, or two absorbing clouds, but a continuous clumpy medium (IGM)



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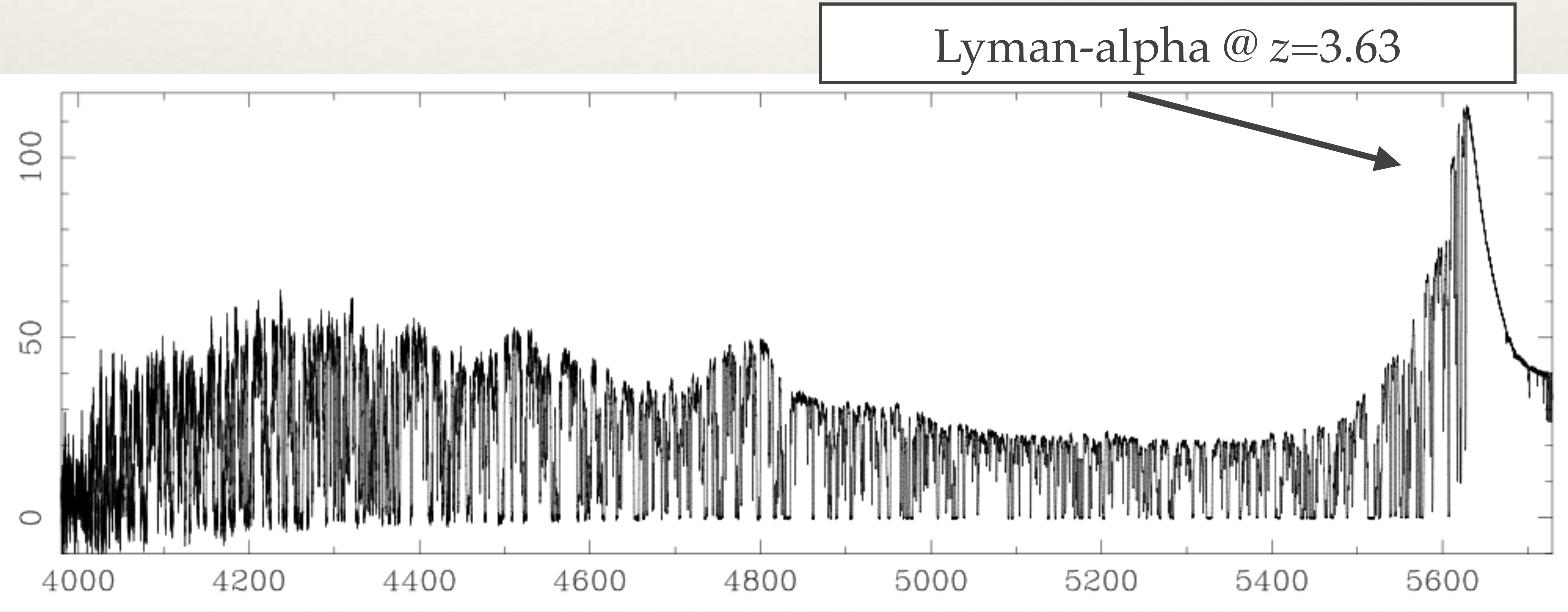

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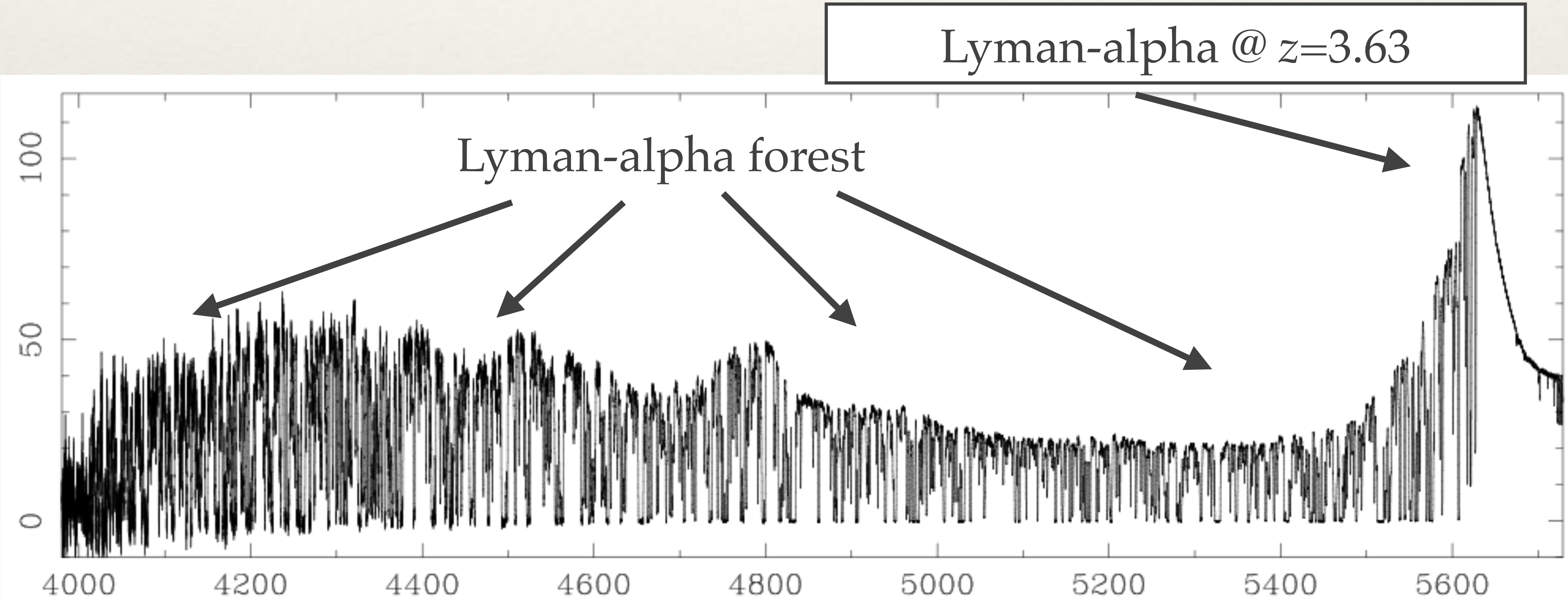

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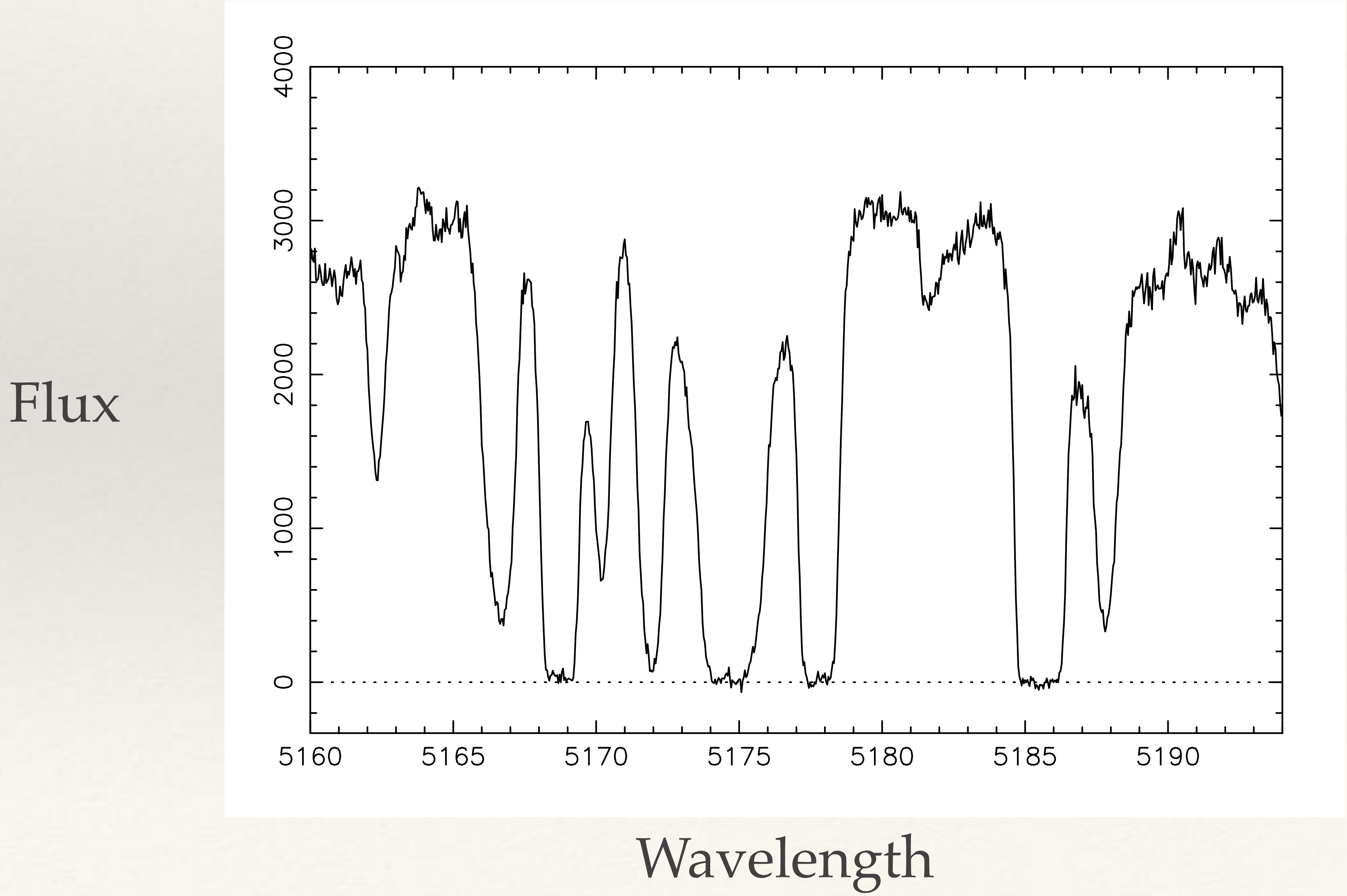

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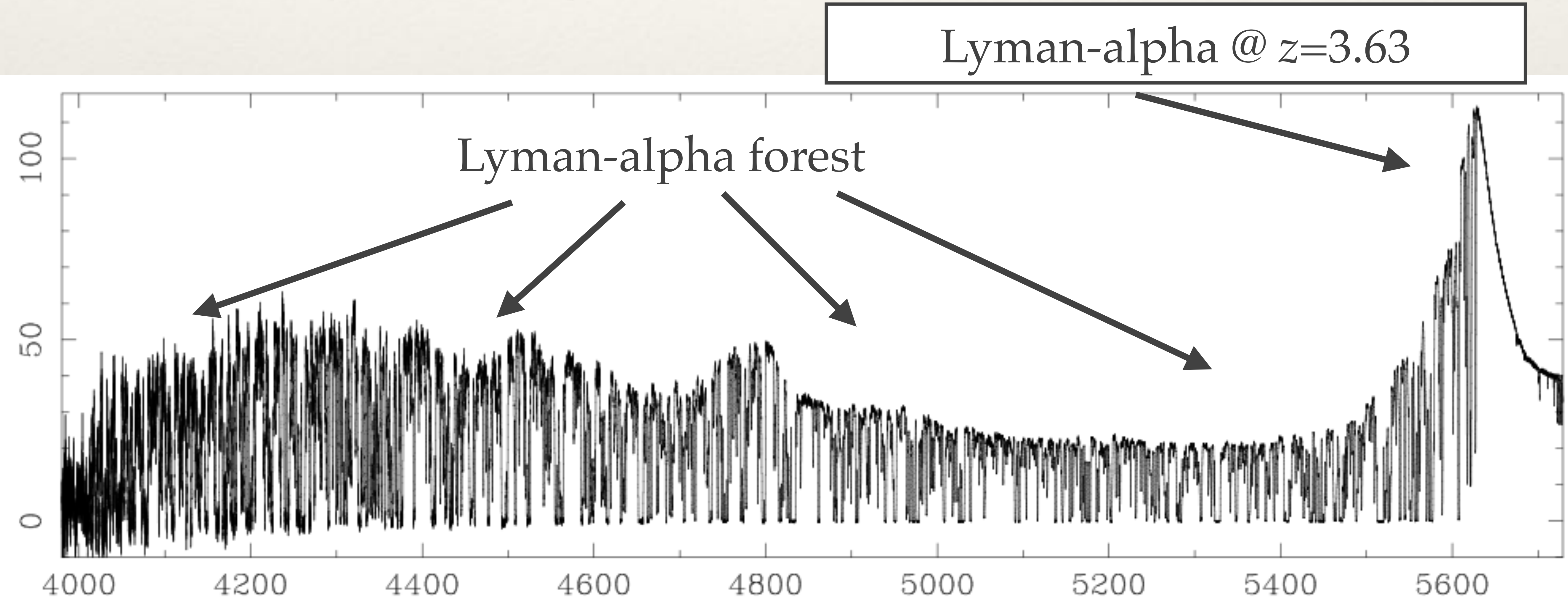
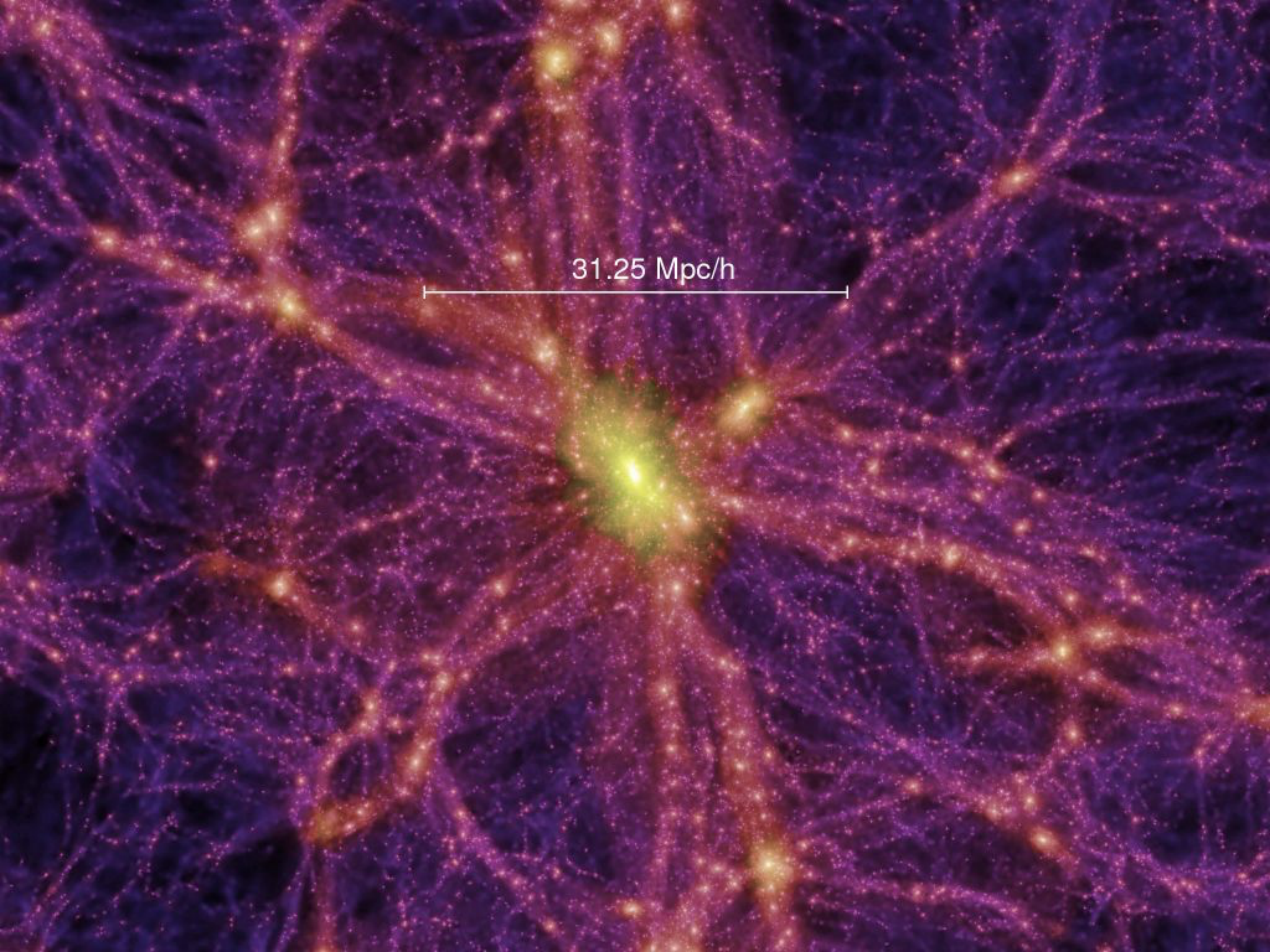
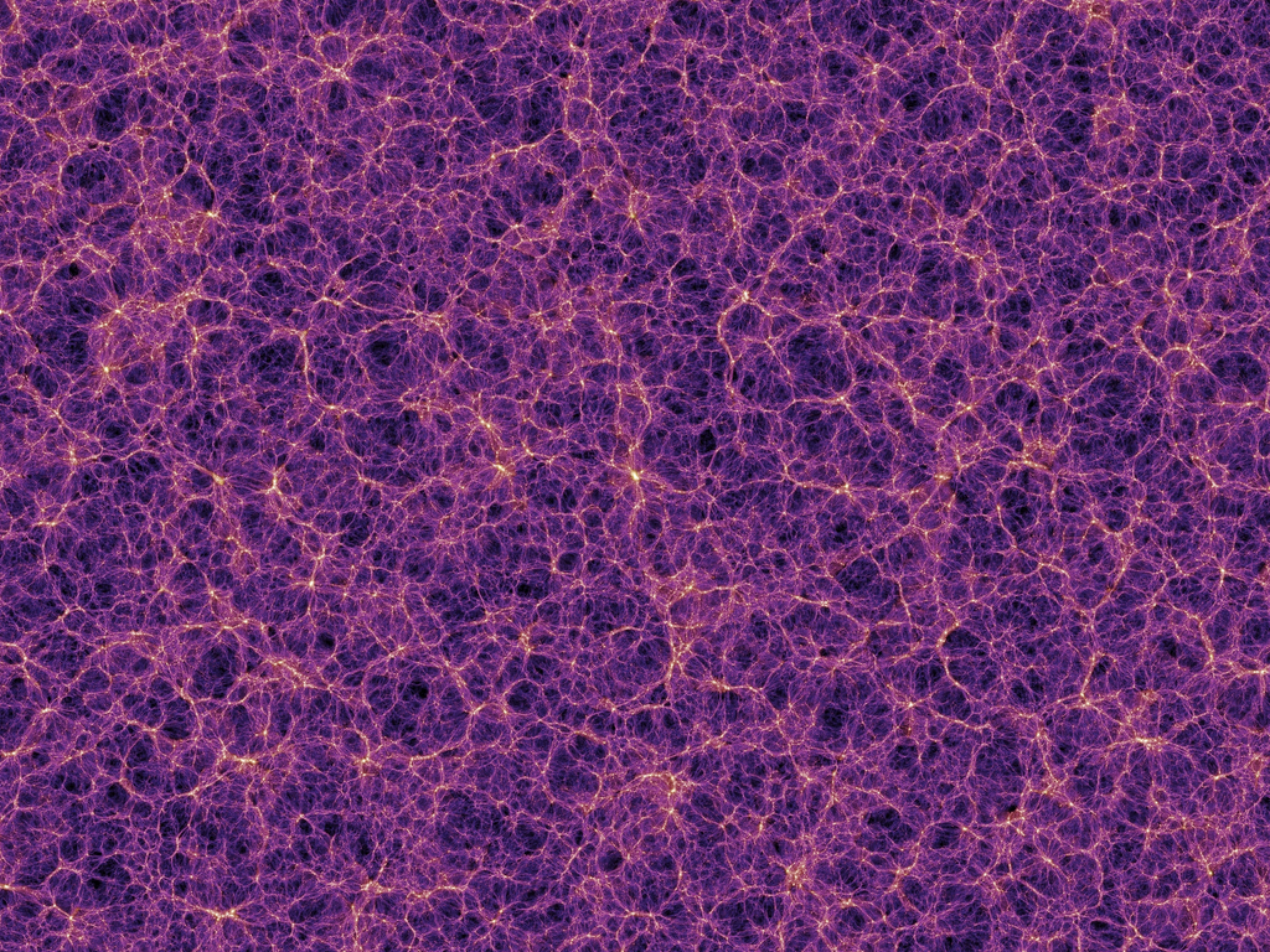
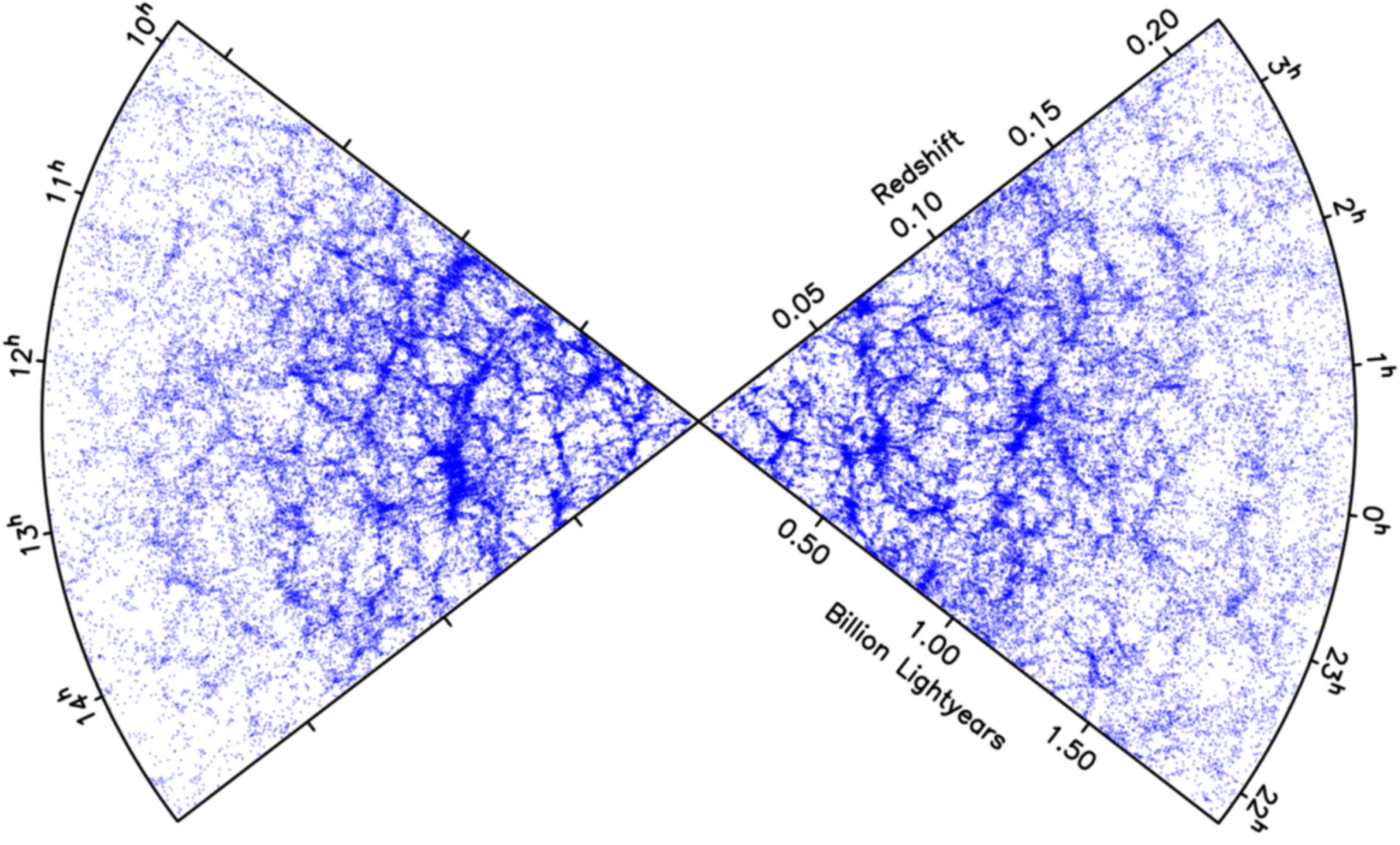


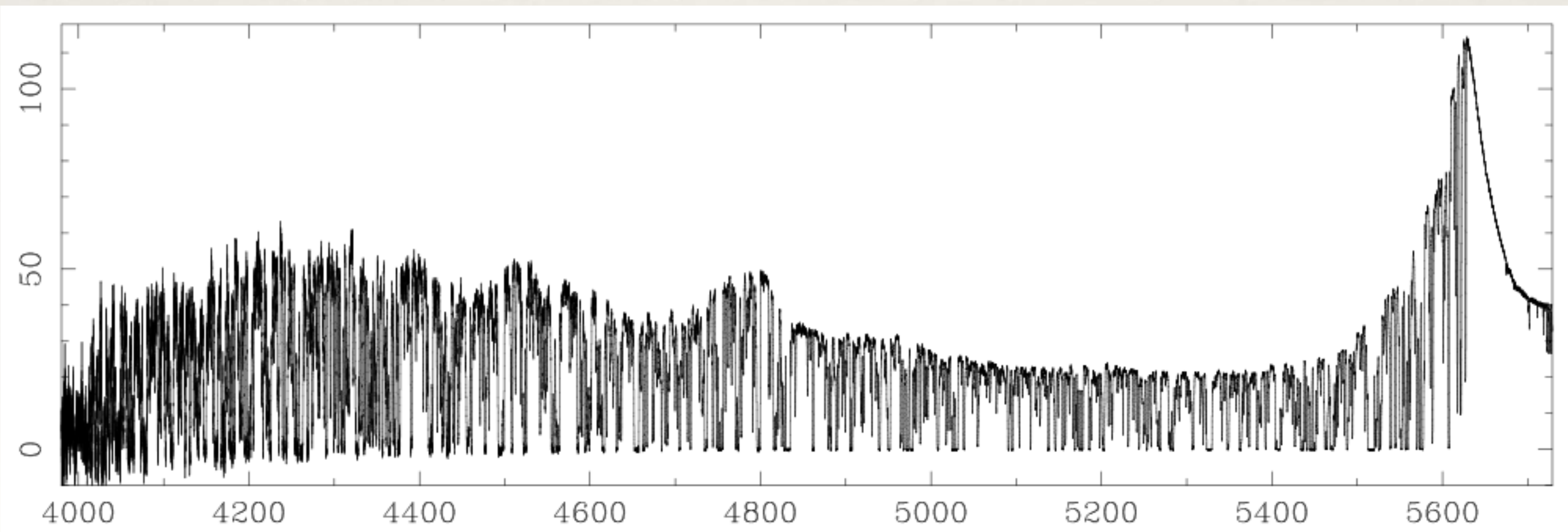

31.25 Mpc/h




10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50

# The ‘Lyman-alpha forest’

By looking at many quasar spectra — many sight lines through the Universe — we can map structure (traced by HI)



# Optical astronomy (II)

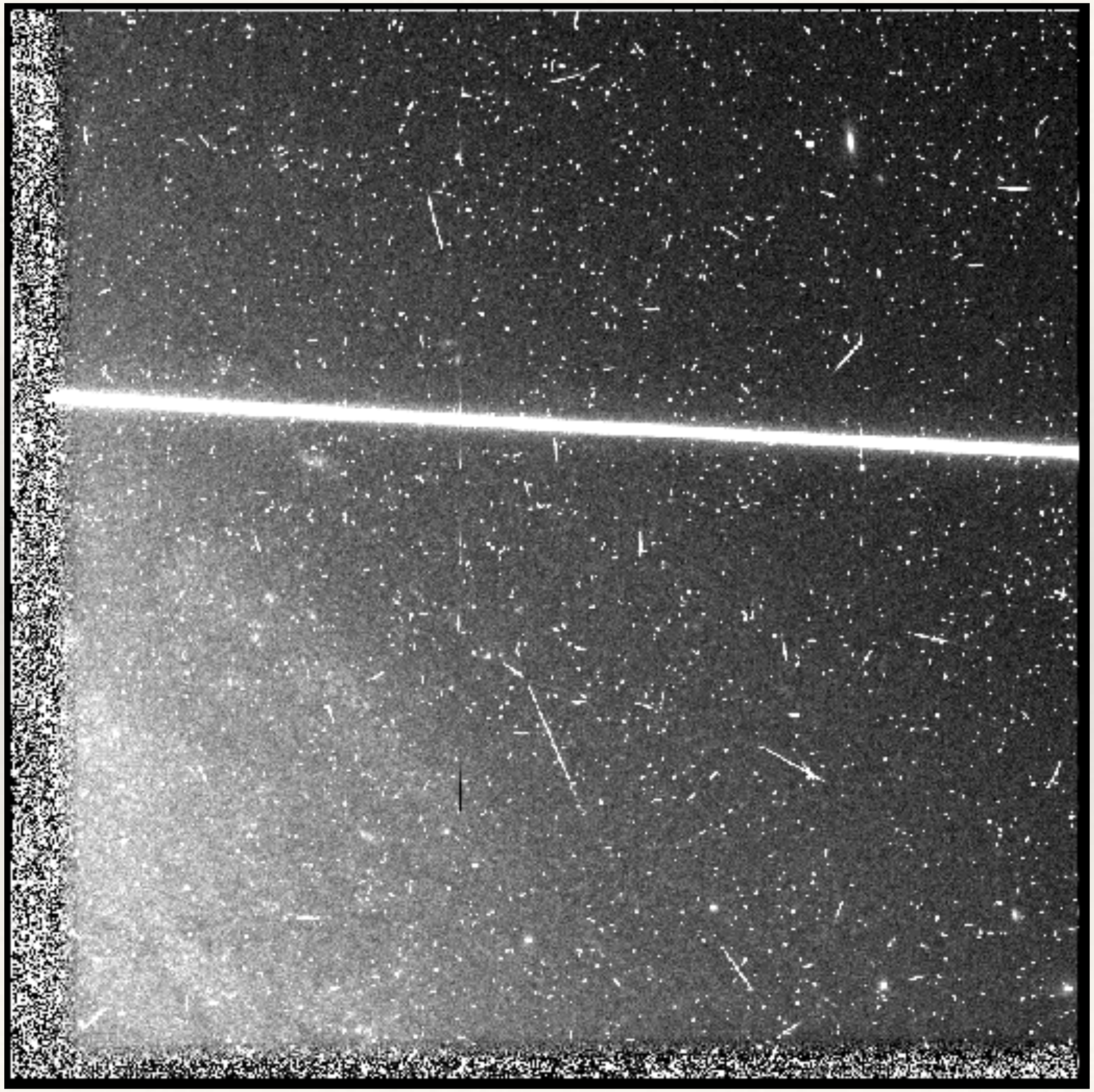
- Photometry
- Spectroscopy
- `Reduction’ of astronomical data

# Astronomical data reduction

- CCDs are not perfect photon detectors — there are several steps between receiving photons and making an image
- Each step can introduce error, and must be accounted for as part of making observations

# Raw data

Raw data from HST (admittedly, a particularly bad frame)



Noise

Cosmic rays

Satellite trail

# Data reduction steps

- Dark frame (caused by thermal noise in instrument)
- Flat field (sensitivity variation of CCD and optics)
- Other (cosmic rays, bad pixels)

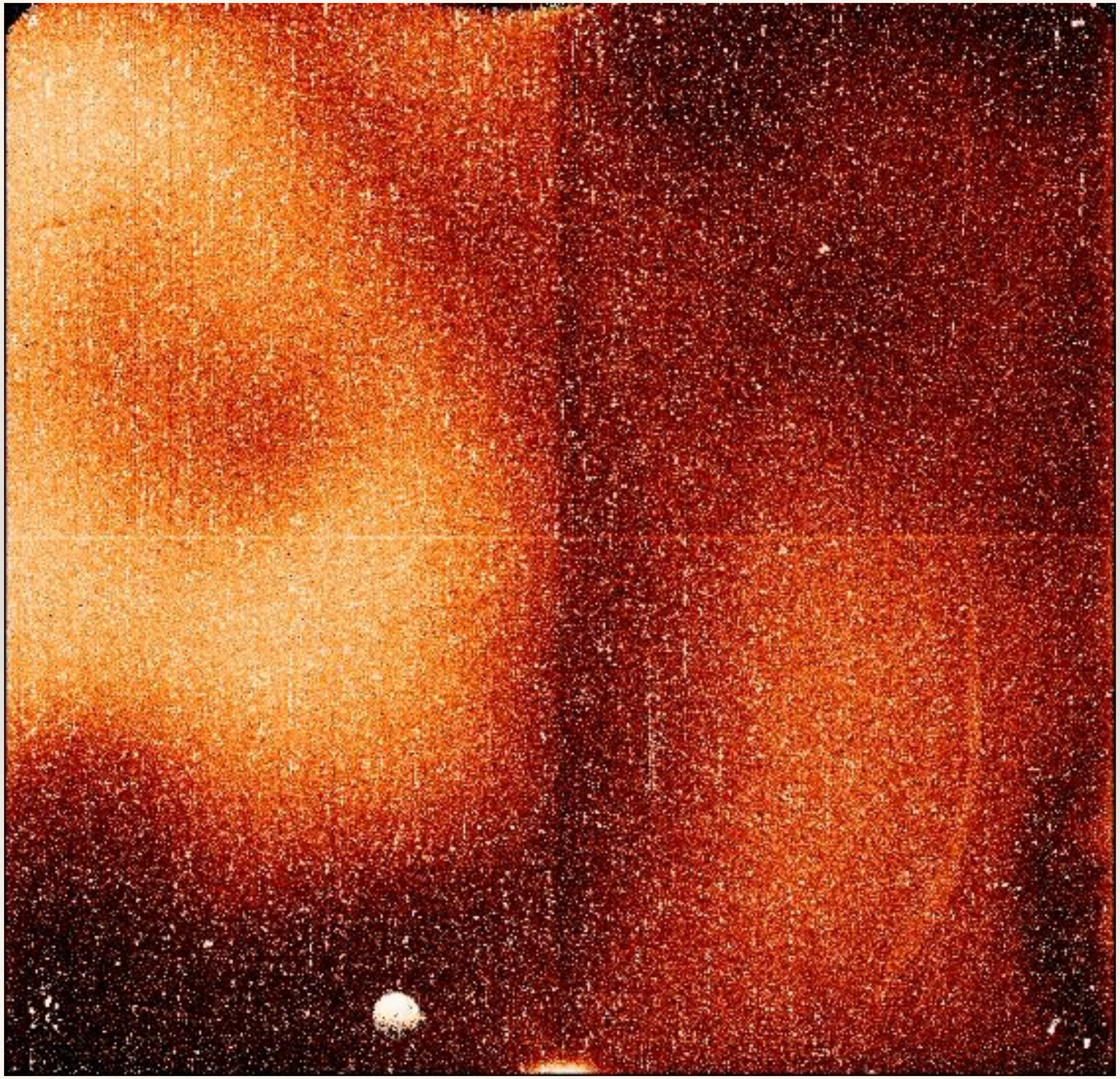
# Data reduction steps: dark

'Dark current' is the response of the CCD to thermal noise in the instrument

It increases over time — so dark frames are taken with significant exposure time, with the shutter closed

# Data reduction steps: dark

HST-WFC3
Dark current

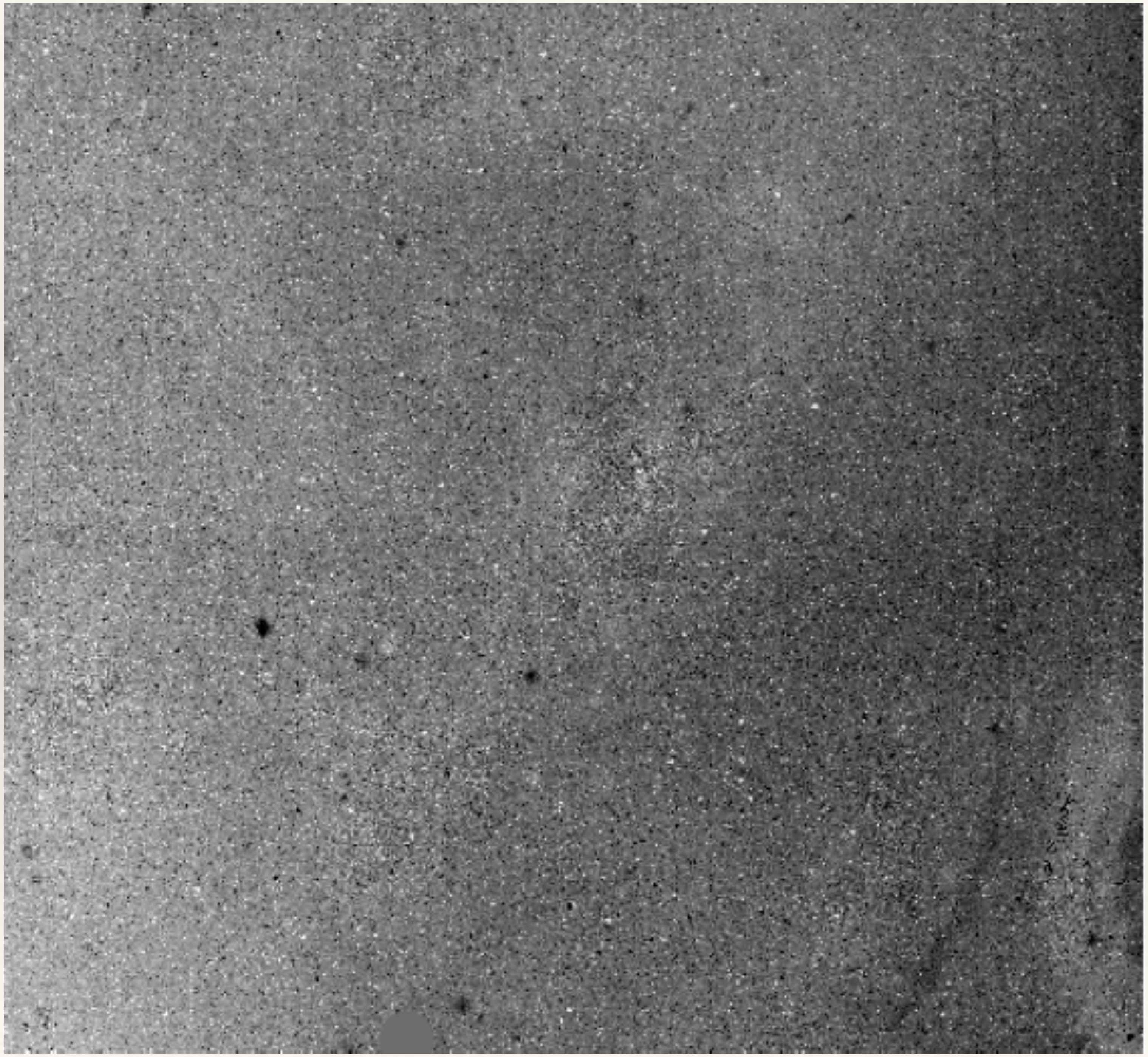


# Data reduction steps: flat

A ‘flat field’ measures the telescope+CCD response to a uniformly illuminated source

# Data reduction steps: flat

HST-WFC3
Flat field



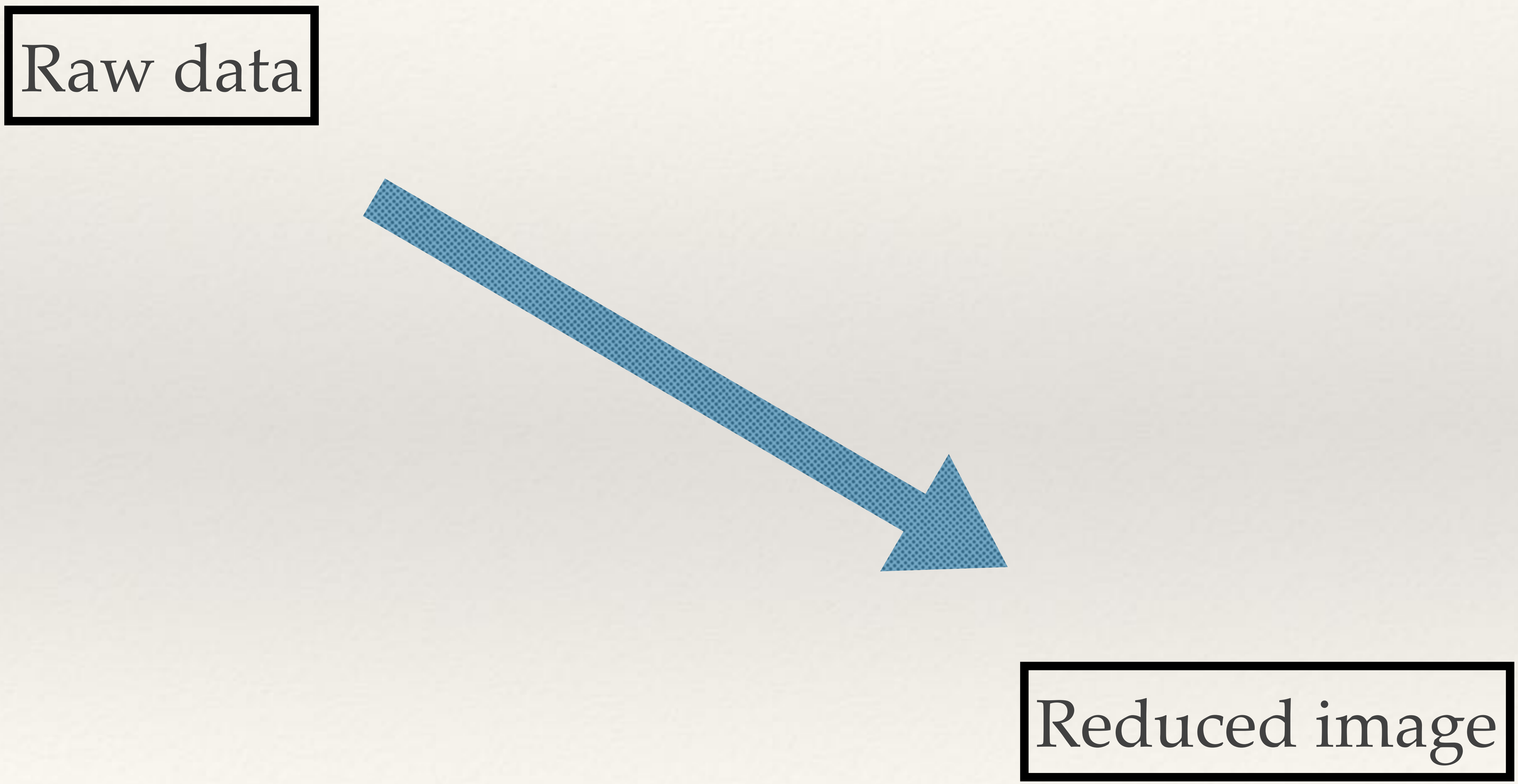
# Data reduction steps: flat

A ‘flat field’ measures the telescope+CCD response to a uniformly illuminated source

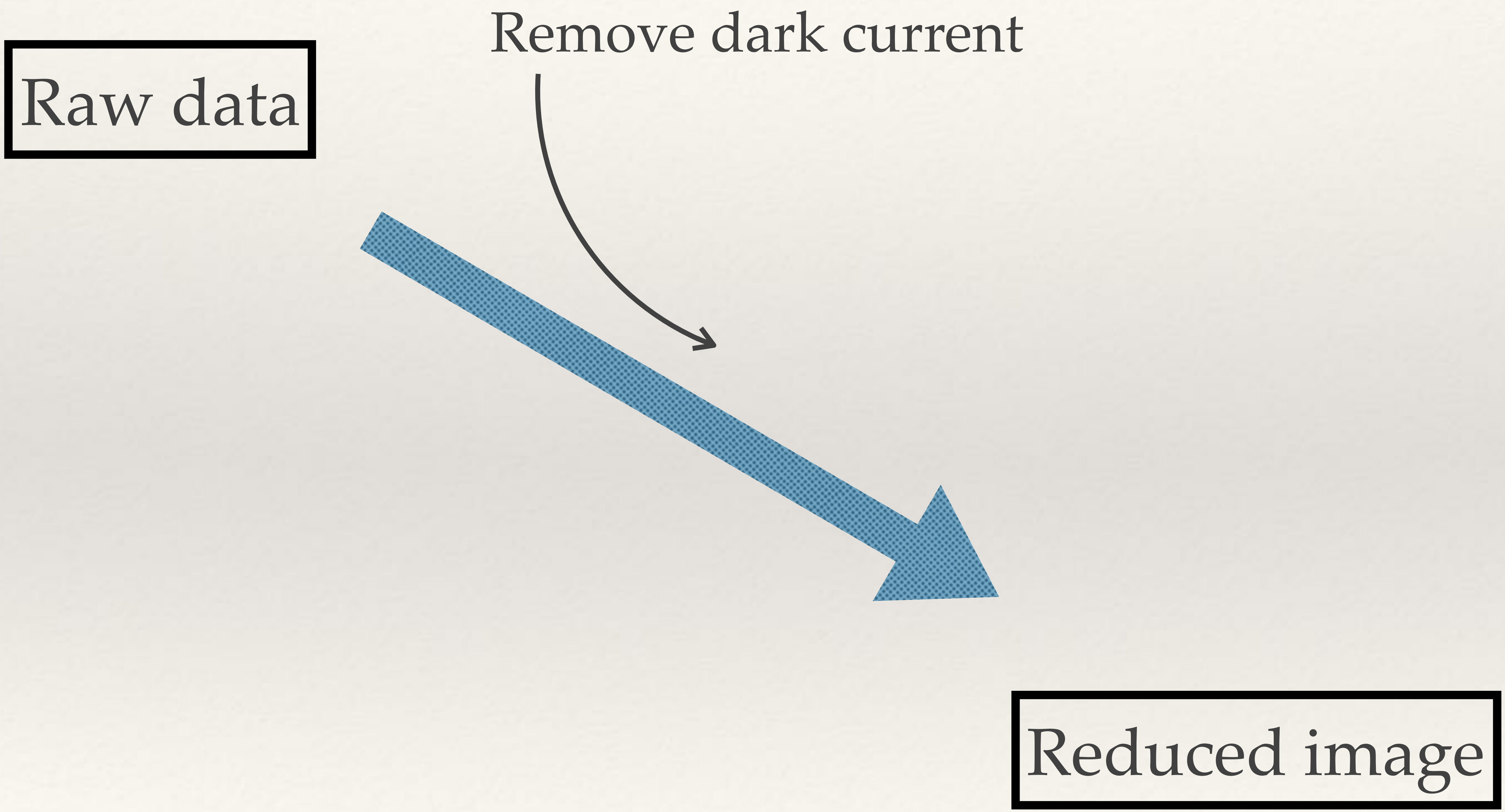
These are typically the inside of the telescope dome (‘dome flats’), or the twilight sky (‘sky flats’)

Dome flats can be done at any time during the day, BUT aren’t great (uniform illumination is hard). Sky flats are better, but time sensitive

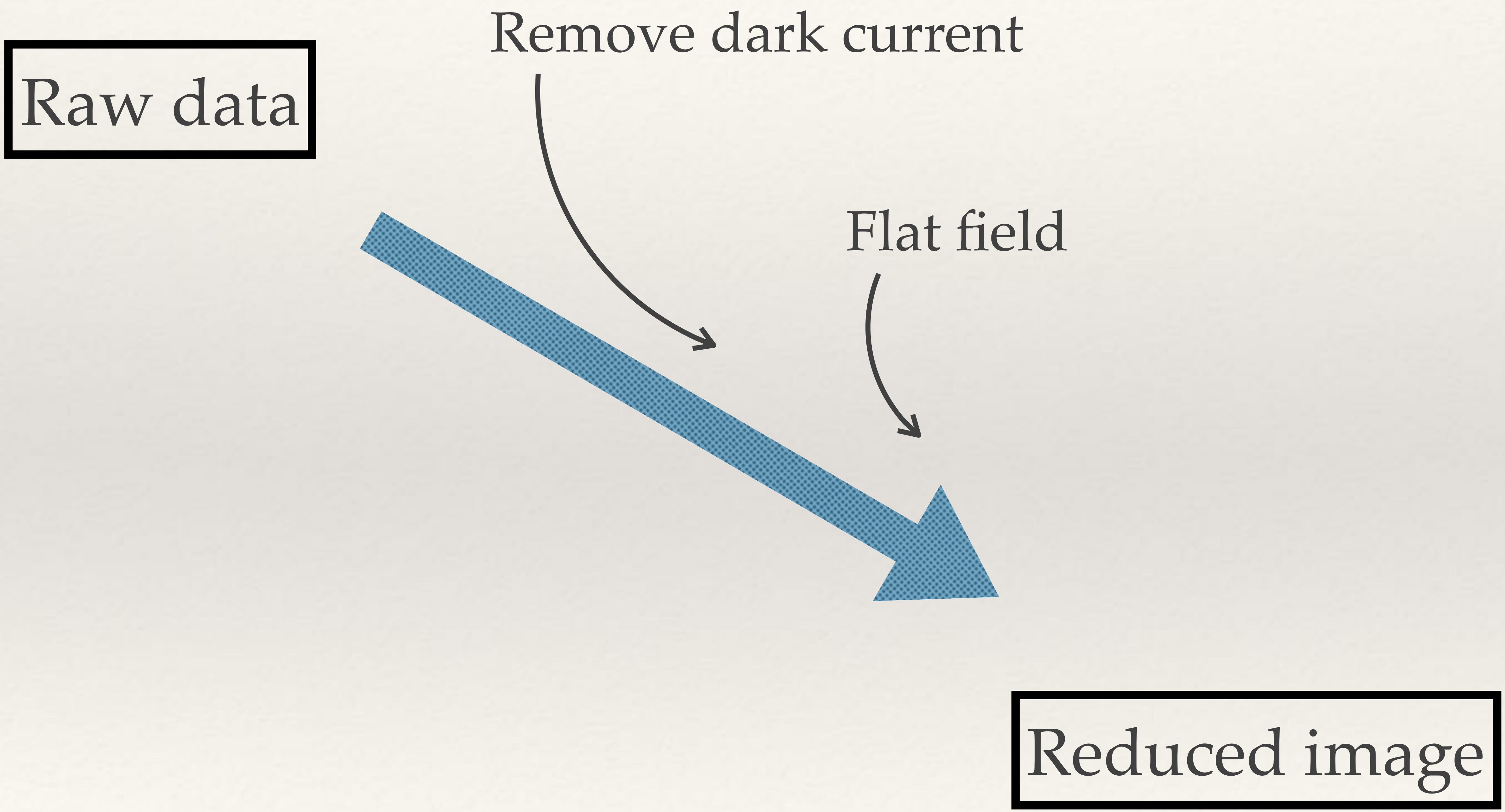
# Data reduction



# Data reduction

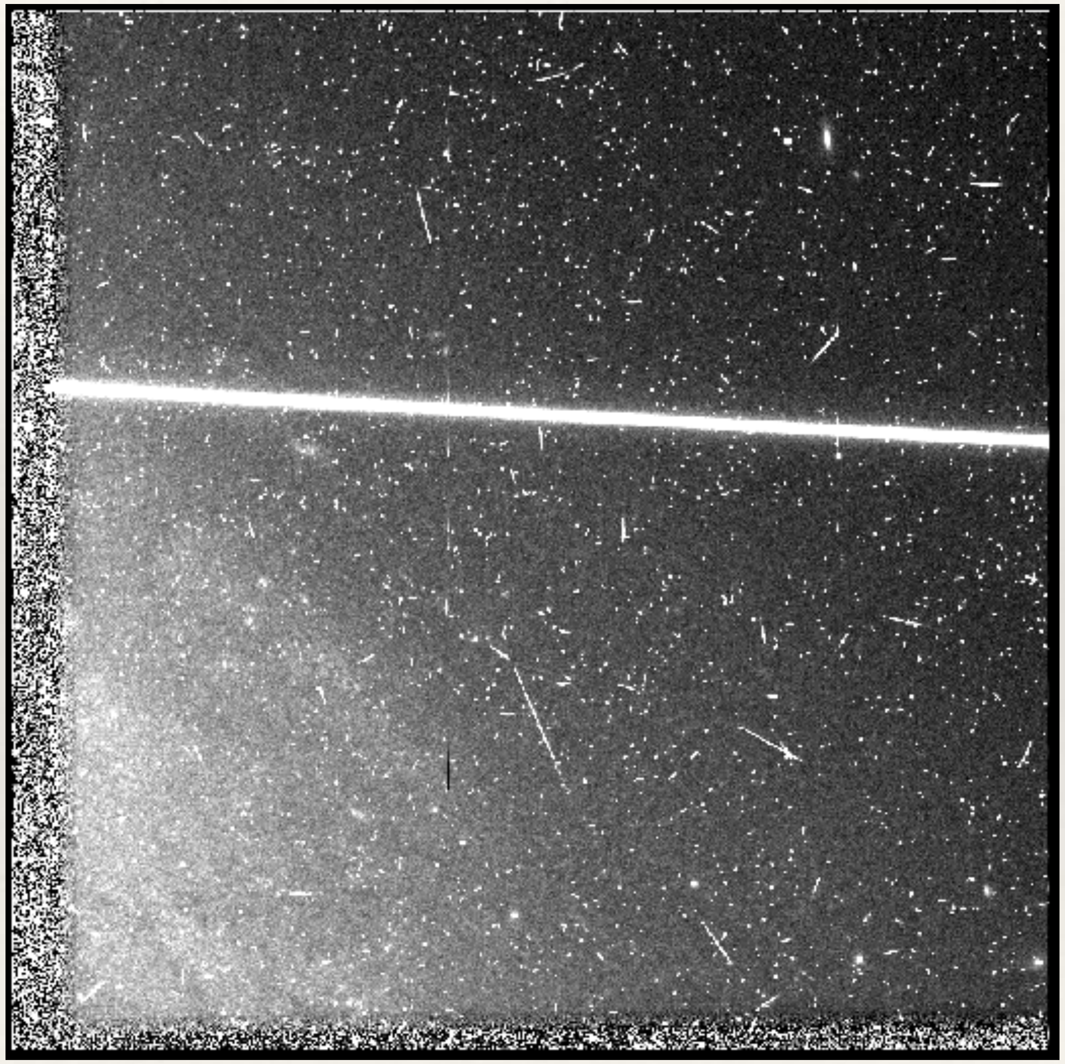


# Data reduction

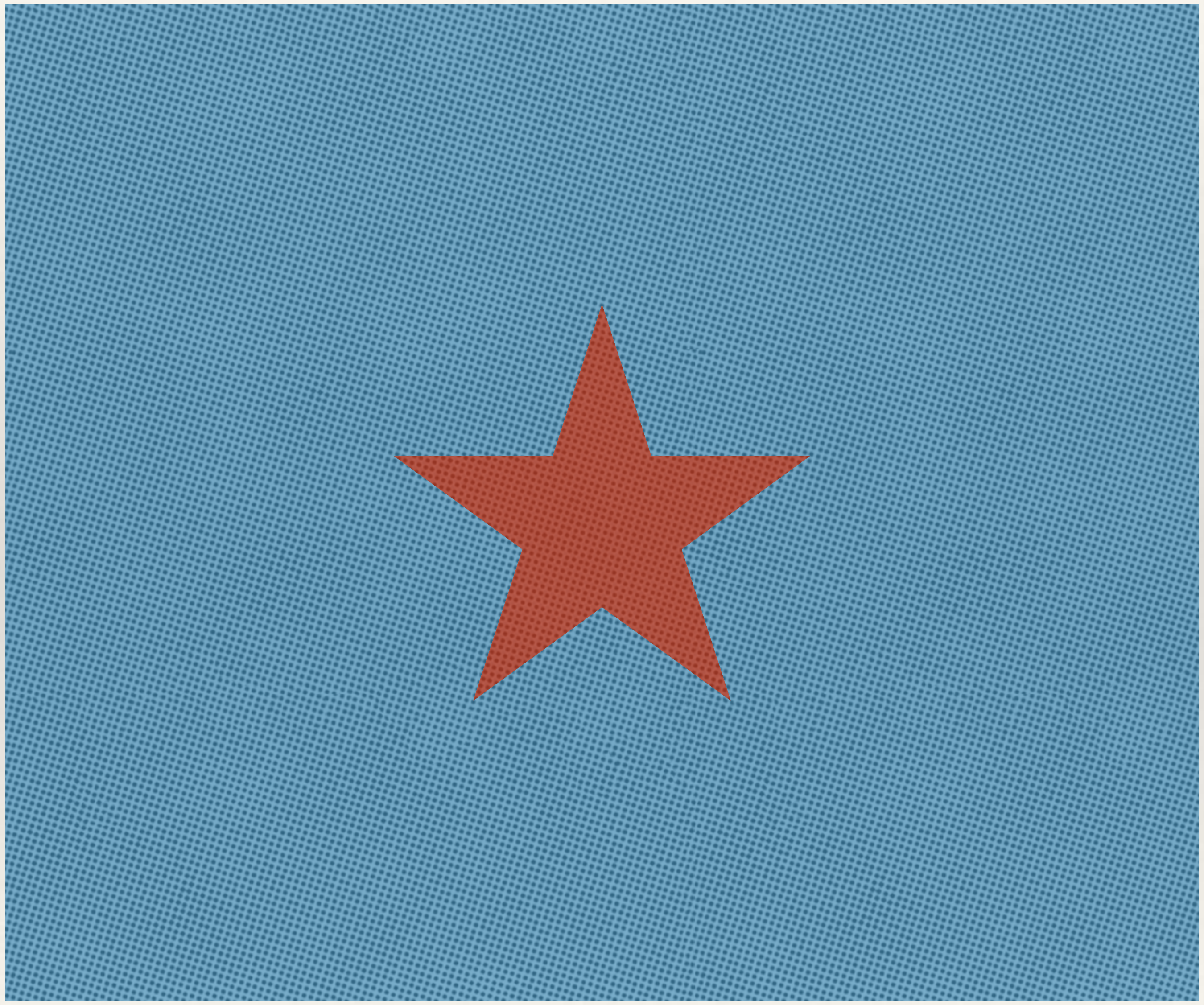


# Image stacking

- Even after these steps (bias, dark, flat), the image may be noisy and full of cosmic rays
- By stacking images, we can statistically remove noise

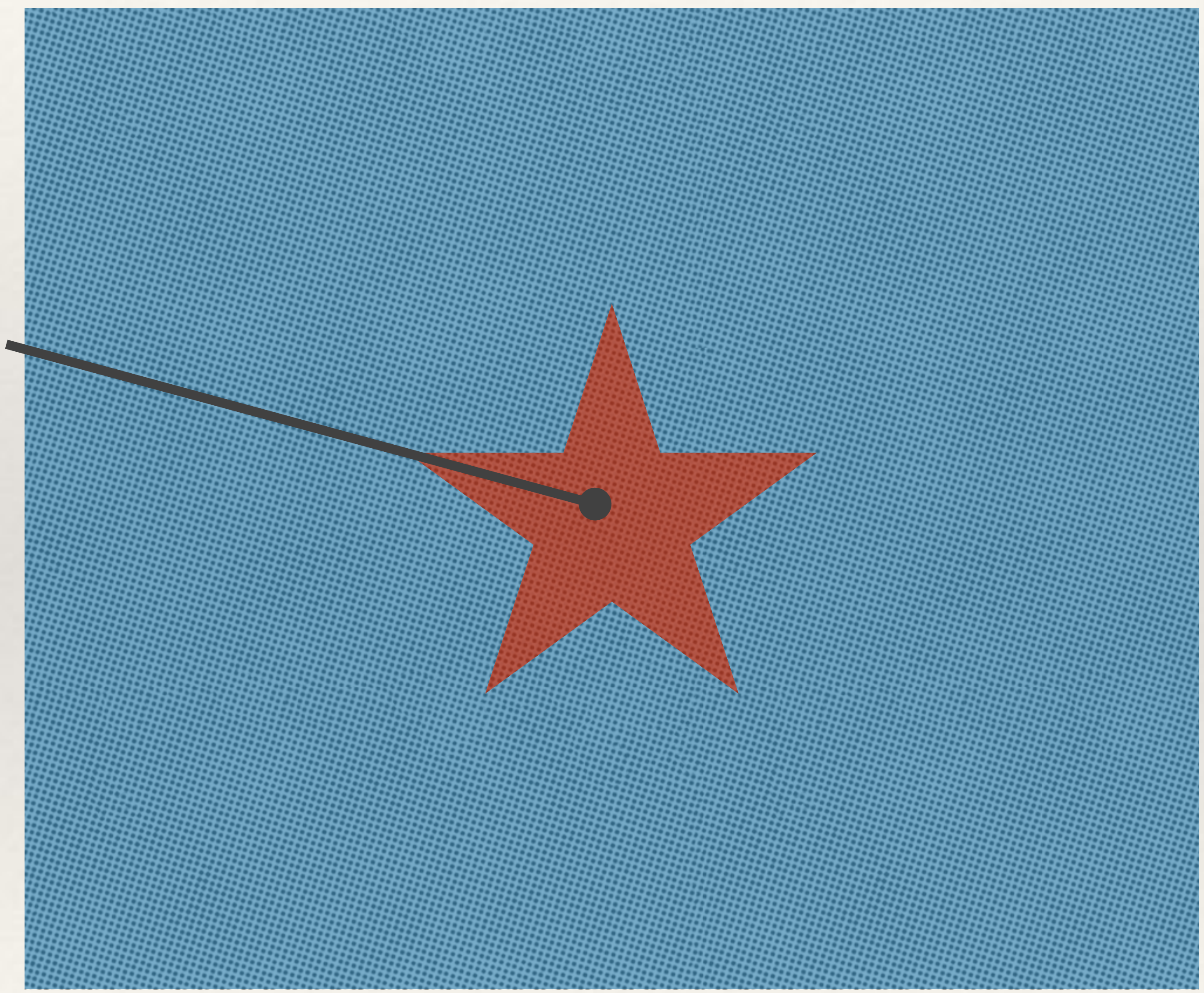


# Image stacking

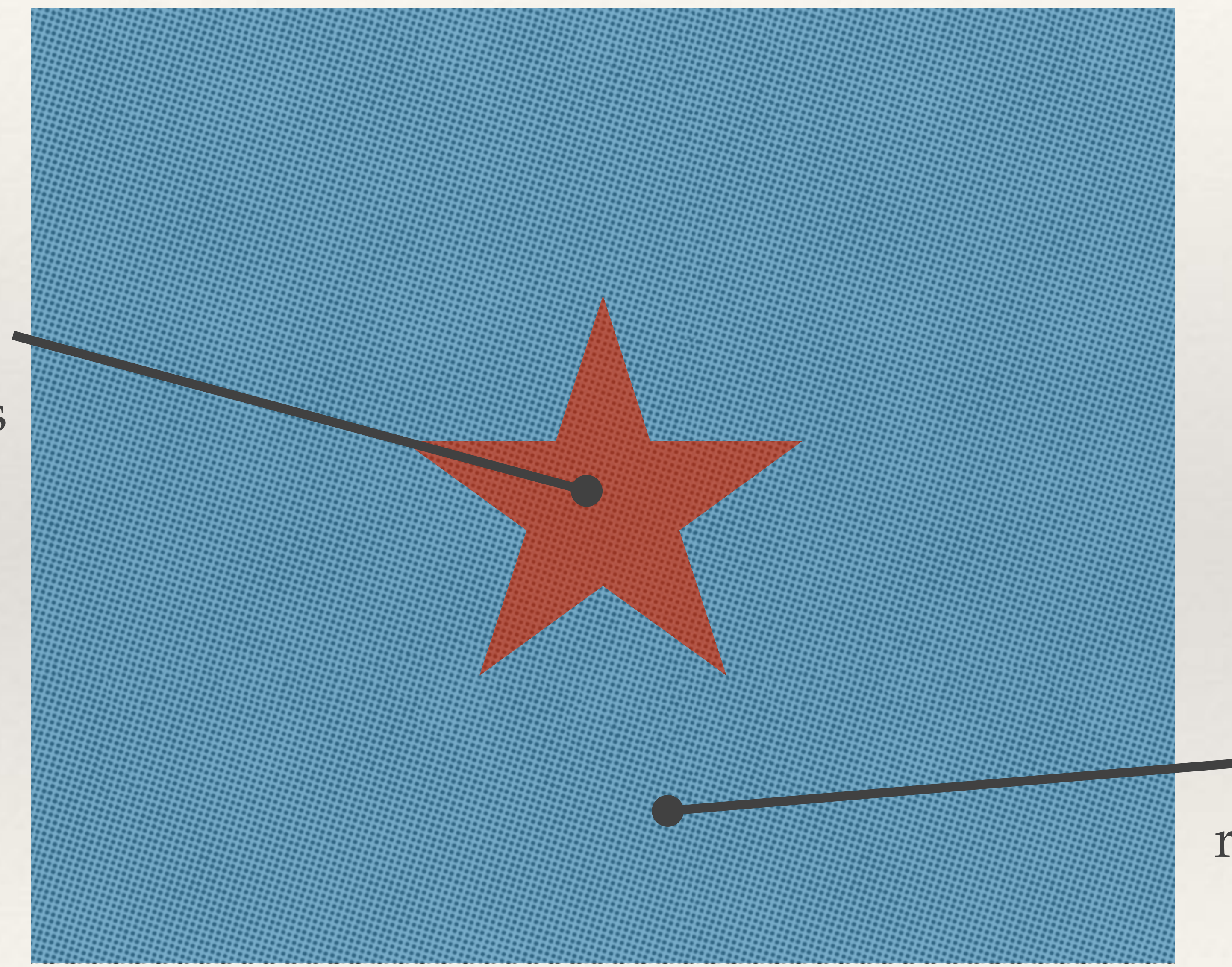


# Image stacking

Area containing
SIGNAL will always
contain signal with
repeated observations



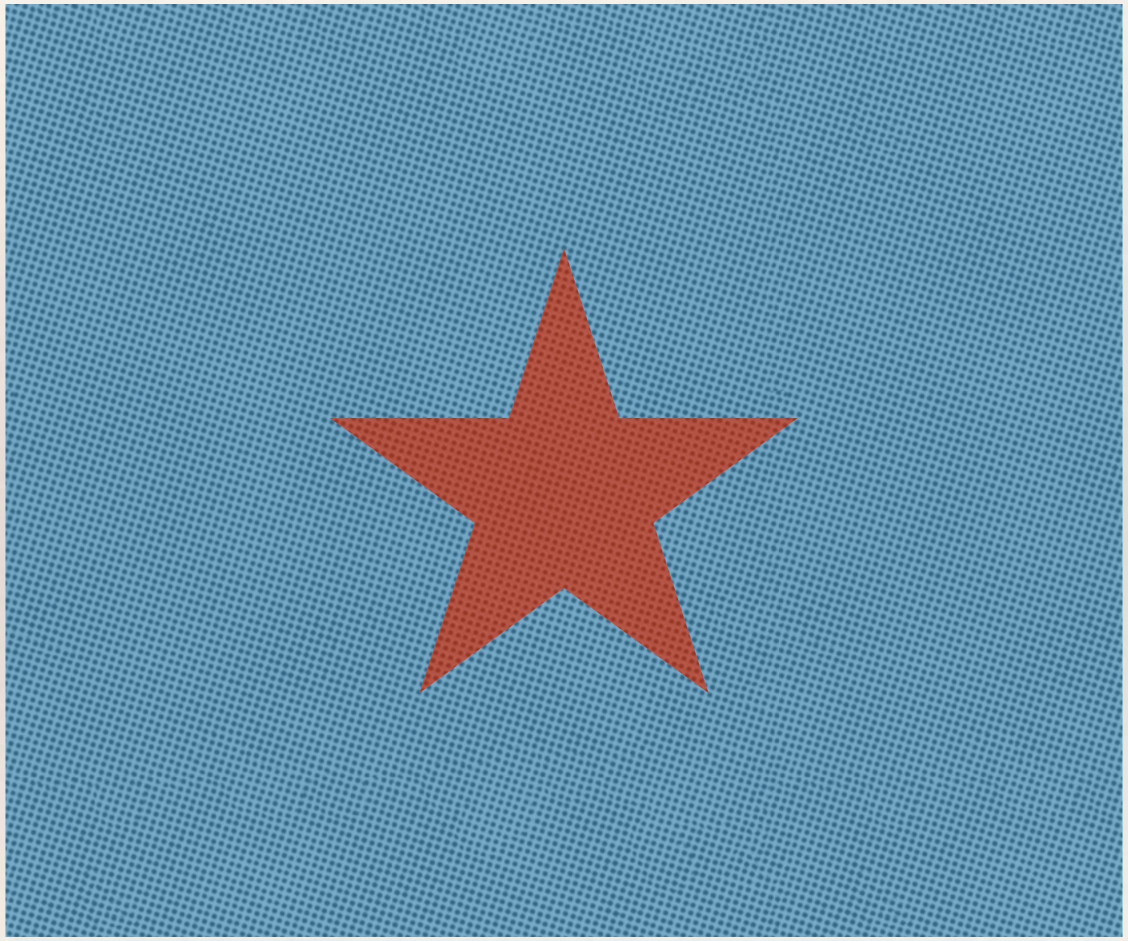
# Image stacking



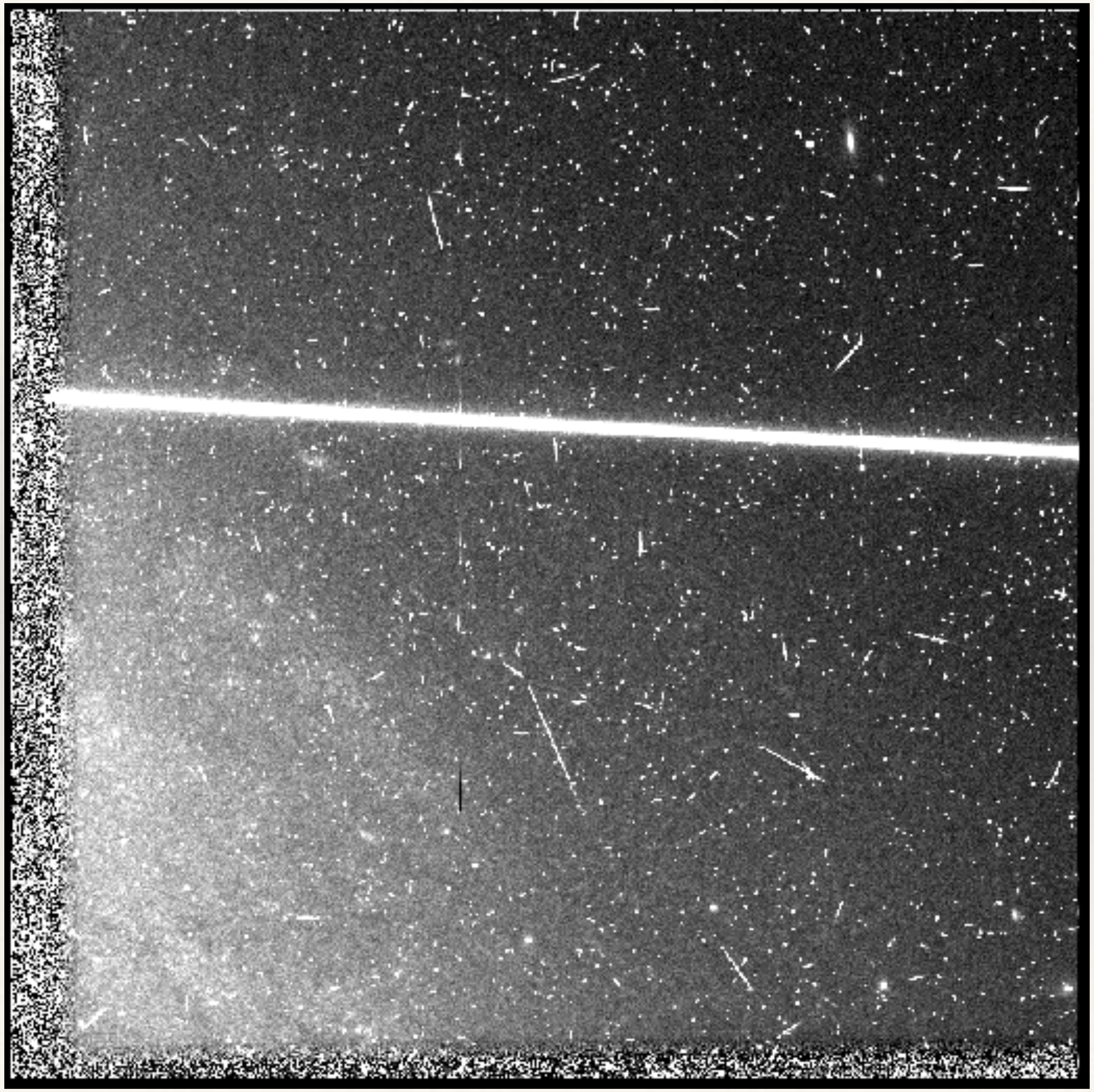
# Image stacking

- Stacking the signal will boost signal over time
- Stacking the noise will tend towards zero
- Stacked images have better signal-to-noise

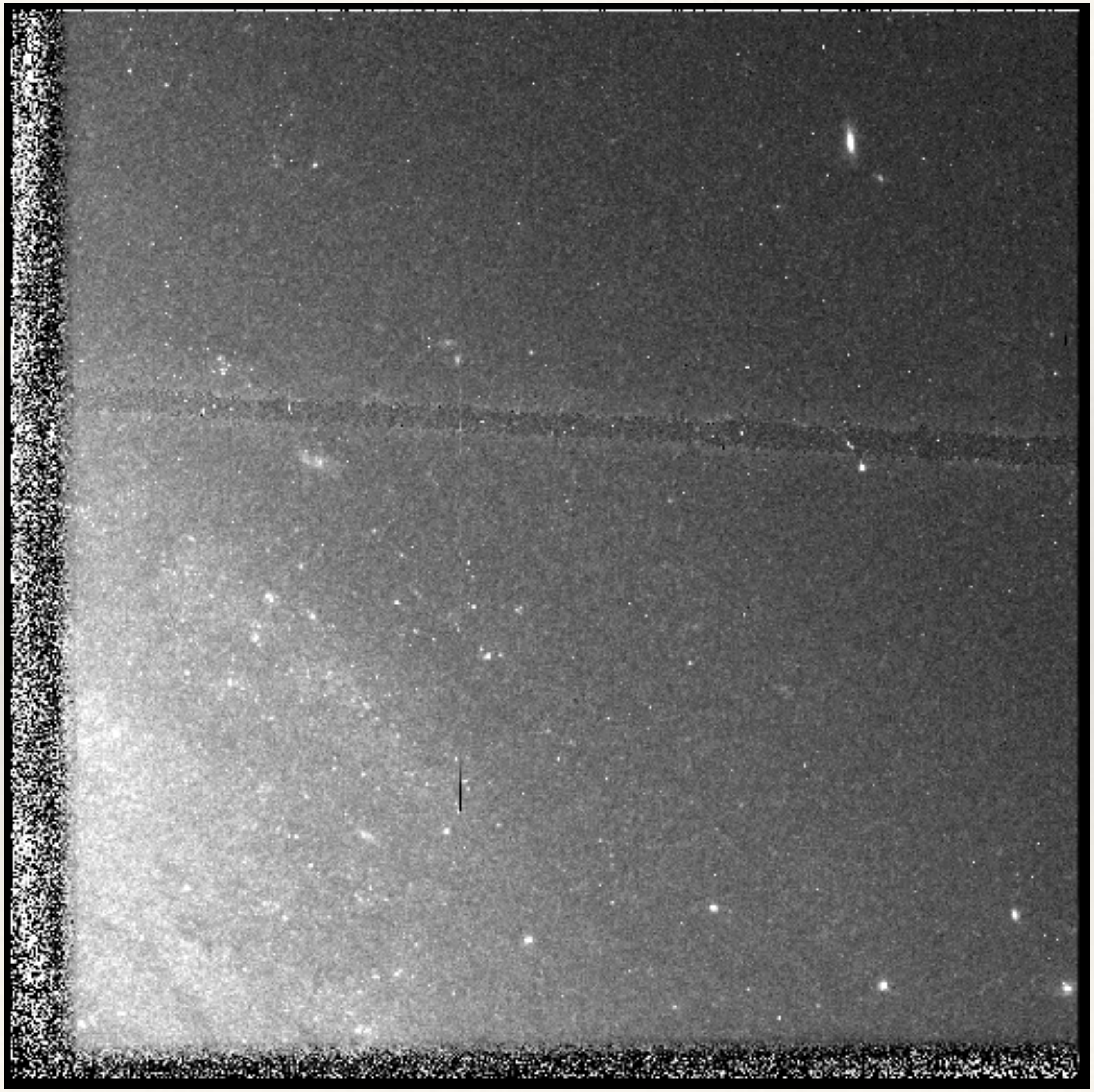
$$\mathrm{S/N} \sim \sqrt{t}$$



# Image stacking



# Image stacking



# Image stacking