Optical astronomy (II)

Photometry, Spectroscopy, and data reduction

Optical astronomy (II)

- Photometry
- Spectroscopy
- `Reduction' of astronomical data

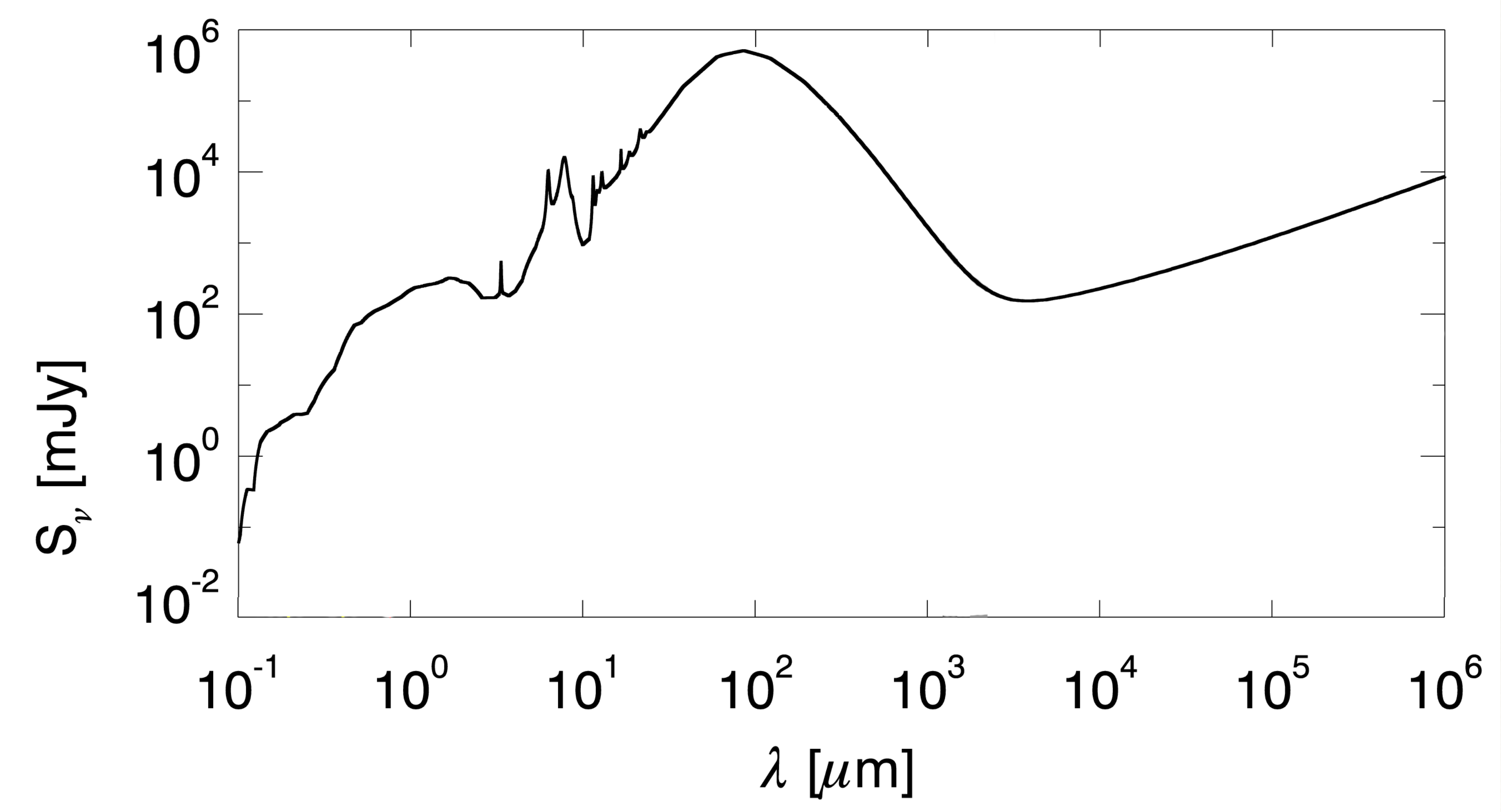
Photometry vs. Spectroscopy

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

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

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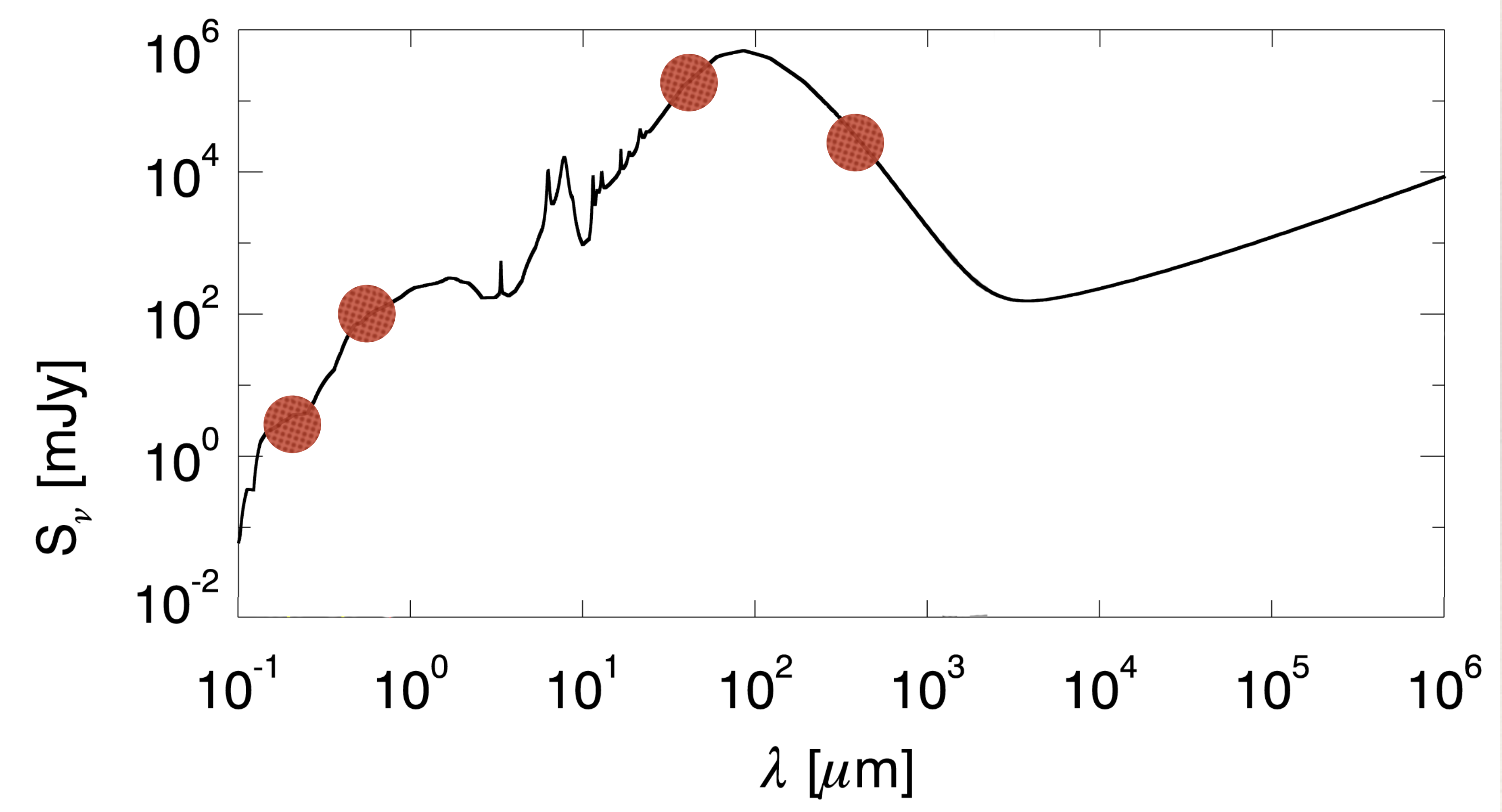
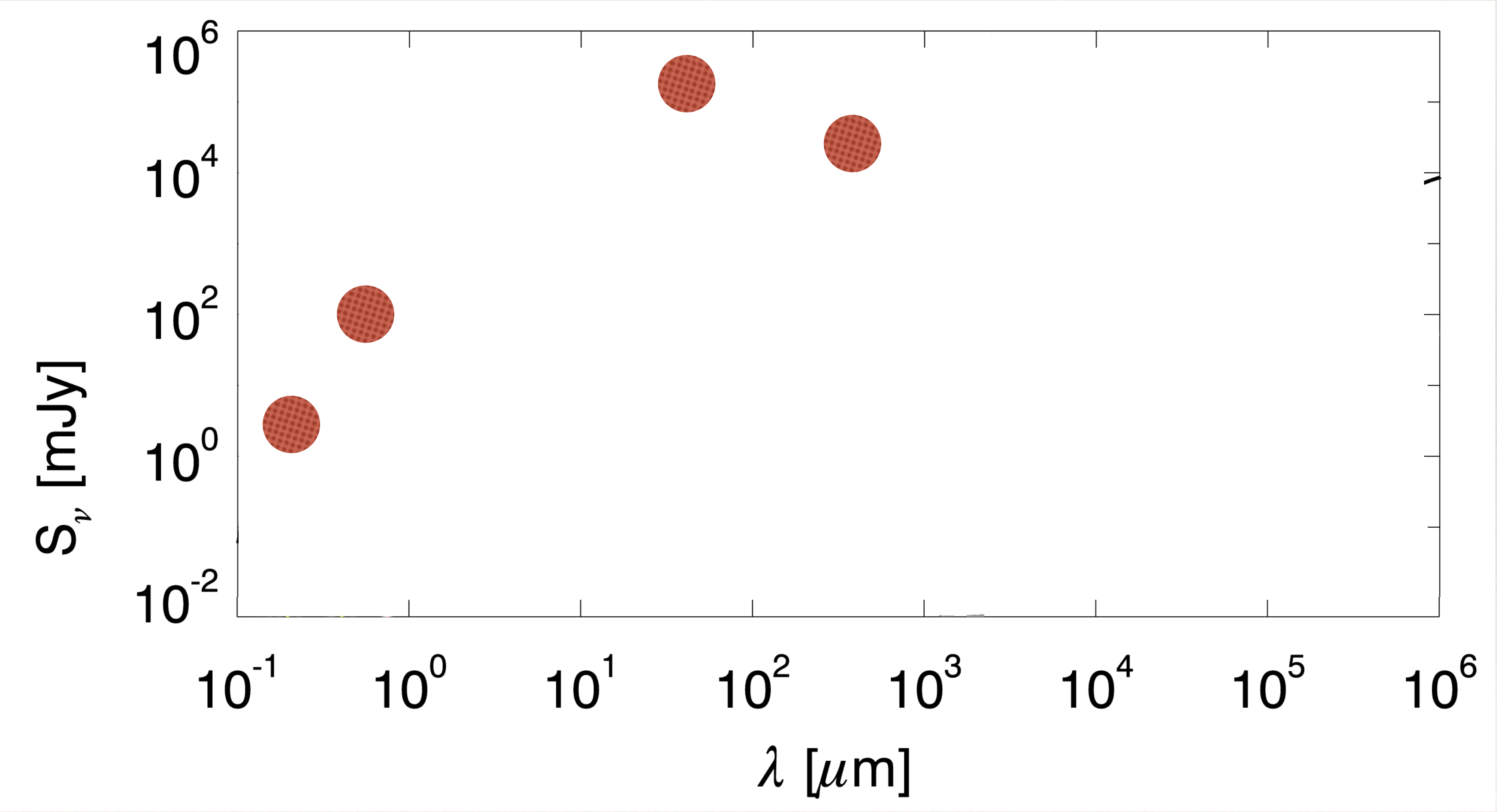


Photometry vs. Spectroscopy

But, photometry can provide a quick approximation



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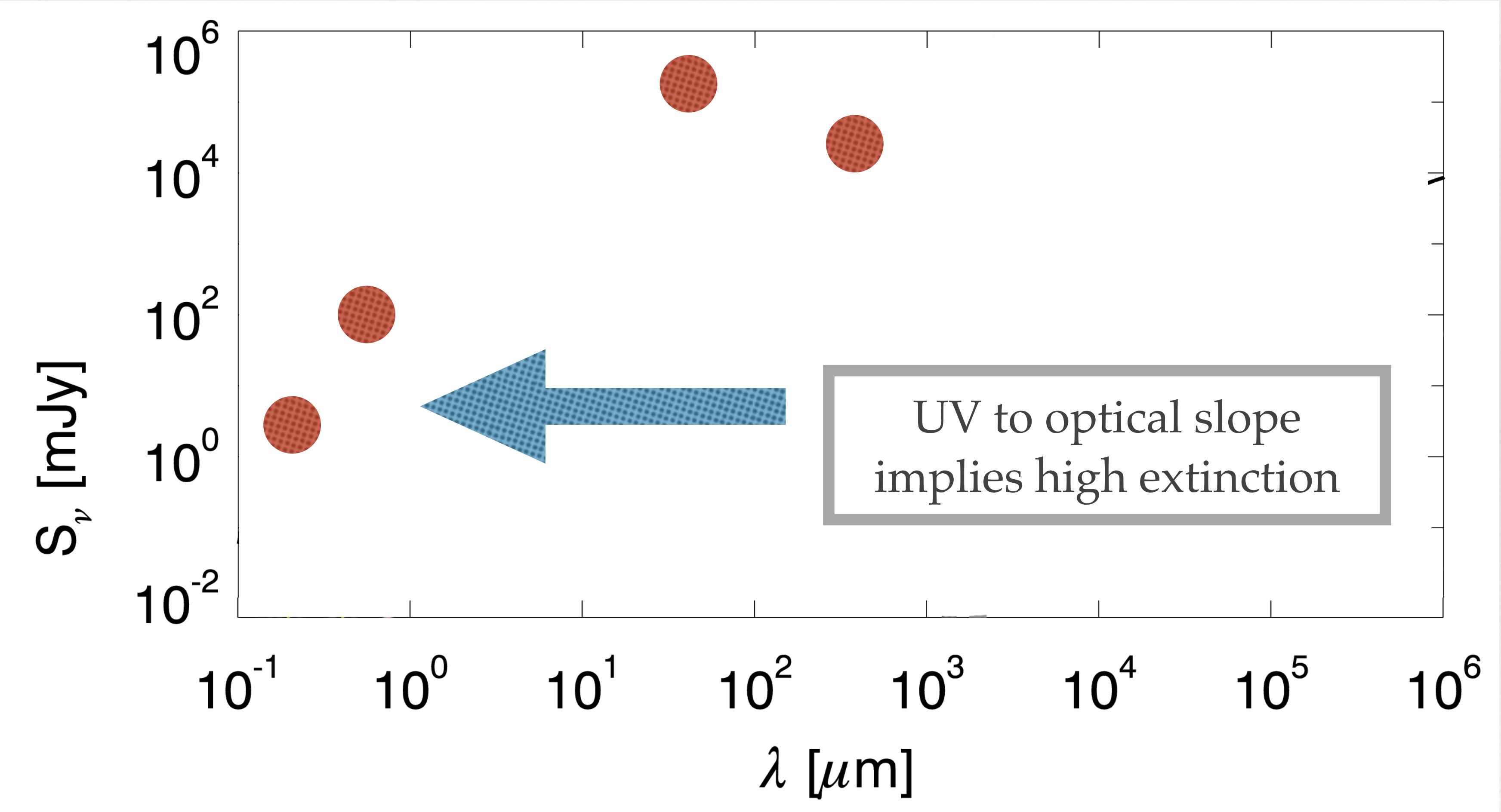

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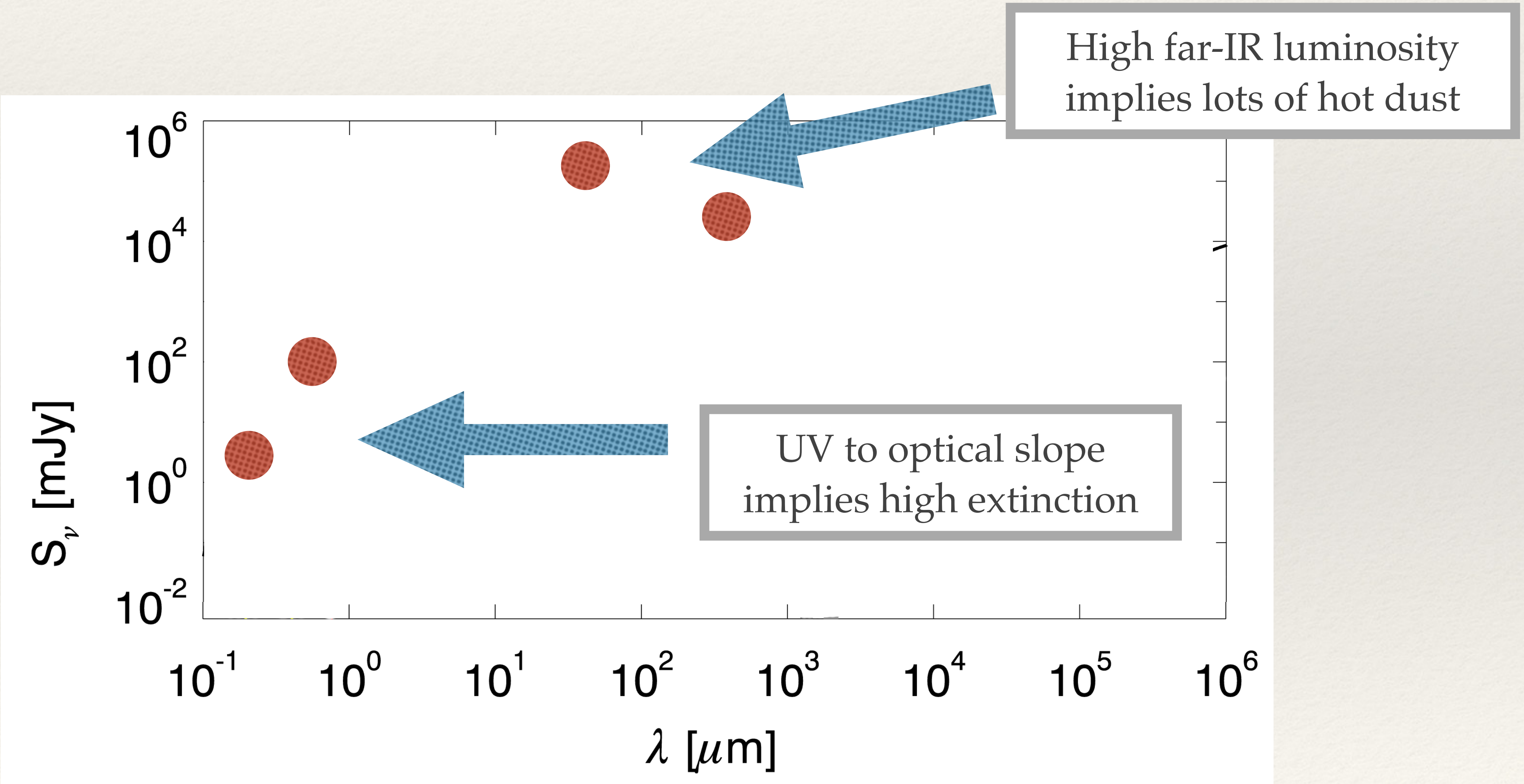


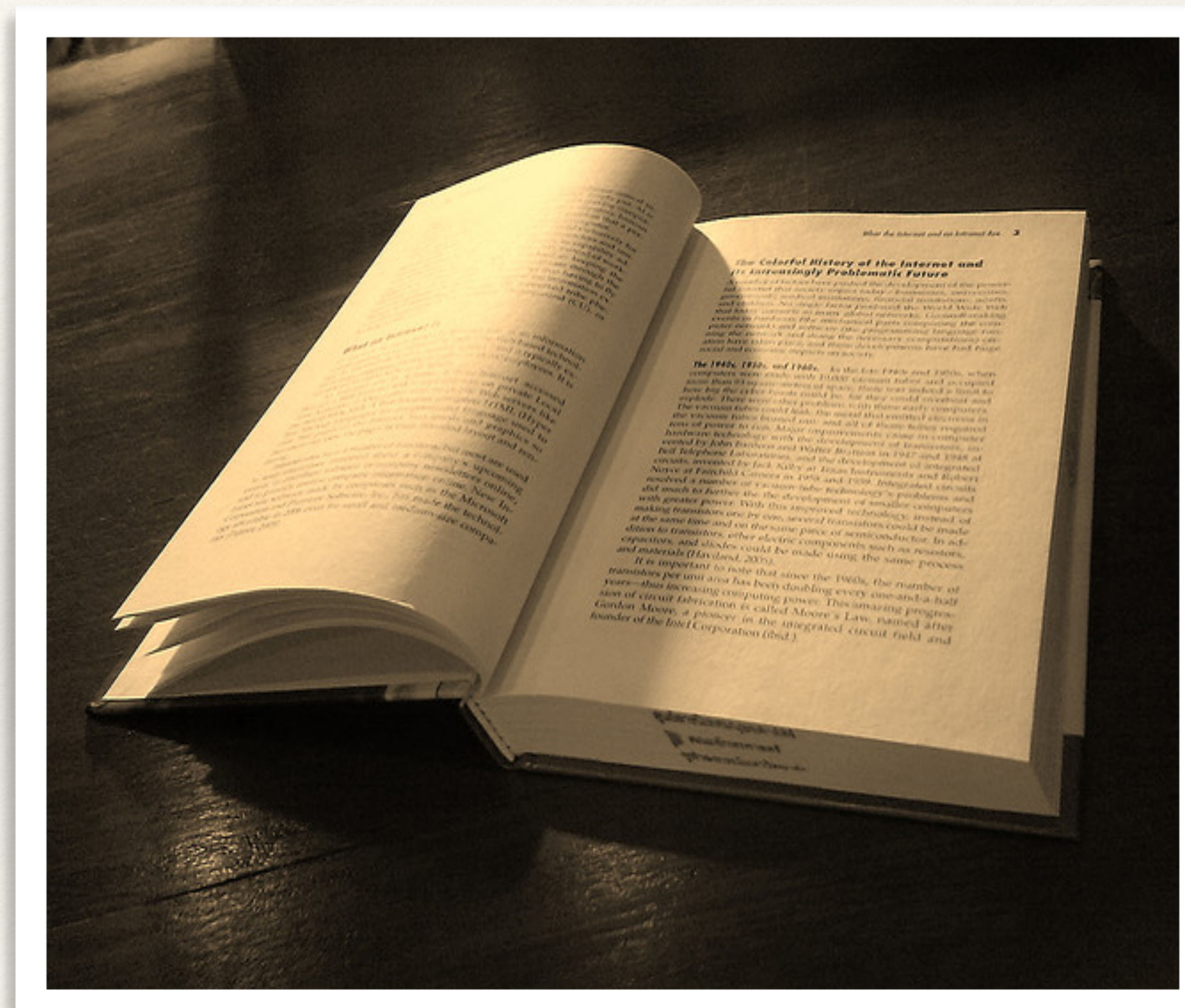
Photometry vs. Spectroscopy

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)

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
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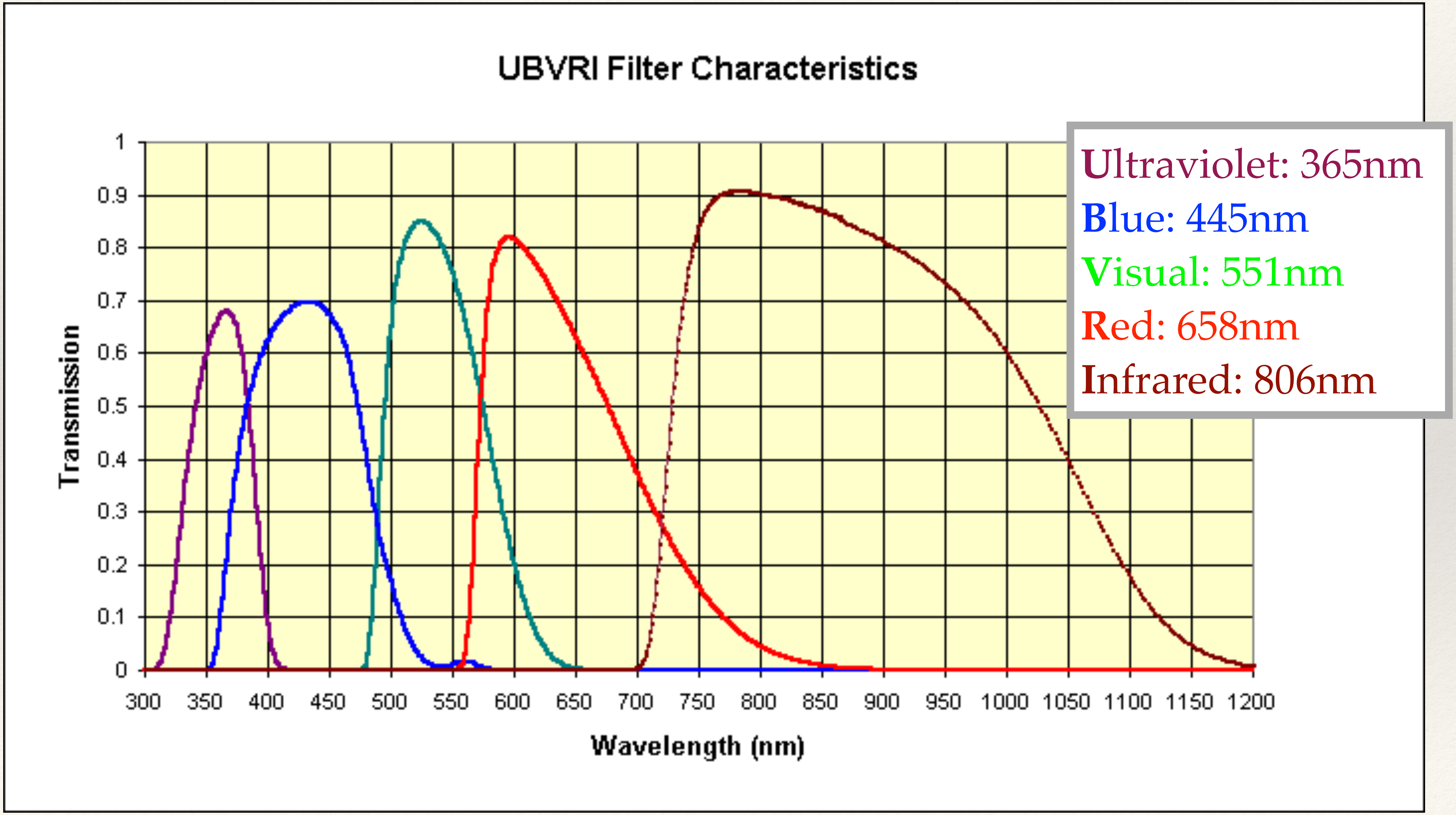
Photometric filters

- 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'

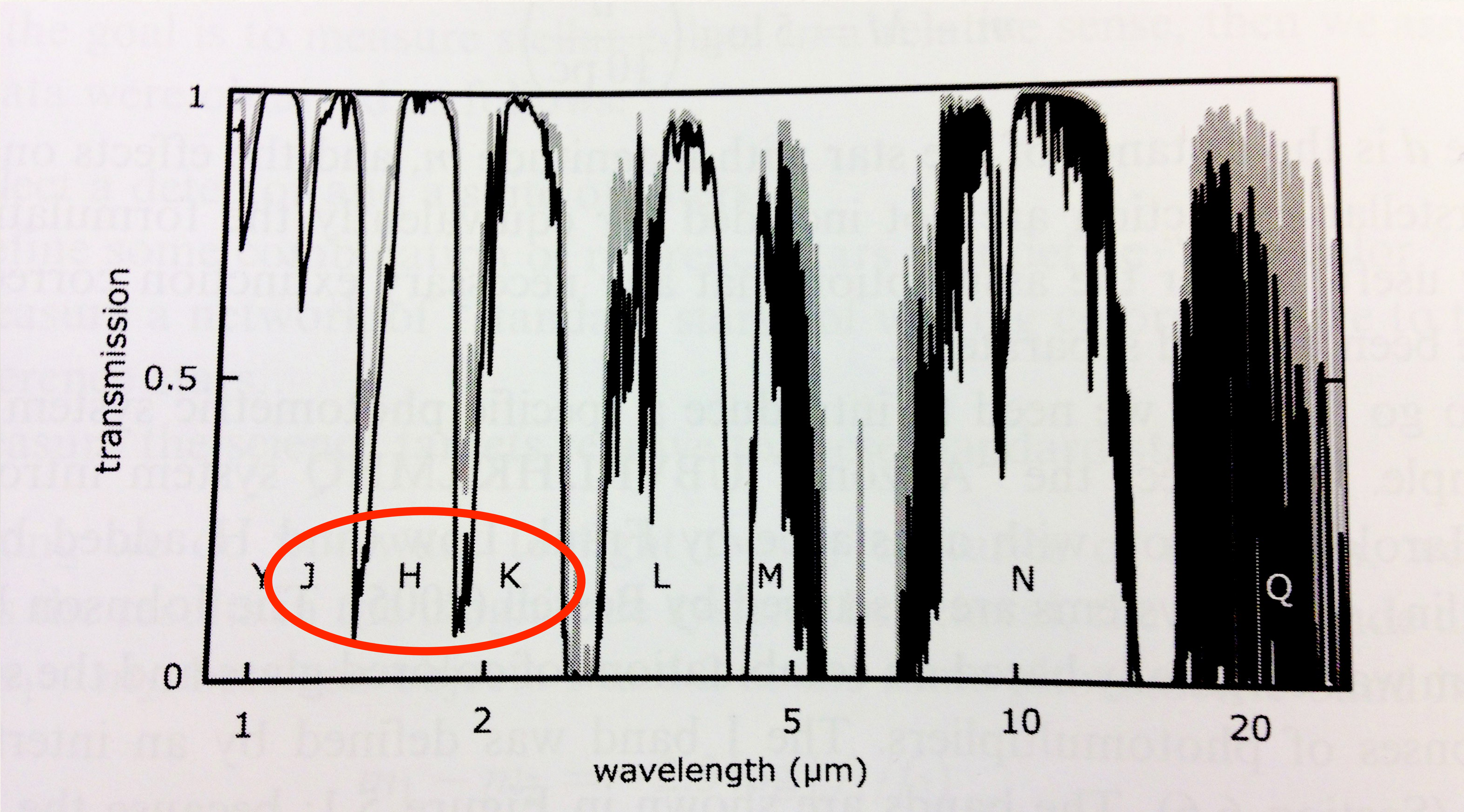
Photometric filters



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’)

Photometric filters (IR)



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)

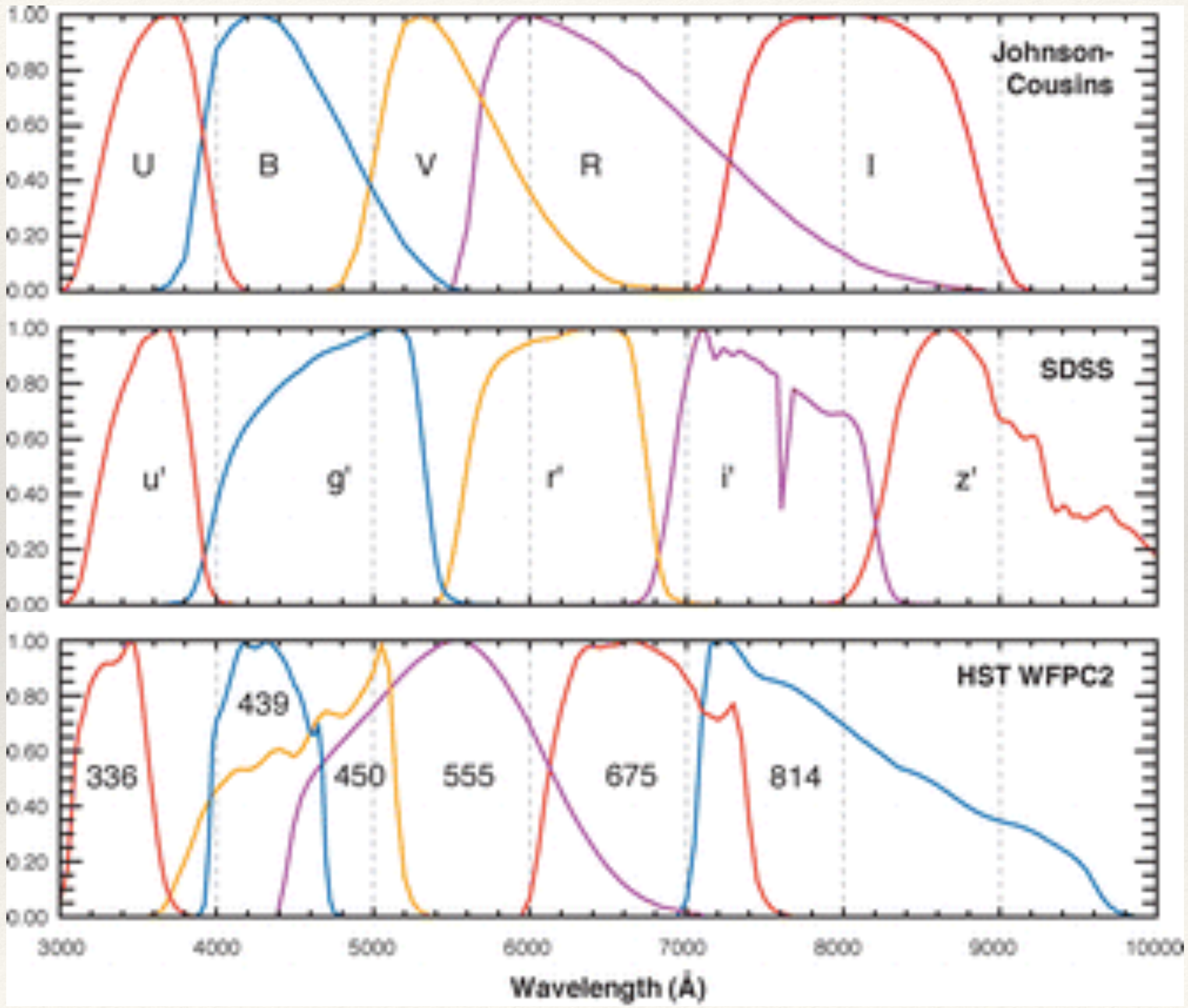
Now, we have dropped the idea of a single defining photometer. So, magnitude systems can differ!

Alternate systems

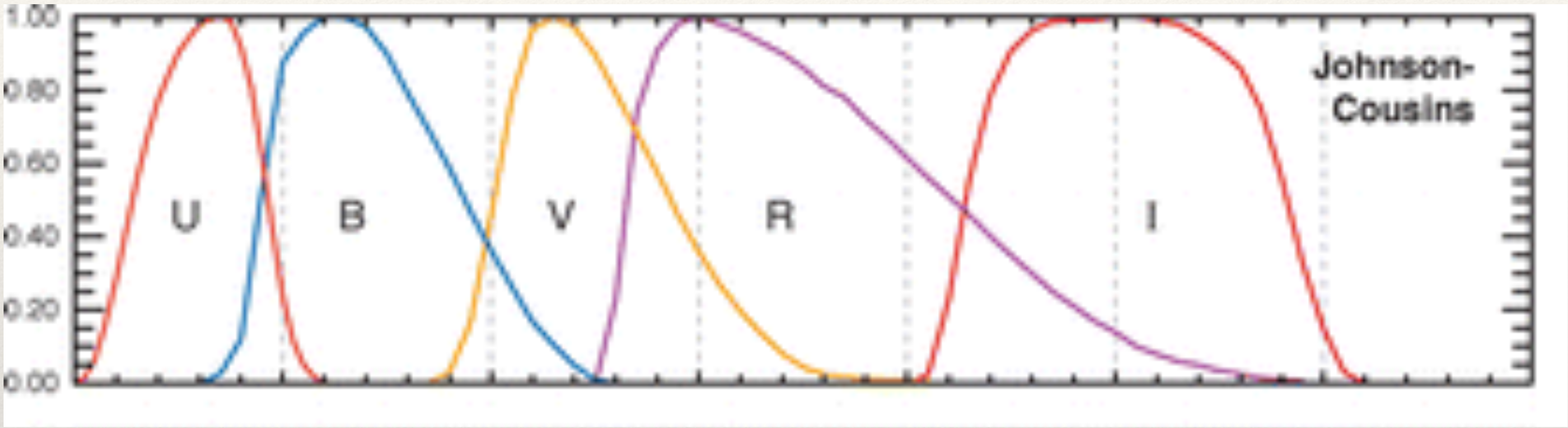
Classic

SDSS

Hubble



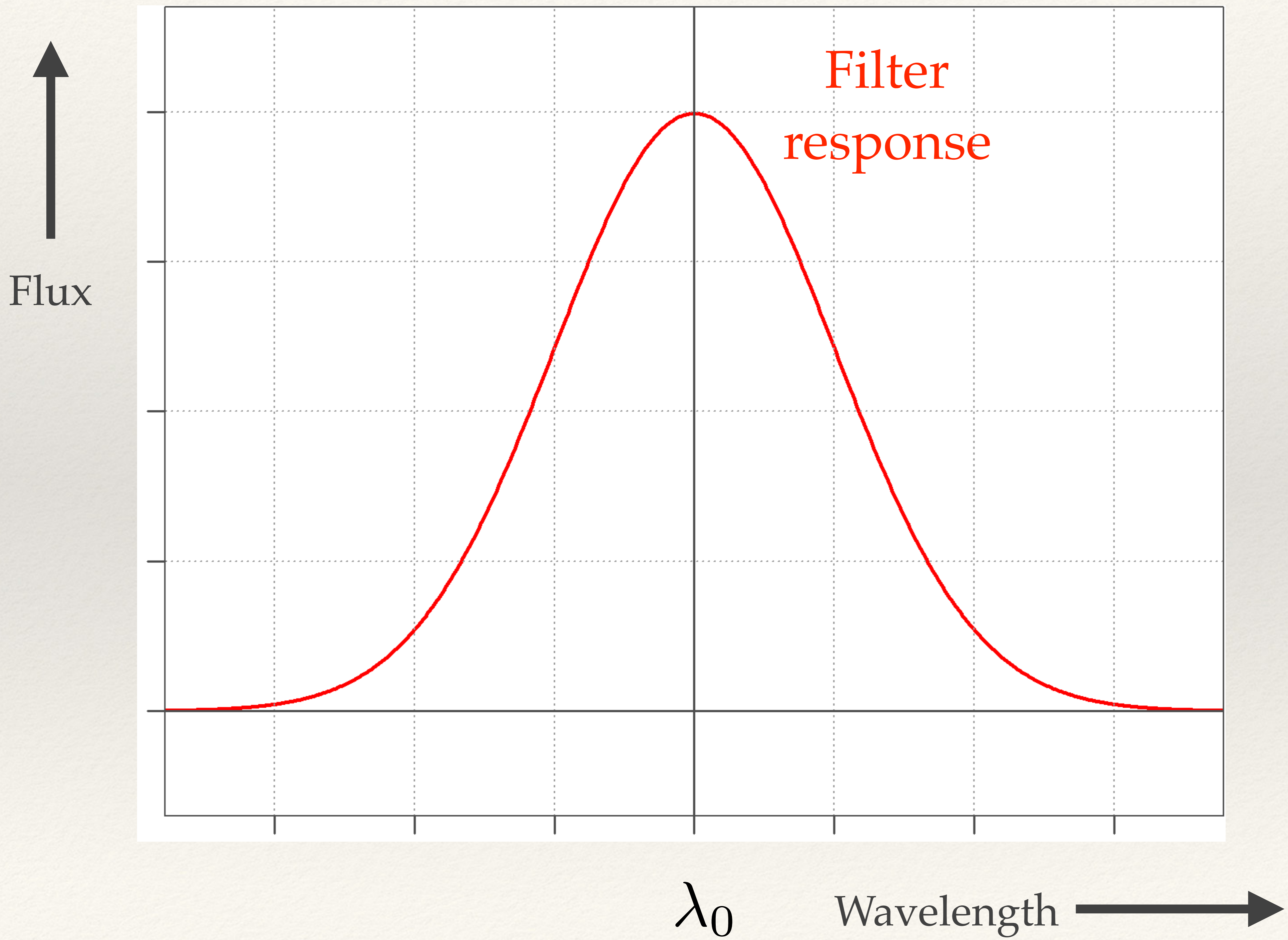
A note on bandpass corrections



Bandpasses are defined relative to their central wavelength (i.e., V=551nm), but they have width

A spectrum that varies across the bandpass can cause problems…

A note on bandpass corrections



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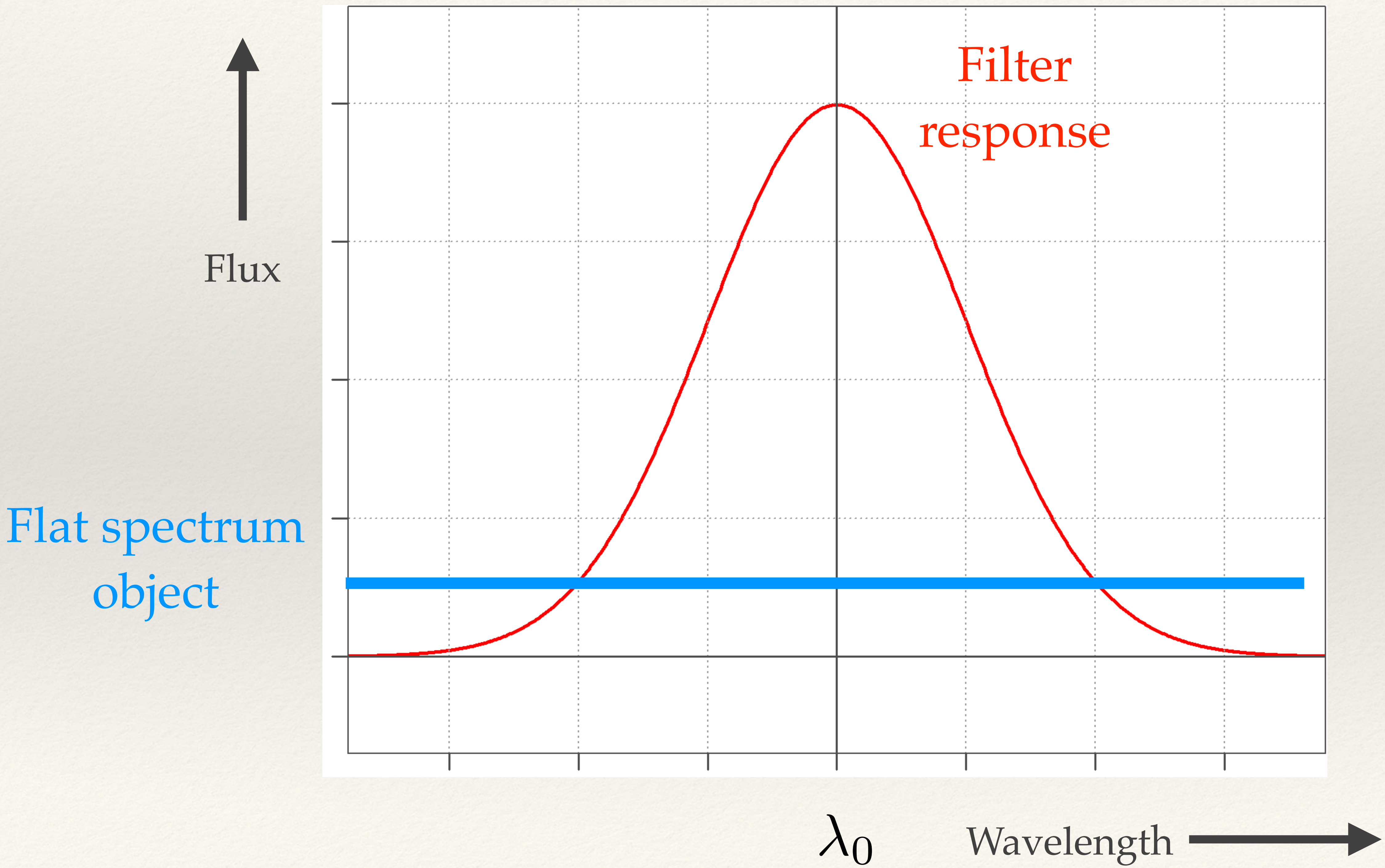

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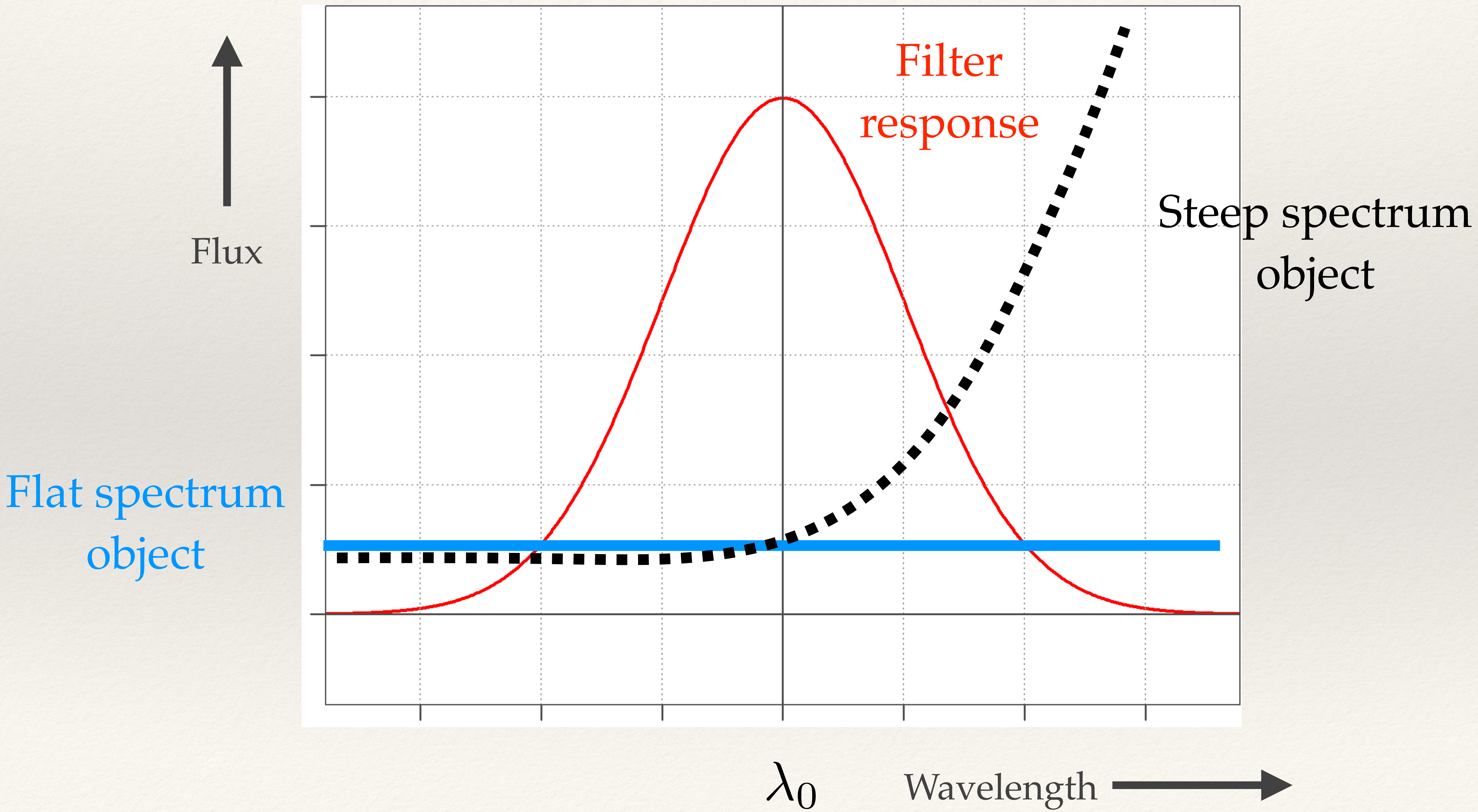

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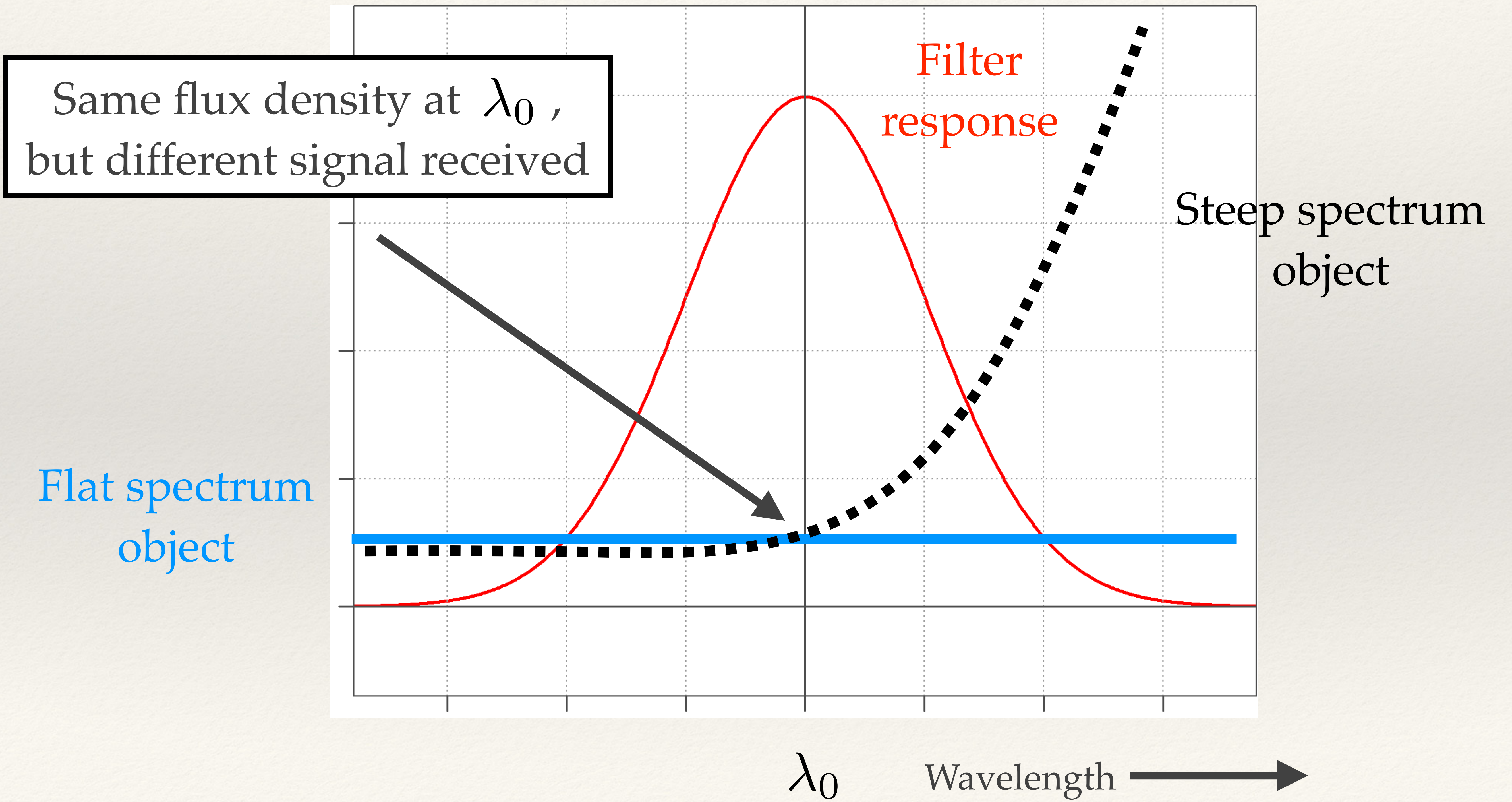
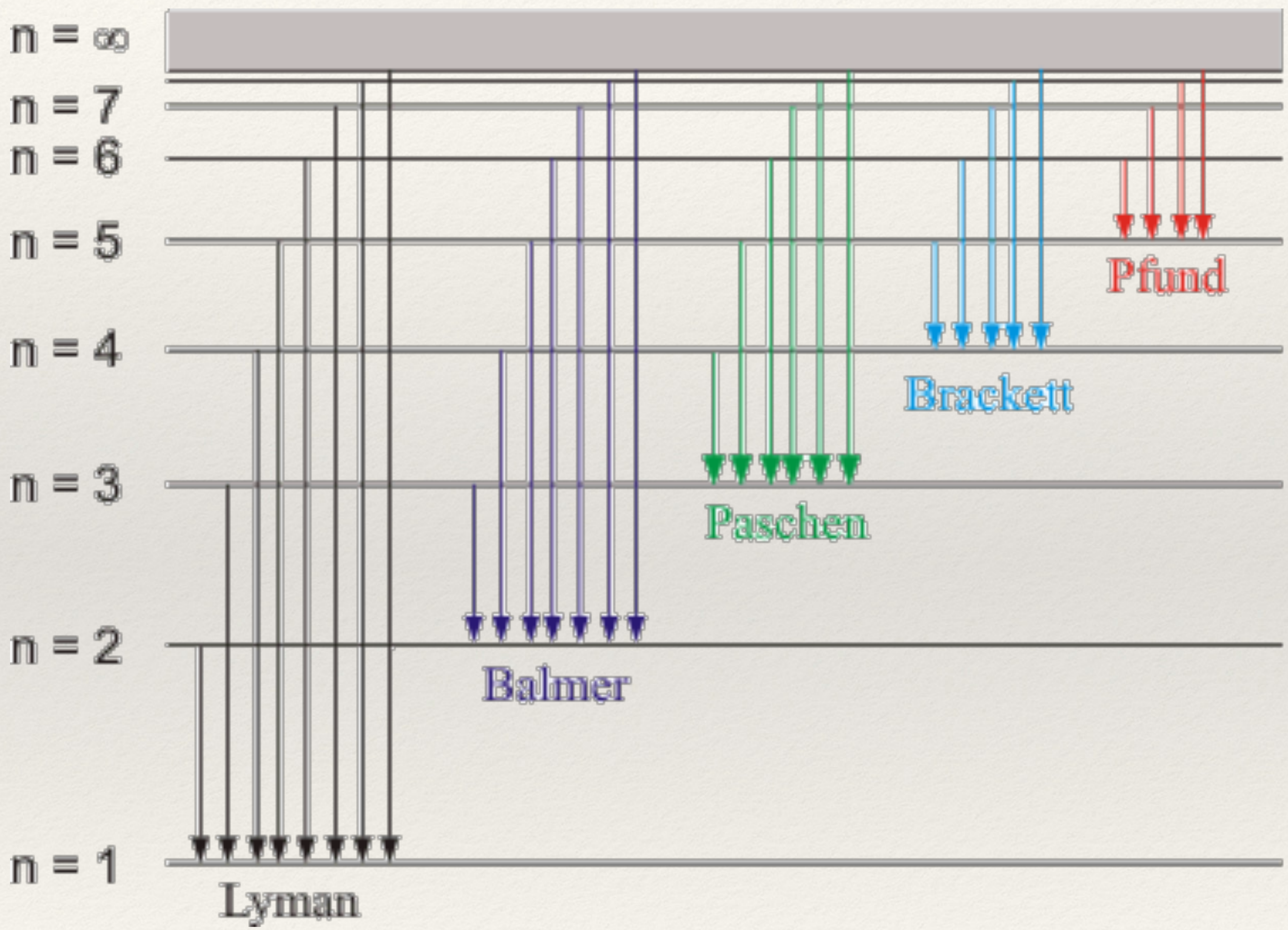


Uses of photometry

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

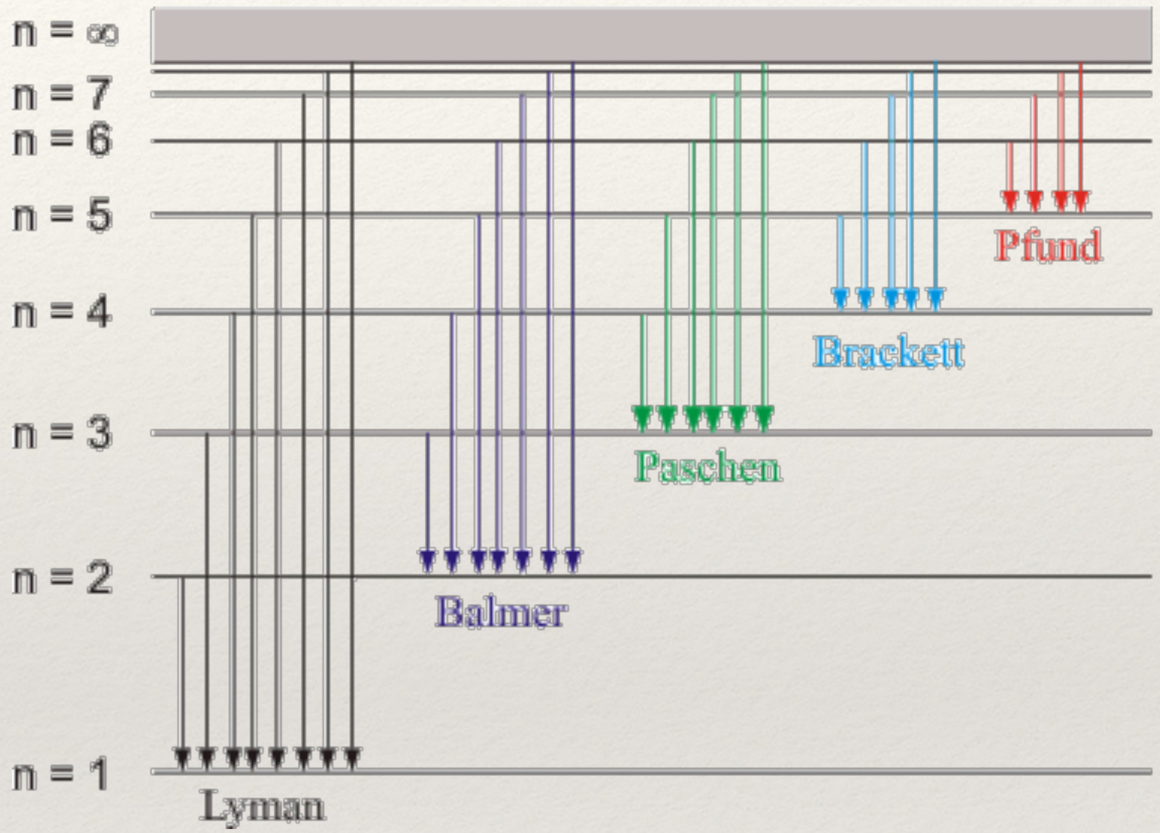
Photometric dropouts



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, $n_1=1$, $n_2=\text{infinity}$

Photometric dropouts

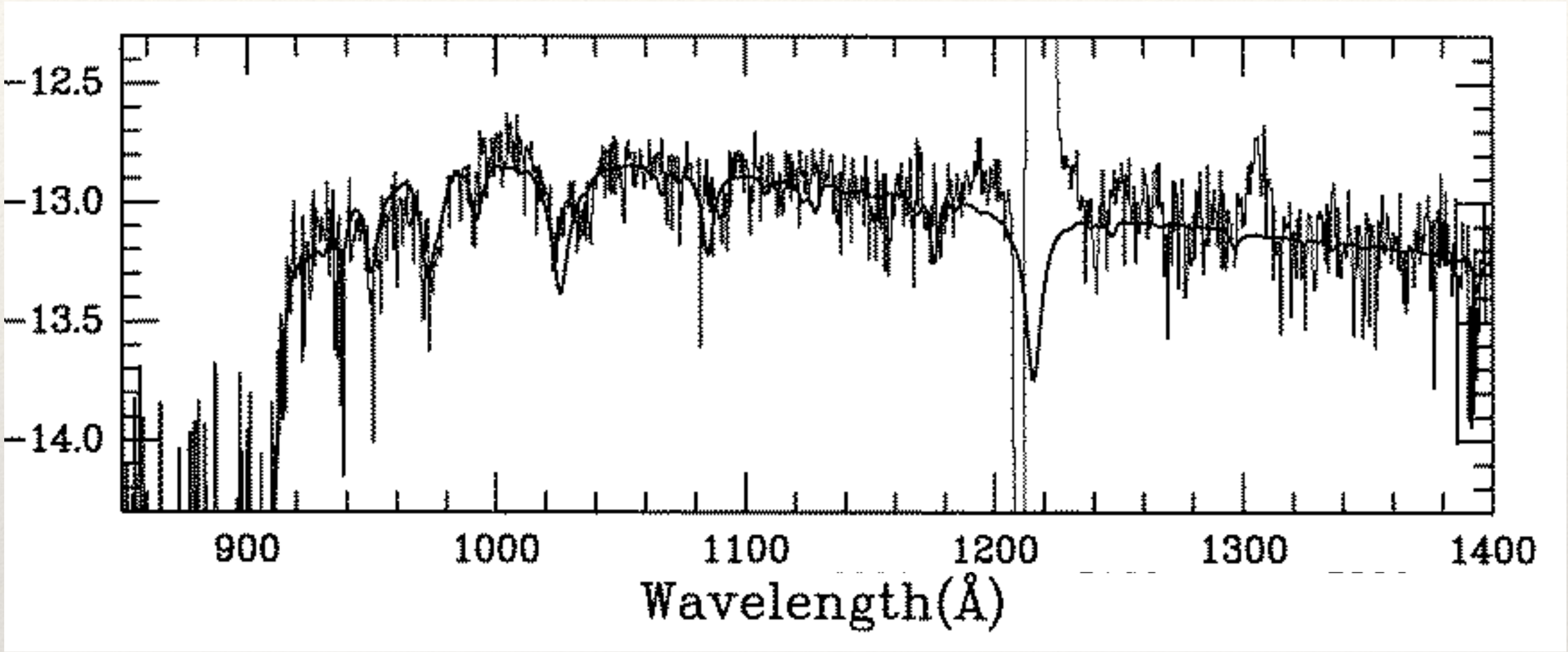
$$1/\lambda = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

$$1/\lambda = R$$

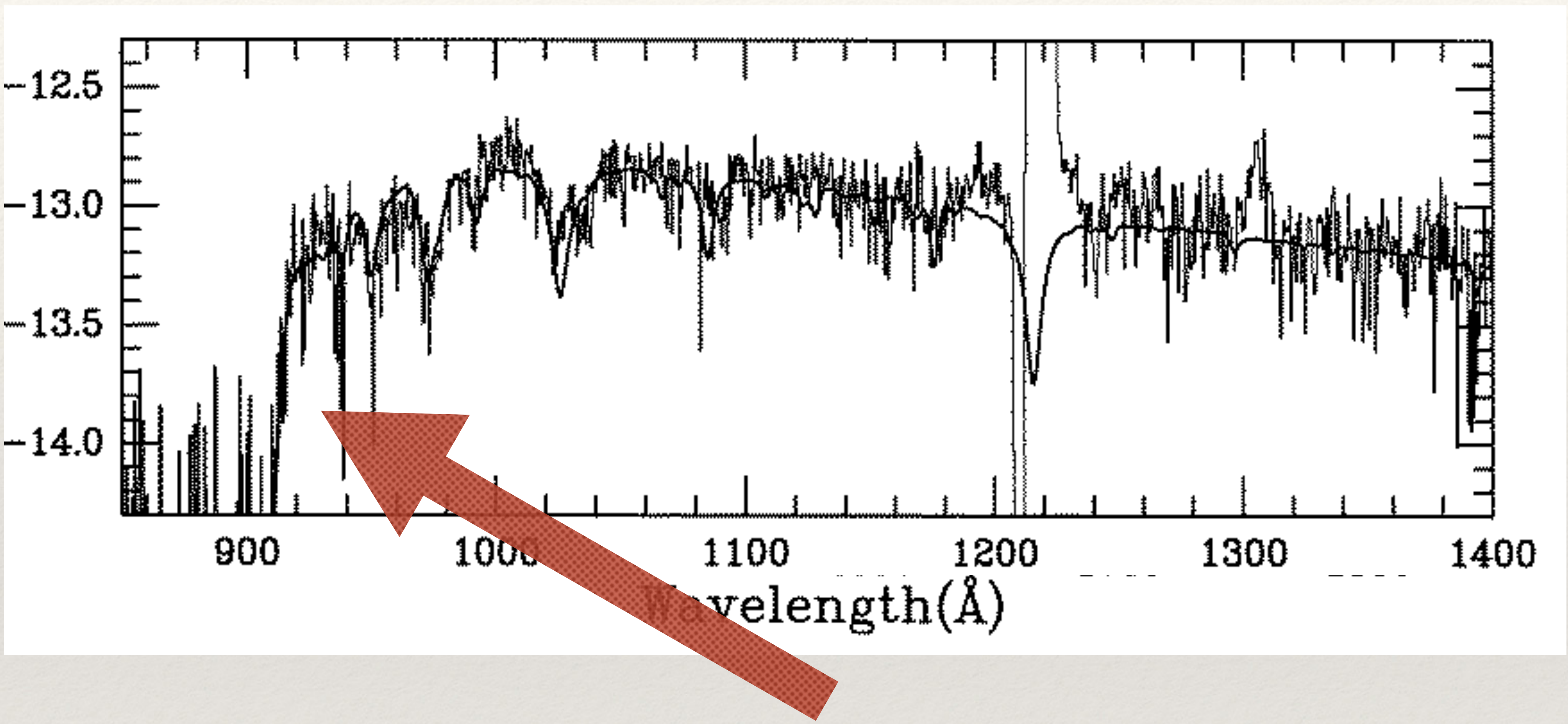
$$\lambda = 91.1\mathrm{nm}$$

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

Photometric dropouts



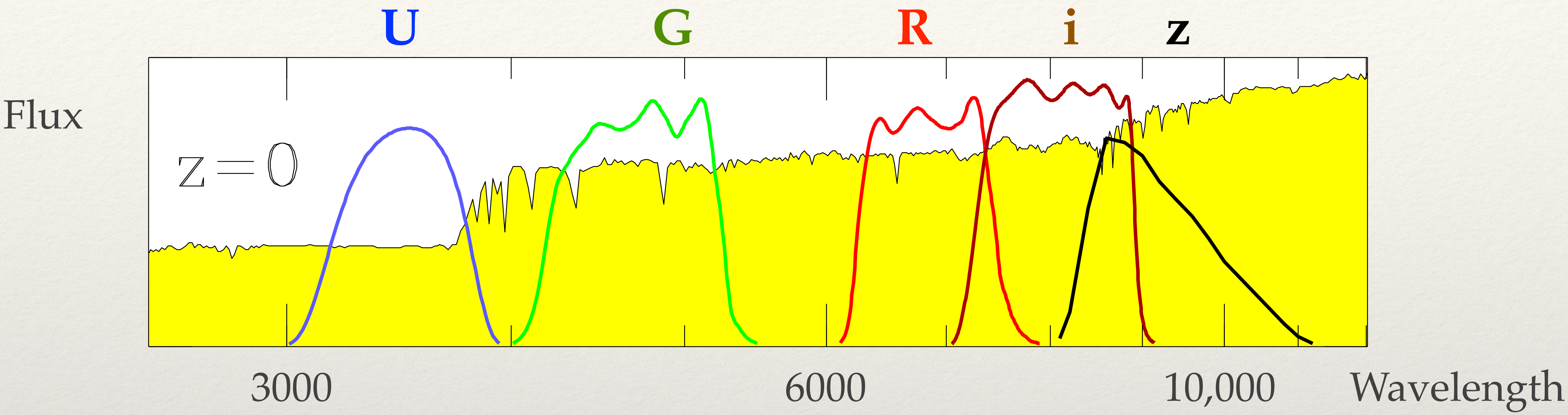
Photometric dropouts



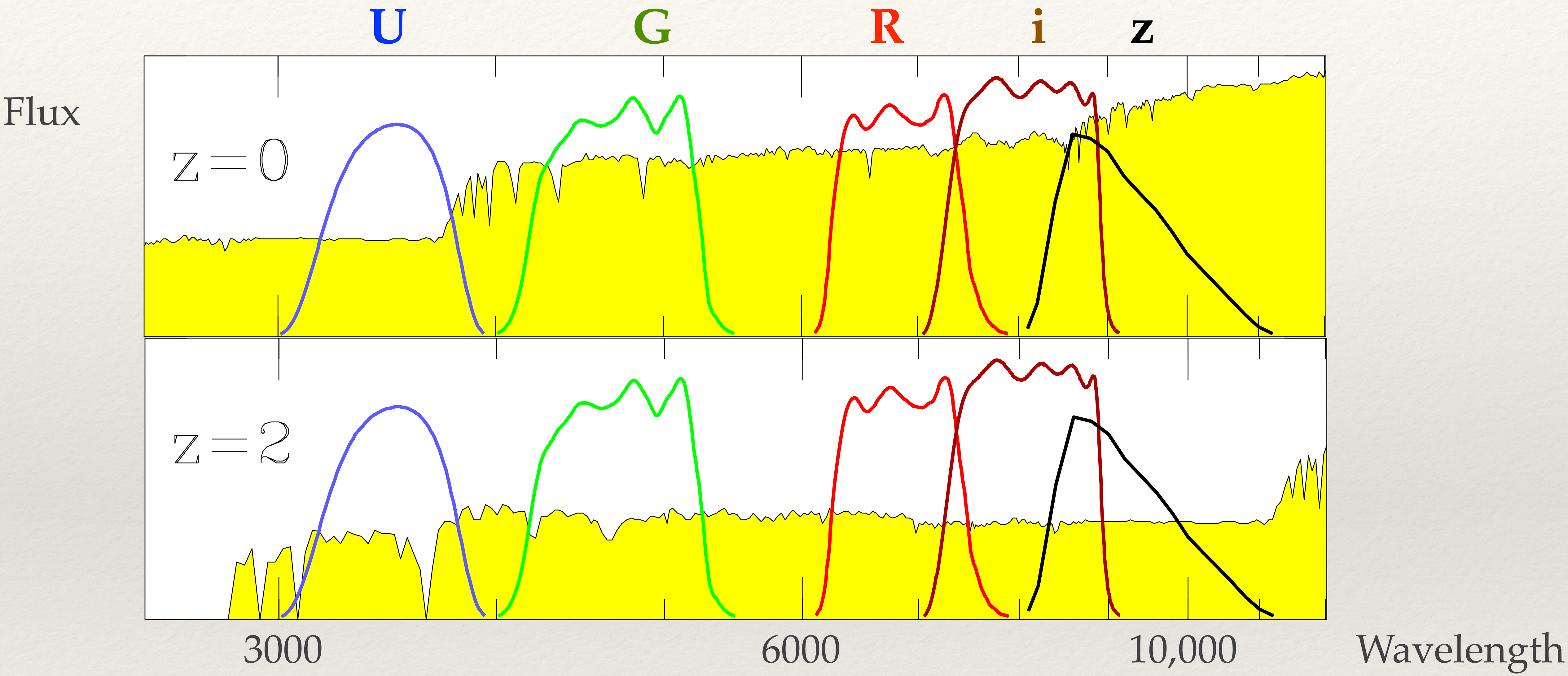
Spectral drop-off after 'Lyman Limit'

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

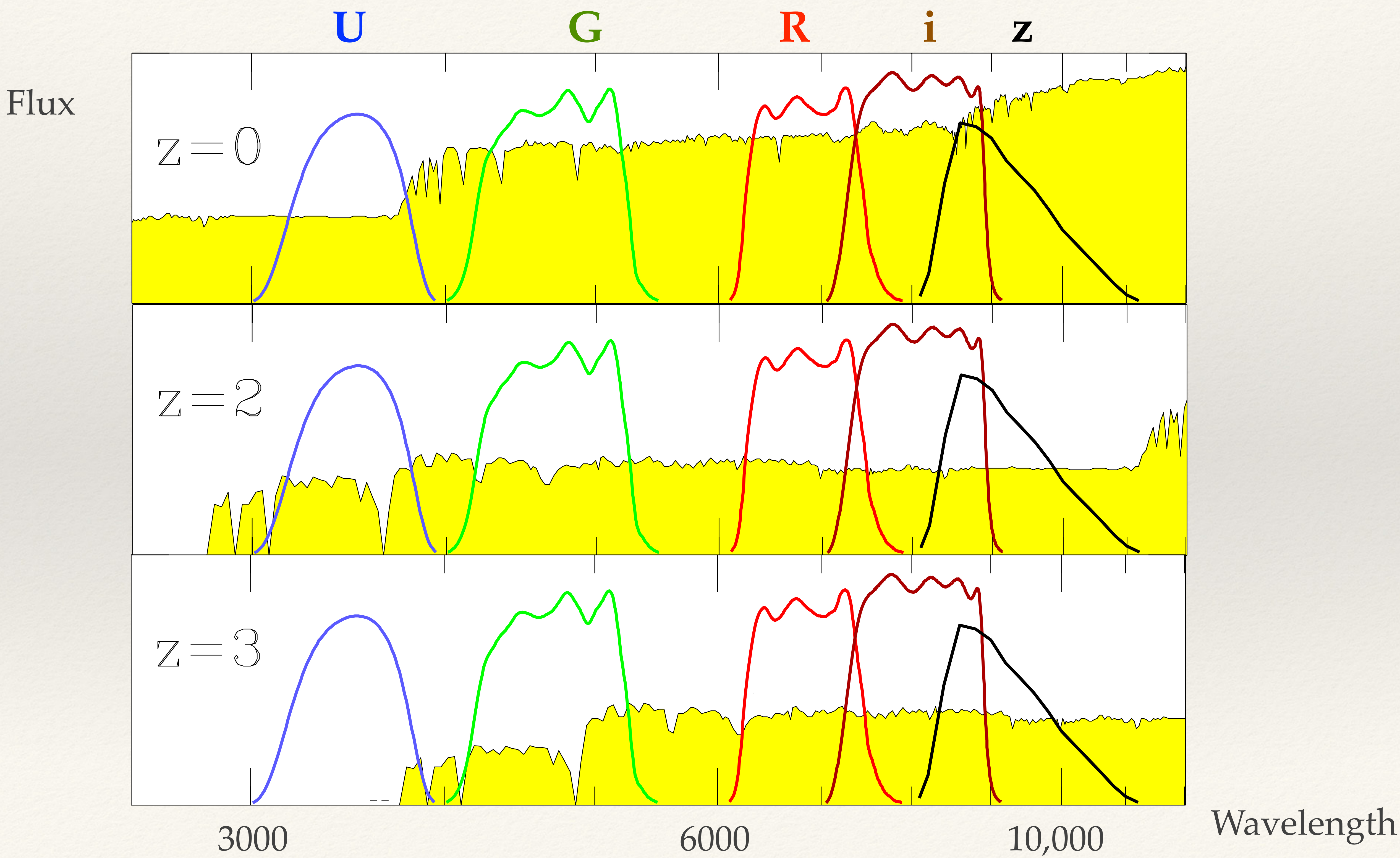
Photometric dropouts



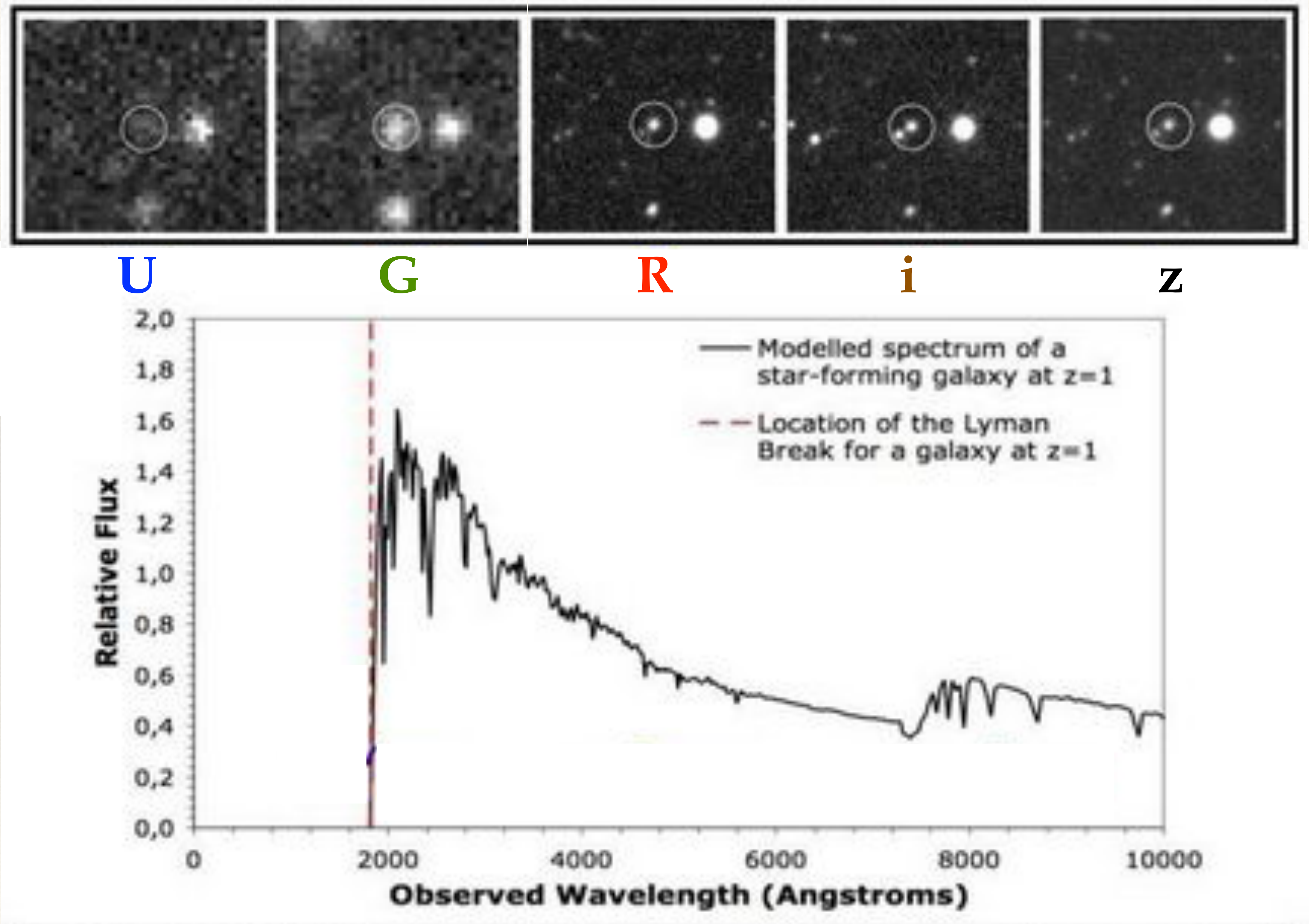
Photometric dropouts



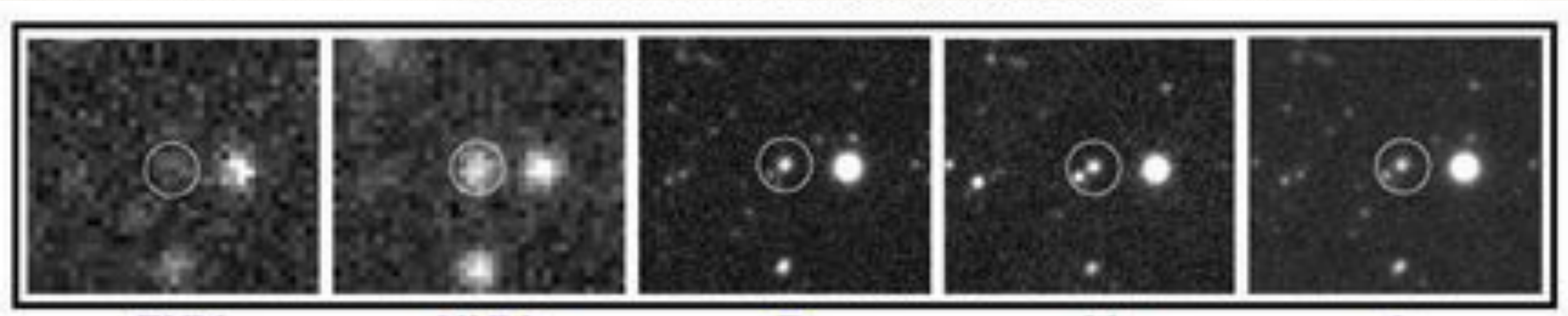
Photometric dropouts



Photometric dropouts



Photometric dropouts

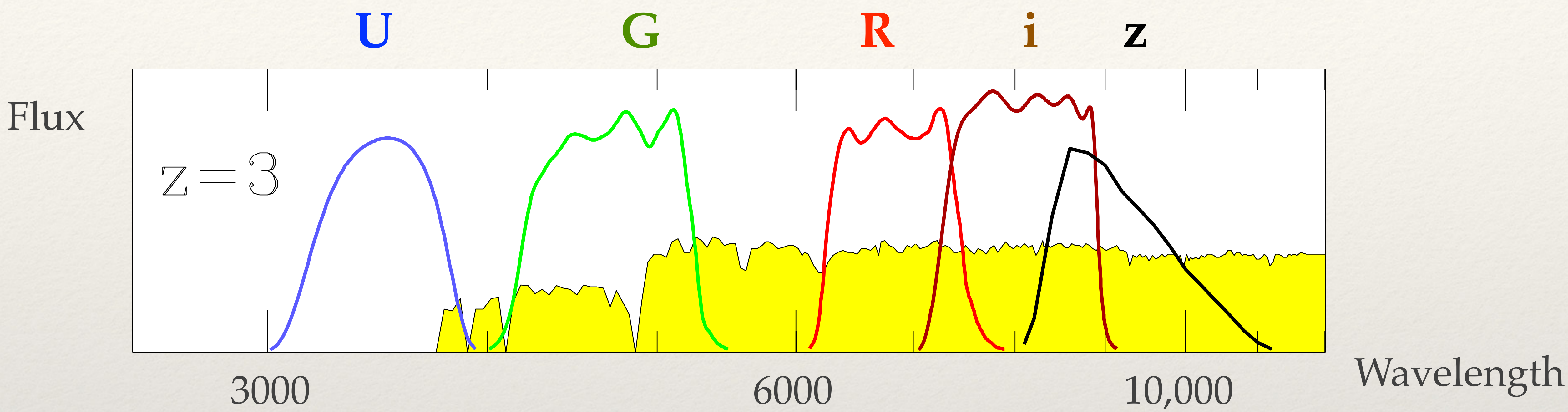


U G R i z

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)

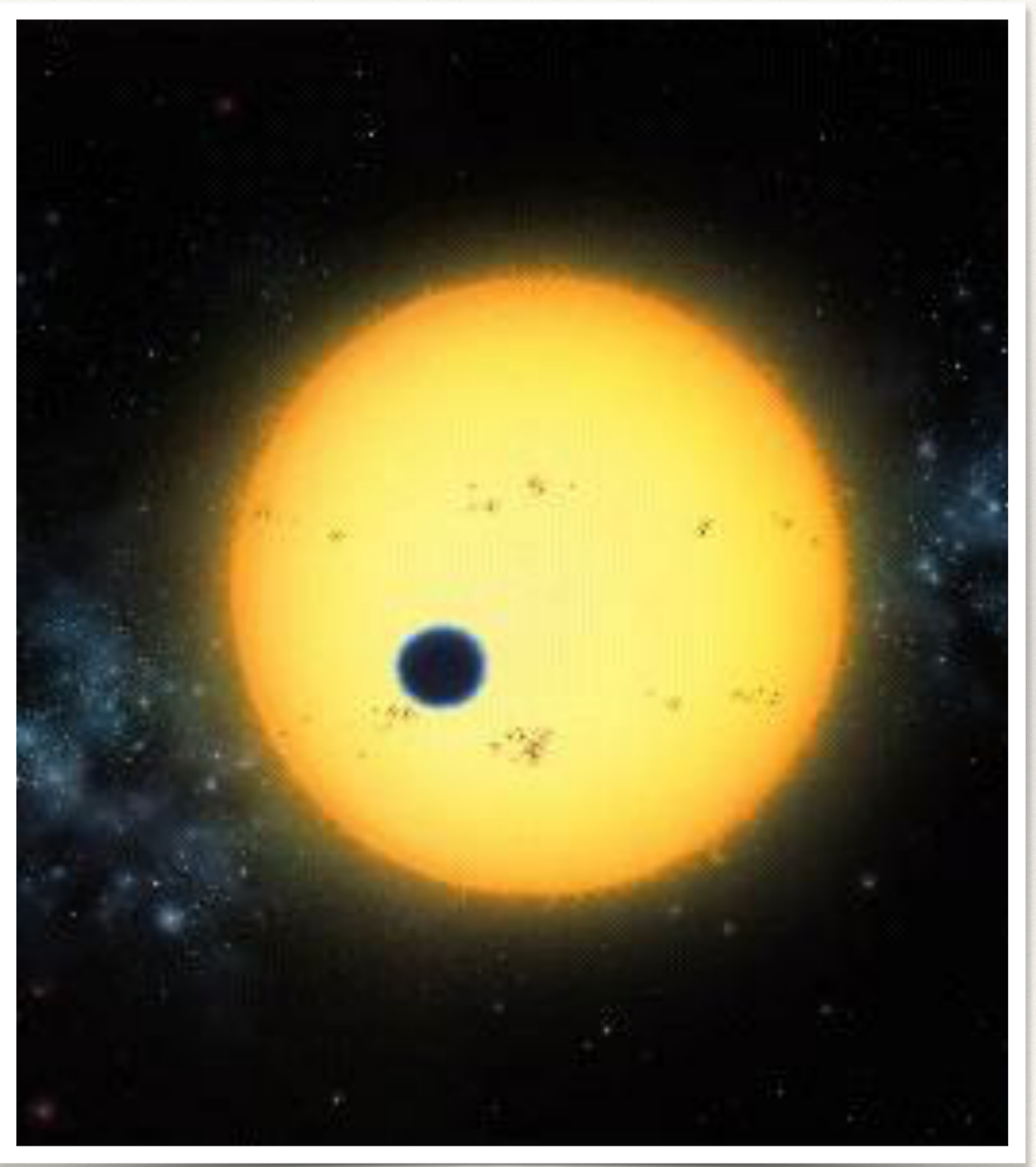
Galaxies found using this method are called 'Lyman-Break' Galaxies (LBGs)

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)

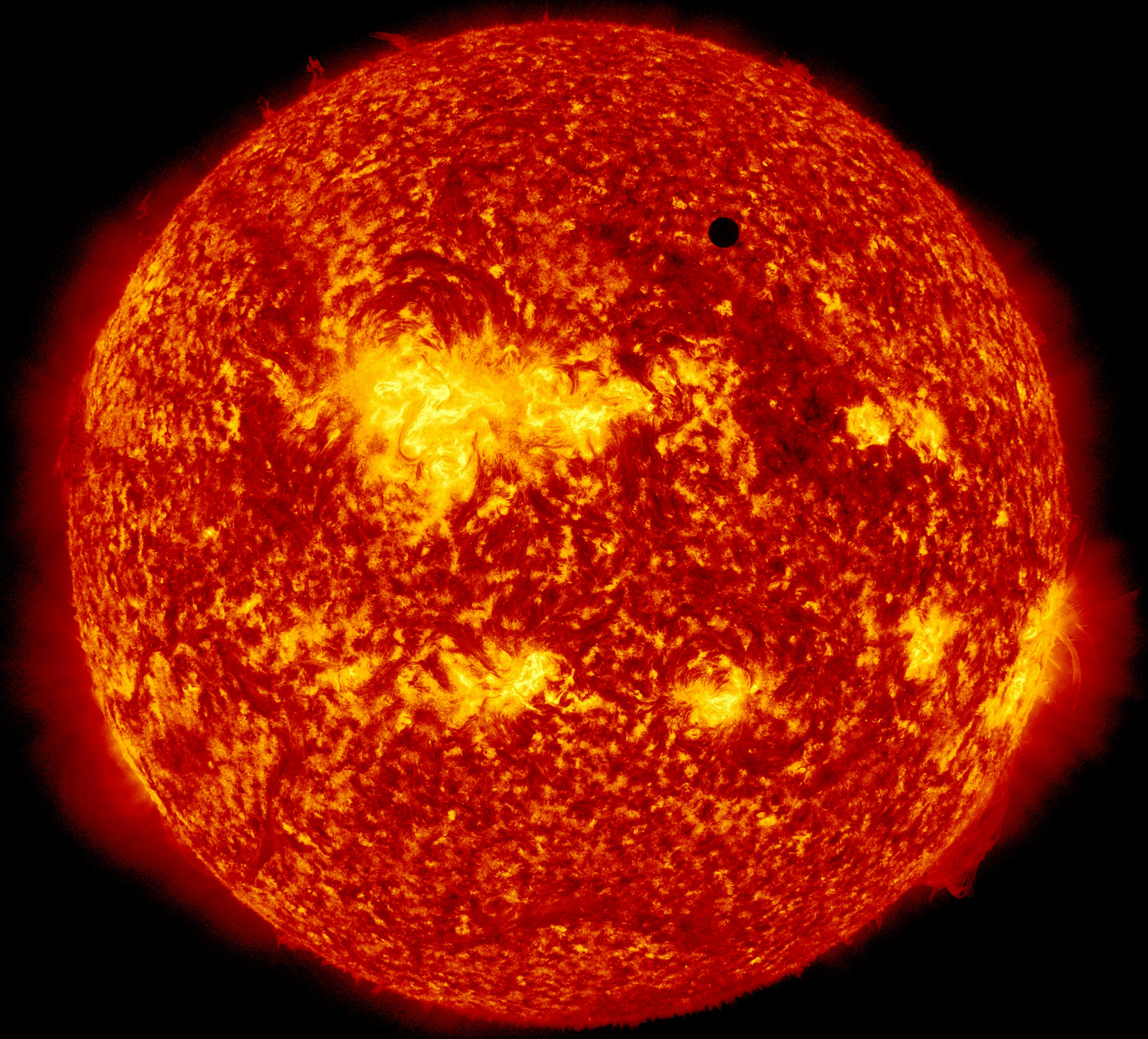
At the highest redshifts (dropouts in very red bands), galaxies are too faint for spectroscopy

Detecting transiting exoplanets

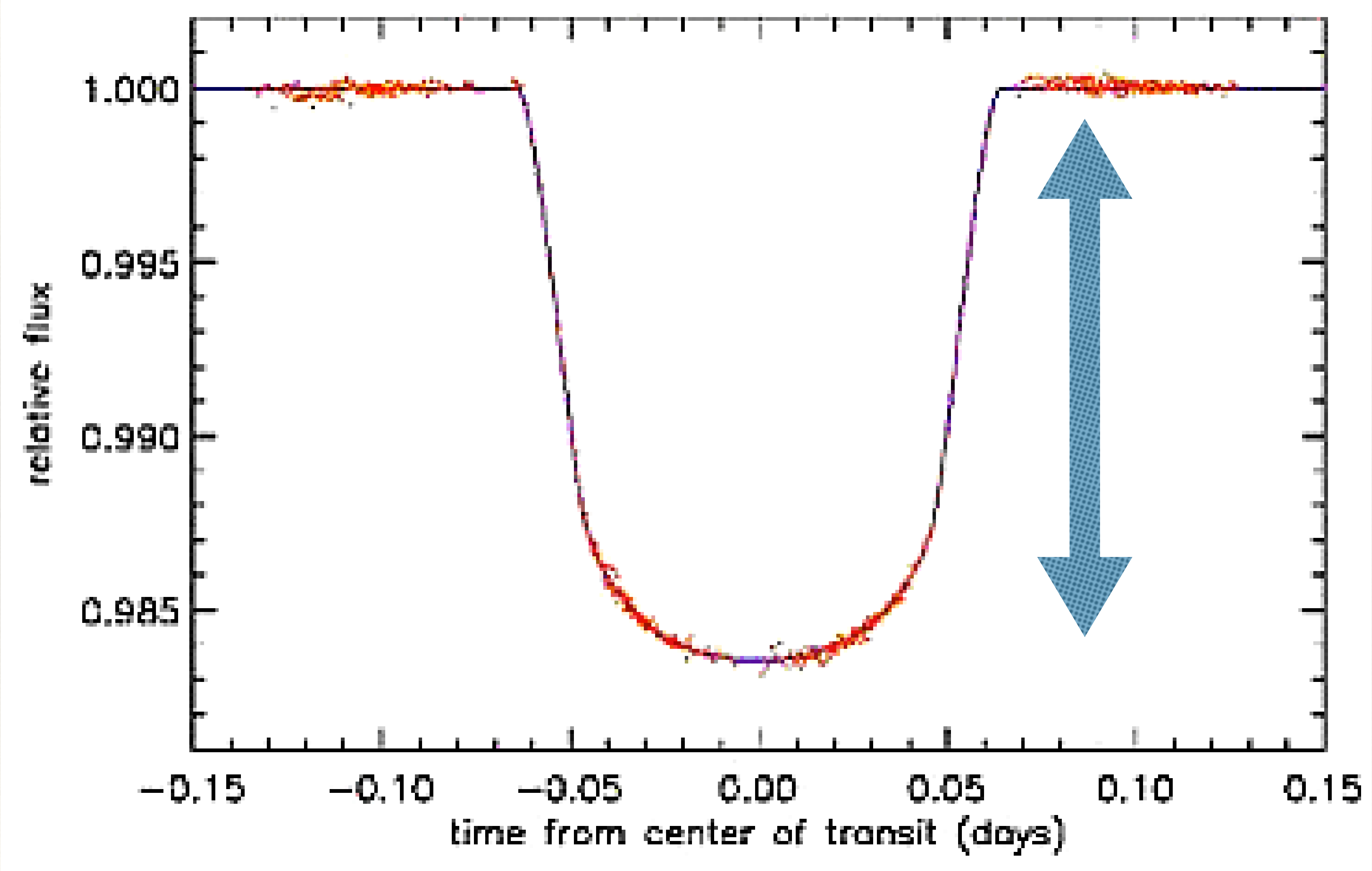
- Using very high precision photometry, it's possible to detect transiting exoplanets
- Method relies on detecting a drop in stellar flux as the exoplanet transits the star
- Drop in flux depends on star/planet radius ratio, and is typically tiny: $(R\_jupiter/R\_sun)^2 = 1\%$



Transit of Venus



Detecting transiting exoplanets



Flux drop =1.6%

Detecting transiting exoplanets

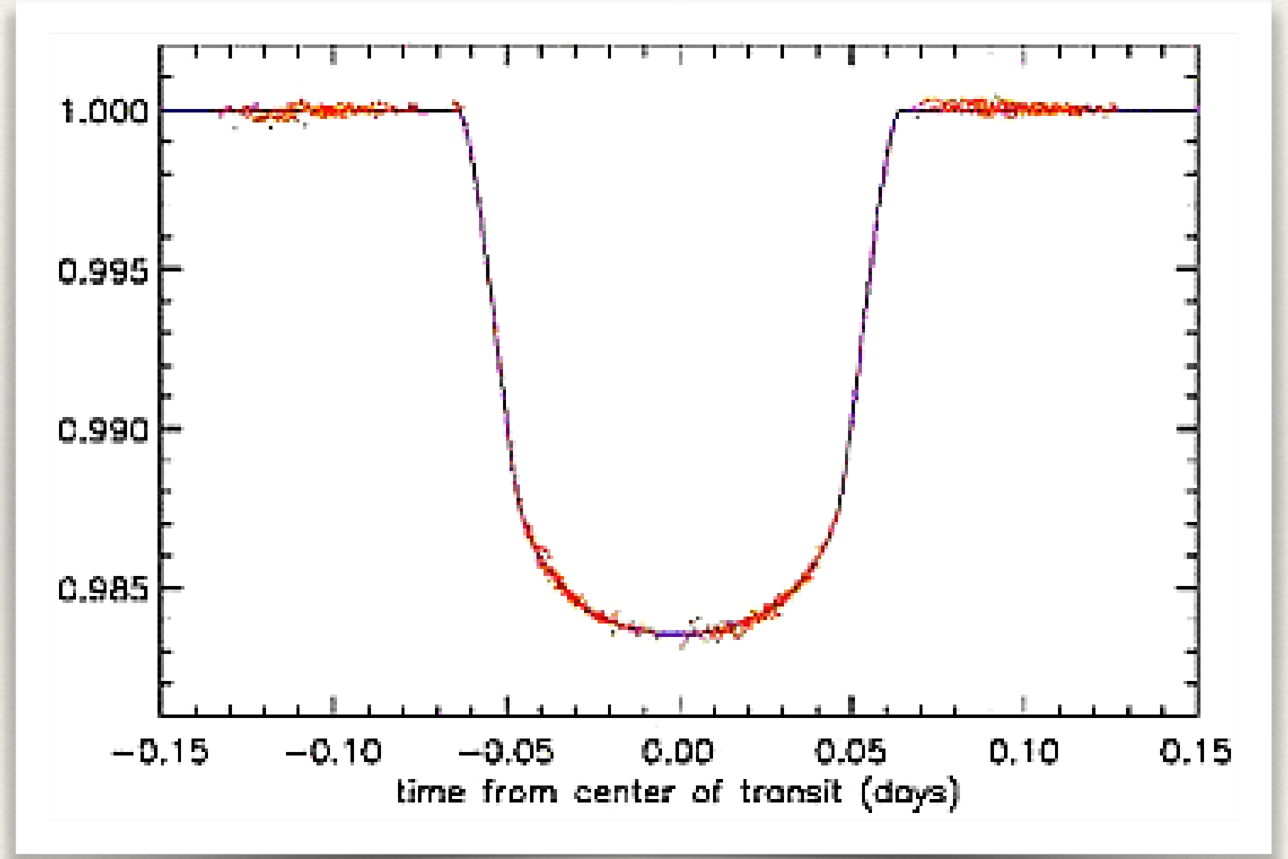
Flux drop depends on ratio of star/ planet radii

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

$$R_P = 0.13\ R_S$$

Star is G0V, R ~ 1.15 R_sun

$$R_P = 0.16\ R_\odot$$



Detecting transiting exoplanets

Photometric transits are also useful for giving us
inclination angles

Detecting transiting exoplanets

Photometric transits are also useful for giving us *inclination angles*

Planetary masses are measuring using ‘doppler wobble’

Detecting transiting exoplanets

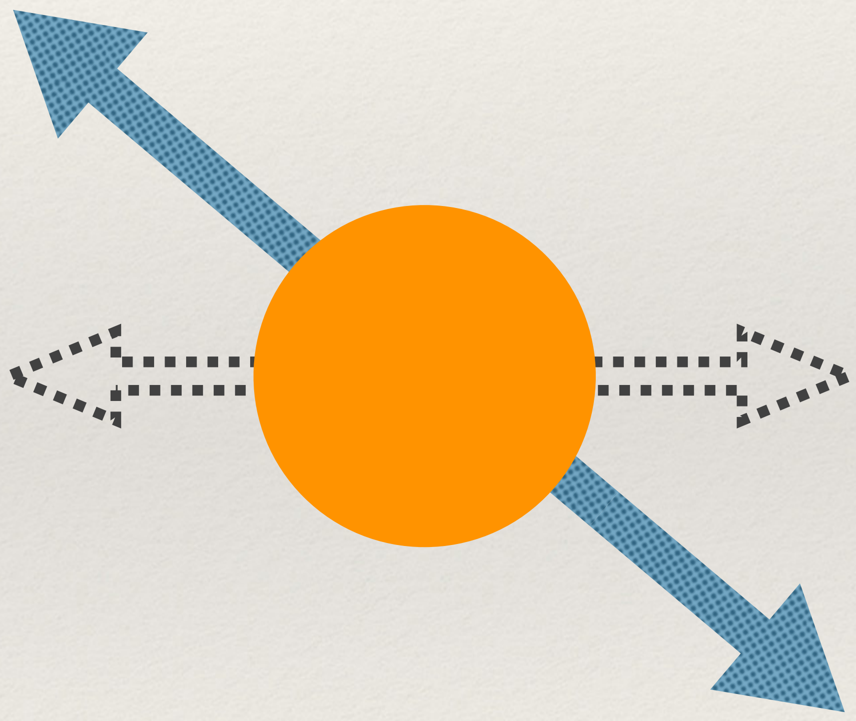
Photometric transits are also useful for giving us
inclination angles

Planetary masses are measuring using 'doppler wobble'

We only measure the *projection* of the
stellar movement onto our line of sight

Detecting transiting exoplanets

- For most doppler-measured masses, we can only measure (M sin *i*)
- But, if exoplanets are transiting, then $i \sim 90^o$
- So, we get mass (as *i* is known) and radius (from flux drop).
- Therefore we get radius (tells us composition)



Also… pretty pictures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Optical astronomy (II)

- Photometry
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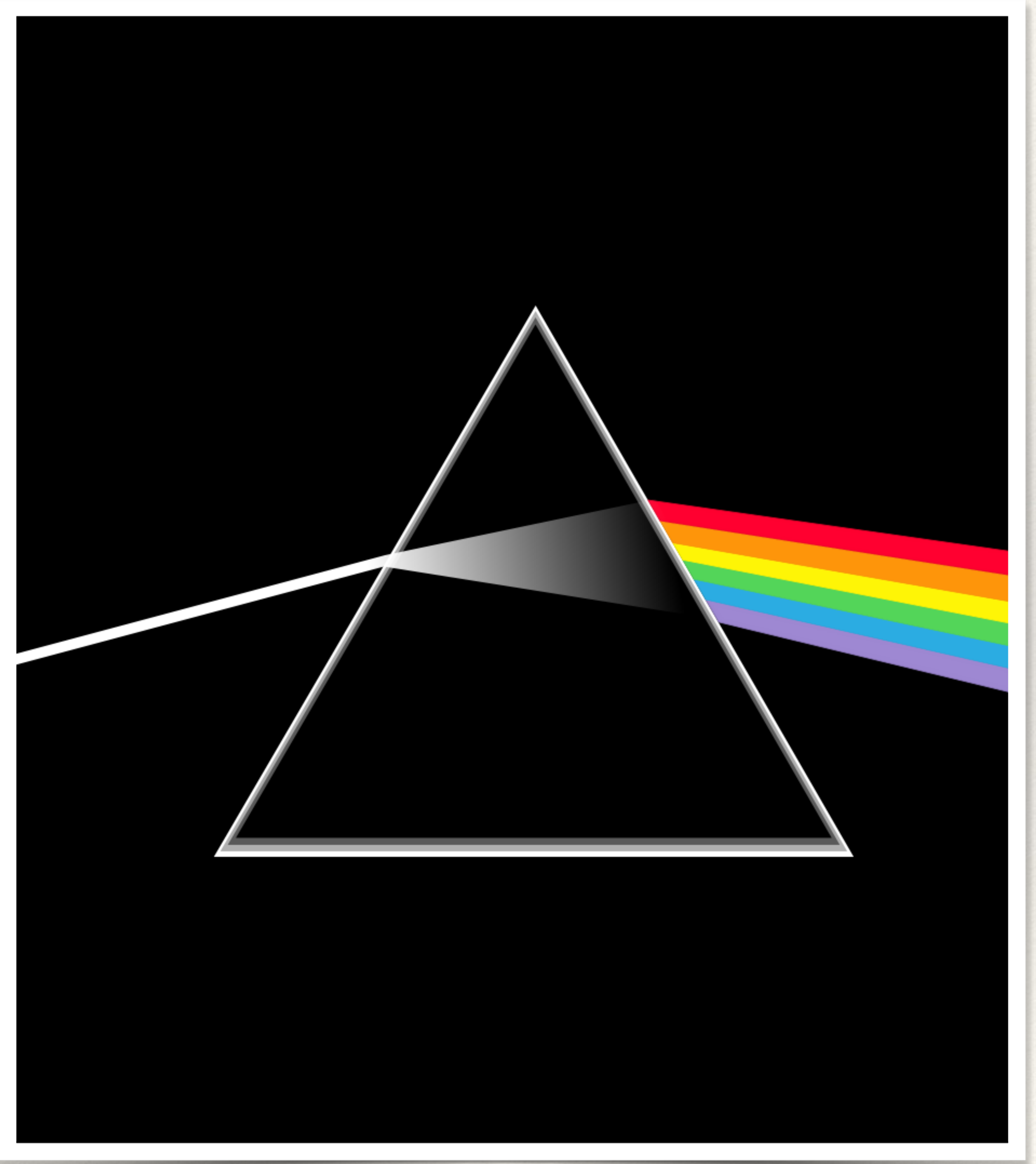
Spectroscopy

- Spectroscopy involves splitting light at wavelength λ 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



Spectroscopy

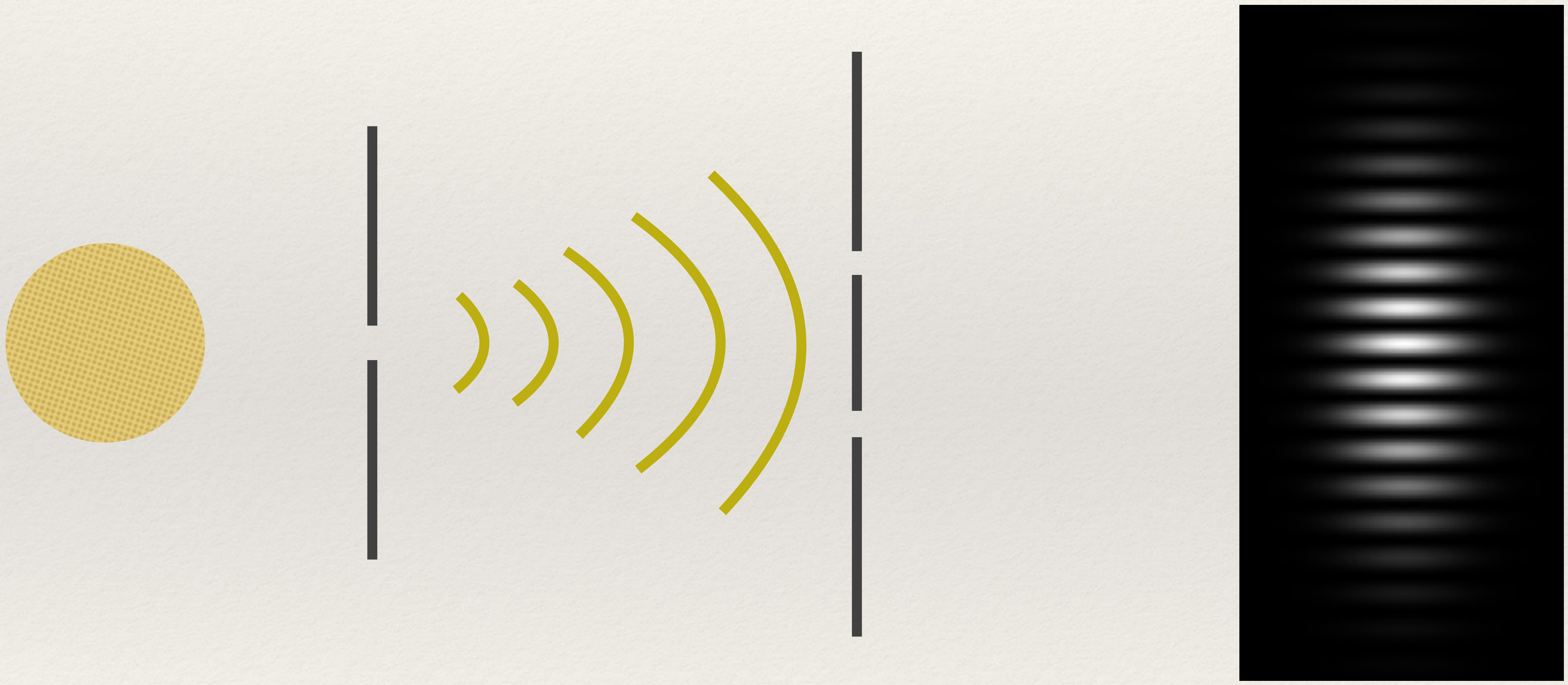
Two main mechanisms for dispersing light for spectroscopy:

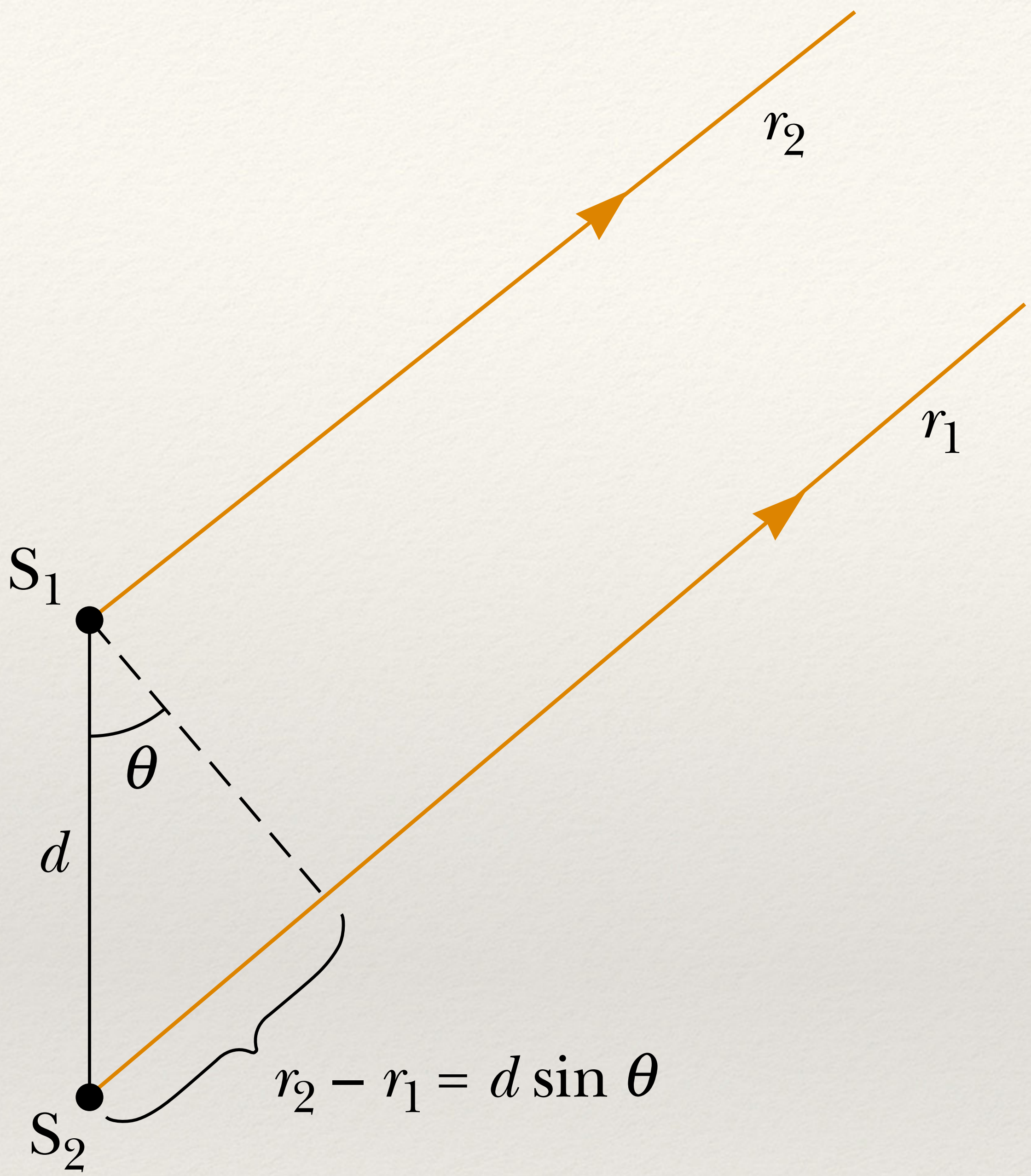
(1) Refraction (i.e., prisms). Not much used in modern astronomy

(2) Interference (based on phase-delay). Diffraction gratings are built on this principle

Diffraction gratings

Young's "two slit experiment"





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

= constructive interference.
Bright patch

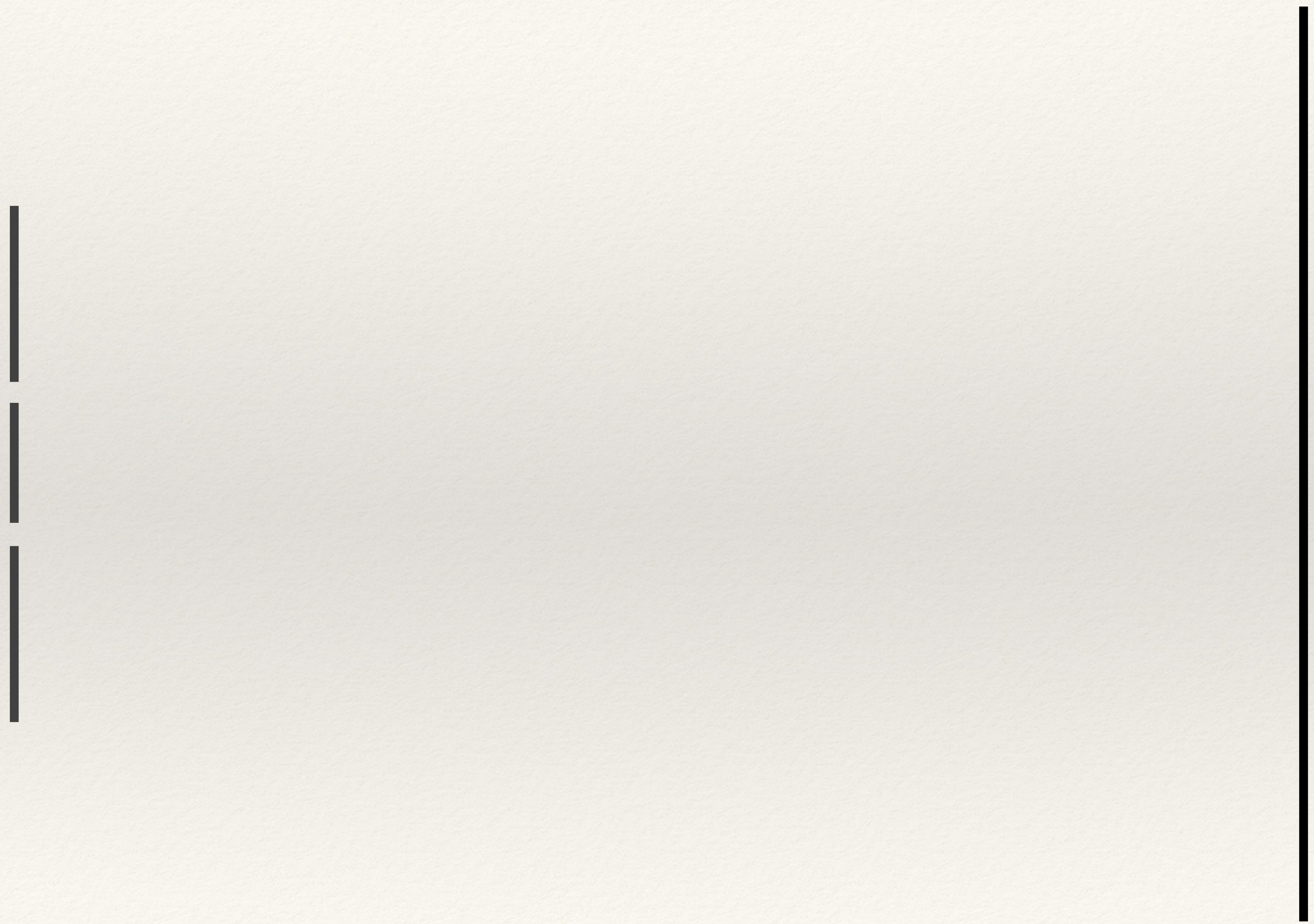
$$d \sin \theta = (m + 1/2)\lambda$$

= destructive interference.
Dark patch

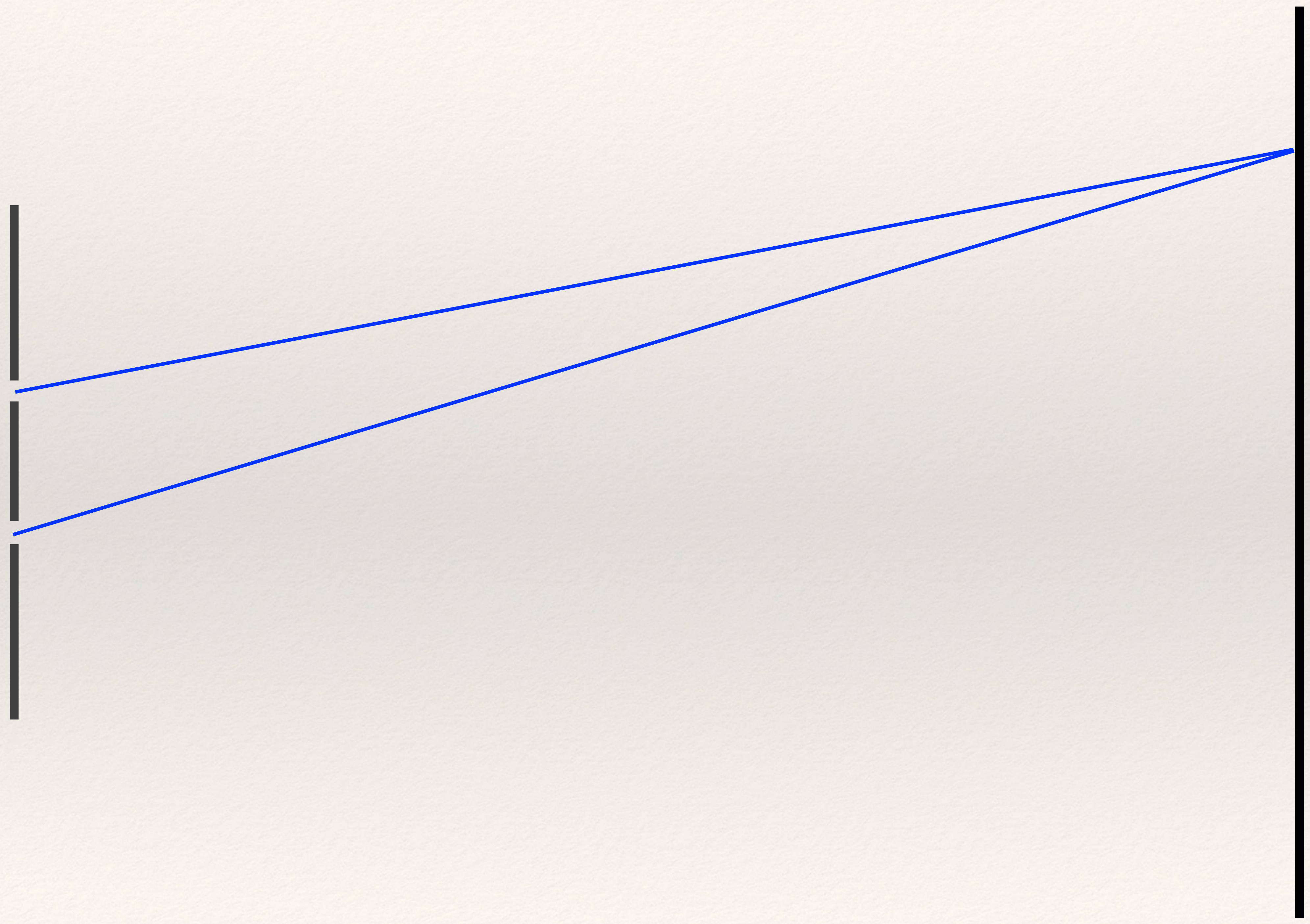
Diffraction gratings

Diffraction gratings

Diffraction gratings



Diffraction gratings



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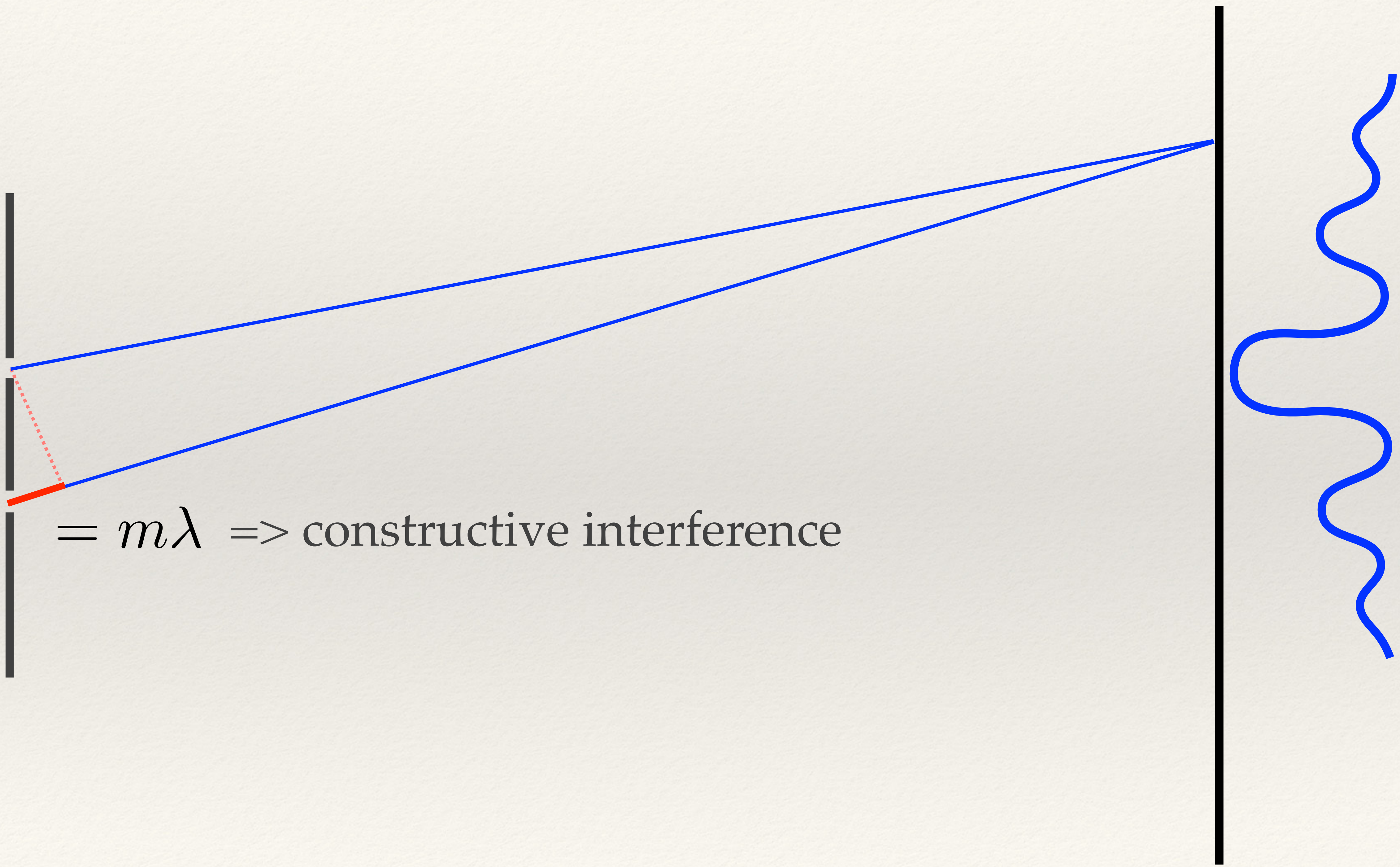

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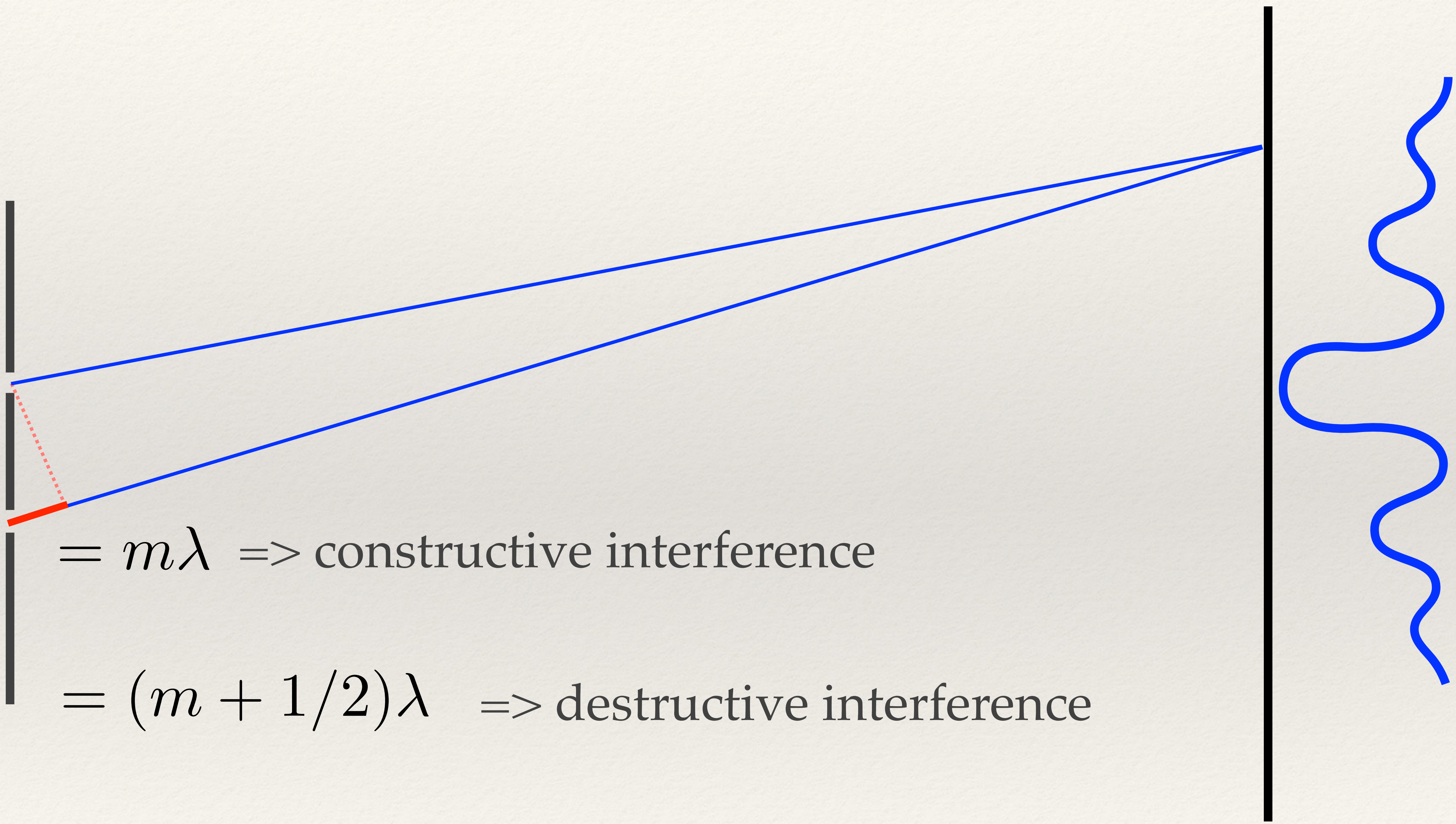


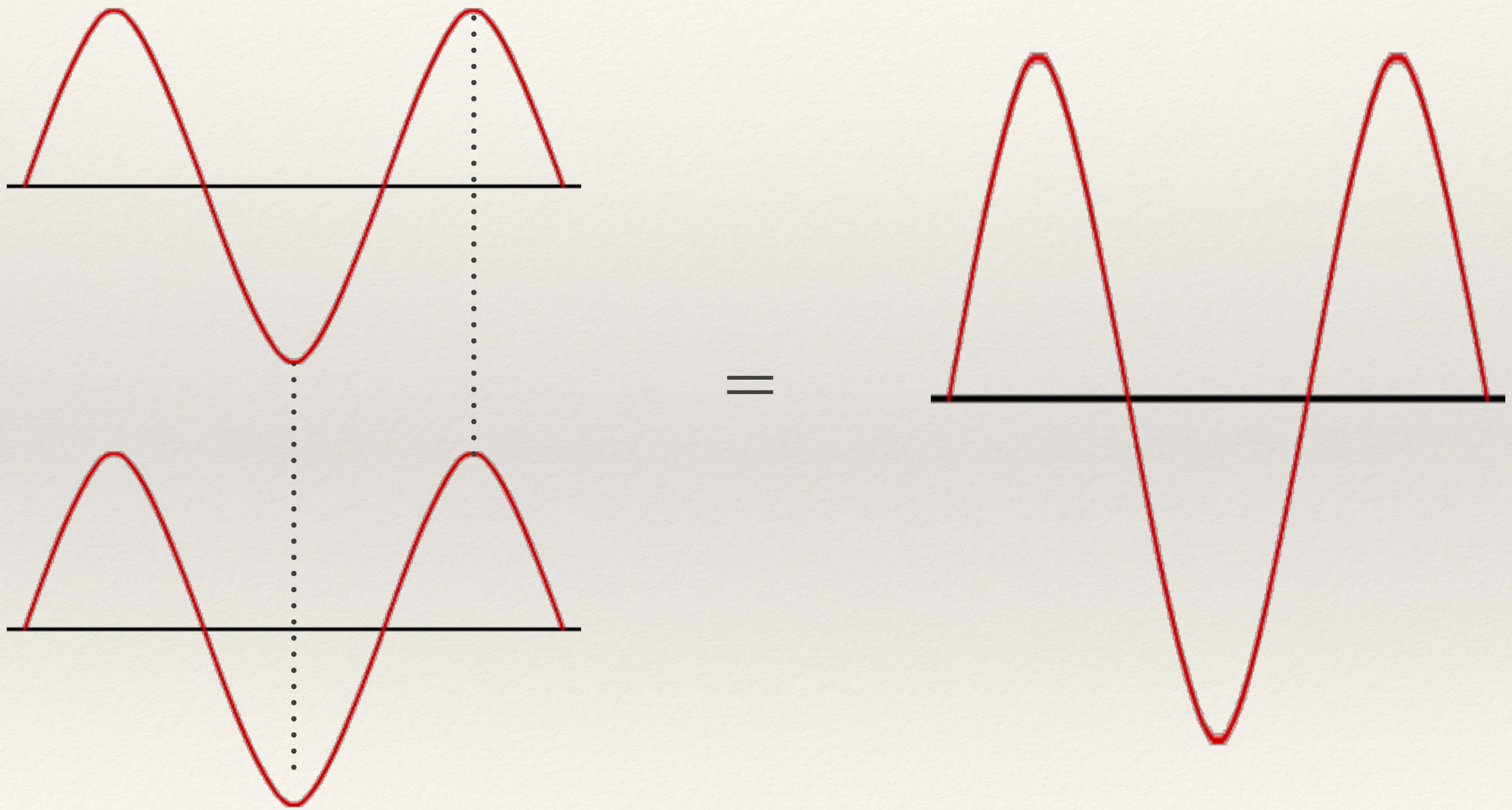
$= m\lambda$ => constructive interference

$= (m + 1/2)\lambda$ => destructive interference

There is a smooth transition between these two states

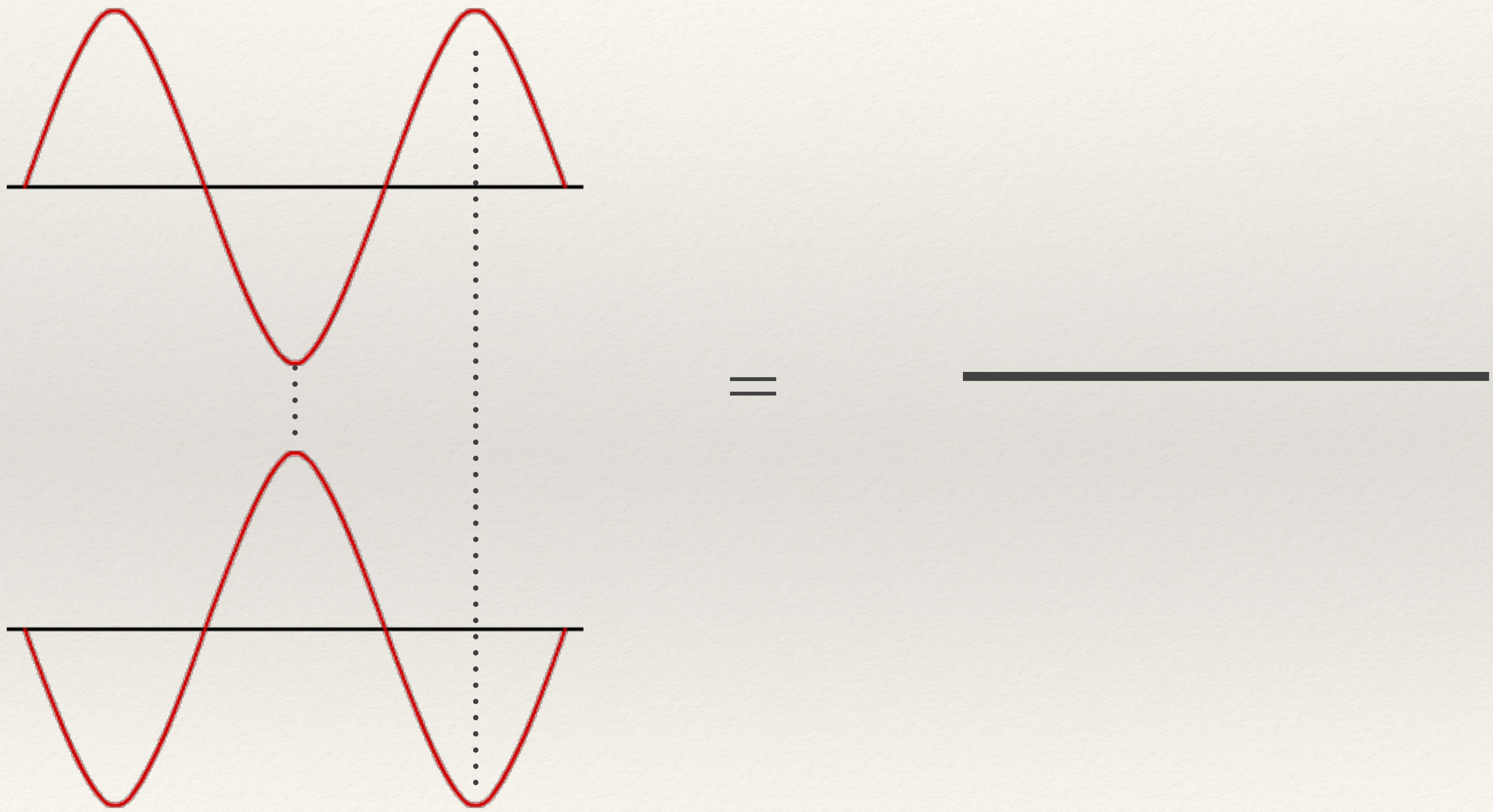
Diffraction gratings

$m\lambda$ => constructive interference



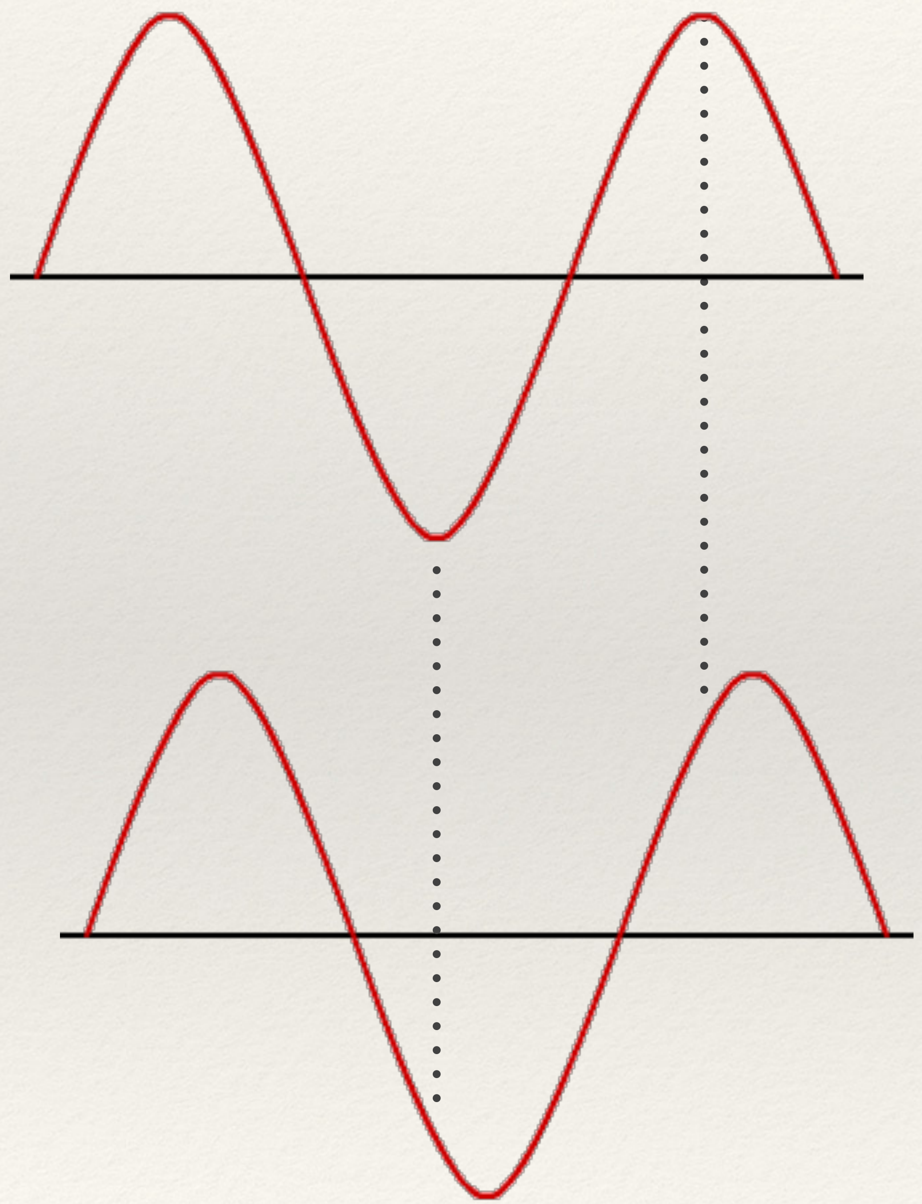
Diffraction gratings

$(m + 1/2)\lambda$ => destructive interference



Diffraction gratings

$(m + 1/10)\lambda$ => mostly constructive interference



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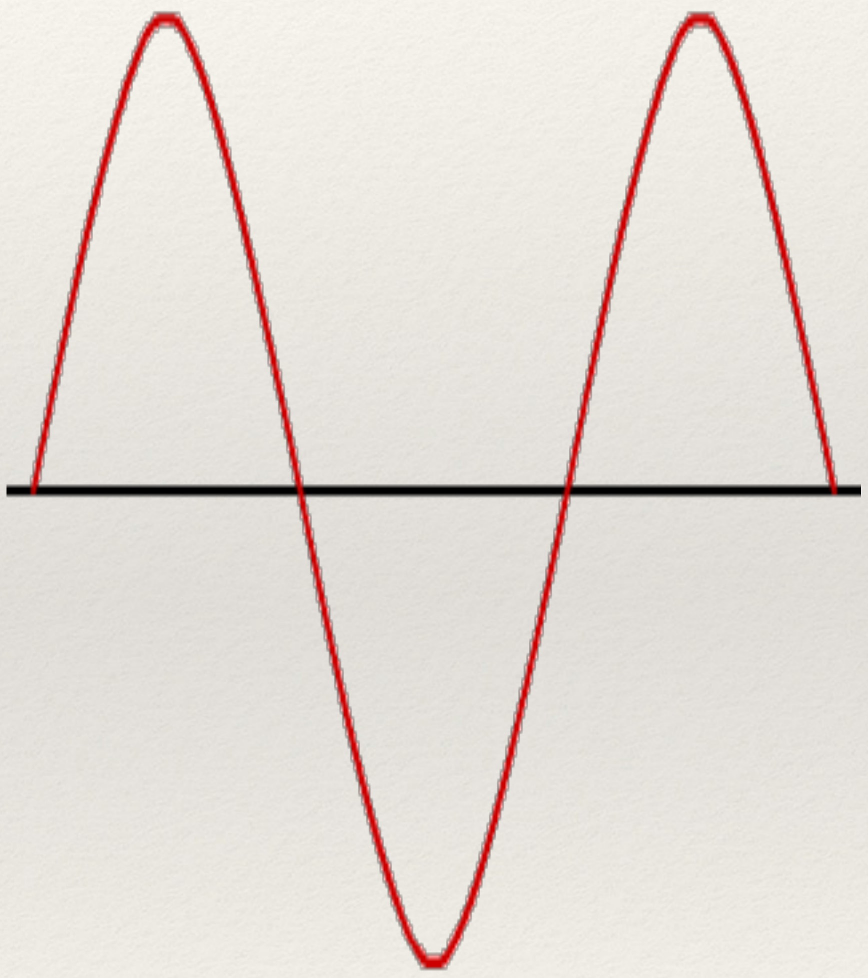
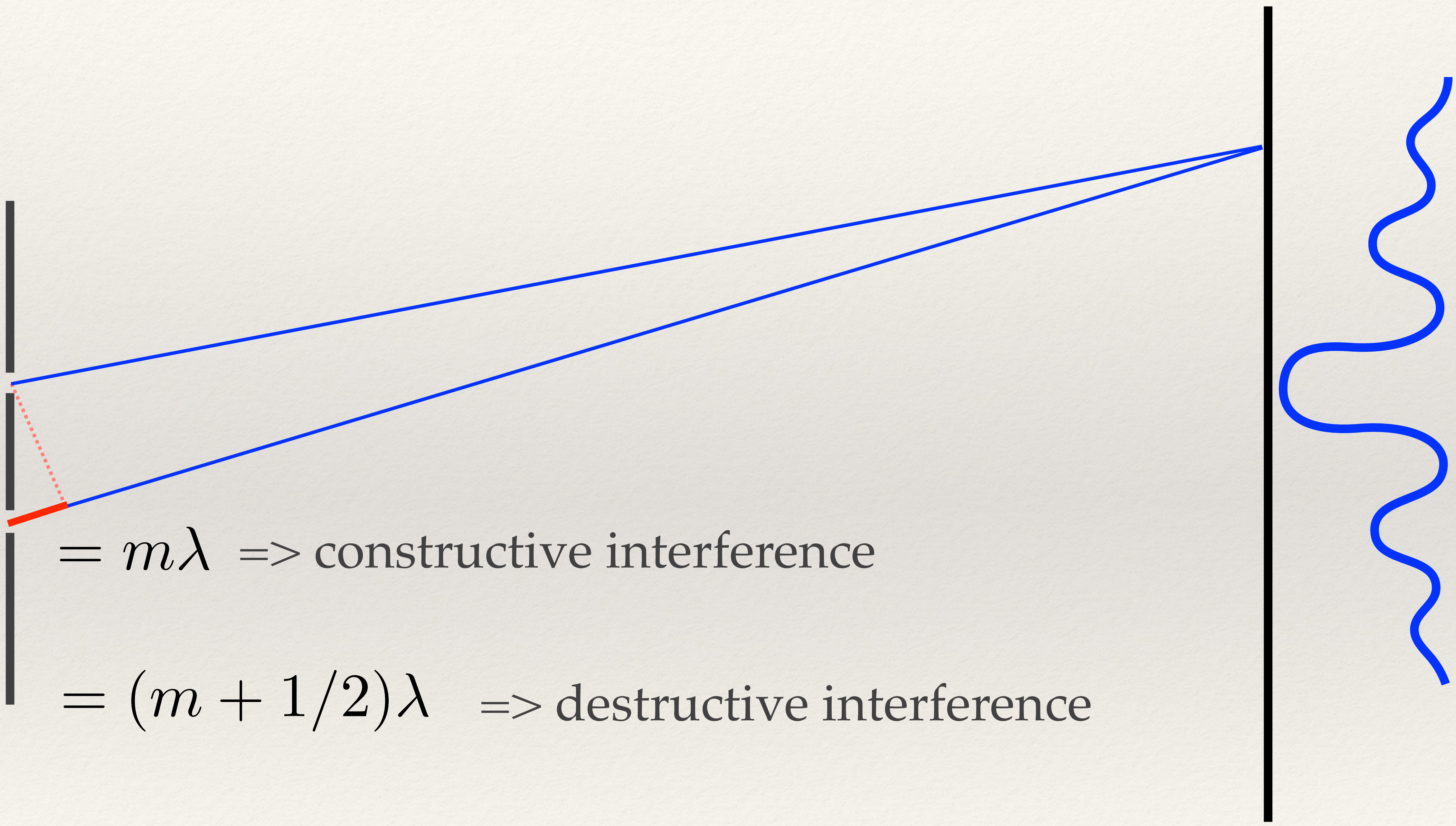


Diffraction gratings



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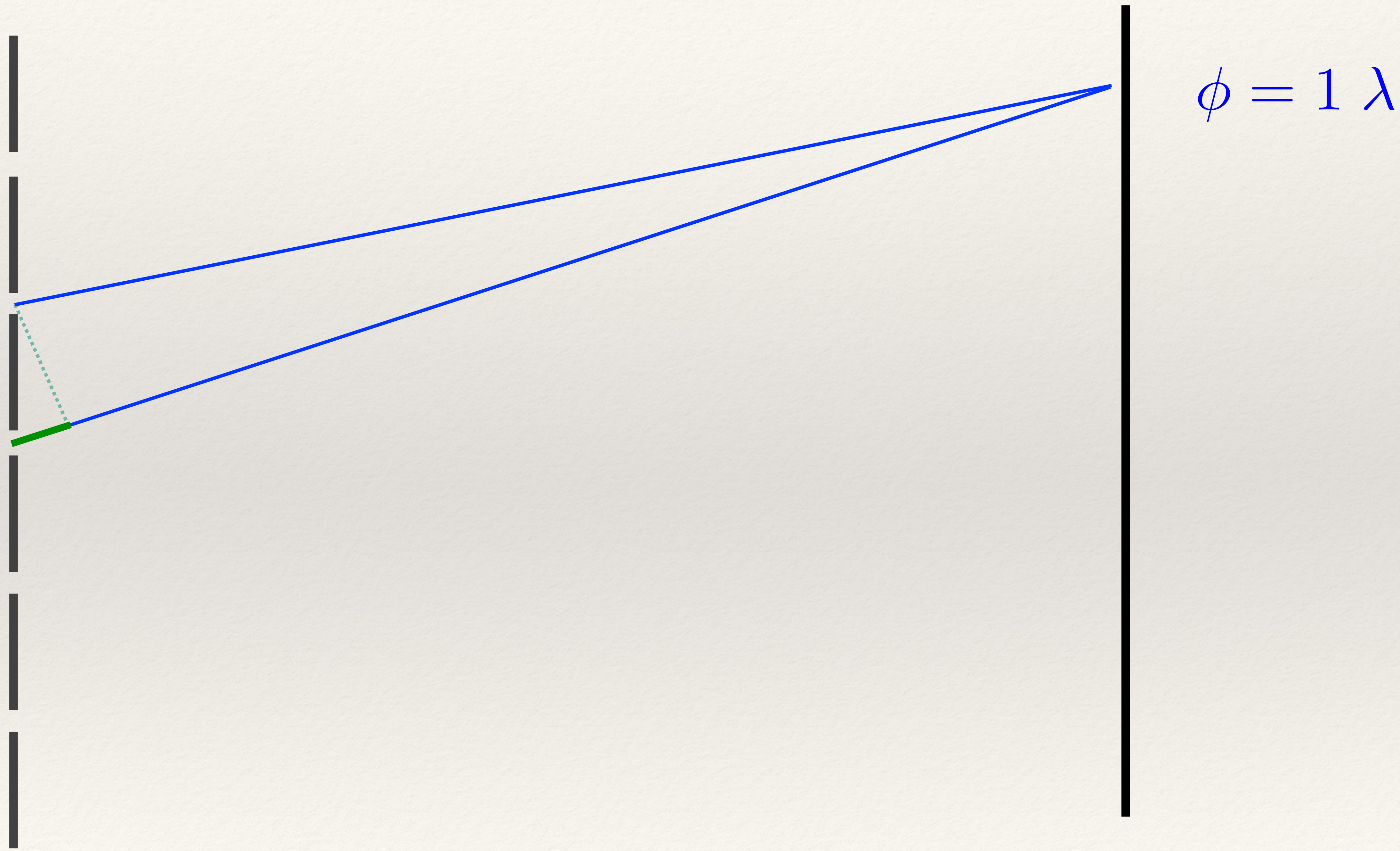
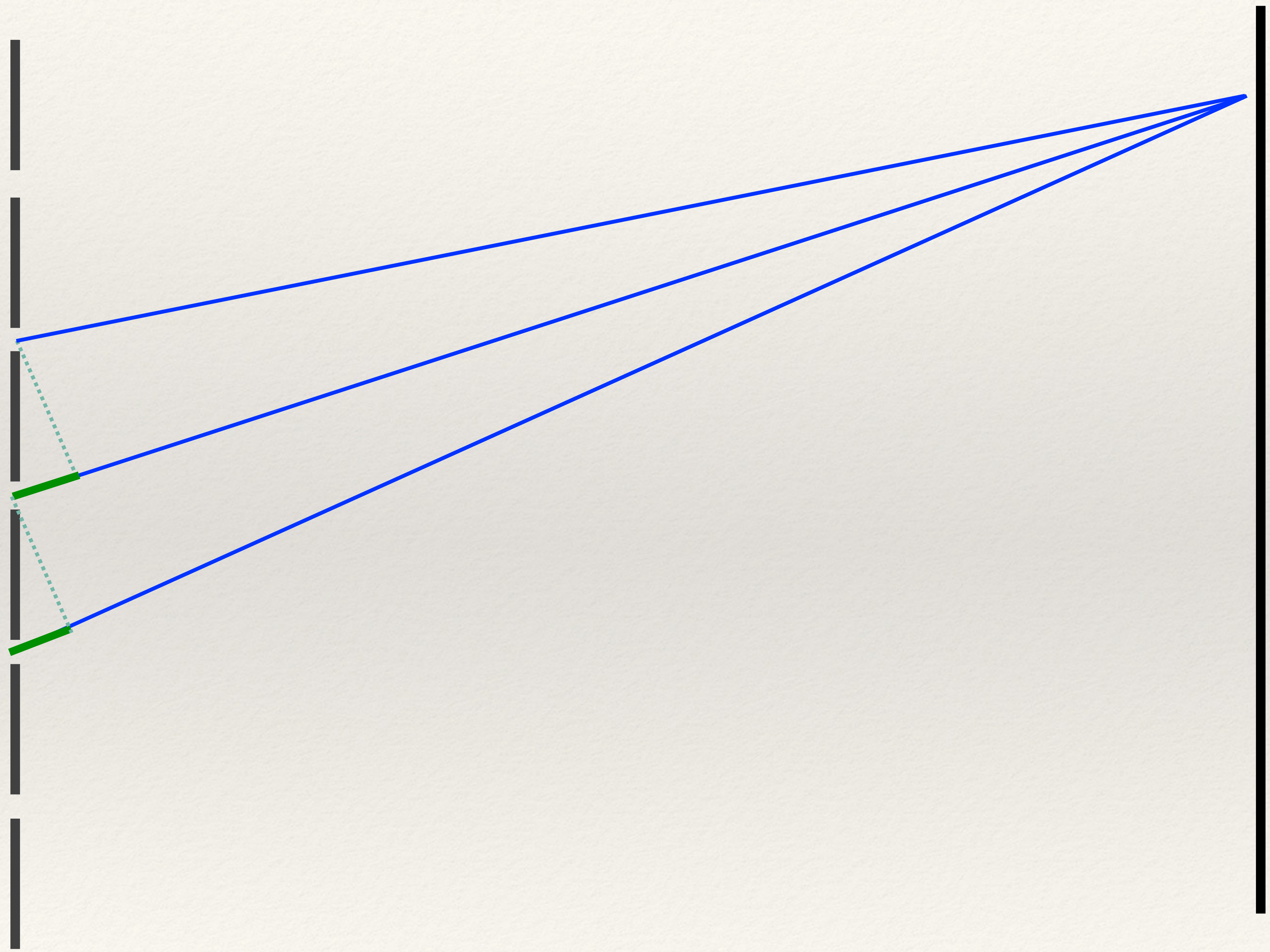
Diffraction gratings

Diffraction gratings



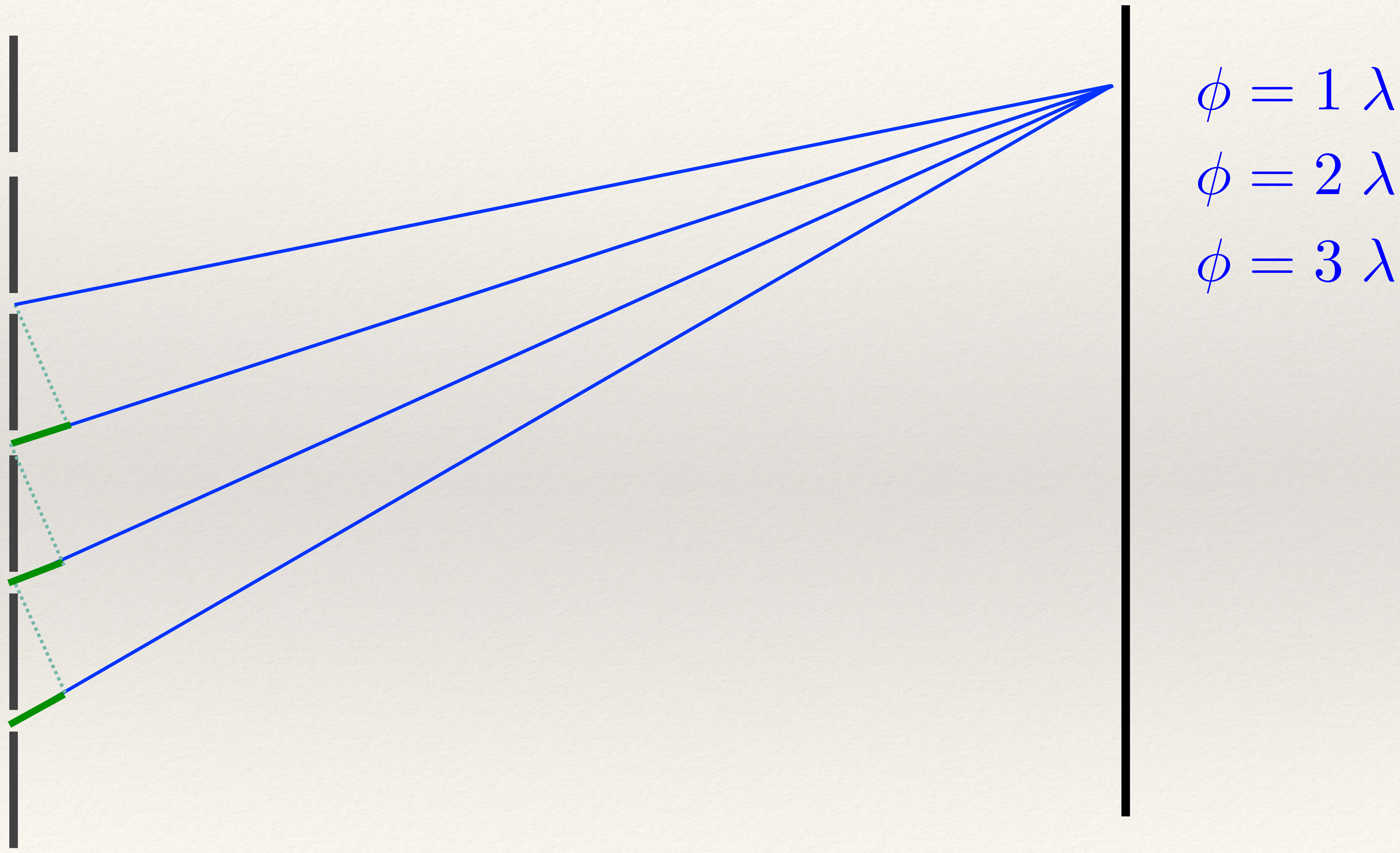
Diffraction gratings



$\phi = 1\ \lambda$

$\phi = 2\ \lambda$

Diffraction gratings



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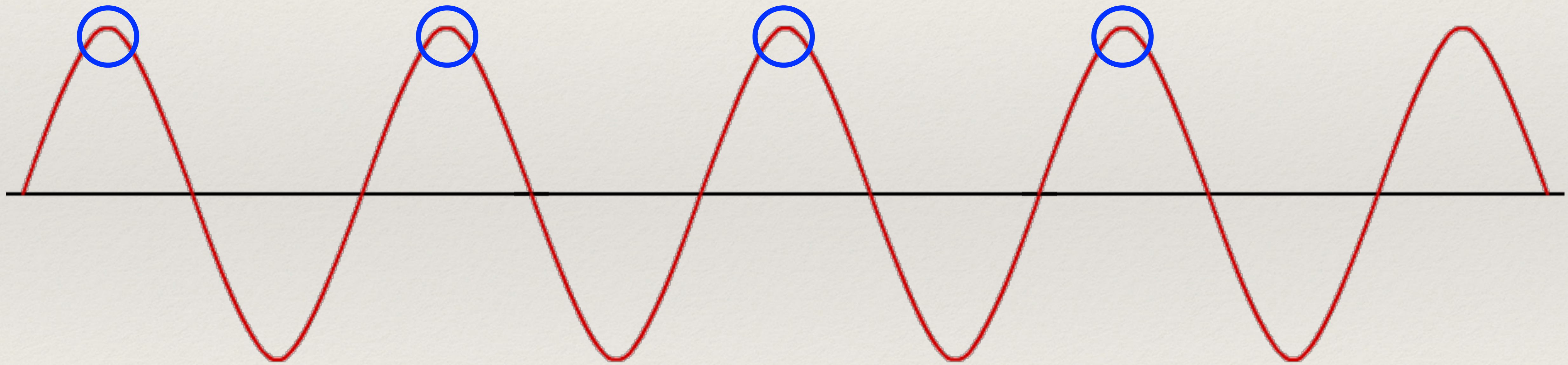

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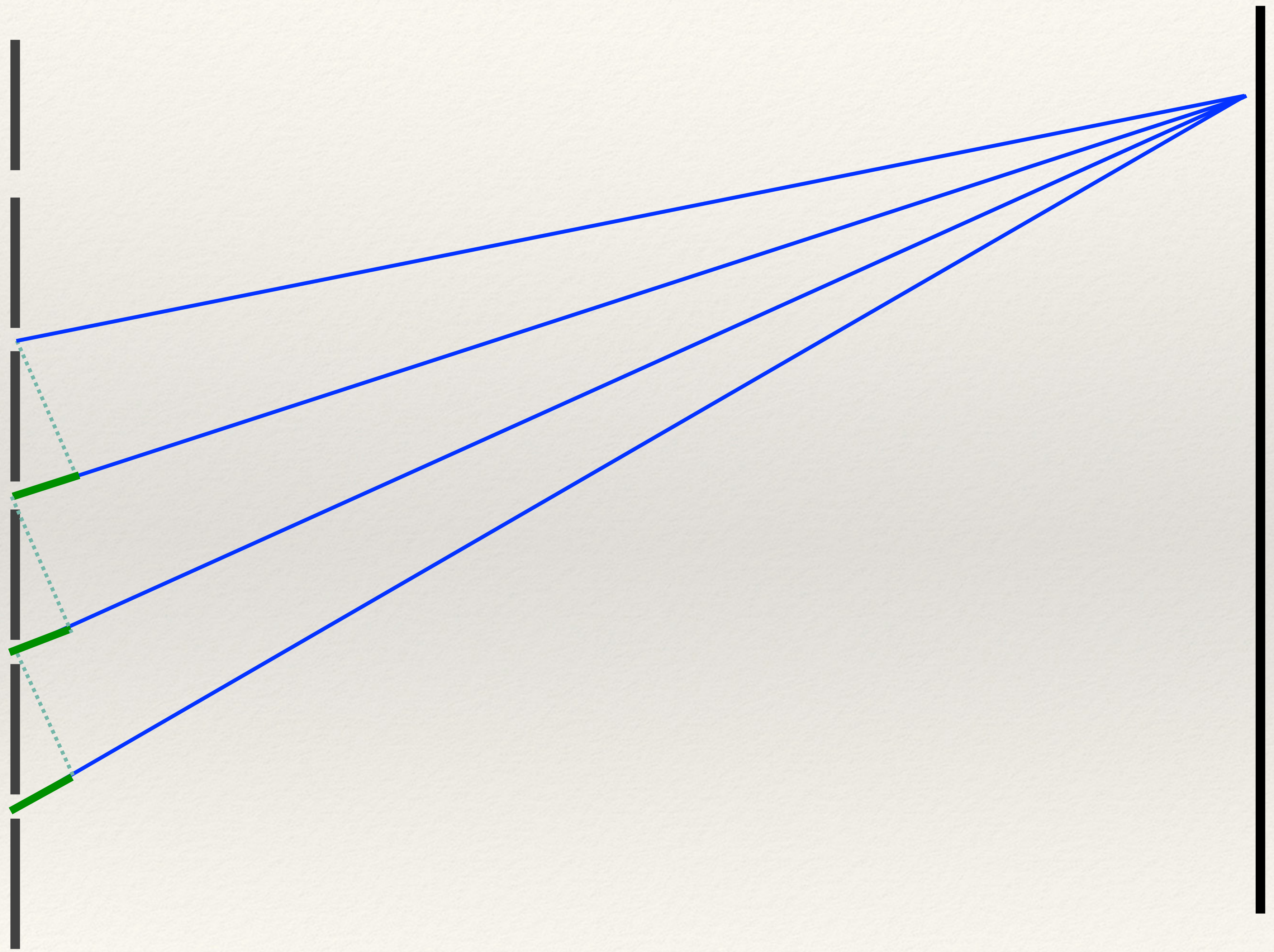

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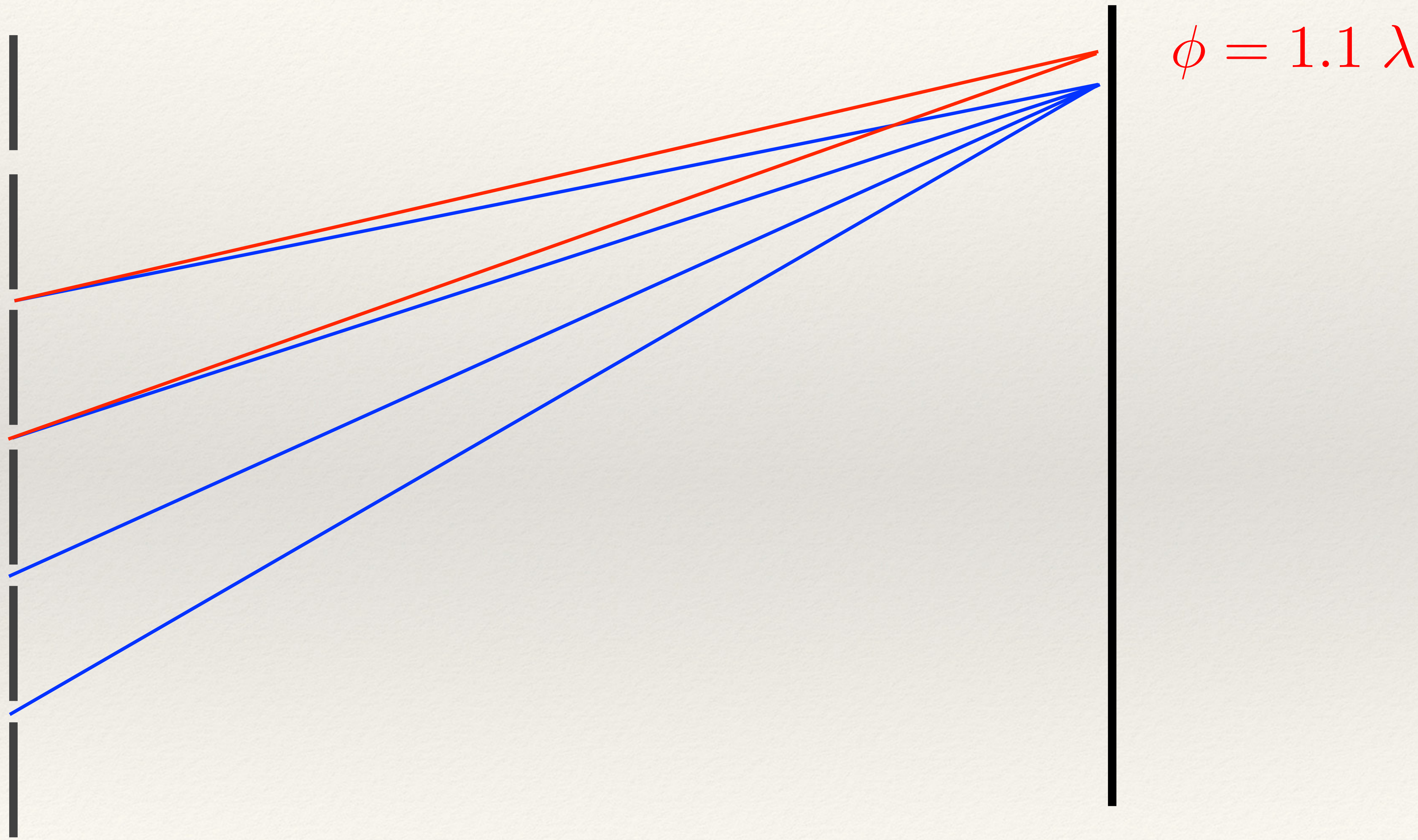

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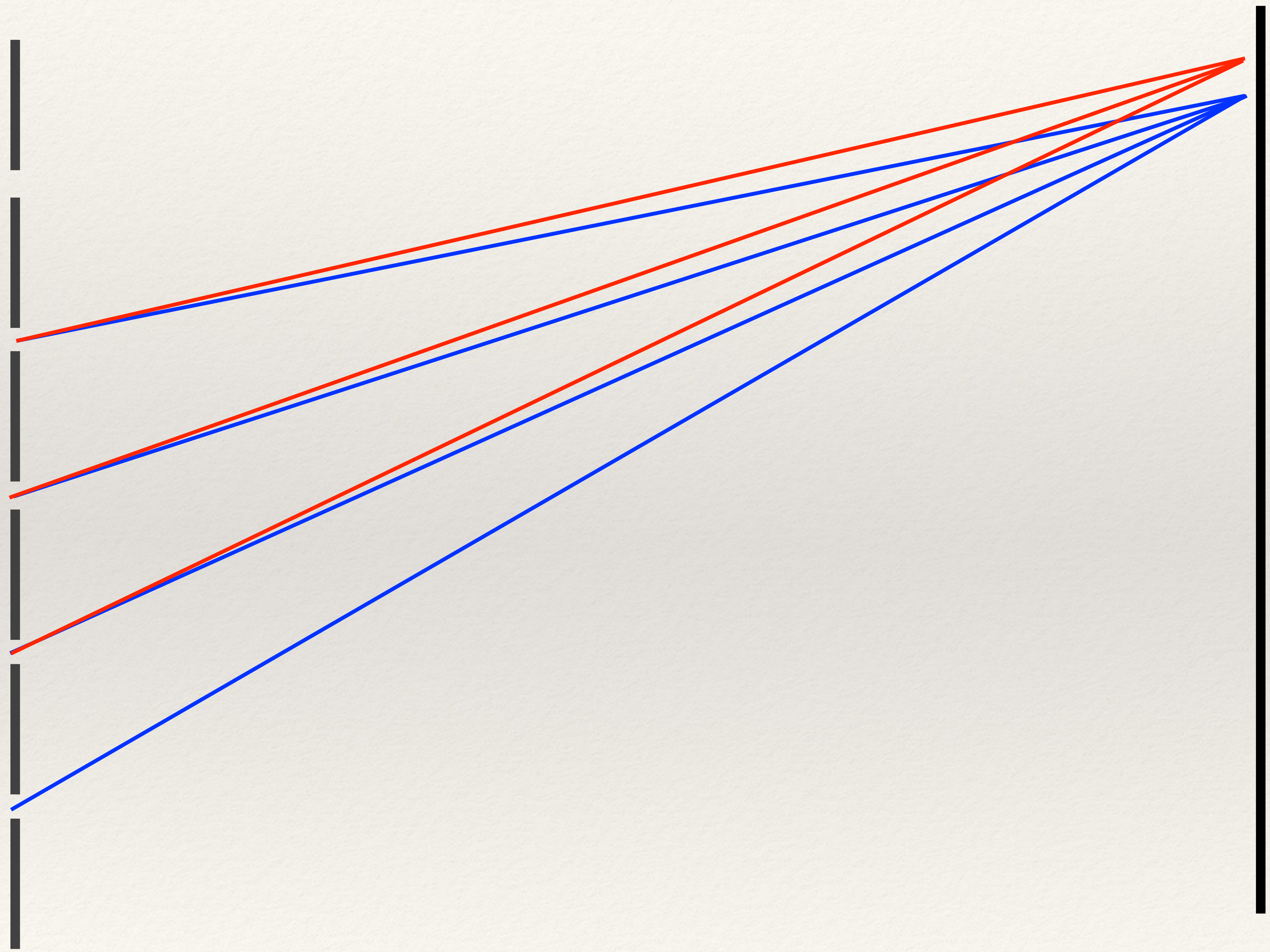

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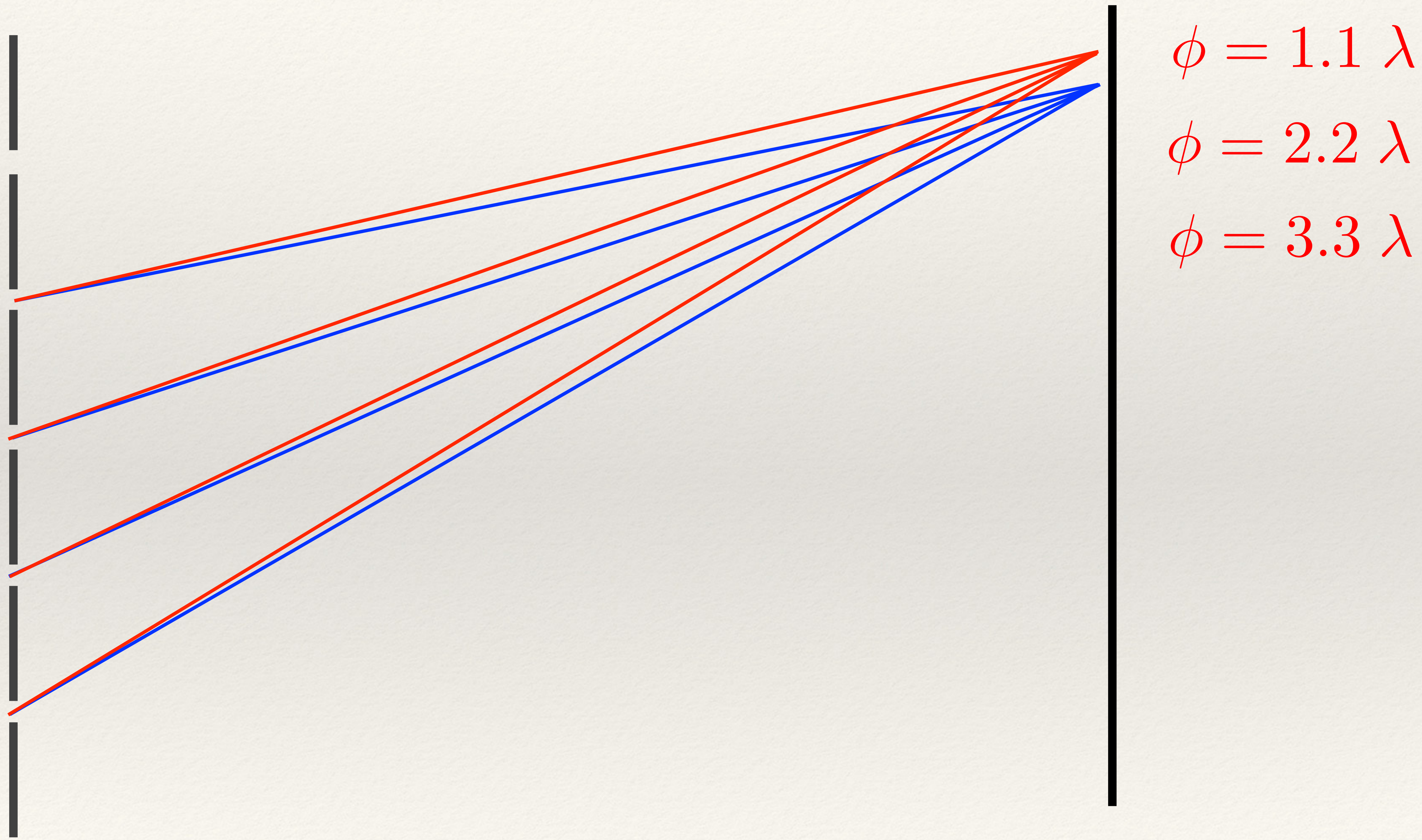

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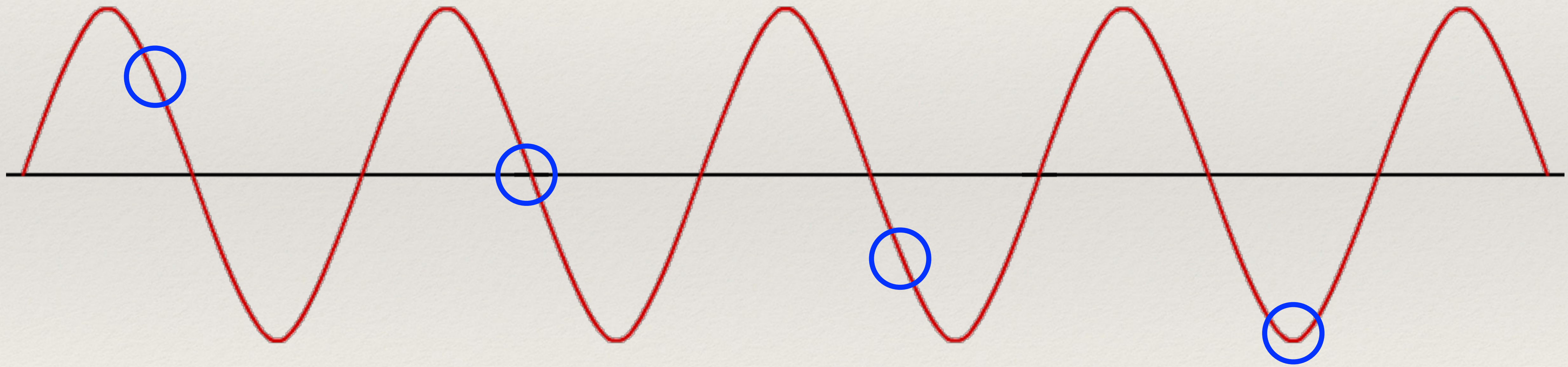

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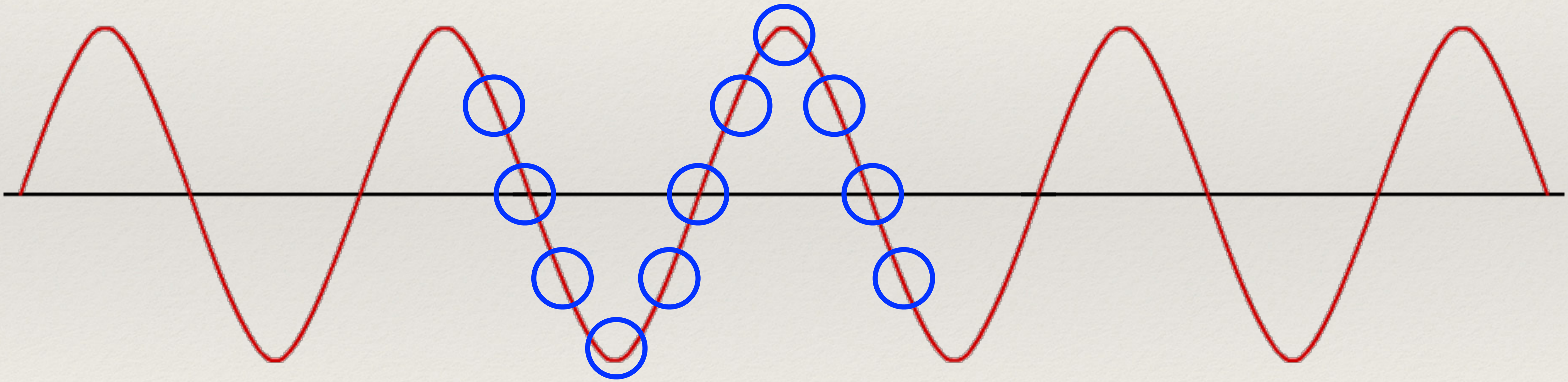

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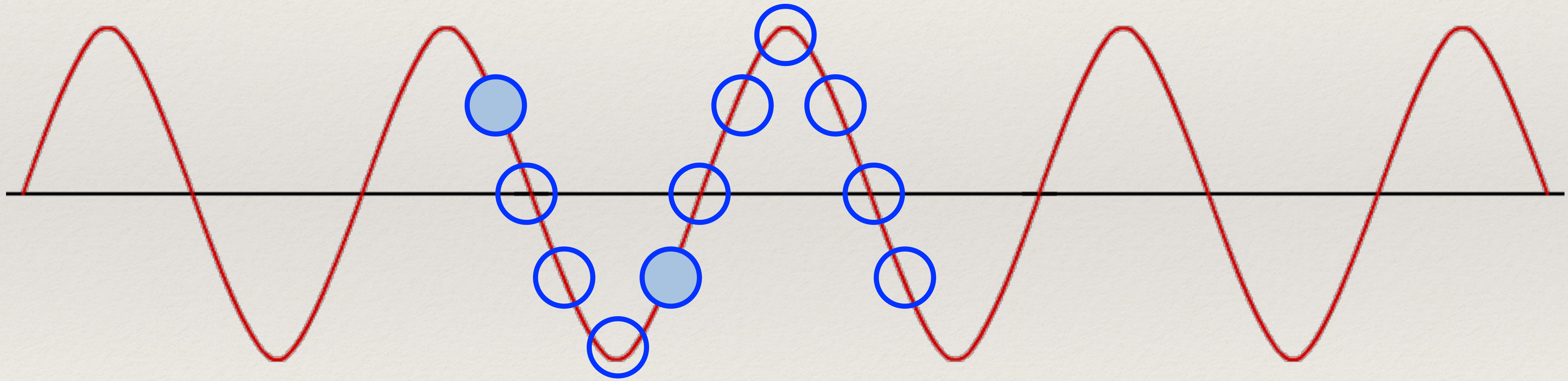
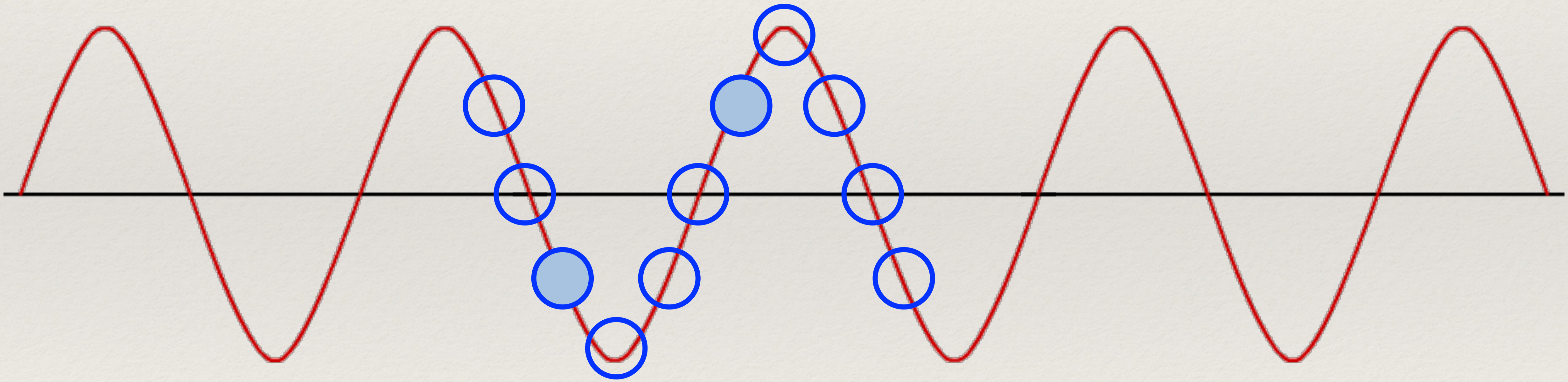


Diffraction gratings



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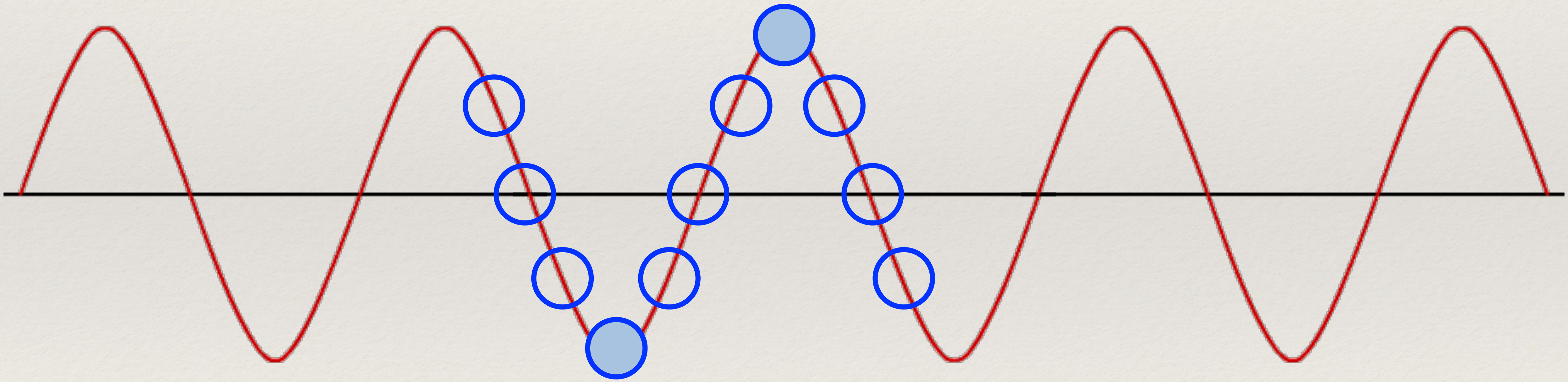
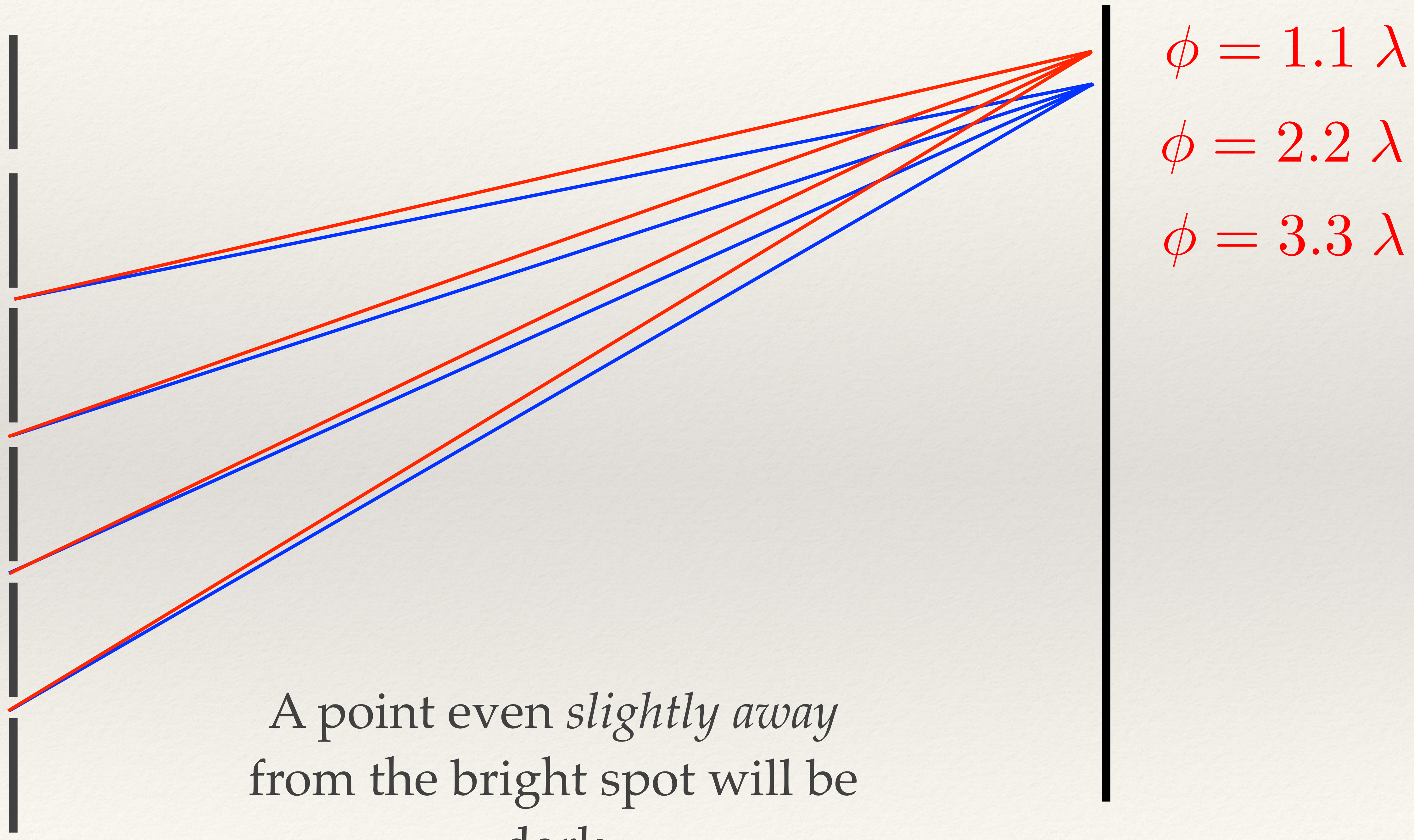
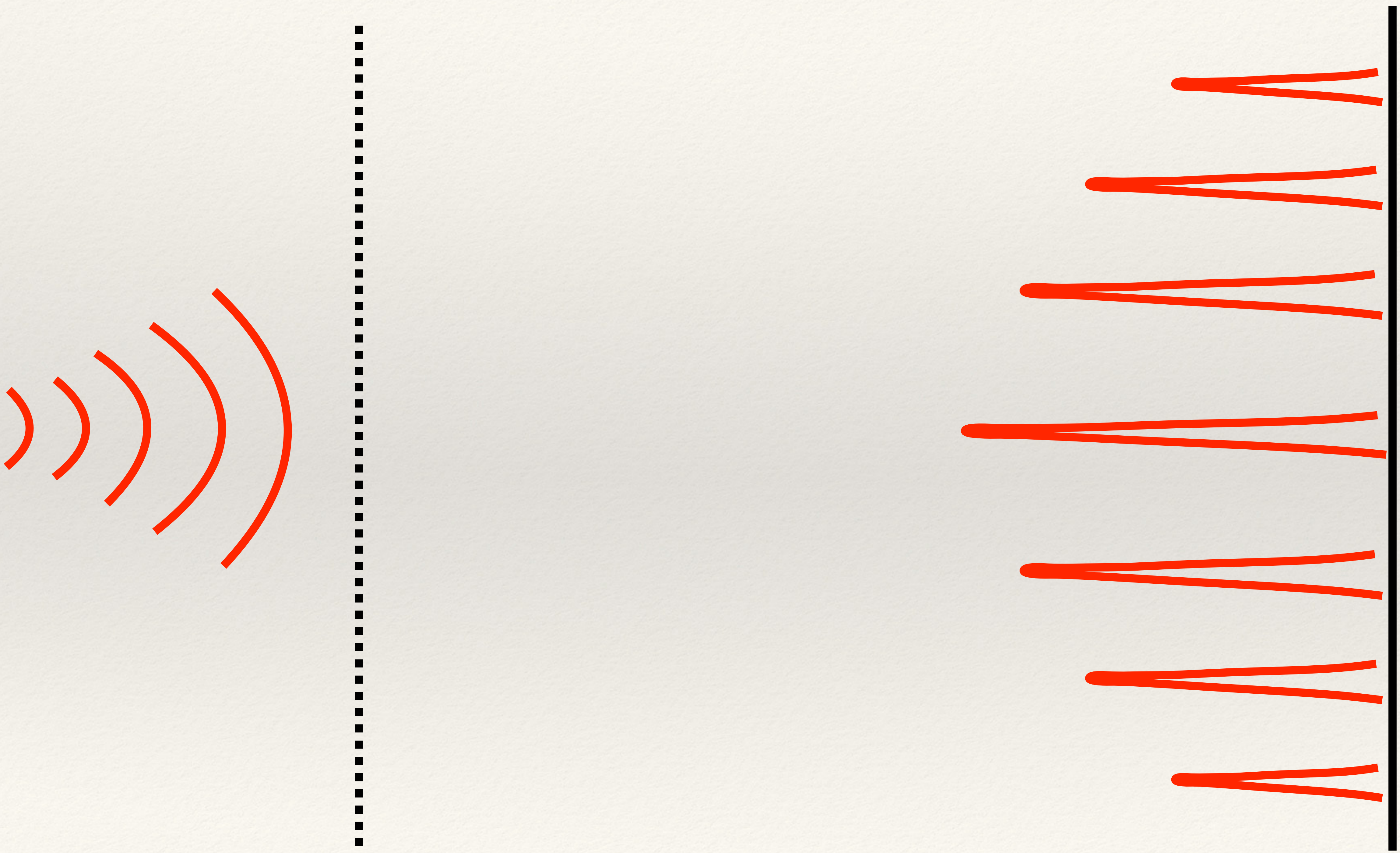


Diffraction gratings

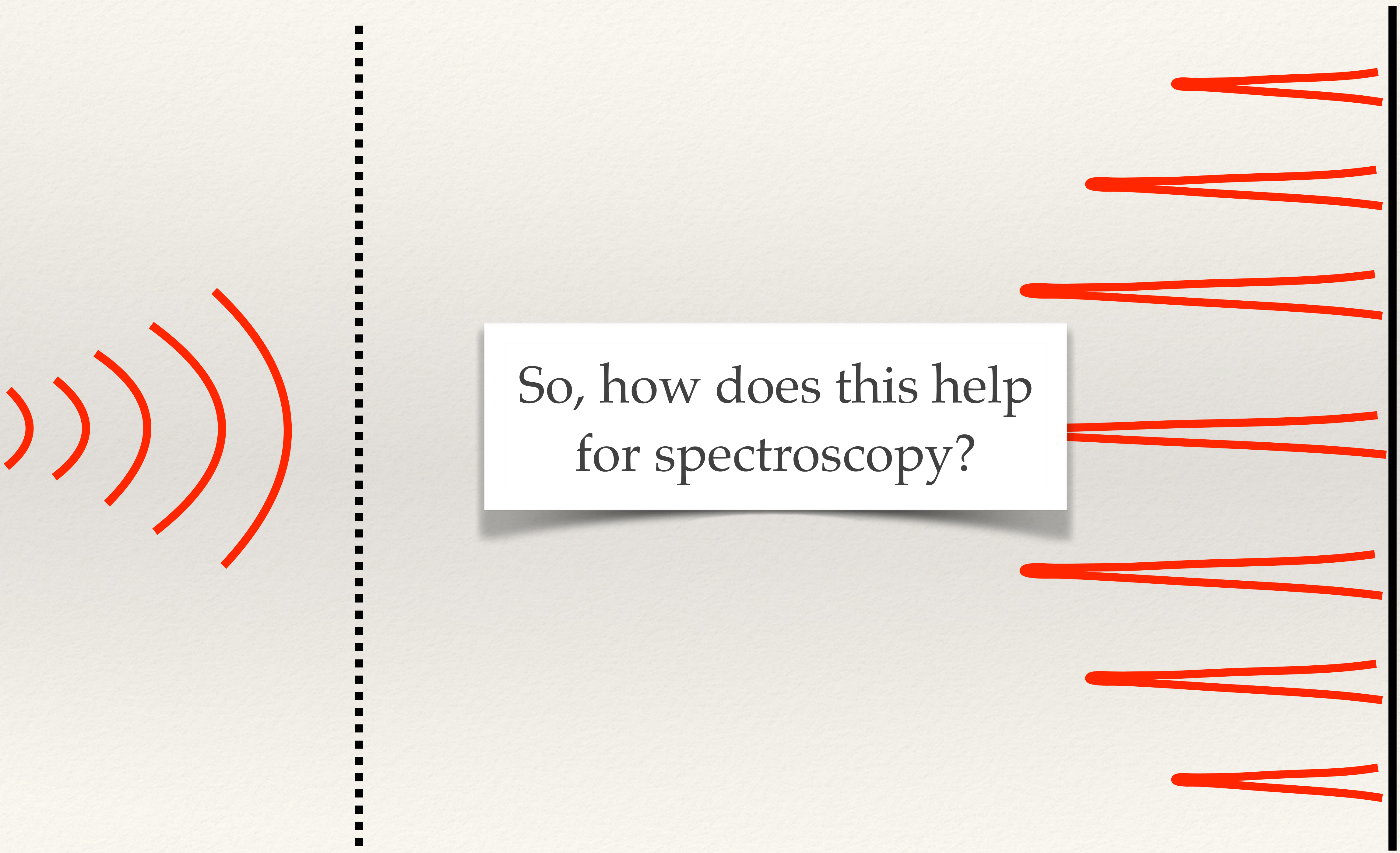


A point even *slightly away* from the bright spot will be dark

Diffraction gratings



Diffraction gratings



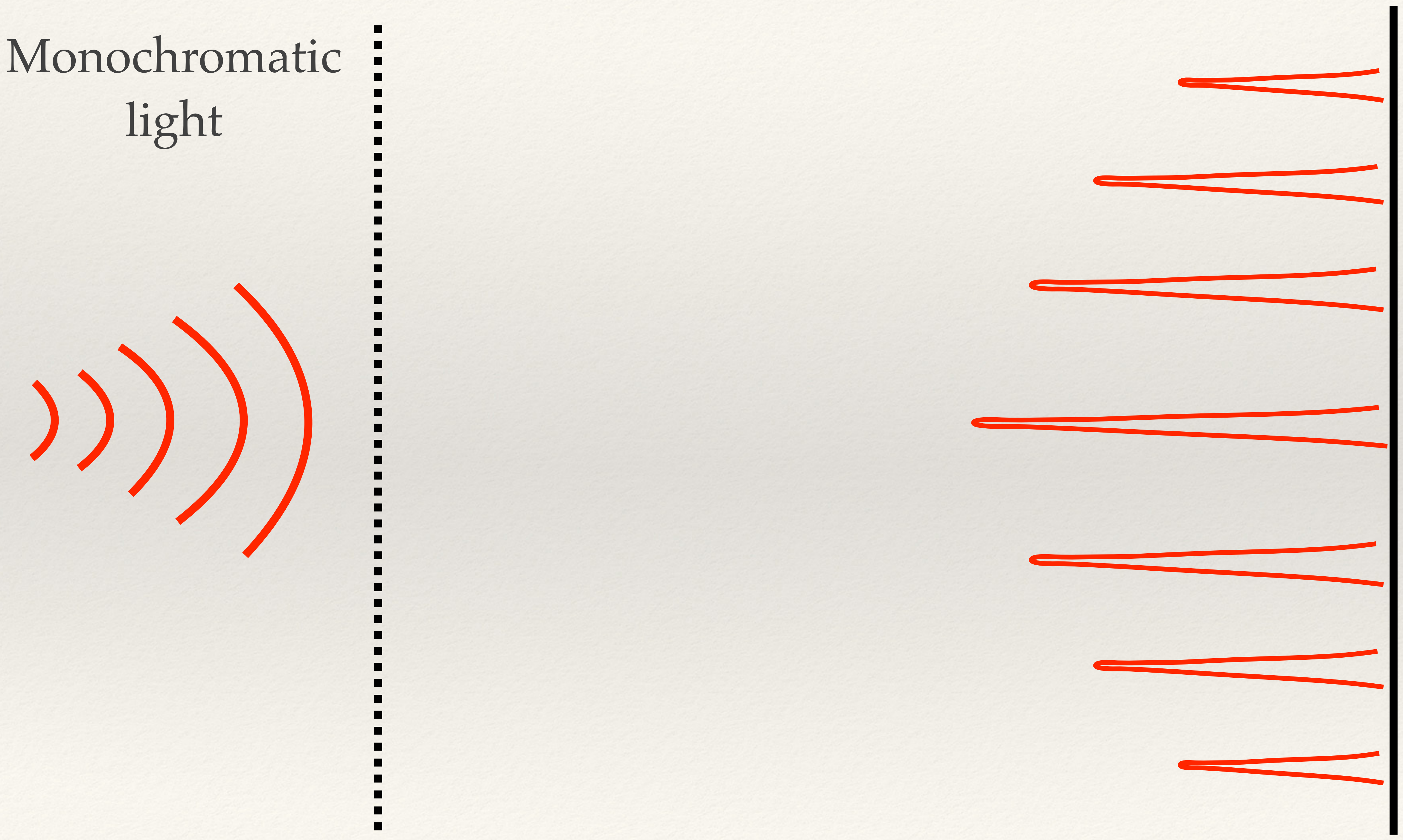
Diffraction gratings

Recall that constructive interference happens when

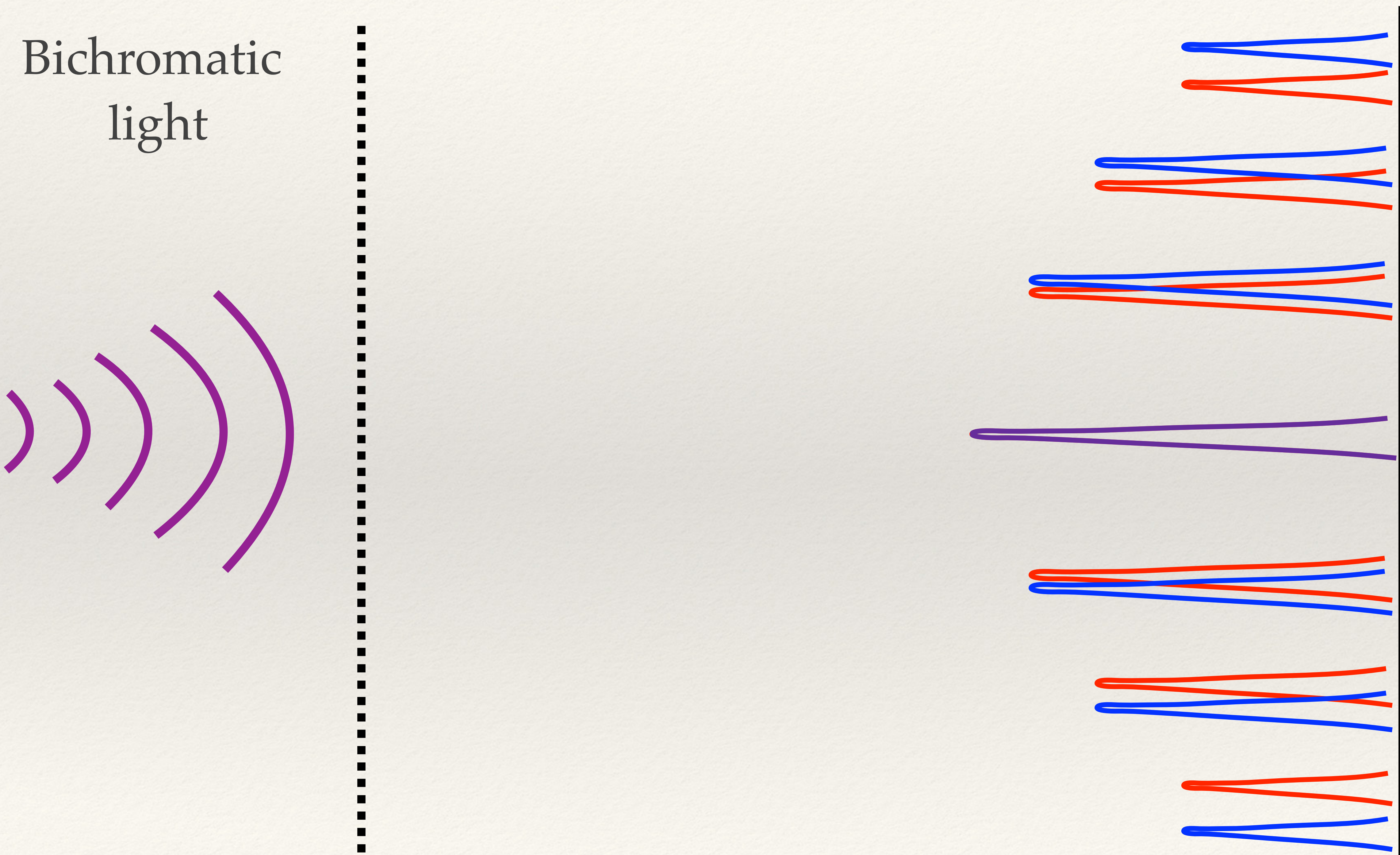
$$d \sin \theta = m\lambda$$

<u>Light of a different wavelength will diffract at a different angle</u>

Diffraction gratings

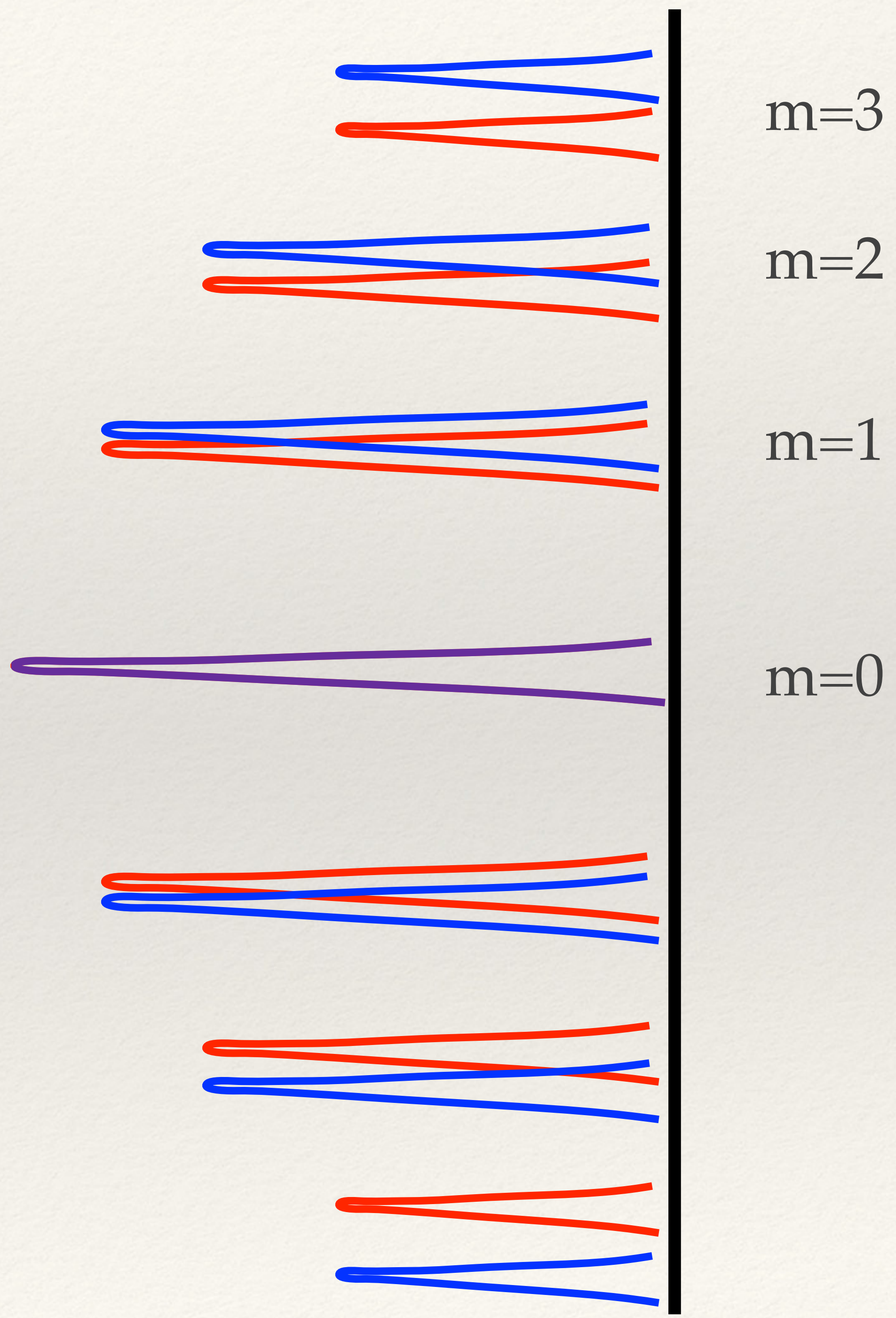


Diffraction gratings



Diffraction gratings

- With continuous spectrum light, each 'bright spot' will be a spectrum
- The narrow nature of the bright spots from a diffraction grating keep the spectrum 'clean'
- We classify the resulting spectra in terms of 'order', *m*



Spectral resolution

Principle maxima are at angles $$\theta = \sin^{-1}\left(\frac{m\lambda}{d}\right)$$

Spectral resolution

Principle maxima are at angles

$$\theta = \sin^{-1}\left(\frac{m\lambda}{d}\right)$$

"Rayleigh Resolution"

(Width of principle maxima)

$$W' = \frac{\lambda}{N d \cos\theta}$$

Spectral resolution

We want to know the spectral resolution, which is the ability of our spectroscope to separate wavelengths.

$$W_\lambda = W' \frac{d\lambda}{d\theta}$$

$$\frac{d\lambda}{d\theta} = \frac{d}{m} \cos\theta$$

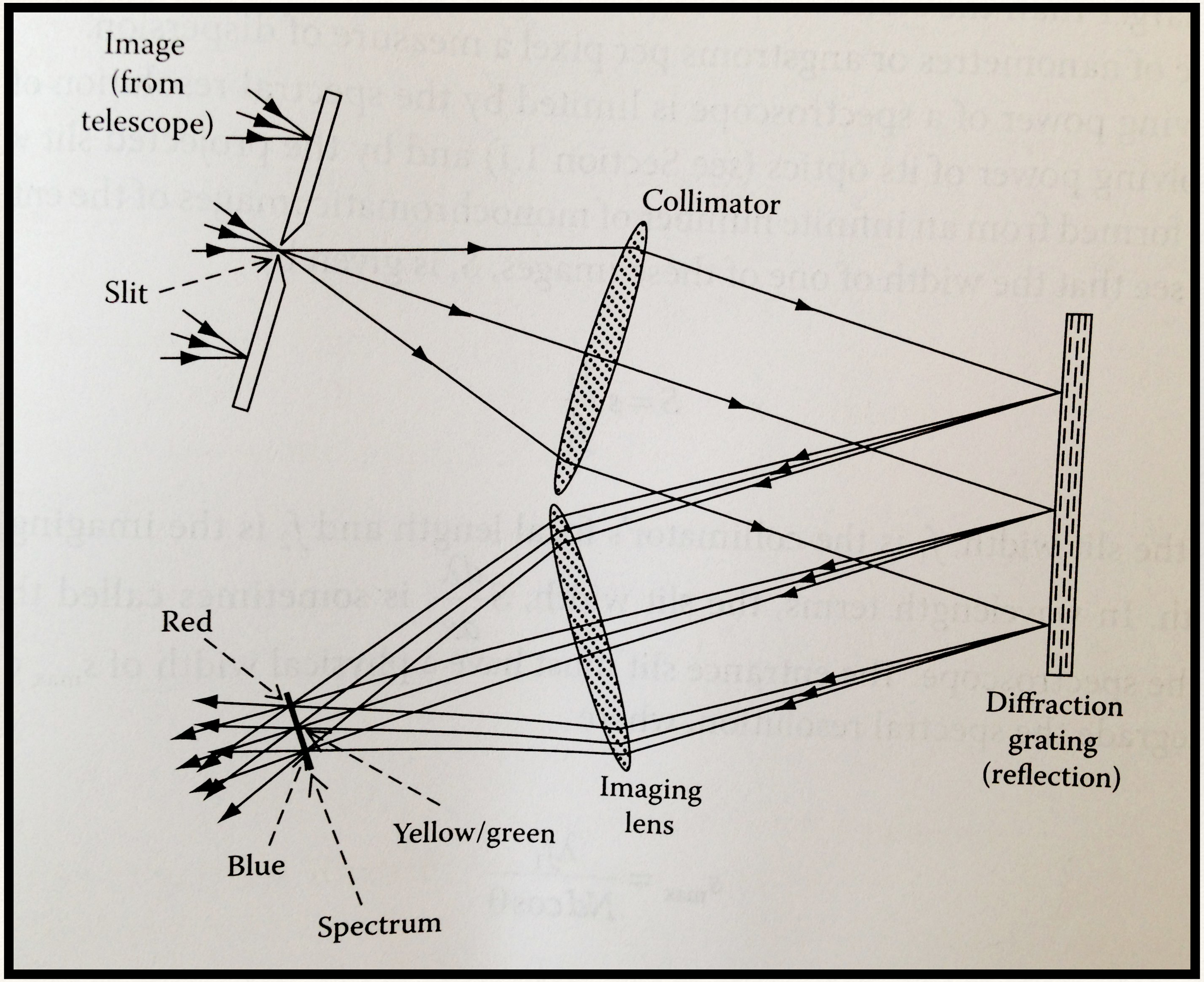
$$\implies \quad W_\lambda = \frac{\lambda}{Nm}$$

Grating spectroscope

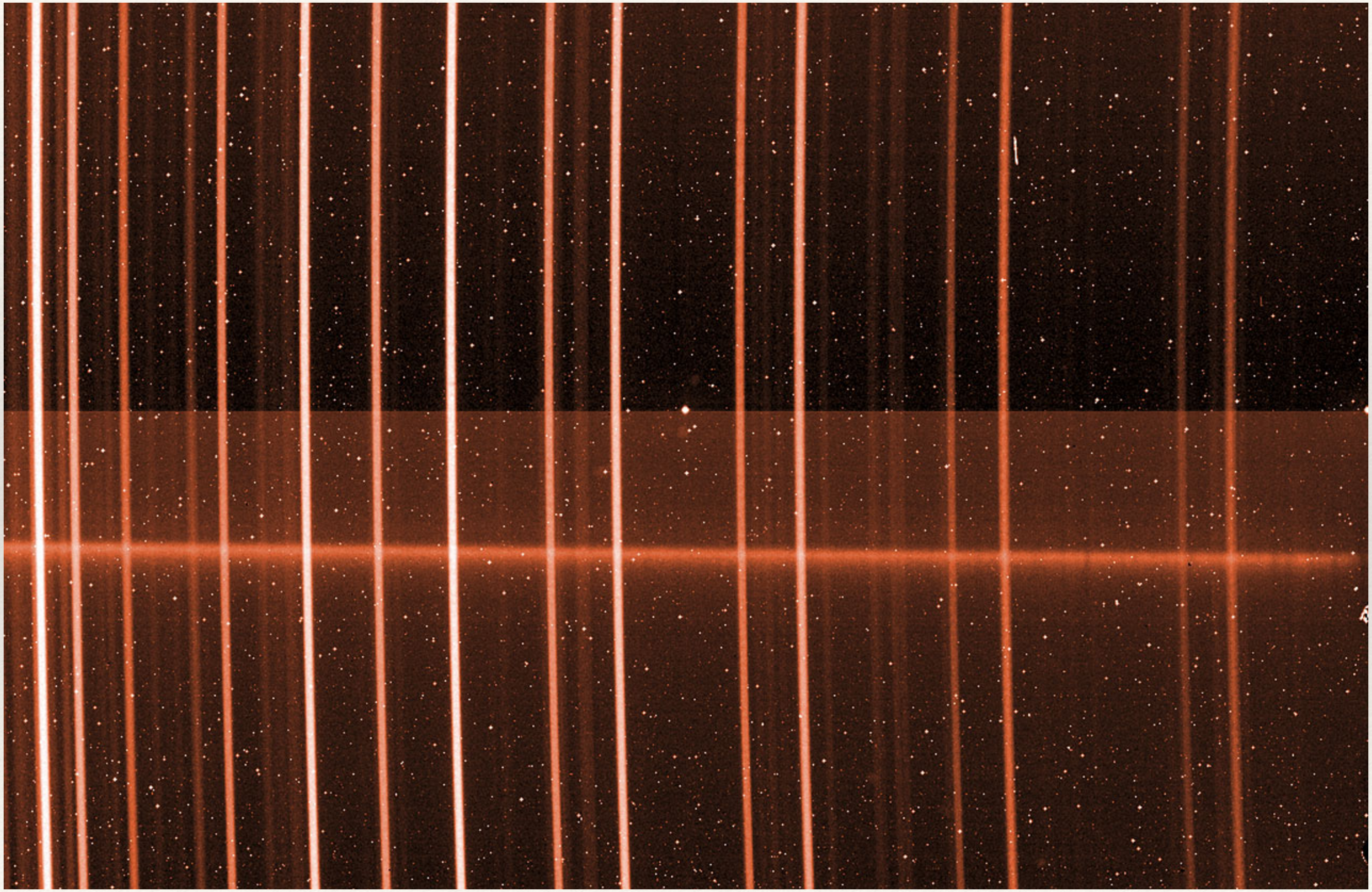
Although discussion has centred around diffraction from multiple *apertures*, each aperture can be replaced with a small mirror, with the same results

This forms a *reflection grating*, which is what is actually used by most astronomical spectrographs

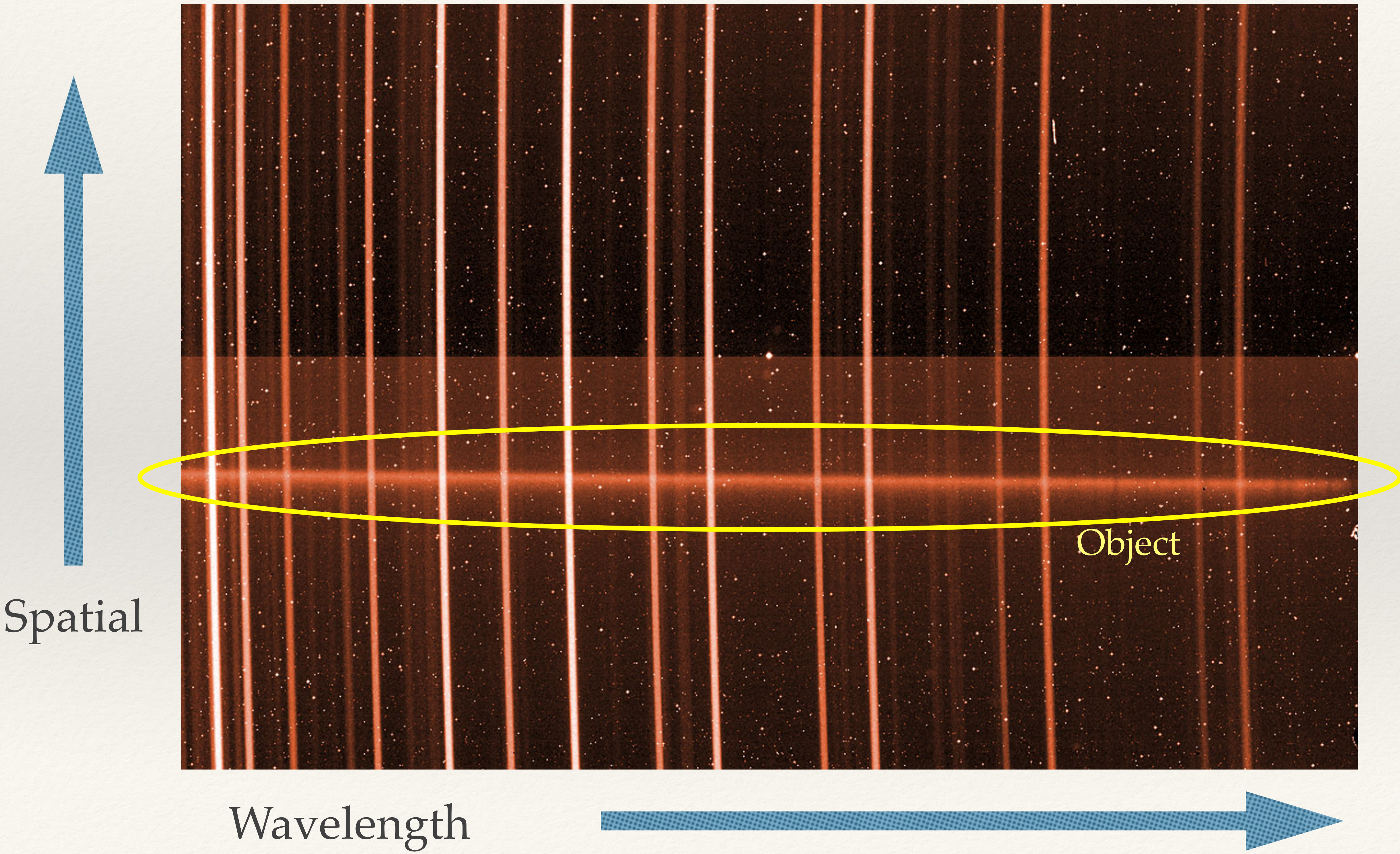
Grating spectroscope



Raw spectrum

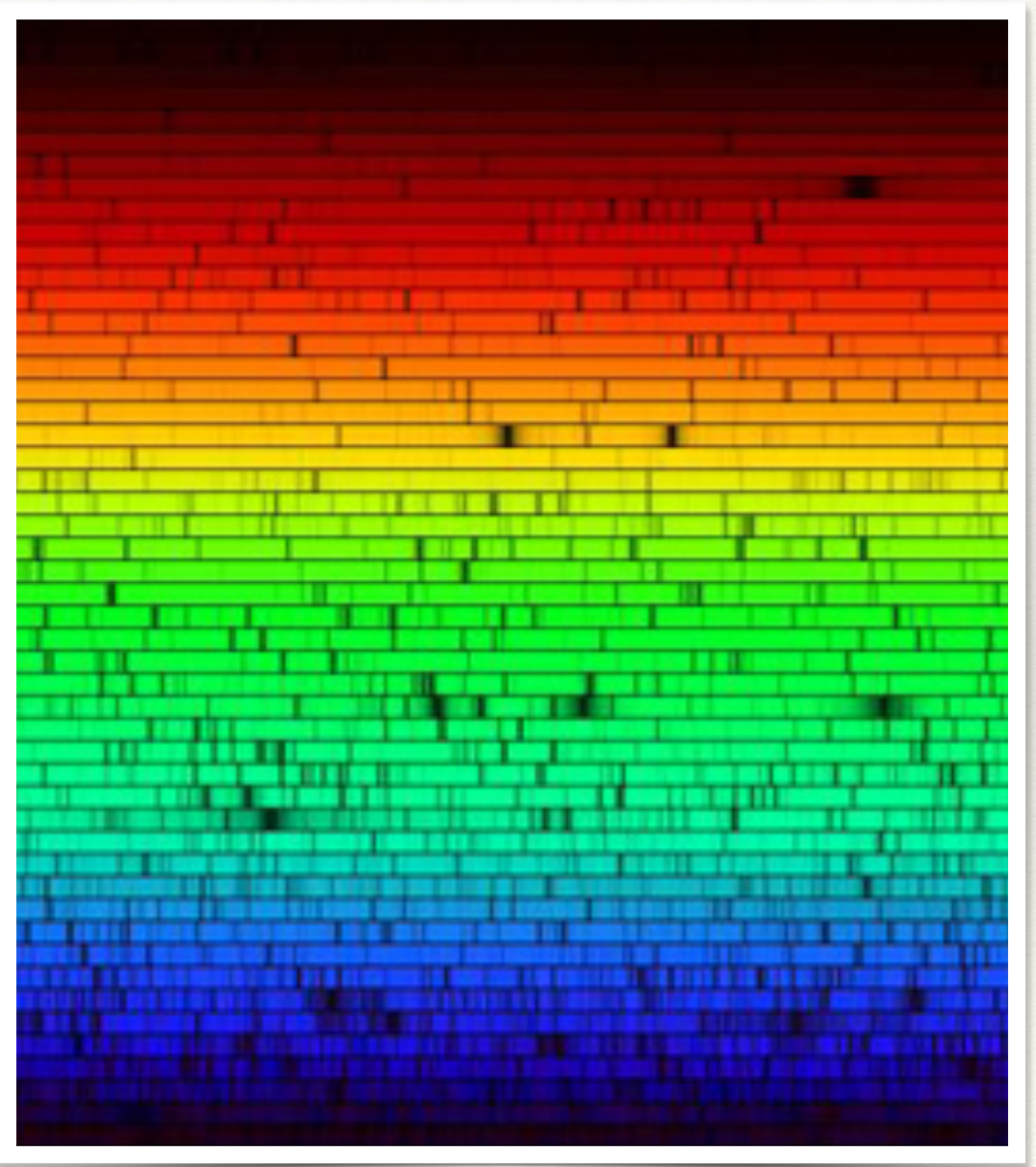


Raw spectrum



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)

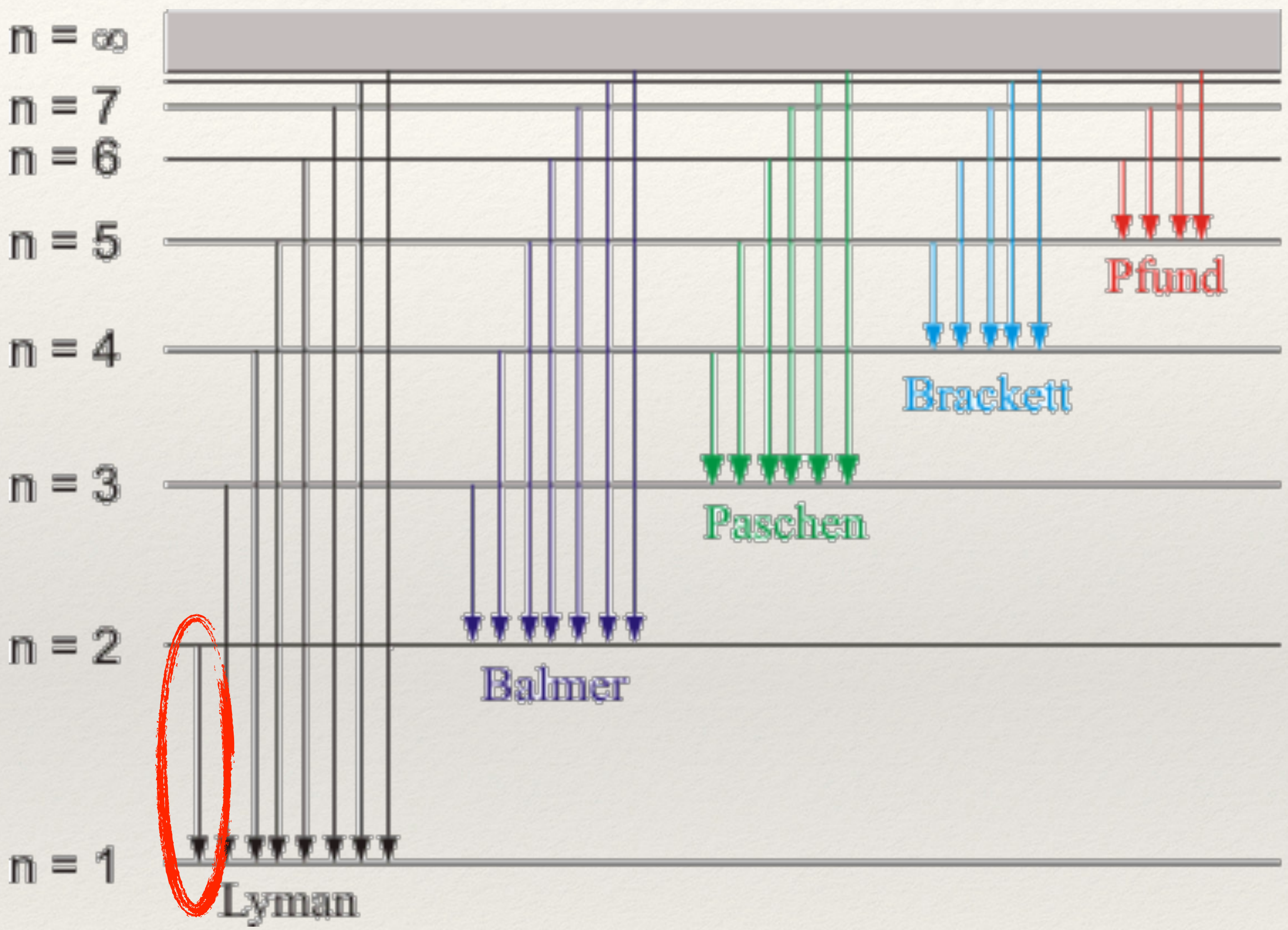


The ‘Lyman-alpha forest’

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

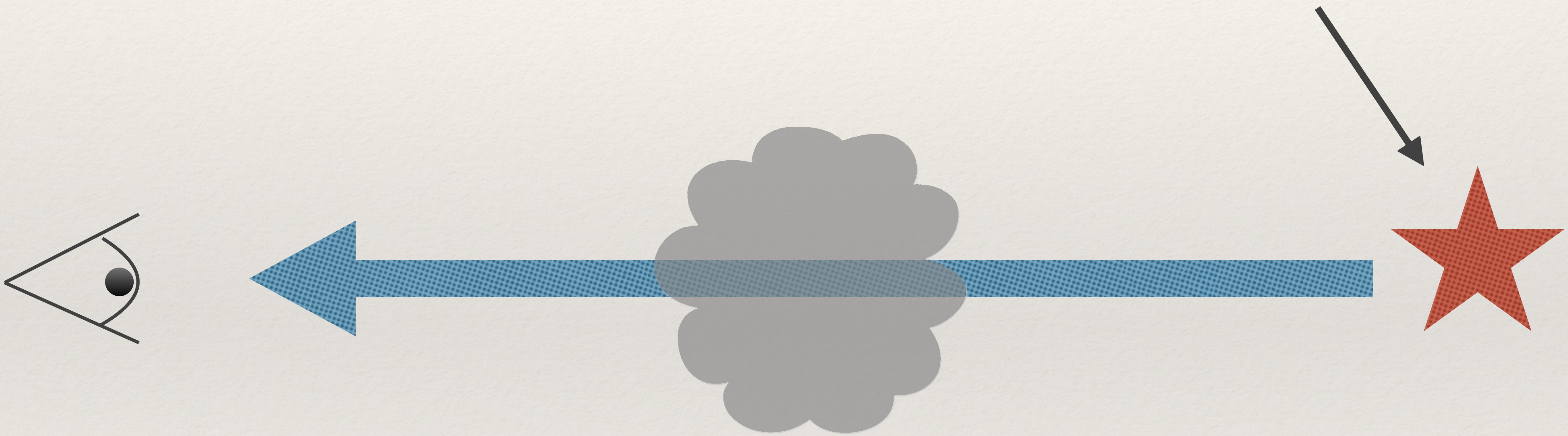
Wavelength = 1215.67 A

The ‘Lyman-alpha forest’

Distant quasar:
Emits broad-spectrum light

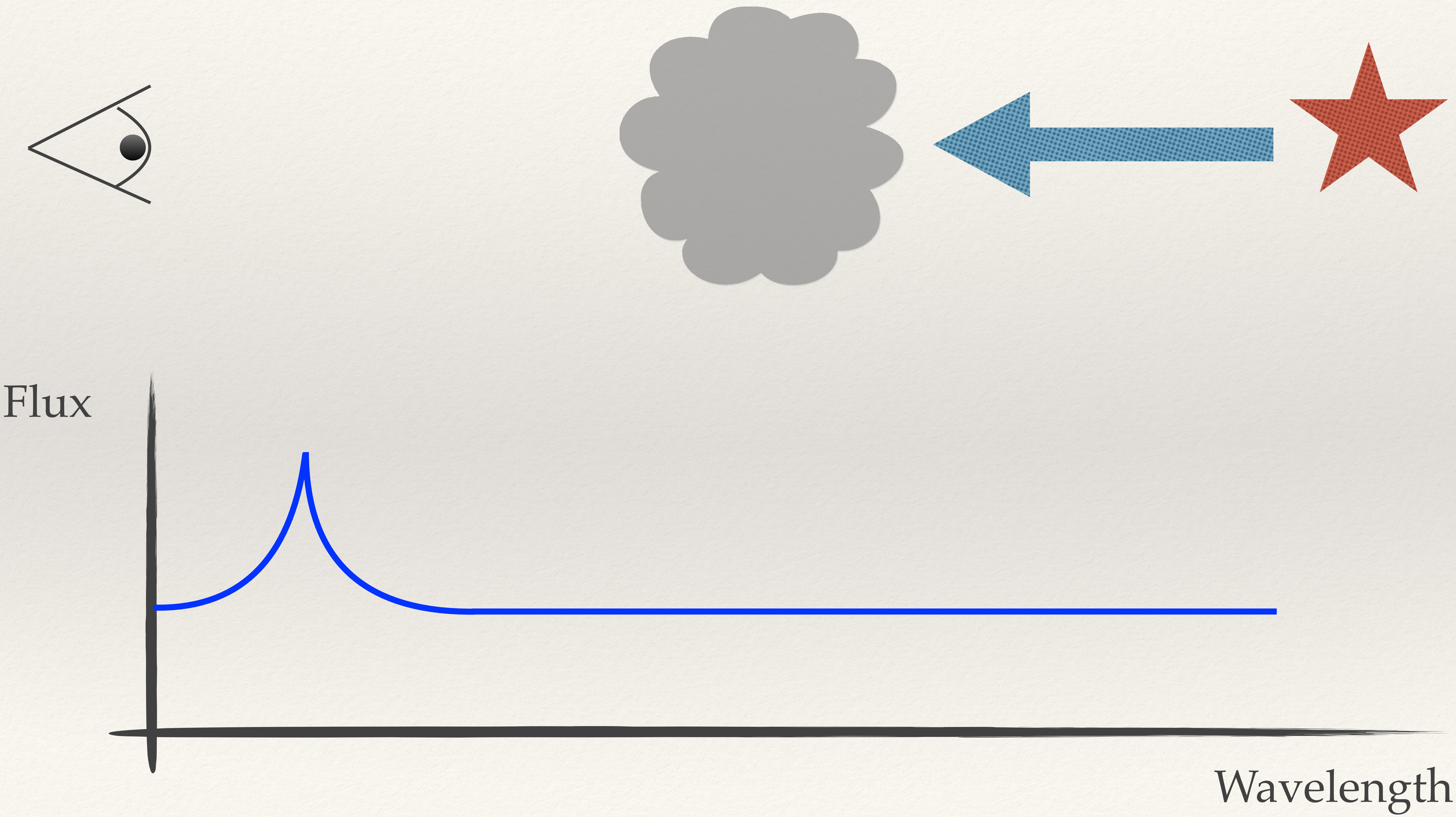
The ‘Lyman-alpha forest’

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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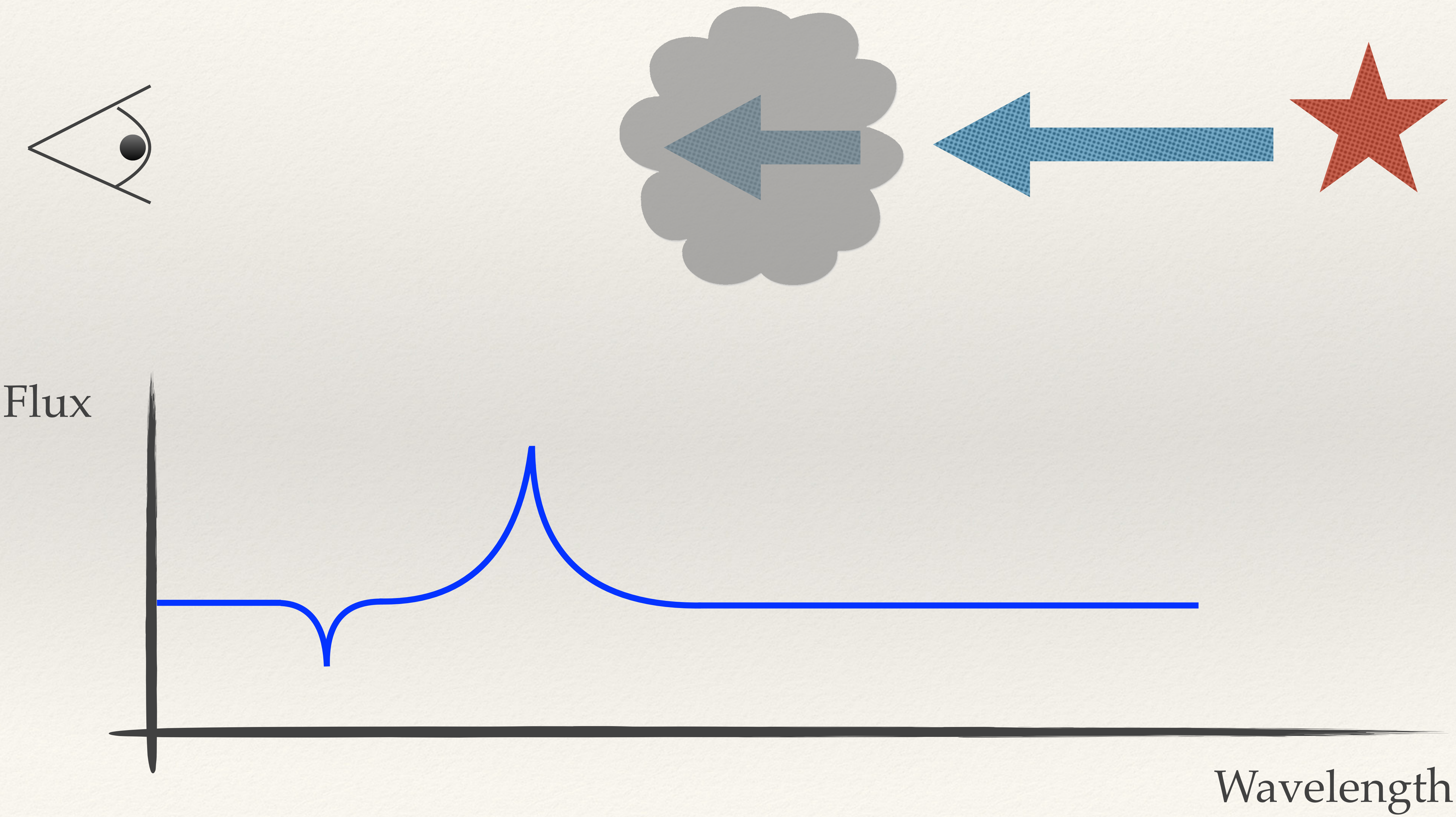

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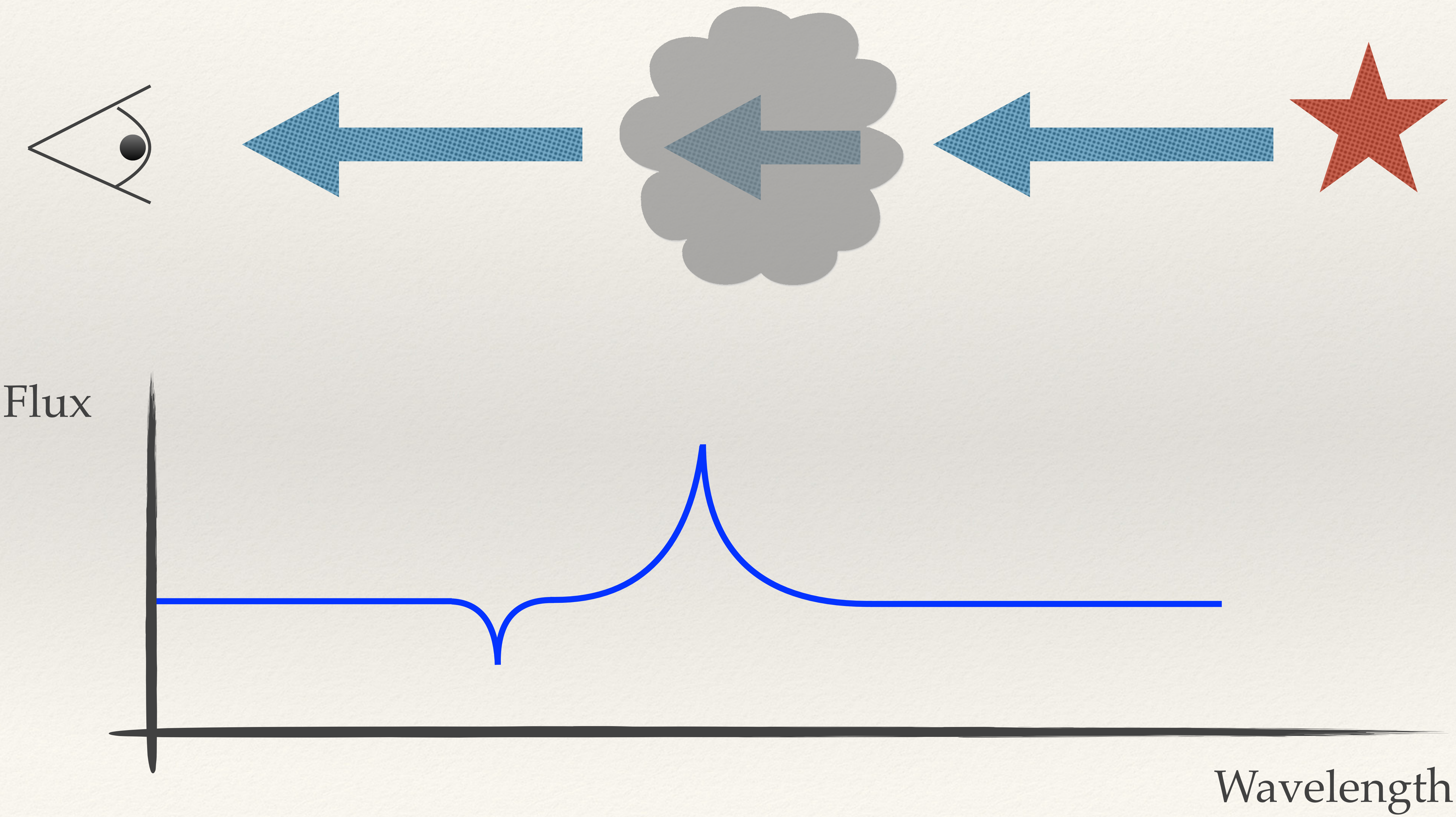

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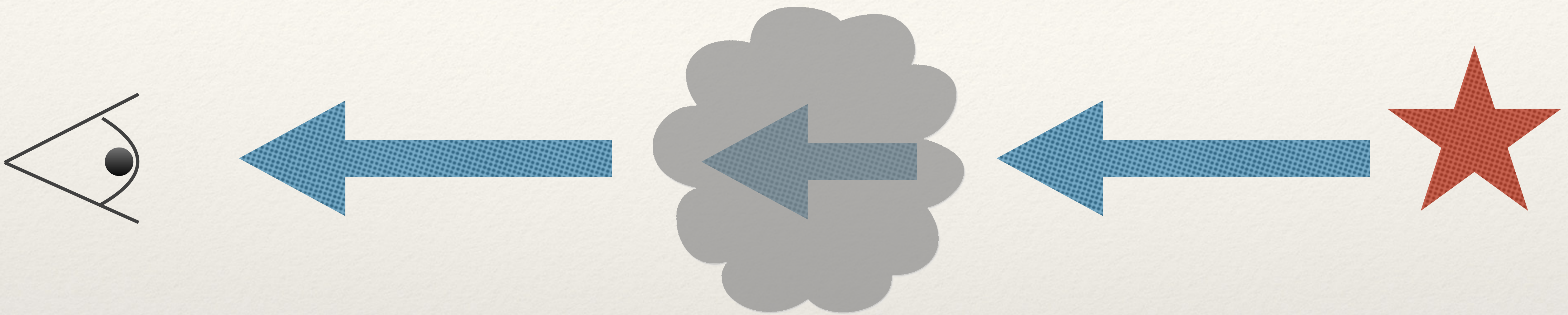

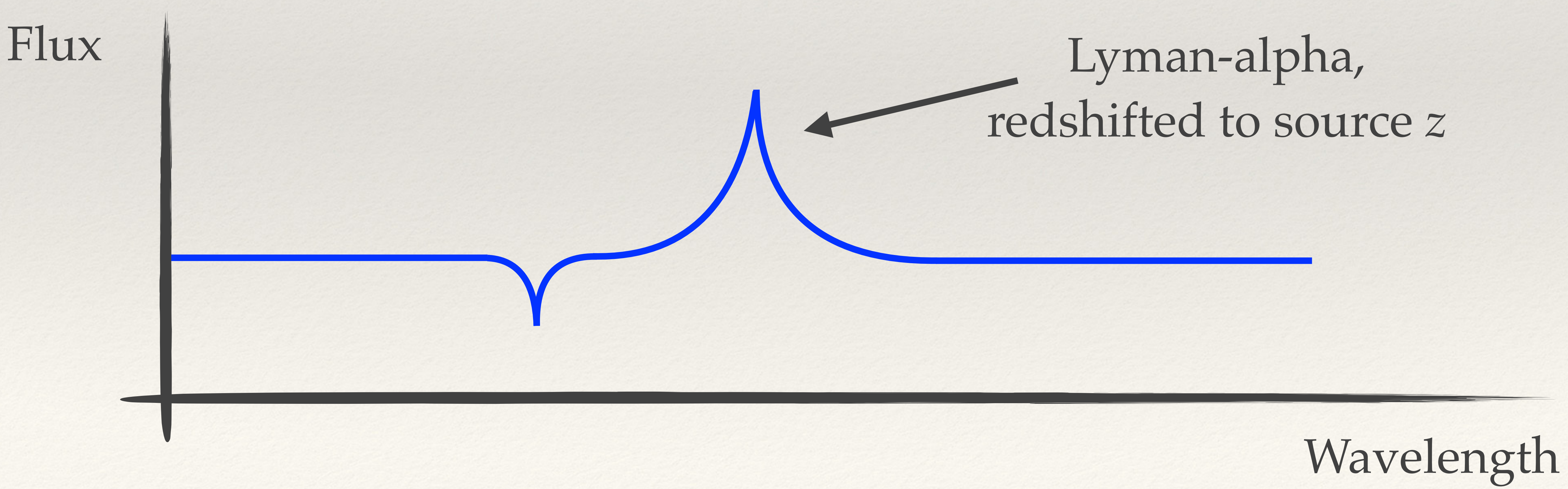

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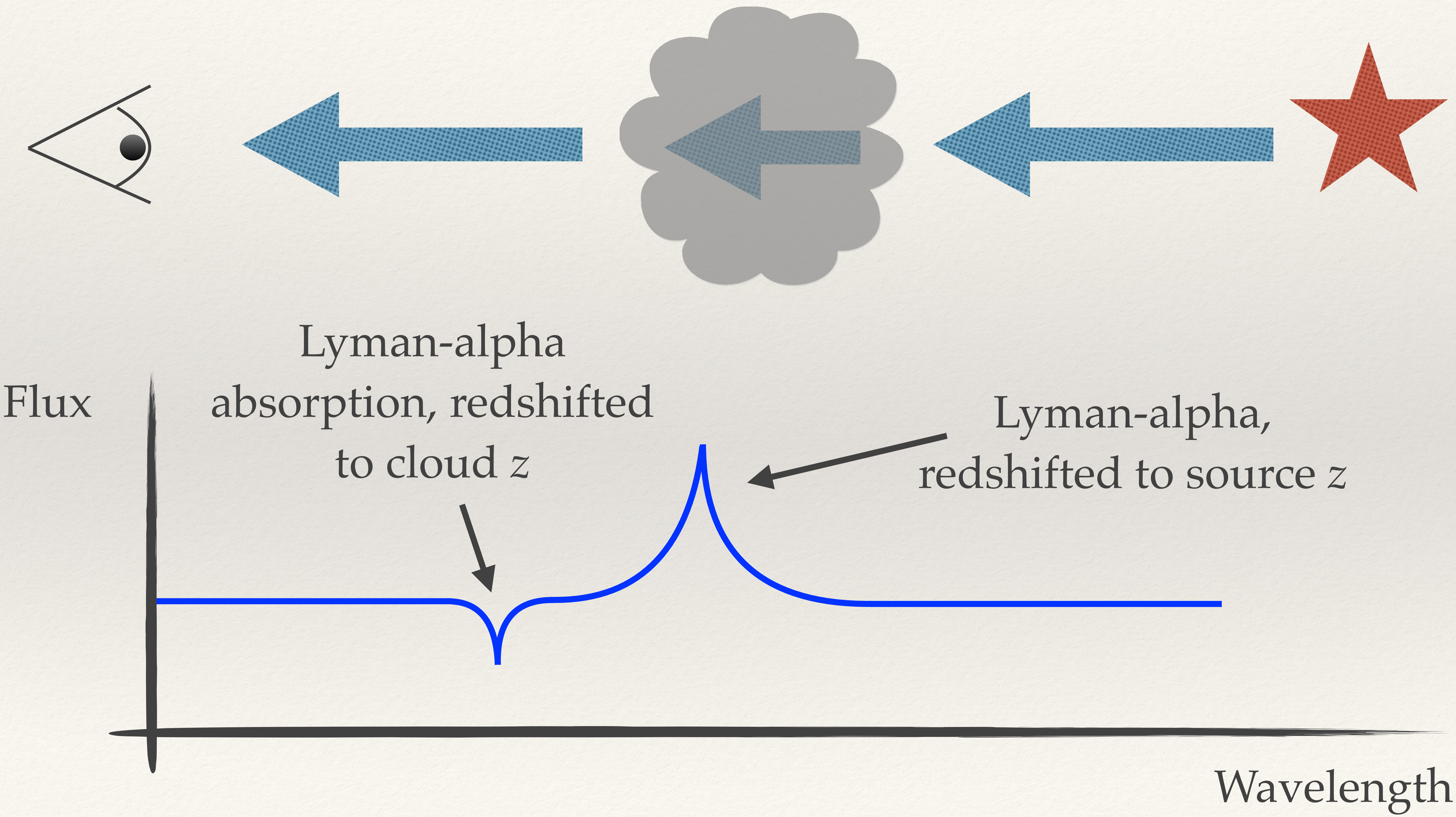

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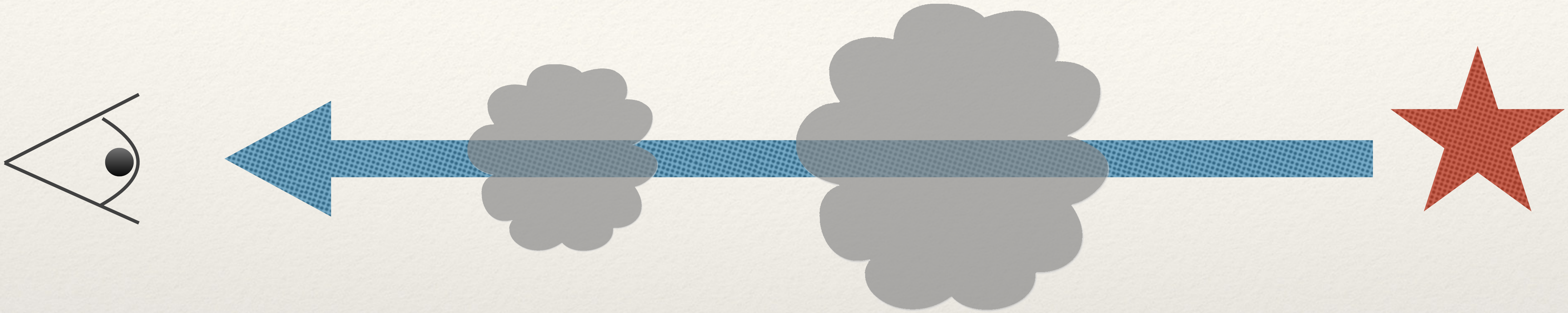
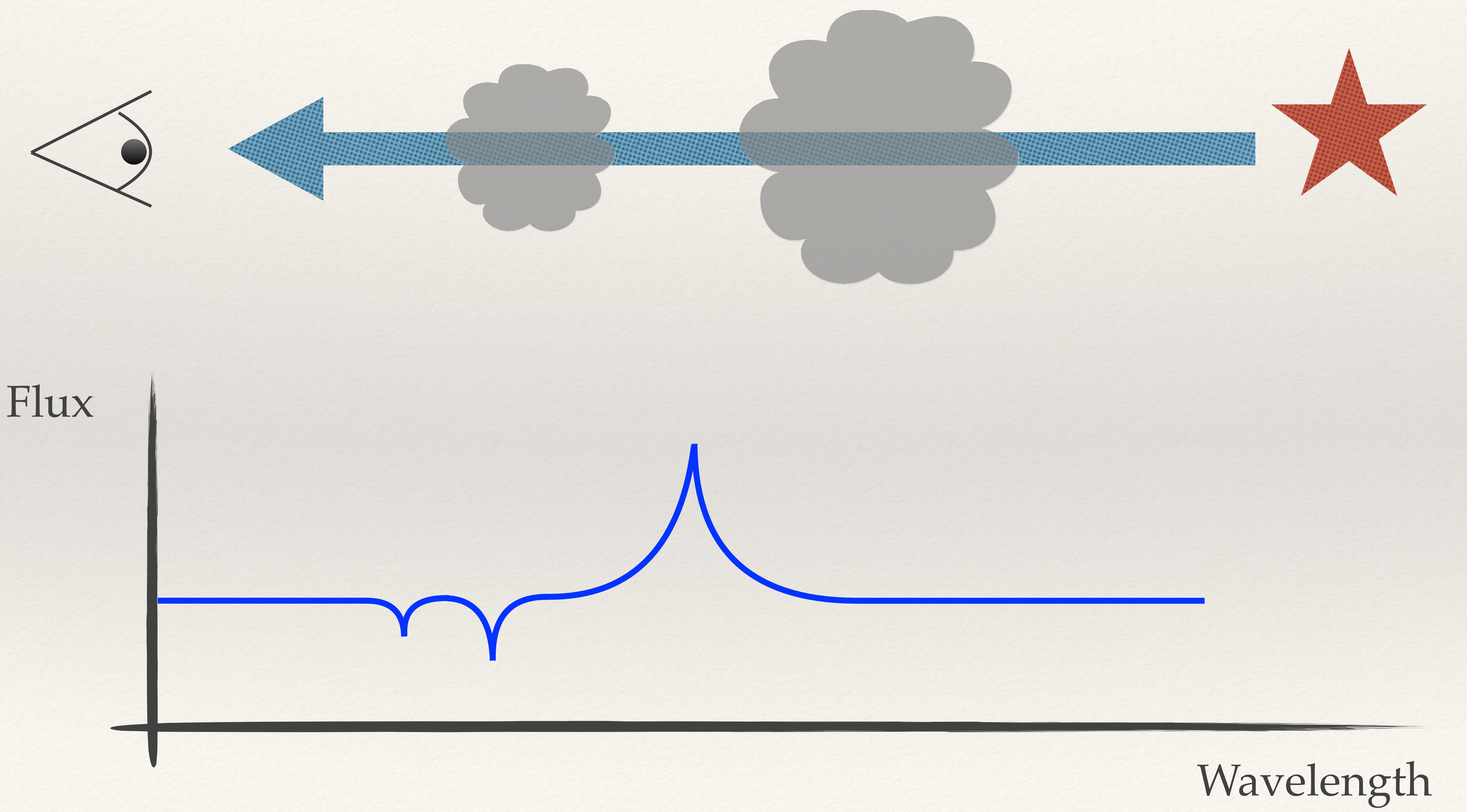
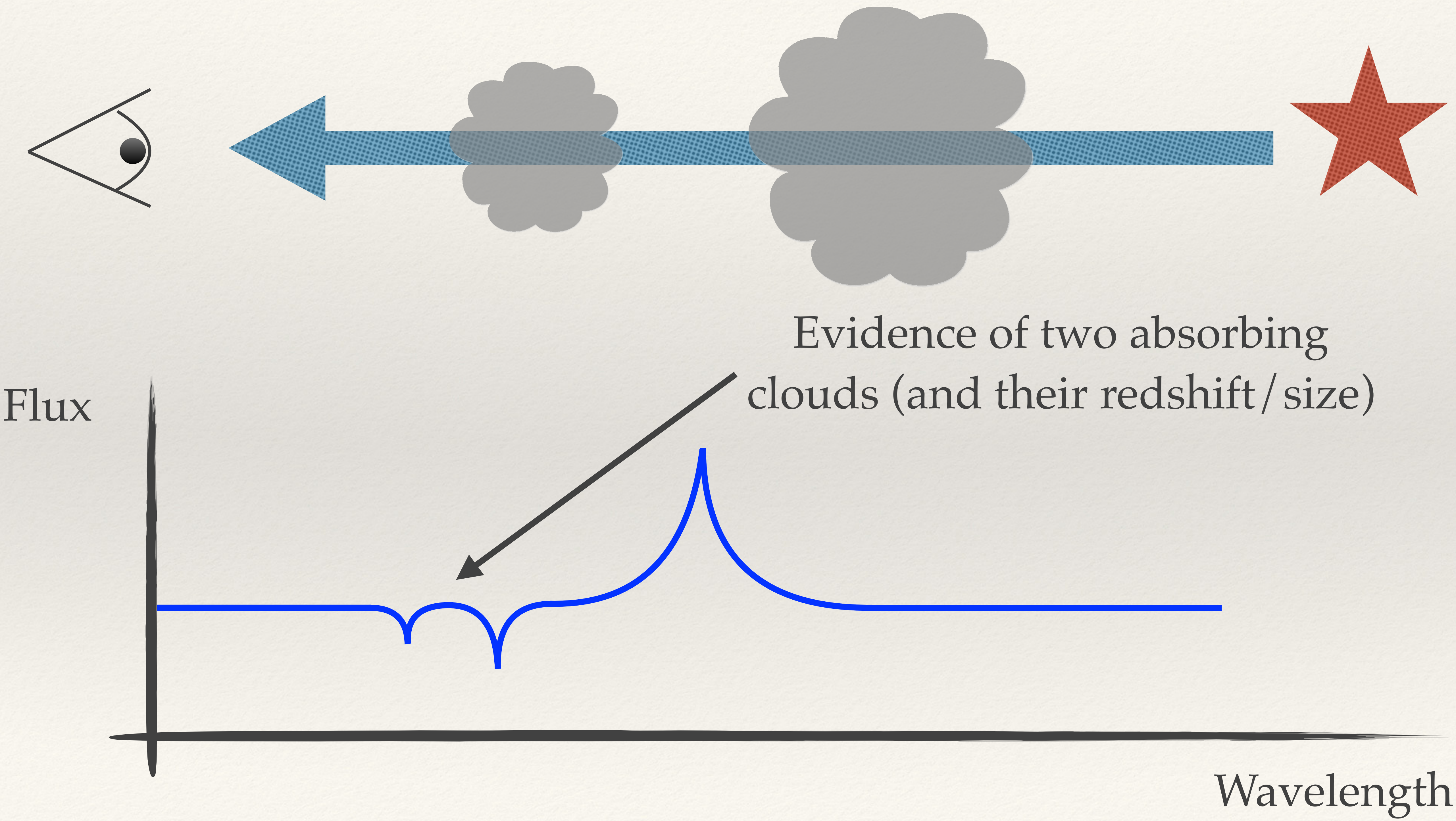


The 'Lyman-alpha forest'

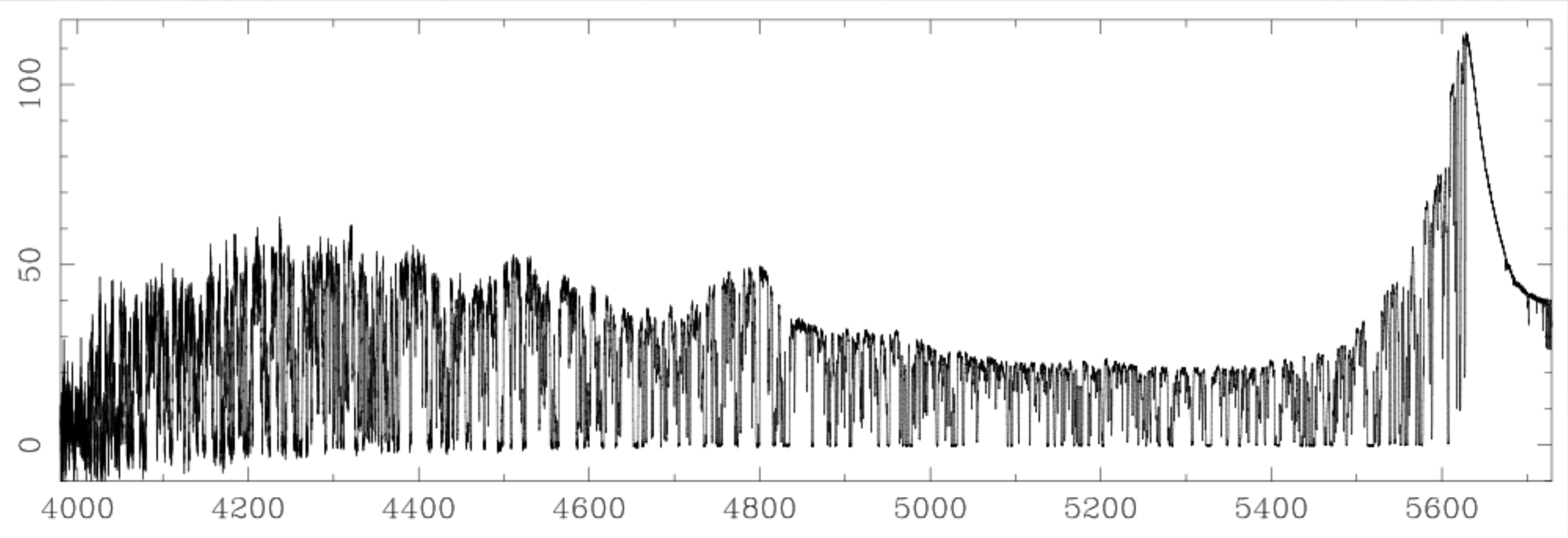


The ‘Lyman-alpha forest’



The ‘Lyman-alpha forest’

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



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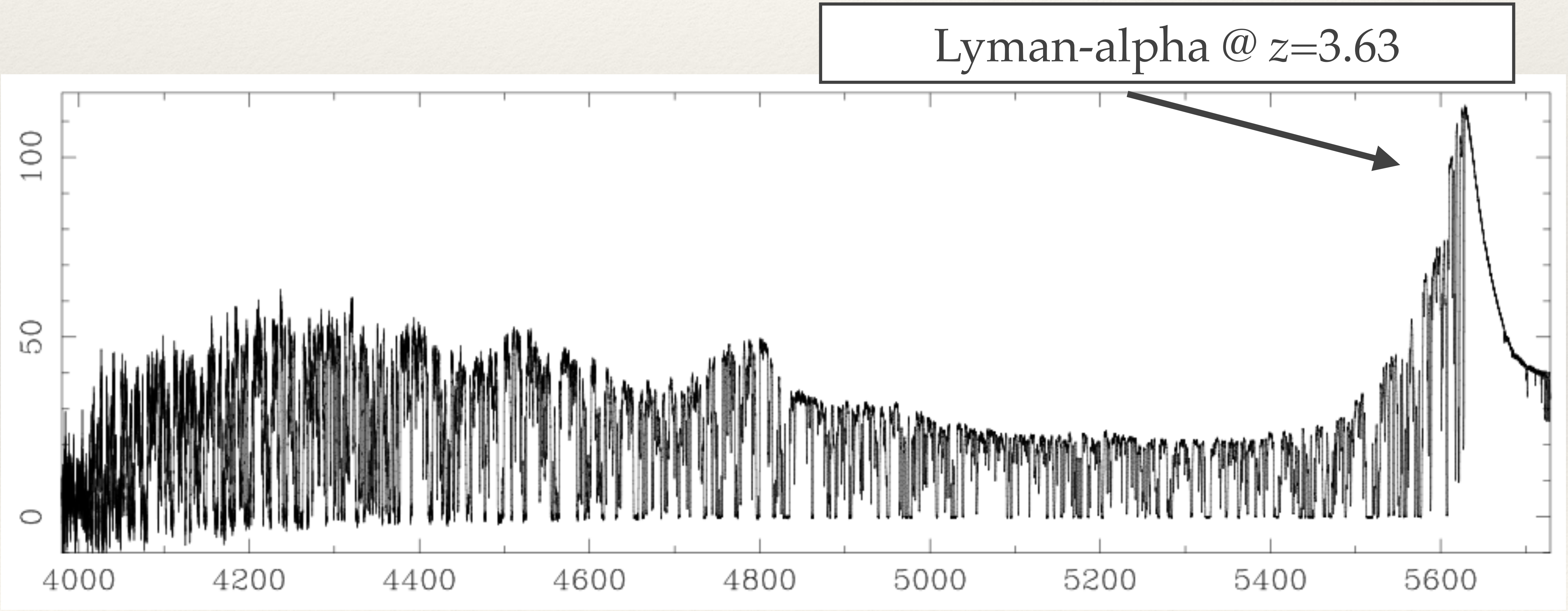

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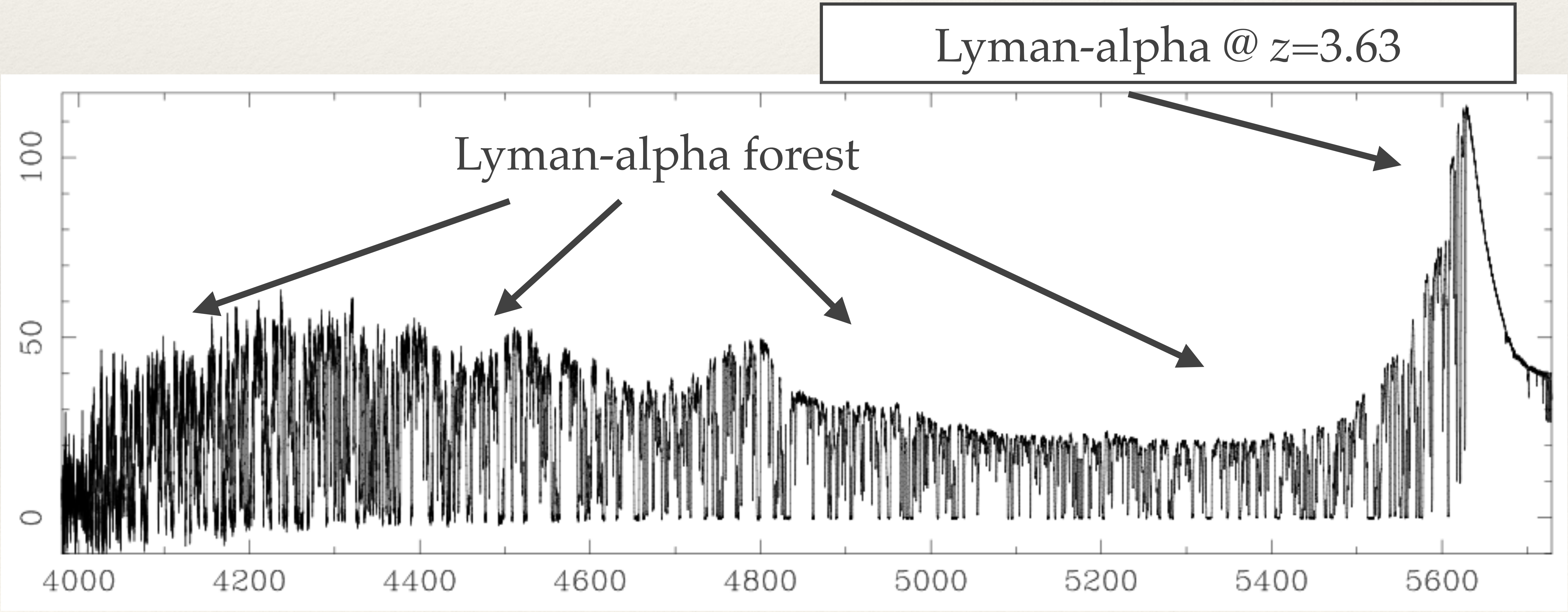
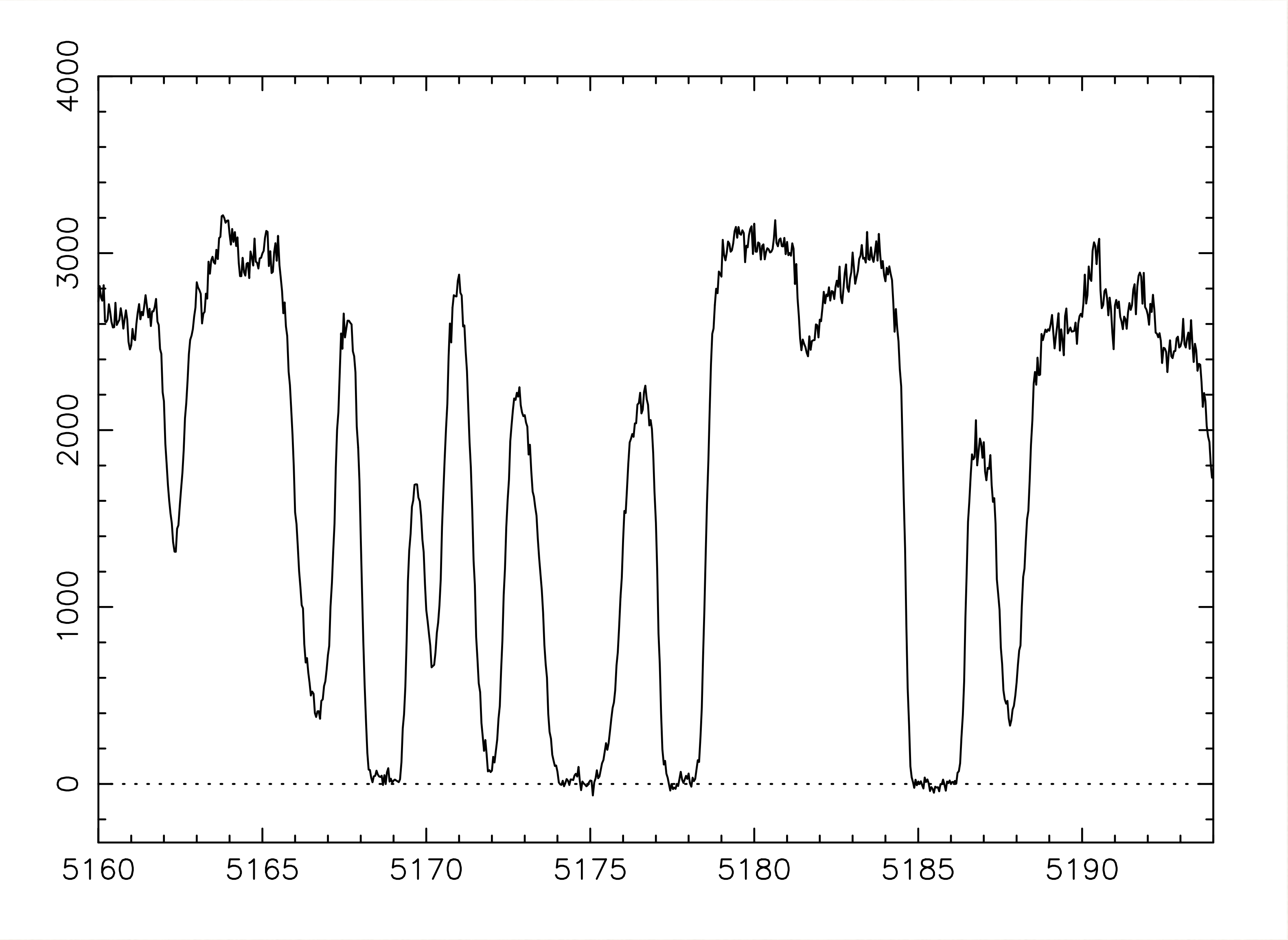


The 'Lyman-alpha forest'

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

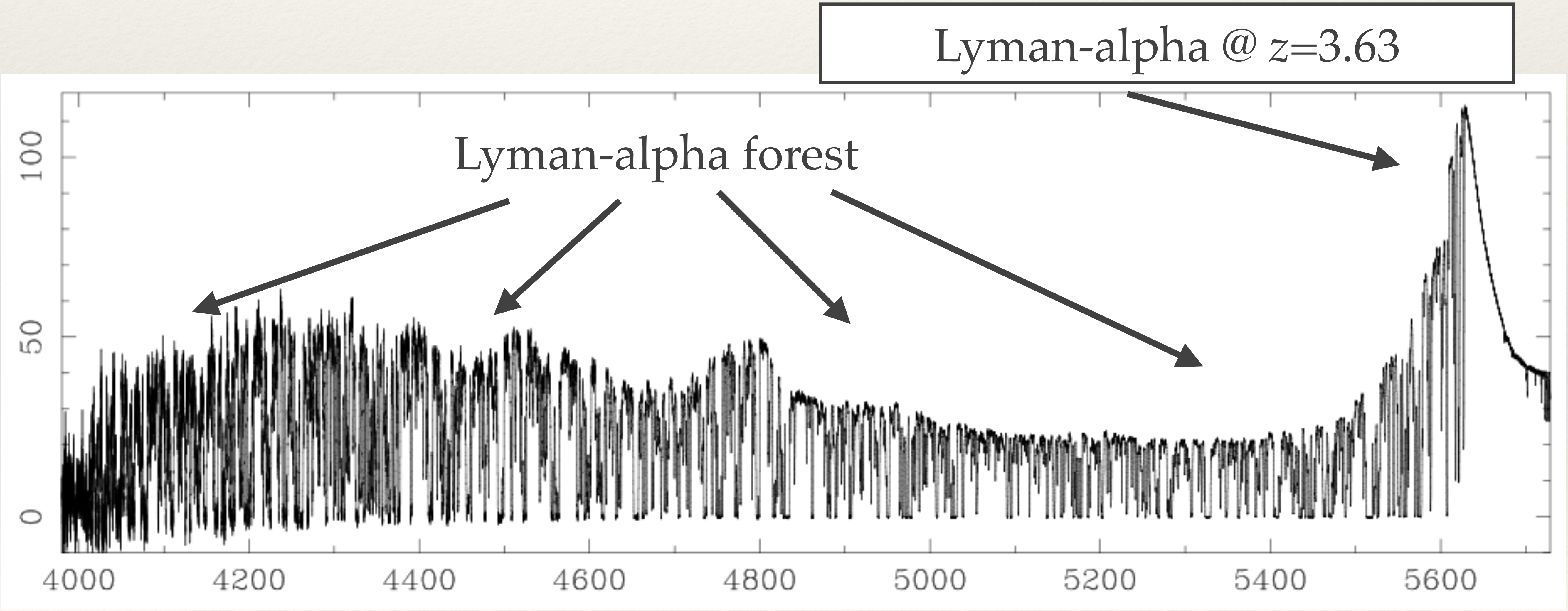
Flux

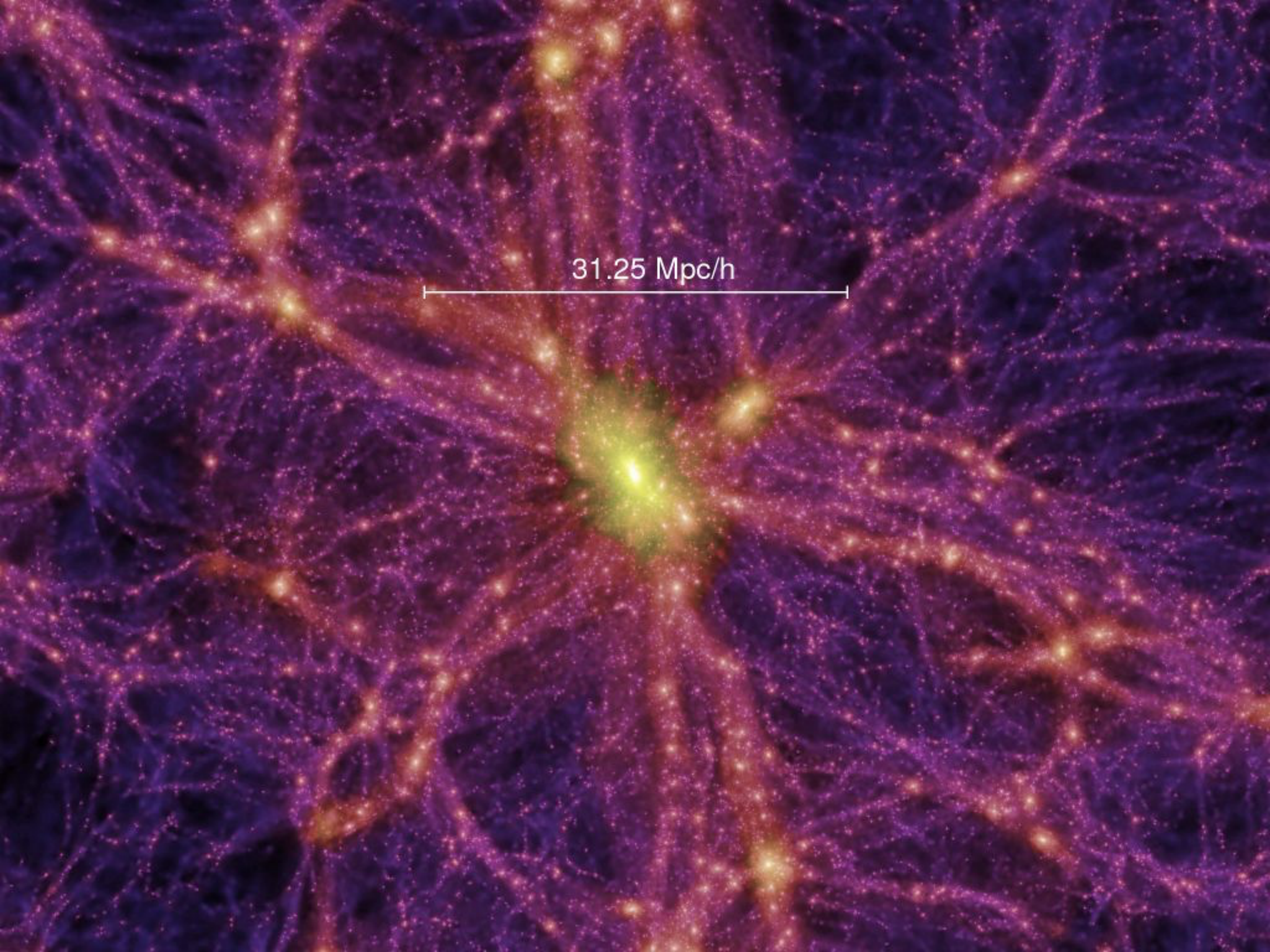


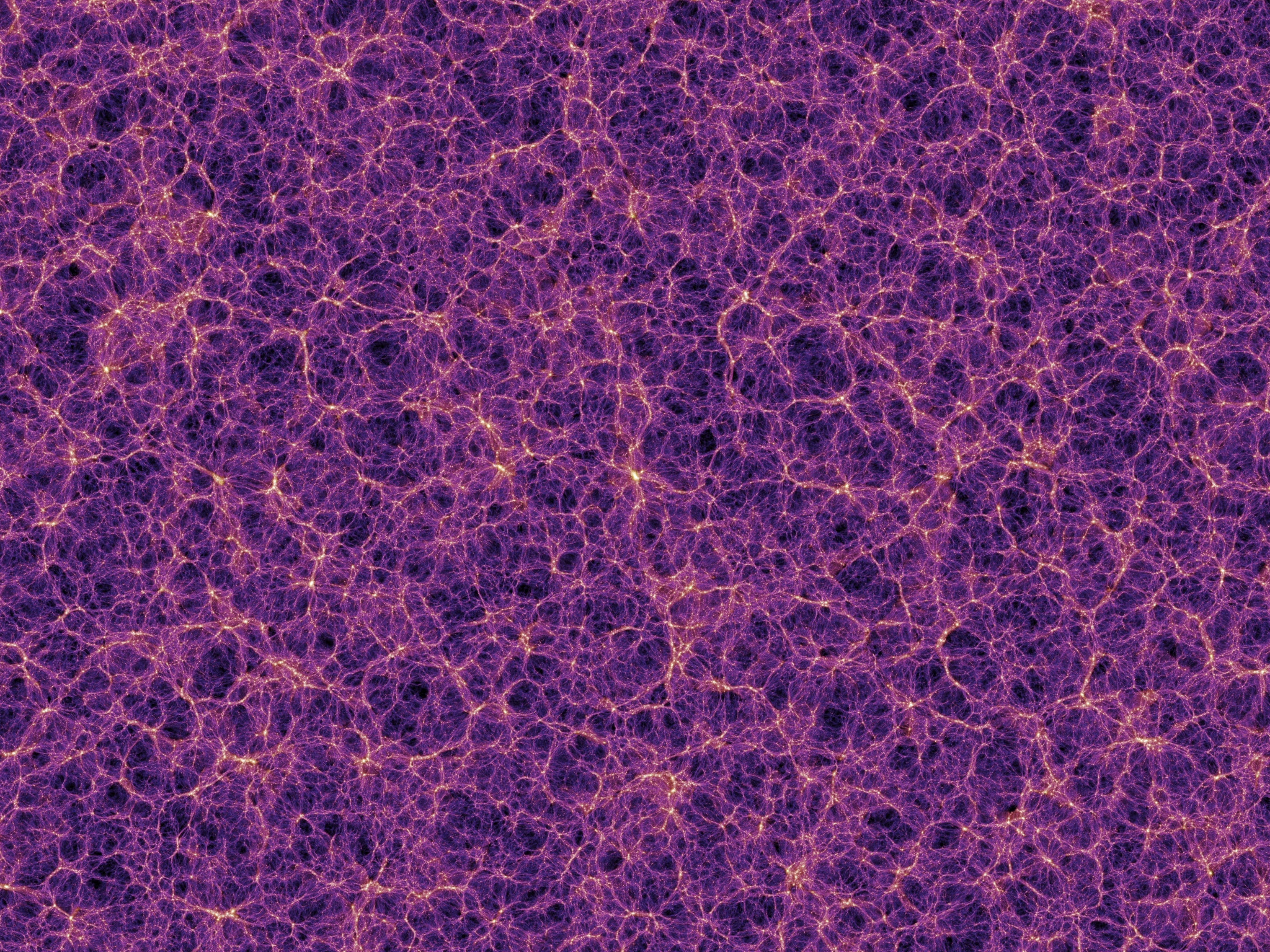
Wavelength

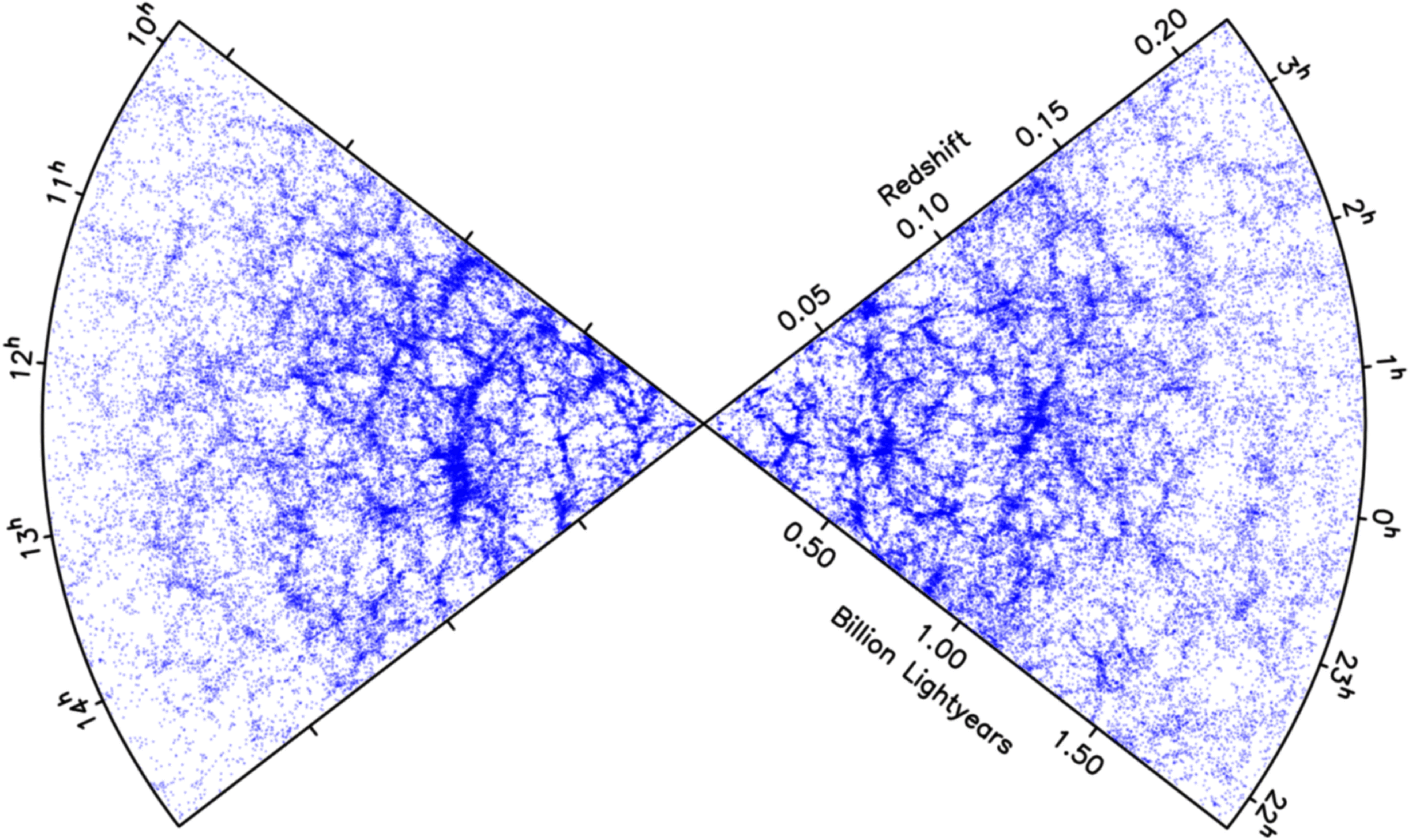
The 'Lyman-alpha forest'

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




31.25 Mpc/h

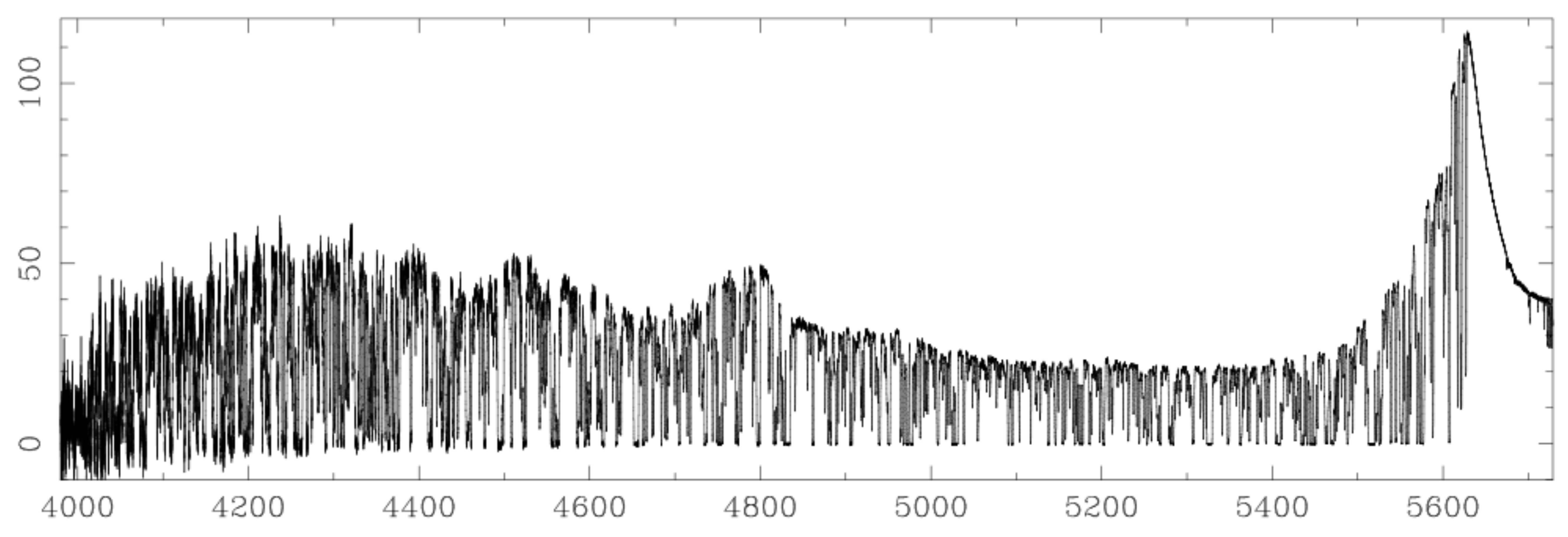




10h
11h
12h
13h
14h
Redshift
0.05
0.10
0.15
0.20
3h
2h
1h
0h
23h
22h
Billion Lightyears
0.50
1.00
1.50

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)

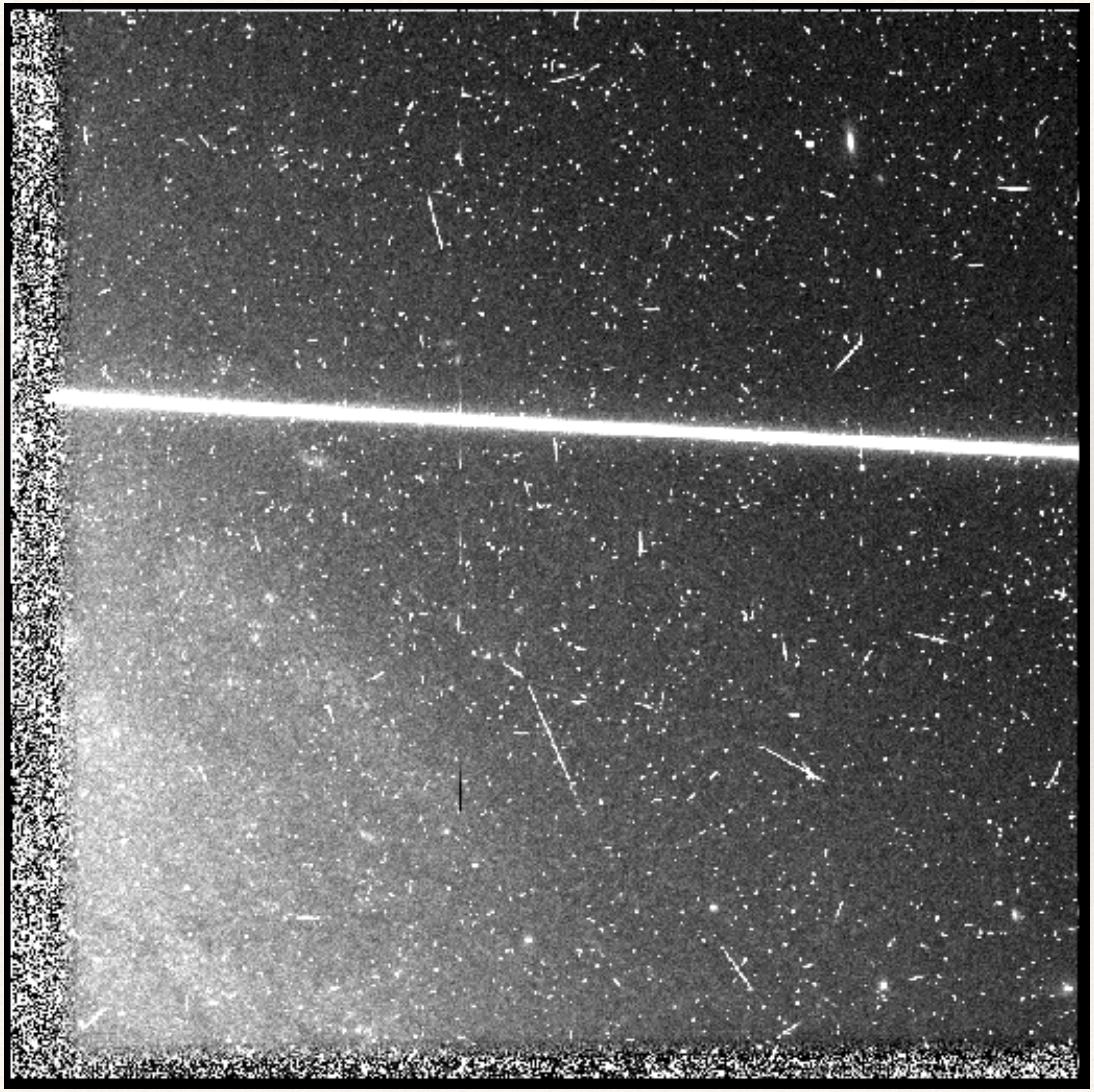
- Photometry
- Spectroscopy
- `Reduction' of astronomical data

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)

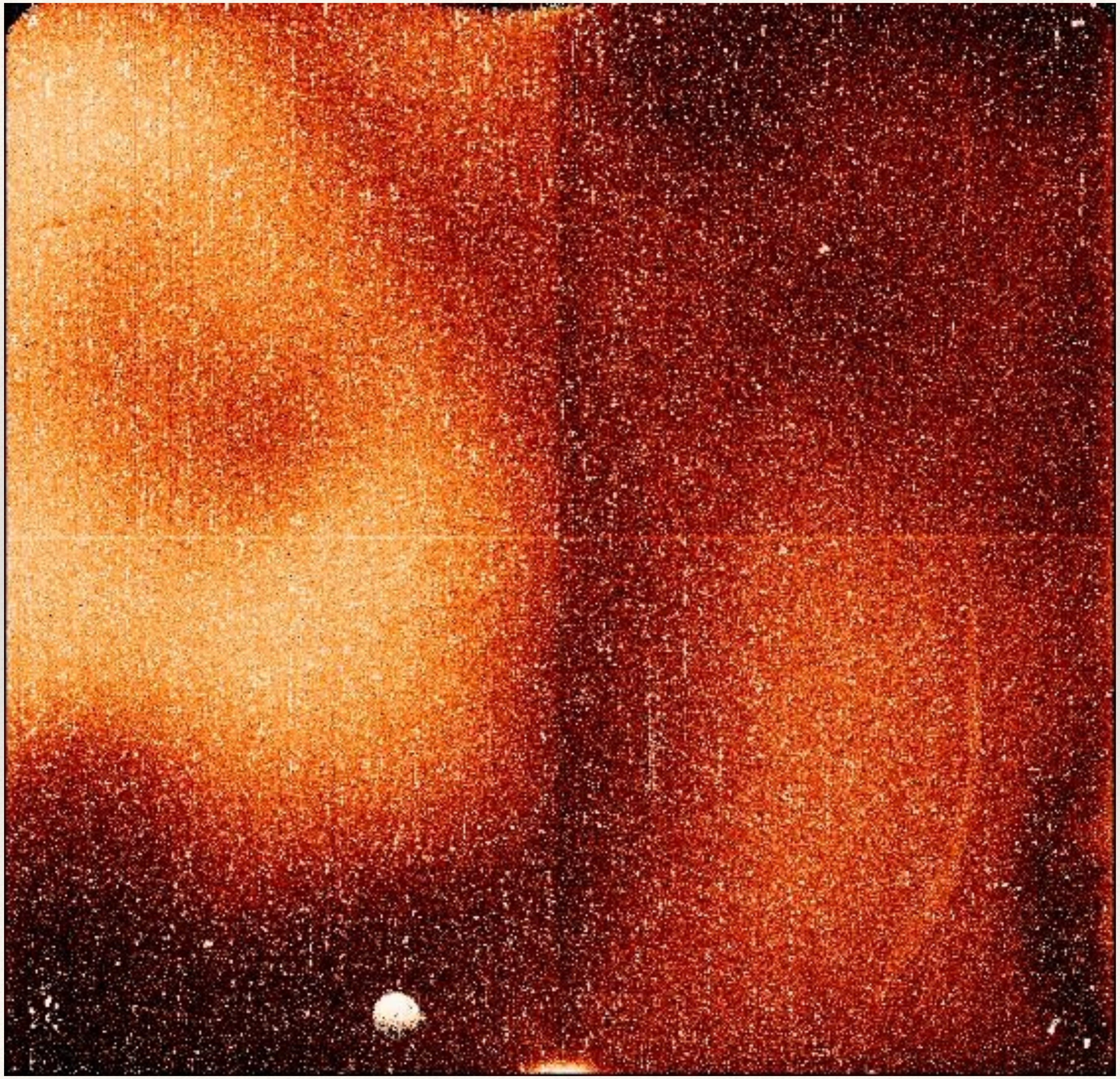
Data reduction steps: dark

'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

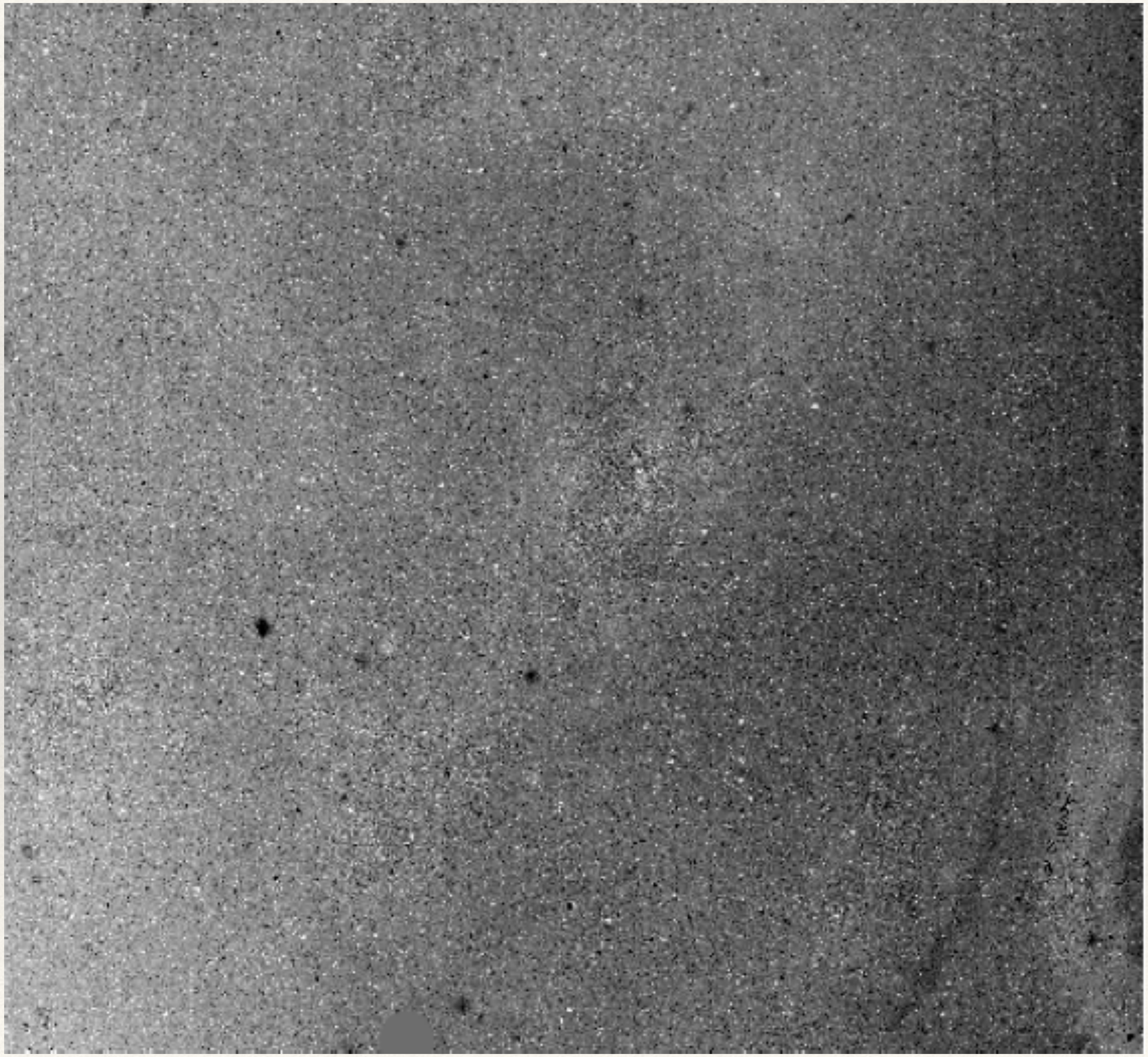


Data reduction steps: flat

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

Data reduction steps: flat

HST-WFC3
Flat field



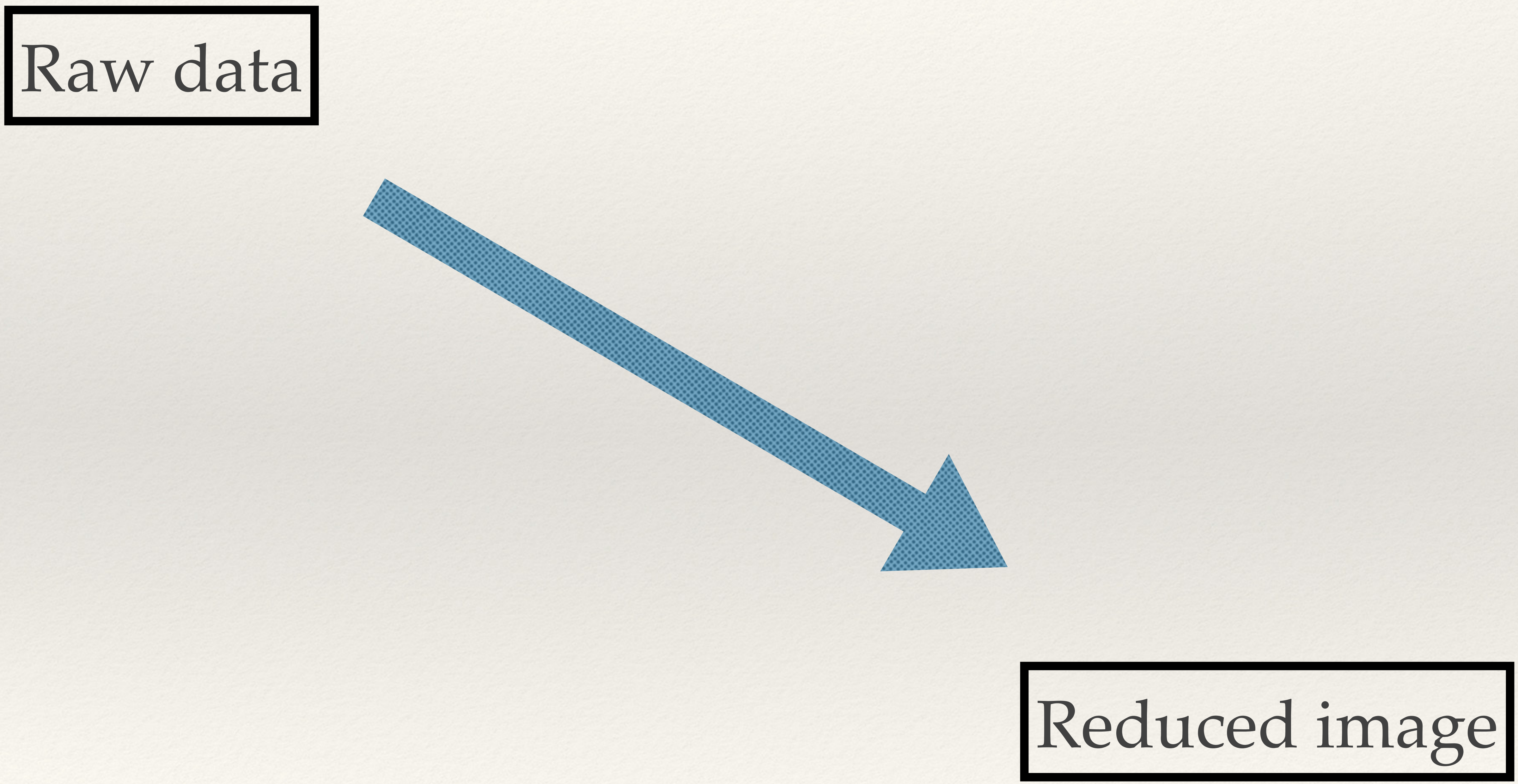
Data reduction steps: flat

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

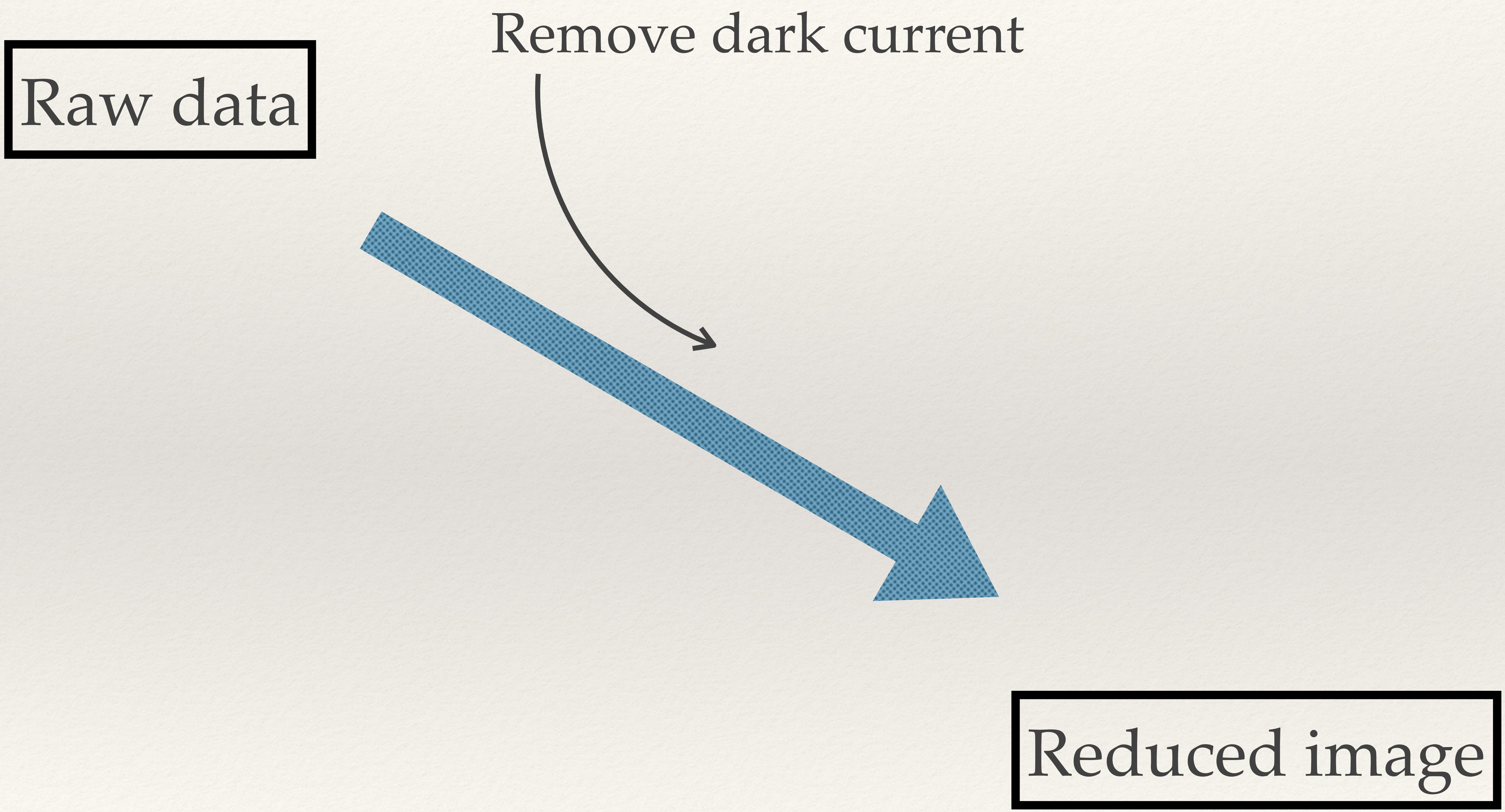
These are typically the inside of the telescope dome (‘dome flats’), or the twilight sky (‘sky flats’)

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

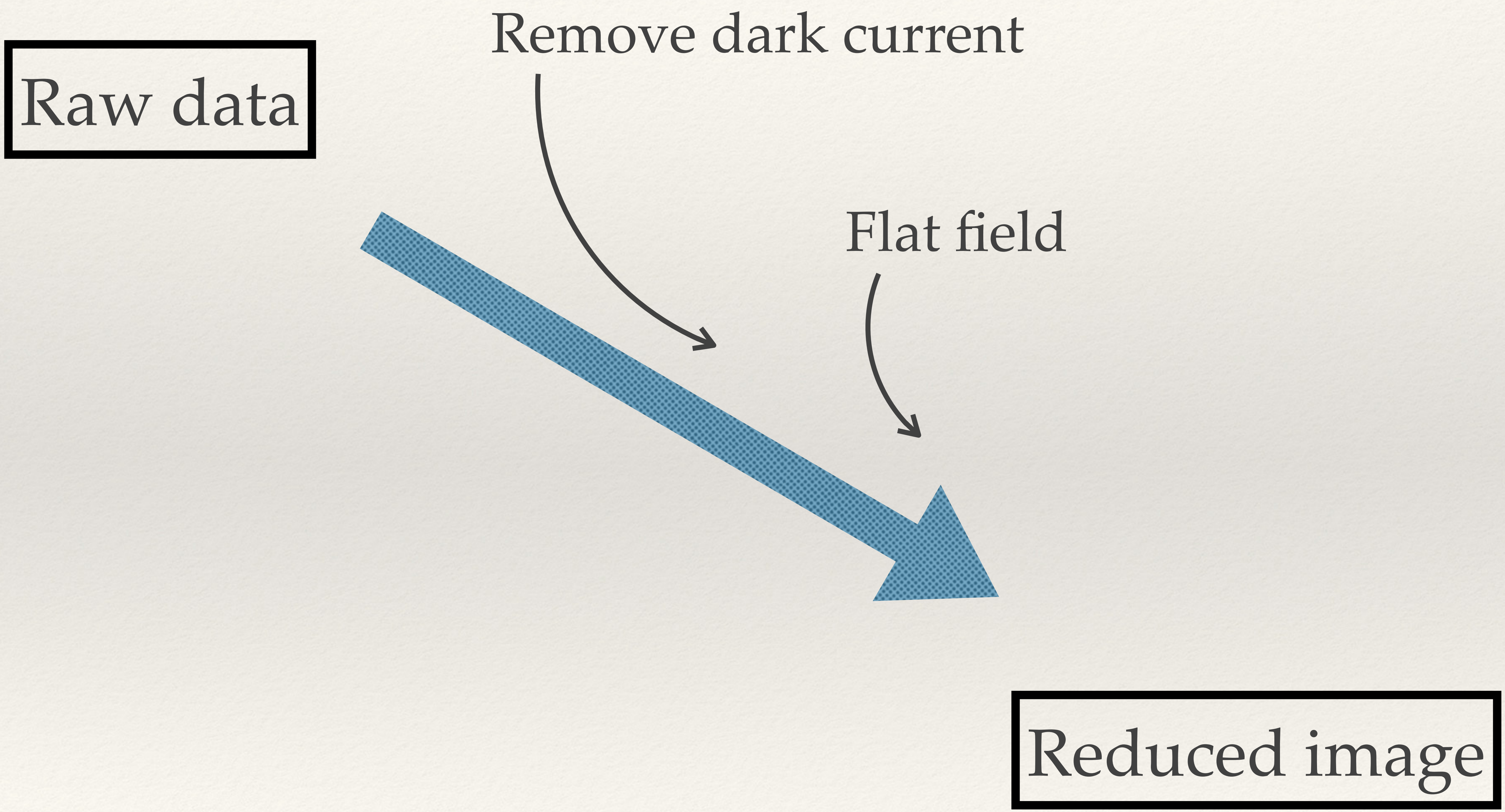


Image stacking

- 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

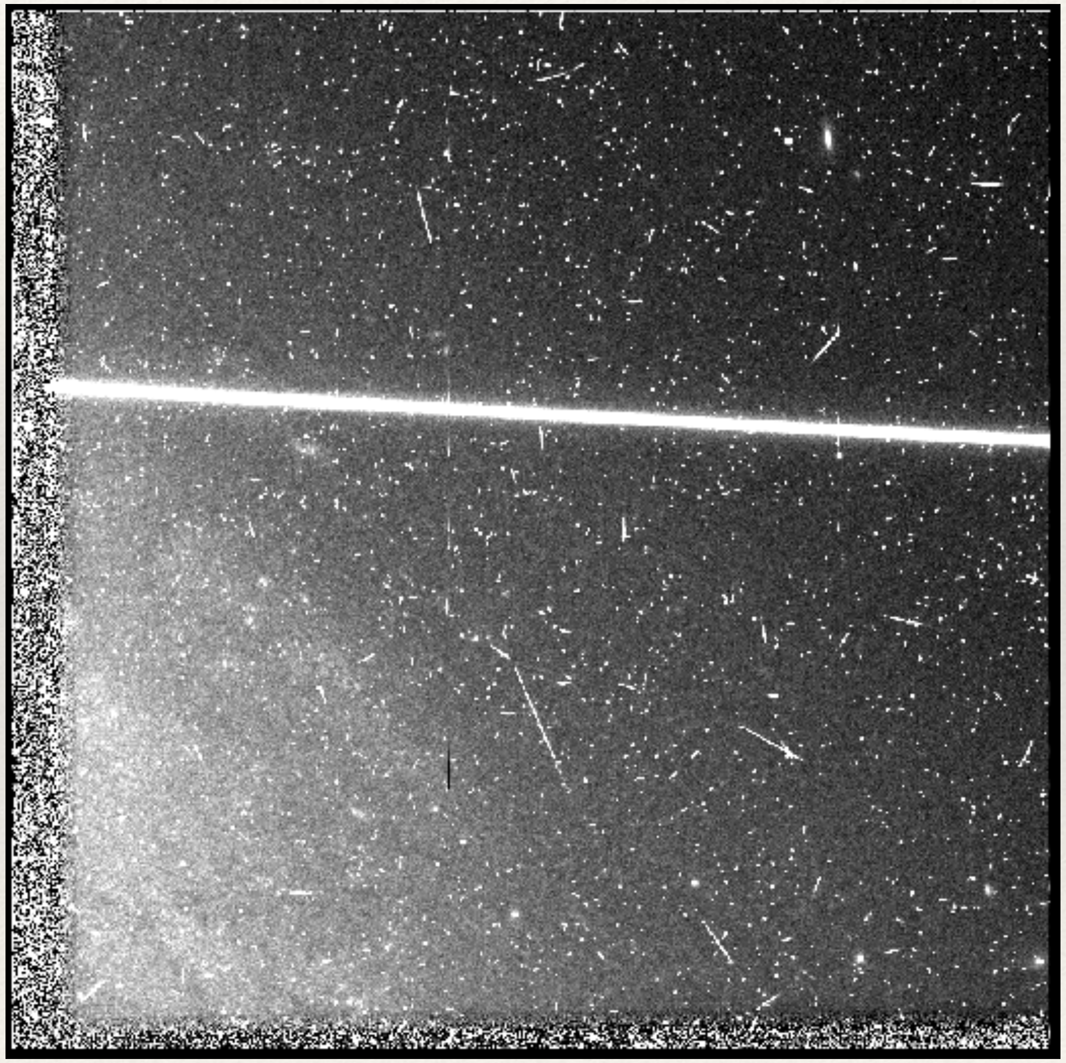


Image stacking

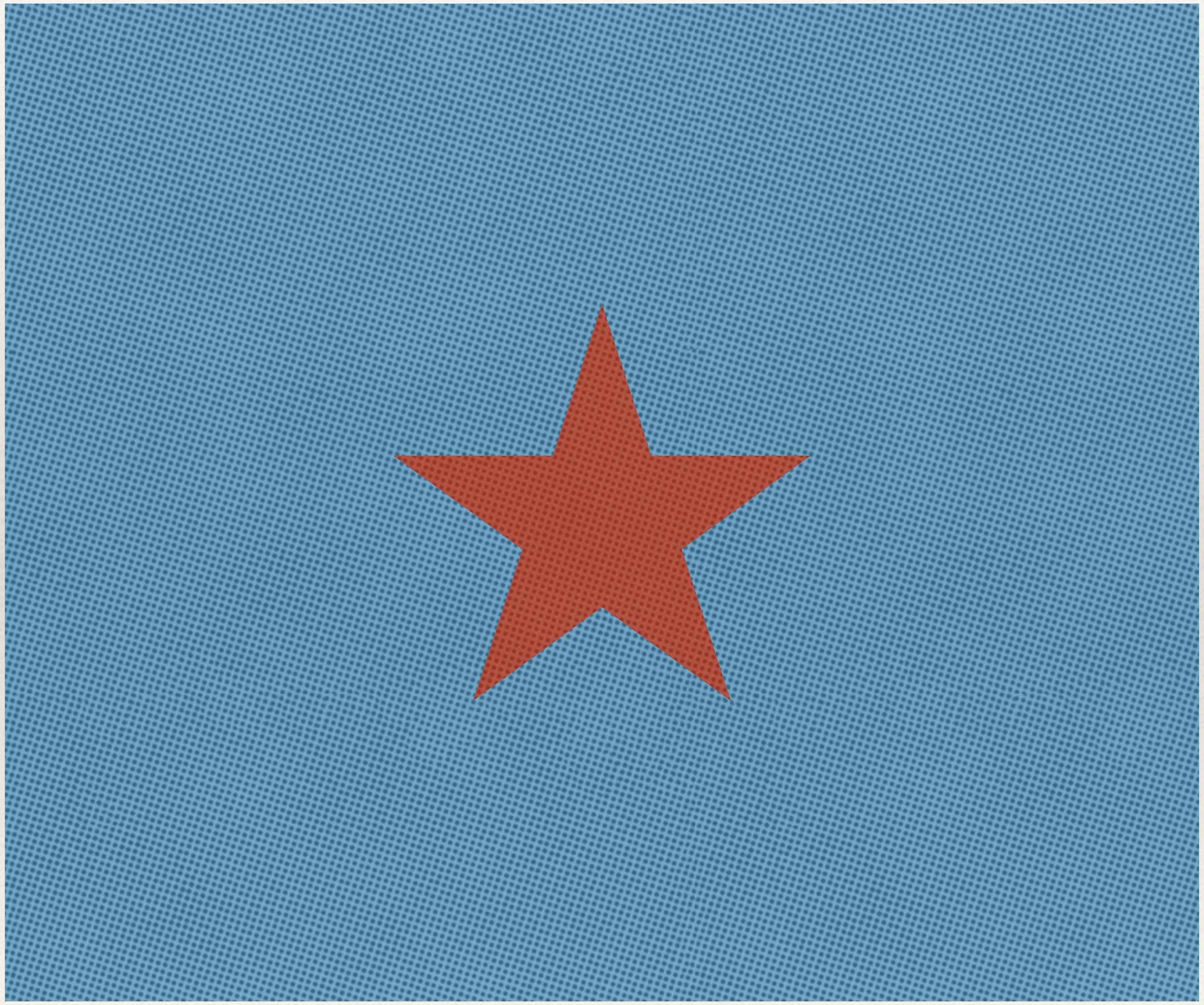


Image stacking

Area containing SIGNAL will always contain signal with repeated observations

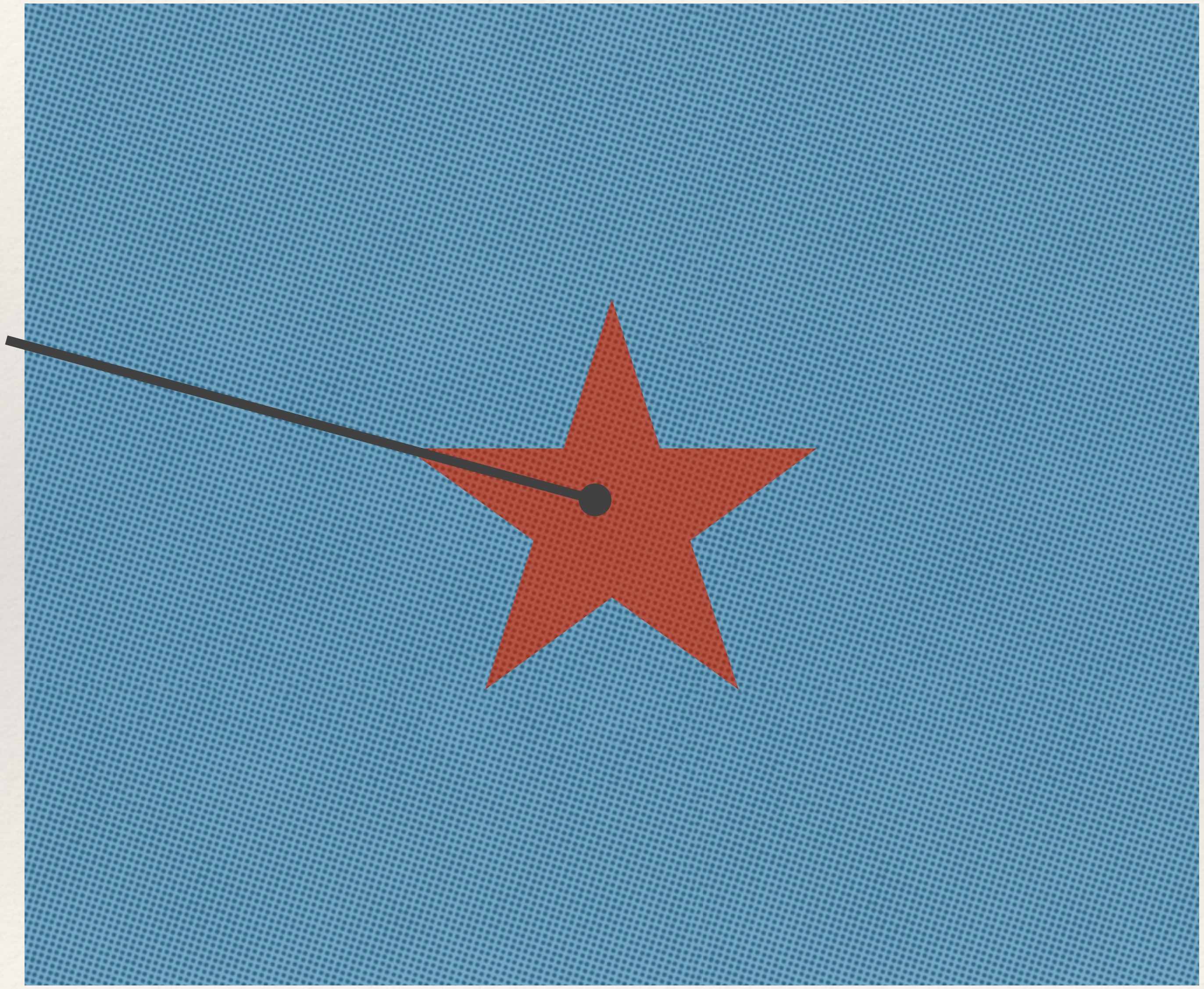


Image stacking

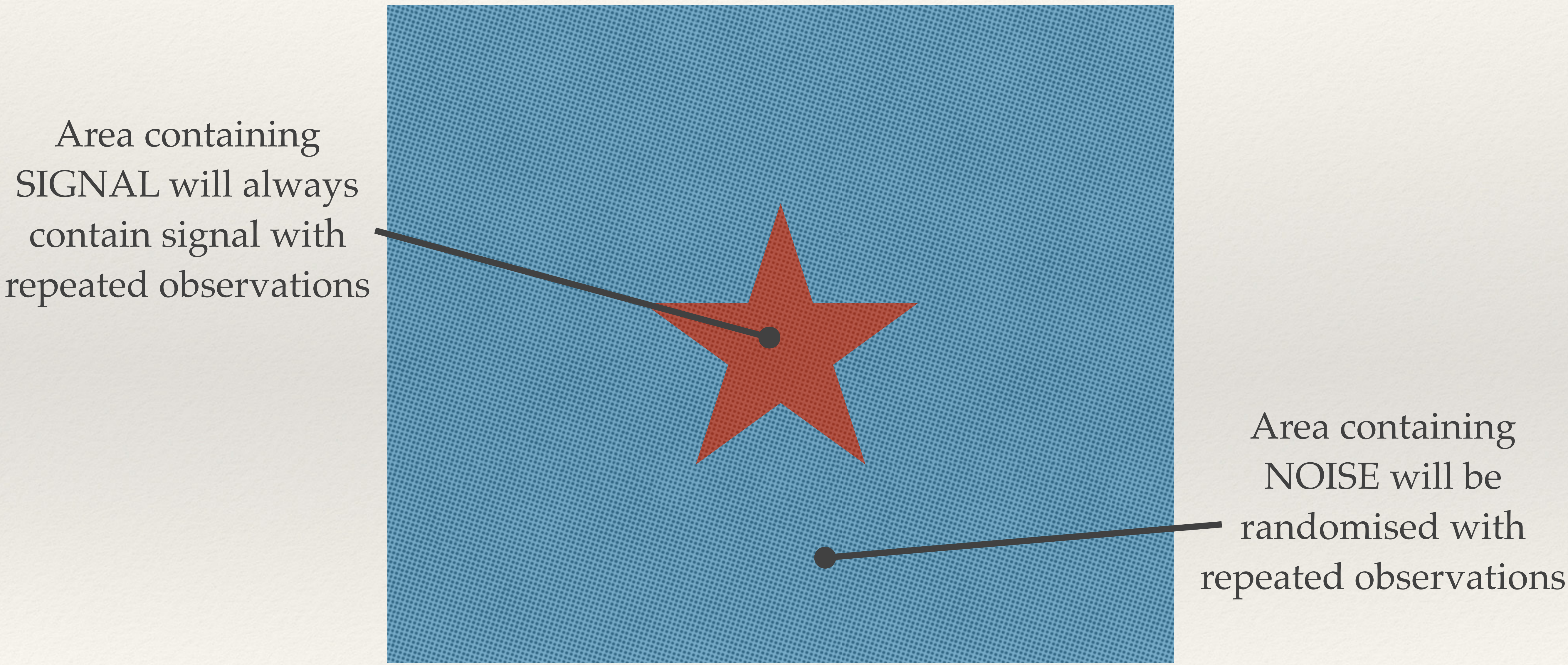


Image stacking

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

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

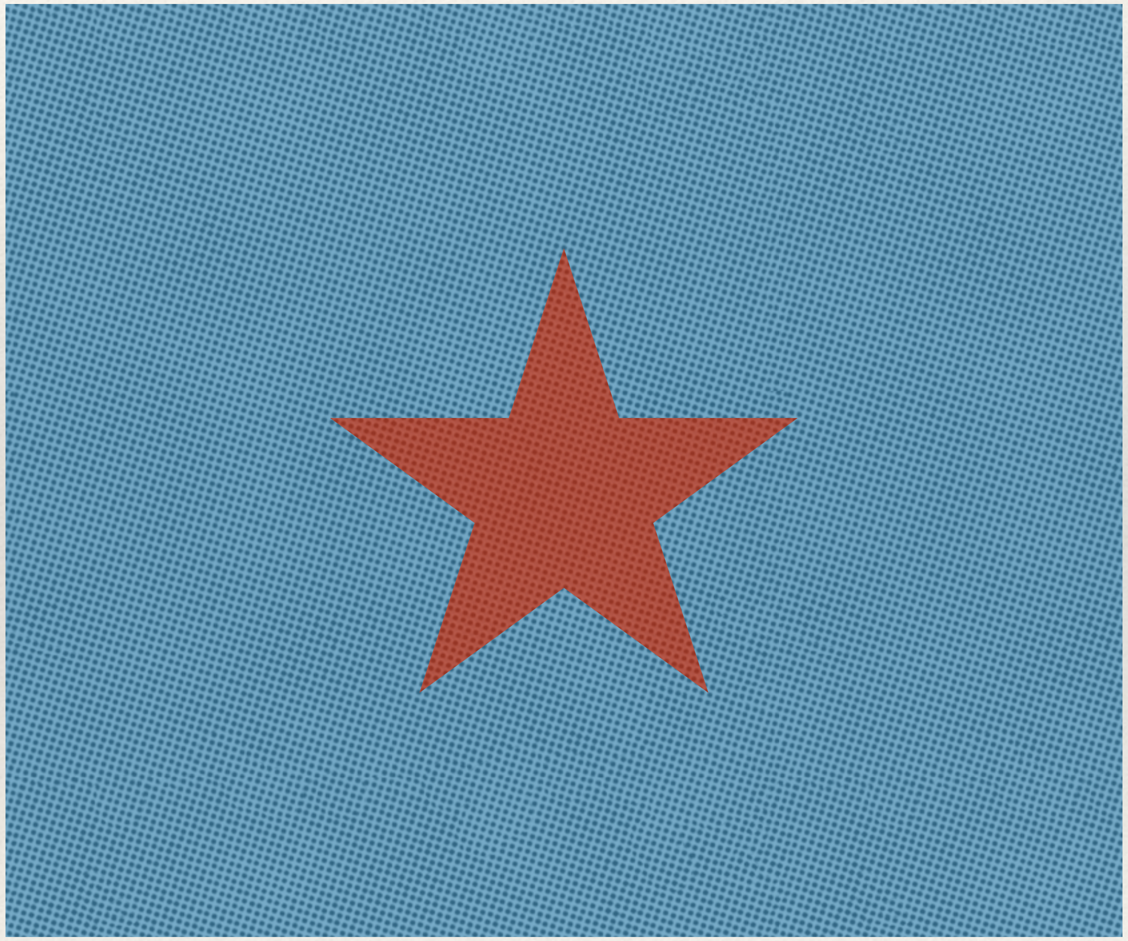


Image stacking

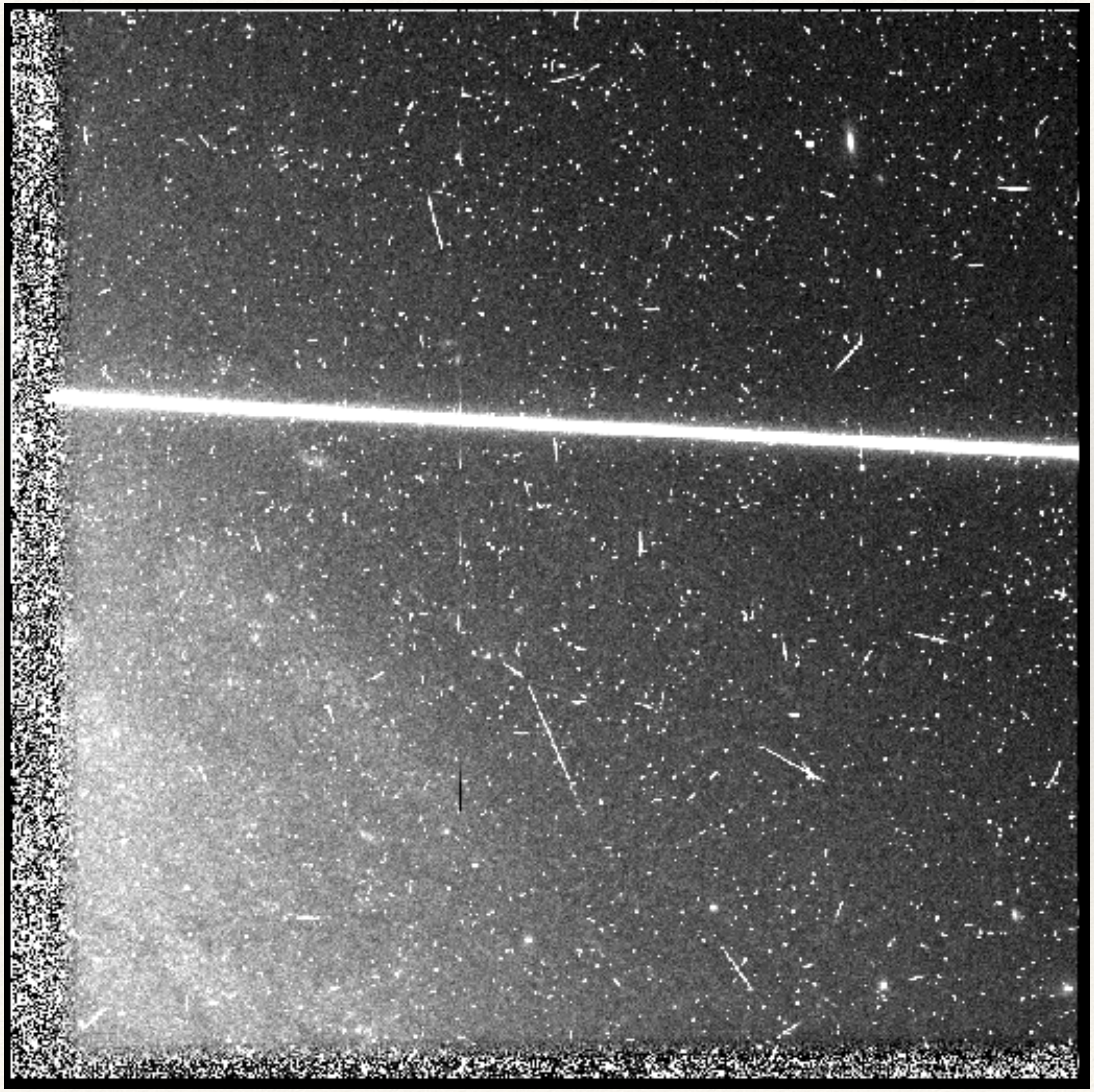


Image stacking

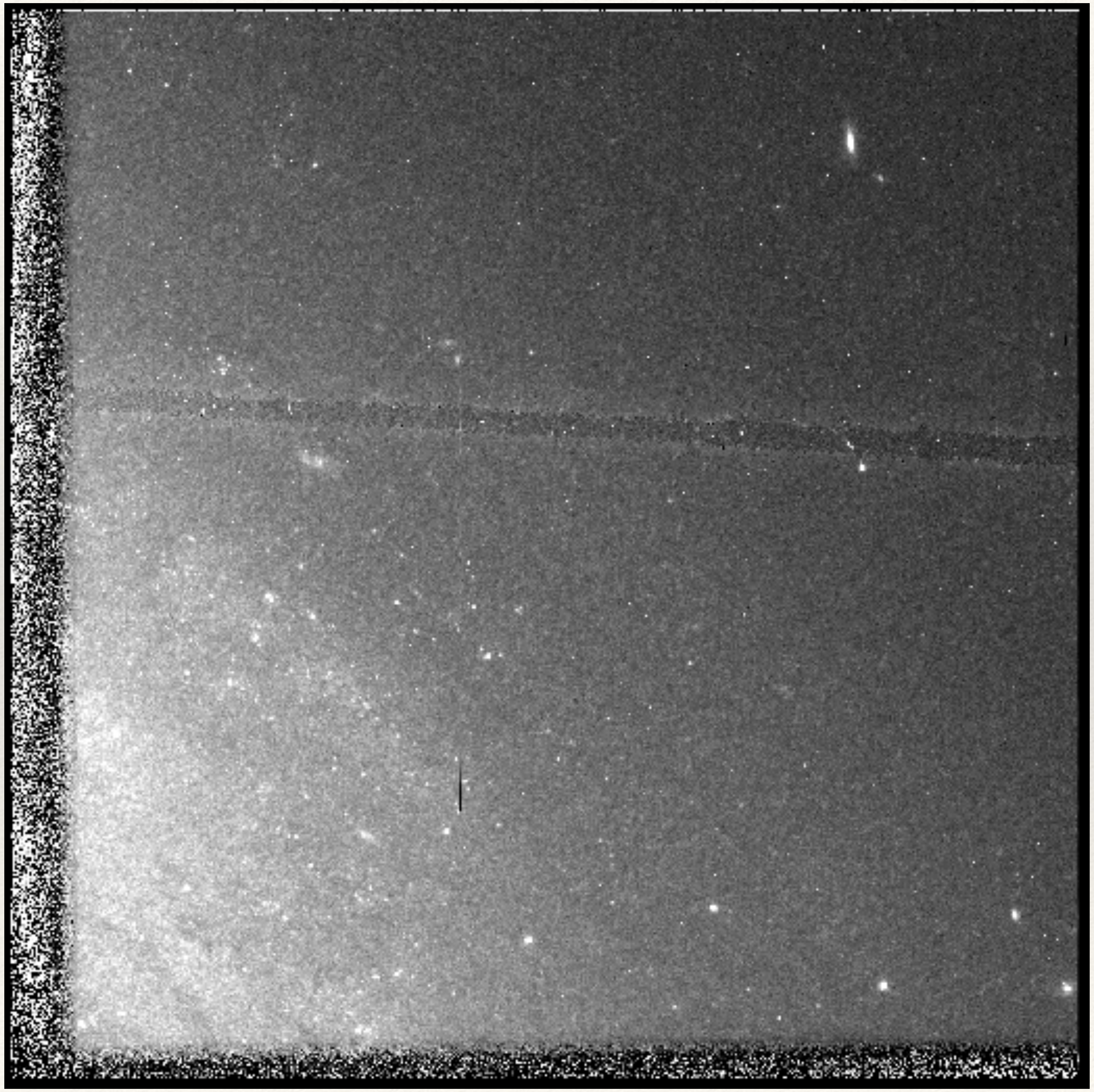


Image stacking

Optical astronomy II: summary

- Photometry (Filter systems)
- Spectrometry, spectrographs
- Data reduction