PHYS 7810: Solar Physics with DKIST

Lecture 2: Measured Quantities and Intro to Telescopes

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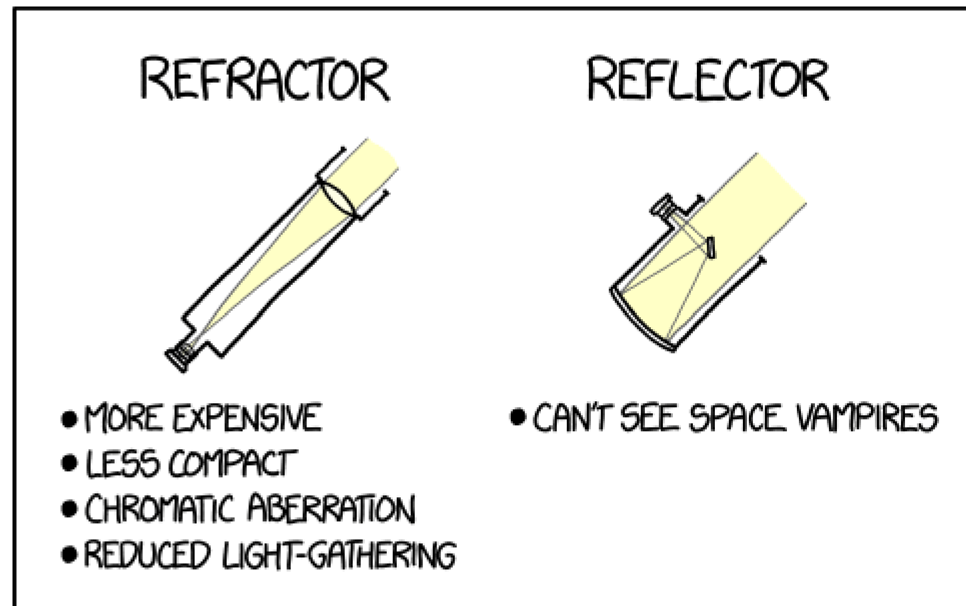
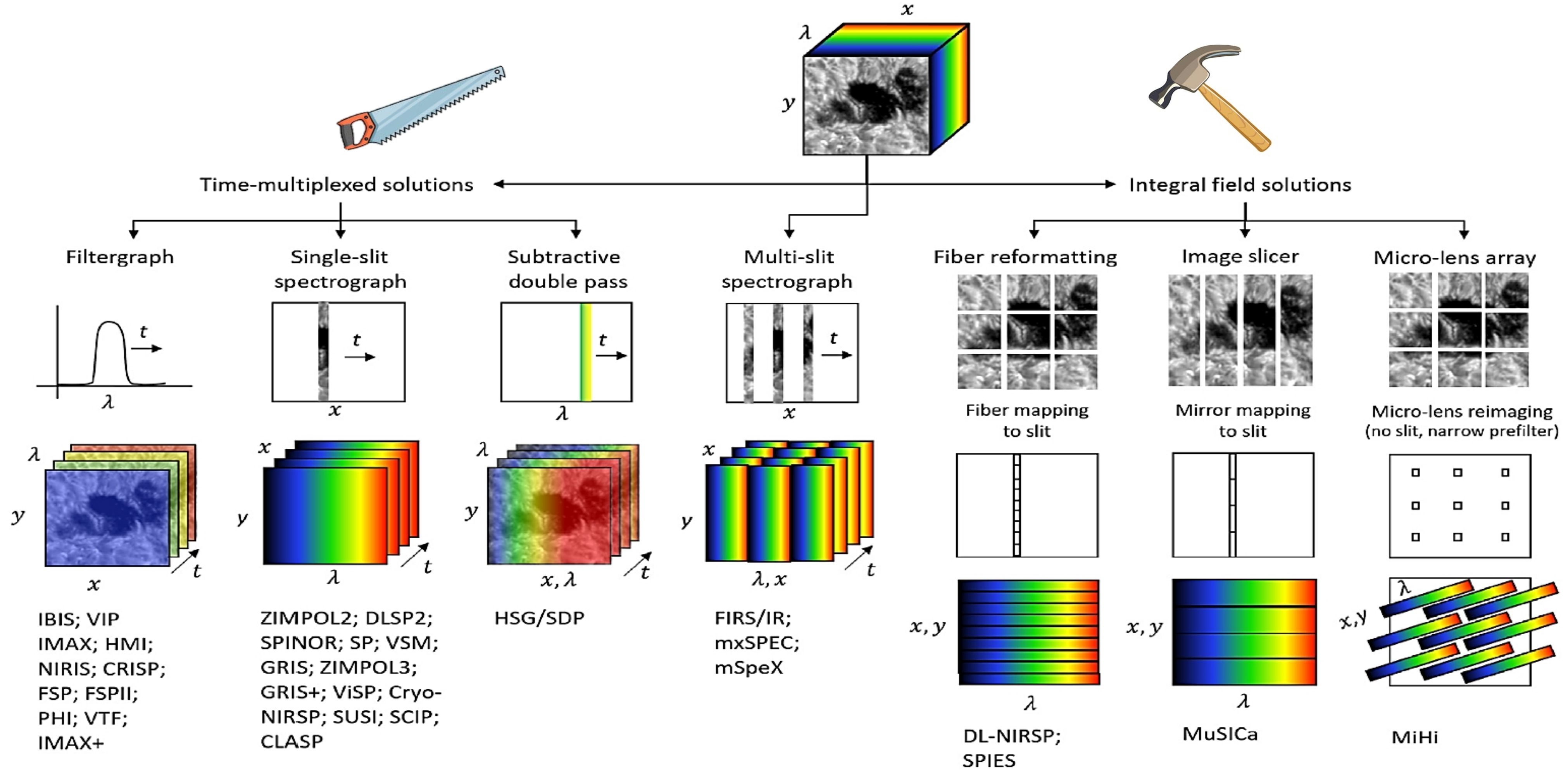


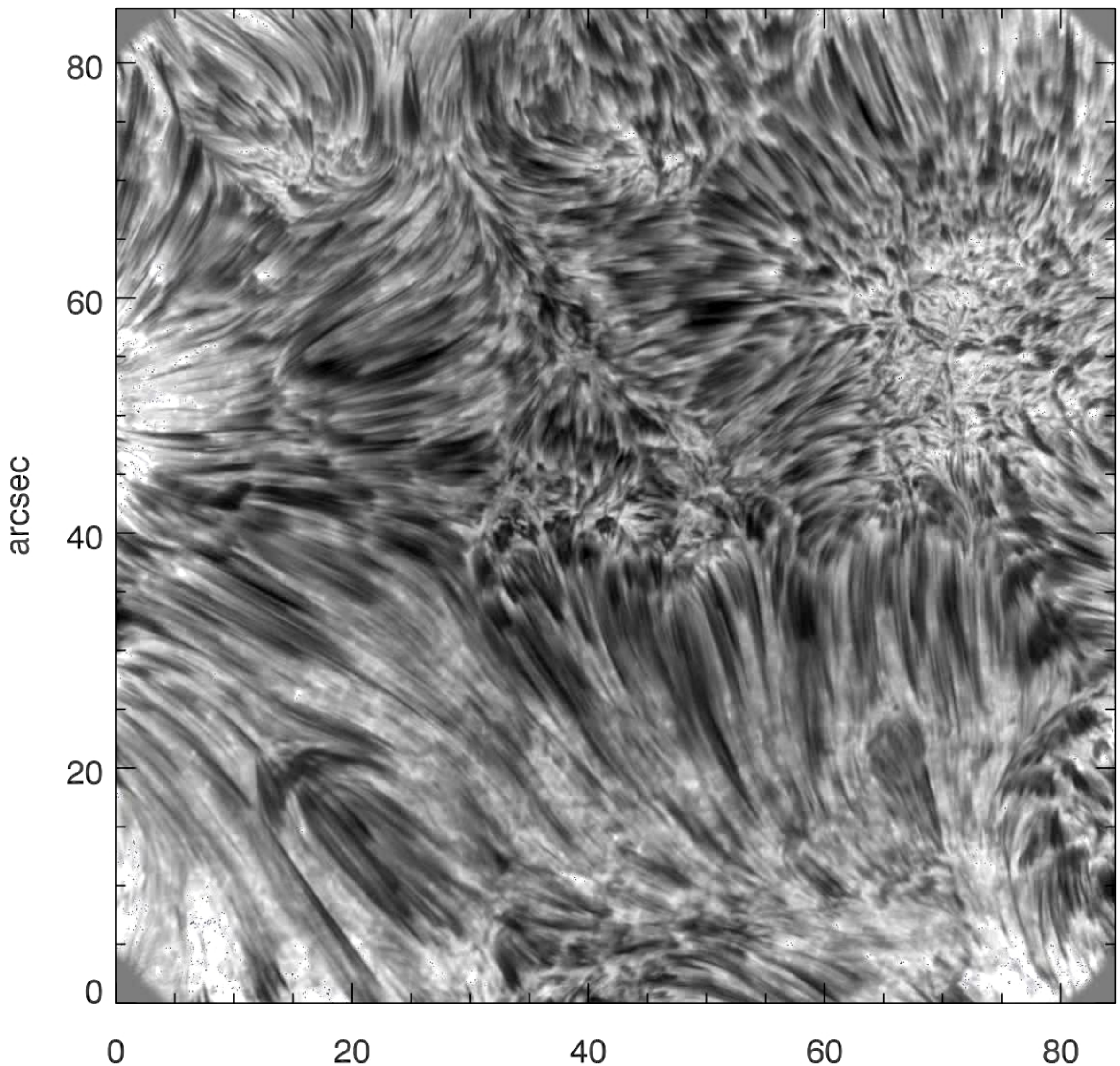
Previous class

- We discussed the structure of the Sun very briefly and focused on the fact that the light that we directly receive comes to us from **the atmosphere.**
- We discussed few physical phenomena that happen in the atmosphere.
- We emphasized that we need specifically designed observations to understand the phenomena (spectra in case of granulation, spectra/polarization in case of the sunspots, polarization in case of prominences, etc.)
- I stressed (perhaps annoyingly much) the importance of having multiwavelength observations.
- These can be images in **different filters (e.g. SDO),** or, when we do spectroscopy, **3D datacubes.** (two spatial coordinates + wavelength, HINODE, various ground based data).

Spectroscopic mapping



Example of a “datacube”:



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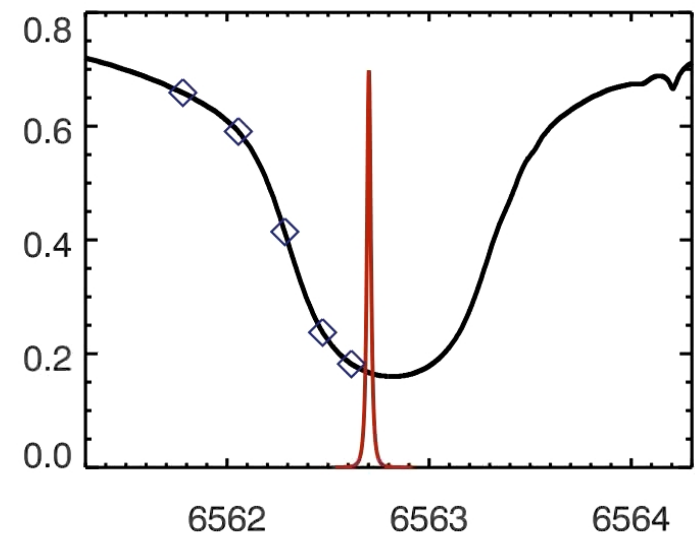
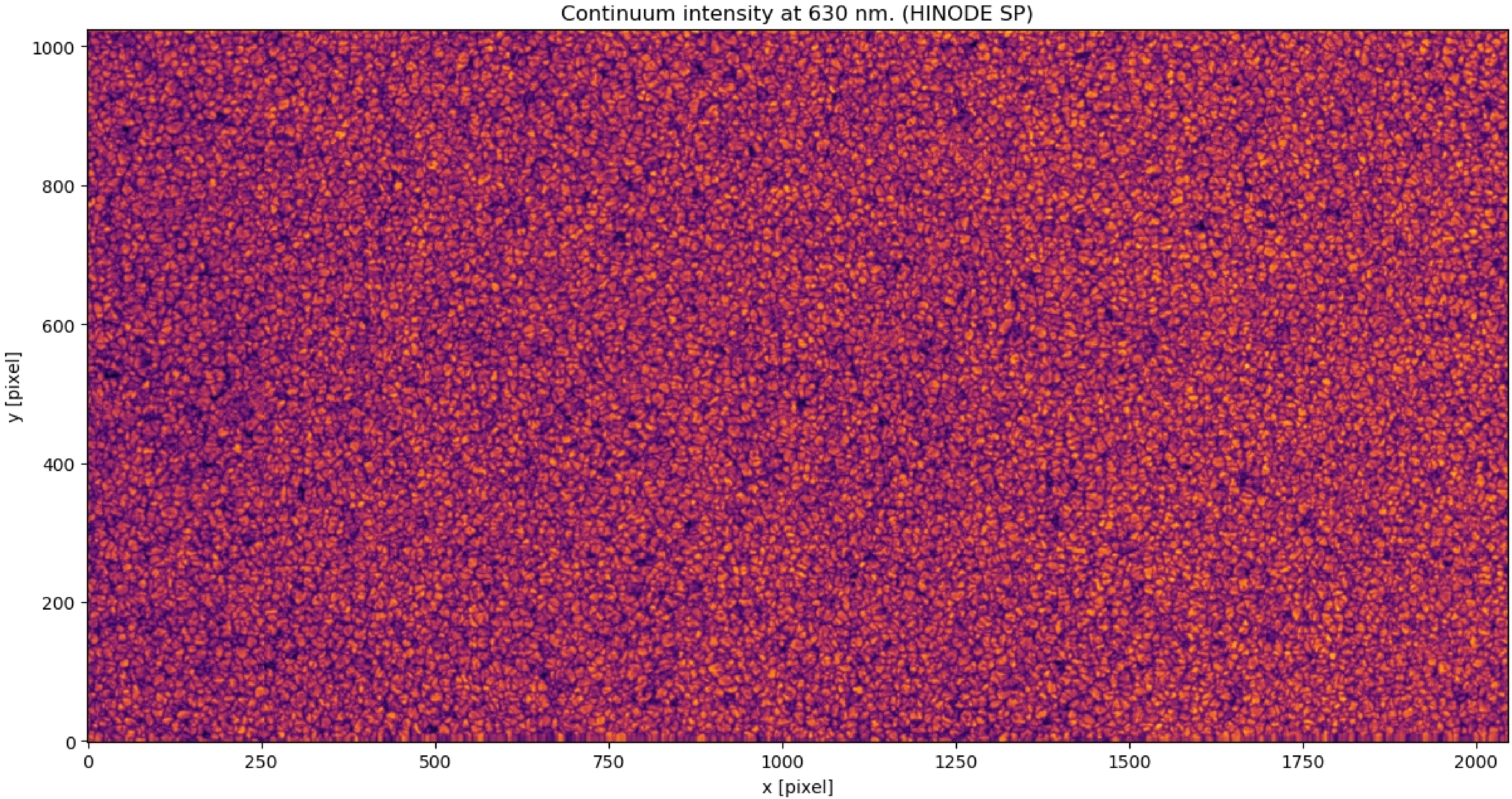


Let’s try and infer “something” from this plot:

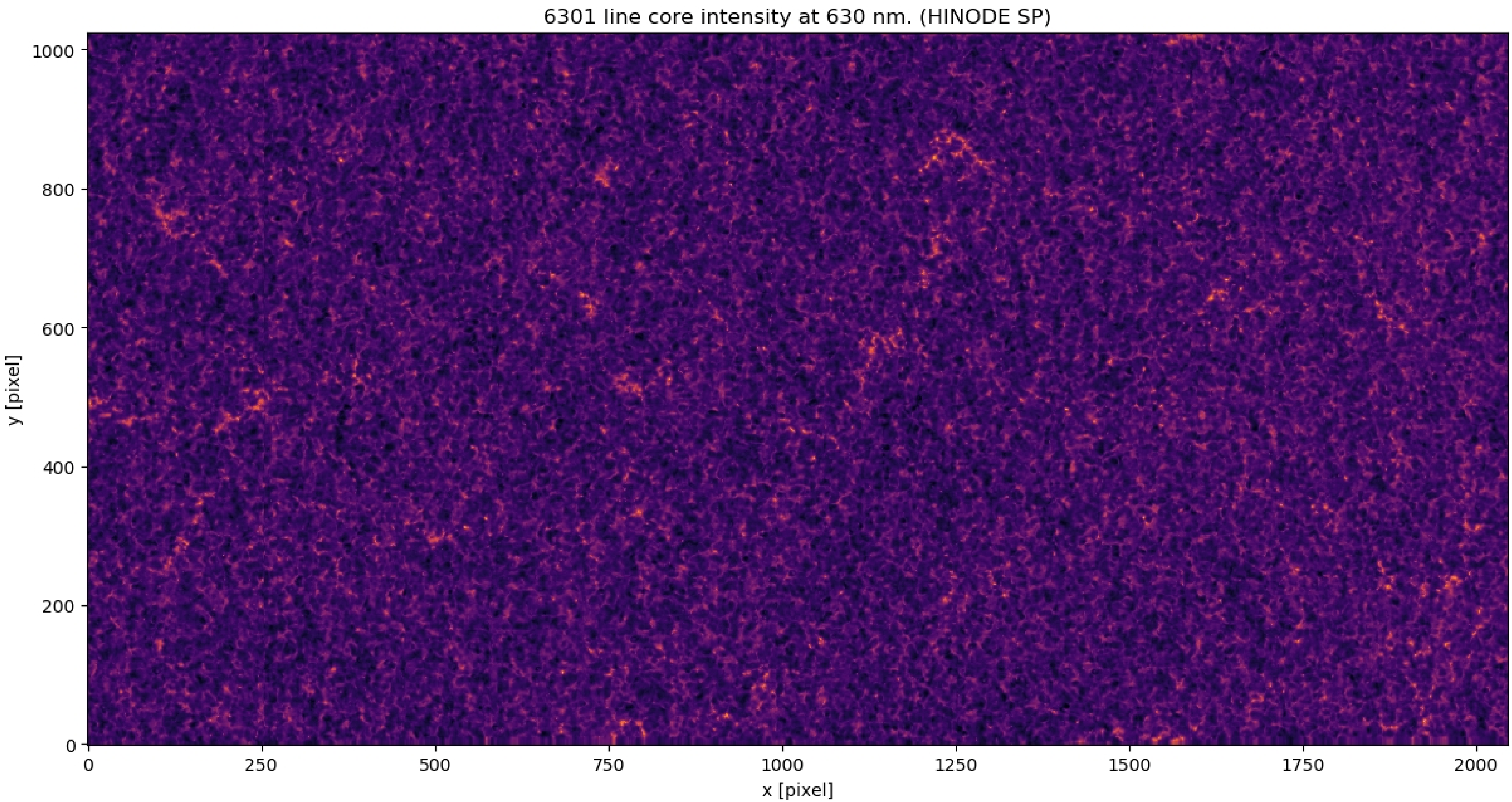


How would you proceed?

$$I_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

- Zeroth level approximation would be to say the atmosphere radiates as a blackbody.
- But how to infer the specific intensity?
- Compare intensity at each pixel to the mean quiet Sun intensity and infer temperature that way?
- What are the problems of this approach.
- What about looking at this figure at a different wavelength?

What could you infer from this intensity?

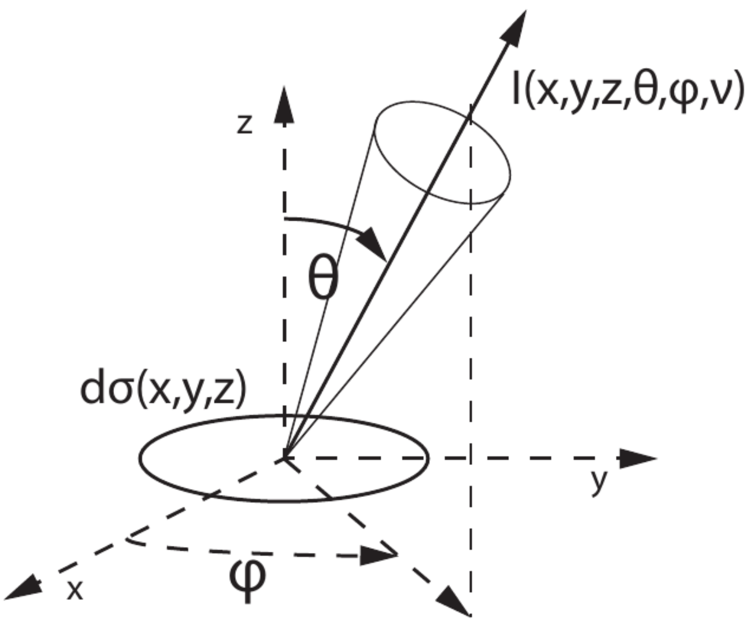


What do we want to measure : Specific monochromatic intensity

$$I_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

This is the intensity corresponding to a specific approximation (blackbody)

- Let's work out the units for this together and understand what it tells us.



This is the definition:

$$I_\lambda = \frac{d^4 E}{d\sigma \cos\theta \, dt \, d\Omega \, d\lambda}$$

$$[I] = \left[\frac{\mathrm{J}}{\mathrm{m}^2 \, \mathrm{s} \, \mathrm{srad} \, \text{Å}} \right]$$

Let's see if we understand what this means

- Specific monochromatic intensity perpendicular to a given pixel (100 km x 100 km) in given direction at wavelength of 630 nm is 2E13 in SI units.
- How would you go on about estimating total number of photons leaving that surface in the given solid angle (say, 5E-22 srad), in a wavelength band 0.01A wide, in one second? *(take 5 mins to solve this one)*

$$N = \frac{E}{hc/\lambda} = I \times \Delta\sigma \times \Delta\Omega \times \Delta\lambda \times \Delta t$$

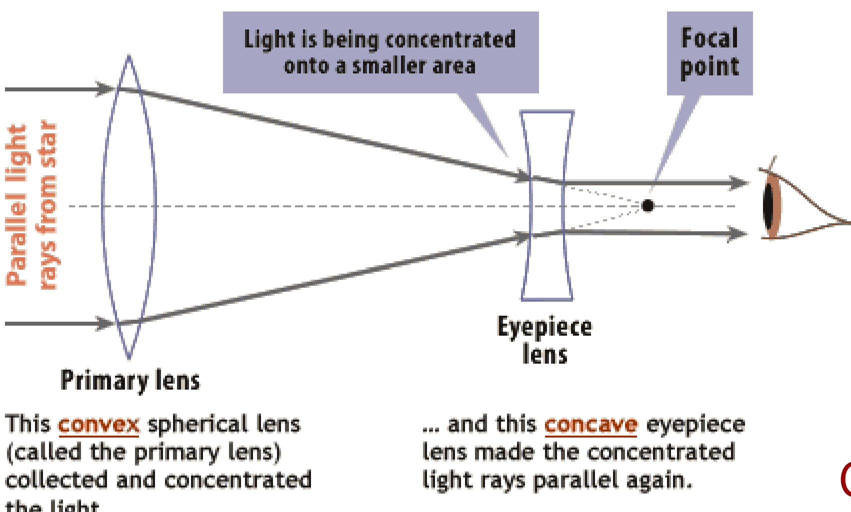
Right, the result is: ~ 4E8

The reason why I chose these specific numbers will become clear soon ;)

How the telescopes work, a rough sketch

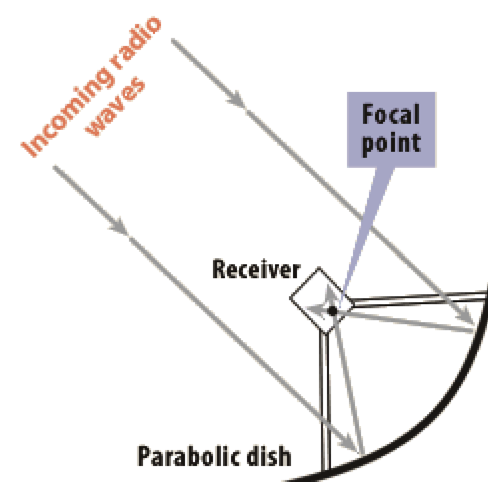
Why don't we use our eyes for solar observations?

- Telescopes have better "resolving power" (can see smaller details, more about this in the next class)
- Telescopes can collect more light.
- We can hook up various instruments to the telescope and measure spectral distribution and polarization.
- Telescopes have good pointing ;)



Courtesy NRAO

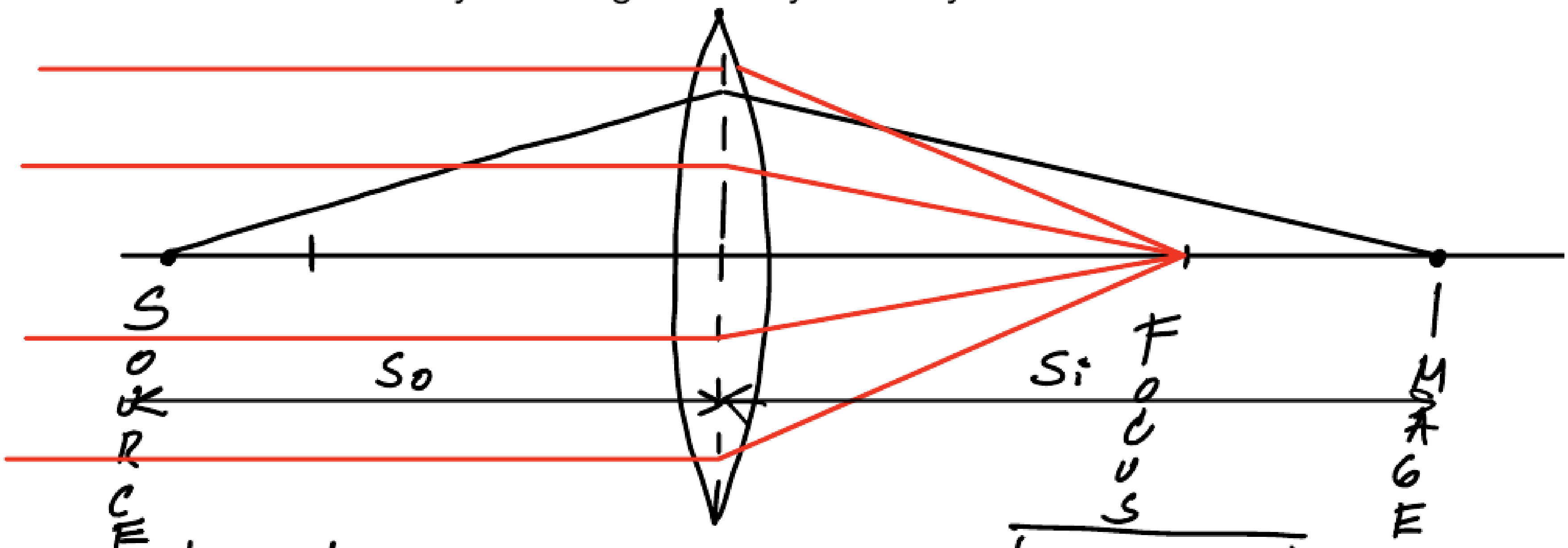
The Very Large Array in New Mexico



Credits : amazing SPACE

Image formation – imagine a telescope as a lens

We are interested in the rays coming from very far away

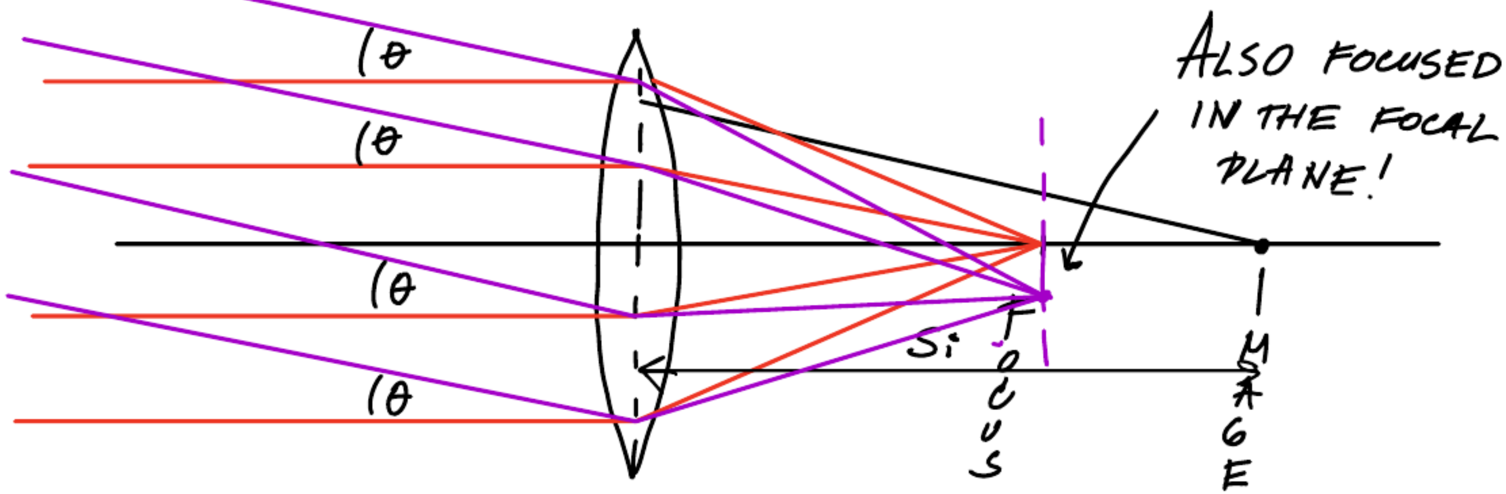


$$\frac{1}{f} = \frac{1}{S_o} + \frac{1}{S_i} \Longrightarrow S_o = \infty \quad \boxed{S_i = f}$$

This tells us where the light is going to be focused. For the Sun. Source is infinitely far away. So, the rays, coming from **a given direction** are focused into **a point** in the focal plane.

Image formation – imagine a telescope as a lens

Now, if we have the light coming from **two different directions**, it is going to be focused in **two different points.**
(This is how spherical lenses work, convince yourself using symmetry).

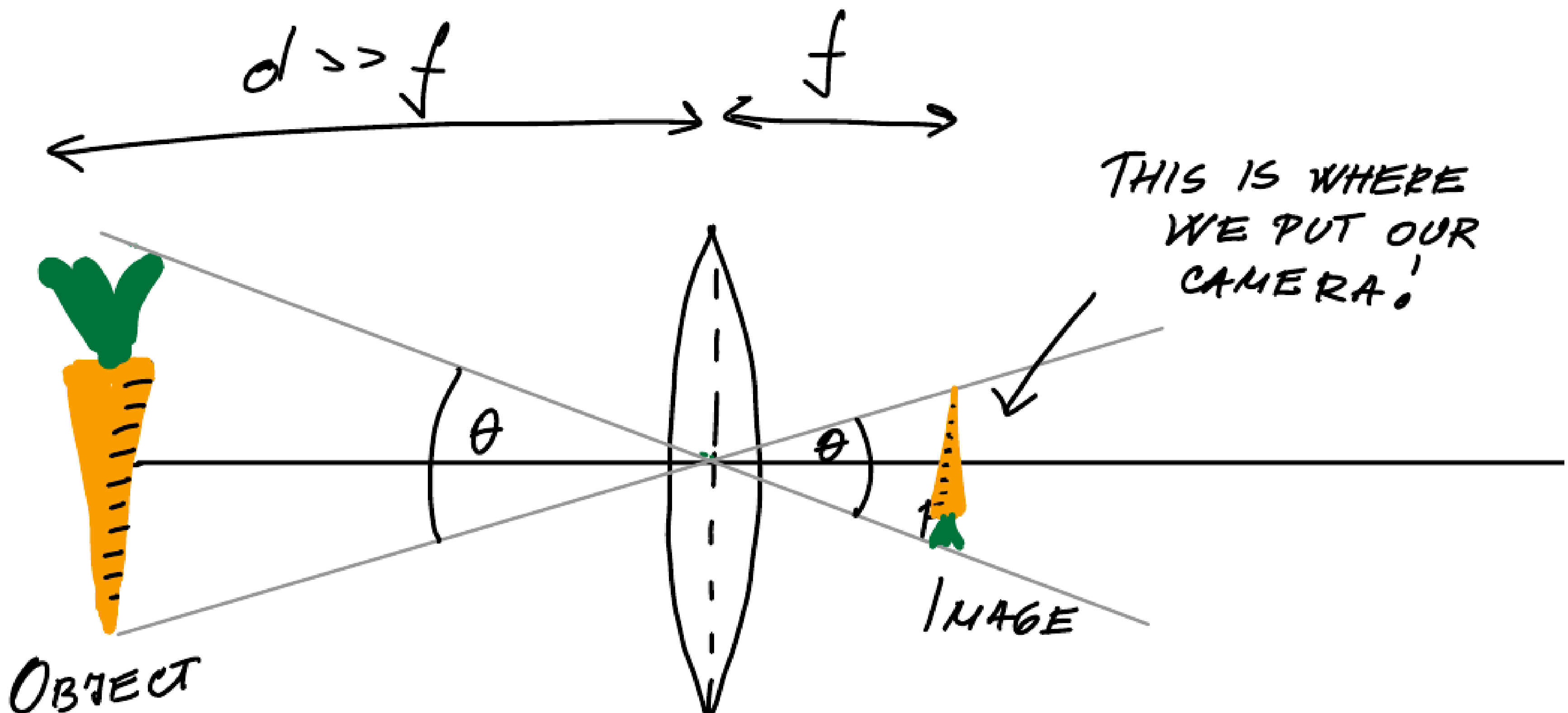


ANGULAR DISTANCE BETWEEN PURPLE AND RED SOURCE IN THE SKY IS θ.

PHYSICAL DISTANCE BETWEEN THEIR IMAGES : $\theta \cdot f$

Image formation – imagine a telescope as a lens

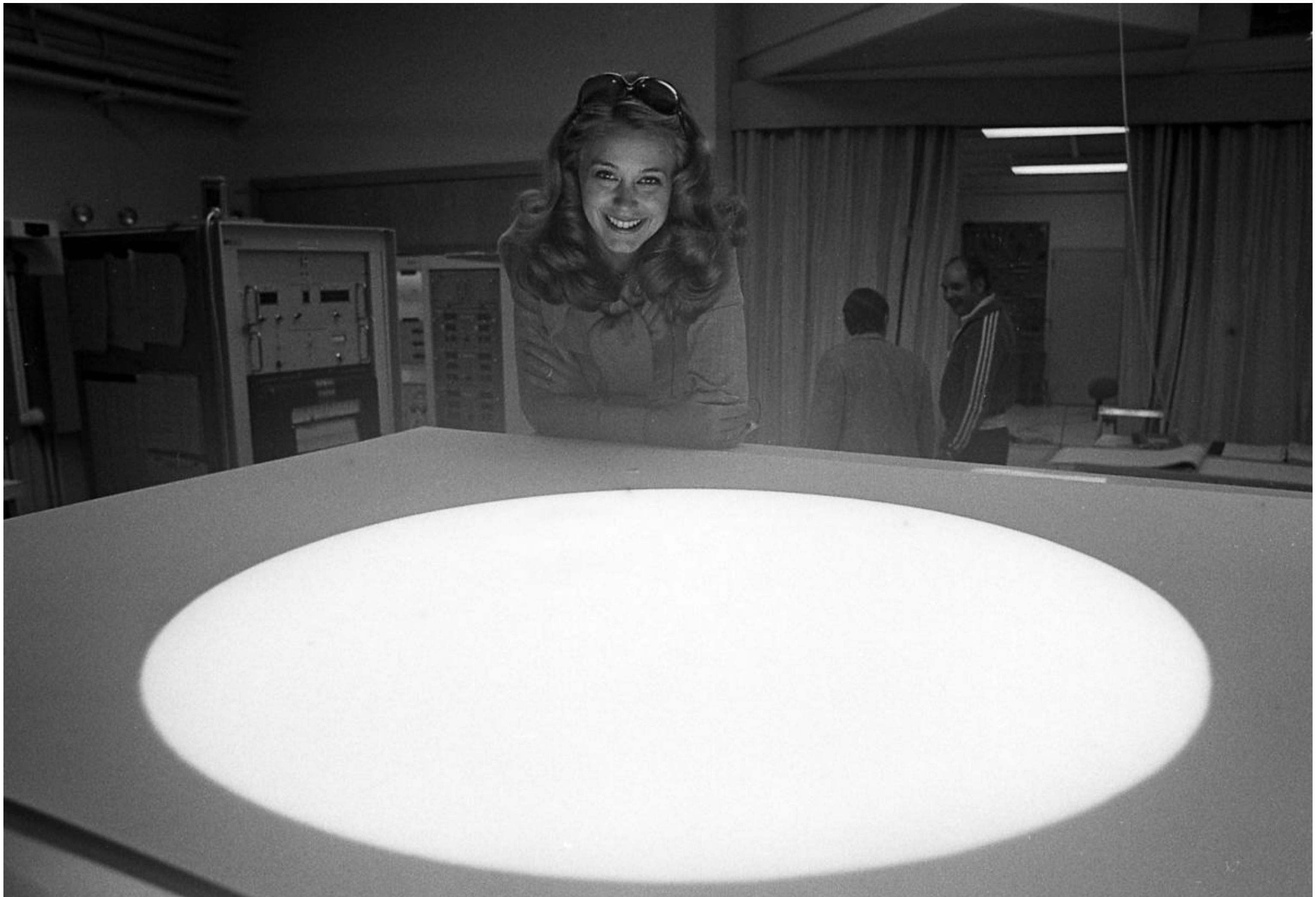
So the **image** of an finite object very far away (not saying infinite on purpose), is going to be formed in the focal plane. **That is where we put our detector.**



Differences between points and finite objects

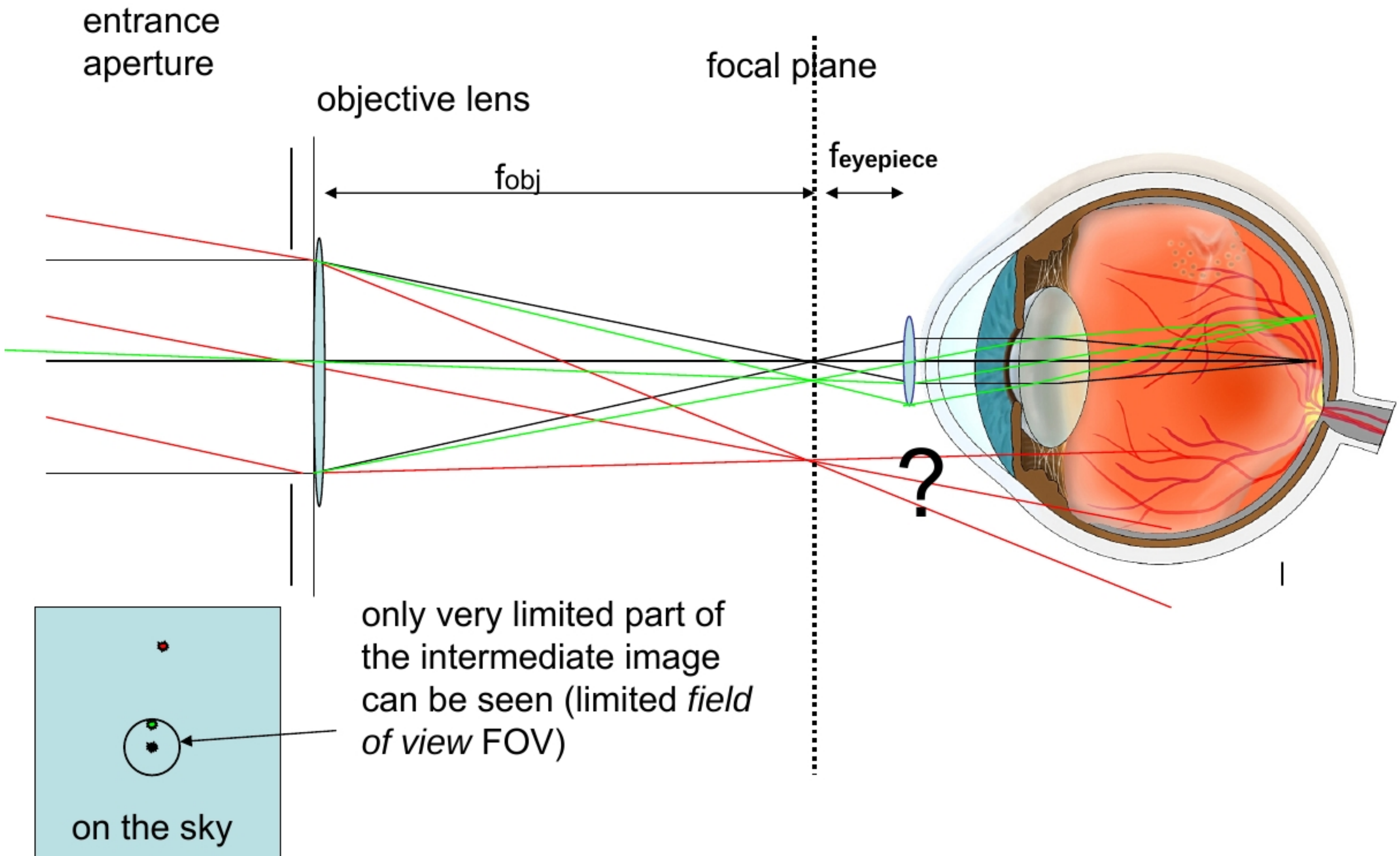
- Stellar image (point) brightness scales as D^2, because the source is neverresolved (D is the diameter of the telescope).
- However, for finite objects, size of image scales with the focal length, so, greater f, smaller image brightness. Scales as (D/f)^2
- In photography, we call D/f – aperture
- In astronomy – f-ratio (f/D)
- High f-ratio – slow system (needs long exposure, but image is bigger, and less heating)
- Low f-ratio – fast system (surprise, surprise, allows fast exposure, but image is smaller, we need to think about limits of our detectors)

For slow telescopes, image can be really big:



Credits : McMath Pierce
Solar Telescope

A telescope we are used to (aperture lens + eyepiece)



only very limited part of the intermediate image can be seen (limited *field of view* FOV)

Credits : Achim Gandorfer

In real telescopes

- Primary telescope focusing elements are mostly mirrors (although for example, SST uses a lens)
- There is more than one focus (this means we have a system of lenses and mirrors), and the measurements are not done in the **primary focus.** (among other things, it would be too hot!)
- Therefore, sketching out the image formation is not as trivial as we did before.
- However, we still can define “effective” focal length, from which we can deduce how is our image going to look.
- It is good to know, at least roughly, how the optics of your telescope works so you can immediately know if your scientific idea is feasible.
- Examples: we can’t look at small scale reconnection using SDO, but we also can’t look at large-scale events using DKIST instruments.

Ok let's do a little test

- Does size of the lens influence the size of the image?
- What does?
- Can you estimate the size of the solar disk as seen by a telescope with effective focal length 5m?
- Typical pixel size of a CCD is ~ 10 micrometers. How big CCD we need to fit the whole Sun?

The size of the solar disk in the focal plane is **4.65 cm**
We need a 4650 x 4650 pixel camera.
Actually, SDO cameras are 4k x 4k. Checks out!
What is the angular coverage of each pixel?

DKIST will have much higher effective focal length, because we want focus on the small regions of the Sun and resolve them.

For example, VBI (Visible Broadband Imager)

- **Imager** → means we are looking primarily to make images of the solar atmosphere
- **Broadband** → We focus on wide "bands" in wavelengths. For solar physics, everything over 1 Angstrom is wide :)
- **Visible** → Means we focus on visible wavelengths (DKIST can also observe in IR, not in UV though)
- Optical field of view – 2 arcmins Physical (CCD) – 45 arcsec in blue, 69 arcsec in the red

Spectral Range and Resolution

Within each channel, images at multiple wavelengths are acquired in series.

VBI Blue

Element	Central Wavelength	Full Width Half Max
Ca II K	393.327 nm	0.101 nm
G-band	430.52 nm	0.437 nm
Continuum	450.287 nm	0.41 nm
H-beta	486.139 nm	0.0464 nm

VBI Red

Element	Central Wavelength	Full Width Half Max
H-alpha	656.282 nm	0.049 nm
Continuum	668.423 nm	0.442 nm
TiO	705.839 nm	0.578 nm
Fe IX	789.186 nm	0.356 nm

Credits: www.nso.edu

From emergent intensity to our detector

- Specific monochromatic intensity: energy transported per oriented unit surface, per unit solid angle, in unit time, per unit wavelength.
- If we integrate emergent intensity over angle, wavelength, surface and time we are going to get some **energy.** This integration depends on **sampling.**
- Typically, we integrate over small angle, wavelength, surface and time so we can assume our intensity is constant there.
- Divide that with an energy of a single photon, we get the number of photons.
- These photons eventually get collected by our telescope and detected by our CCD. i.e. they are turned into **digital counts.**
- (This is the ideal case. Photons are lost in the atmosphere, telescope, instrument + CCD does not have 100% efficiency).

So, what does our signal depend on

- Size of the emitting region $\rightarrow$ i.e. spatial sampling. If we divide the Sun in small chunks, we will get less photons per chunk.
- Wavelength band $\rightarrow$ wide bands give us more photons. High spectral resolution gives us less photons (per wavelength chunk).
- Integration time $\rightarrow$ bigger temporal chunk - more photons.
- Solid angle $\rightarrow$ Bigger telescope spans greater solid angle (as seen from the Sun) $\rightarrow$ more photons. (Provided the chunk sizes are kept constant).
- By compromising on the spatial, spectral or temporal resolution we risk to miss the details of the actual physical process underneath!
- This is why we always want to build bigger and bigger telescopes, and more efficient instruments!

Some additional photometric quantities (more relevant for stars)

This is the so called (monochromatic) flux

$$F_\lambda = \oint I(\theta, \phi)_\lambda \cos\theta \sin\theta \, d\theta \, d\phi$$

$$L_\lambda = \oint F_\lambda d\sigma$$

We can call this (monochromatic) luminosity (i.e. total flux)

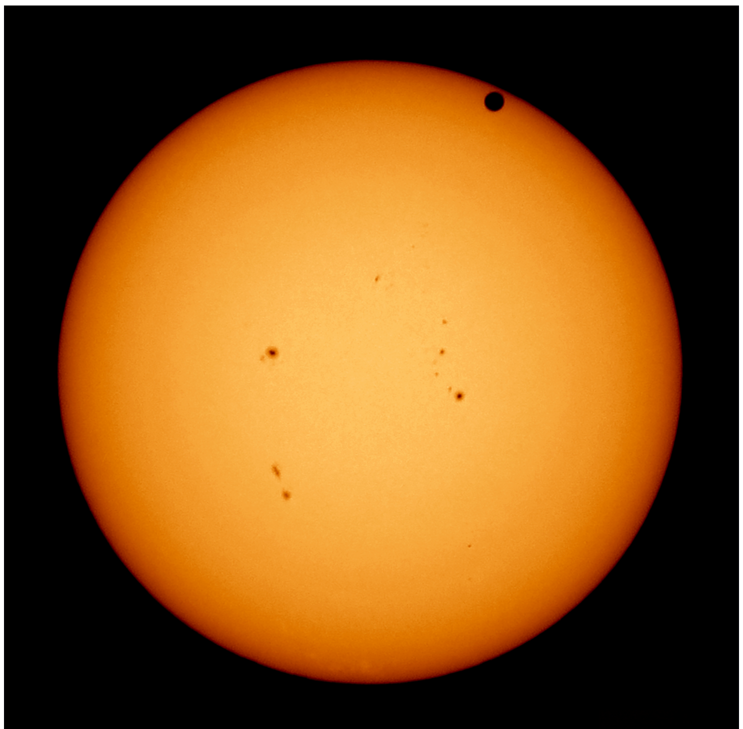
$$\epsilon_\lambda = L_\lambda / 2\pi d^2$$

This would be monochromatic irradiance. We can measure this.

Let's spend a moment discussing what are the units here, and how to describe the quantities.

Solar context

- When we look at the sun, we look at spatially, and "directionally" resolved data. So we can say that we are measuring a quantity proportional to the specific intensity.



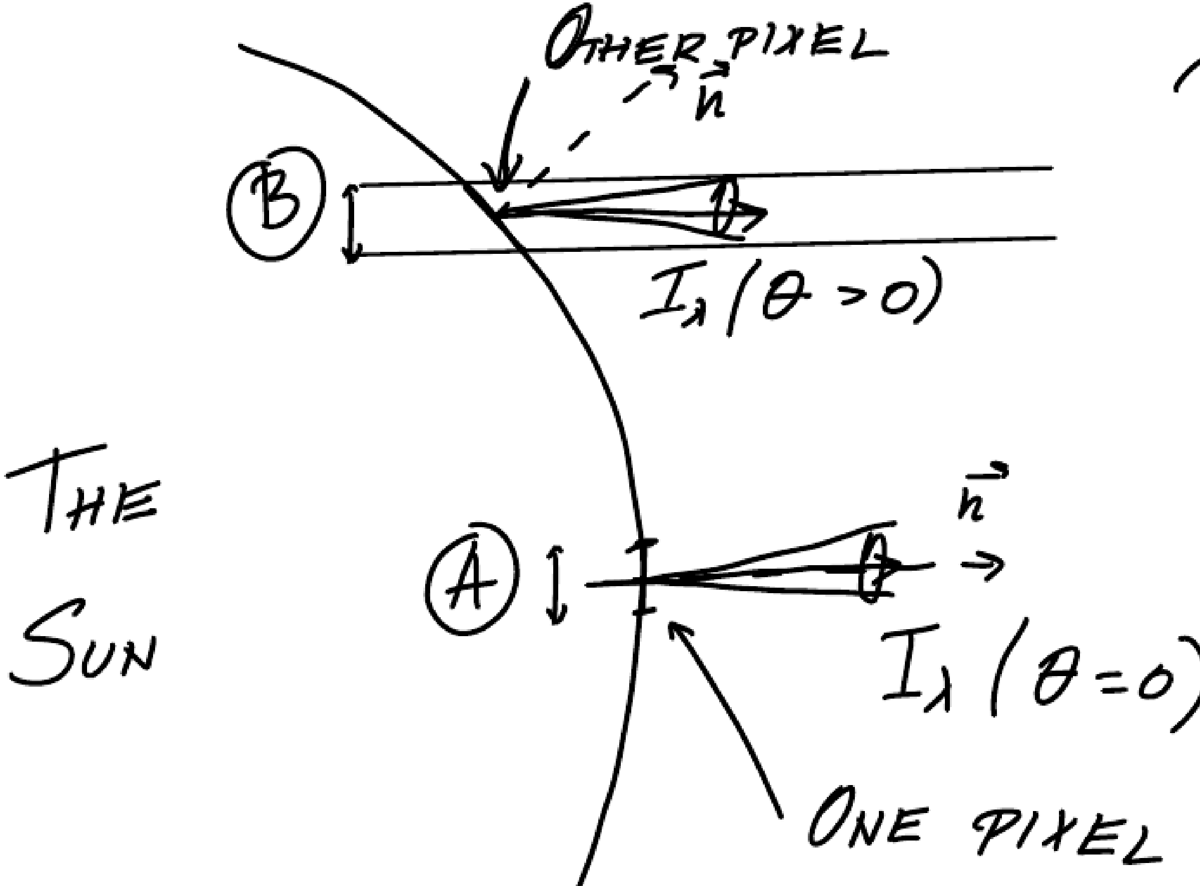
This is a phenomenon referred to as limb darkening.

This would mean that the intensity is decreasing with angle w.r.t. atmospheric normal.

Let's spend a moment and convince ourselves that this is what it really means.

Remember, we measure:

$$N = \frac{E}{hc/\lambda} = I \times \Delta\sigma \times \Delta\Omega \times \Delta\lambda \times \Delta t$$



PIXEL B COVERS GREATER SURFACE THAN PIXEL A.

HOW IS A THEN BRIGHTER THAN B?

$$I_A = \frac{d^4E}{d\sigma_A \cos\theta_A \, dt \, d\Omega \, d\lambda}$$

$$I_B = \frac{d^4E}{\underbrace{d\sigma_B \cos\theta_B}_{\equiv \sigma_A \cdot \cos\theta_A} \, dt \, d\Omega \, d\lambda}$$

$\cos\theta_A = 1 \quad d\sigma_A = \sigma$

$\cos\theta_B \neq 1 \quad d\sigma_B = \dfrac{\sigma}{\cos\theta_B}$

Sampling

- Sampling refers to the frequency (spatial, temporal, spectral) of, well, taking samples of the data :)
- Spatial: in how small chunks you divide your image ("How many megapixels does your mobile camera have???")
- Temporal: How often did we collect the data / how long time interval does the data cover (cadence)
- Spectral: in how many wavelength "bins" did we divide our data (applies to spectrographs; Are there gaps between spectral samples for FP)
- **Sampling is not "resolution" (But it should follow from it.)**
- **Sampling depends on our detector and process of measuring. Resolution depends on our optical system / dispersion elements.**
- Why can't these quantities be arbitrary? *(E.g. why don't we take a gazillion pixel camera and make most amazing images of the Sun? - discuss)*

So to recoup

- We measure counts on the detector (camera)
- These counts are ultimately related to the specific monochromatic intensity that leaves the surface of the Sun (that is, the top of the atmosphere)
- We can also measure the degree of polarization (soon more about it)
- There are many instrumental effects modifying what we measure (part 1 of the course)
- Even in the ideal case, if we could measure counts perfectly and infer the intensities perfectly, we cant measure physical parameters perfectly (part 2 of the course).
- Let’s discuss now a bit, where does the intensity come from?

Let’s look at a datacube that can be used for science

- Open lites_qs.fits
- Visualize varios “slices” and familiarize yourself with the data
- You will need python with matplotlib, numpy and astropy