PHYS 7810: Solar Physics with DKIST

Lecture 7: Wavelength Discriminators: Fabry-Perot filter

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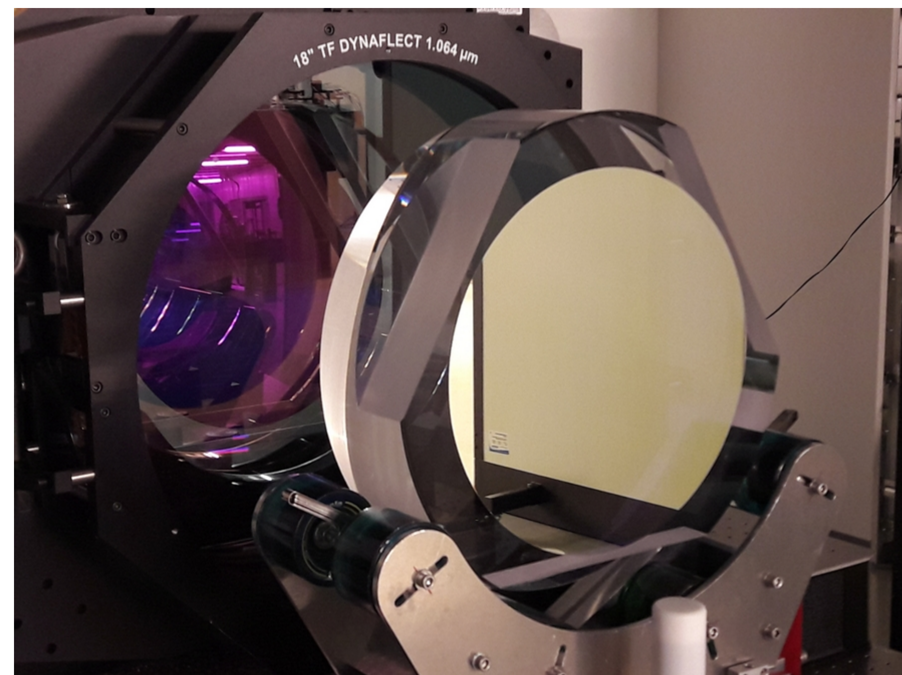
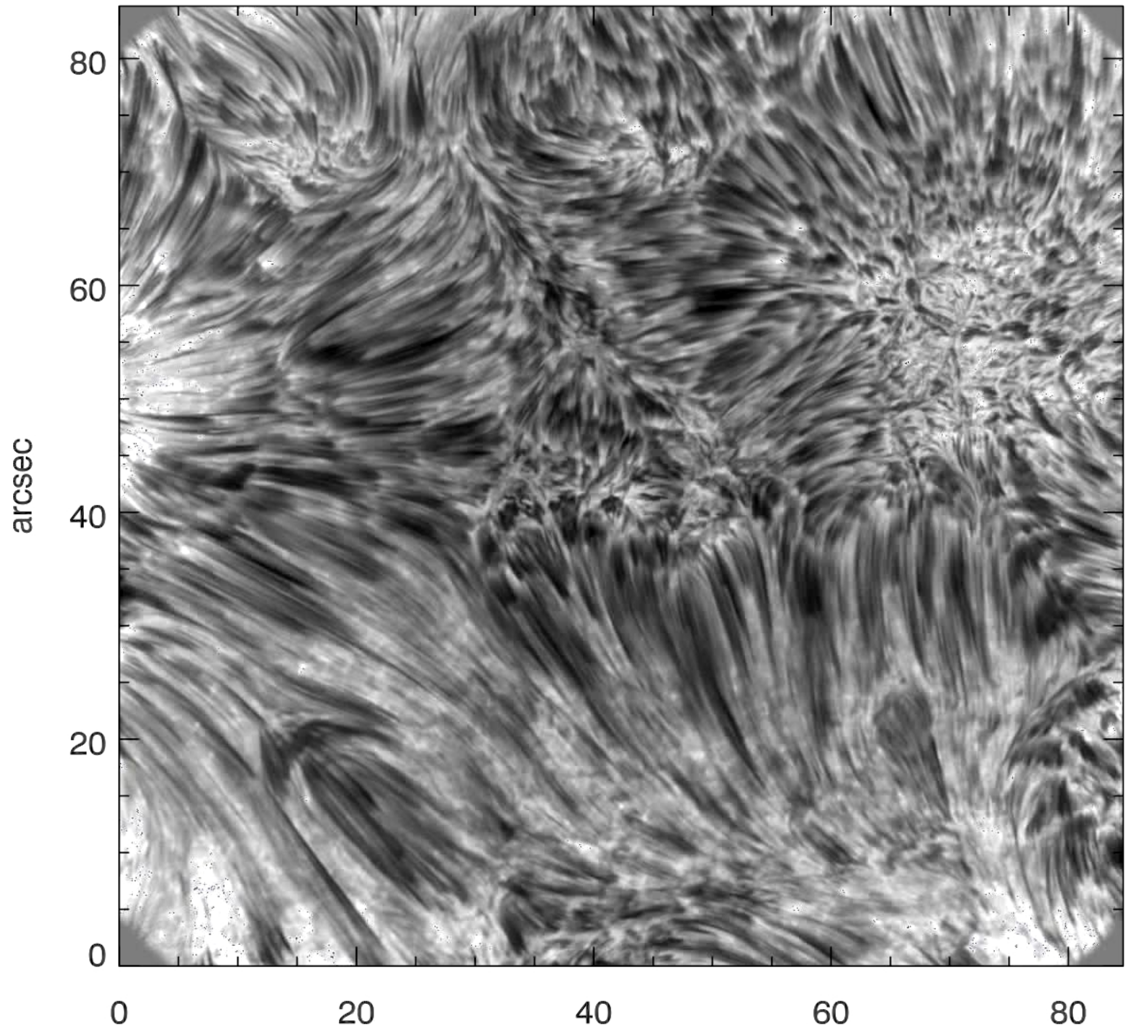


Previous classes

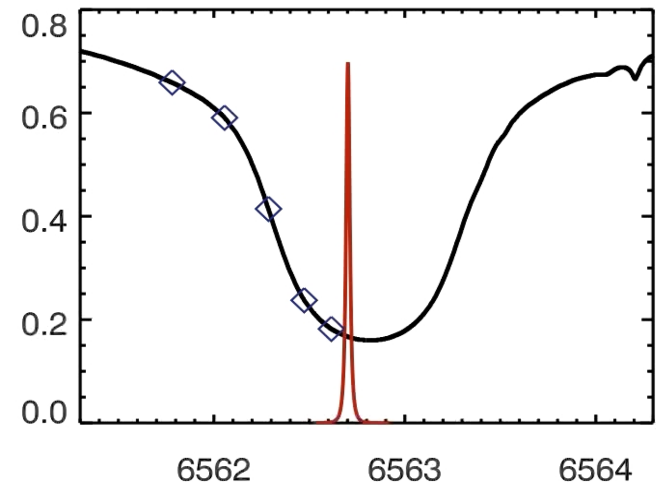
- We discussed image formation
- We “image” , that is, focus, the light coming from different direction on solar surface to on our detector (CCD), and we record the spatial (angular) distribution of the intensity
- Image undergoes some degradation because of the finite size of the primary and the effects of the Earth’s atmosphere
- We learned how to “reconstruct” the image and partially compesate for these effects (deconvolution, AO, MOMFBD, speckle reconstruction)
- Recall my favorite sentence: **different wavelengths sample different depths**
- How do we obtain wavelength information?

Example of a “datacube”:



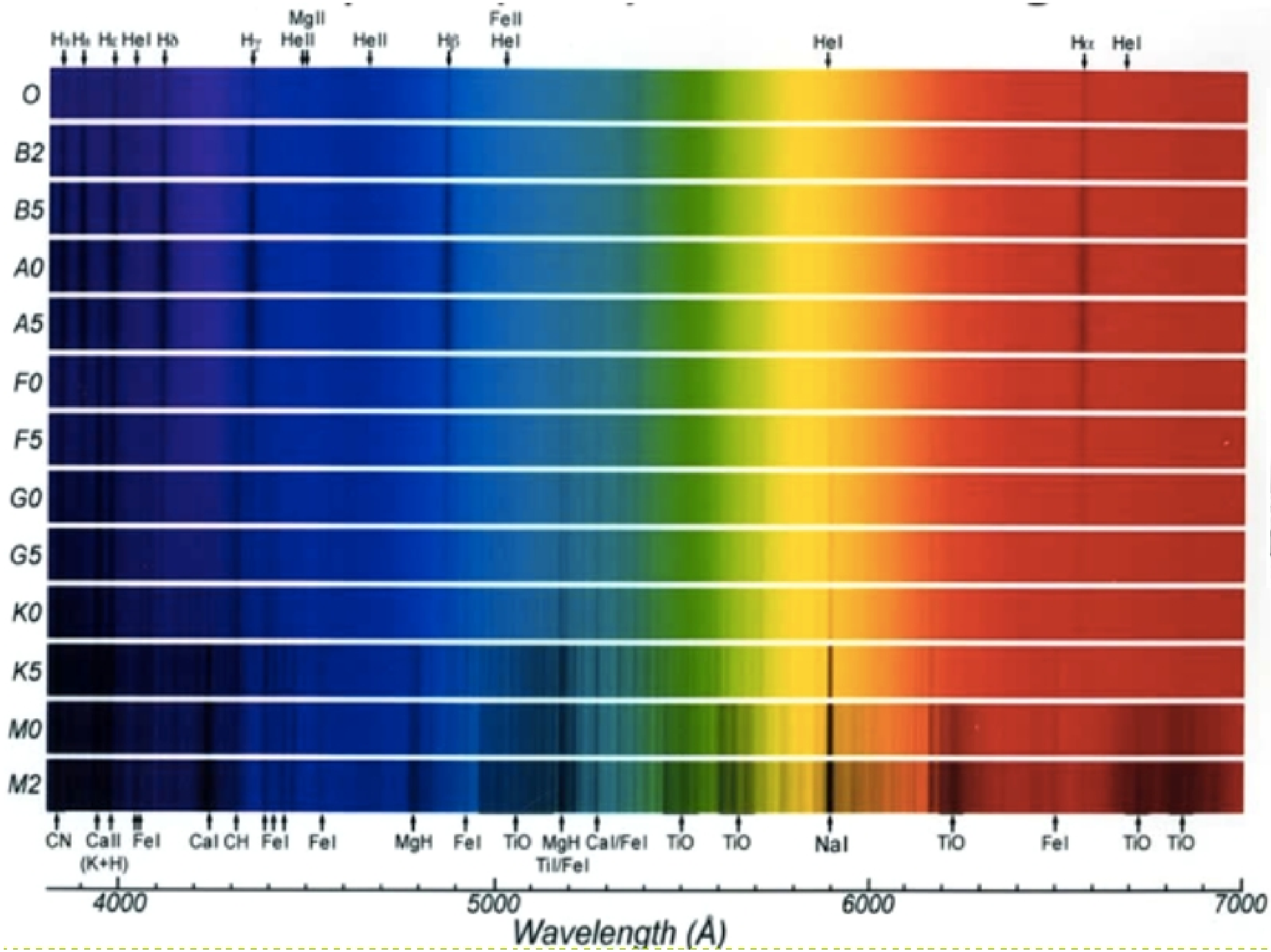
IBIS

23 April 2017



Credits : DST/ IBIS

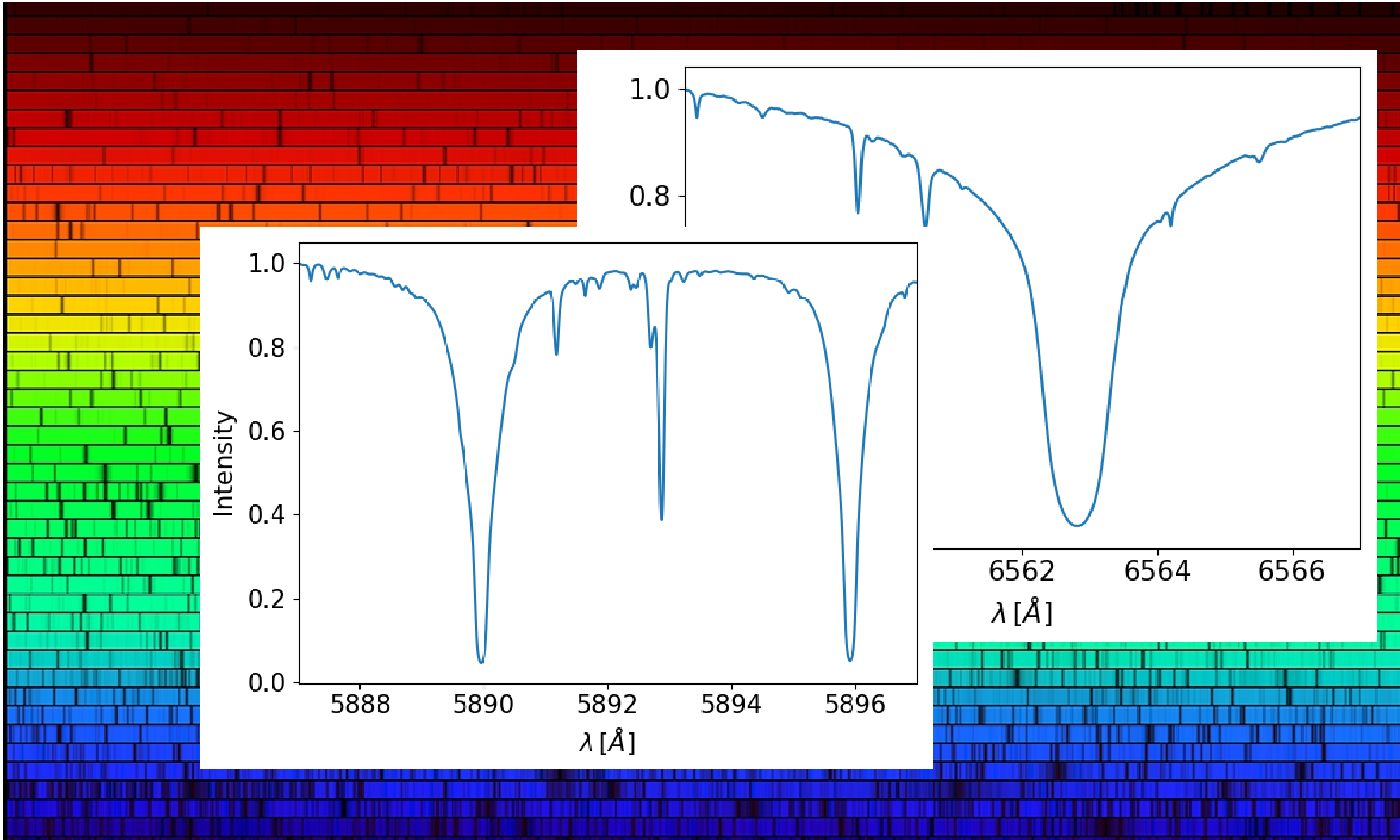
We are somewhat familiar with the spectra, right?



Credits: NOAO/AURA/NSF

Annie Jump Cannon,
Harvard classification.

Spectral lines are highly structured



N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

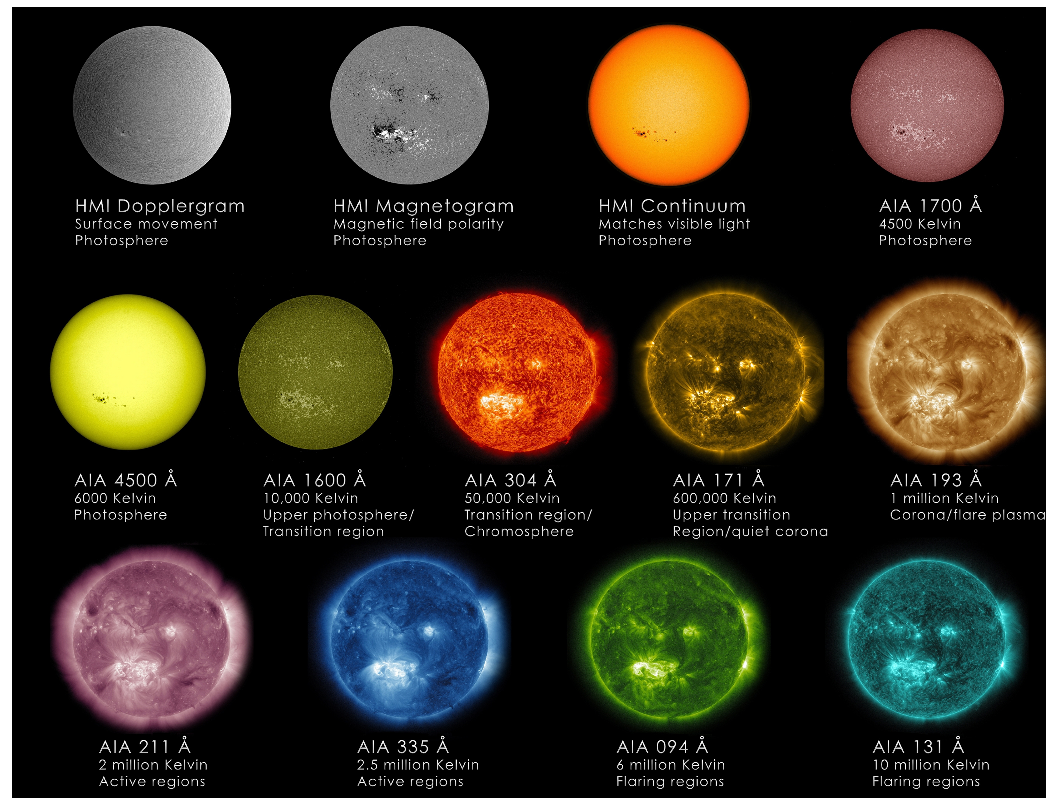
Why do we want to study the spectral lines?

Why do we want to study the spectral lines?

- Stronger lines – more absorbing material
- Positions of the lines – velocity
- Asymmetry in the lines – velocity gradients
- Presence of "weird features" tells us about some other interesting features (emission peaks, splitting, etc)
- Plus there is polarization (next week)
- We will understand fully these effects and learn to exploit them in the second part of the course.
- **One spectra per pixel → one atmosphere per pixel.**

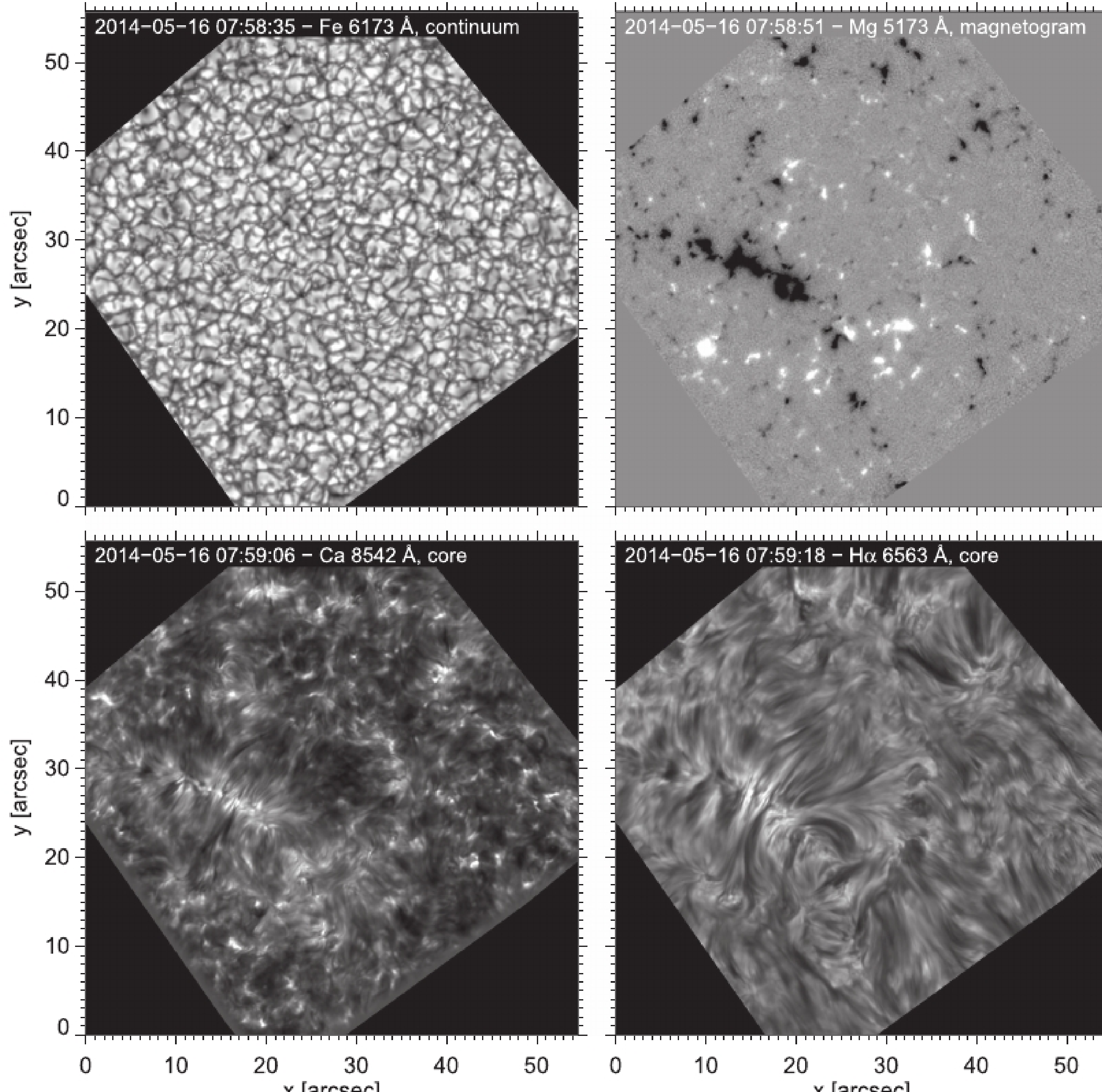
How to do it?

- The fundamental problem is that **x,y, lambda** is a 3D data hypercube
- Our optics and our detectors are made to record images, not cubes, **so they are 2D.**
- What if we made image on a very narrow wavelength range and then somehow finely tuned the central wavelength?



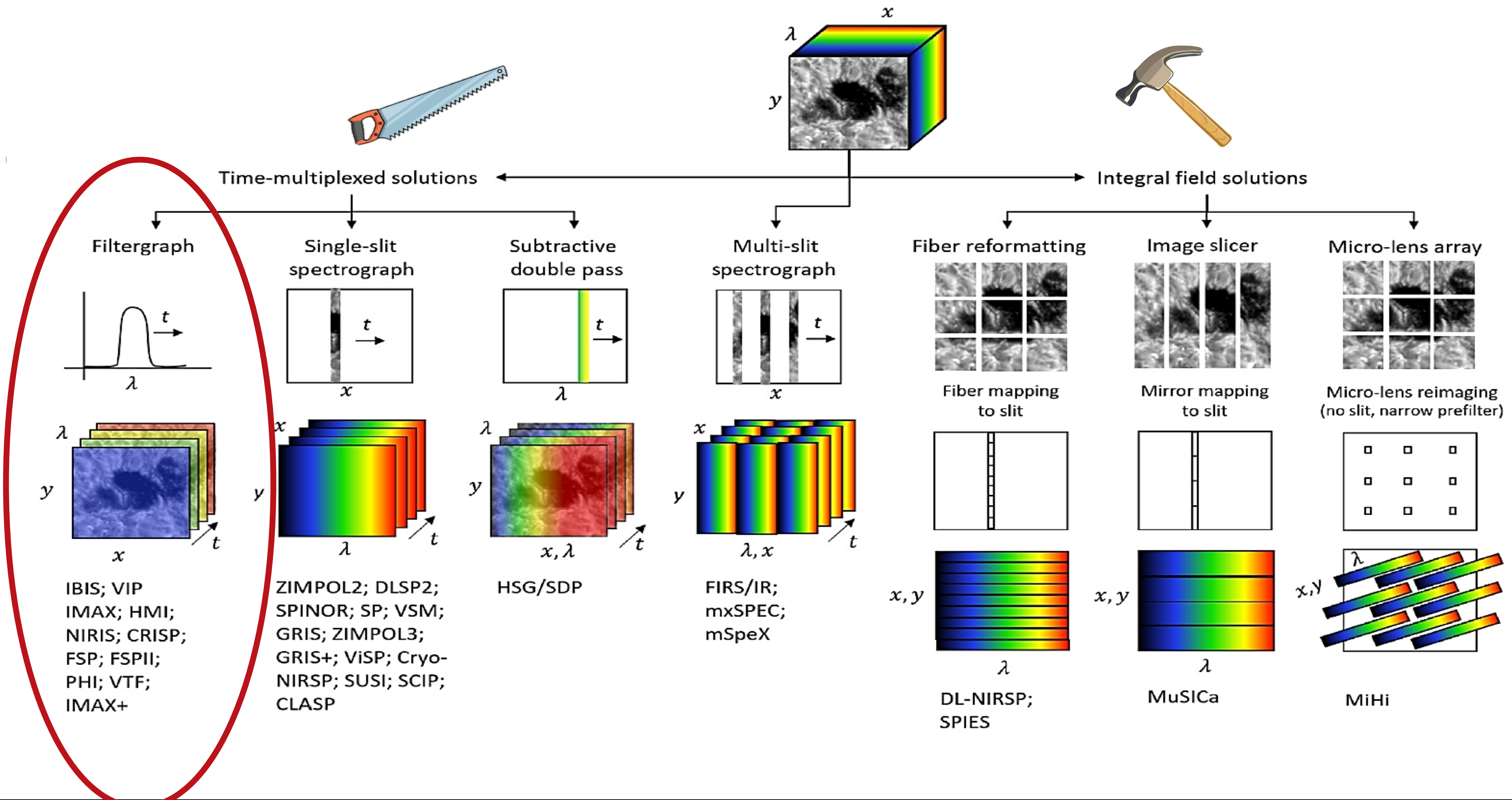
Let's discuss an example

What do you see in this image? Look at the text/numbers too!



Gosic et al. 2018

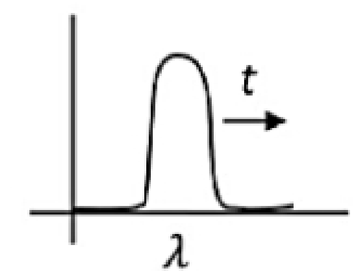
Spectroscopic mapping

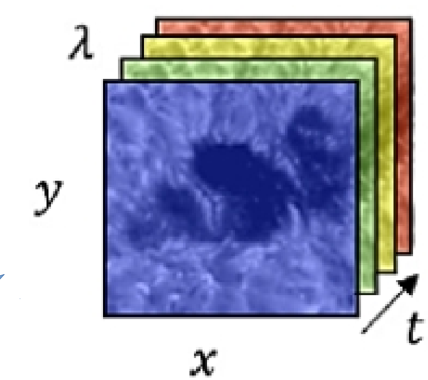


What is our goal then?

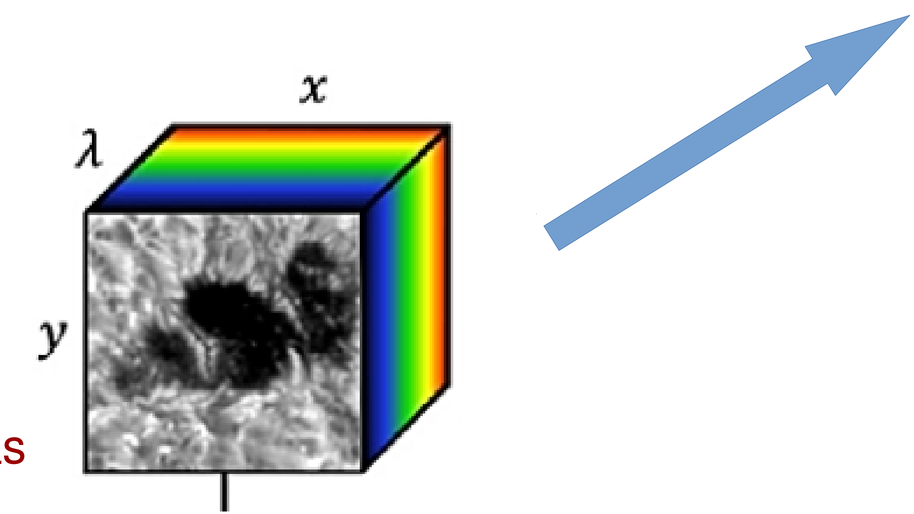
- To make an image at a specific wavelength, in a very small wavelength interval
- Then change the wavelength, then make an another image…
- **We are trading the time for the spectral sampling**
- **How does it work then?**

Filtergraph

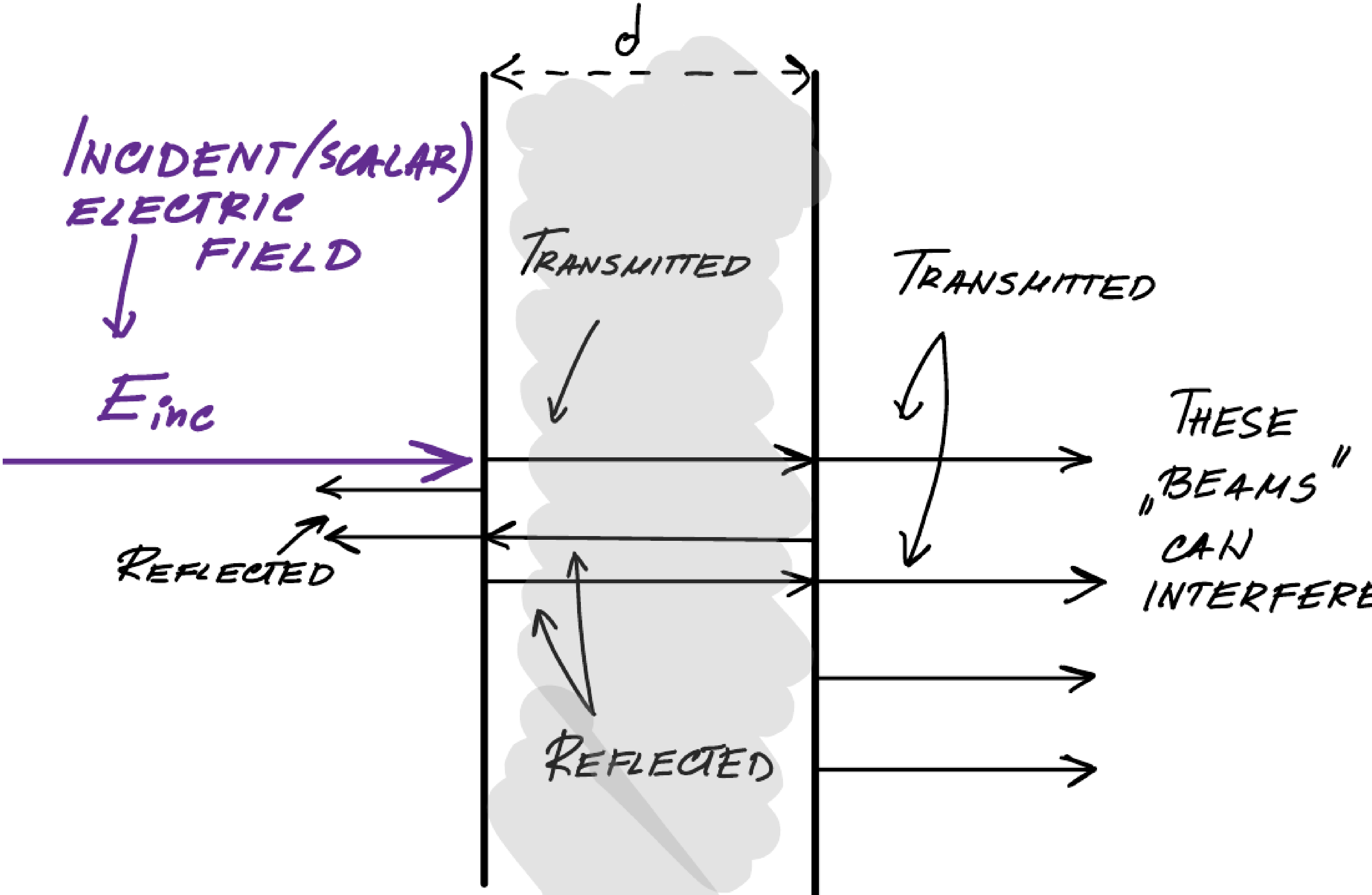




IBIS; VIP
IMAX; HMI;
NIRIS; CRISP;
FSP; FSPII;
PHI; VTF;
IMAX+



Courtesy of Francisco Iglesias


d
INCIDENT (SCALAR) ELECTRIC FIELD
E_{inc}
TRANSMITTED
TRANSMITTED
THESE „BEAMS" CAN INTERFERE
REFLECTED
REFLECTED

LET'S SUM THE OUTGOING ELECTRIC FIELDS:

$$E_0(t) = E_{inc} \cdot tt' \cdot e^{-i\omega t}$$

$$E_1(t) = E_{inc}\, tr^2 t' \cdot e^{-i\omega t} \cdot e^{i2dnk}$$

PHASE DIFFERENCE DUE TO DIFF. PATHS

$$E_2(t) = E_{inc}\, tr^4 t' \cdot e^{-i\omega t} \cdot e^{i4dnk}$$

$\vdots$

$$E_m(t) = E_{inc}\, tr^{2m} t' \cdot e^{-i\omega t} \cdot e^{i2mnk}$$

$$E_0 + E_1 + E_2 + \dots = E_{inc} \cdot tt' \cdot e^{-i\omega t} \cdot \sum_{m=0}^{M} r^{2m} \cdot e^{i2mnkd} \quad (2mnkd = m\delta)$$

$$\sum_{m=0}^{M} r^{2m} \cdot e^{i\delta} = \frac{1}{1 - r^2 e^{i\delta}}$$

NOW, LET'S CALCULATE THE INTENSITY ($I \propto EE^*$)

$$I_t = \frac{1}{2} E_t E_t^* = \frac{\frac{1}{2} E_{inc} E_{inc}^* \cdot (tt')^2}{(1+r^2 e^{i\delta})(1+r^2 e^{-i\delta})} =$$

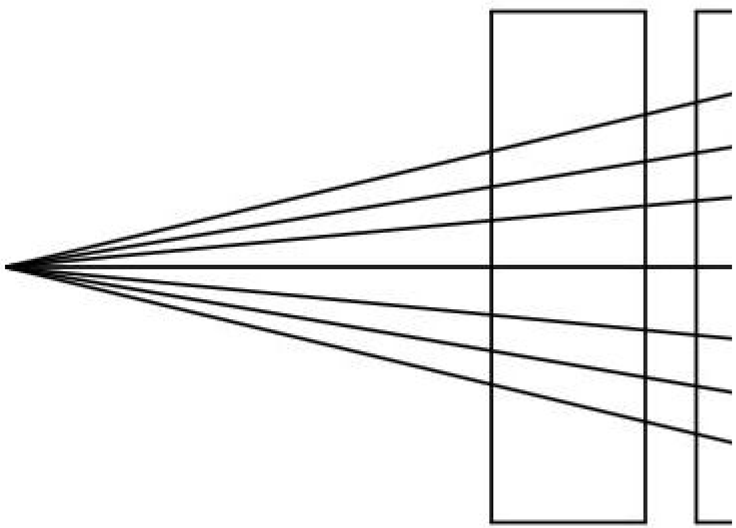
$$= I_{inc} \frac{(tt')^2}{(1+r^4) - 2r^2 \cos\delta} \qquad \cos\delta = 1 - 2\sin^2\frac{\delta}{2}$$

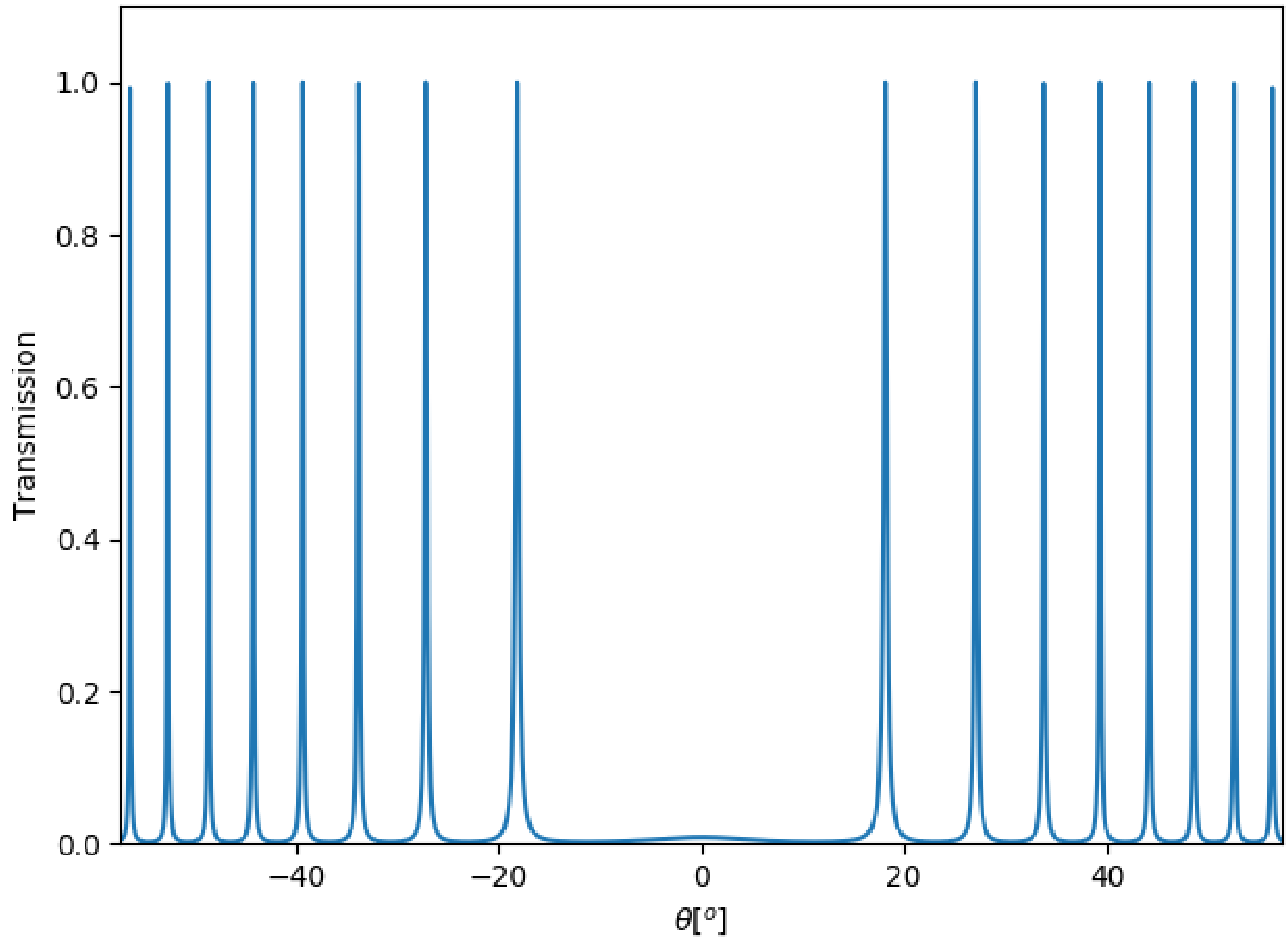
$$I_t = I_{inc} \frac{(tt')^2}{1+r^4 - 2r^2\left(1-2\sin^2\frac{\delta}{2}\right)} \qquad tt' + r^2 = 1 \quad \left(\text{FROM EM}\right)$$

$$I_t = I_{inc} \cdot \frac{1}{1+\frac{4r^2}{(1-r^2)^2}\sin^2\frac{\delta}{2}} \quad \xRightarrow[r^2=R]{} \quad \frac{I_t}{I_{inc}} = \boxed{\frac{1}{1+\frac{4R}{(1-R)^2}\sin^2\frac{\delta}{2}}}$$

$\left(\frac{4R}{(1-R)^2} \equiv F\right.$, COEFFICIENT OF FINESSE$\left.\right)$

A “school” example of this interference is this:





However, using different colors:

The transmission depends on the phase difference

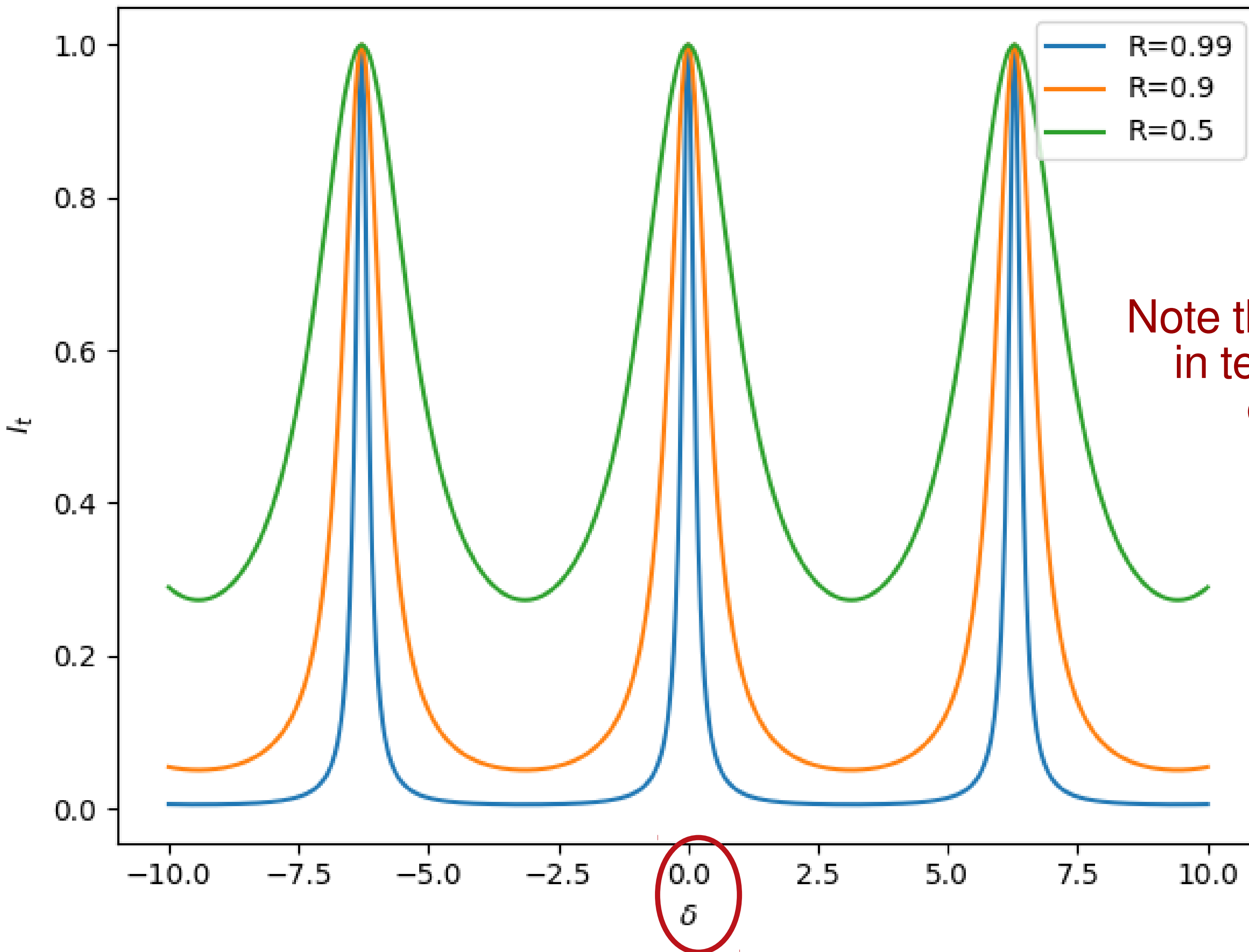
$$\delta = 2knd\cos\theta = \frac{4\pi n d \cos\theta}{\lambda}$$

Index of refraction (n), Thickness (d), Angle (θ), Wavelength (λ)

$$\frac{I_t}{I_{inc}} = \frac{1}{1 + F\sin^2\delta/2}$$

$$F = \frac{4R}{(1-R)^2}$$

The role of reflectivity



Note that I am plotting in terms of phase difference

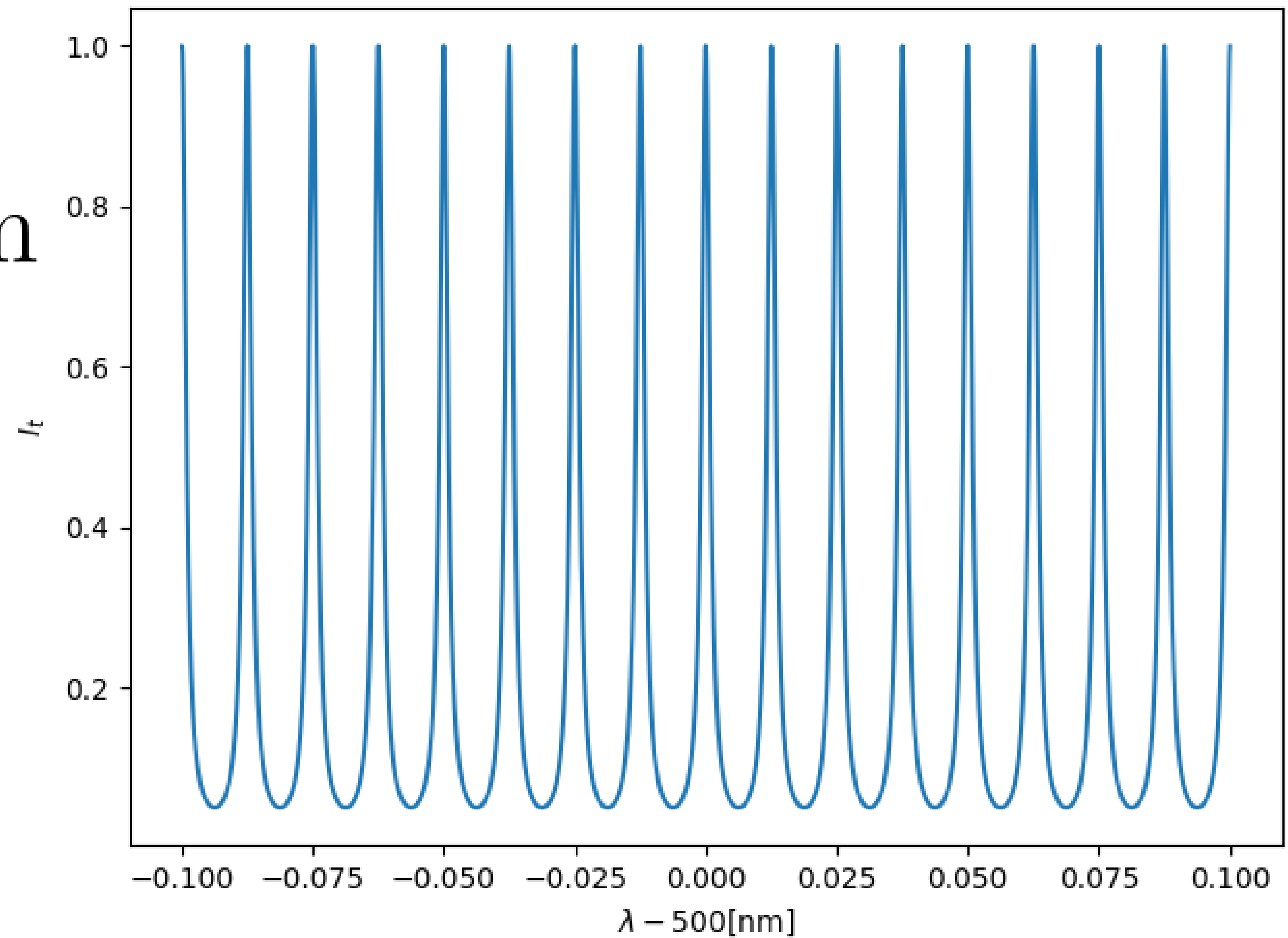
Ok, let's plot transmittance vs wavelength

$$\lambda = 500\,\mathrm{nm}$$

$$d = 1\,\mathrm{cm}$$

$$n = 1$$

$$R = 0.9$$



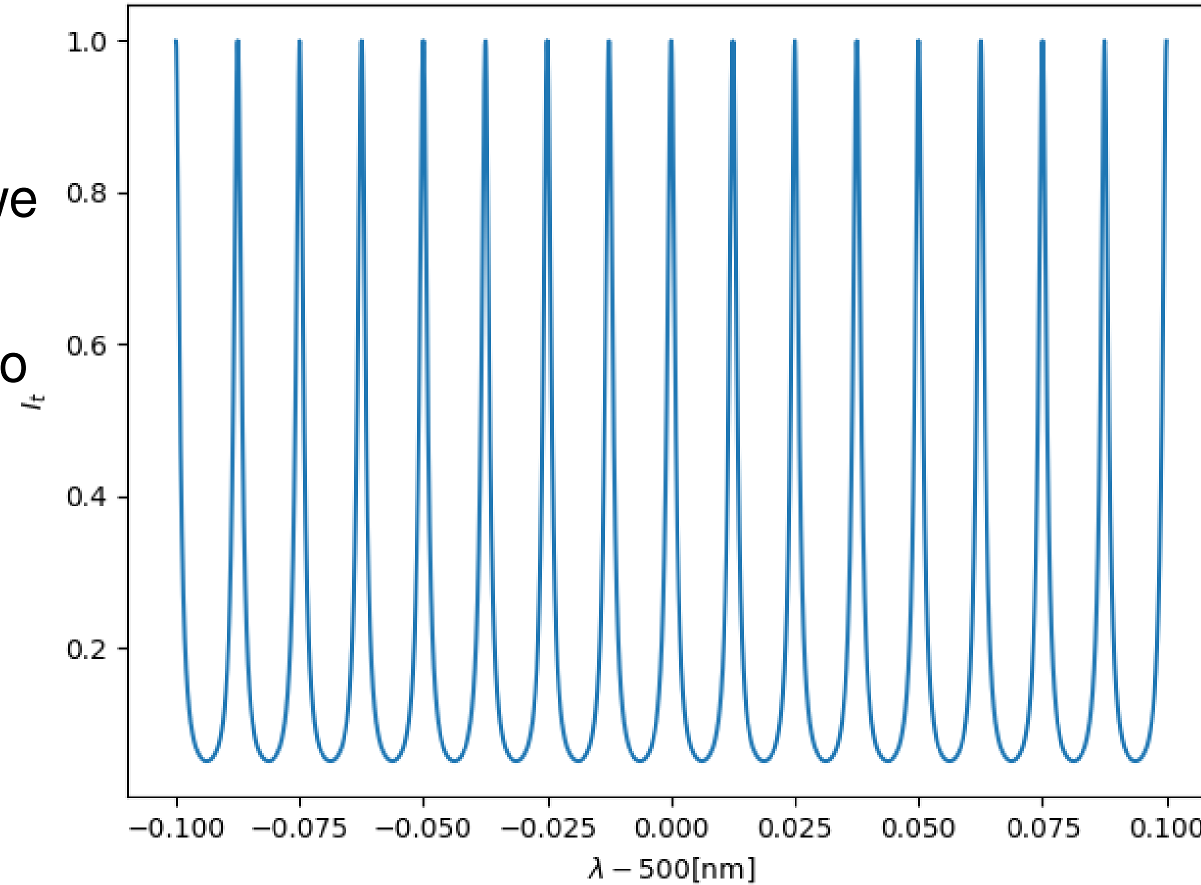
Let's discus... what are we measuring?

Transmittance

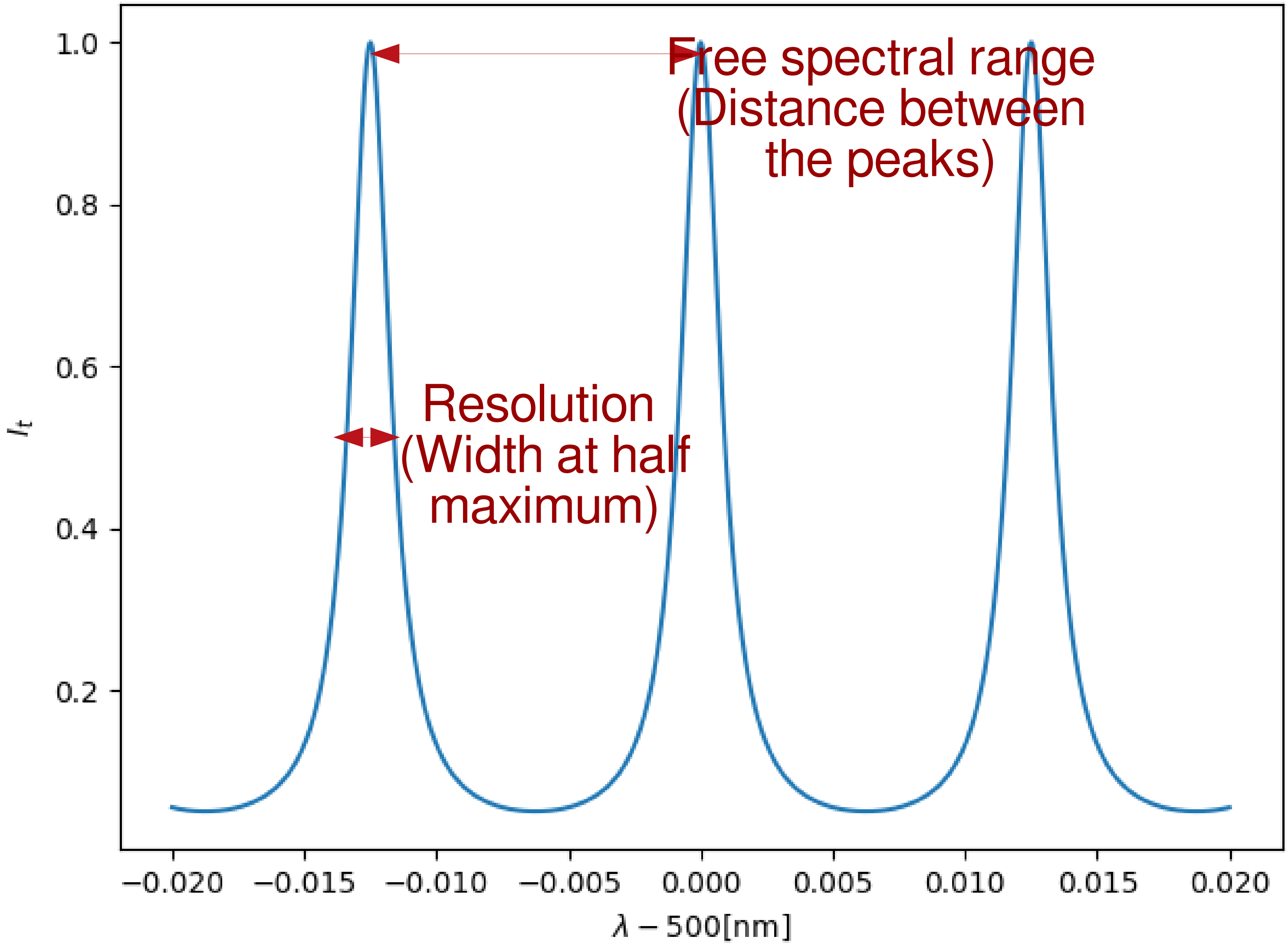
$$I_{\text{measured}} = \int_0^\infty I_0(\lambda) T(\lambda) d\lambda$$

So what do we want?

- We want well separated peaks – we want to see only one wavelength
- But also narrow peaks – we want to have that one wavelengt well defined
- Let's see how that works...



Spectral resolution and free spectral range



Let's derive these quantities – take 5' to derive FSR

$$T(\lambda) = \frac{1}{1 + F \sin^2 \frac{\delta}{2}} \Rightarrow T = \text{MAX FOR } \sin\frac{\delta}{2} = 0$$

$$\delta = m \cdot 2\pi \quad (m \text{ IS INTEGER})$$

$$\Delta\delta = 2\pi = \frac{d\delta}{d\lambda} \cdot \Delta\lambda = \frac{4\pi n d}{\lambda^2} \Delta\lambda_{FSR}$$

$$\Delta\lambda_{FSR} = \frac{2\pi \lambda^2}{4\pi n d} = \frac{\lambda^2}{2nd}$$

Now similar approach for the so called spectral resolution

$$I_T = \frac{1}{2} I_T^{max} \quad (\text{HALF MAXIMUM}) \qquad \frac{1}{1+F\sin^2\frac{\delta}{2}} = \frac{1}{2}$$

$$\delta_{1/2} = 2\sin^{-1}\left(\frac{1}{\sqrt{F}}\right) \approx 2\frac{1}{\sqrt{F}}$$

$$\mathscr{f} = 2\delta_{1/2} = \frac{4}{\sqrt{F}} \leftarrow \text{WIDTH AT HALF MAXIMUM, IN RADIANS}$$

HOW TO TRANSLATE IT TO WAVELENGTH?

$$\mathscr{f} = \frac{\partial\delta}{\partial\lambda}\cdot\Delta\lambda = \frac{4\pi n d}{\lambda^2}\cdot\Delta\lambda$$

$$\Delta\lambda = \frac{\lambda^2 \cdot \frac{4}{\sqrt{F}}}{4\pi n d} = \frac{\lambda^2}{\sqrt{F}\pi n d}$$

$$\frac{\Delta\lambda_{FSR}}{\Delta\lambda} \propto \sqrt{F}\,!$$

Let's calculate spectral resolution of an example FP

$$\frac{\lambda}{\Delta\lambda} = \frac{\sqrt{F}\pi n d}{\lambda}$$

$$F = 4R/(1-R)^2$$

$$R = \frac{\lambda}{\Delta\lambda} = \frac{\sqrt{360} \times 3.14 \times 1 \times 0.01}{500 \times 10^{-9}} \approx 10^6$$

In practice this is a factor of few smaller, due to various imperfections in the filter, and other general deviations from the perfect case.

Now what if I want to look at a different wavelength?

- We tune the maximum transmittance wavelength by changing thickness of the etalon
- Let's see how fine the change needs to be

$$\varkappa = \frac{\partial \delta}{\partial d} \cdot \Delta d = \frac{4\pi n}{\lambda} \cdot \Delta d$$

$$\Delta d = \frac{\lambda \cdot \varkappa}{4\pi n} = \frac{\lambda \cdot K}{4\pi n \sqrt{F}} = \frac{500 \cdot nm}{60 \cdot 3.14} \approx 2.5\ nm$$

- KIS webpage states that VTF's piezo-actuators can obtain 0.1 nm! Imagine that!

This all looks great, let’s summarize some properties

- Fabry-Perot “isolates” desired wavelengths, we tune it to one wavelength at the time
- **We slice our 3D cube paralel to x,y plane**
- F-P works on the principle of multi-beam intereference
- Better reflectance $\rightarrow$ better waveleng resolution, but less total photons pass
- We need to avoid other maxima $\rightarrow$ another etalon or at least pre-filter
  (We increase free spectral range)
- Challenge: etalon has to be parallel (d = const), over the whole surface, to have uniform transmittance
- “Wings” can be non-negligible : keep in mind when interpreting
- The image is (in principle) the same you would see if there was no filter – depends on optics and the camera
- **Wavelenght sampling can be chosen according to your scientific question.**

Some Fabry-Perot instruments

- IMAX at SUNRISE (scans 5/12 pre-determined wavelengths around 525.0 nm Fe line)
- IBIS at DST (550 – 860 nm) – double etal
- TESOS at VTT – triple etalon
- CRISP and CHROMIS at SST
- All these instruments (or, instrument suites) also perform polarimetry (to infer magnetic field). We will see next week what is is. In principle, polarimetry and F-P filter are two separate instruments.
- And, upcoming VTF (Visible Tunable Filter) at DKIST!

Now let’s look at VTF’s webpage and see if we understand everything...

- **https://www.nso.edu/telescopes/dkist/instruments/vtf/**

- After that, let’s look again at an example IBIS data