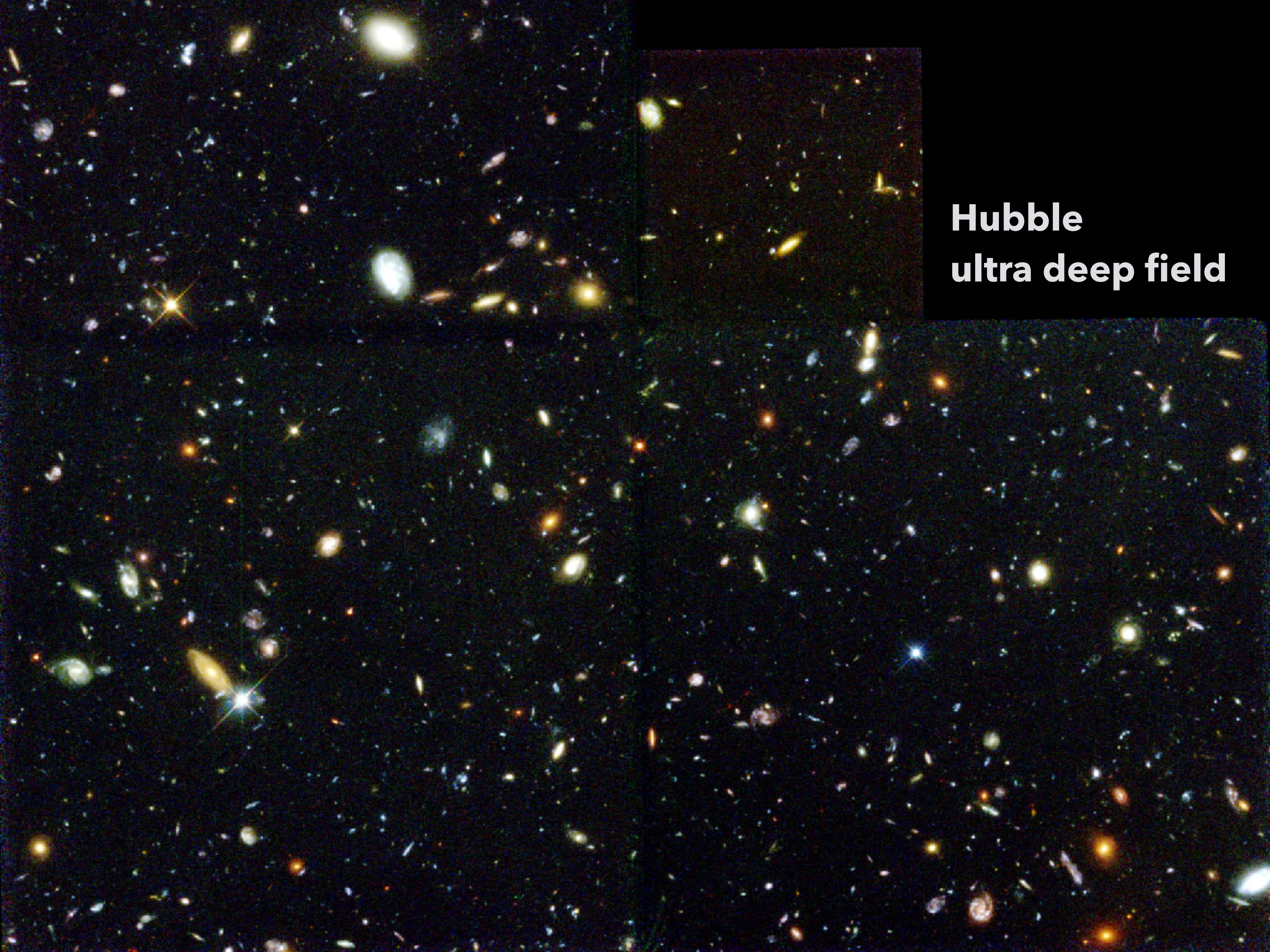
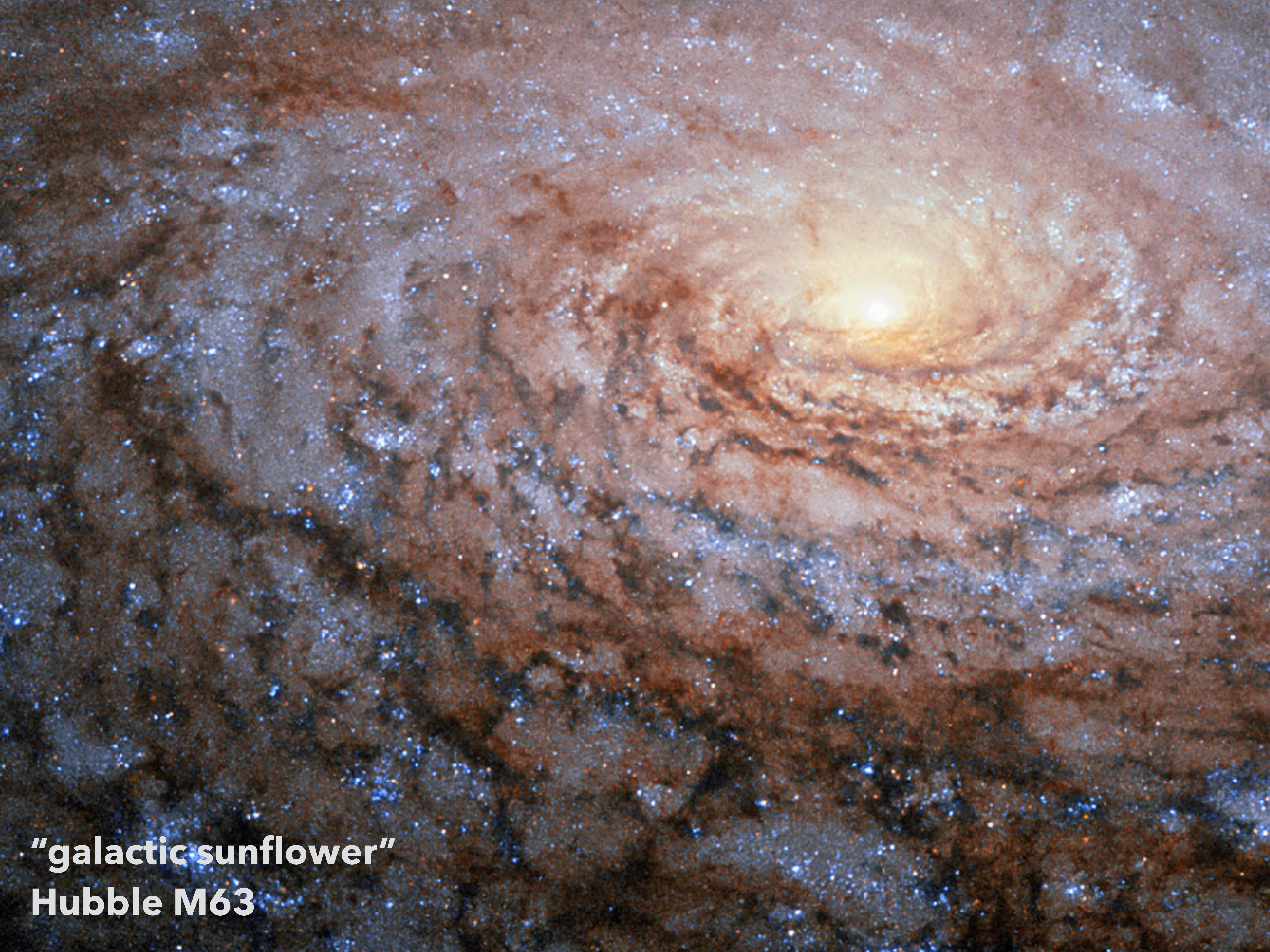
Infrared Spectroscopy for Astronomy

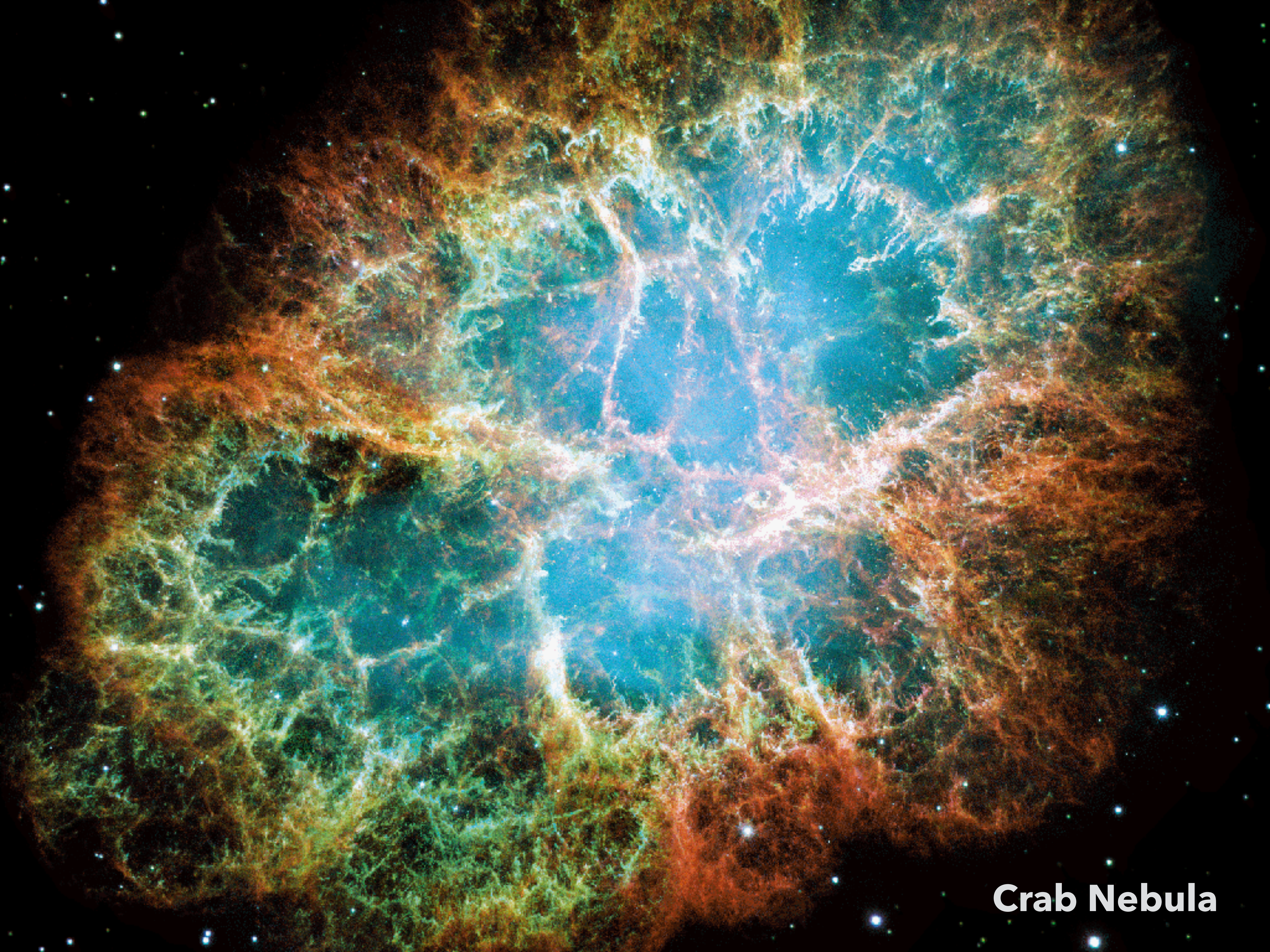
1. How spectroscopy changed the world
2. Continuum and Line Formation
3. Spectrograph : system
4. Spectrograph : diffraction grating
5. Spectrograph : detector and noise

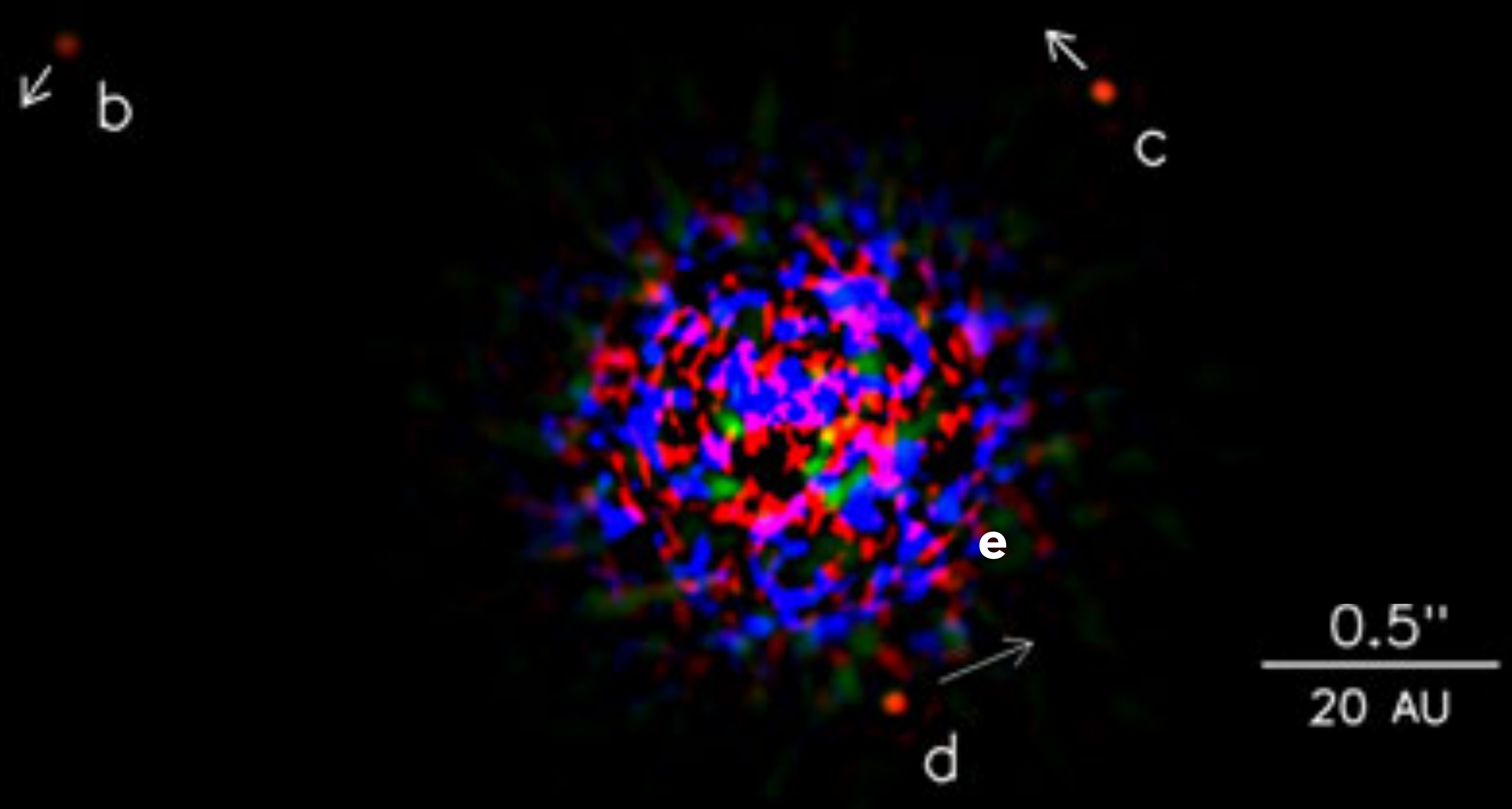
What do you observe?



Hubble
ultra deep field

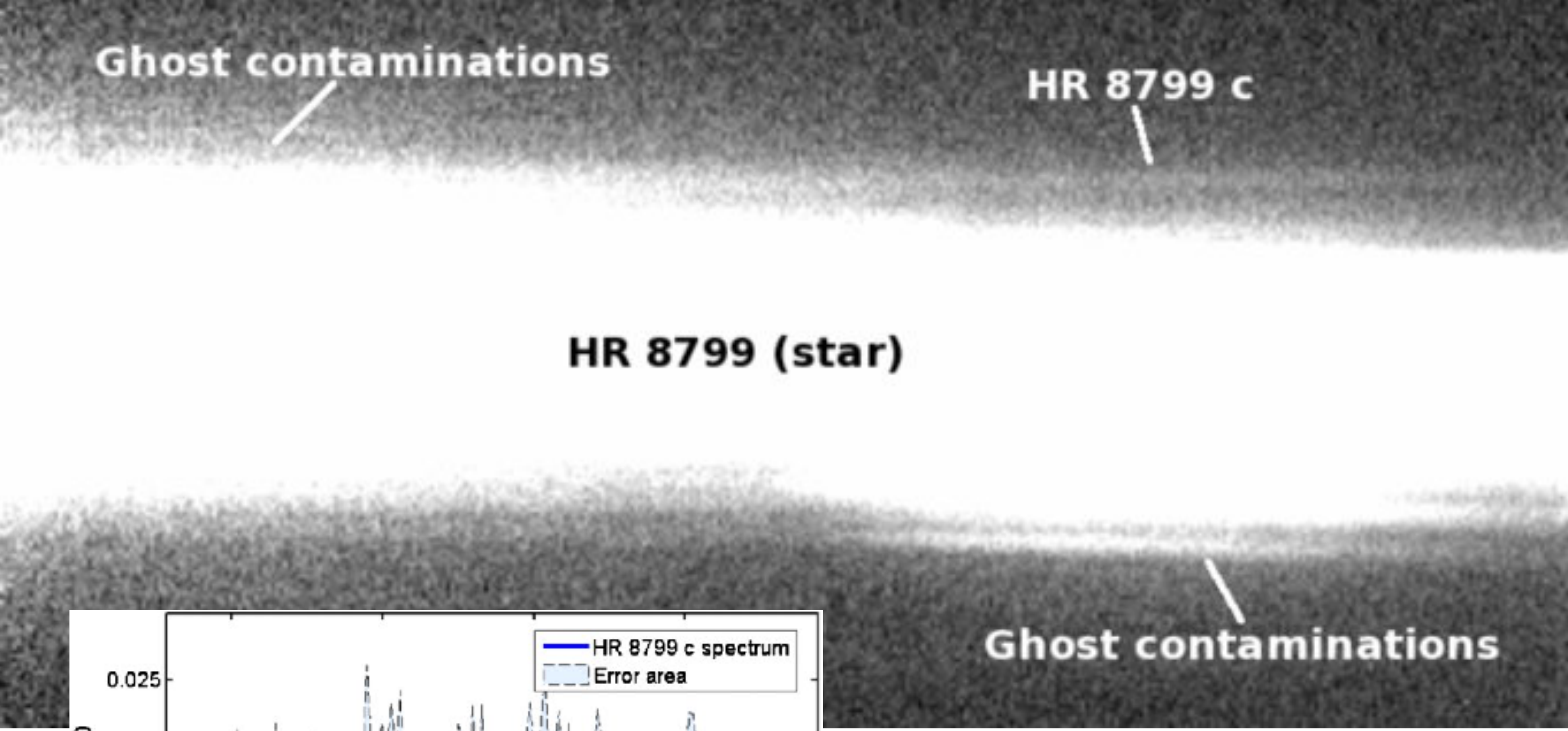

“galactic sunflower”
Hubble M63

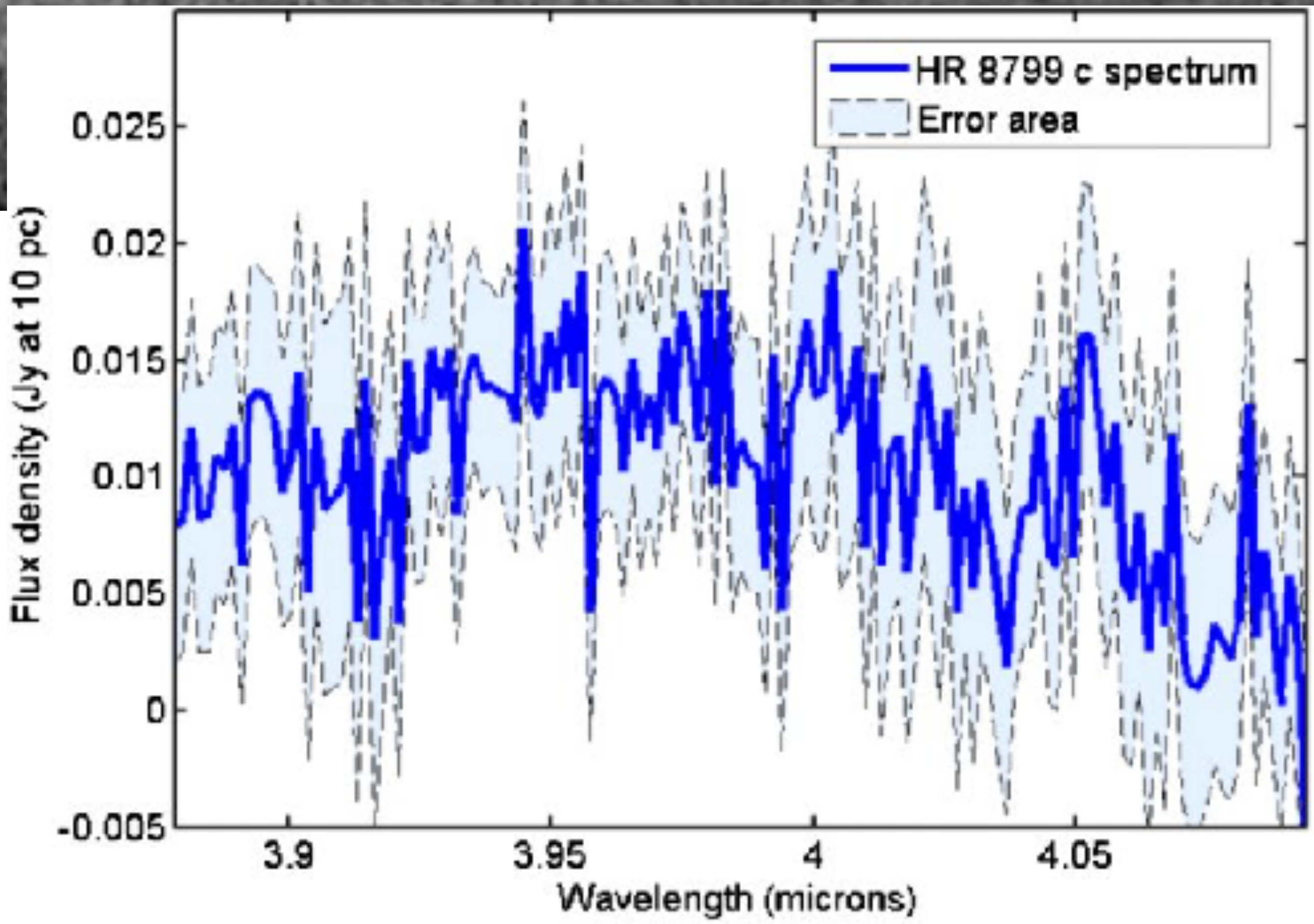

Crab Nebula



HR 8799

Marois et al. 2008, Science, 322, 1348
"Direct Imaging of Multiple Planets Orbiting the Star HR 8799"





Spatially Resolved Spectroscopy of The Exoplanet HR 8799 c

Janson et al, 2010, ApJL, 710L, 35

What we are told

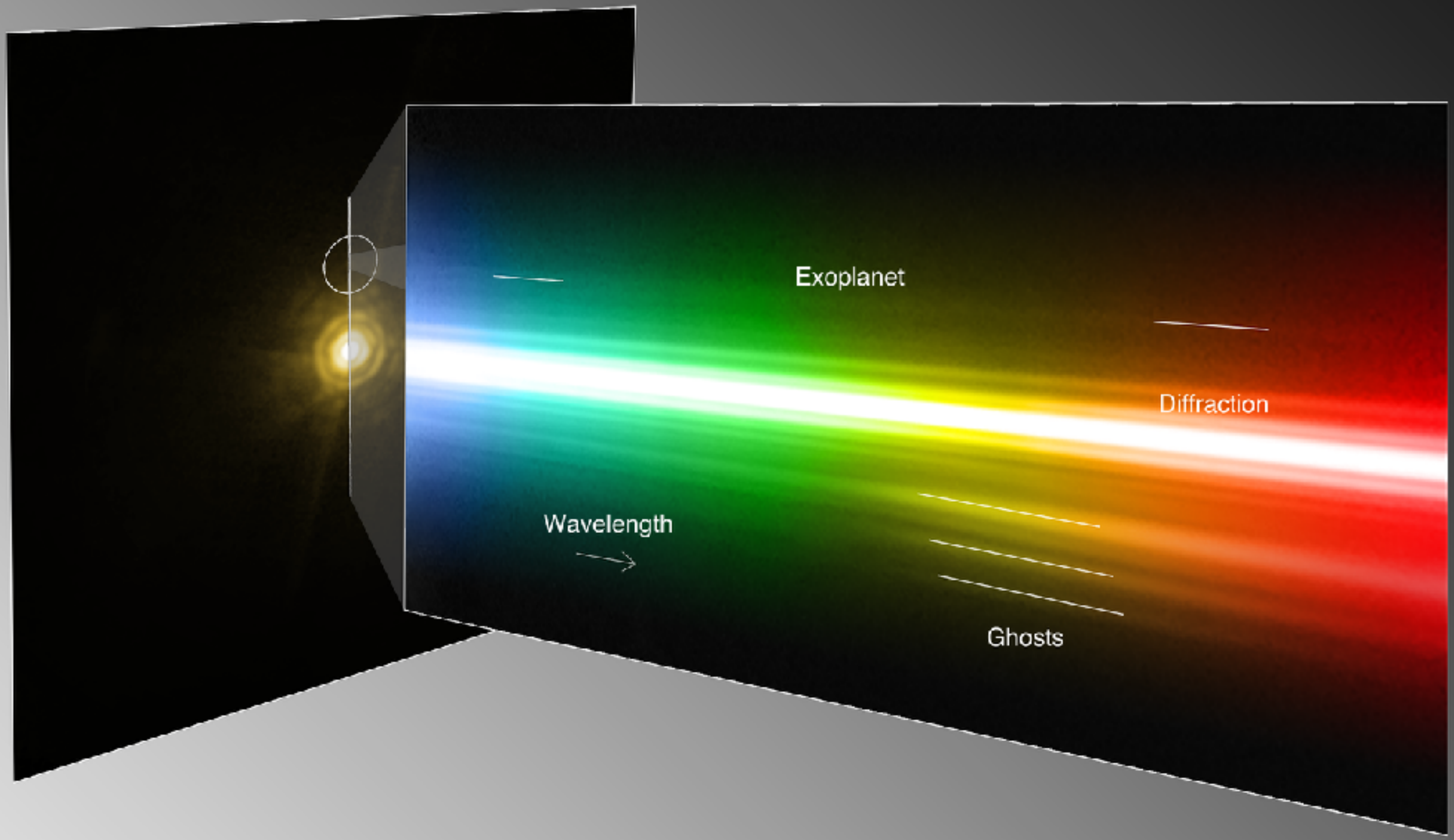
- Spectroscopy does not look good
- It is unpopular among reporters, because
- It does not look fancy on

  newspapers
  web sites

- Images are much easier to “understand”

I want to change this

ESO press release



Pretty images hard to publish

- model dependent
- your role as an observer is less important

Spectroscopy straightforward to publish

- can derive observables
- some glitches in

instrumentation
data reduction

we will learn them next half an year.

Style of lecture

1. understand small number of basic things but clearly

   do not cover a textbook cover to cover

2. no preparation, no review, you understand real time
3. please stop me (come forward and be seated front)
4. let us not waste time

   it is most important that you bring something home.

5. sorry, unit system is mostly cgs.

   column density, volume density...

Form of lecture

12:00 - 13:00	lecture
13:00 - 13:10	quick exercise
13:10 - 13:30	solution

Seminar

1. you all are given the list of topics to discuss in the talk.

   at round December

   e.g.
   - a spectrograph of your choice
   - what is "Langevin rate"?
   - line by line derivation : spherical harmonics
   - ELT vs JWST

2. we will discuss which one you take in the lecture
3. 20 min talk. questions. every one can attend.
4. you will get additional 2 ECT for that.

   need to satisfy minimum standard. no score.

Form of lecture

12:00 - 13:00	lecture a
13:00 - 13:10	quick exercise
13:10 - 13:30	solution

Examination

1. On 12 February, here.
2. Written examination.
3. 60 min.
4. similar to exercises every lecture.
5. no smart phone, no pocket calculator
6. this goes to your score.

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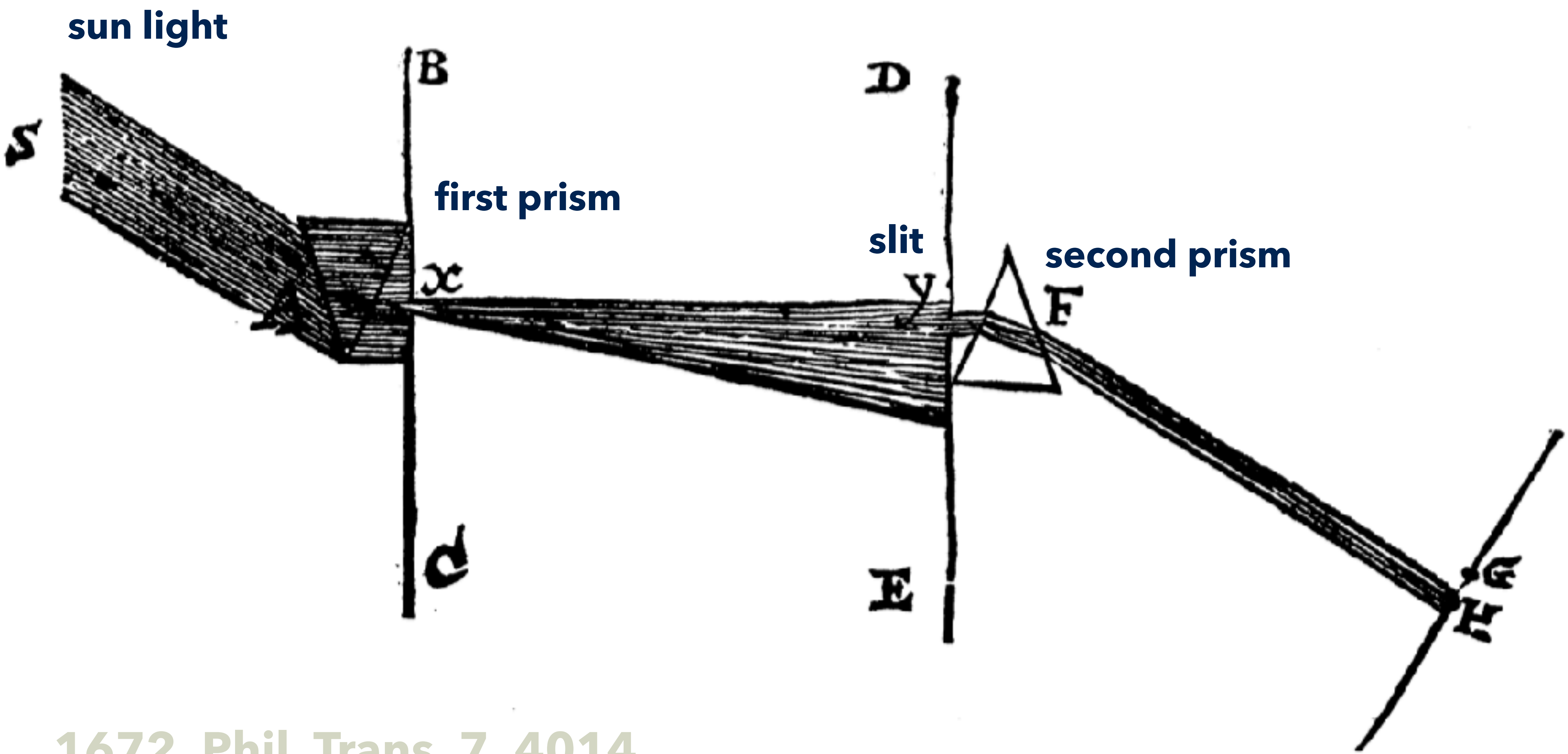
Office hour : every day until 2 pm

How spectroscopy started

Isaac Newton 1671, Phil. Trans. 6, 3075

"New Theory about Light and Colors"



1672, Phil. Trans. 7, 4014

How spectroscopy started

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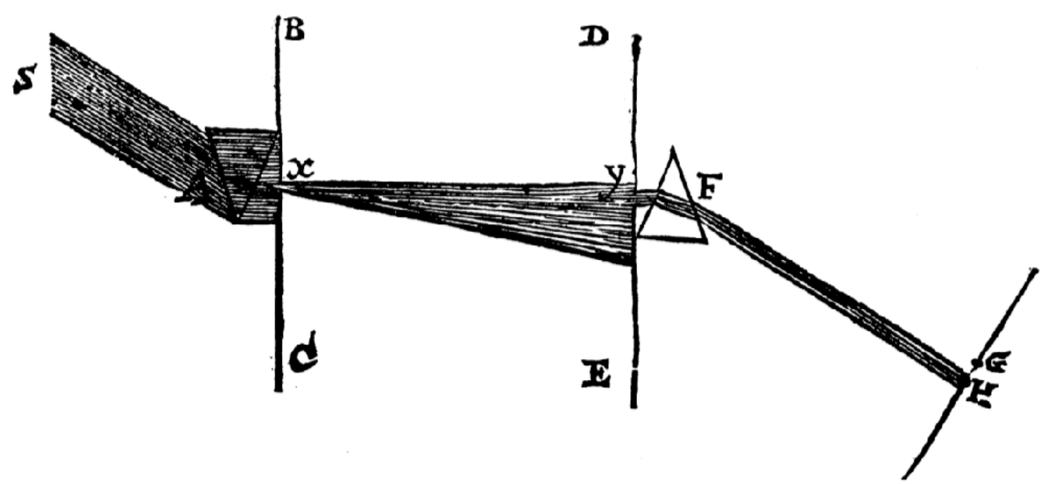


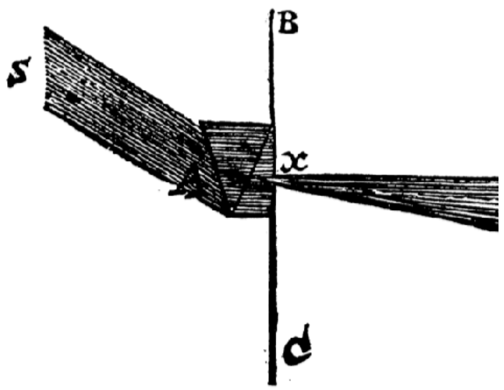
stained glass
prism

- color is not something you put on light
- original and connote property of light
- once dispersed color does not change by second prism
- white light contains all colors
- use prism opposite way, returns to white light

How spectroscopy started

Isaac Newton 1671, Phil. Trans. 6, 3075

"New Theory about Light and Colors"



They were terminated at the ſides with ſtreight lines, but at the ends, the decay of light was ſo gradual, that it was difficult to determine juſtly, what was their figure; yet they ſeemed *ſemicircular*.

Comparing the length of this coloured *Spectrum* with its breadth, I found it about five times greater; a diſproportion ſo extravagant, that it excited me to a more then ordinary curioſity of examining, from whence it might proceed. I could ſcarce think,

- Newton's first paper
- First use of the word "*Spectrum*"
- light dispersed by broken glass was known
- start of publishing in scientific journals

Copernicus	*De revolutionibus orbium coelestium*
Kepler	*Astronomia nova*
Galileo	*Il Saggiatore*

Josef Fraunhofer (1817) Denkschr. Konigl. Akad. Wiss., München, V, 193

“Bestimmung des Brechungs– und des Farbenzerstreungs–Vermögens verschiedener Glasarten in Bezug auf die Vervollkommnung achromatischer Fernröhre”

“Determination of the Refractive and Dispersive Power of Different Kinds of Glass, with Reference to the Perfecting of Achromatic Telescope”

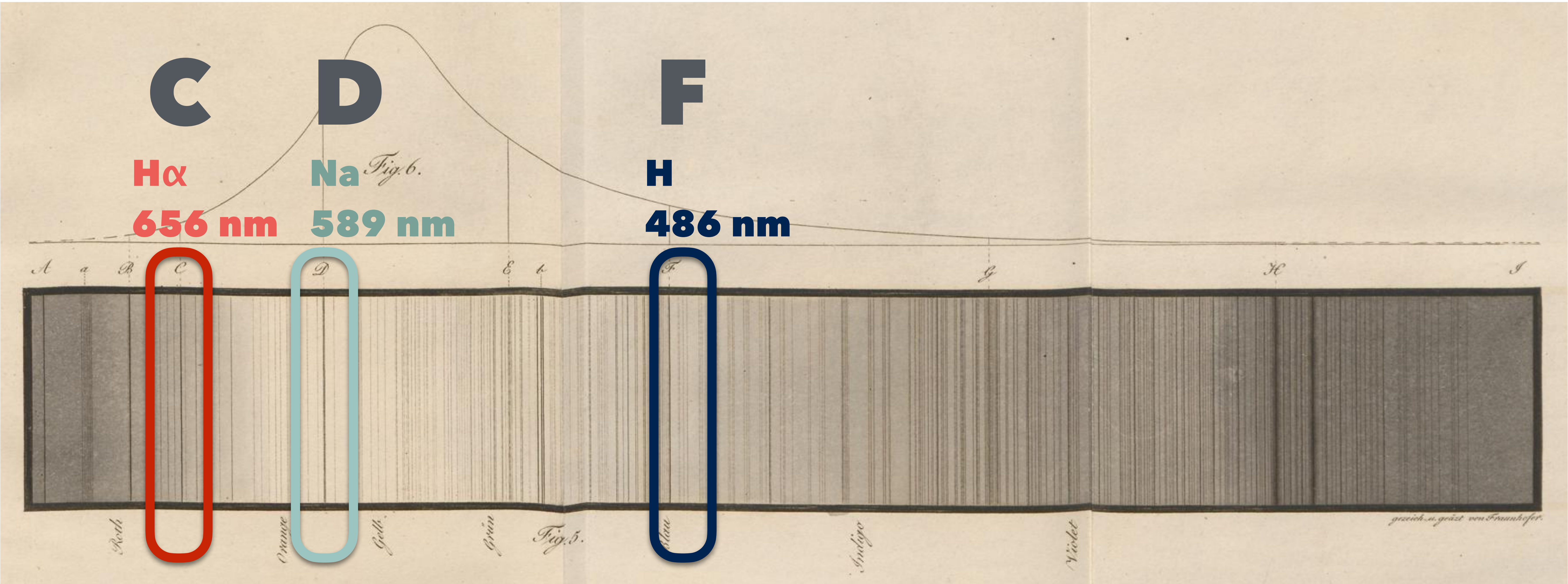
Josef Fraunhofer (1817) Denkschr. Konigl. Akad. Wiss., München, V, 193

- In order to make a achromatic telescope, combination of lens material needed
- would like to measure refractive indices / dispersion of glasses
- looking for good light source with emission lines
- tried sun light, and found absorption lines
- recorded them
- (presence of D lines are known by W. Wollaston before)

Josef Fraunhofer

(1817) Denkschr. Konigl. Akad. Wiss., München, V, 193

les dem Winkel des gebrochenen Strahles gleich war. Ich wollte suchen, ob im Farbenbilde von Sonnenlichte ein ähnlicher heller Streif zu sehen sey, wie im Farbenbilde vom Lampenlichte, und fand anstatt desselben mit dem Fernrohre fast unzählig viele starke und schwache vertikale Linien, die aber dunkler sind als der übrige Theil des Farbenbildes; einige scheinen fast ganz schwarz zu seyn. Wurde das Prisma so gedreht, daſs der Einfallswinkel gröſser



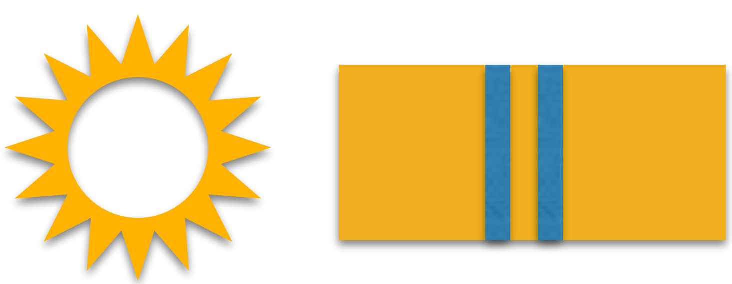
Gustav Kirchhoff

"Ueber die Fraunhofer'schen Linien"

XIV. *Ueber die Fraunhofer'schen Linien;*
von G. Kirchhoff.

(Aus d. Monatsbericht. d. Berl. Acad. October 1859.)

Fraunhofer hat bemerkt, dafs in dem Spectrum einer Kerzenflamme zwei helle Linien auftreten, die mit den beiden dunklen Linien *D* des Sonnenspectrums zusammenfallen. Dieselben hellen Linien erhält man leicht stärker von einer Flamme, in die man Kochsalz gebracht hat. Ich entwarf ein Sonnenspectrum und liefs dabei die Sonnenstrahlen, bevor sie auf den Spalt fielen, durch eine kräftige Kochsalzflamme treten. War das Sonnenlicht hinreichend gedämpft, so erschienen an Stelle der beiden dunklen Linien *D* zwei helle Linien; überstieg die Intensität jenes aber eine gewisse Gränze, so zeigten sich die beiden dunklen Linien *D* in viel gröfserer Deutlichkeit, als ohne Anwesenheit der Kochsalzflamme.

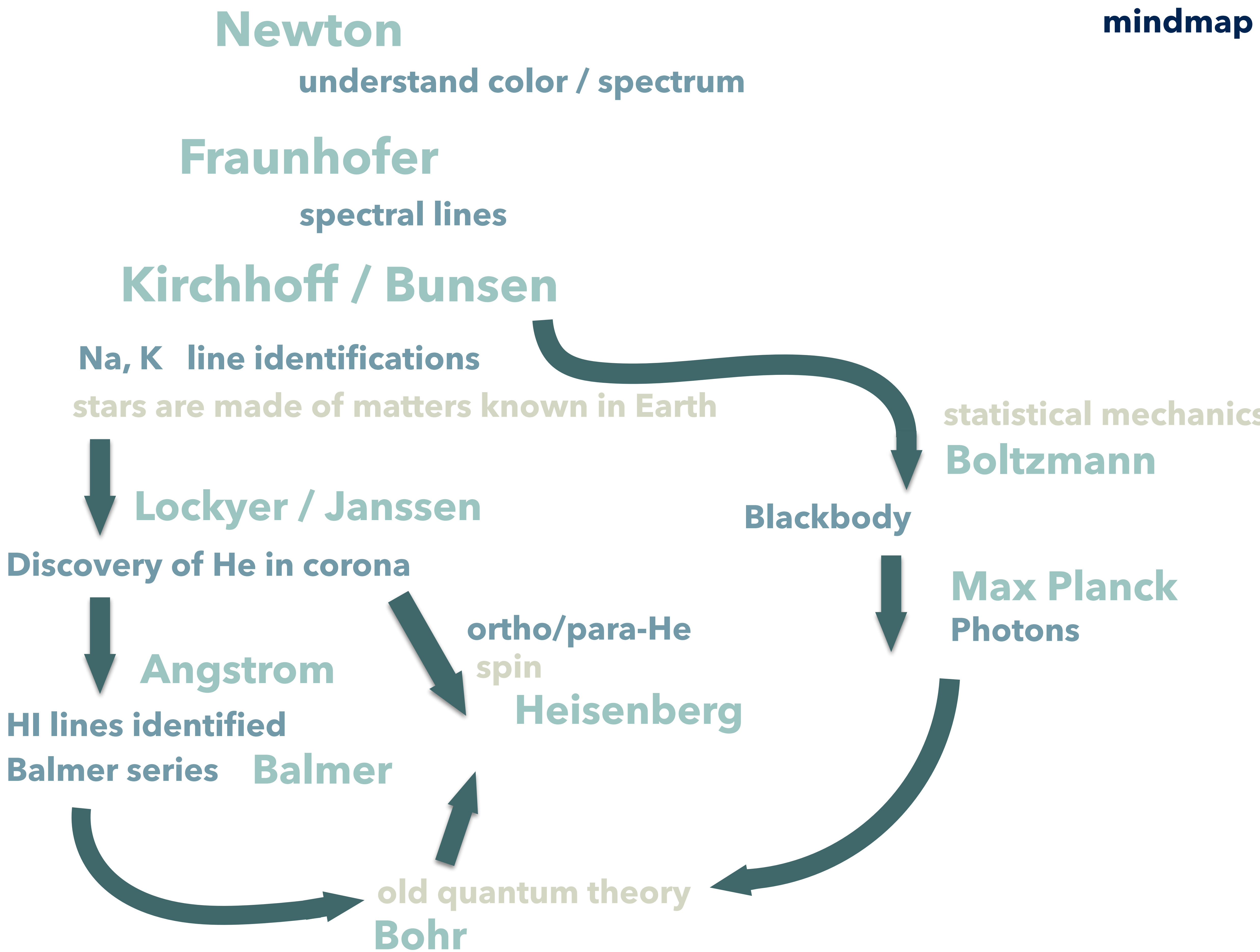


Discussing chemical composition of a star

is no longer philosophical / religious questions

but simply a decent physics question

mindmap

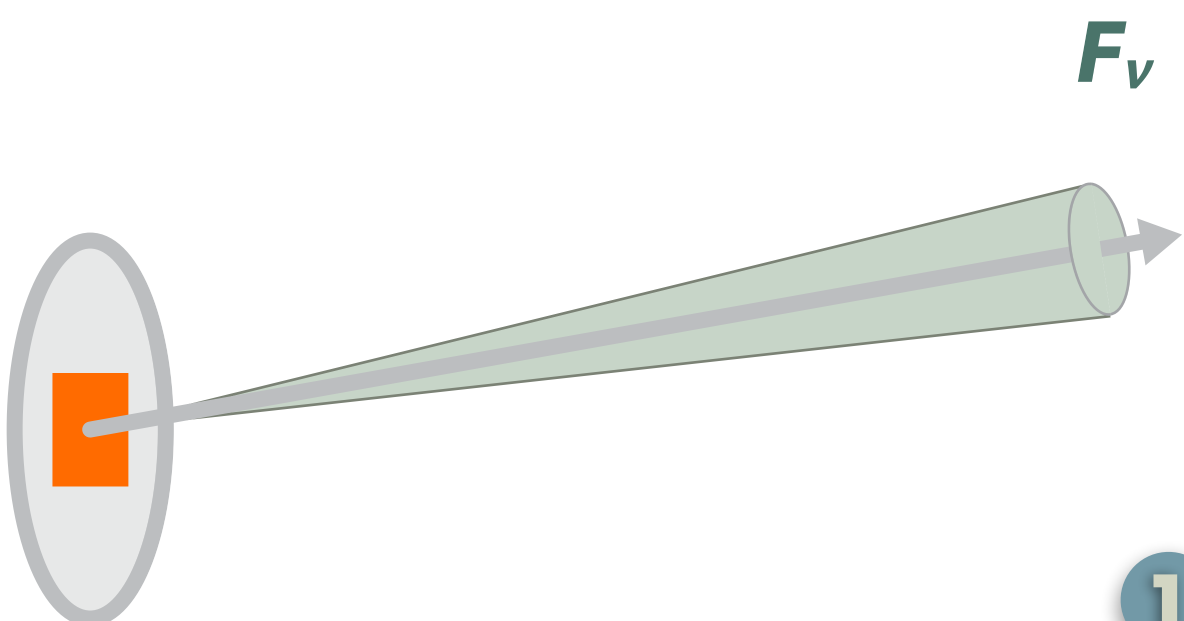


Newton
understand color / spectrum
Fraunhofer
spectral lines
Kirchhoff / Bunsen
Na, K line identifications
stars are made of matters known in Earth
Lockyer / Janssen
Discovery of He in corona
Angstrom
HI lines identified
Balmer series
Balmer
ortho/para-He
spin
Heisenberg
statistical mechanics
Boltzmann
Blackbody
Max Planck
Photons
old quantum theory
Bohr

Glossary : intensity vs flux

$$dE_\nu = I_\nu \, dA \, dt \, d\Omega \, d\nu$$

[cm^{-2}] [s^{-1}] [str^{-1}] [Hz^{-1}]



$$dE_\nu = F_\nu \, dA \, dt \, d\nu$$

$d\Omega$ integrated

1. **intensity** does not change with distance

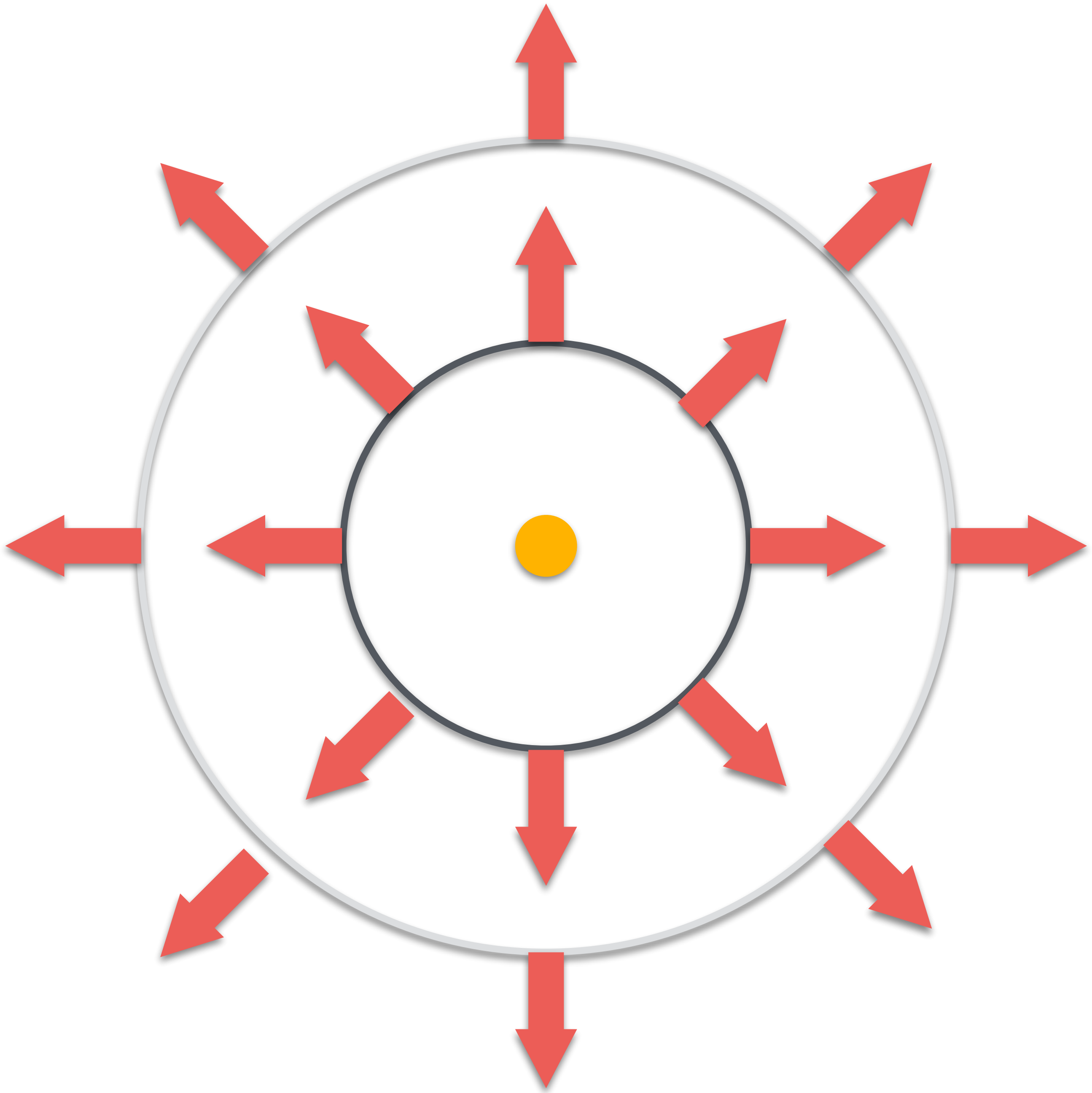
2. **flux** dose

L_ν is the total energy that passes boundary $= \text{constant}$

$4\pi r^2$ is the size of the boundary

$$L_\nu = 4\pi r^2 \cdot F_\nu$$

$$F_\nu = \frac{L_\nu}{4\pi r^2}$$



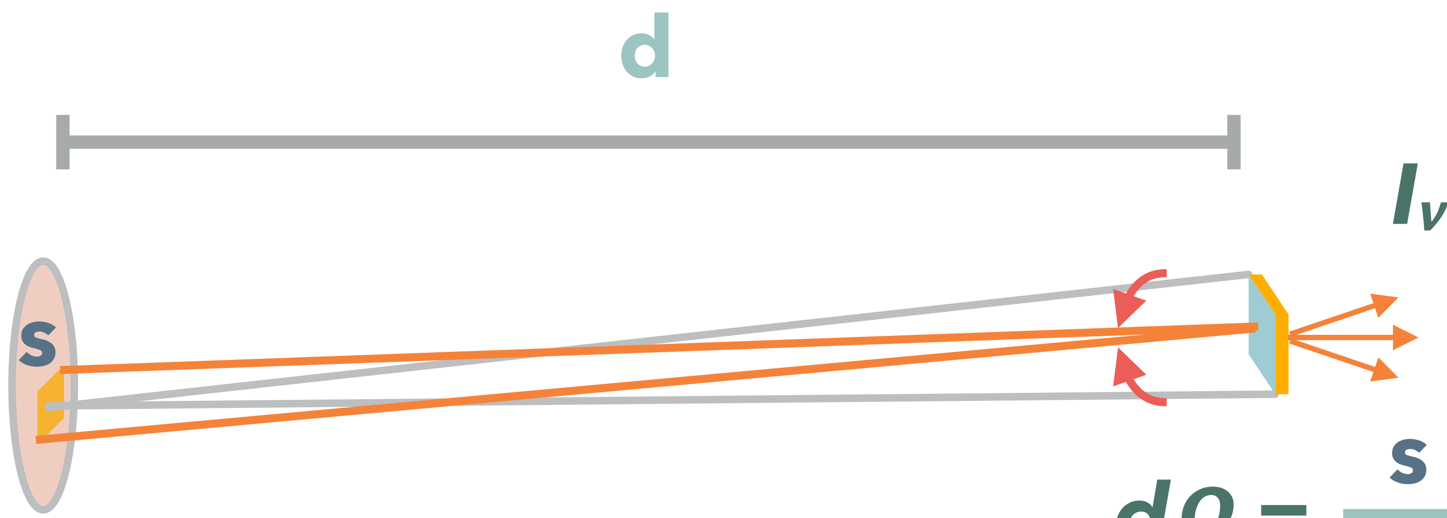
if I_ν constant $F_\nu \propto \dfrac{1}{d^2}$?

$$F_\nu = I_\nu \, d\Omega$$

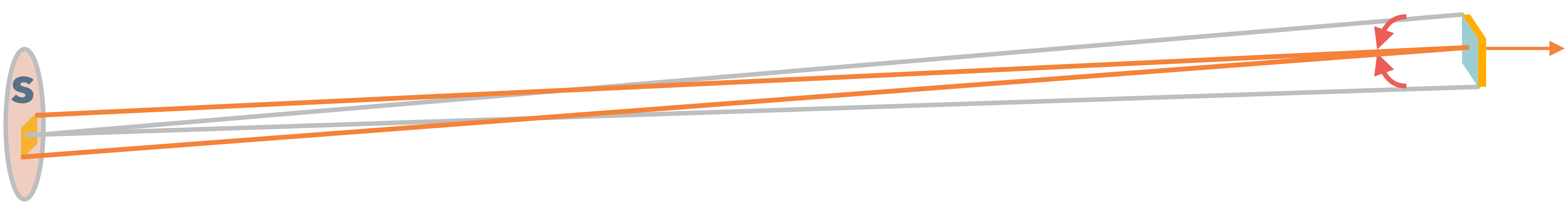
$$I_\nu = \frac{F_\nu}{d\Omega} \propto \frac{1}{d^2 \, d\Omega}$$

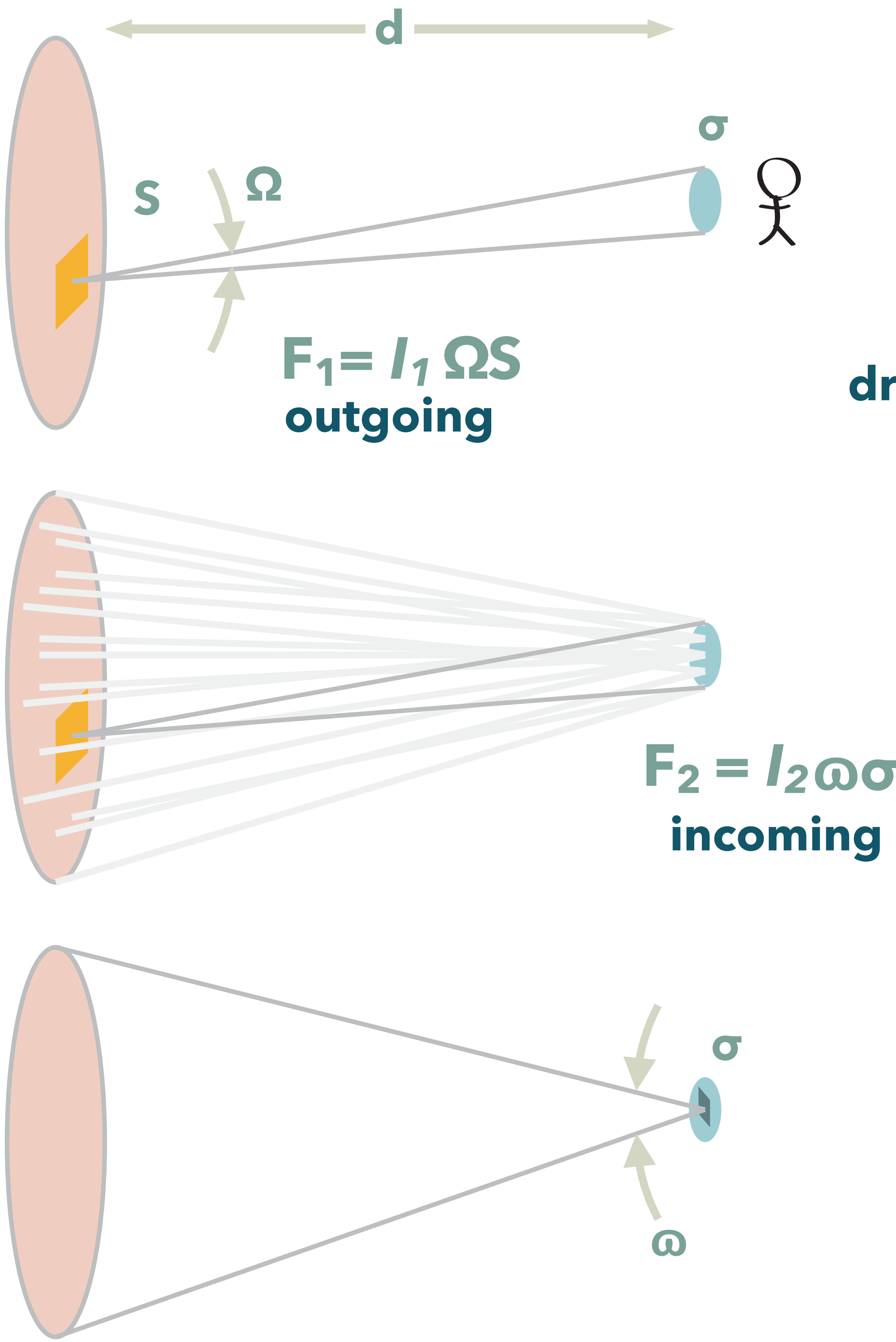
$$= \frac{1}{d^2 \, \frac{s}{d^2}}$$

$$= \text{not dependent on } d$$



$$d\Omega = \frac{s}{d^2}$$





draw all possible rays

that start from S and hit σ

$$F_2 = F_1$$

$$\Omega = \frac{\sigma}{d^2}$$

$$\Omega S = \frac{\sigma S}{d^2} = \varpi \sigma$$

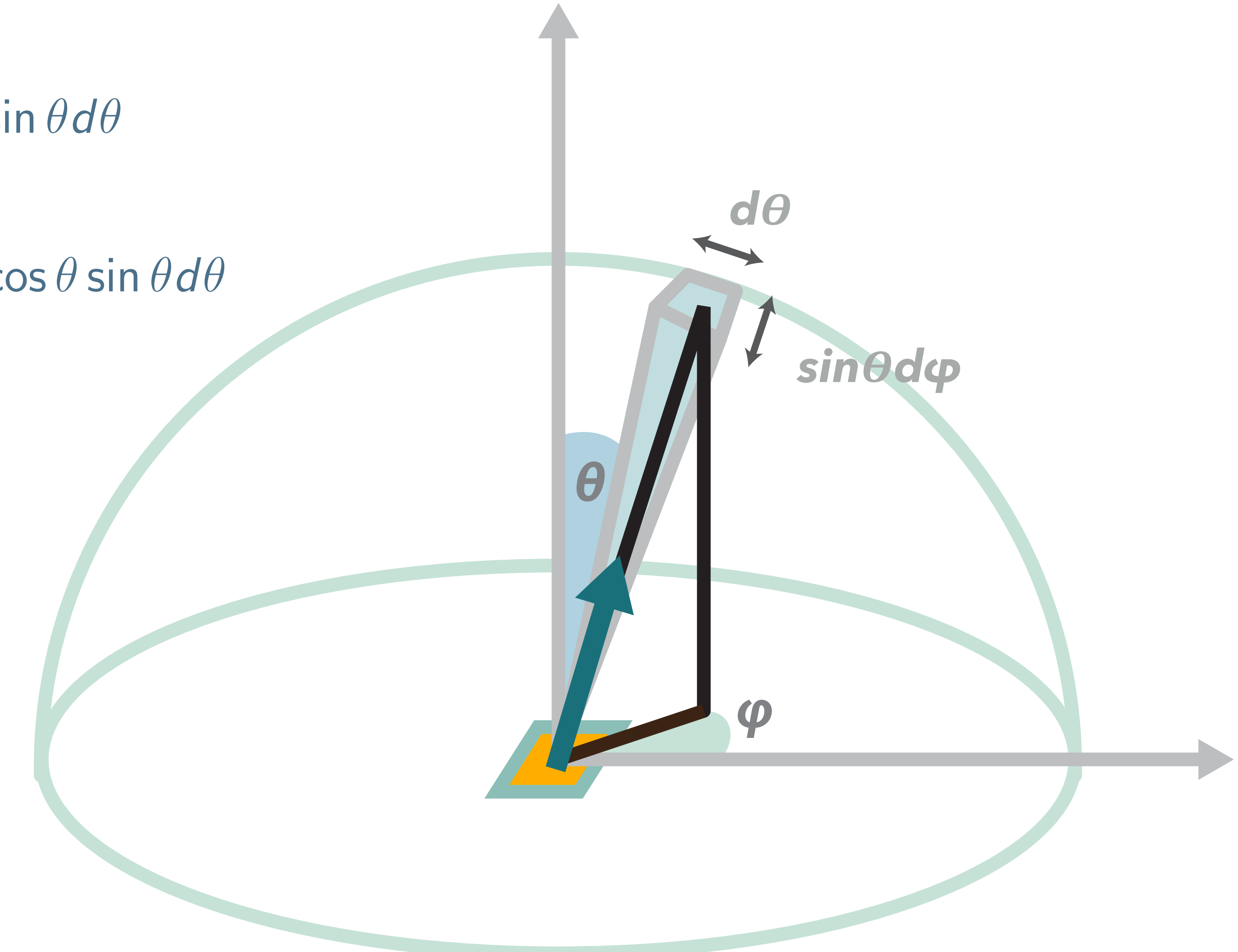
$$\varpi = \frac{S}{d^2}$$

$$I_2 = I_1$$

Surface

$$(\cos\theta)' = -\sin\theta d\theta$$

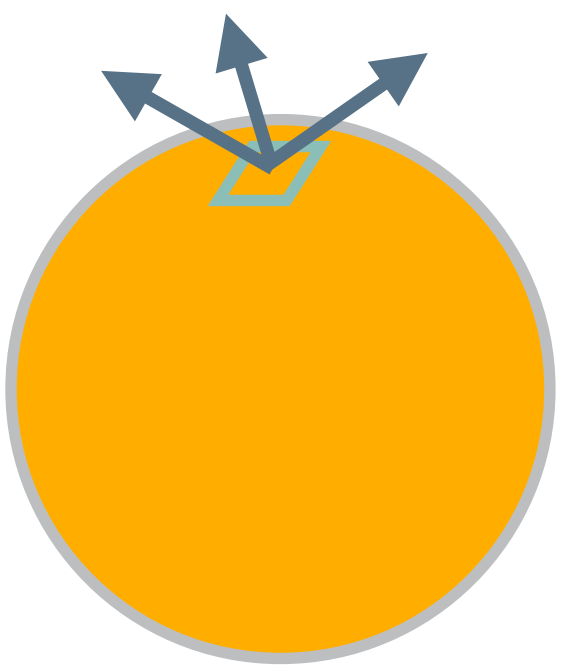
$$\left(\frac{\cos^2\theta}{2}\right)' = -\cos\theta\sin\theta d\theta$$



$$F_\nu = I_\nu \int d\Omega$$

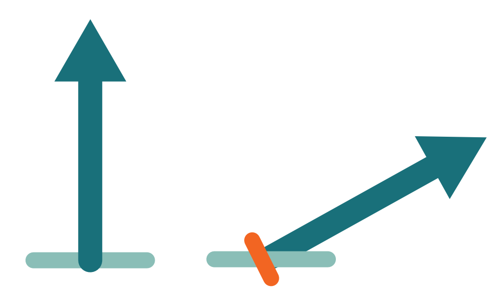
$$= I_\nu \cos\theta \int_0^{\frac{\pi}{2}} \int_0^{2\pi} d\theta \sin\theta d\phi$$

$$= I_\nu \cdot 2\pi \int_0^{\frac{\pi}{2}} \cos\theta \sin\theta d\theta$$



$$= I_\nu \cdot 2\pi \left[\frac{-\cos^2\theta}{2}\right]_0^{\frac{\pi}{2}}$$

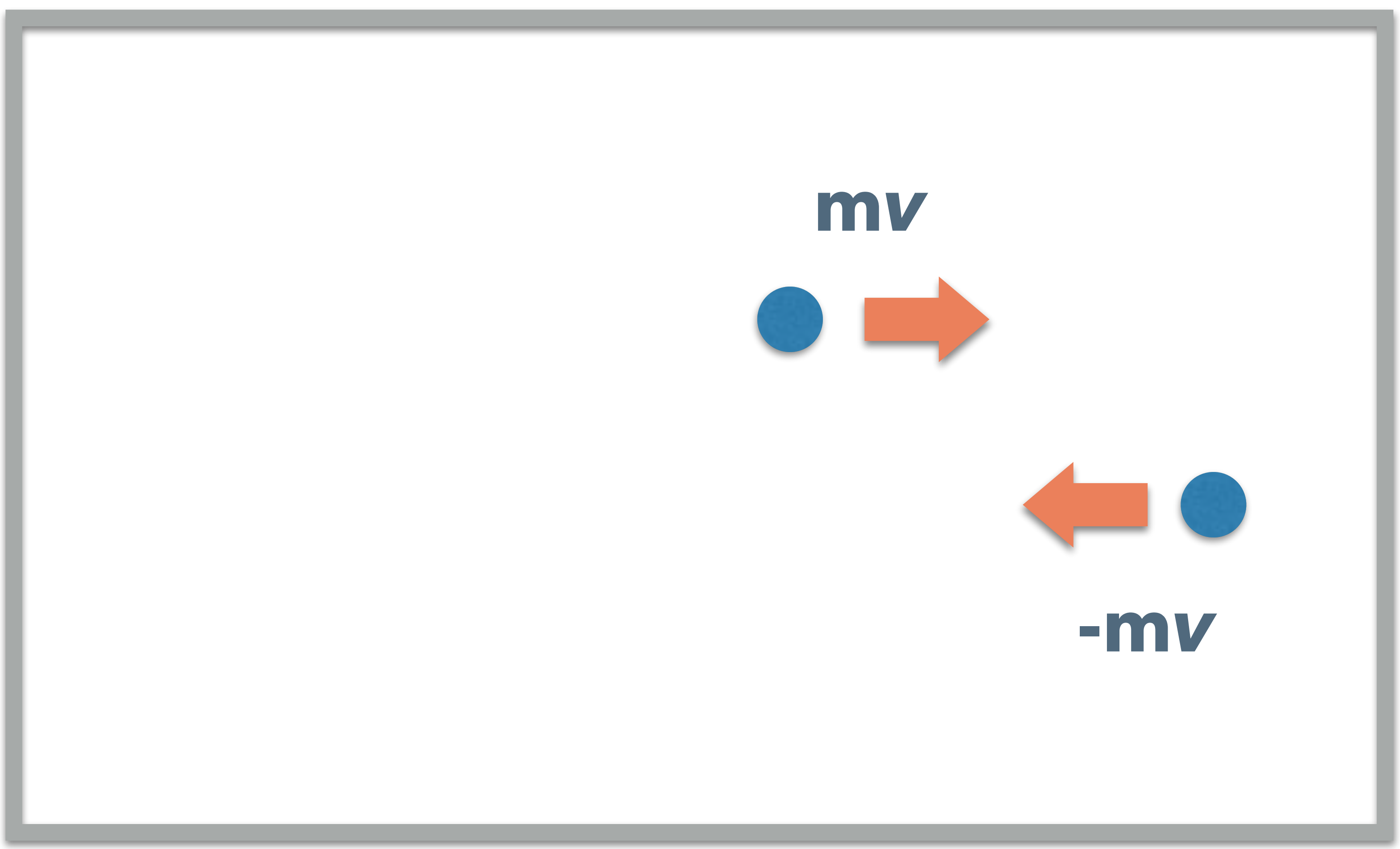
$$= I_\nu \cdot 2\pi \left[0 - (-\frac{1}{2})\right]$$



$$= \pi I_\nu$$

Radiation pressure

pressure is momentum (temporal change of it)



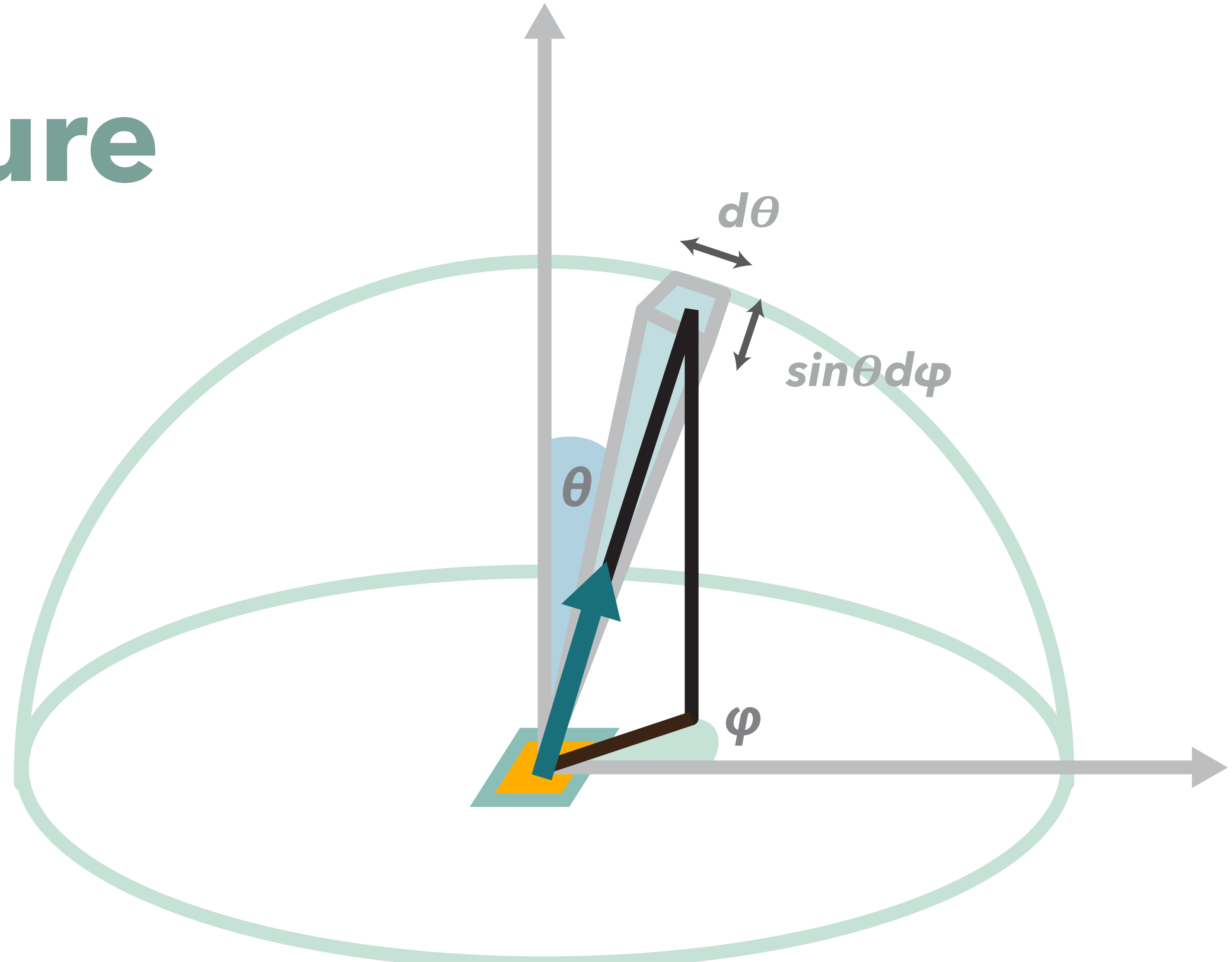
$$F = ma$$

$$= m\frac{dv}{dt}$$

Radiation pressure

$$p = \frac{E}{c}$$

momentum of photon



force

$$F = I \cdot 2\pi \int_0^{\frac{\pi}{2}} \cos^2\theta \sin\theta d\theta$$

$$= I \cdot 2\pi \left[\frac{-\cos^3\theta}{3}\right]_0^{\frac{\pi}{2}}$$

$$= I \cdot 2\pi \left[0 - (-\frac{1}{3})\right]$$

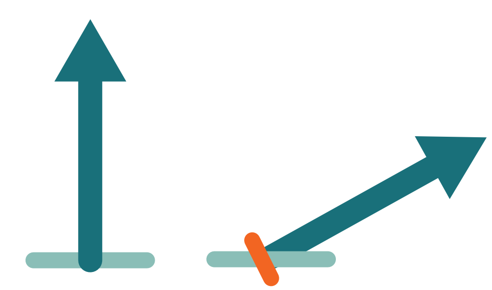
$$= \frac{2\pi}{3c} I$$

$$(\cos\theta)' = -\sin\theta d\theta$$

$$\left(\frac{\cos^3\theta}{3}\right)' = -\cos^2\theta \sin\theta d\theta$$

1 **it is actually** $= \frac{4\pi}{3c} I$

why?



I_ν vs u_ν

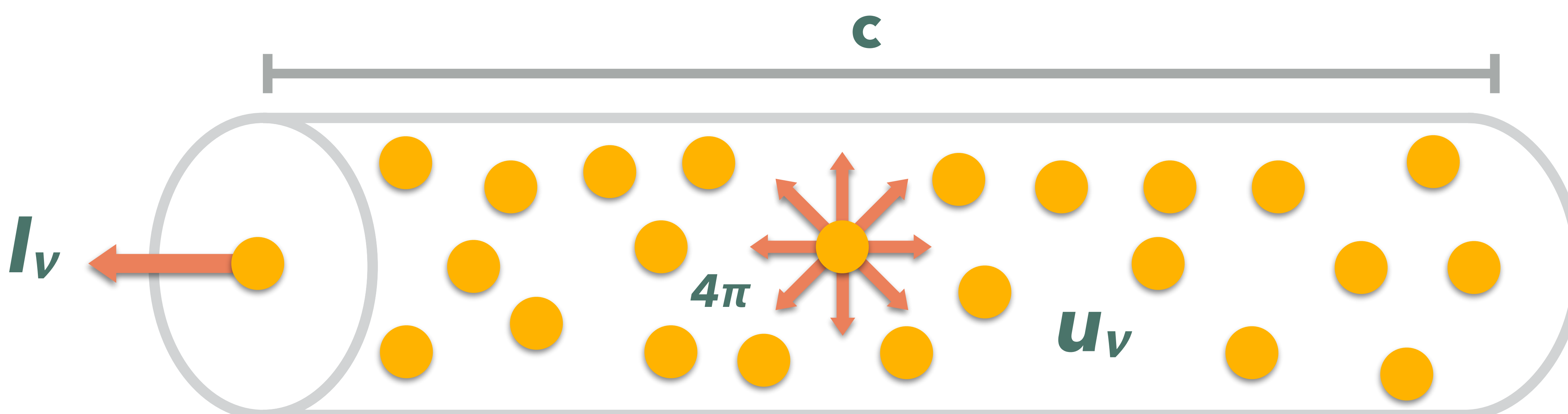
intensity energy density

$$dE_\nu = I_\nu \, dA \, dt \, d\Omega \, d\nu$$

[cm^{-2}] [s^{-1}] [str^{-1}][Hz^{-1}]

$$dE_\nu = u_\nu \, dV \, d\nu$$

[cm^{-3}][Hz^{-1}]



$$I_\nu = \frac{u_\nu}{4\pi} \cdot c$$

$$u = \frac{4\pi}{c} I$$

$$p = \frac{u}{3}$$

$$u_\nu = \frac{4\pi}{c} I_\nu$$

$$p = \frac{4\pi}{3c} I$$

2 check if the unit is consistent

What is spectrum?

Continuum + Spectral Features

Blackbody

free-free

absorption / emission

atom
molecules

high res.

ice
dust

low res.

Exercise today

1 **it is actually** $= \frac{4\pi}{3c} I$

why?

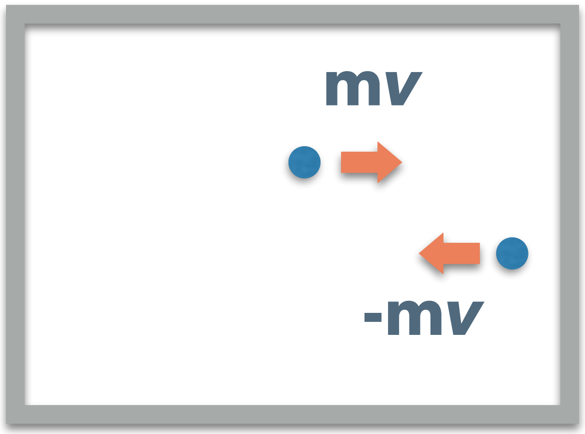
$$p = \frac{E}{c}$$

momentum of photon

force $F = I \cdot 2\pi \int_0^{\frac{\pi}{2}} \cos^2\theta \sin\theta d\theta$

2 **check if the unit is consistent**

$$p = \frac{u}{3}$$



$$F = ma$$

$$= m\frac{dv}{dt}$$