Radial velocity and line broadening in spectra

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SMSW2, 22 February 2019

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@drkedevi

Background

- Physics
  - Carleton College (Northfield MN)
- Astronomy
  - University of Wisconsin (Madison)
  - Early conditions of massive star forming environments
  - Internal properties of infrared dark clouds
- College of Idaho
  - Physics professor since 2009
  - Intro and upper division physics
  - Intro astronomy

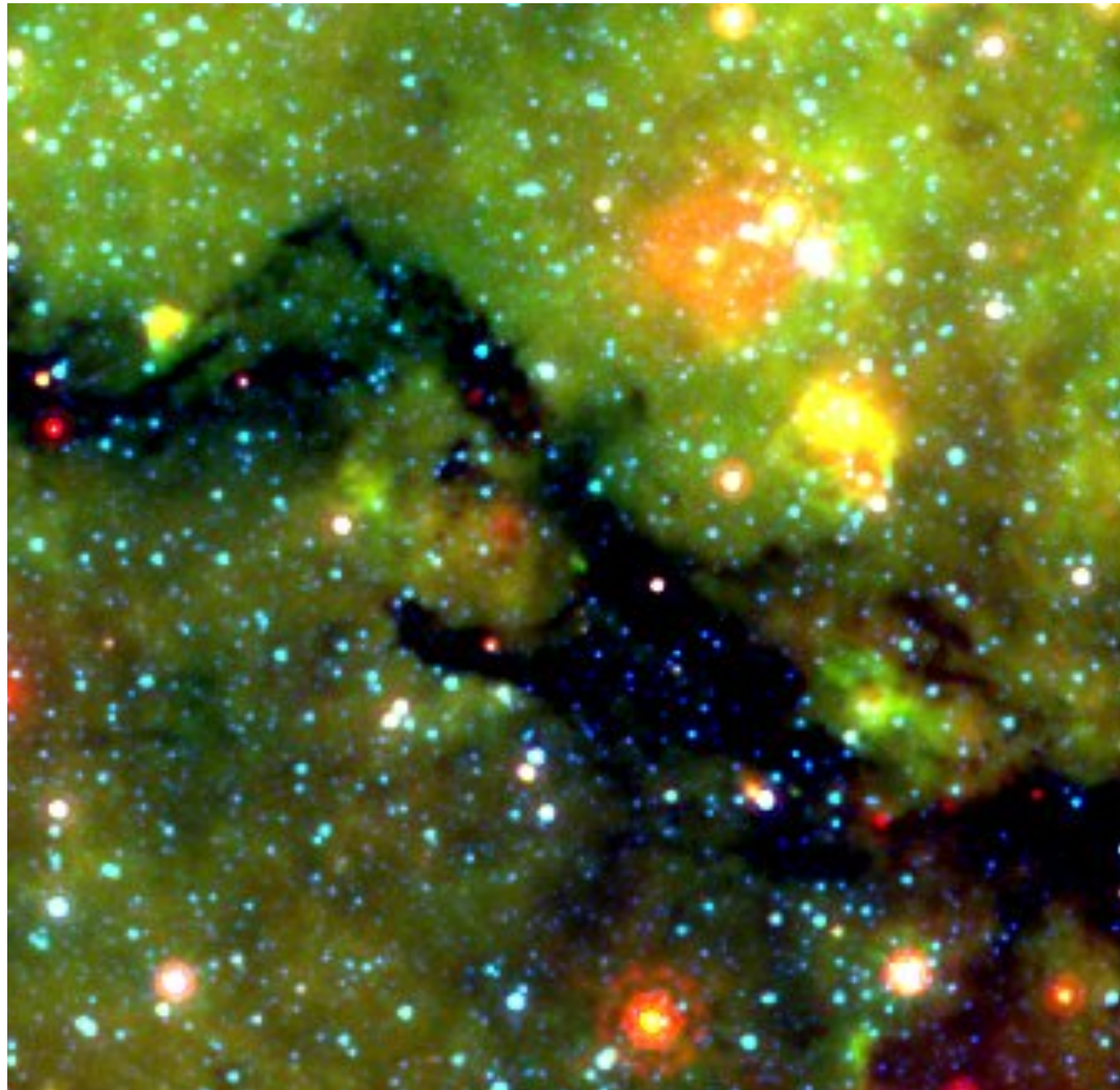


Image credit: Milky Way Project (milkywayproject.org)

Infrared dark clouds are seen in silhouette aga
background glowing dust emission.

Research

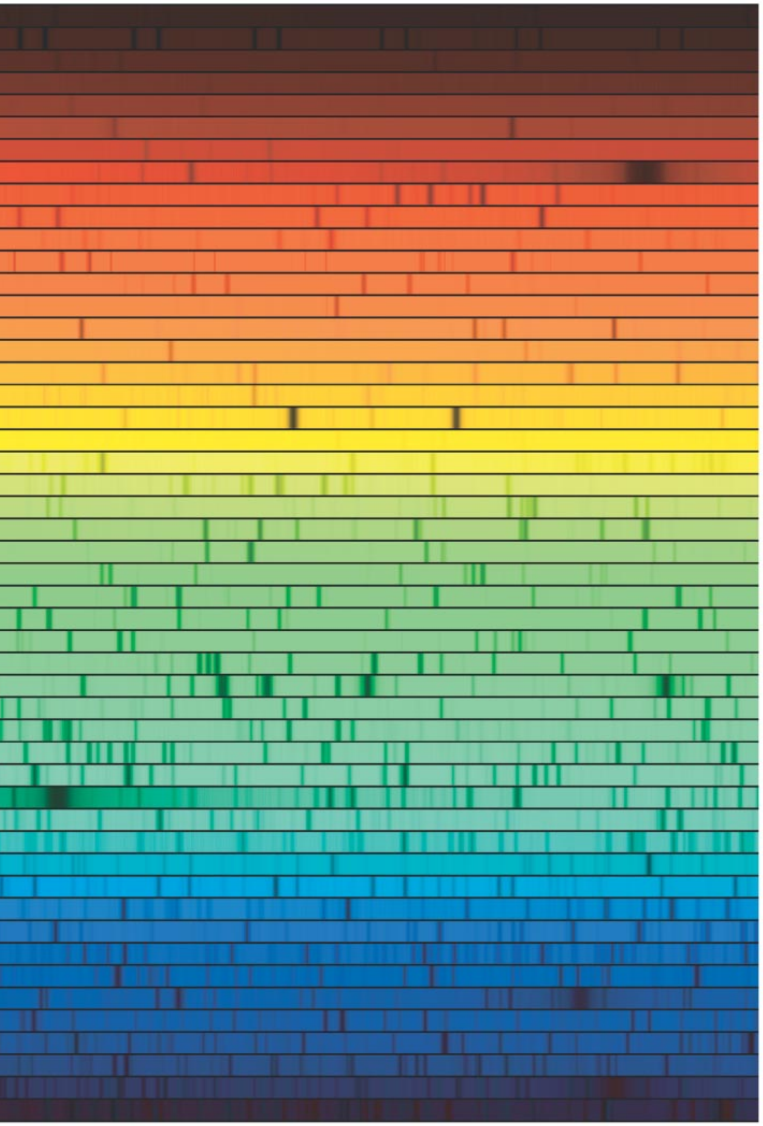
- ssive Star Formation
  - Radio: VLA, Green Bank Telescope
  - nfrared: Spitzer, Herschel

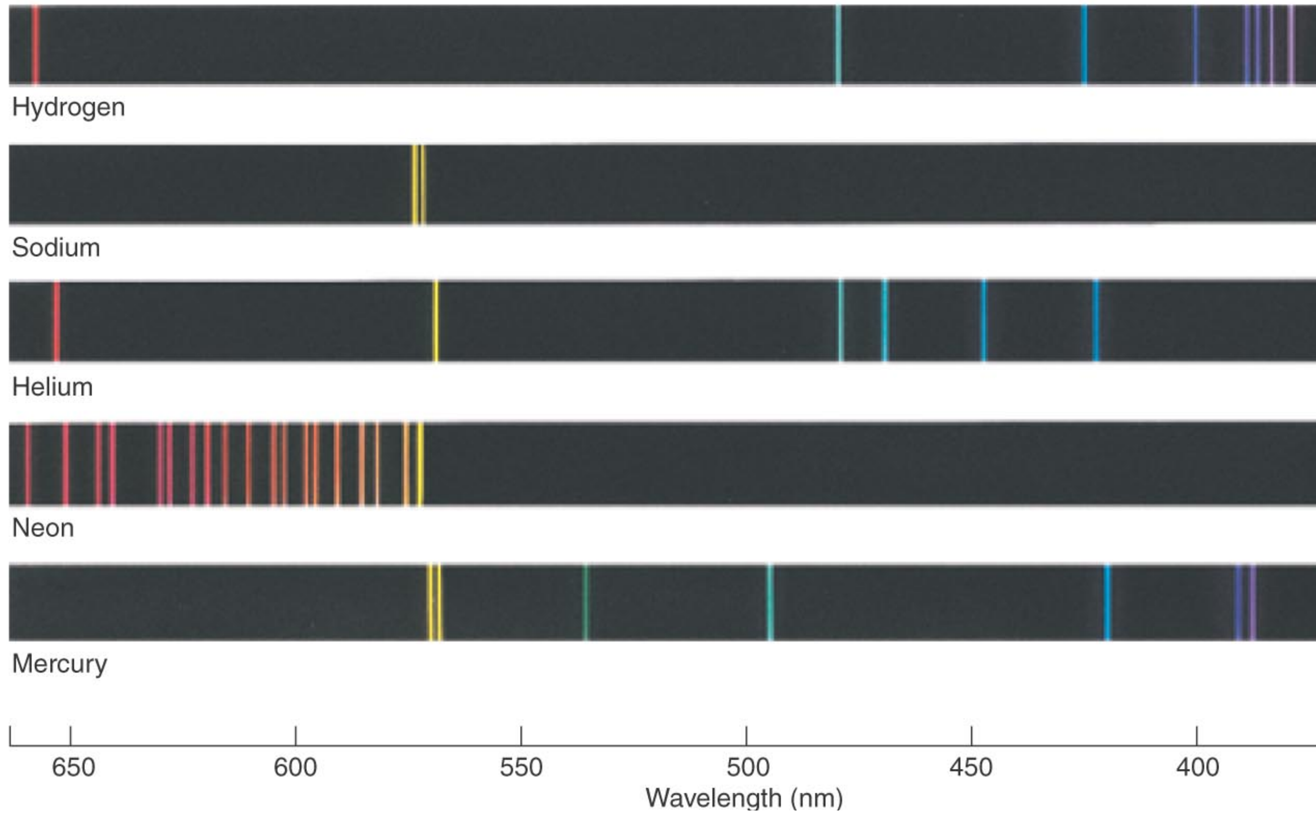
- rarchical star formation
  - Bubbles
  - Yellowballs

- connection to this ference: **I use radio spectral s to determine conditions of lecular gas in star forming as.**

Image credit: NASA/JPL-Caltech
Milky Way Project volunteers first pointe "yellowballs" to researchers (2012).

mission and Absorption Lines (Spectral nes)





"Fingerprints" of atoms and molecule

Images: Pearson e

Atoms and Absorption Lines: The usual model

Absorption can boost an electron to the second (or higher) excited state

Ways to decay:

1. To ground state
2. Cascade one orbital at a time

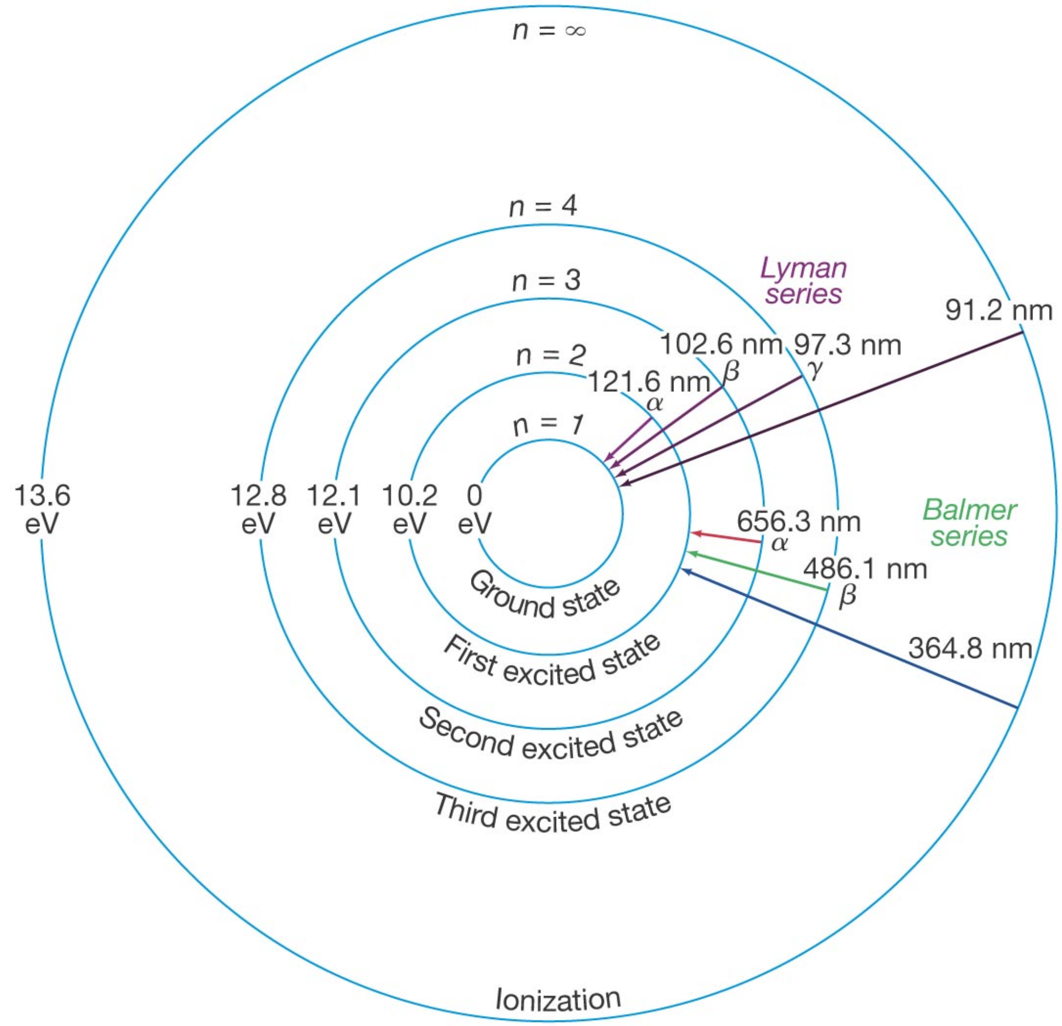


Image: Pearson ec

here are other ways generate emission nes besides "eating hotons"

- isional excitation: can be used to neasure the density, emperature of gas

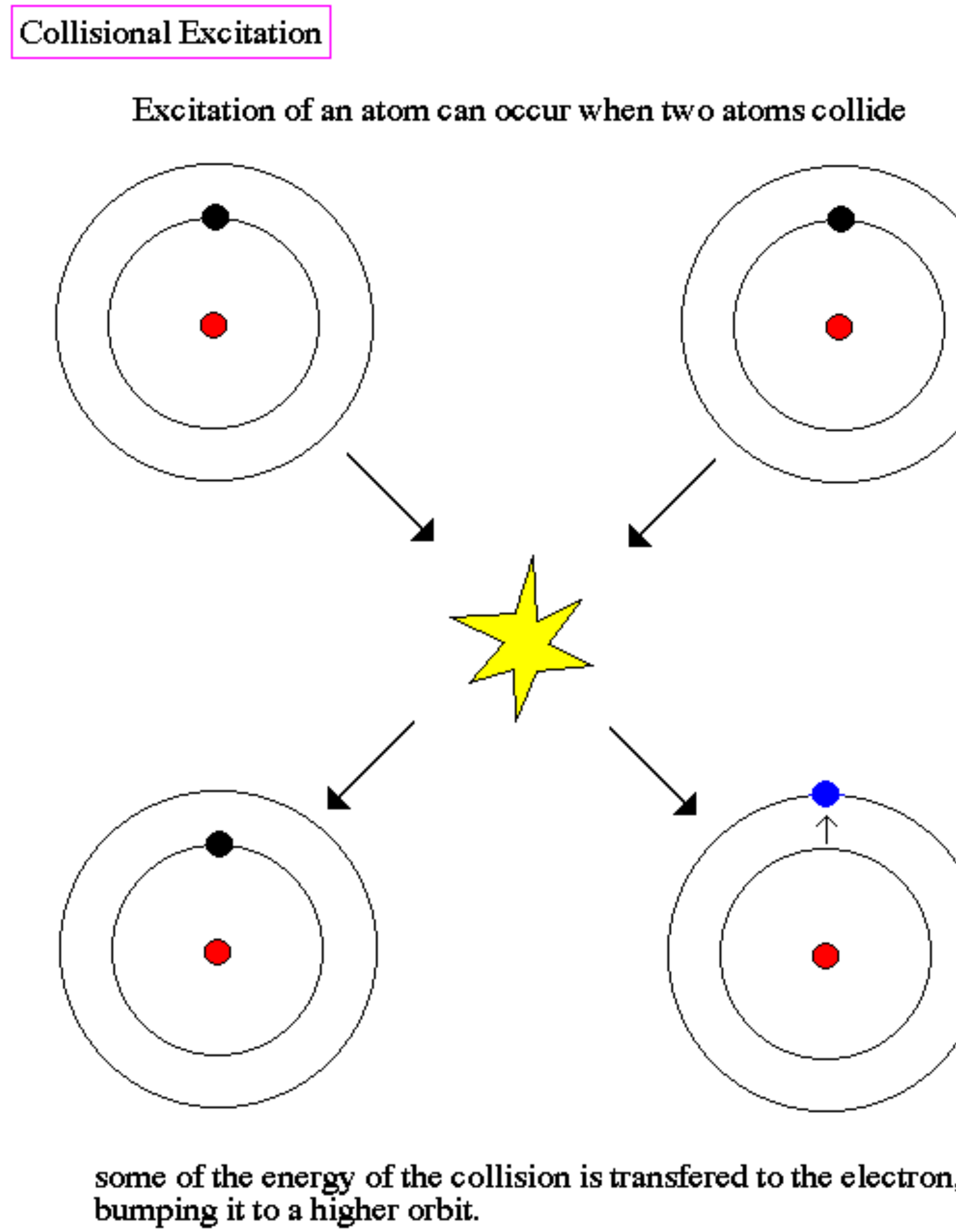
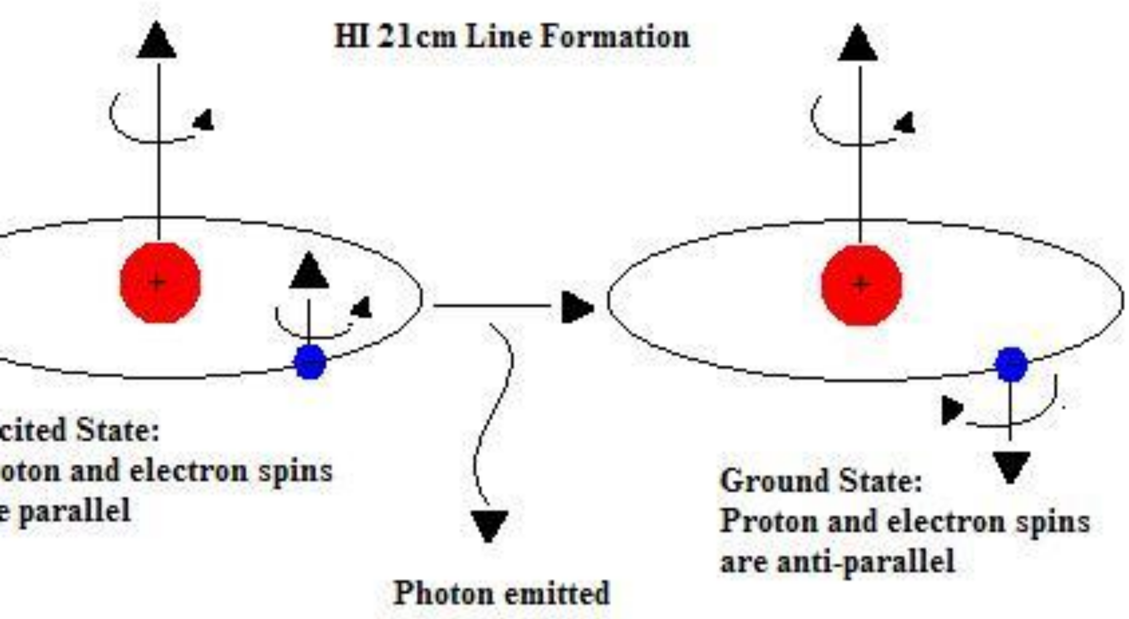
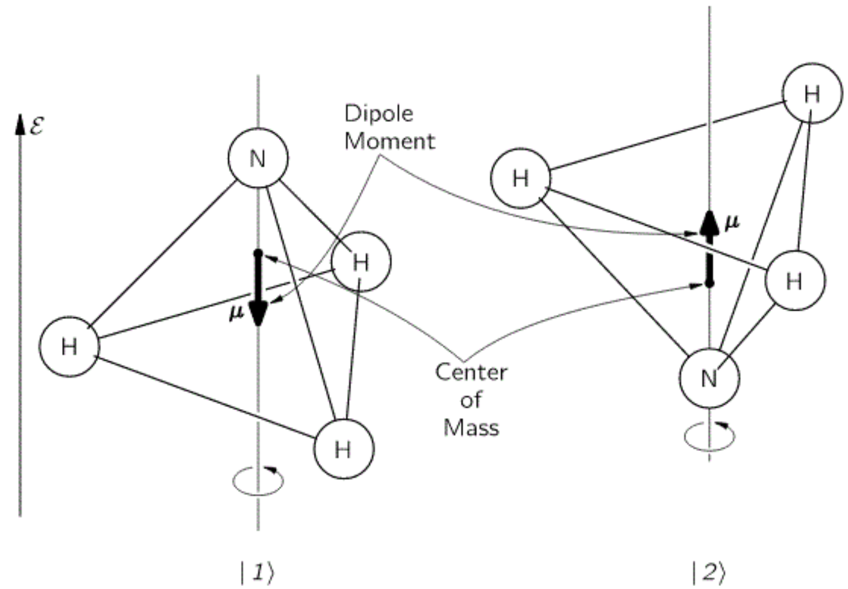


Image: http://abyss.uoregon.edu/~js/glossary/excita

\dditional types of energy levels of atoms
ınd molecules



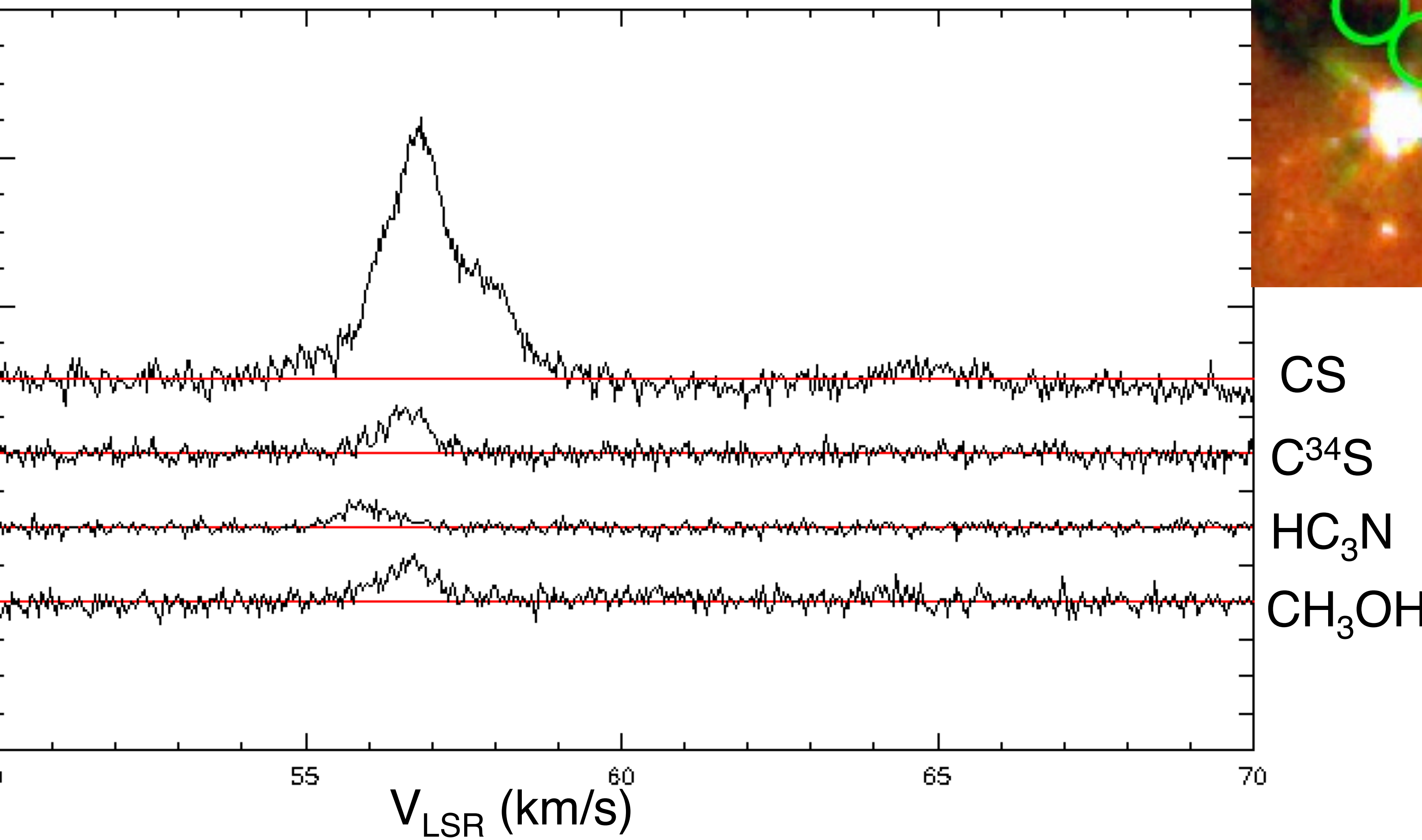


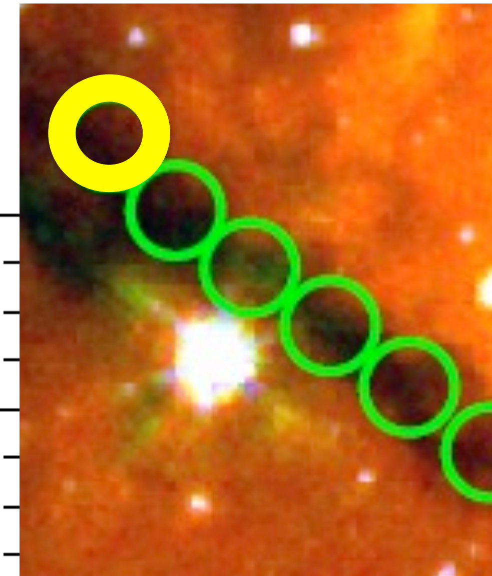
ctron/proton spin alignments have
ifferent energies. Example: 21 cm
ne in hydrogen.

Molecule's direction of rotat
around its axis of symmet
Example: position of N at
ammonia (NH_3).

Image: teachastronomy.com, readingfeynma

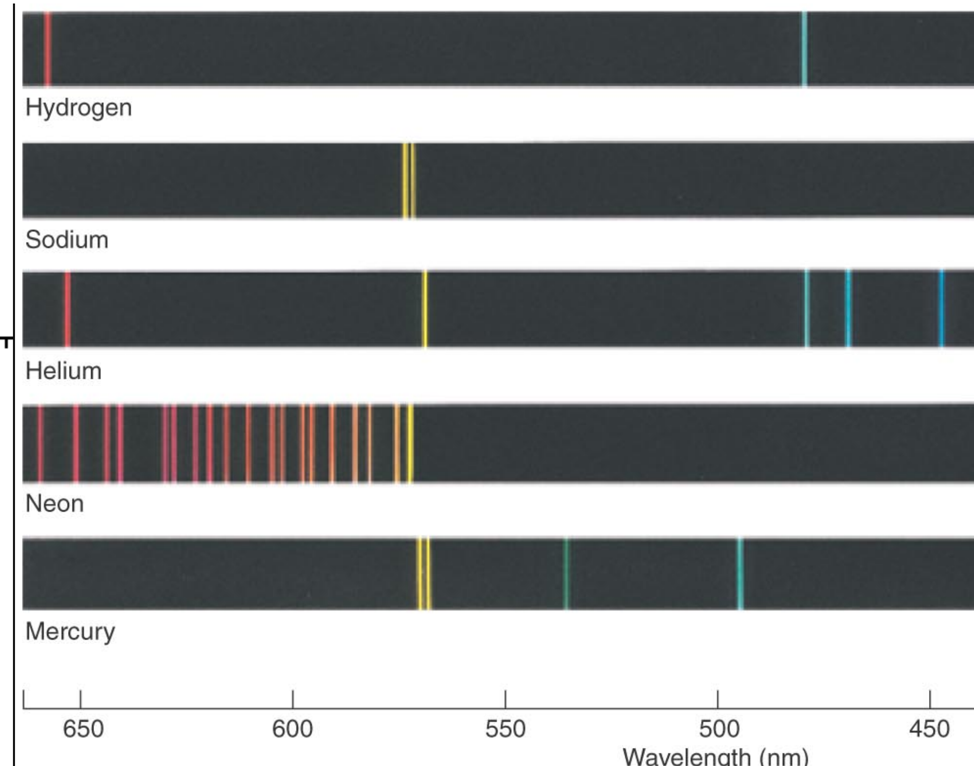
adio example: emission line

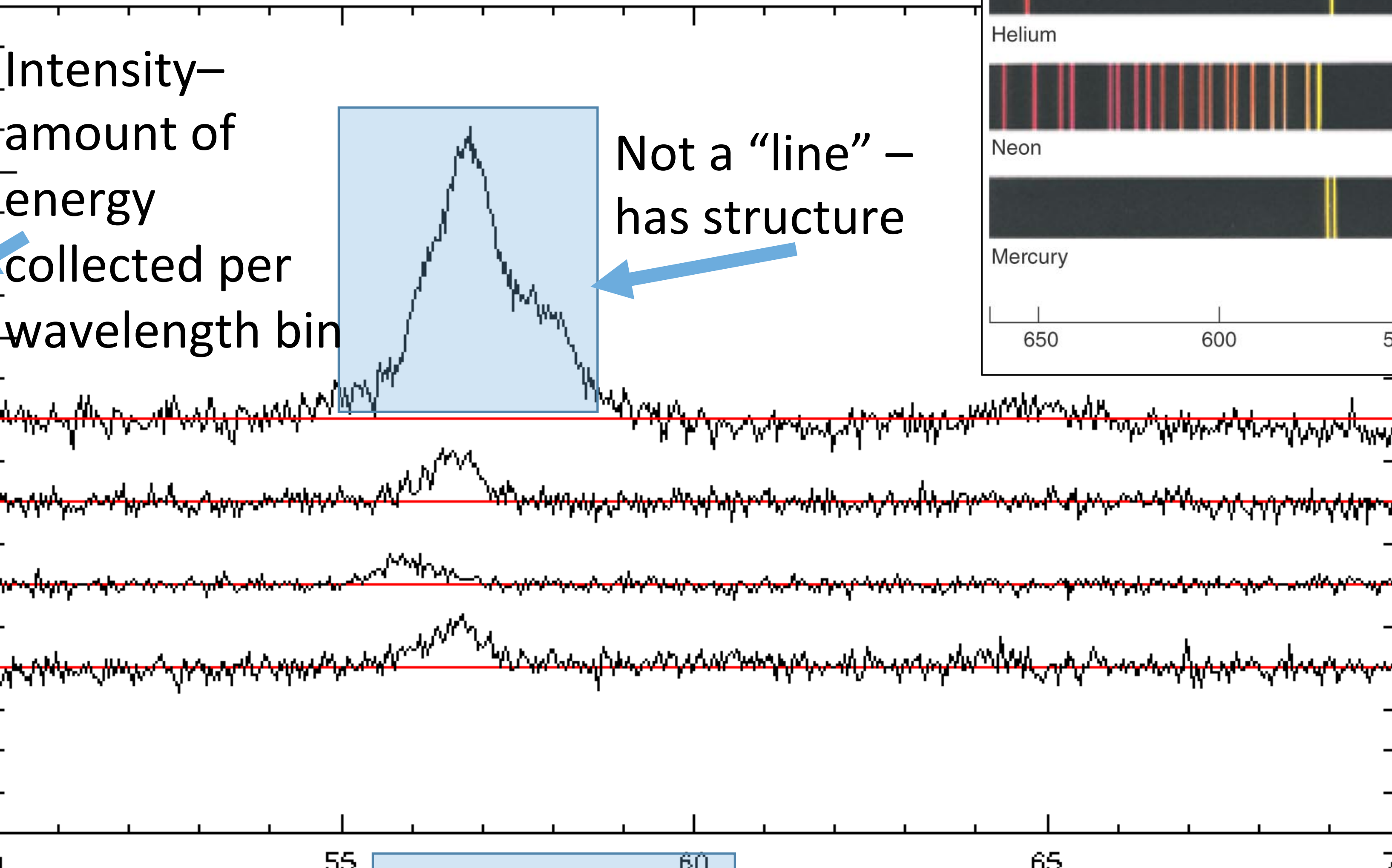




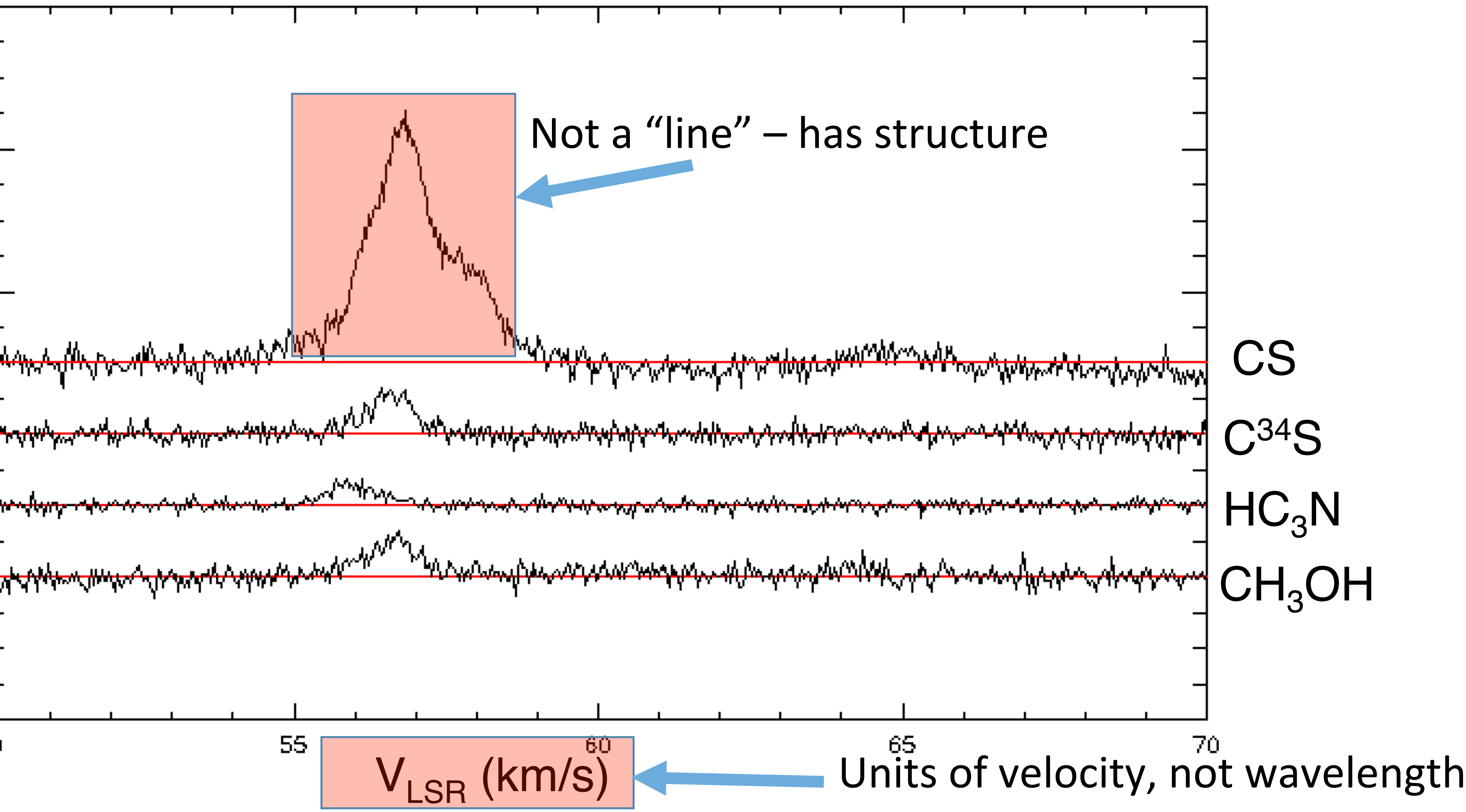
Devine et a

portant Features

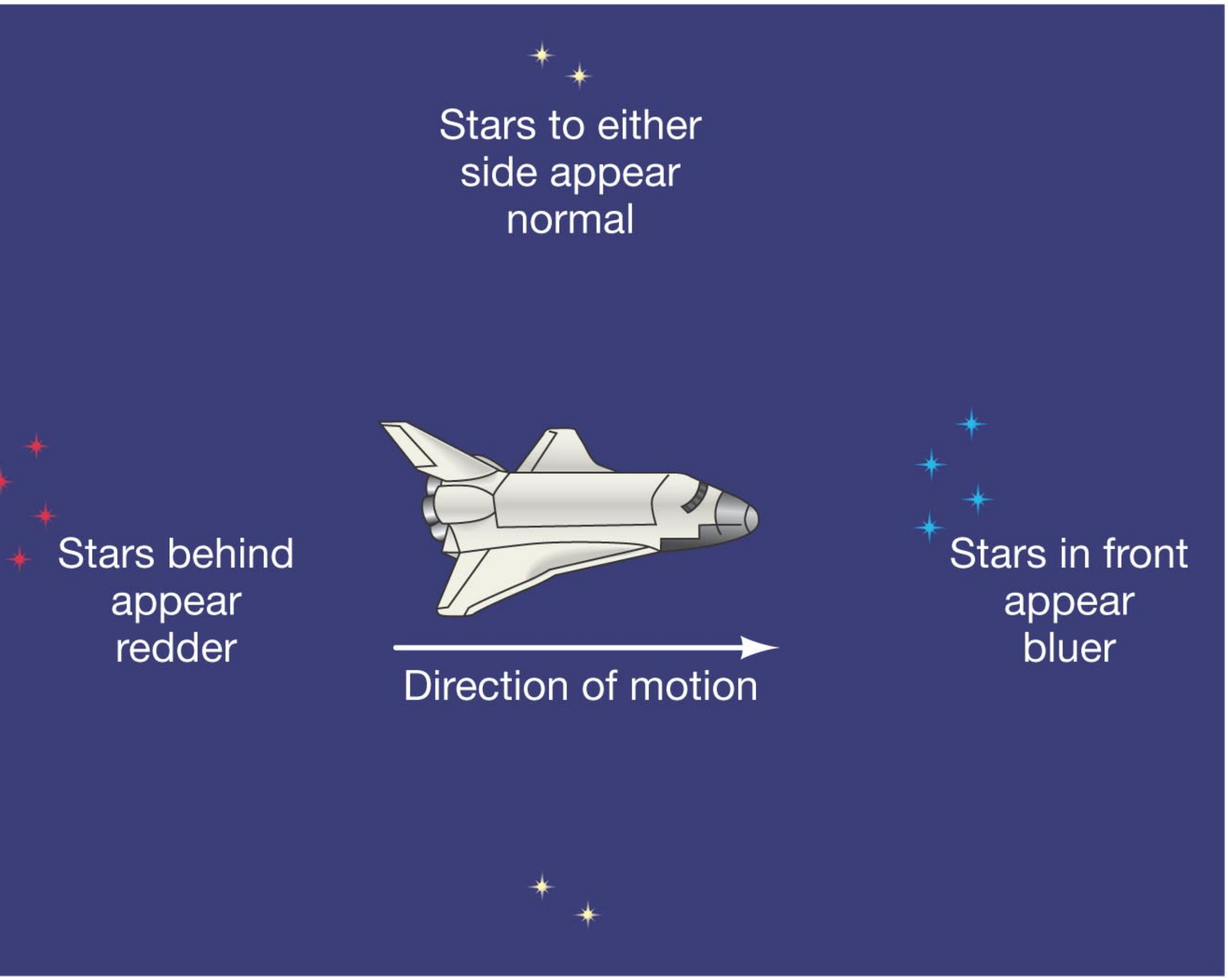




adial Velocity and Line Broadening



The Doppler Effect



Light can’t travel faster (o
slower) than the speed of
light, even if it is emitted
from a moving source.

If one is moving toward a
source of radiation, the
wavelengths seem shorte
(higher energy photons); i
moving away, they seem
longer (lower energy
photons).

Image: Pearson ec

The Doppler Effect

pends only on the relative
tion of source and
erver… motion must be
dial" (towards or away
m line of sight) to cause
ppler Effect

$=v/c$

re shift = higher radial
ocity

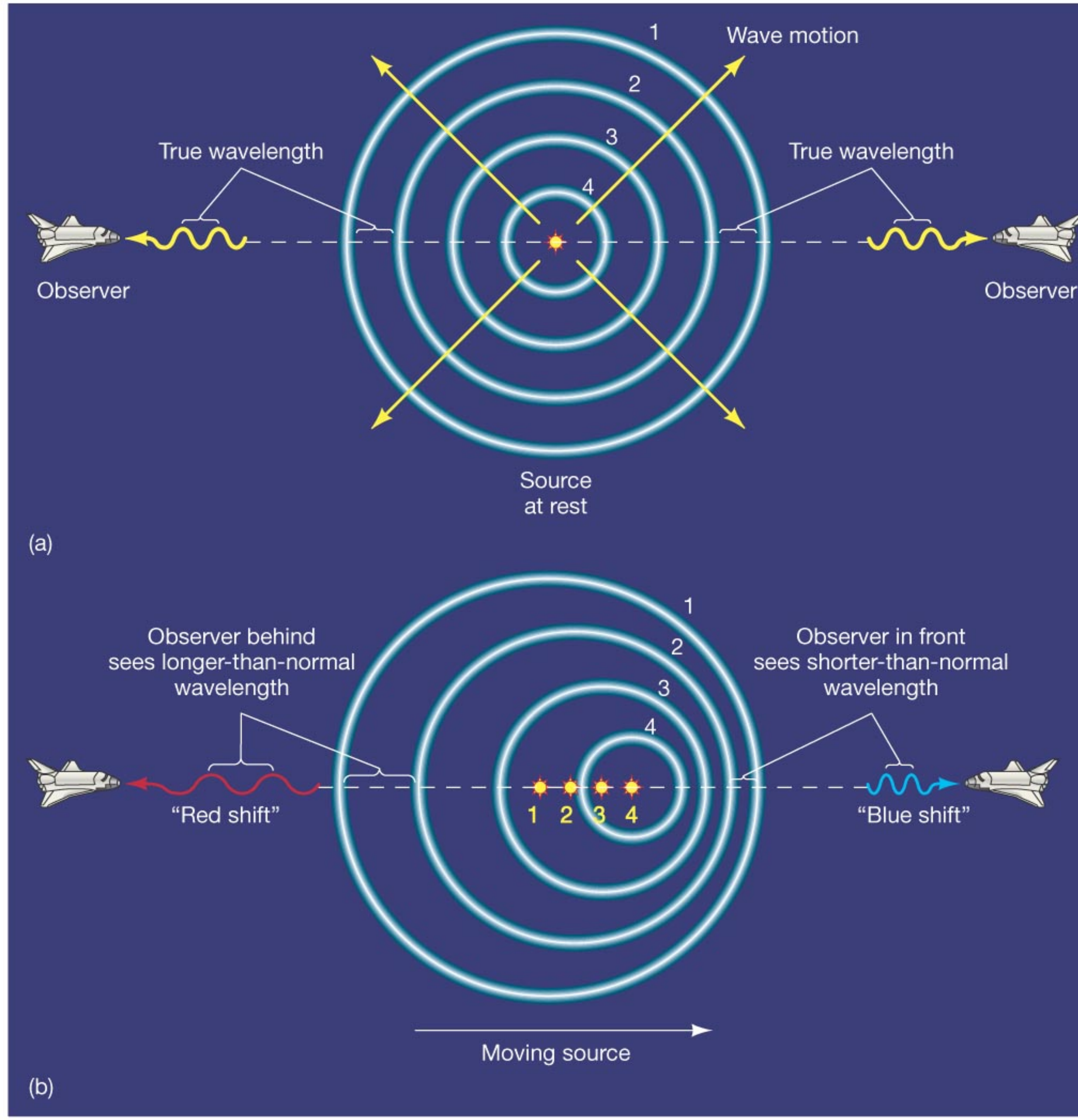
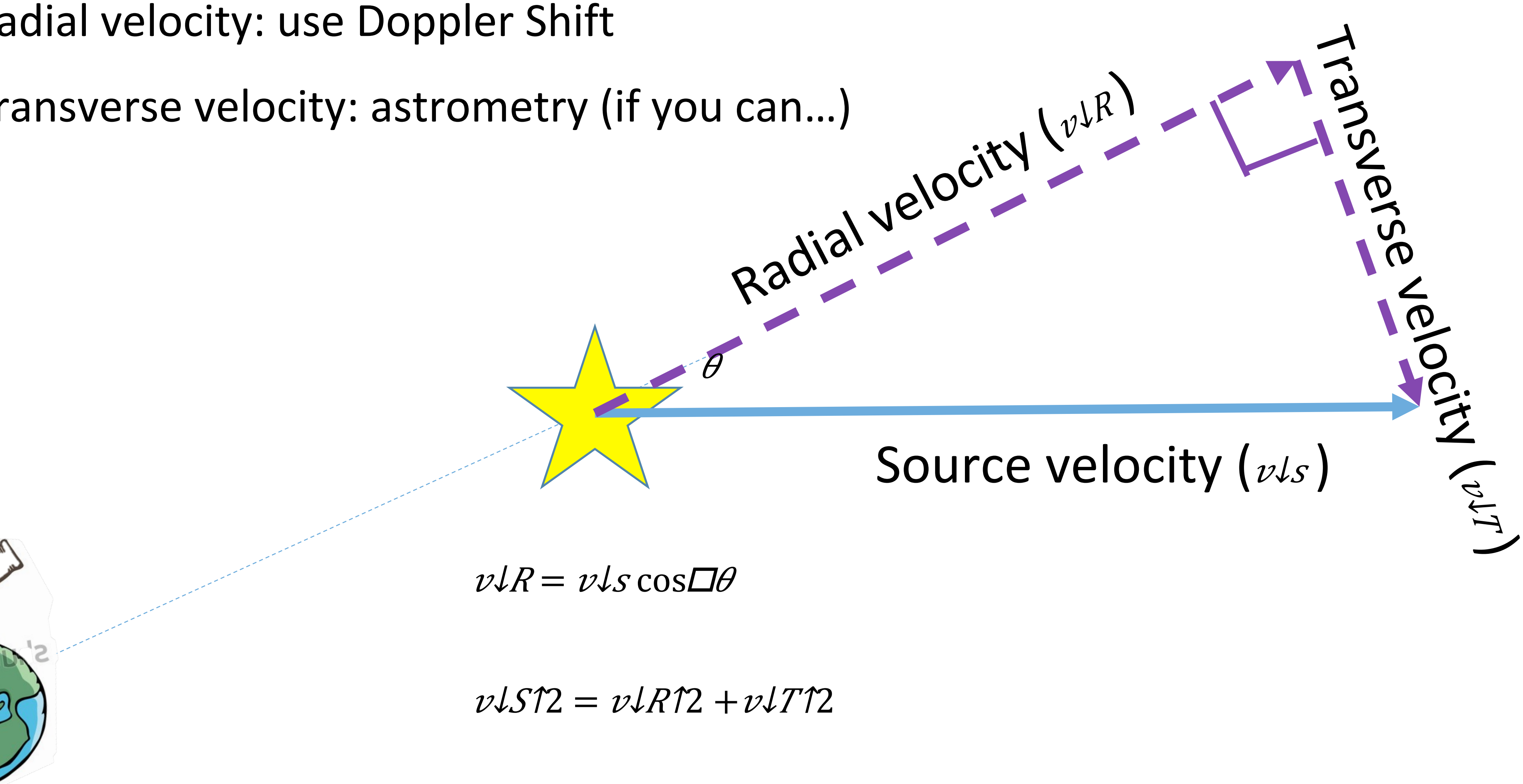


Image: Pearson ed

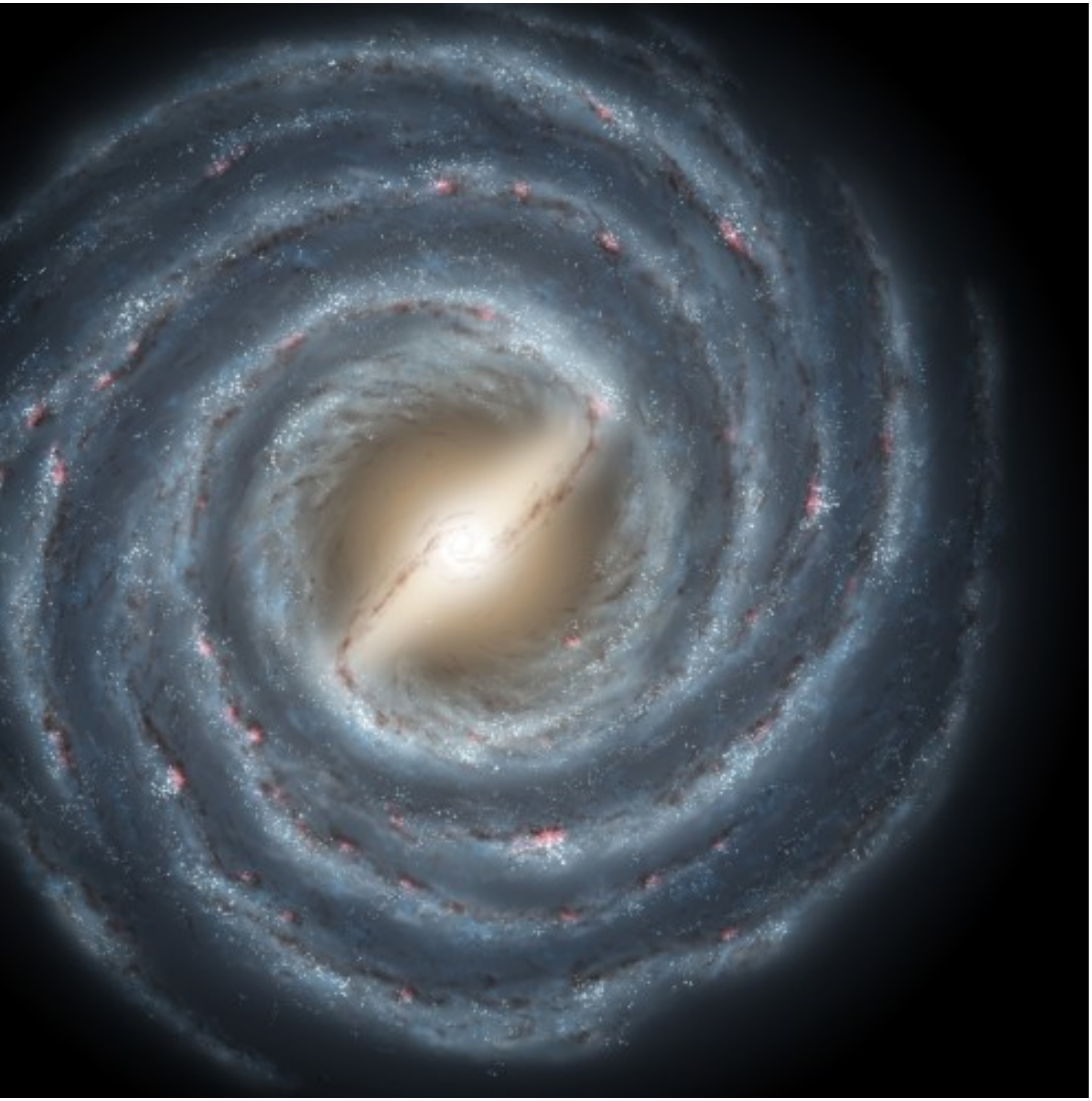
Radial velocity vs. source velocity

- adial velocity: use Doppler Shift
- ransverse velocity: astrometry (if you can…)



$$v_R = v_s \cos\theta$$

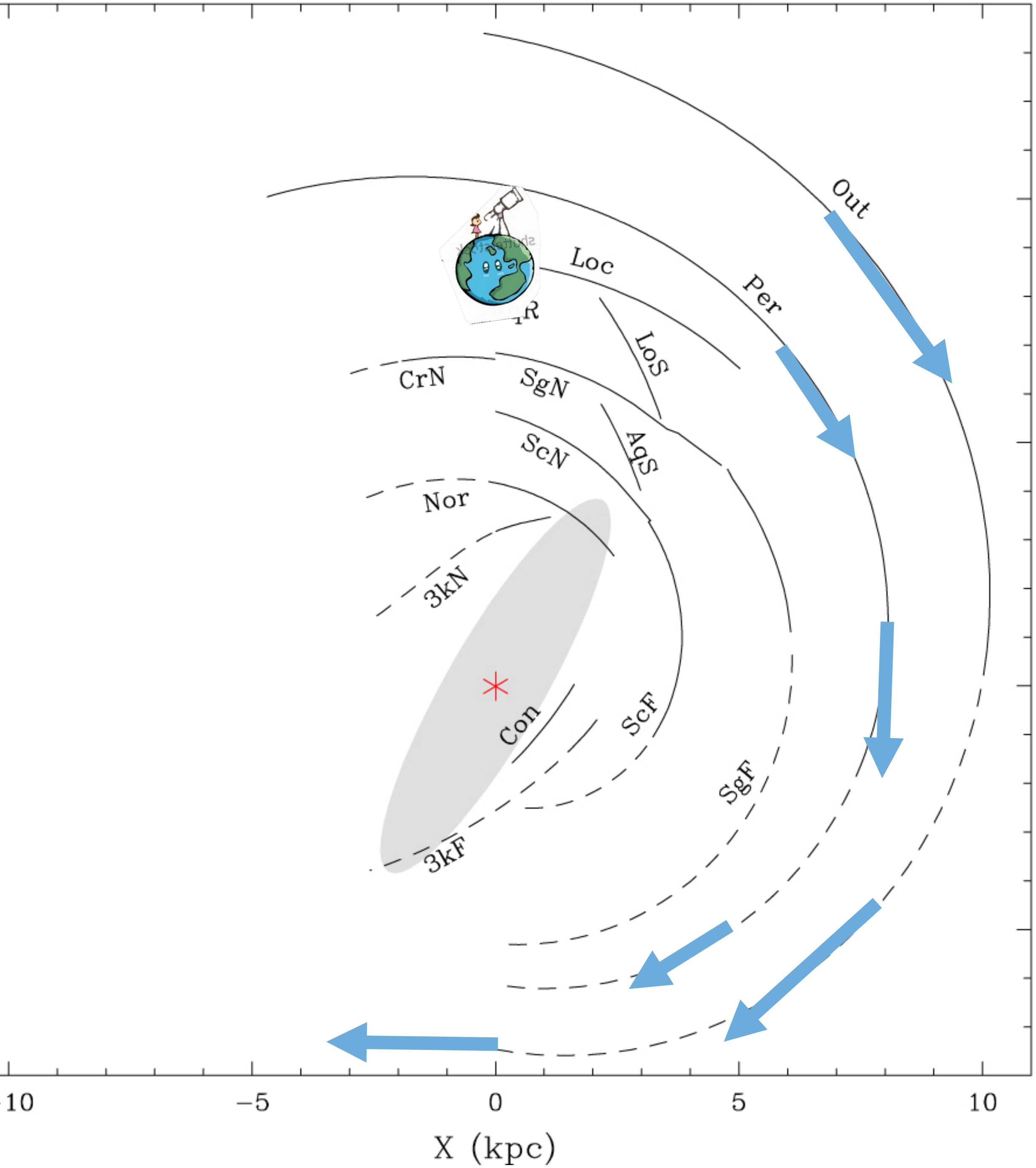
$$v_S^2 = v_R^2 + v_T^2$$



Velocity in Our Galaxy: Galactic Rotatio

Radial velocity (relative t
Sun) of gas in Milky Way
spiral arms

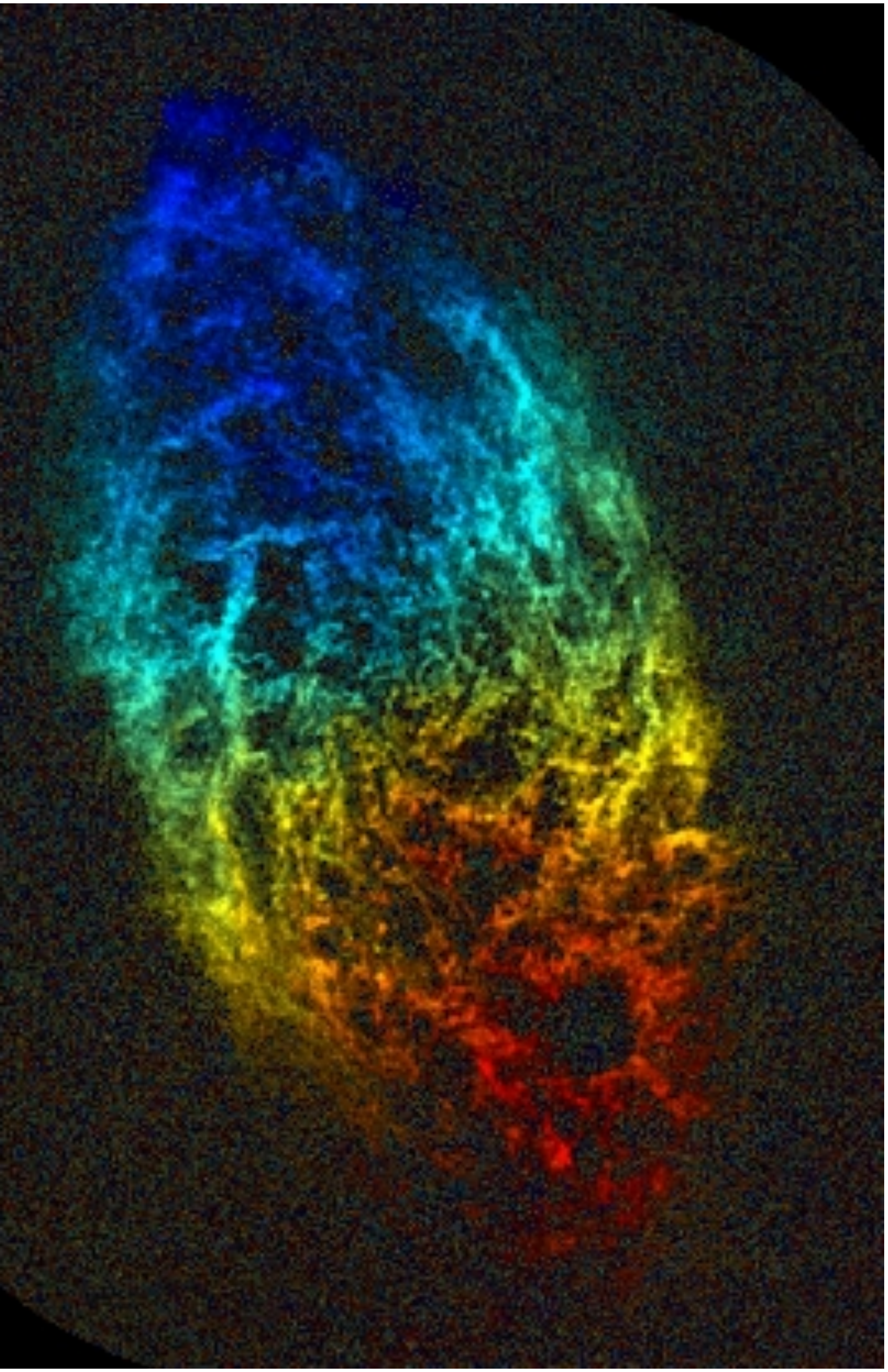
Image: NASA (APOD 25 A
2005)



Velocity in Our Galaxy: Galactic Rotatio

Radial velocity as tool to getting distances to objec in spiral arms *("We obtained source distance using a kinematic model..*

Reid et al., ApJ, 2016

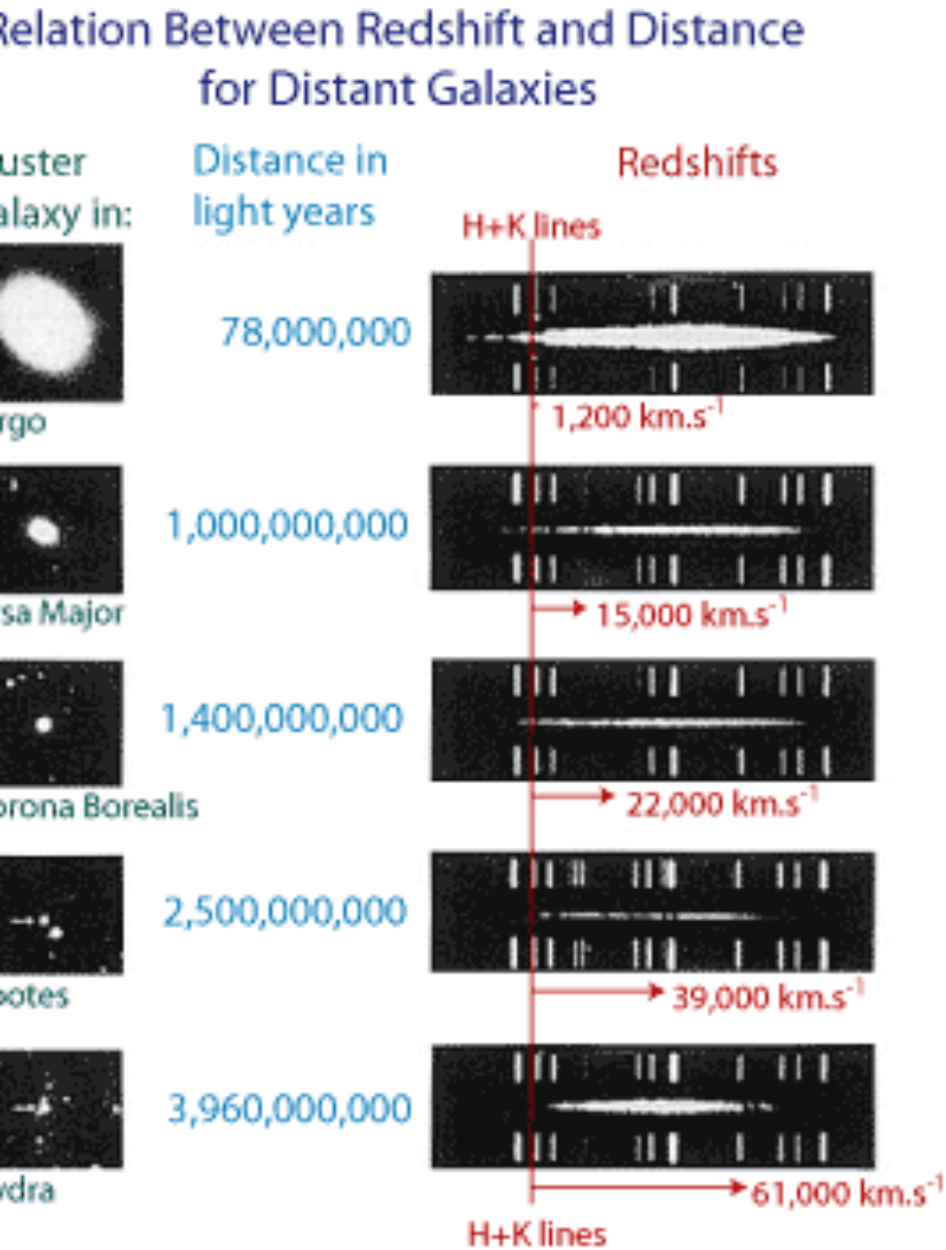


Gas in other galaxies

Hydrogen in M33 (Triangulum or Pinwheel Galaxy) imaged by VLA and Westerbork telescopes.

Image: NRAO, https://www.nrao.edu/pr/2001/m33gas/


Image Credit & Copyright: Giovanni Beni
(NASA APOD 2016 September 17

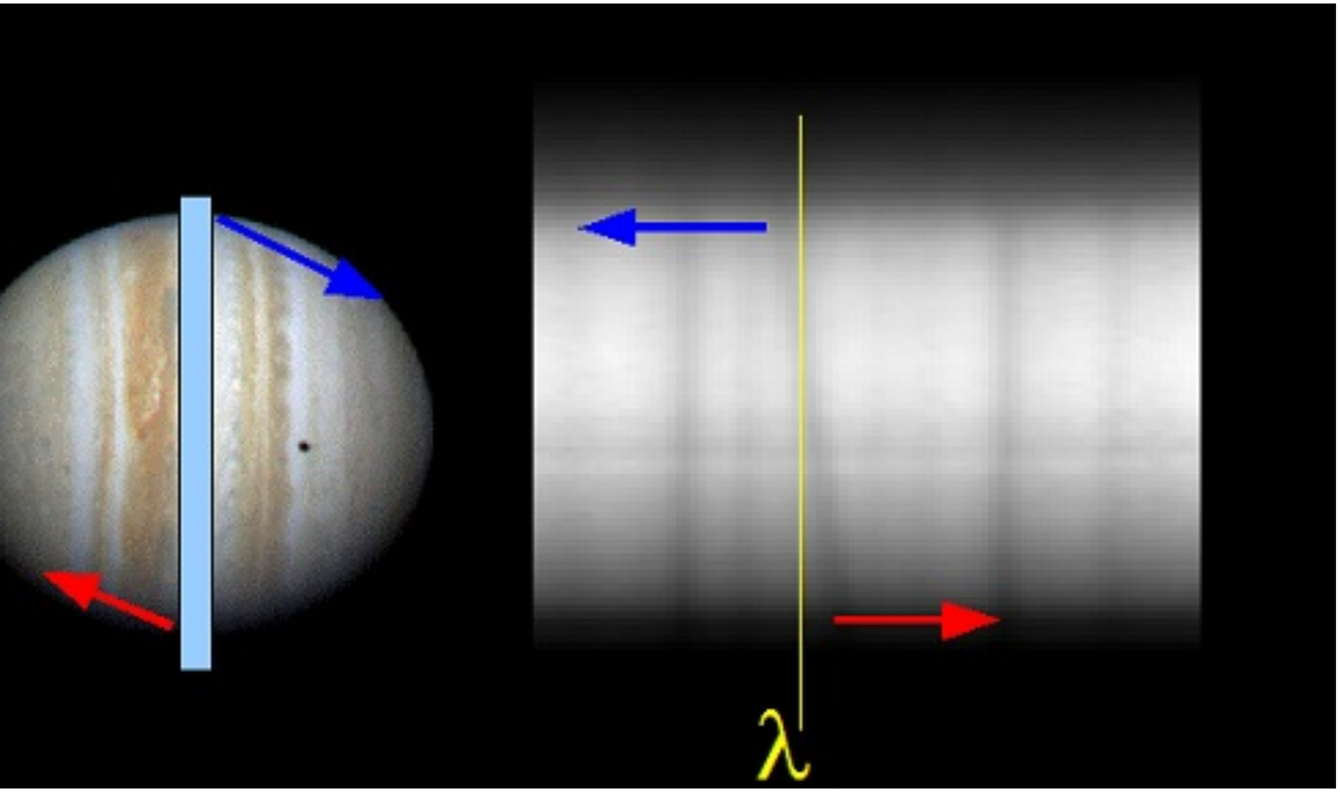


Velocities of other galaxies

Edwin Hubble’s observations of galaxies with the redshift in their spectral lines (1943).

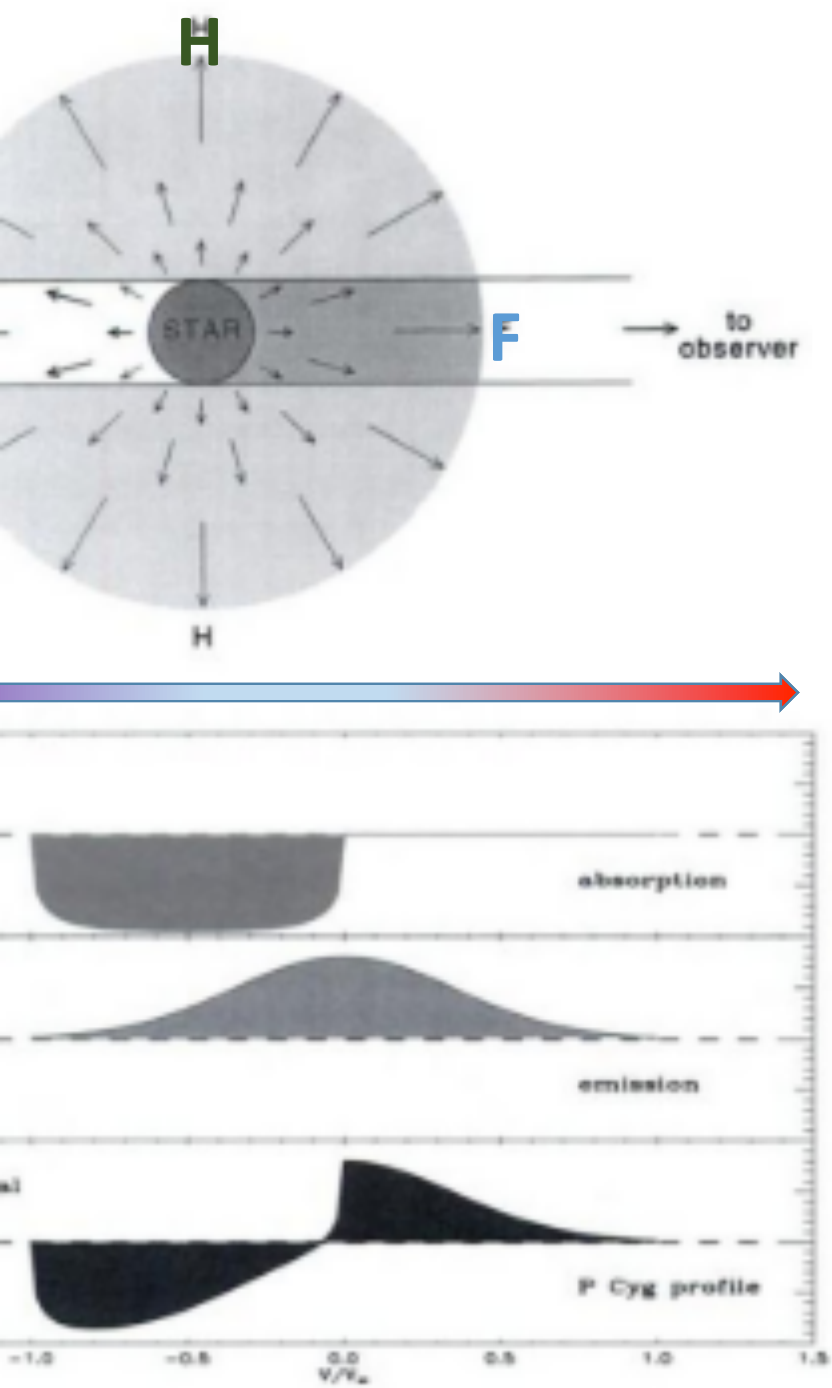
Expansion, motion within Galaxy clusters, rotation of galaxies

Planetary Rotation



Example: Rotation of Ju

Image: Shelyak.com

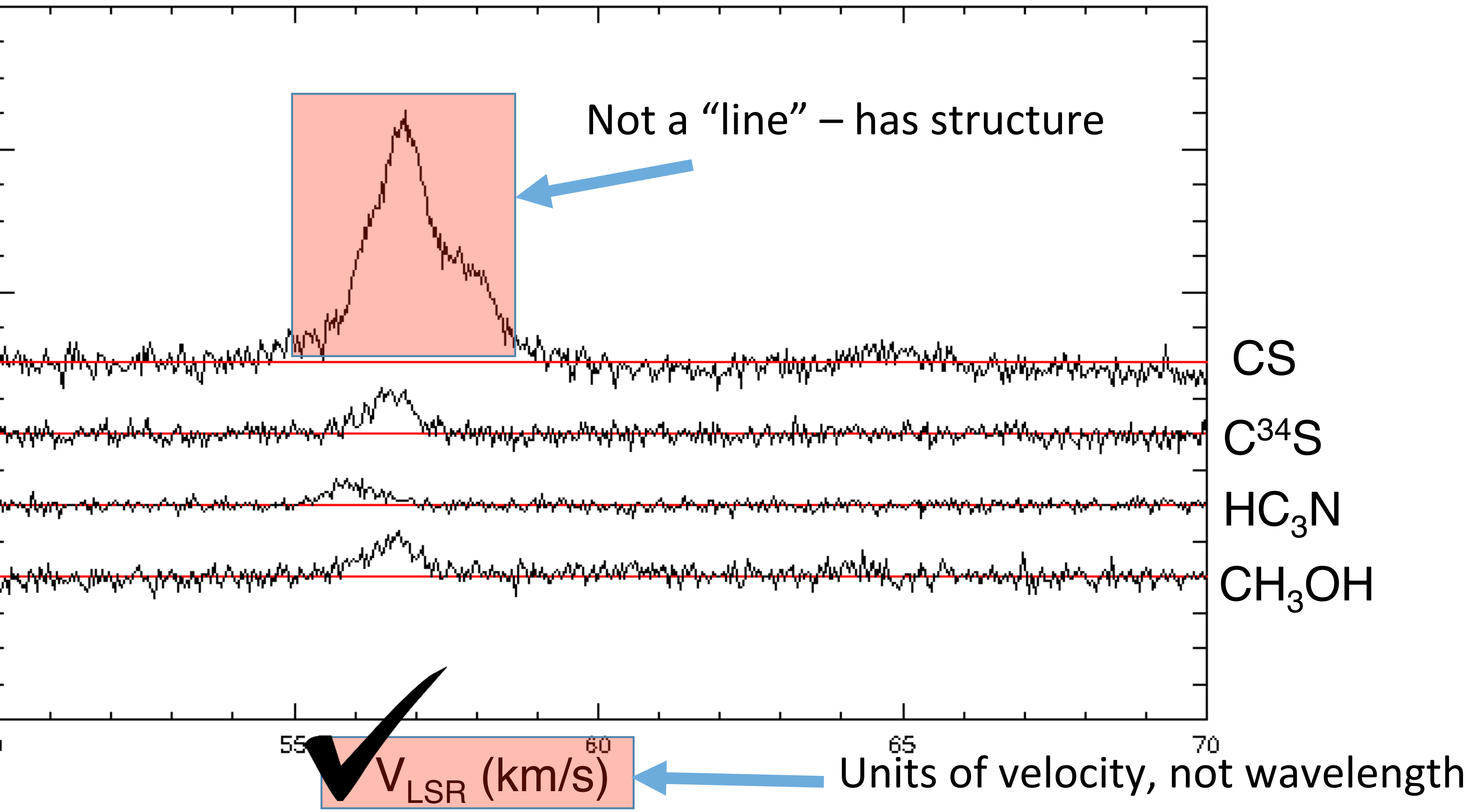


P-Cygni Profiles

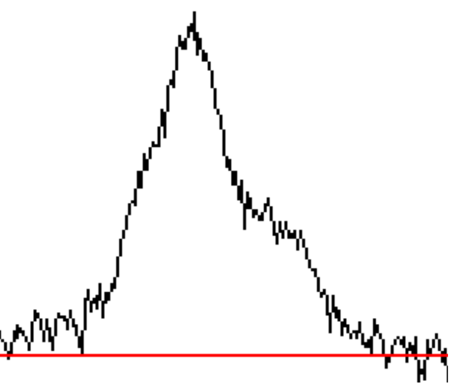
Bottom shows the continuum from star wit absorption in front (F) a emission from halo (H)

Image: Figure 2.4 from Lamers & Cassinelli, *Introduction to Stellar Wi* 1999, Cambridge University Press

adial Velocity and Line Broadening



ne Broadening



Dispersion:

Natural broadening

Pressure broadening

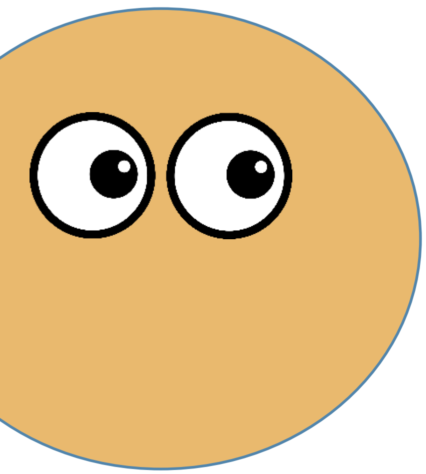
Gaussian:

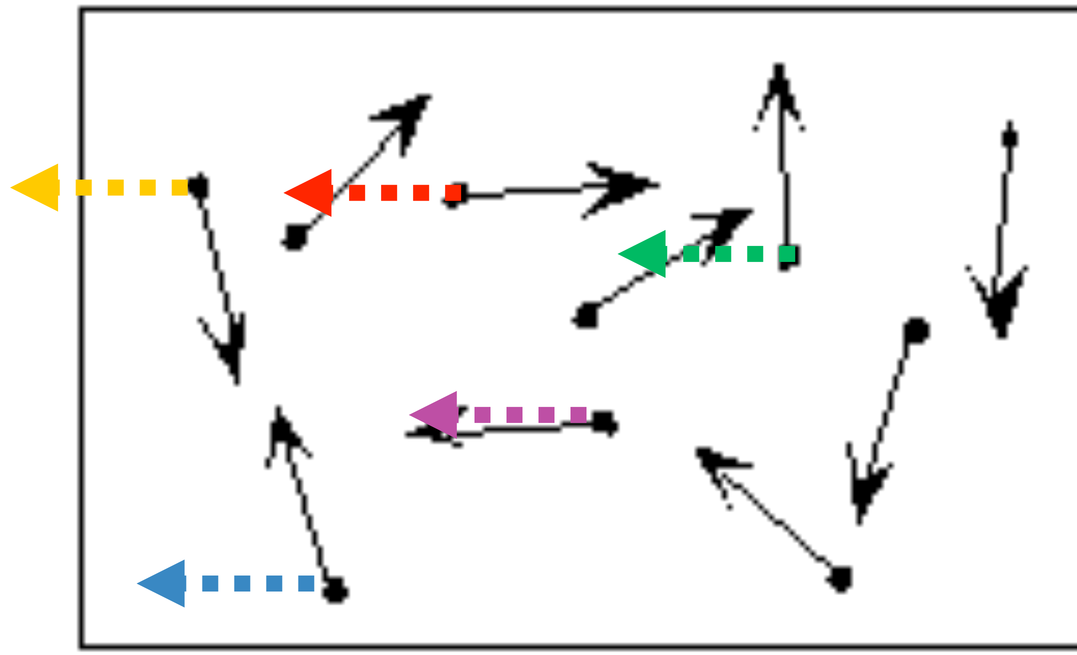
Thermal

Turbulence

See David Whelan's talk for more!

locity of Individual Atoms: Statistical ysics





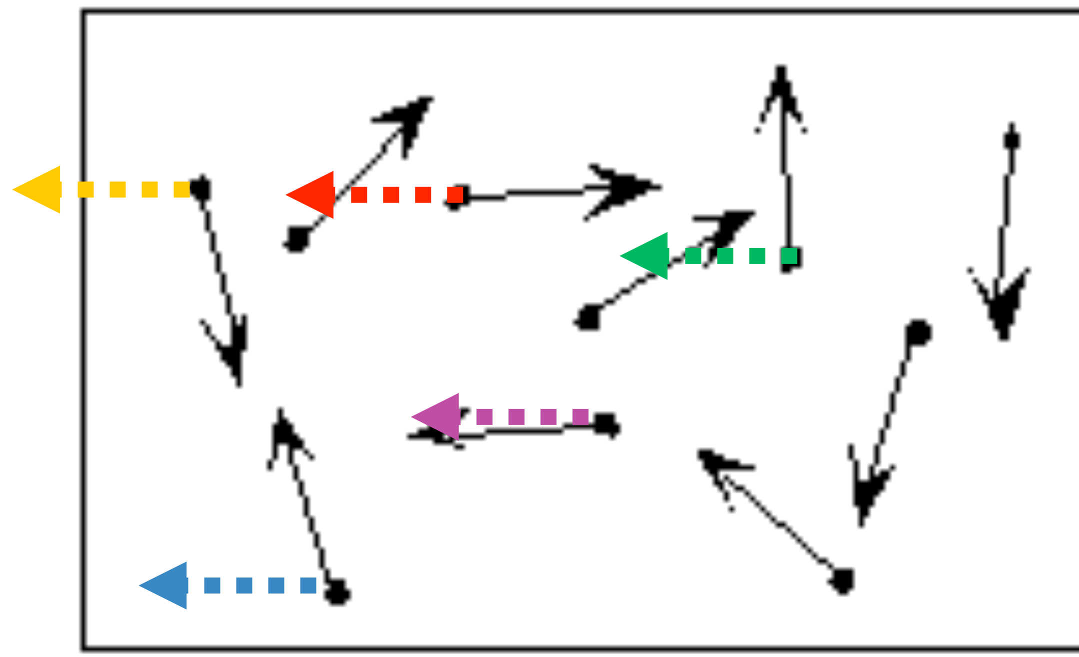
(molecular motion)

v is fraction of atoms with velocity between v and $v+dv$

Image credit: http://cronodon.com/SpaceTech/CVAccretic

locity of Individual Atoms: Statistical ysics

- $)dv$ is fraction of atoms with city between v and $v+dv$
- $)dv$ is “probability distribution” depends on gas properties
- ability distribution determines ne shape



(molecular motion)

Image credit: http://cronodon.com/SpaceTech/CVAccretic

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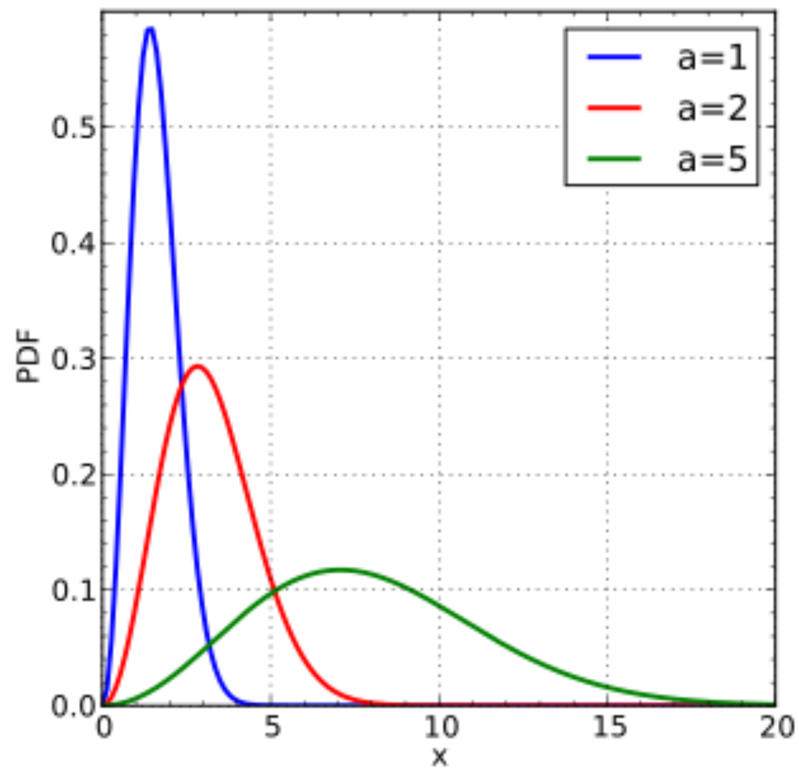

Maxwell-Boltzmann distribution– ideal g with random motions

locity of Individual Atoms: Statistical ysics

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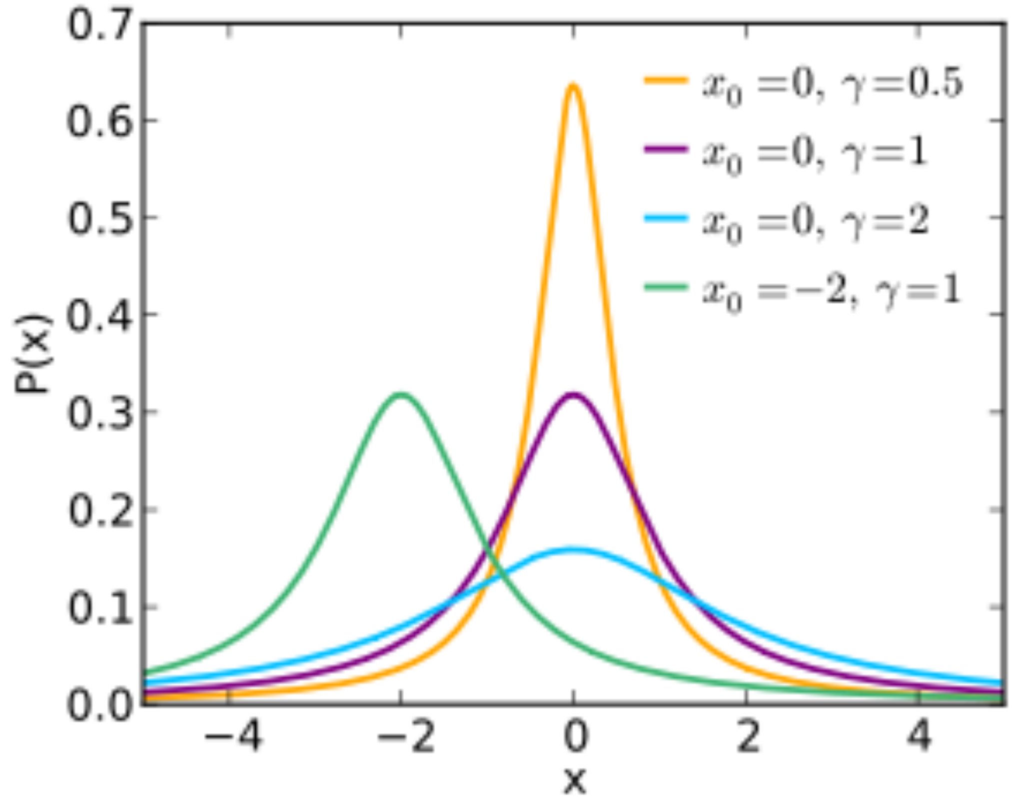
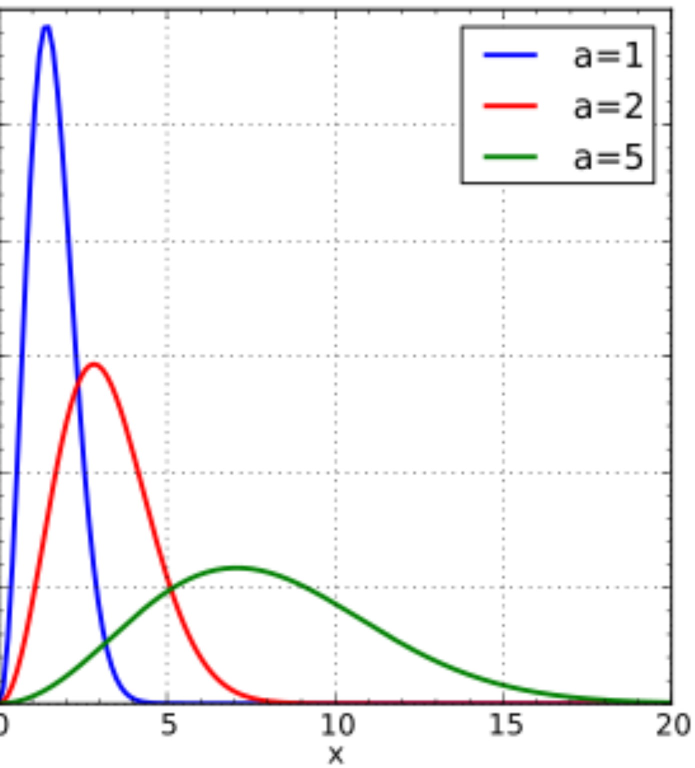
ability distribution determines ne shape

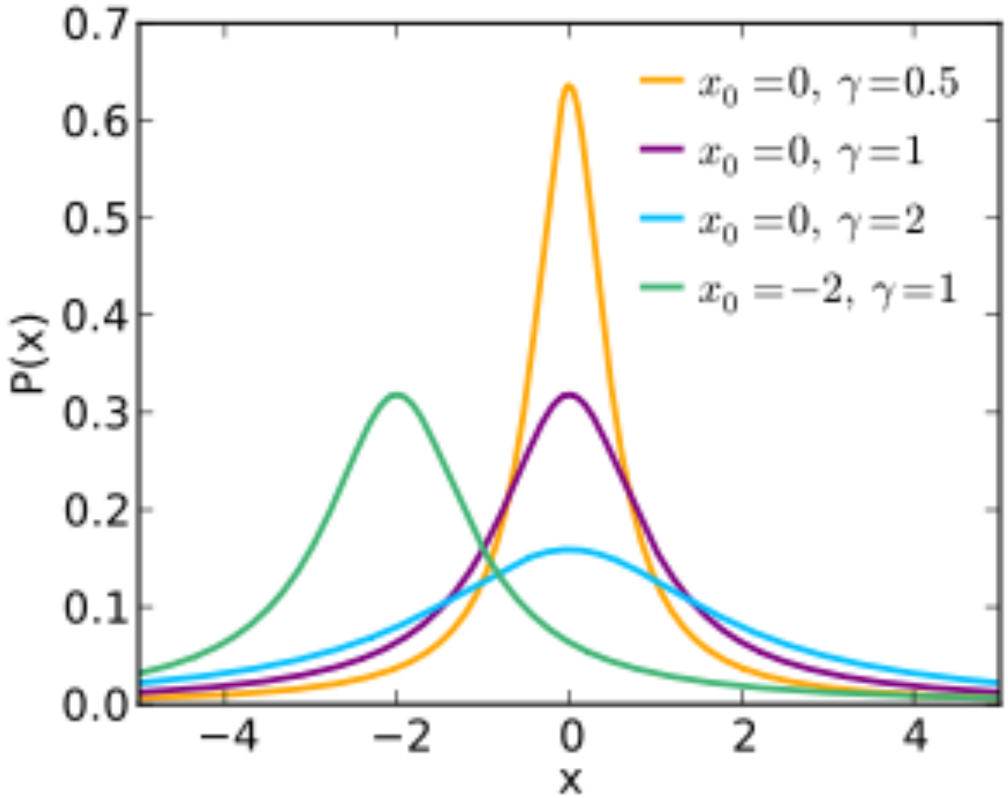


Cauchy–Lorentz (Lorentzian) distributio homogeneous broadening

Image credit: http://cronodon.com/SpaceTech/CVAccretio

locity of Individual Atoms: Statistical ysics





axwell-Boltzmann distribution:
hermal (Doppler) broadening

Lorentz distribution:
Natural (uncertainty principle) broadeni
Collisional broadening

locity of Individual Atoms: Statistical ysics

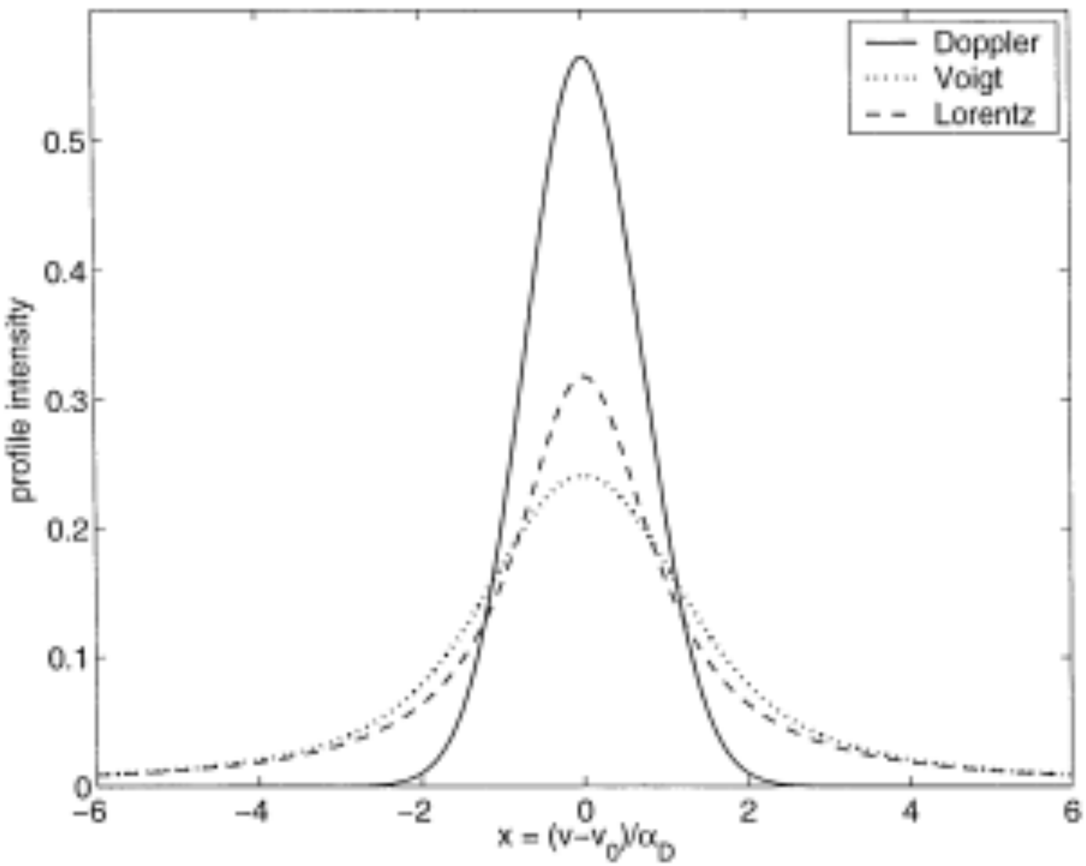
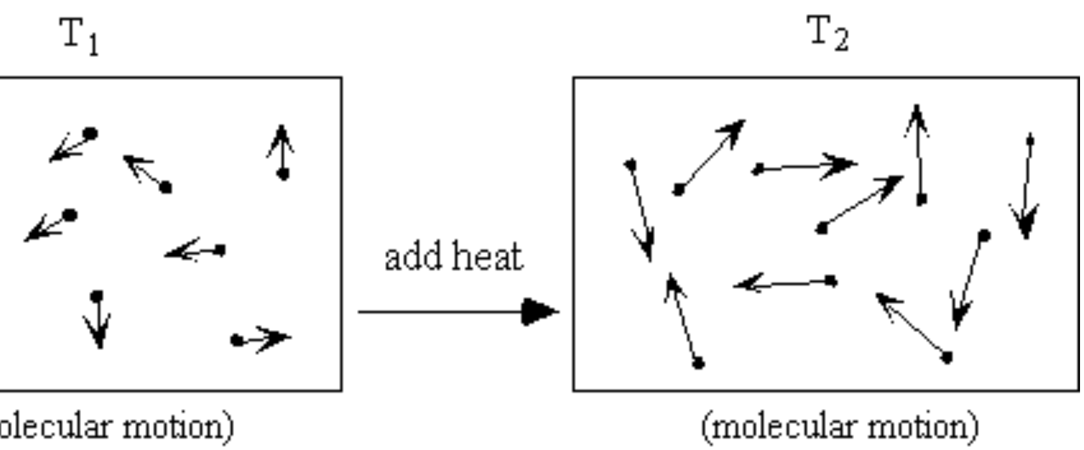


FIG. 2. The Lorentz profile (dashed line) and the Doppler profile (solid line) with the same half-widths ($\alpha_L = \alpha_D = 1$). The dotted line is the corresponding Voigt profile. Here, x is defined as $x = (\nu - \nu_0)/\alpha_D$.

Voigt profile: convolution of Gaussian and Lorentzian profiles

Figure: Huang & Yung, "A Common Misunderstanding about the Voigt Line Profile" 2003 Journal of The Atmospheric Sciences

Example: Thermal Motion
Temperature is Energy, Energy is Motion



$T = \frac{2}{3} KE_{avg} / k_b$

k_b is Boltzmann's constant, 1.38 x10^{-23}

Rearrange to get average kinetic ener
of a gas:

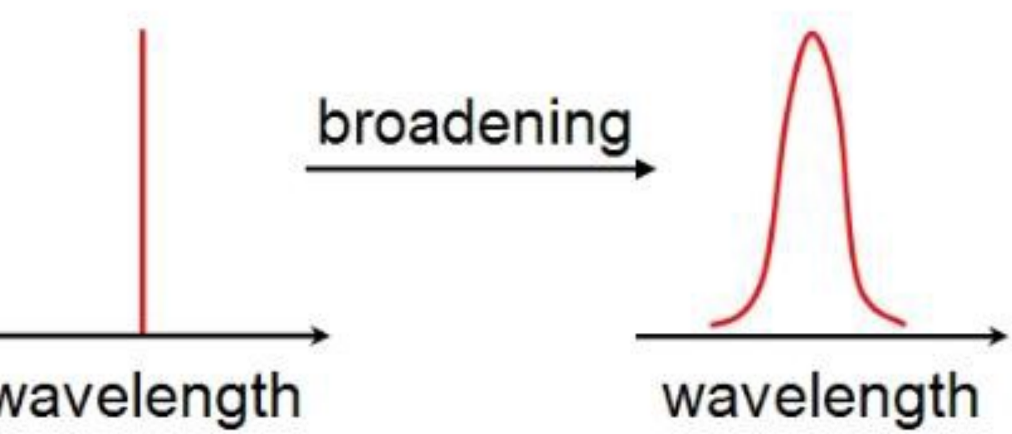
$KE_{avg} = \frac{3}{2} k_b T = \frac{1}{2} m v_{average}^2$

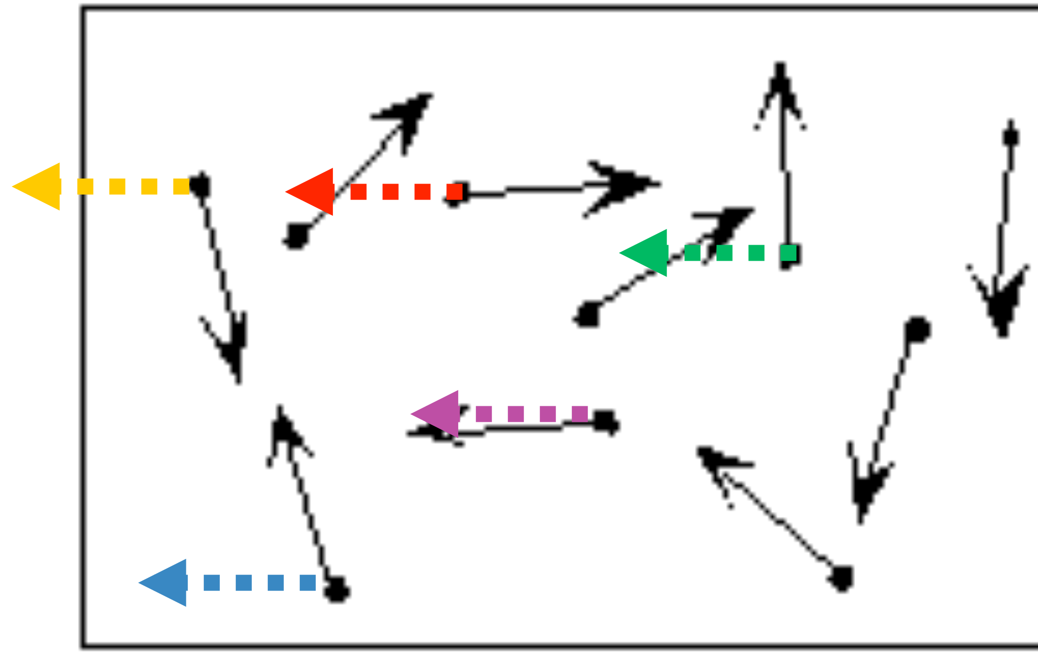
http://web.mit.edu/16.unified/www/FALL/thermodynamics/thermo_4.htm

ermal Linewidths

ning gas random motions follow Maxwell-
nann distribution:

$$(v)=\sqrt{\left(\frac{m}{2\pi kT}\right)^3}\,4\pi v^2 \exp\left[-\frac{mv^2}{2kT}\right]$$





(molecular motion)

$$FWHM=\frac{1}{\lambda}\sqrt{\frac{8kT}{m}\ln 2}$$

Image credit: spectral line broadening via BotReje
at http://cronodon.com/SpaceTech/CVAccretionI

Velocity in Gas: Turbulent motion

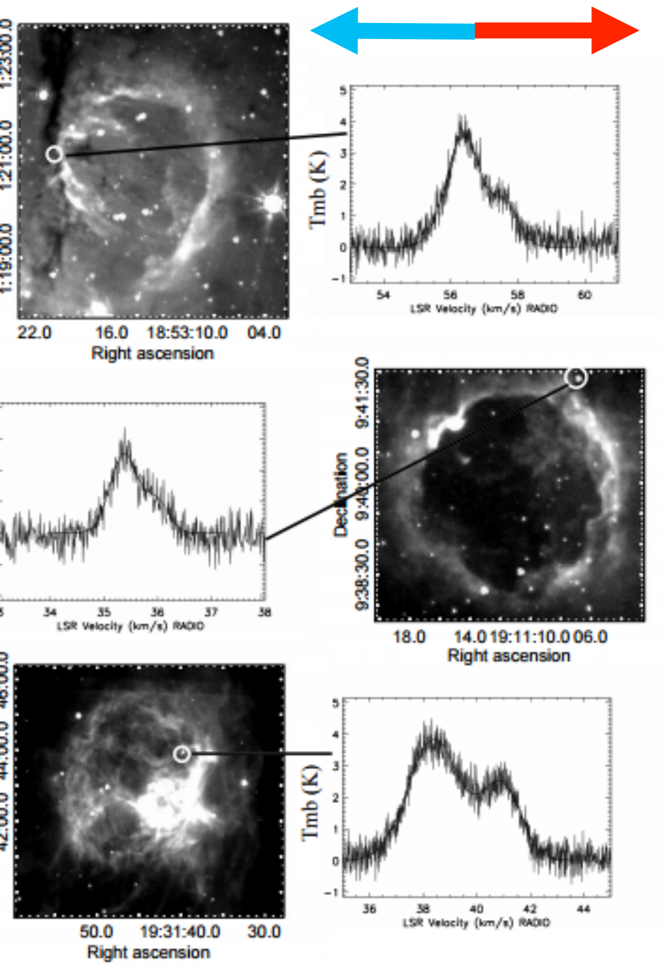
Stars, Gas, and Dust Battle the Carina Nebula

Image Credit & Copyright: Bastien Fouch

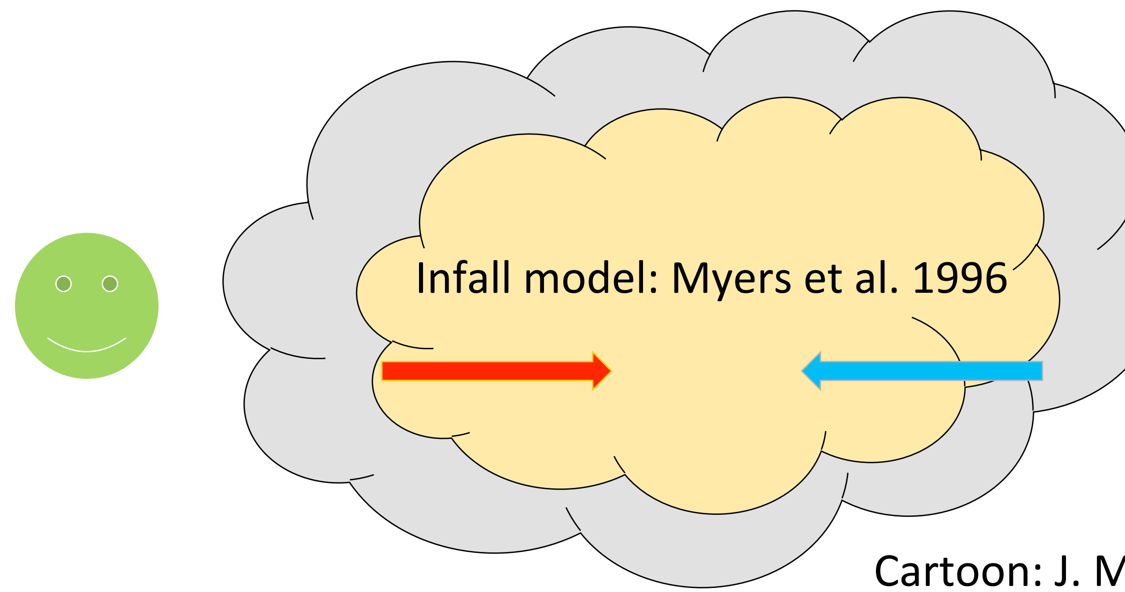
NASA APOD 2017 August 15

Measure the temperature of a gas, and find that lines are broader than thermal linewidths→ there is probably turbulent motion

Fun science example: using spectra to look for evidence of in-falling clouds



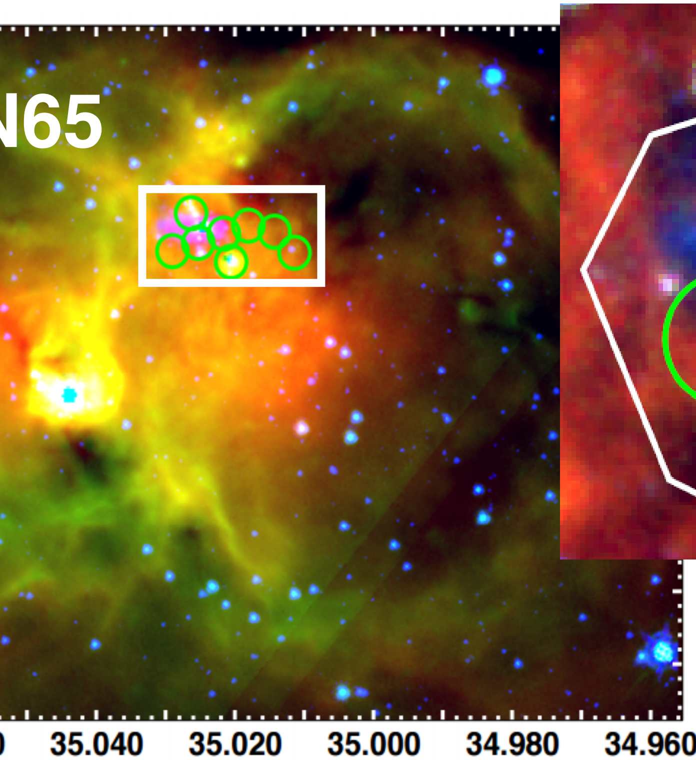
Watson, Devine et al. 2016: CS line profiles show evidence of infall

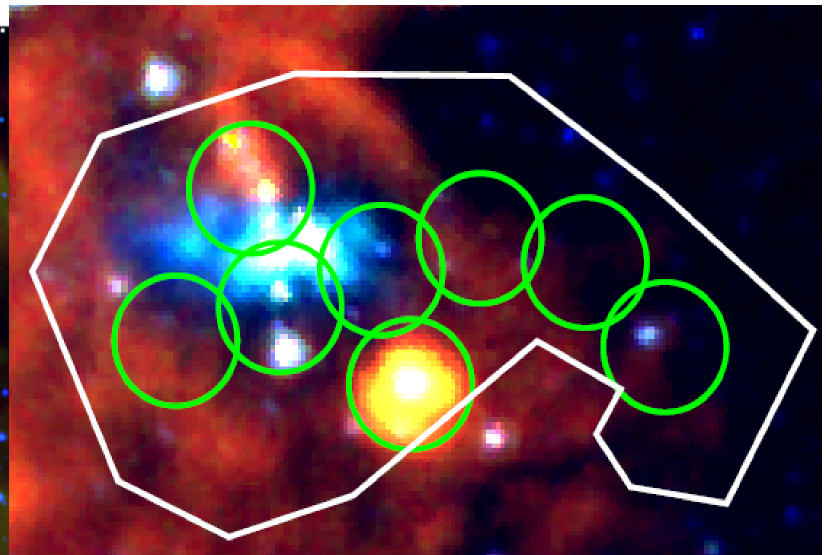


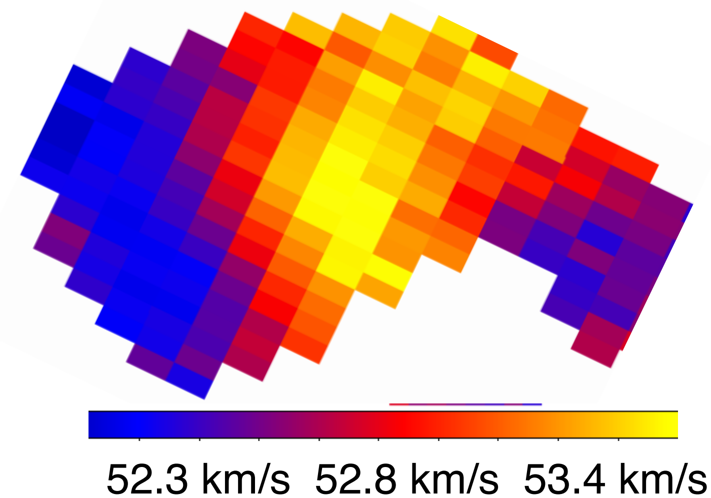
Cartoon: J. M

162-1, b) N90-2 and c) N117-3.

n science example: using spectra to amine motion of gas in clouds







CS (1-0) central velocit

image of N65. White outline shows region apped in CS (1-0).

Watson et al. 201

n science example: using line profiles interpret Be Star spectra

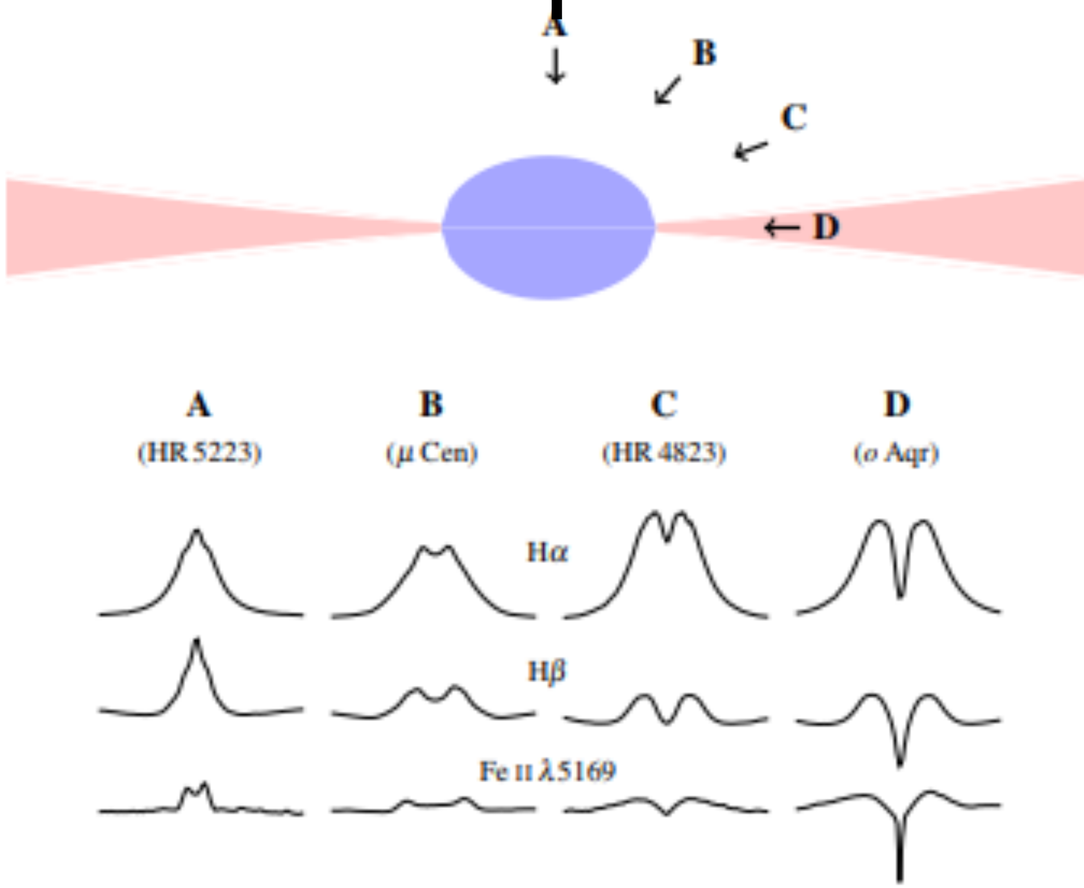


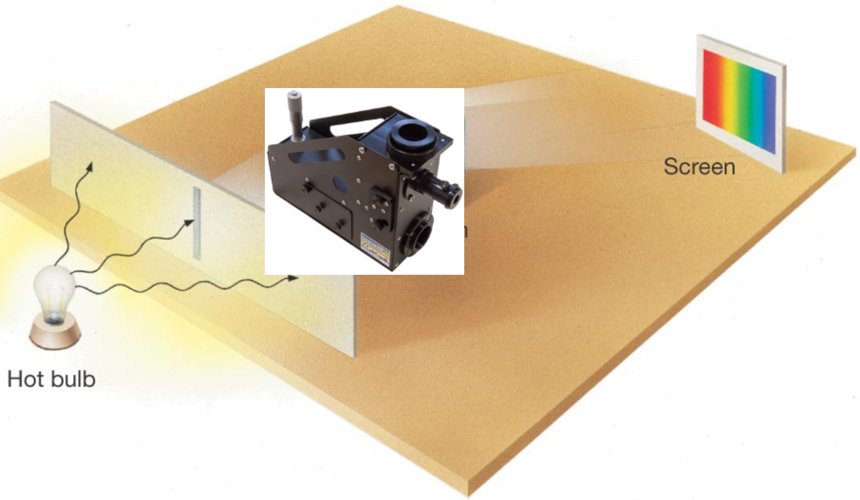
Fig. 1 Schematic view of a Be star at critical rotation and with a flared disk. The lower part shows example spectral profiles from pole-on to shell Be stars

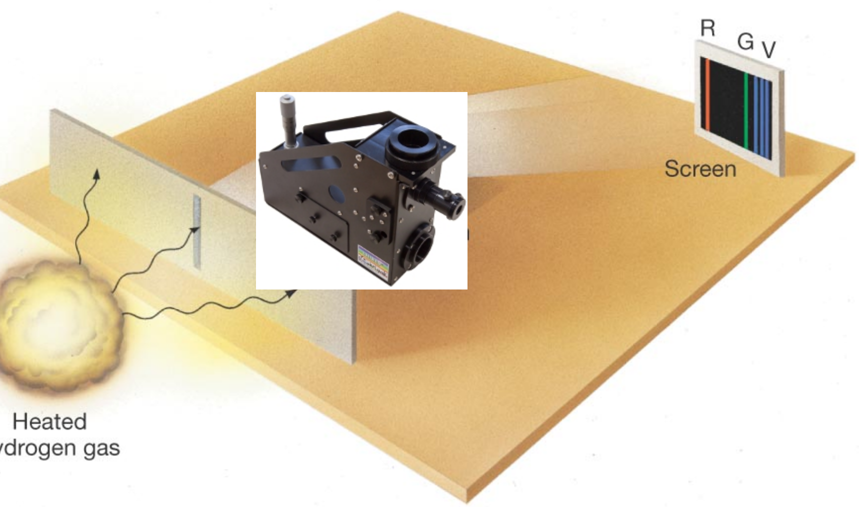
Rivinius, Carciofi & Marta

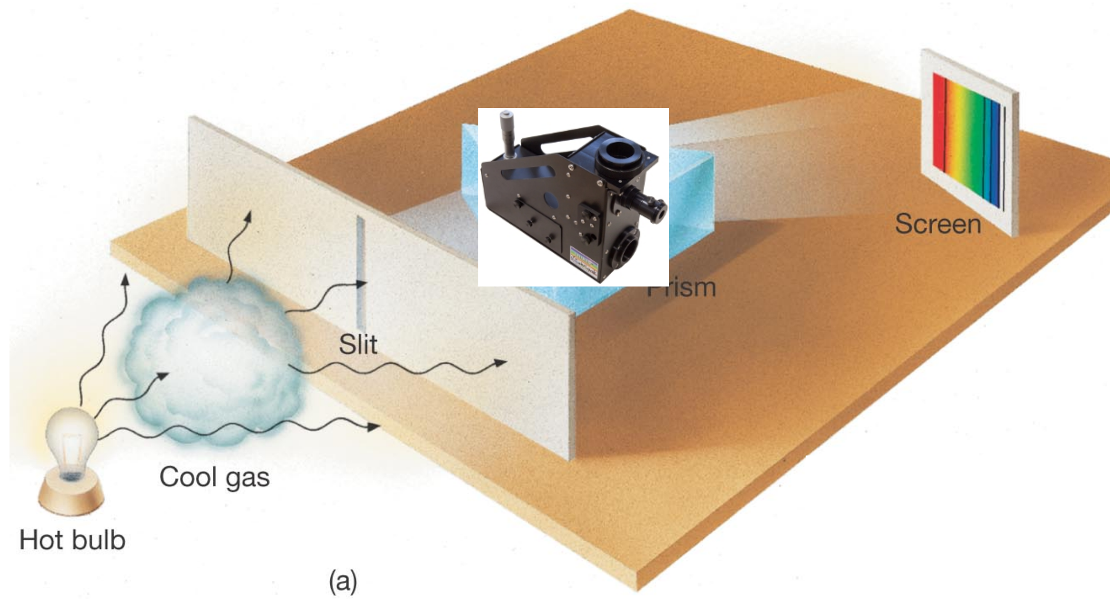
Summary

- Origin of emission/absorption spectra, conditions for each (Kirchhoff's Laws)
- Doppler shift, and how to convert from wavelength to line-of-sight velocity
- Bulk motions of gas: galactic rotations, galactic motion, planetary rotation
- Motion within gas and line broadening, thermal vs. turbulent motion
- Science examples: using line profiles to probe star formation, dense gas conditions, stellar atmospheres

Review: Sources of Emission (simplified version)







Images: Pearson educ

Shelyak Instruments (