Radial velocity and line broadening in spectra

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Background

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

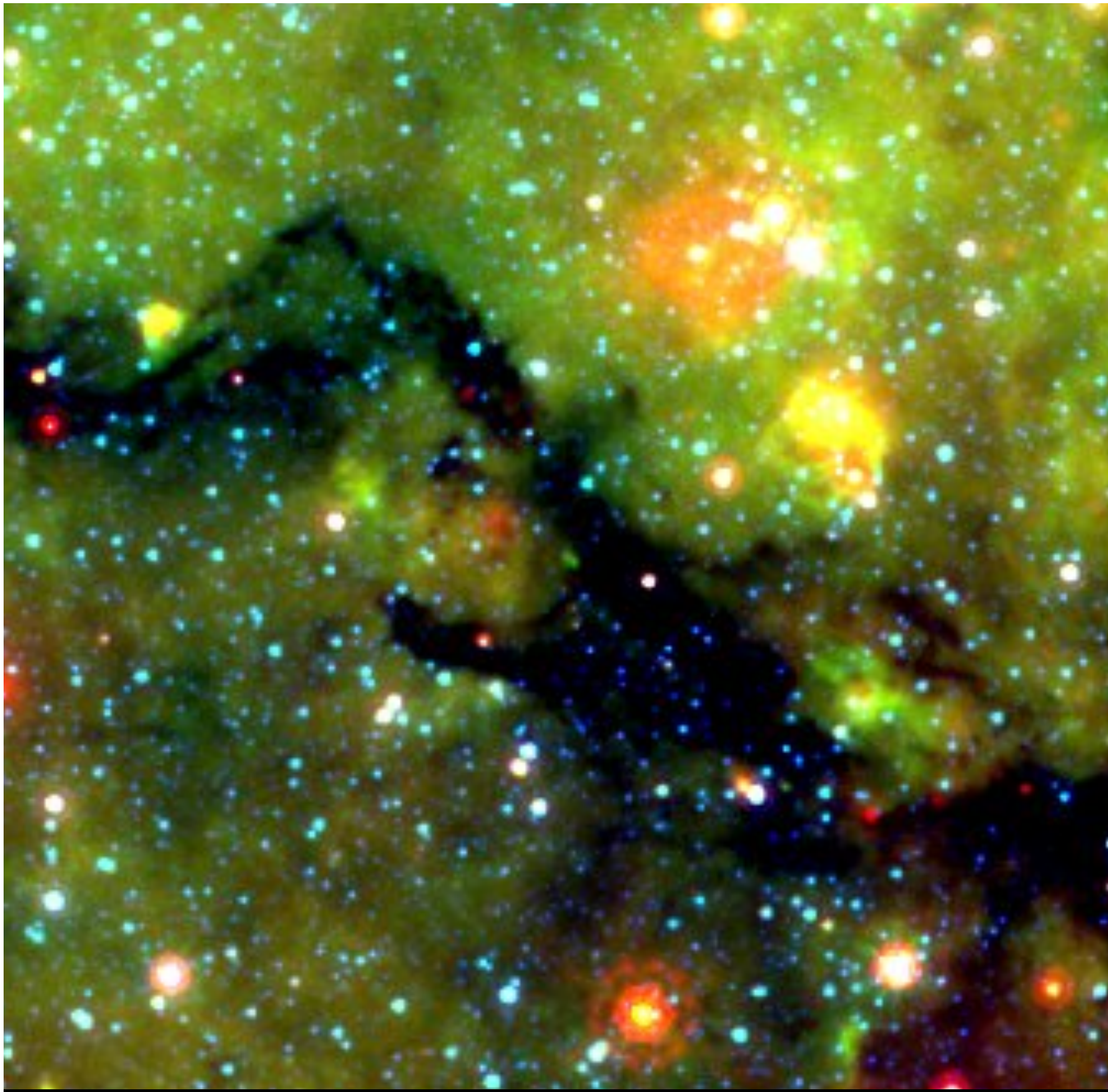


Image credit: Milky Way Project (milkywayproject.org)

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

Research

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

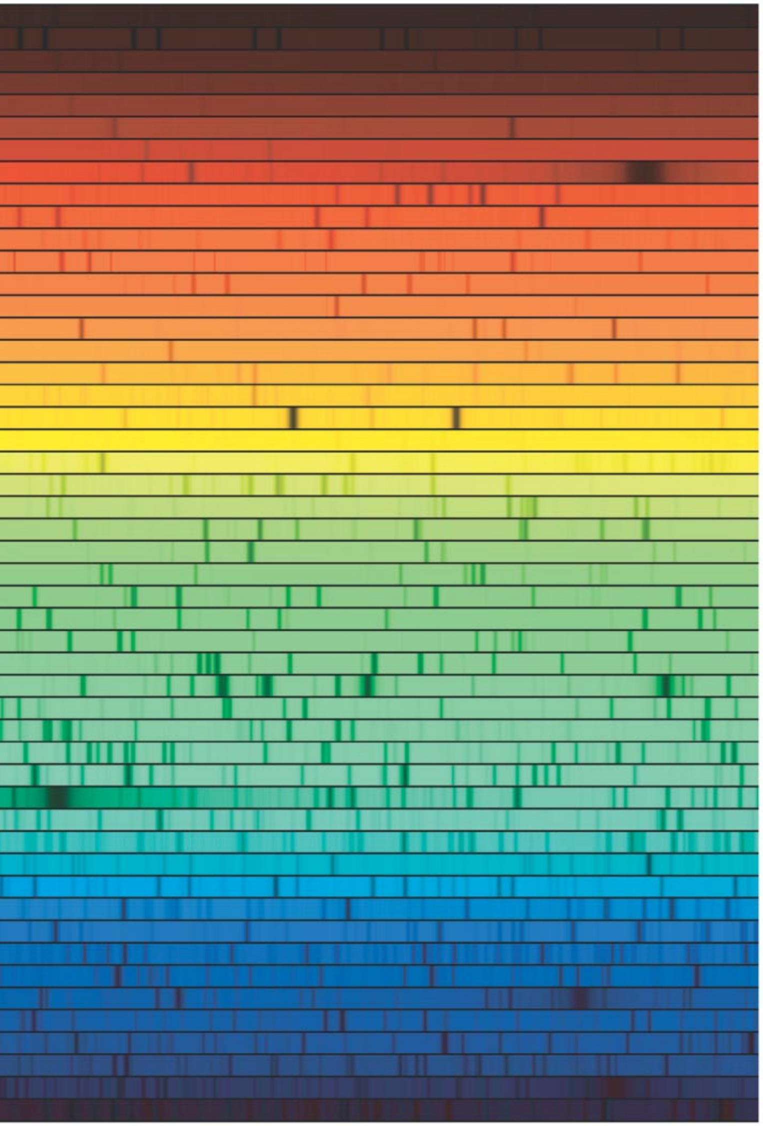
rarchical star formation
- Bubbles
- Yellowballs

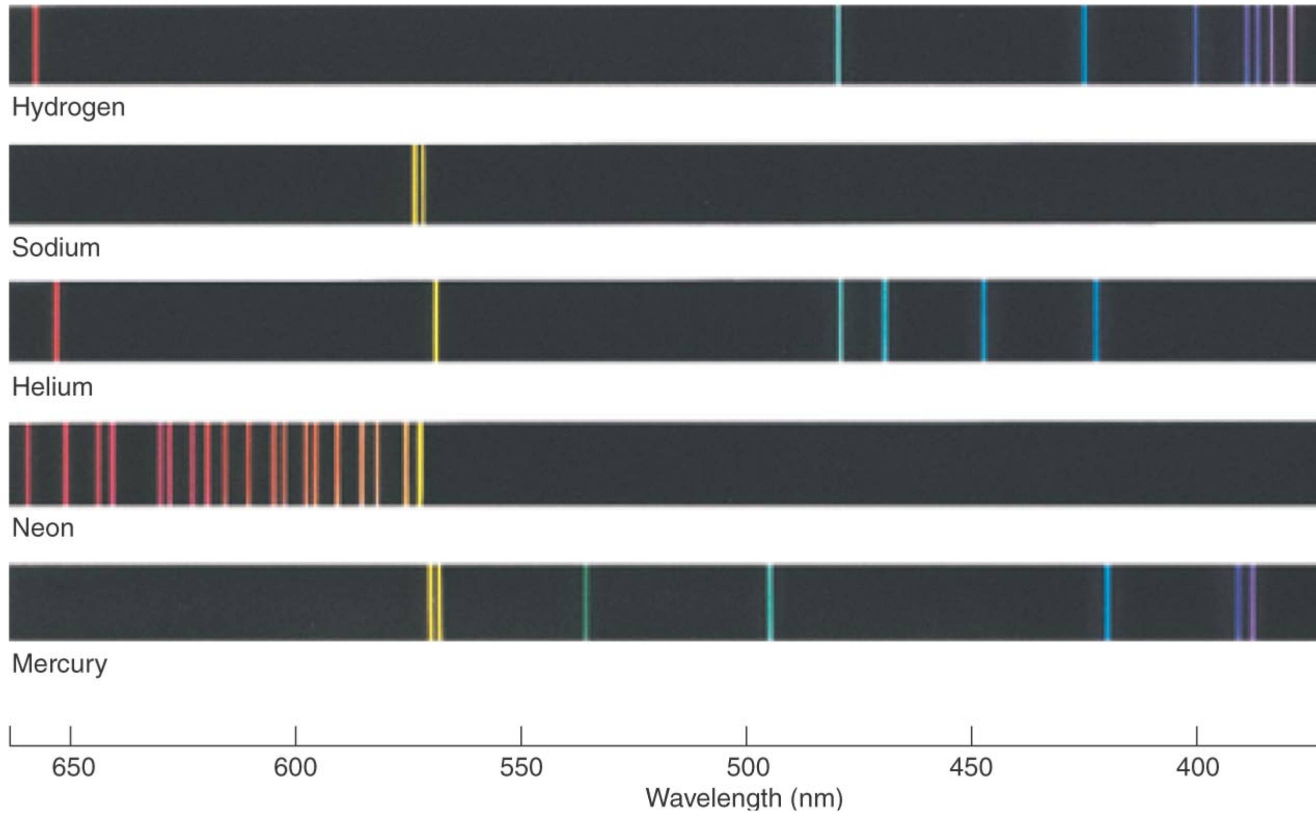
connection to this ference: **I use radio spectral s to determine conditions of lecular gas in star forming as.**

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

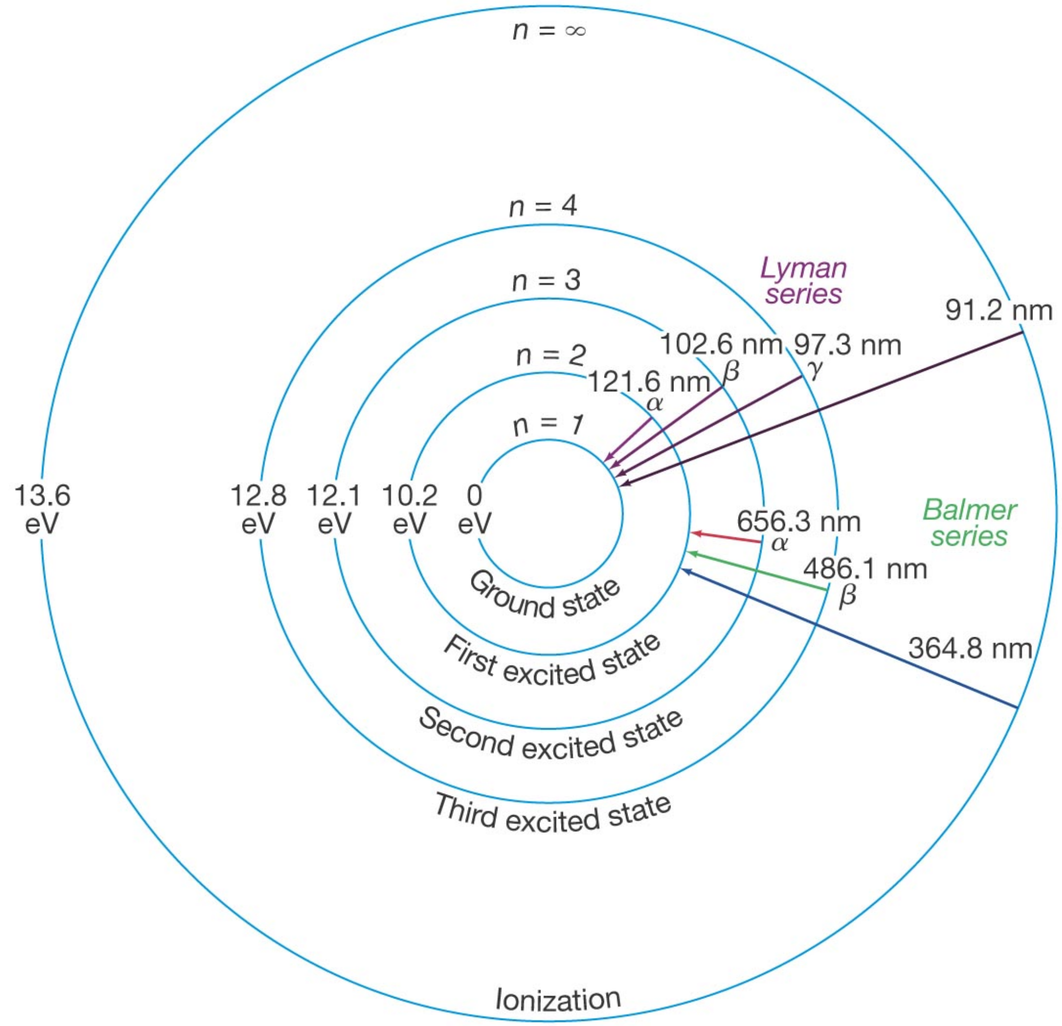


Image: Pearson ec

here are other ways generate emission nes besides “eating hotons”

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

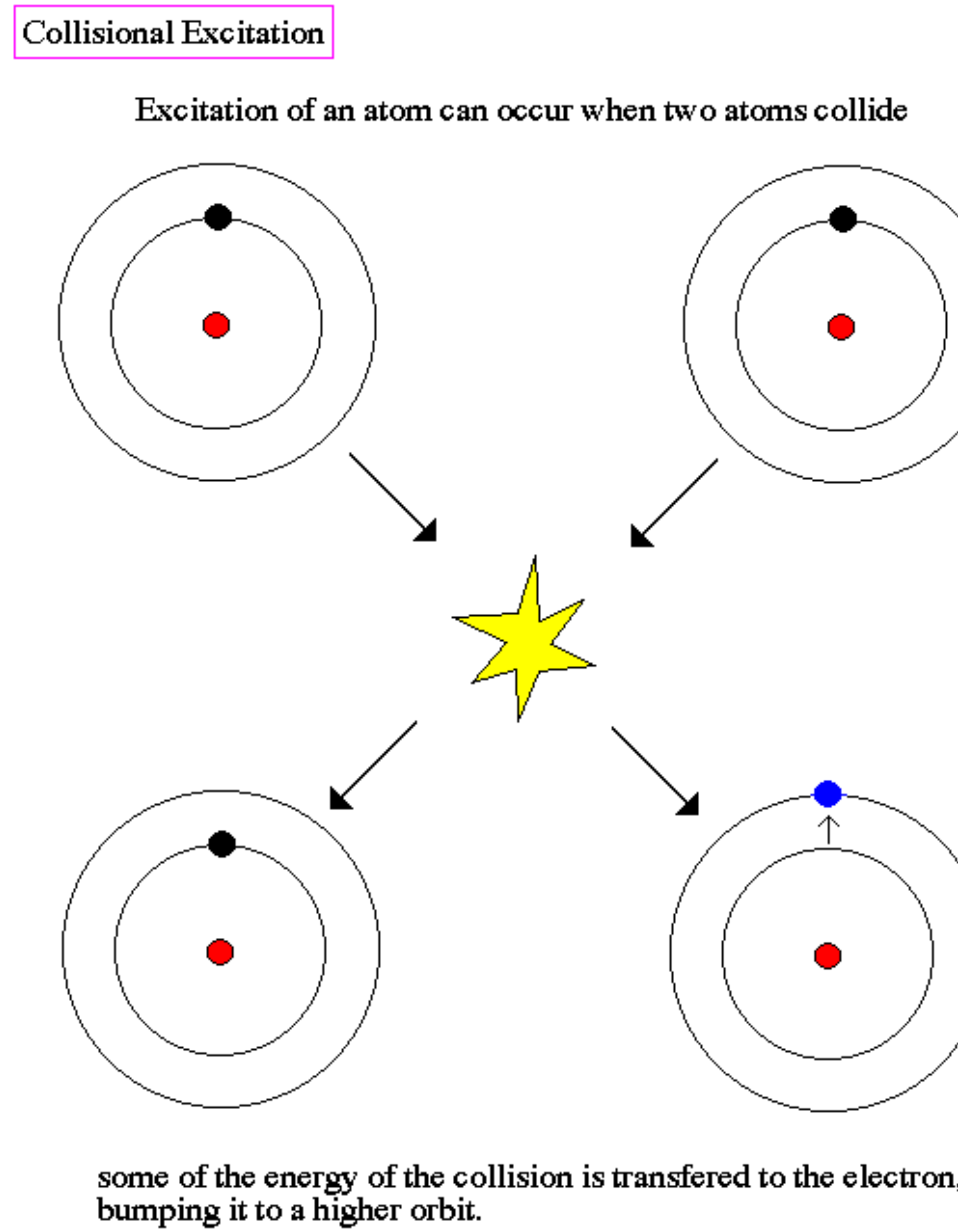
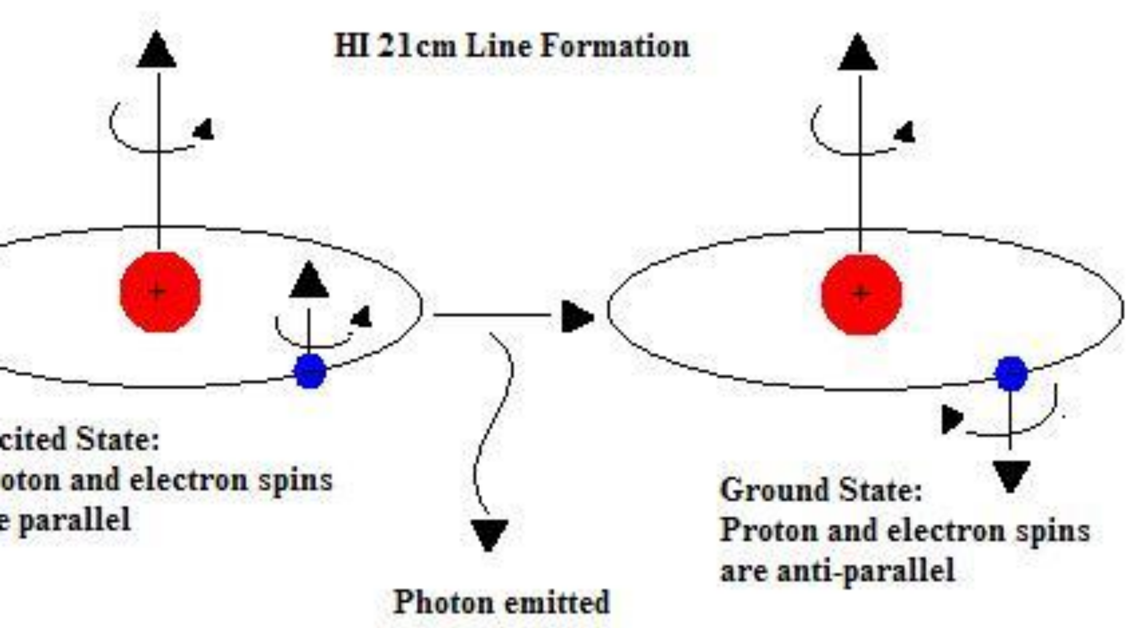
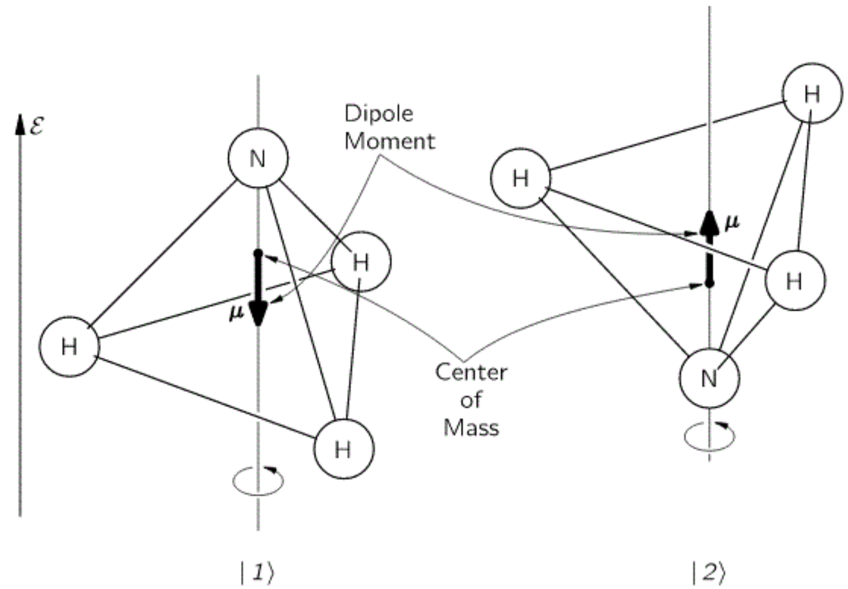


Image: http://abyss.uoregon.edu/~js/glossary/excita

Additional types of energy levels of atoms and molecules



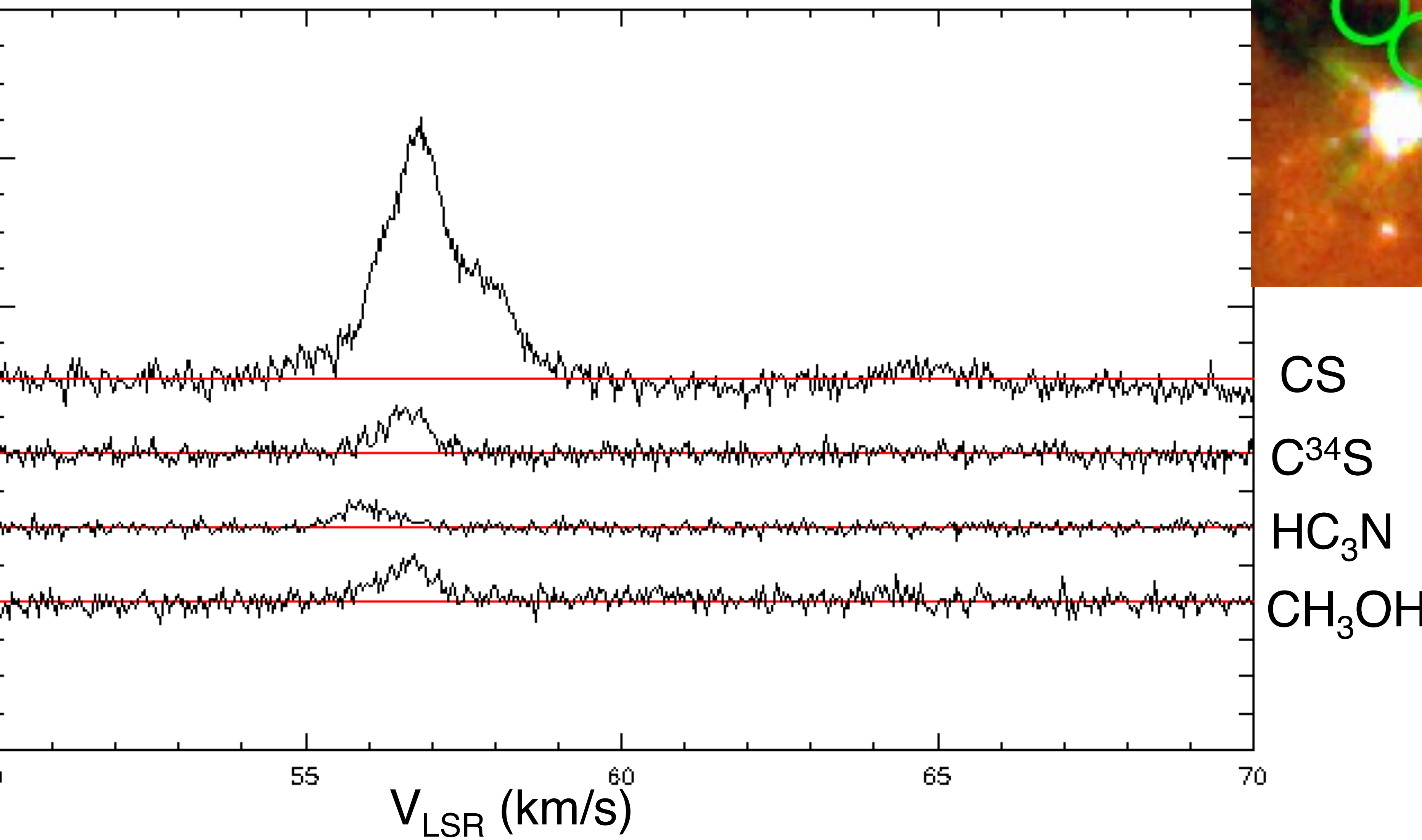
ctron/proton spin alignments have ifferent energies. Example: 21 cm ne in hydrogen.

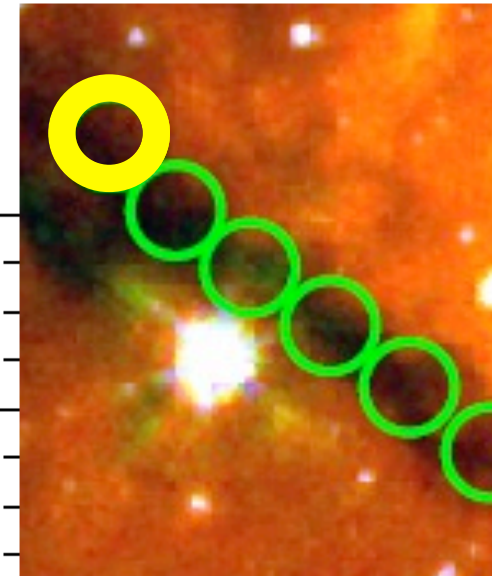


Molecule's direction of rotat around its axis of symmet Example: position of N at ammonia (NH_3).

Image: teachastronomy.com, readingfeynma

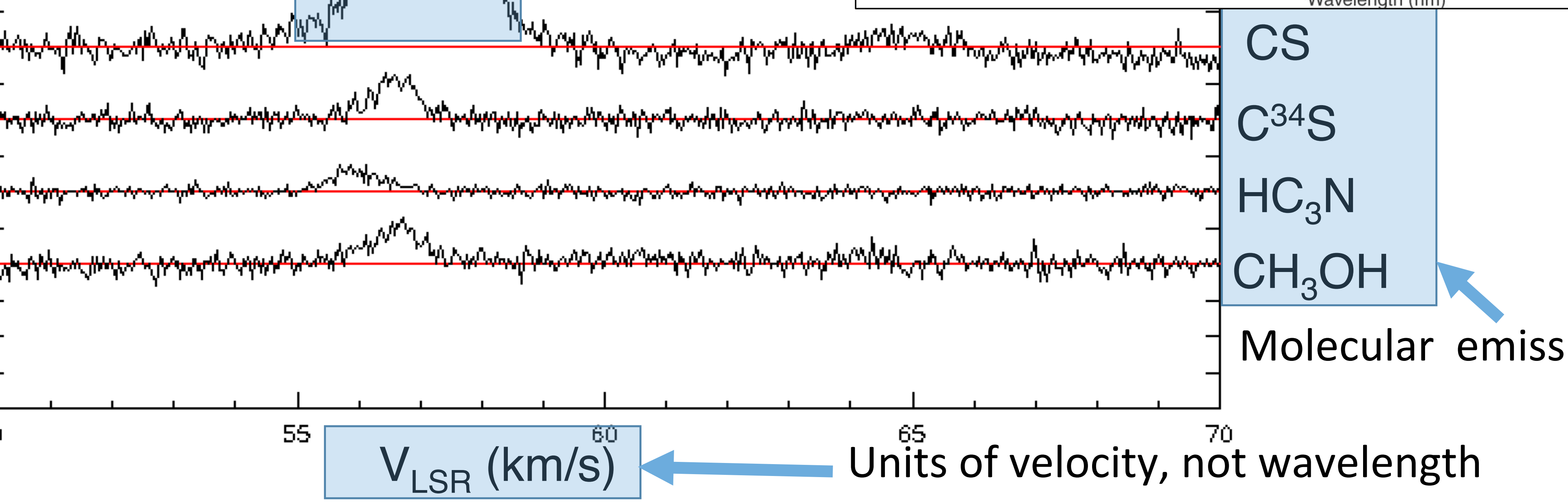
adio example: emission line

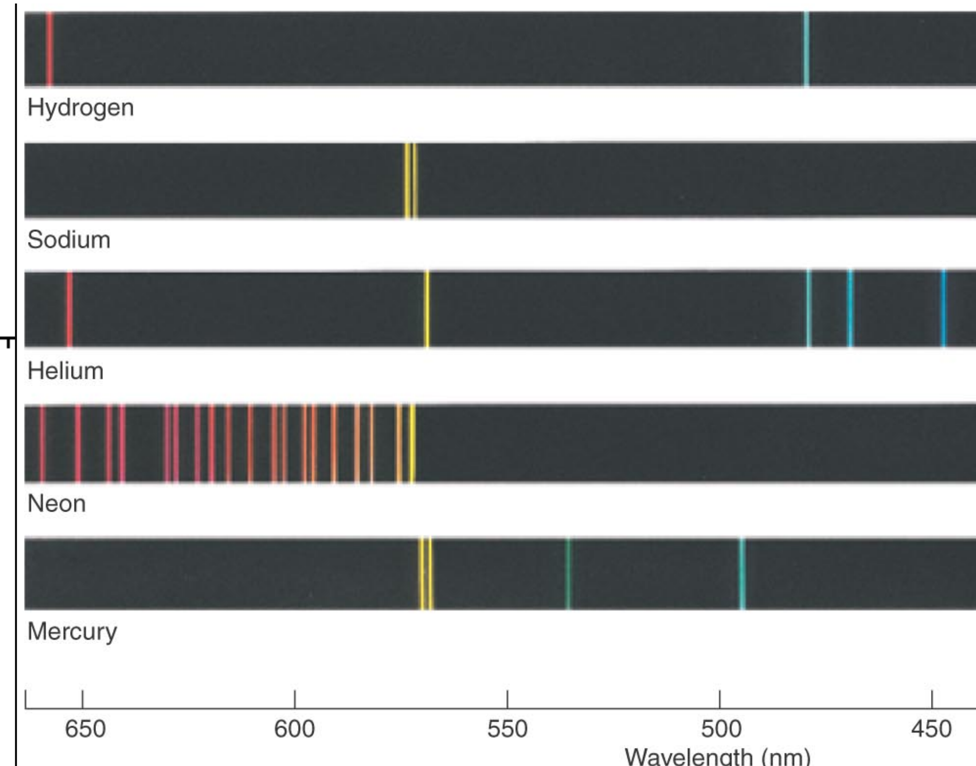




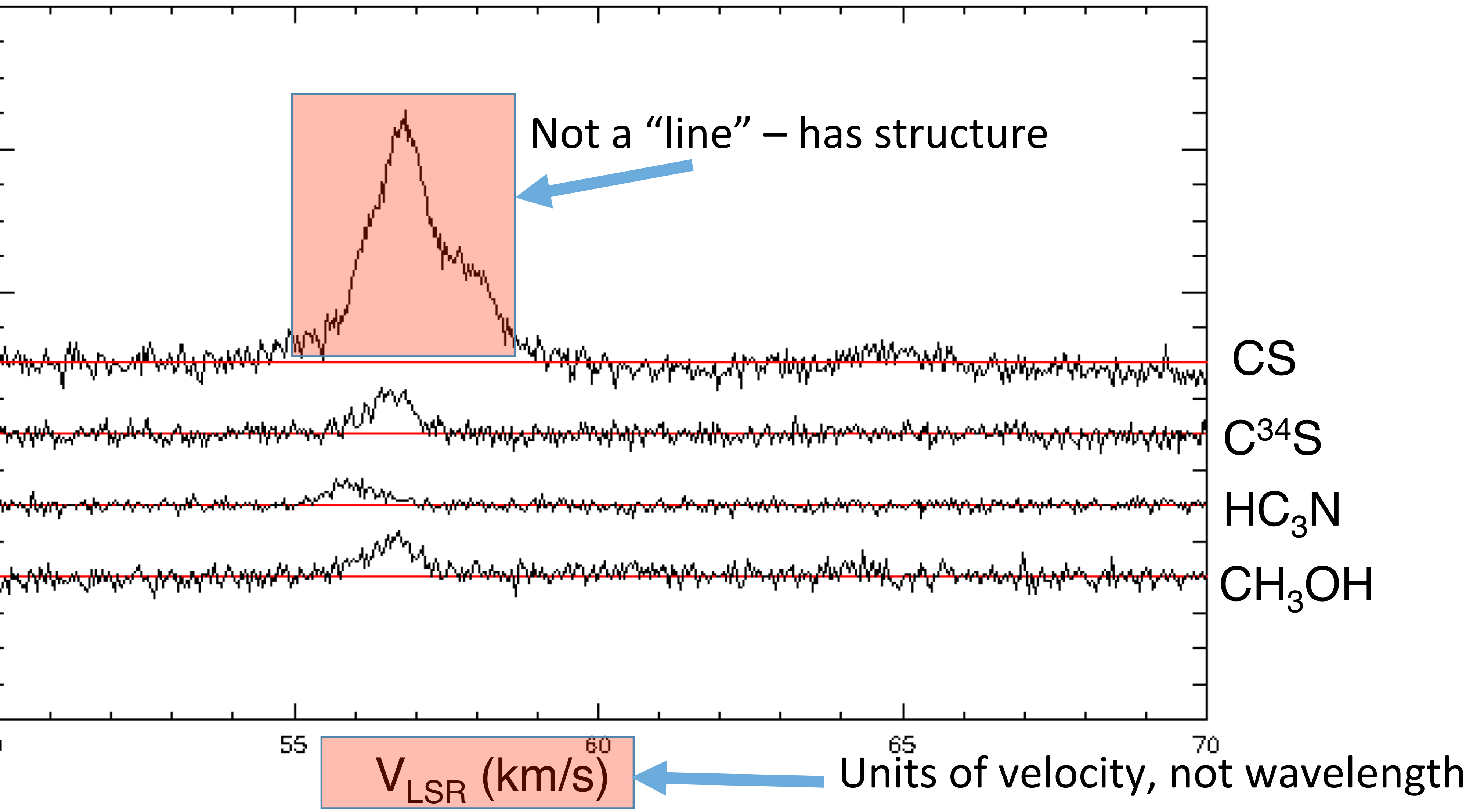
Devine et a

nportant Features

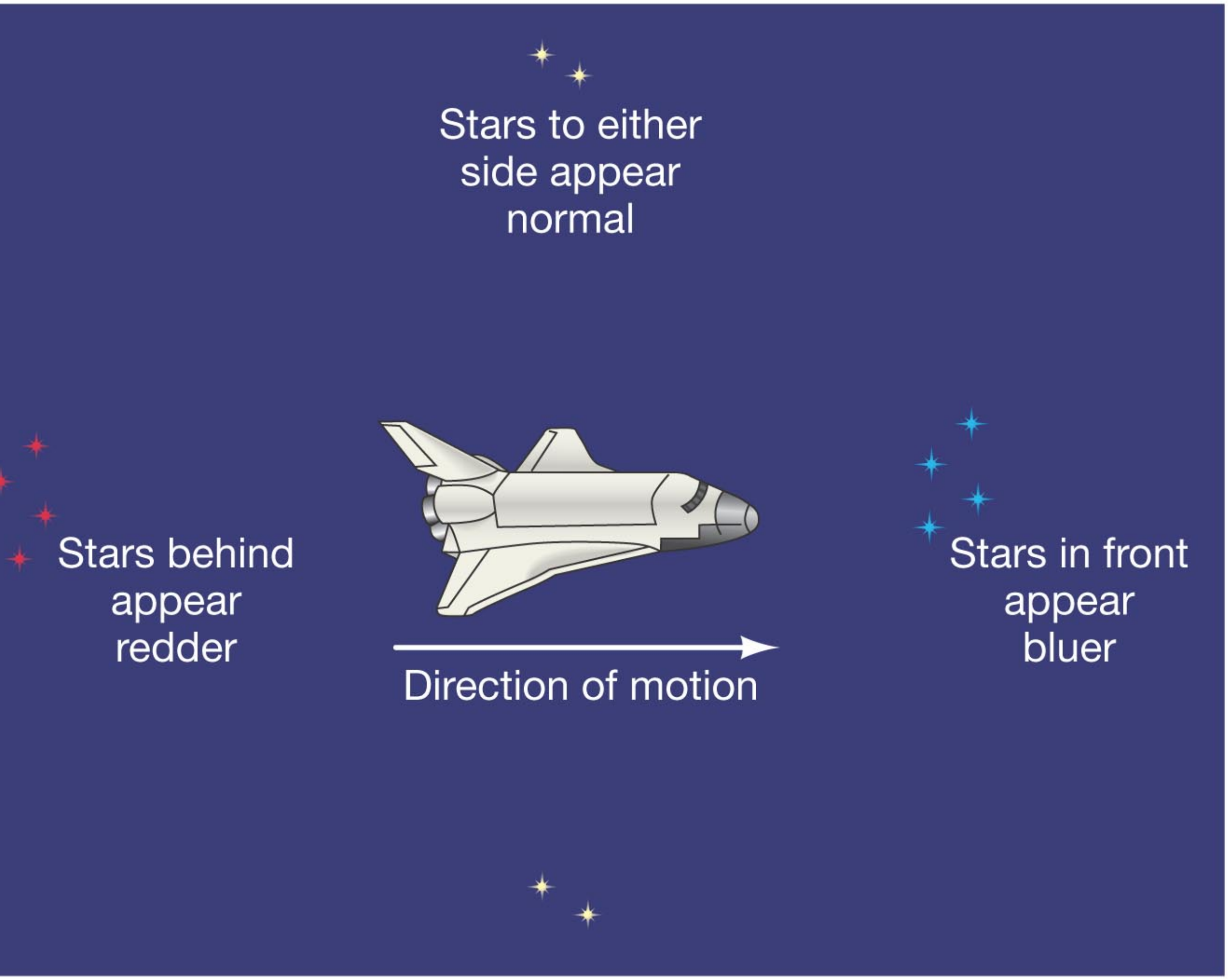




adial Velocity and Line Broadening



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

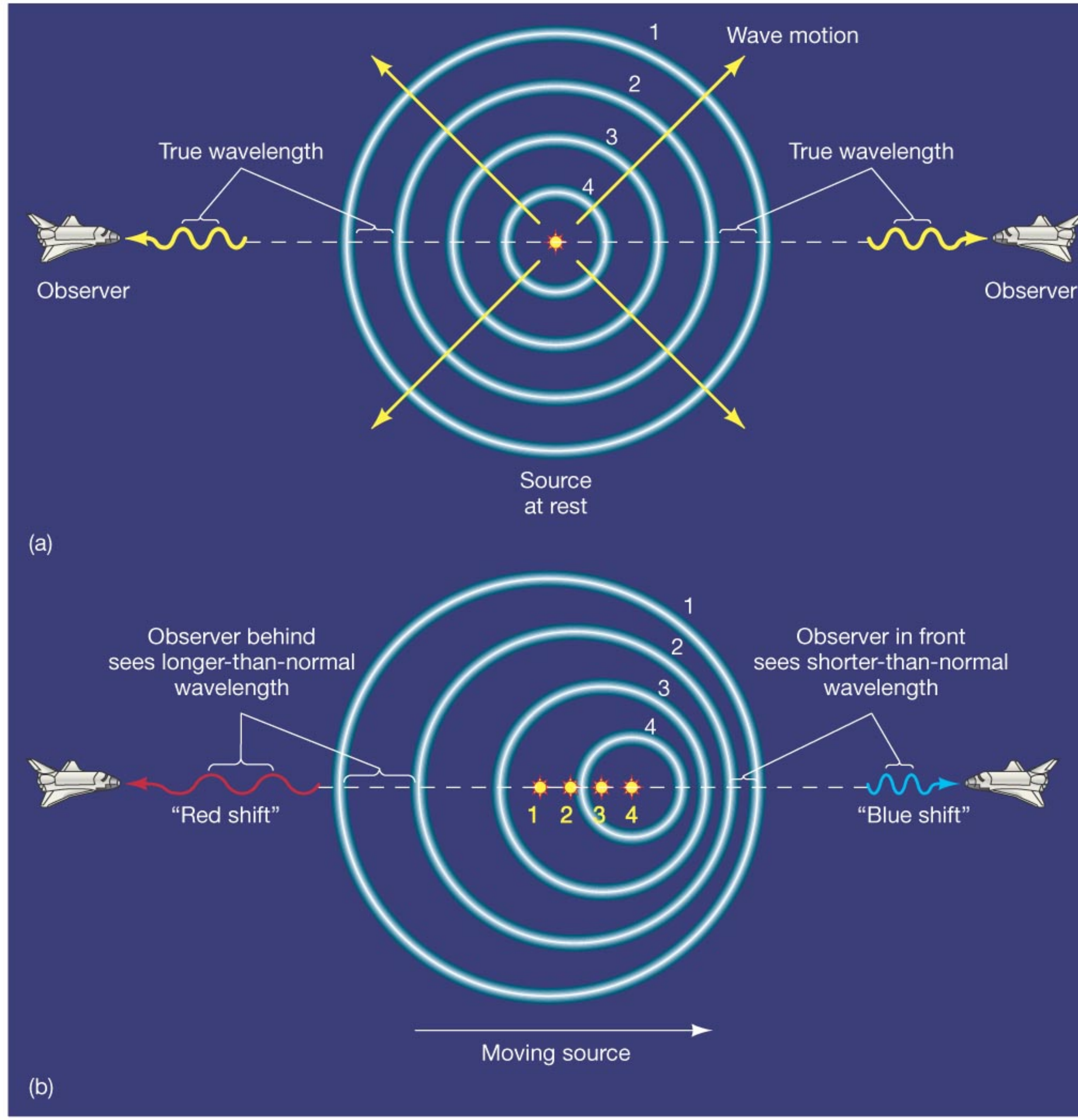
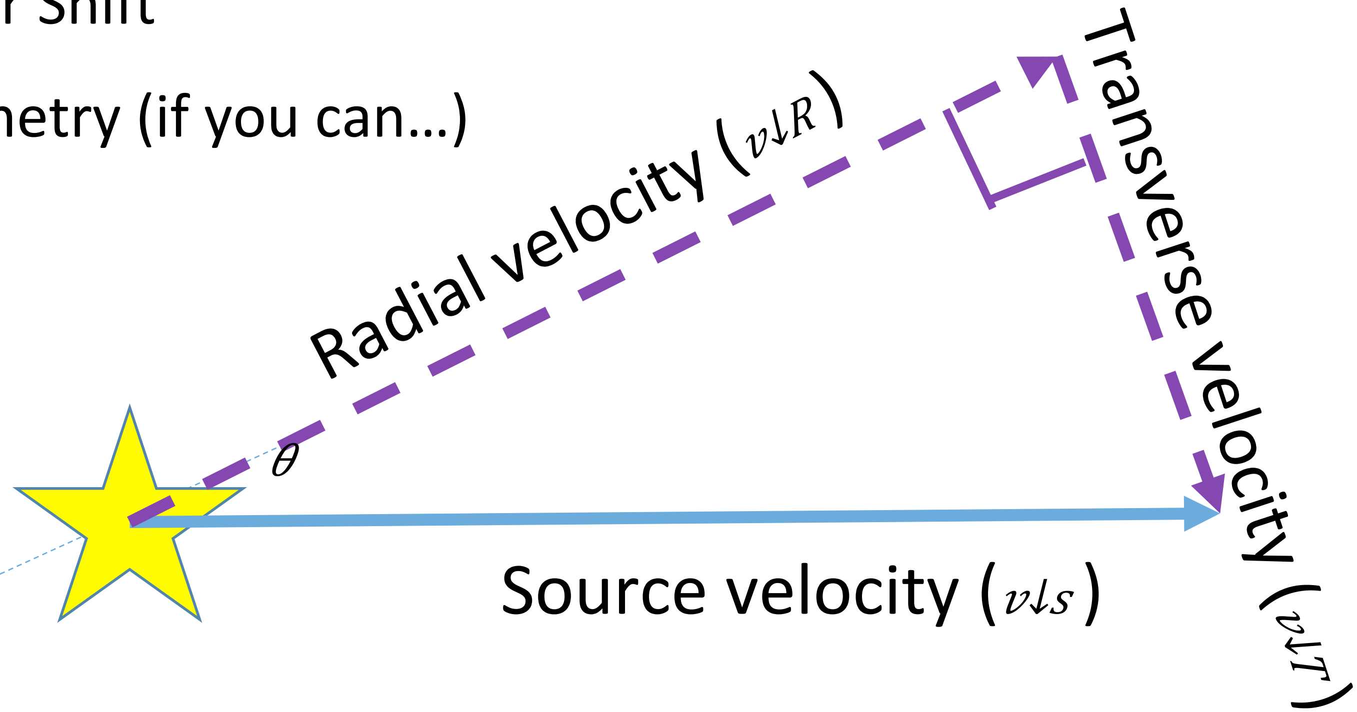


Image: Pearson ed

Radial velocity vs. source velocity

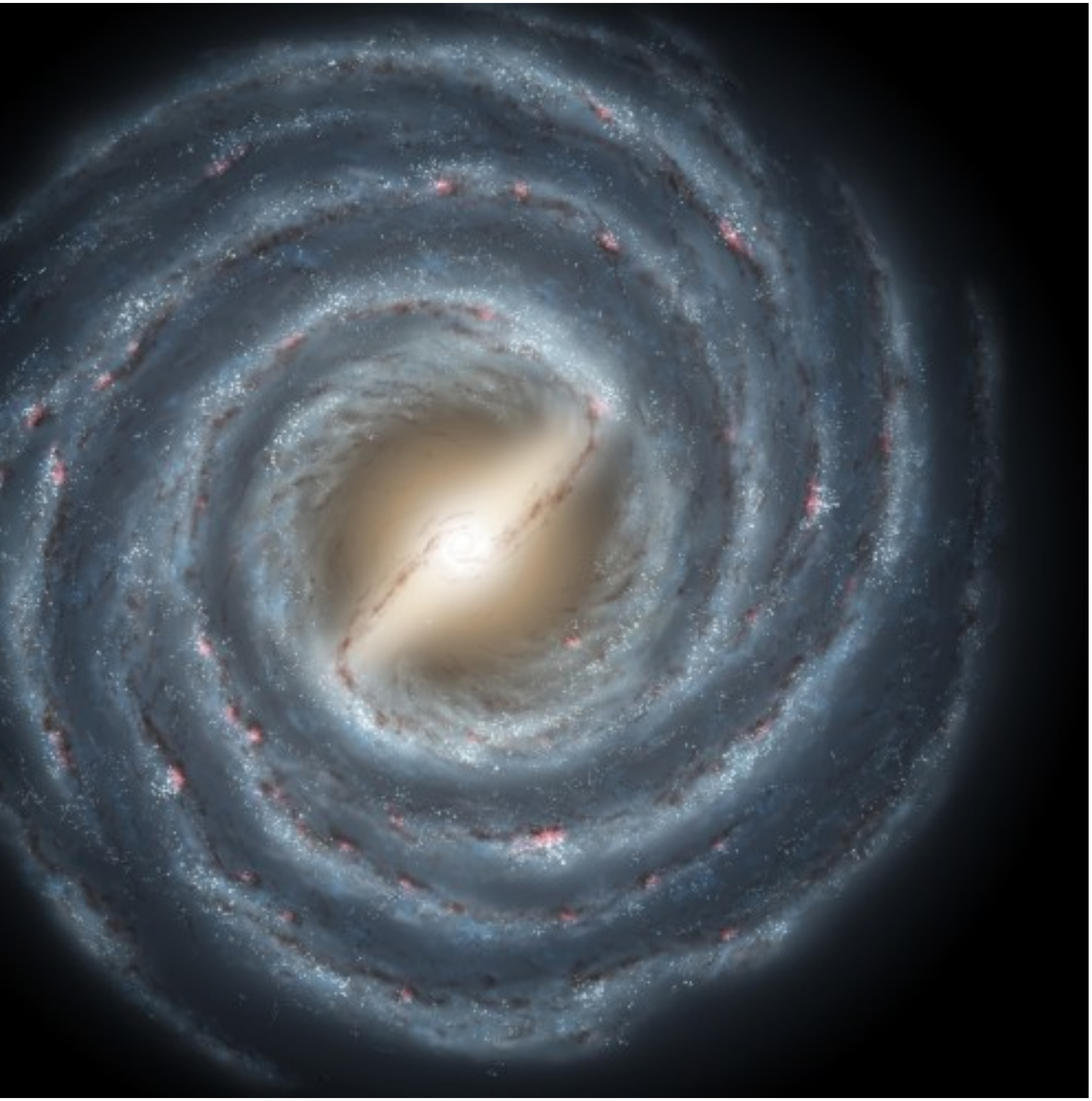
- adial velocity: use Doppler Shift
- ransverse velocity: astrometry (if you can…)



$$v_R = v_s \cos\theta$$

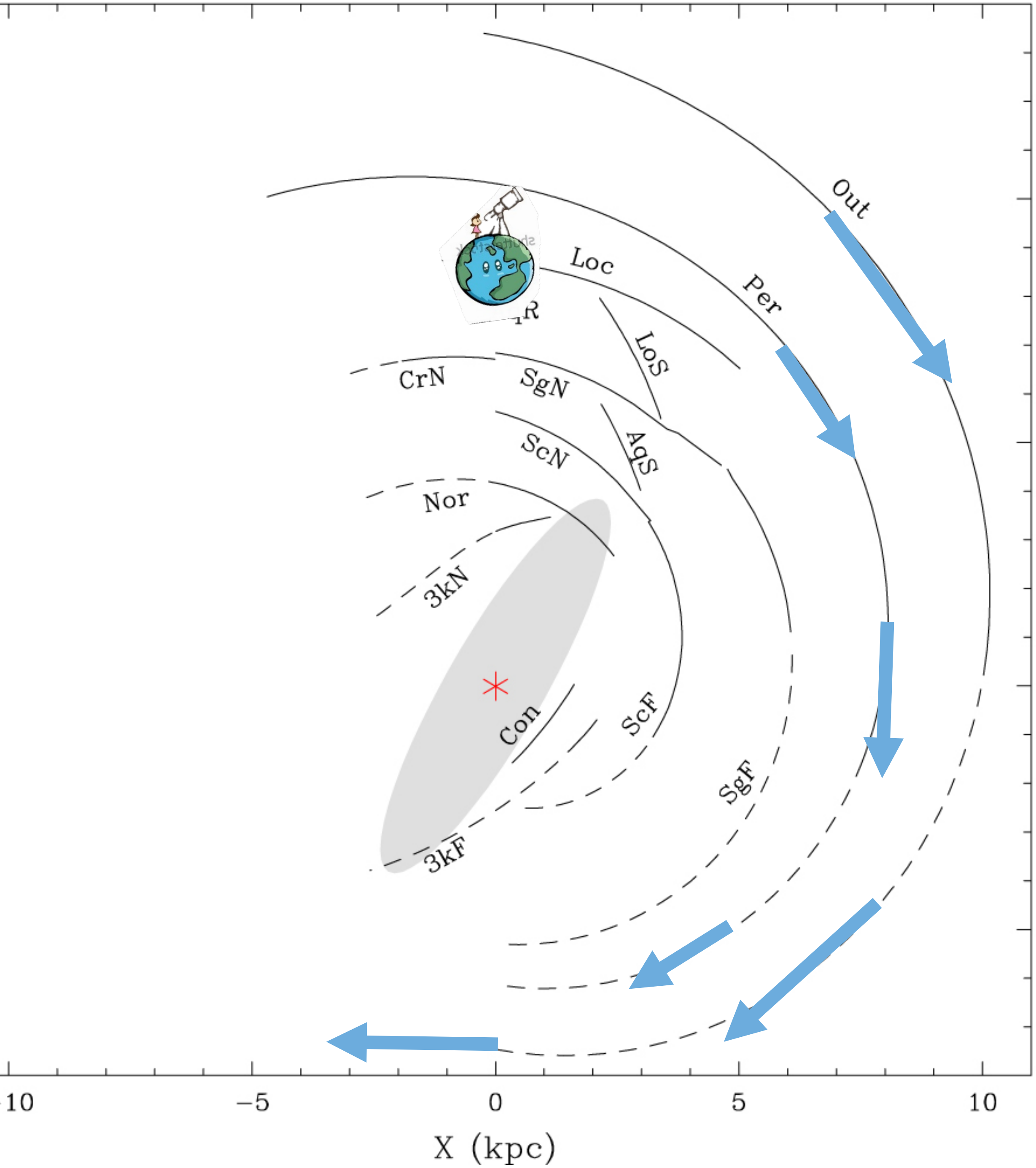
$$v_S^2 = v_R^2 + v_T^2$$

Velocity in Our Galaxy: Galactic Rotatio



Radial velocity (relative to 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.

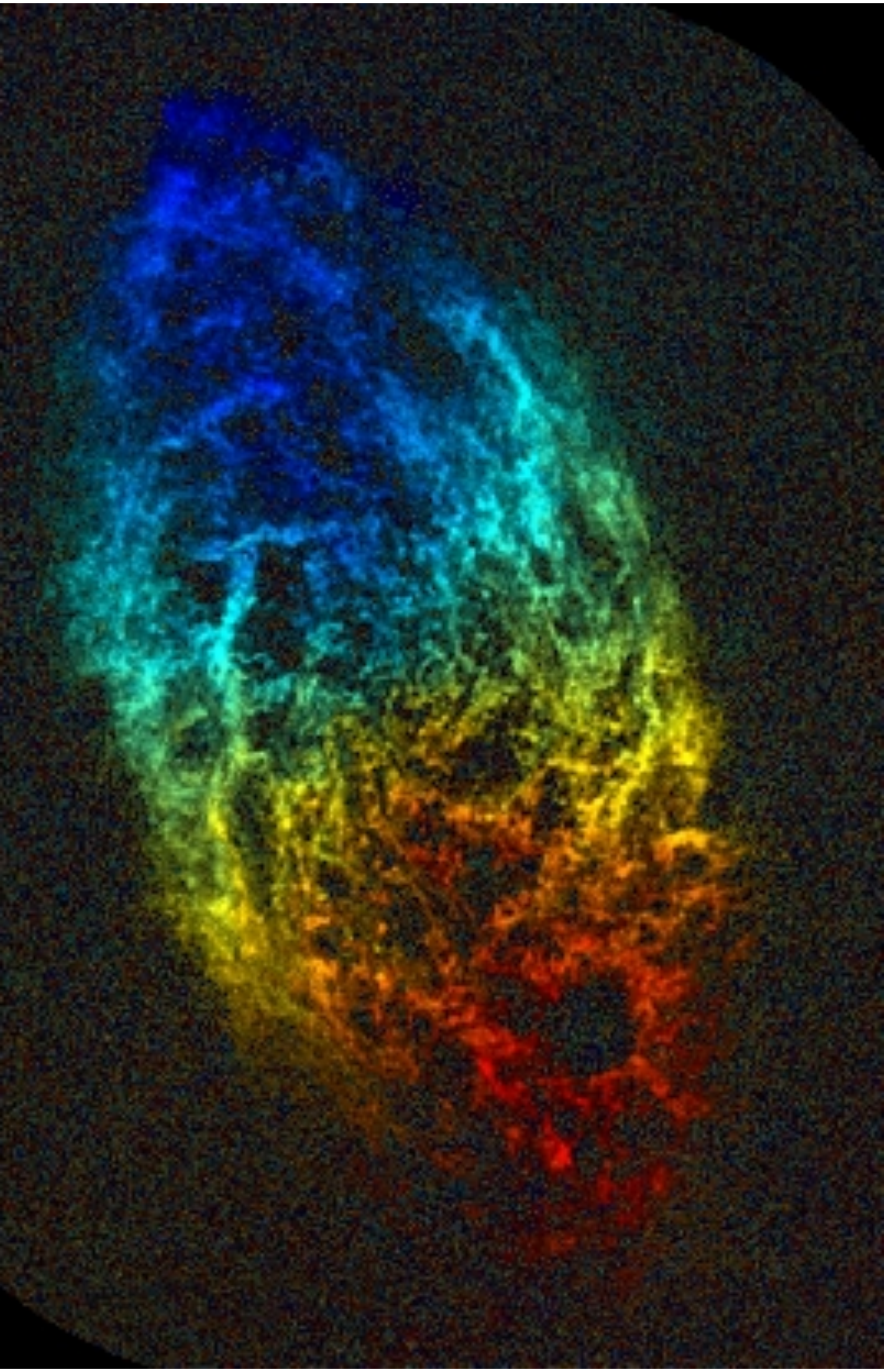
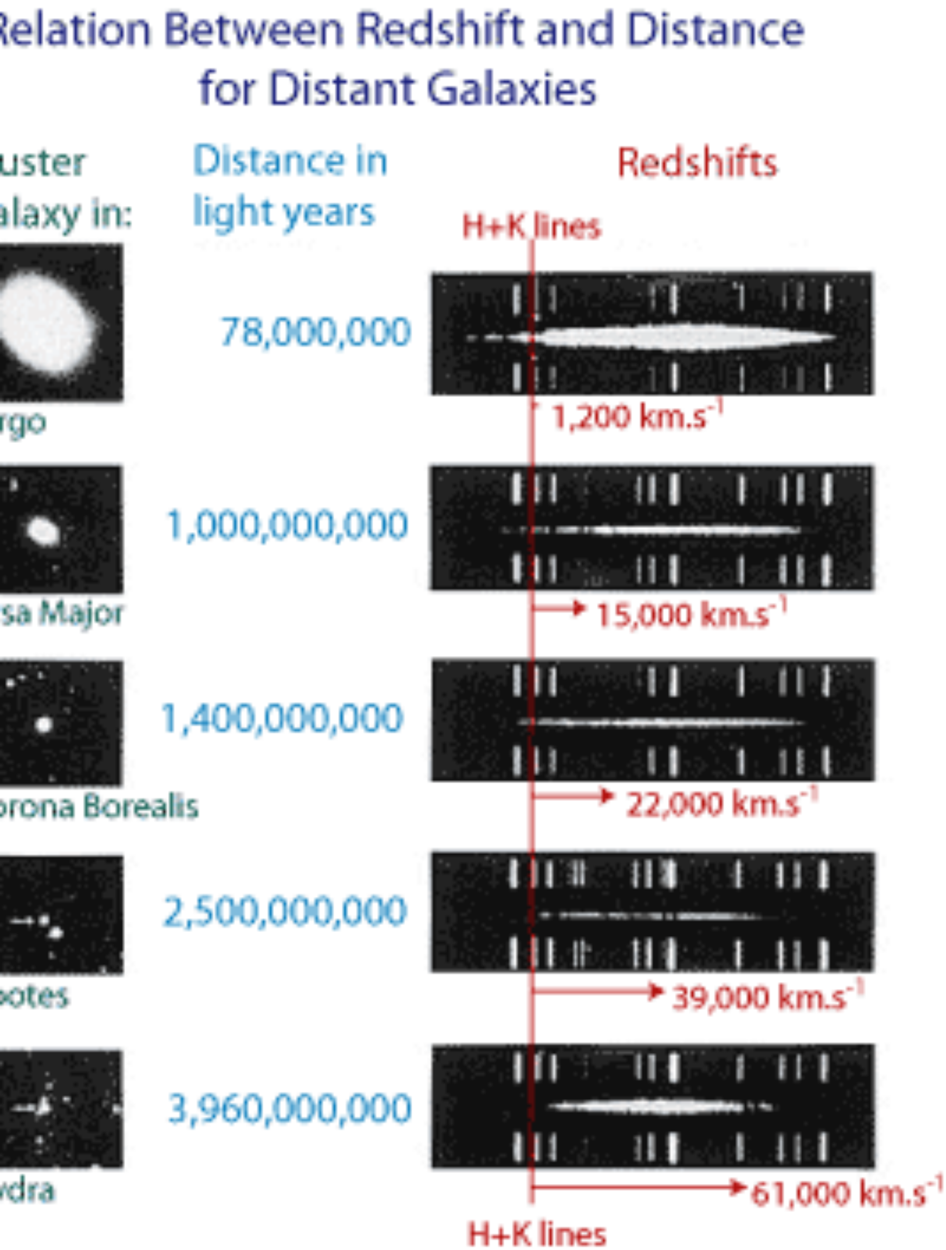


Image: NRAO, https://www.nrao.edu/pr/2001/m33gas/

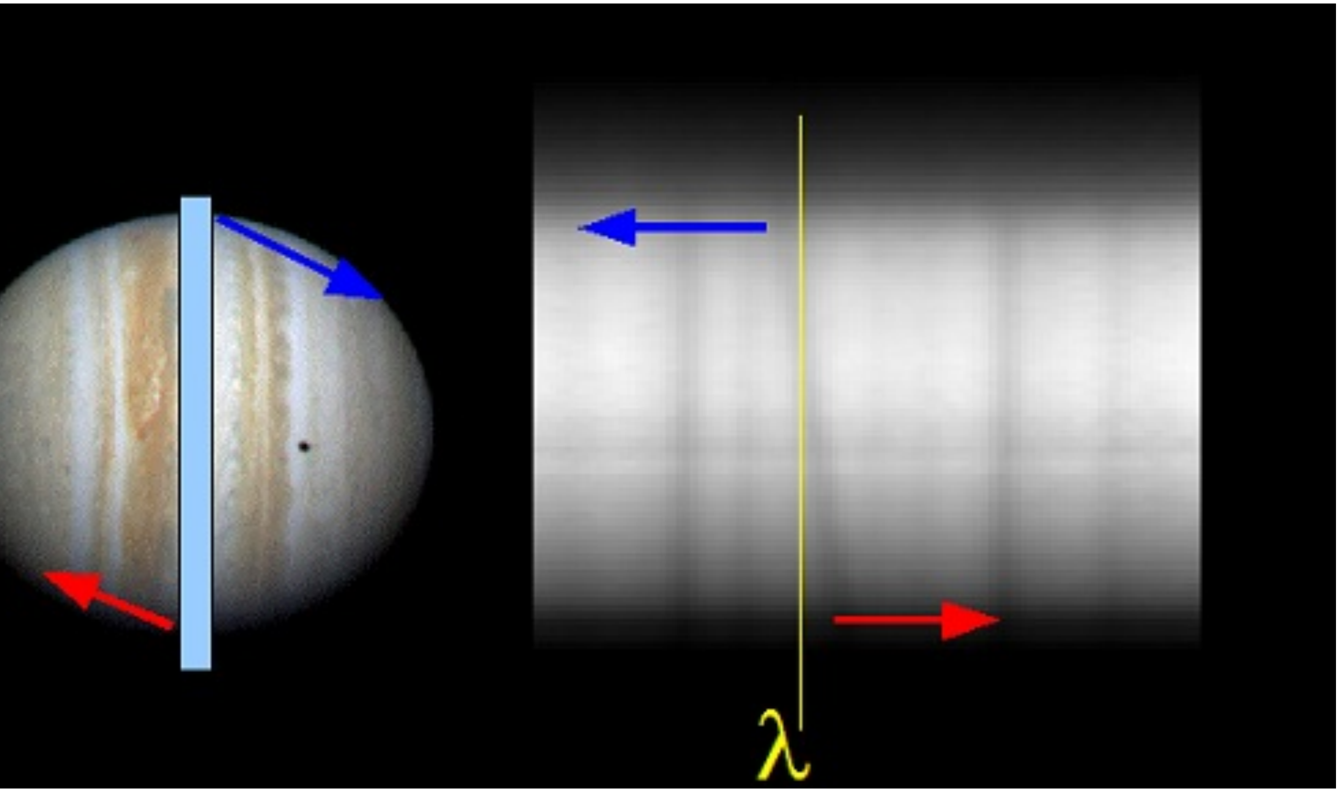


Velocities of other galaxies

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

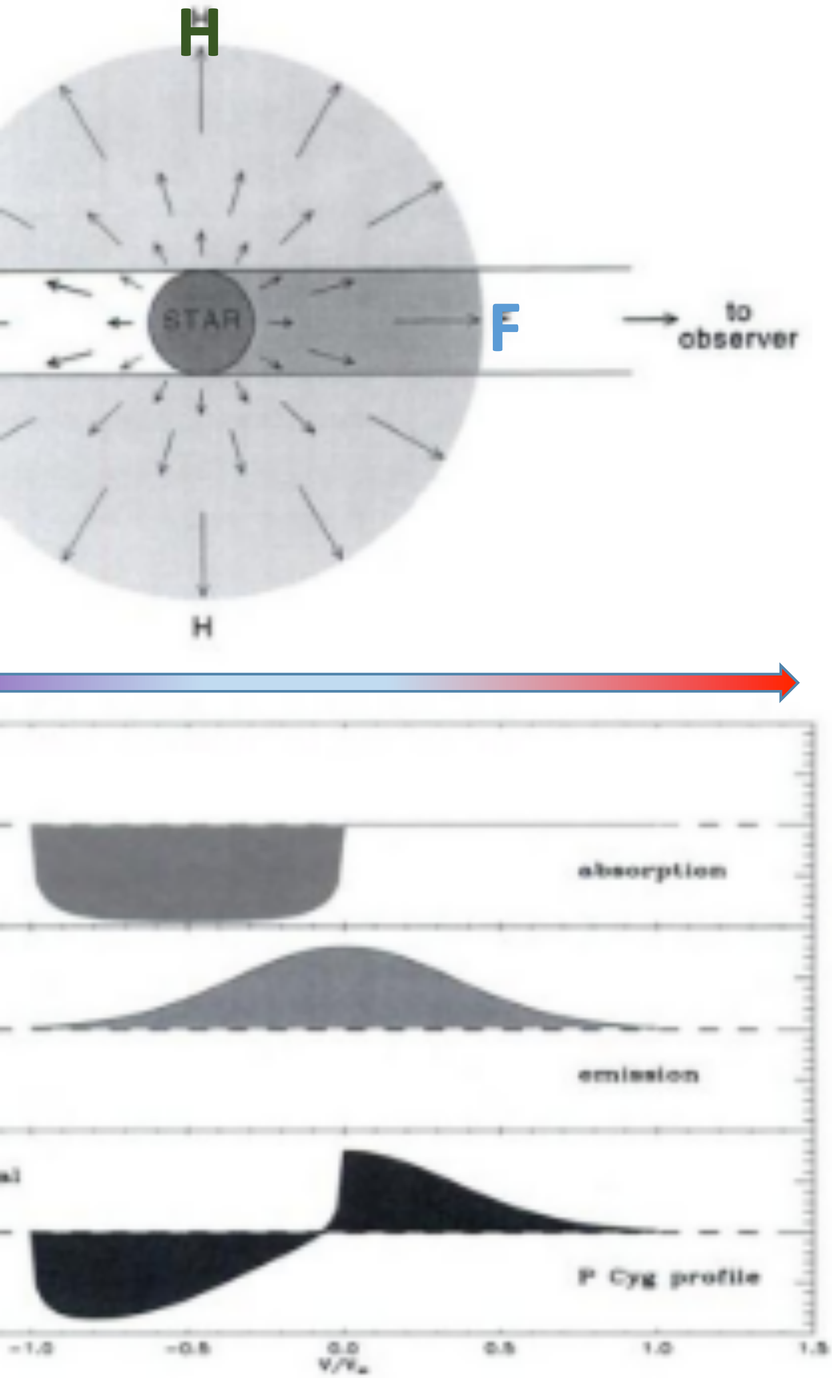
Expansion, motion within Galaxy clusters, rotation of galaxies

Planetary Rotation



Example: Rotation of Ju

Image: Shelyak.com

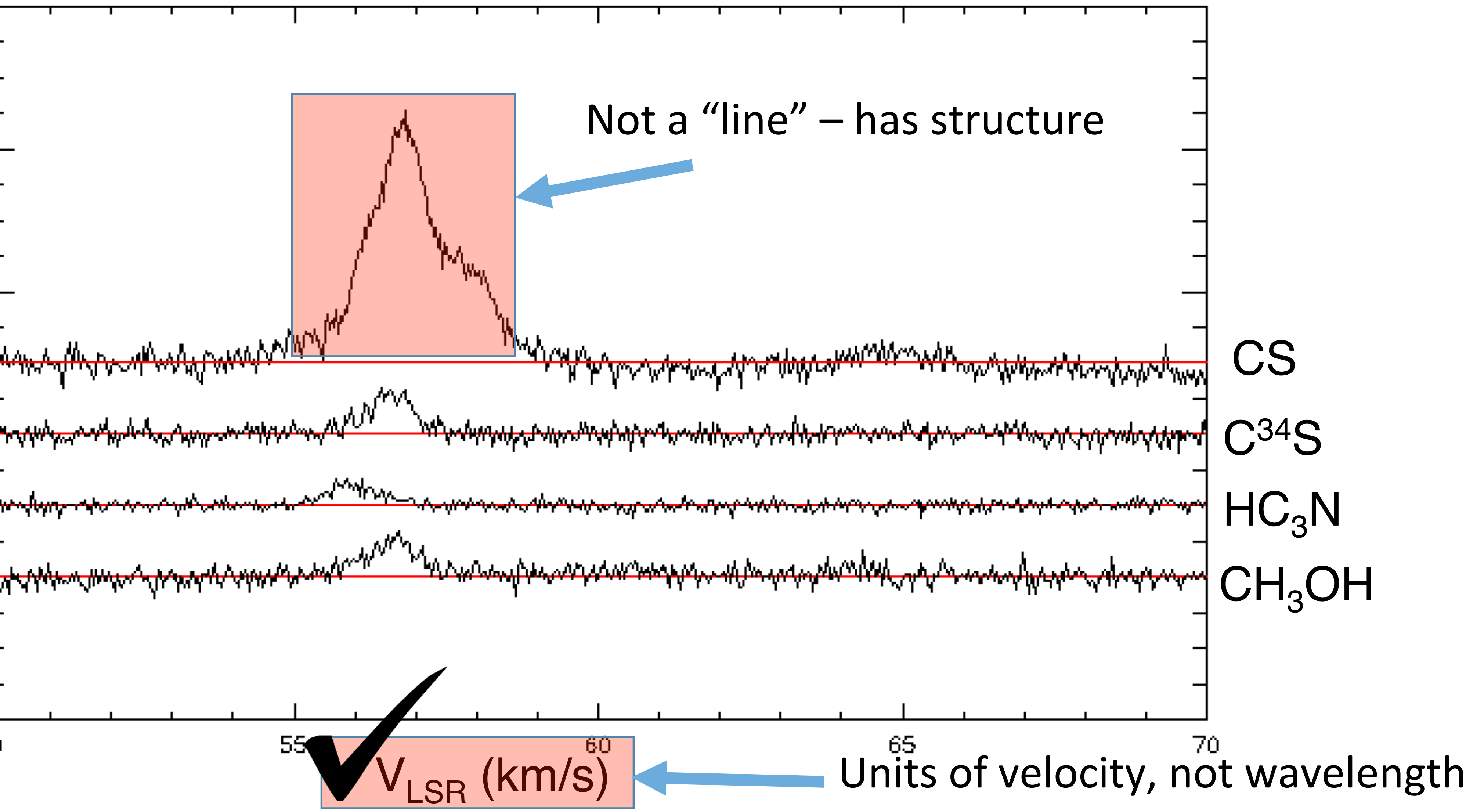


P-Cygni Profiles

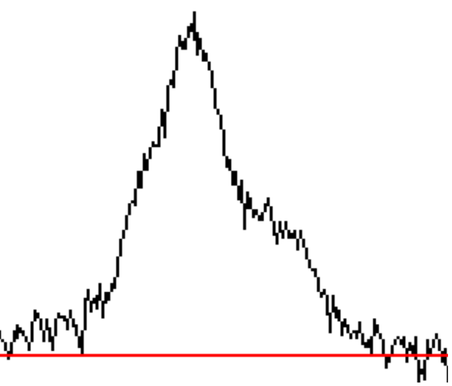
Bottom shows the continuum from star with absorption in front (F) ar emission from halo (H)

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

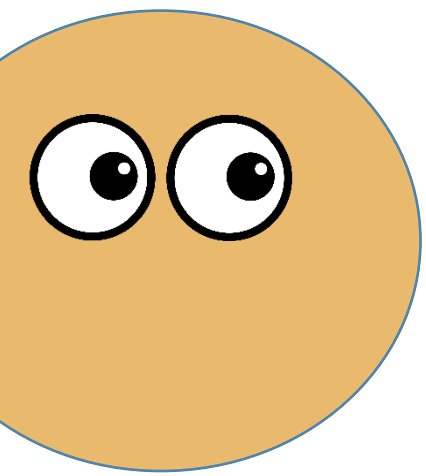
Gaussian:

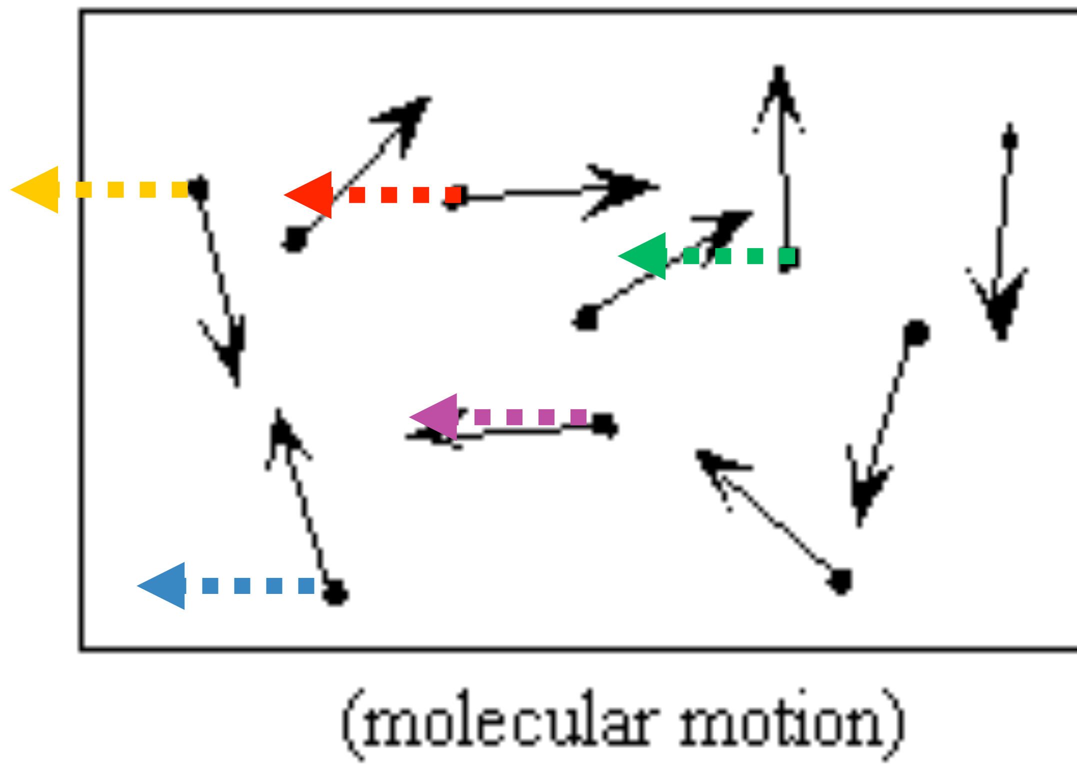
Thermal

Turbulence

See David Whelan’s talk for more!

locity of Individual Atoms: Statistical ysics





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

$v)dv$ is fraction of atoms with city between v and $v+dv$

$v)dv$ is "probability distribution" depends on gas properties

ability distribution determines ne shape

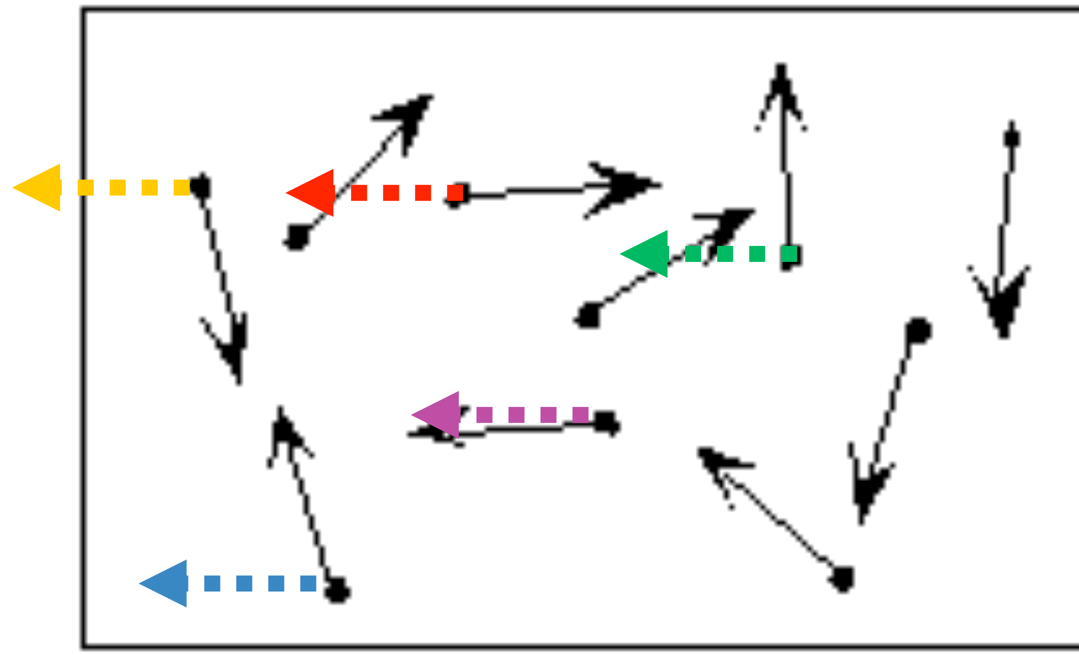

(molecular motion)

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

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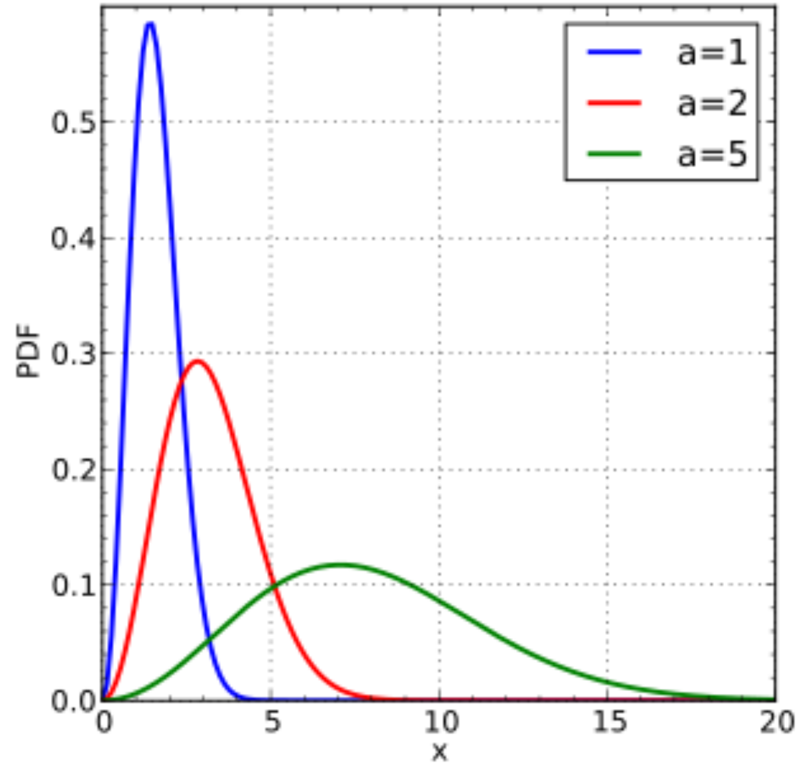

Maxwell-Boltzmann distribution– ideal g with random motions

locity of Individual Atoms: Statistical ysics

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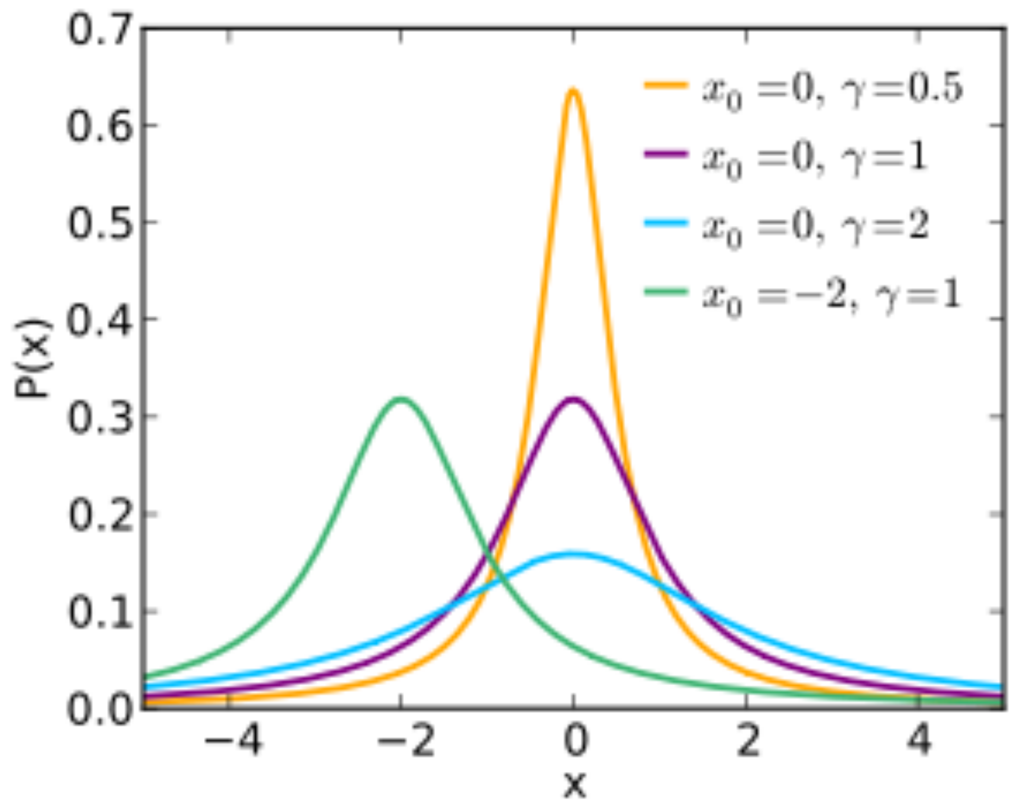
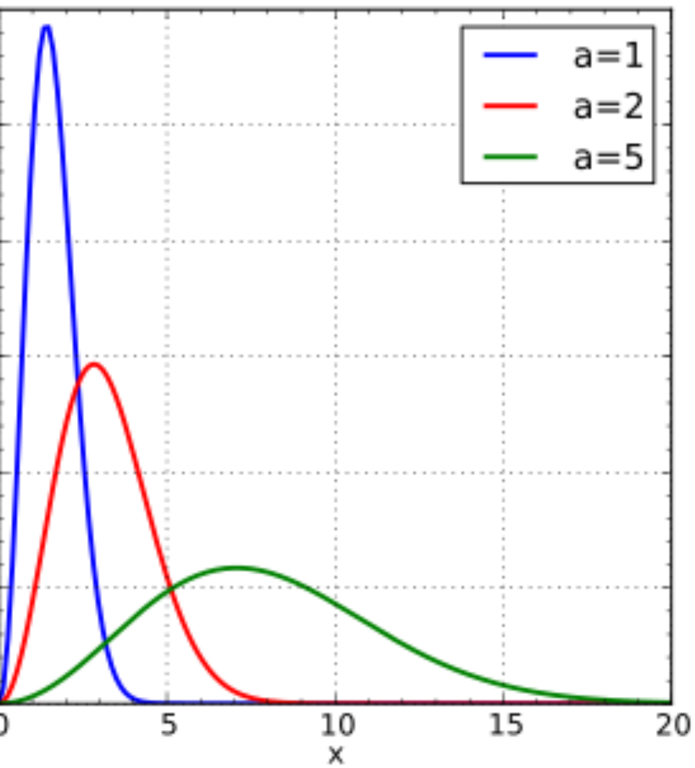


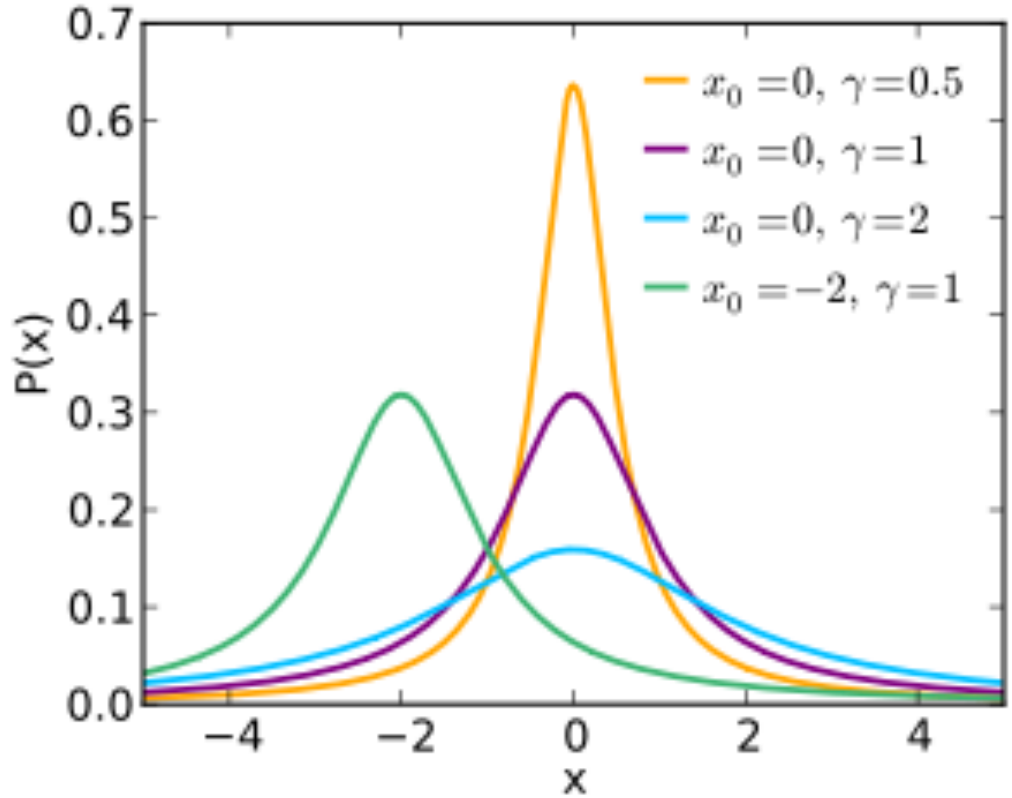
Cauchy–Lorentz (Lorentzian) distributio homogeneous broadening

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

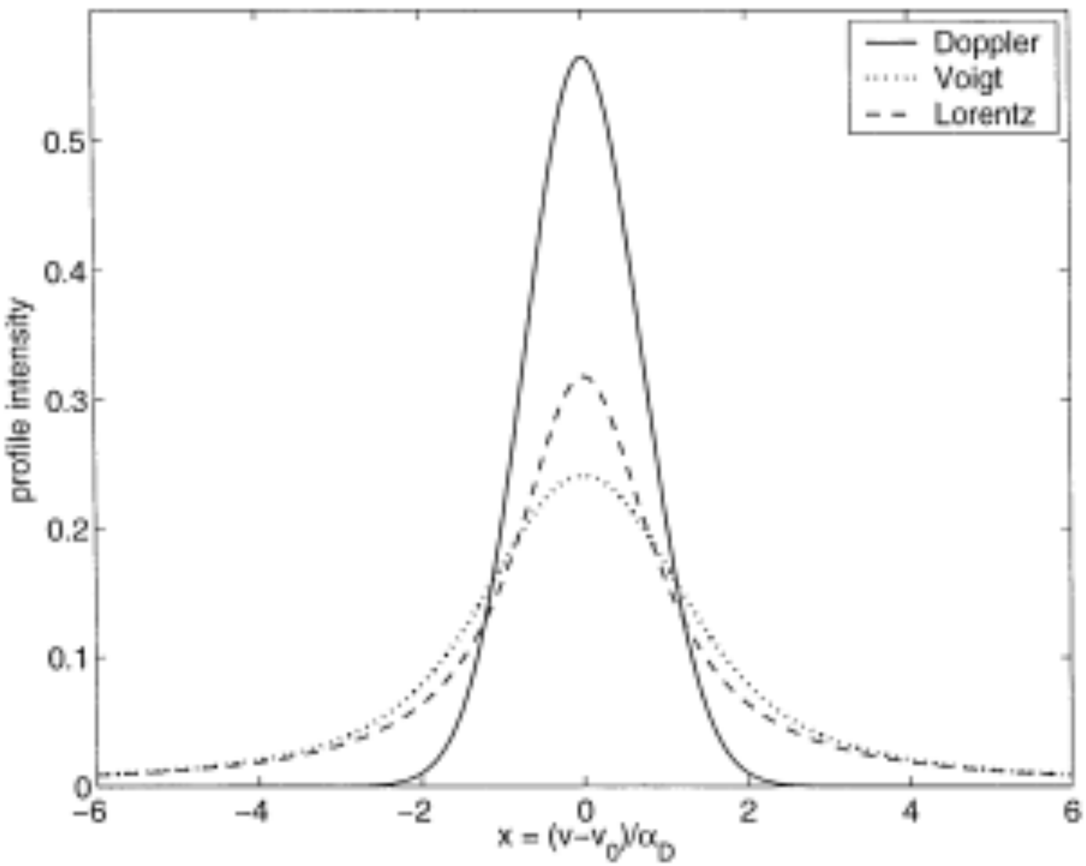
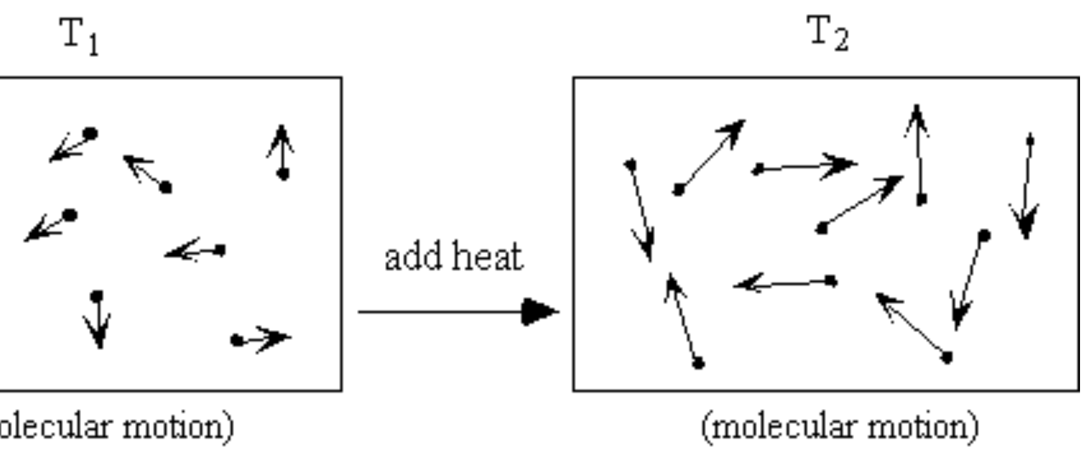


FIG. 2. The Lorentz profile (dashed line) and the Doppler profile (solid line) with the same half-widths ($\alpha_L = \alpha_D = 1$). The dotted line is the corresponding Voigt profile. Here, x is defined as $x = (\nu - \nu_0)/\alpha_D$.

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



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

k_b is Boltzmann's constant, 1.38 x10^{-2}

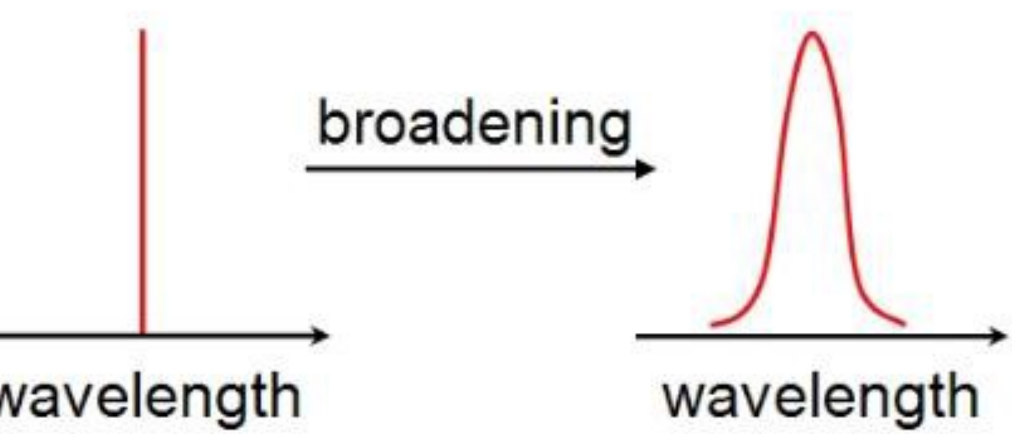
Rearrange to get average kinetic ener
of a gas:
$KE_{avg} = 3/2\ k_b T = 1/2\ m v_{average}^2$

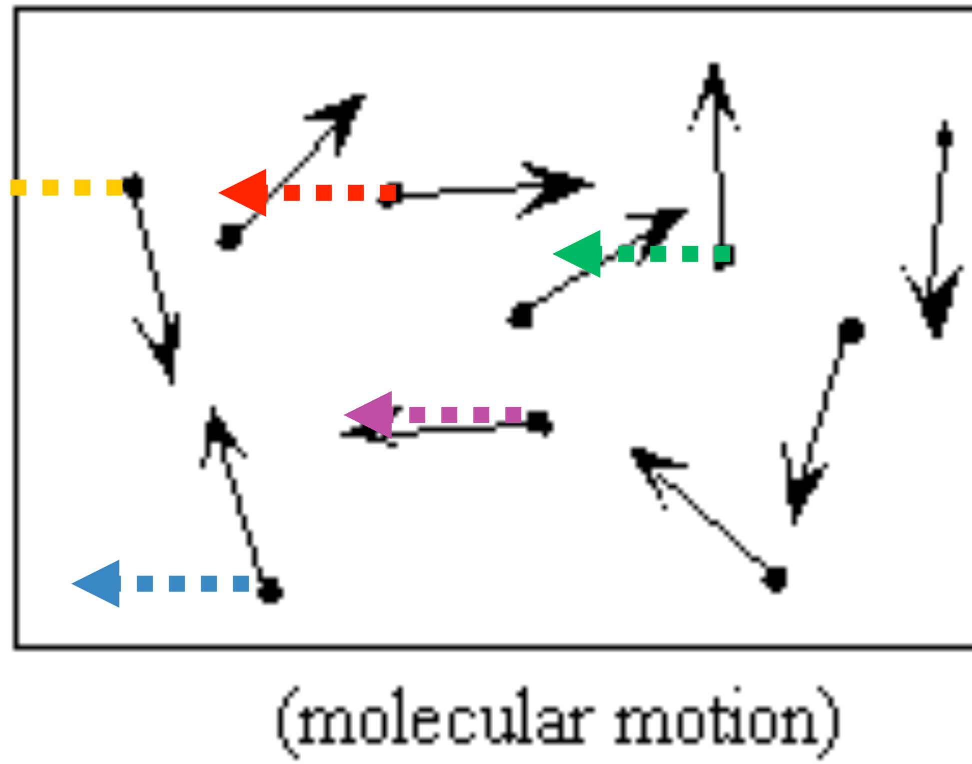
ttp://web.mit.edu/16.unified/www/FALL/thermodynamics/thermo_4.htm

ermal Linewidths

ning gas random motions follow Maxwell-
mann distribution:

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





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

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

Velocity in Gas: Turbulent motion

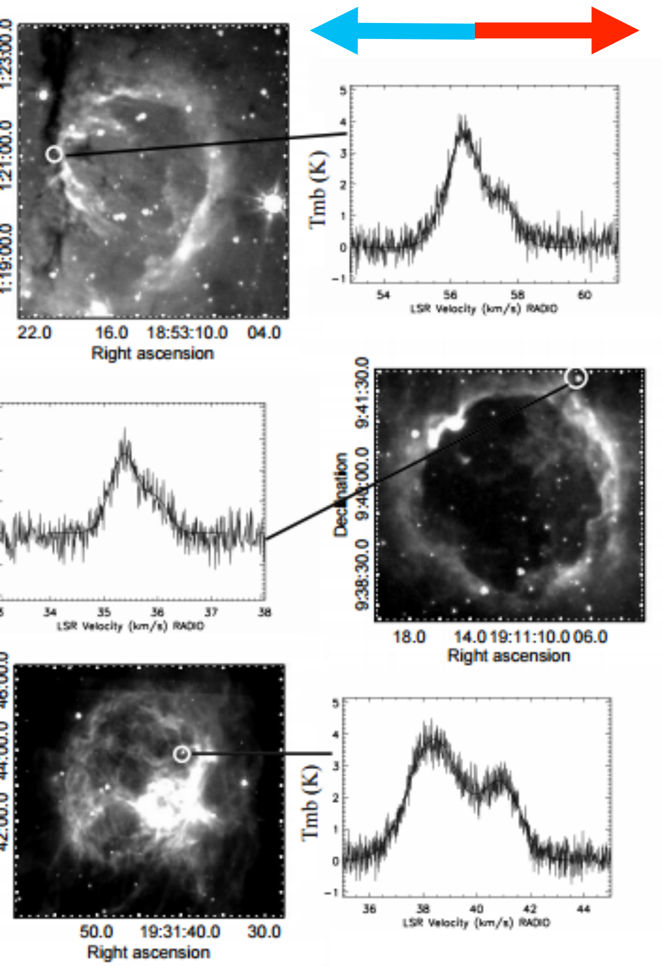
Stars, Gas, and Dust Battle the Carina Nebula

Image Credit & Copyright: Bastien Fouch

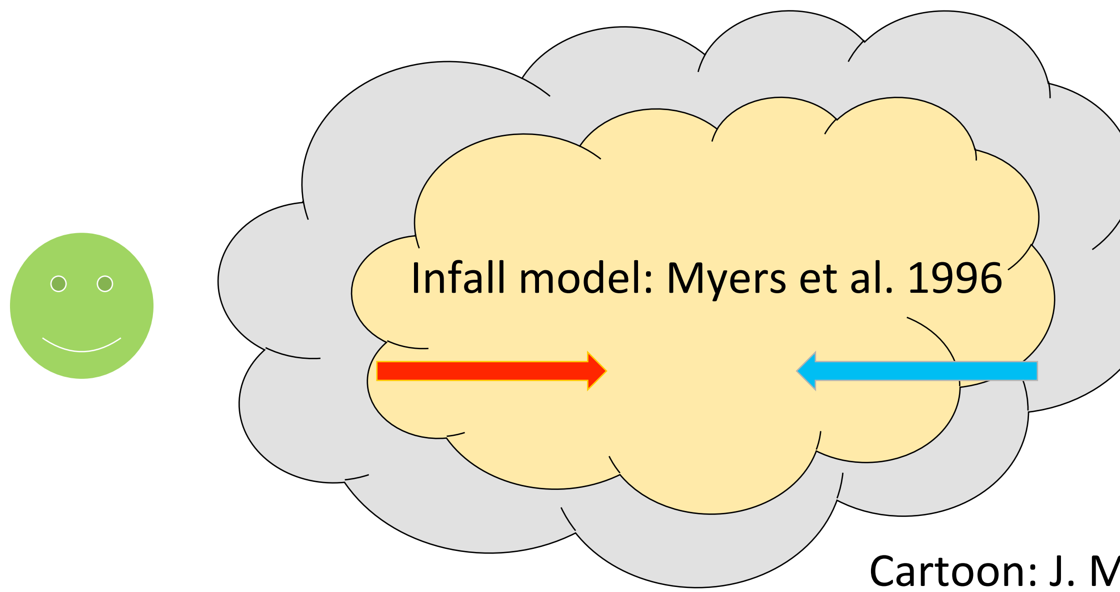
NASA APOD 2017 August 15

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 ook for evidence of in-falling clouds



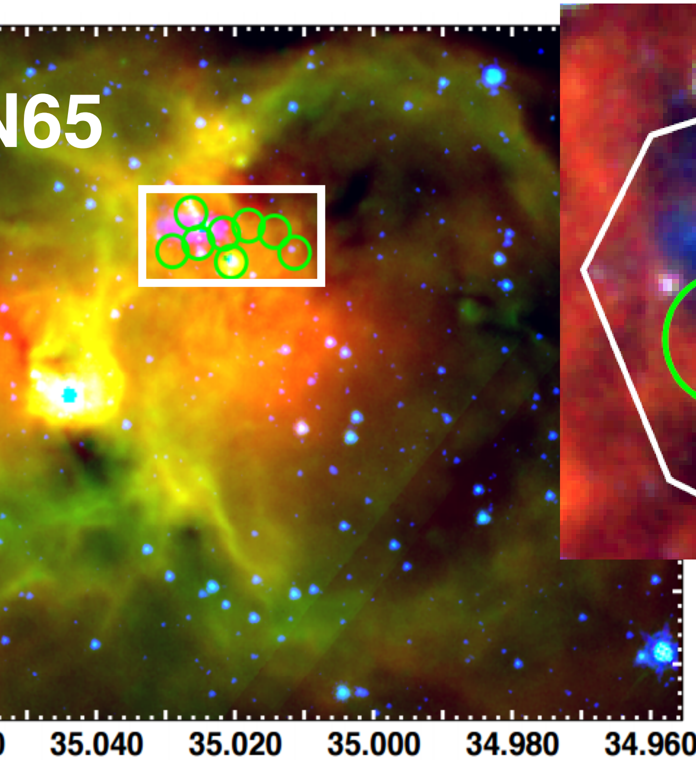
Watson, Devine et al. 2016: CS lin profiles show evidence of infall

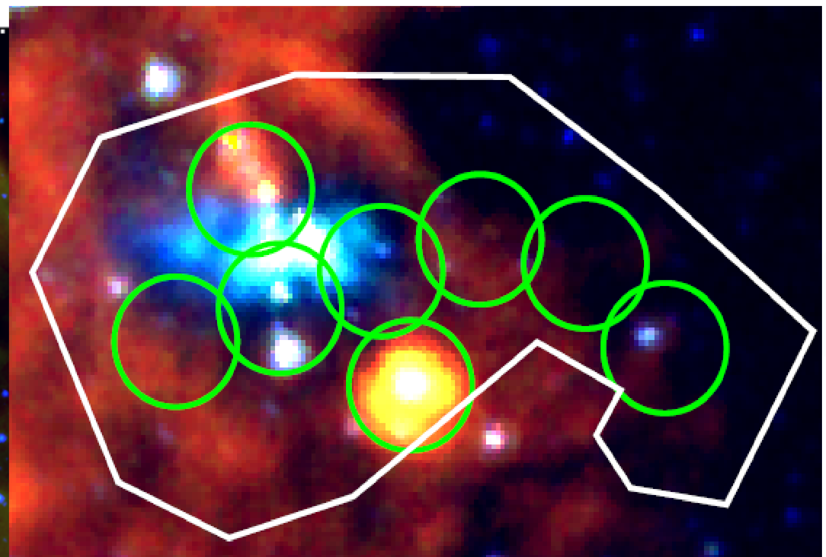


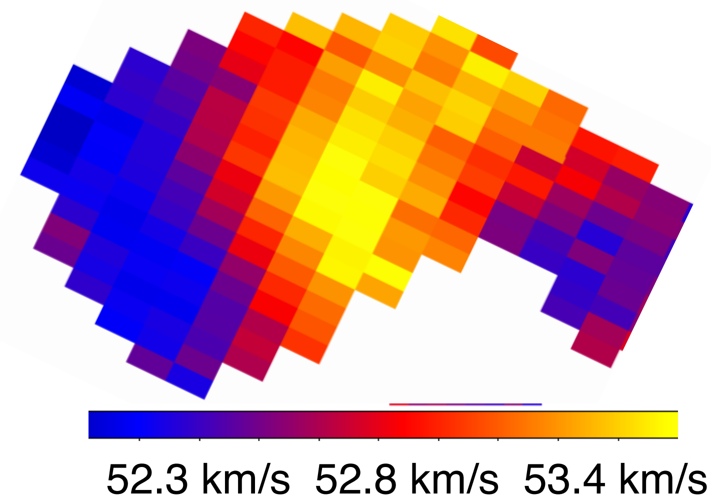
Cartoon: J. M

l62-1, 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

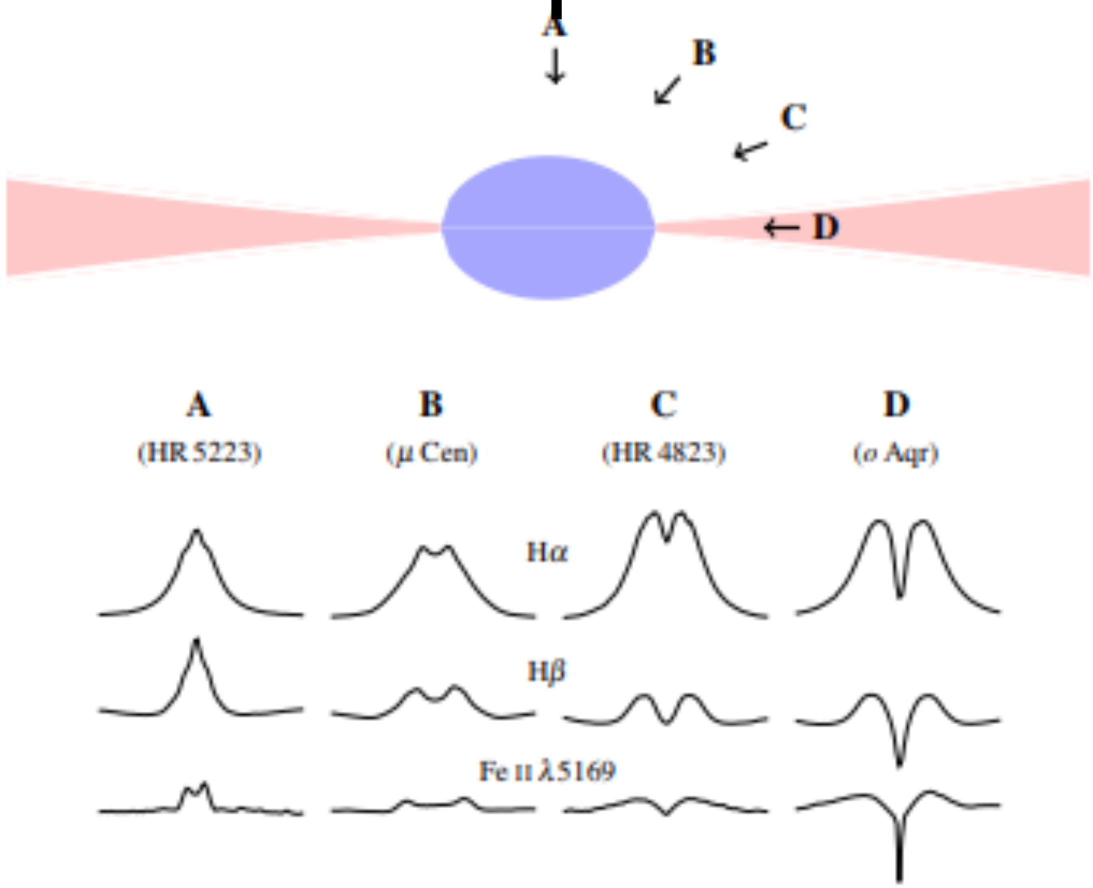


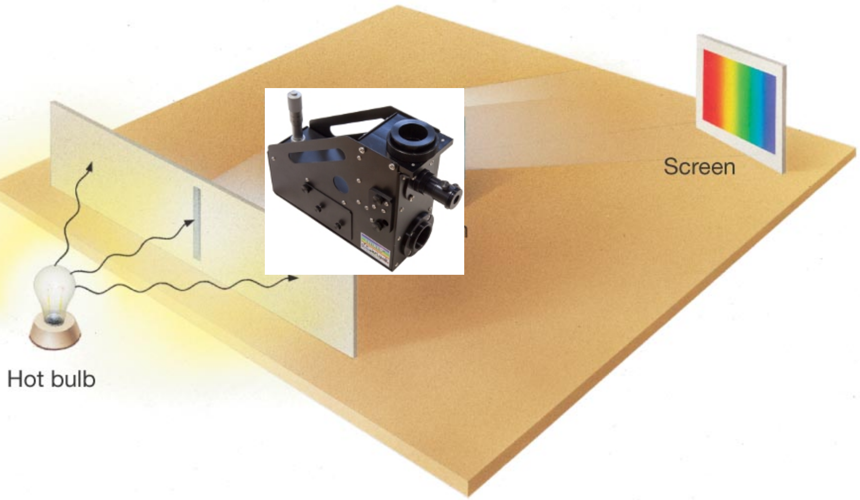
Fig. 1 Schematic view of a Be star at critical rotation and with a flared disk. The lower part shows example spectral profiles from pole-on to shell Be stars

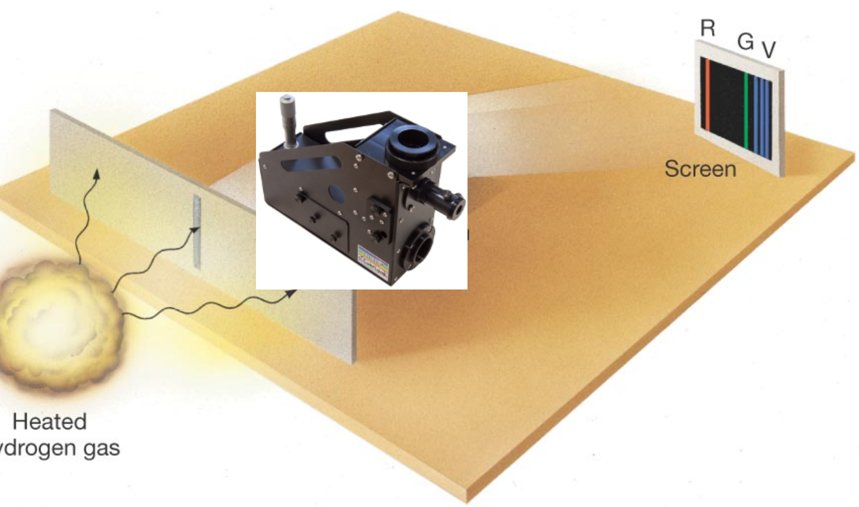
Rivinius, Carciofi & Marta

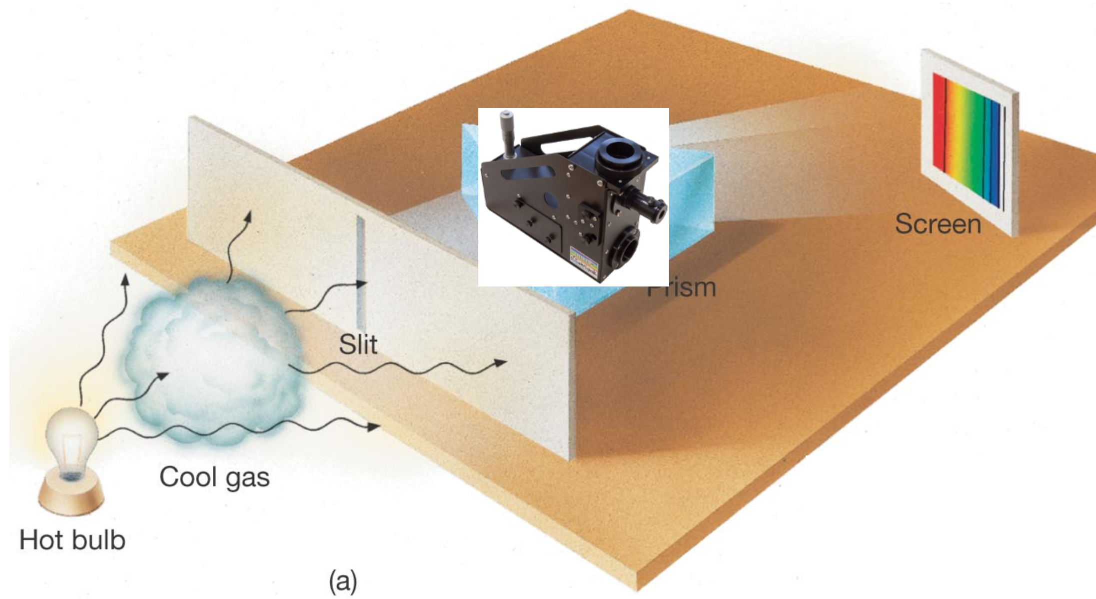
Summary

- 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 (