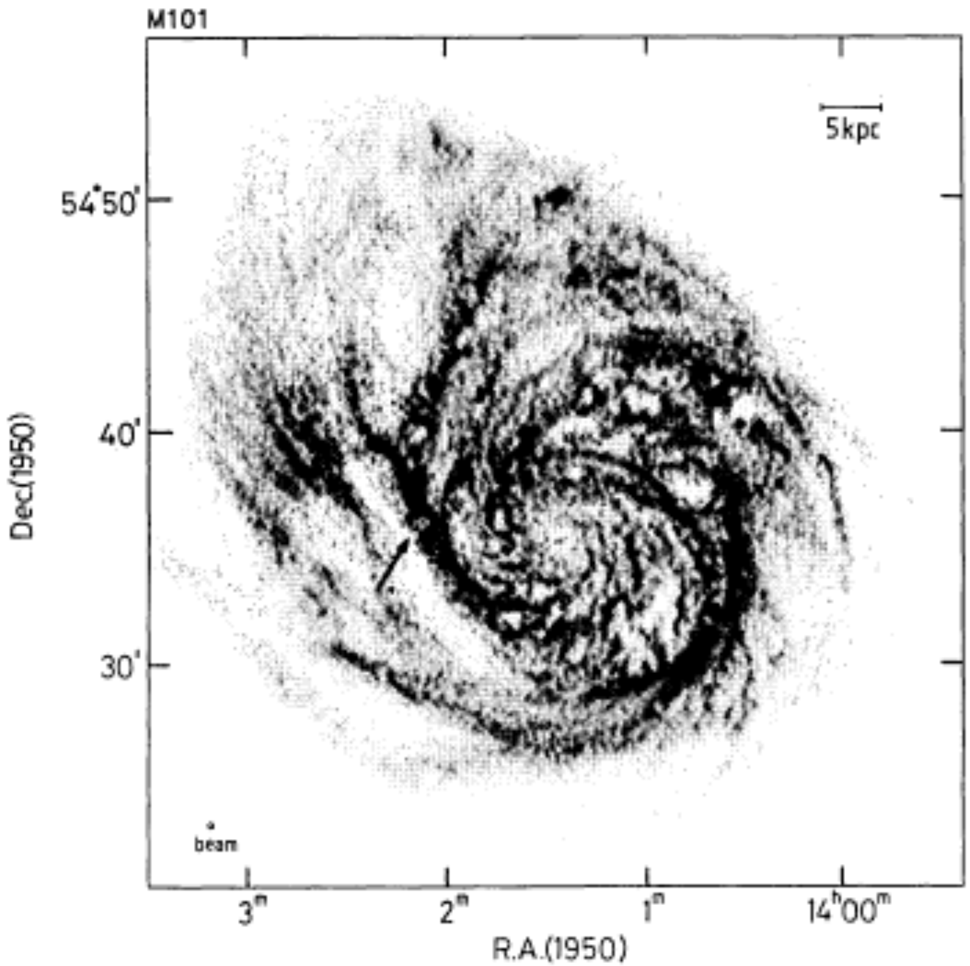
Astronomy 120



Prof. Jeff Kenney

Class 12

June 12, 2018

midterm exam

- thurs june 14 morning? evening?
- fri june 15 morning? evening?
- sat june 16 morning? afternoon?
- sun june 17 morning? afternoon?

observing session

- is ON for tonight, tues june 12
- 8pm-11pm
- complete observing “pre-assignment” before coming
- planetarium show 8-9pm
- observing & observing assignment 9-11pm

After dark matter and stars, which of the following has the most mass in our galaxy?

A. Photons
B. Gas
C. Cosmic rays
D. Dust
E. Planets, comets, asteroids

Today in Astro120:

Gas in Galaxies

- What is in the space between the stars?
- Where does gas in universe come from?
- How do we “see” this gas?
- How does the gas allow us to detect the presence of Dark Matter?

Importance of gas

- Stars form from clouds of gas

- Galaxies form from clouds of gas & dark matter

Where does gas come from?

A. "primordial"

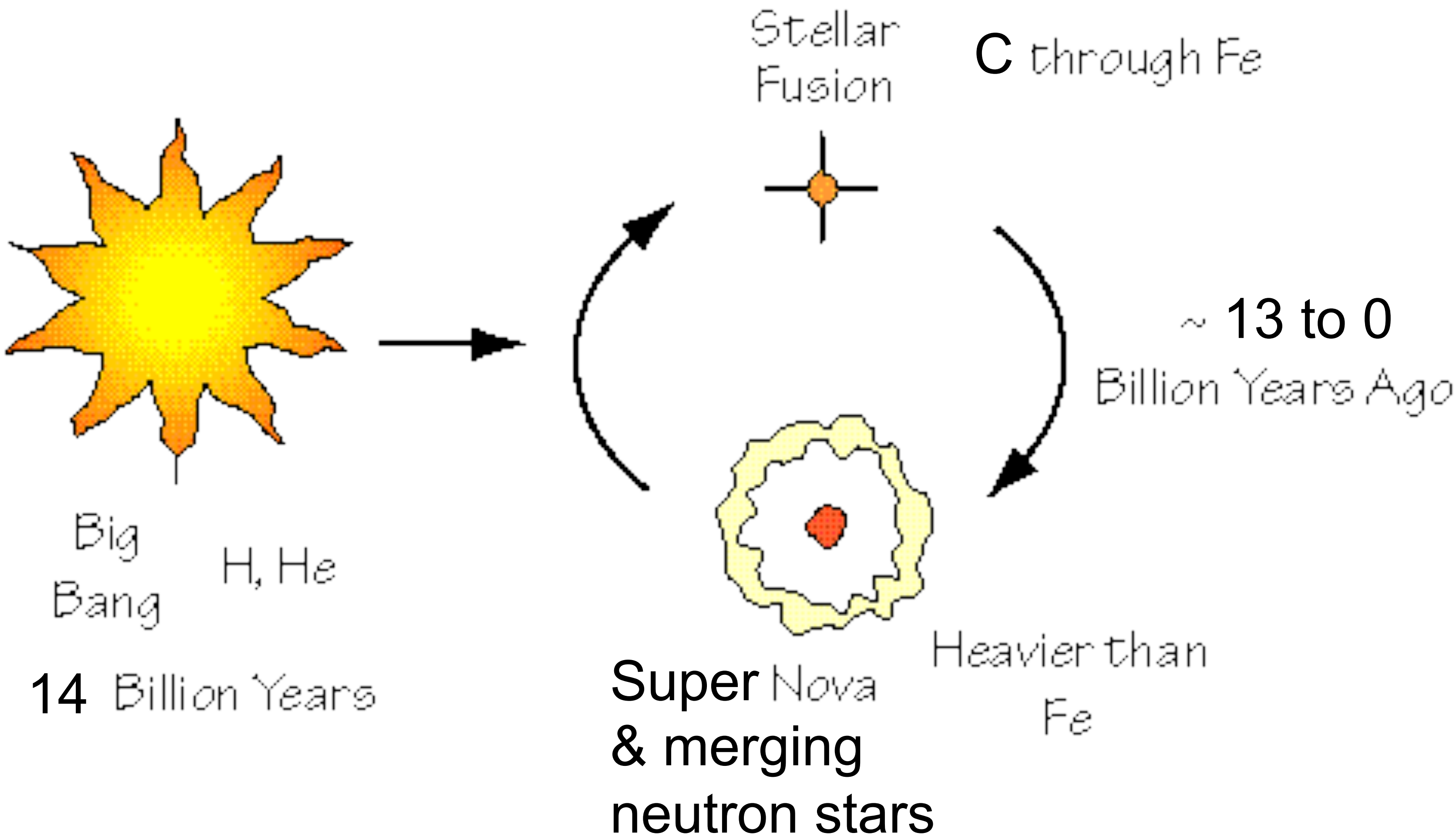
Created in Big Bang in early universe,
existed before stars & galaxies

B. Recycled through stars

Nucleosynthesis in stellar cores (C->Fe) or
supernova & neutron star explosions (heavier than Fe)

It all started as ionized H (just protons) in the Big Bang. Subsequent nuclear reactions turned some of it into heavier elements, either in the early universe (He,Li,Be,B) or later in stars & supernovae (C,N,O & higher)

Formation of the elements in the universe
(oversimplified…)



Where does gas come from?

A. "primordial"

Created in Big Bang in early universe,

existed before stars & galaxies

big clue…. observed elemental abundances of universe:

H 74% by mass (simplest element most abundant)

He 25% by mass

All other elements 1% by mass

prediction for Big Bang Nucleosynthesis:

H 75.5% by mass

He 24.5% by mass

All other elements <<1% by mass

Where does gas come from?

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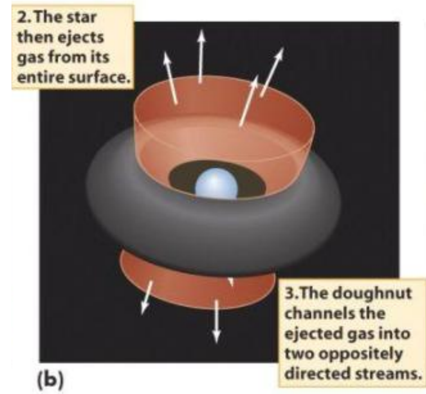
B. Recycled through stars

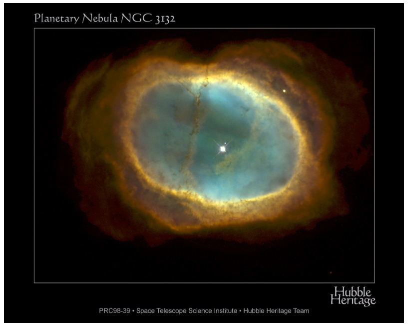
Nucleosynthesis in stellar cores (C->Fe) or supernova & NS explosions (heavier than Fe)

Returned to space by stellar mass loss (stars are always ejecting mass)(stellar winds, envelope ejection in planetary nebula phase) or supernovae

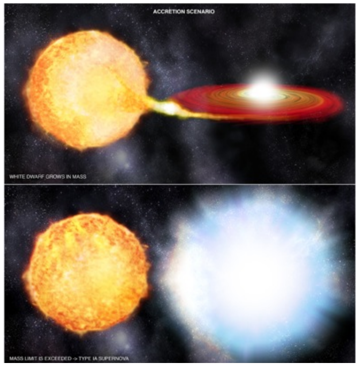
Recycling by stars back into space

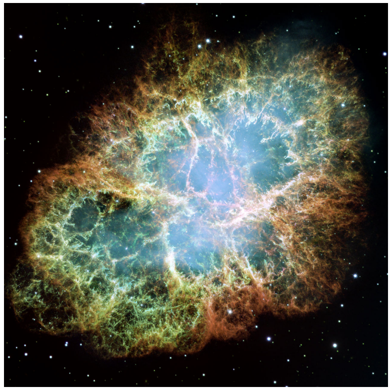
Low mass stars:
Planetary nebulae



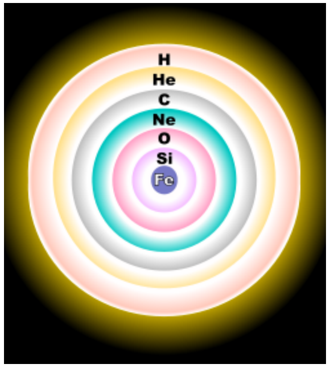


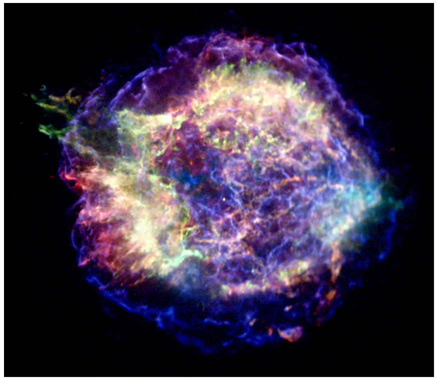
Medium mass stars in binaries:
Type Ia Supernovae





High mass stars:
Type II Supernovae





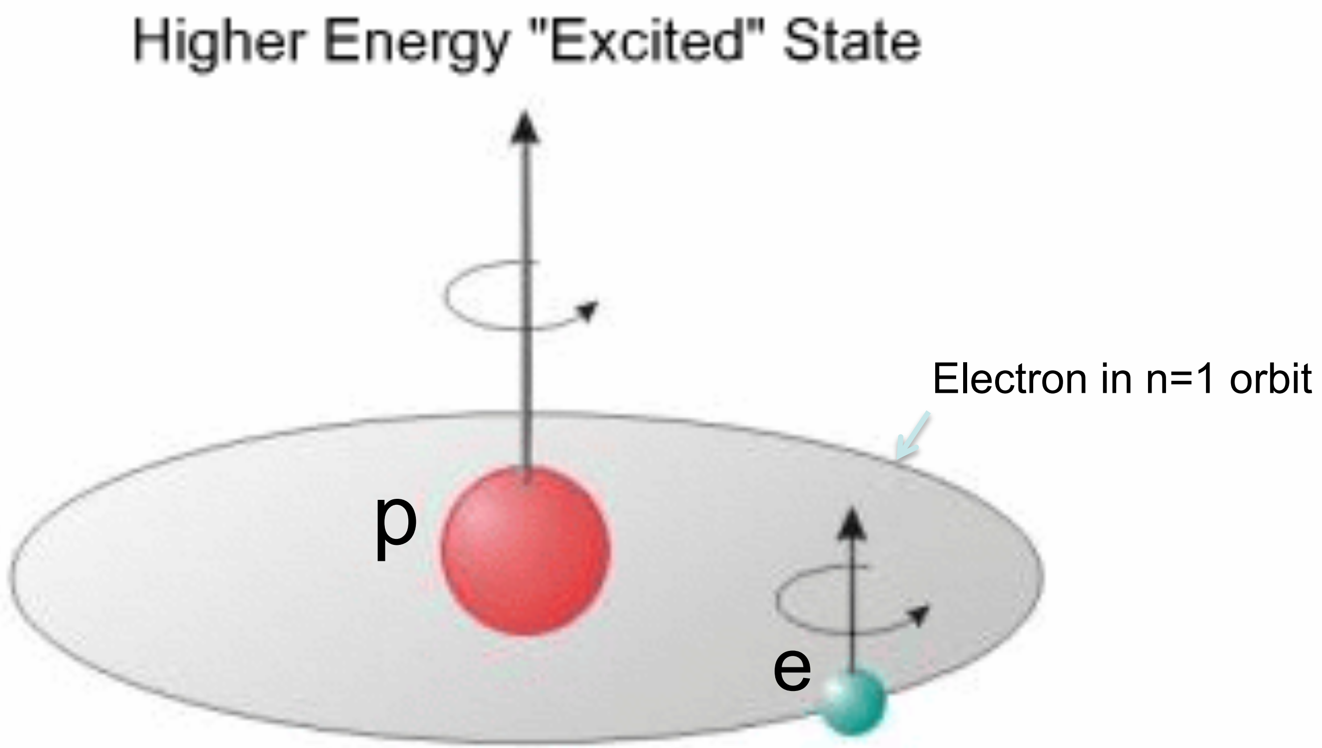
How can we see Gas in the universe?

A. It emits photons
B. Light from stars is doppler shifted by gas particles
C. By its gravitational effect on nearby stars
D. Via the rotation curves of galaxies
E. It absorbs photons
F. You can't see gas, you smell it

Detecting atomic hydrogen with spectral line of HI

H is most abundant element in universe (~74% by mass)

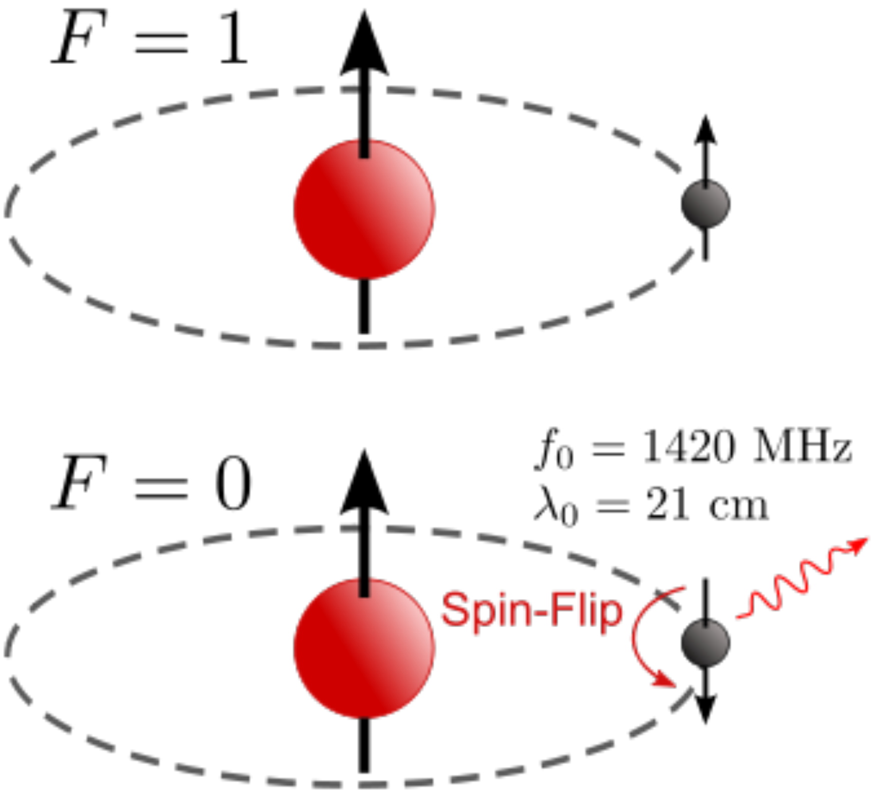
I in HI means atom has all its electrons (only 1 in case of H)



electron in lowest orbit (n=1)

electron and proton have spins in same direction (parallel)

Neutral Hydrogen (HI): λ=21cm spectral line from "spin-flip transition"

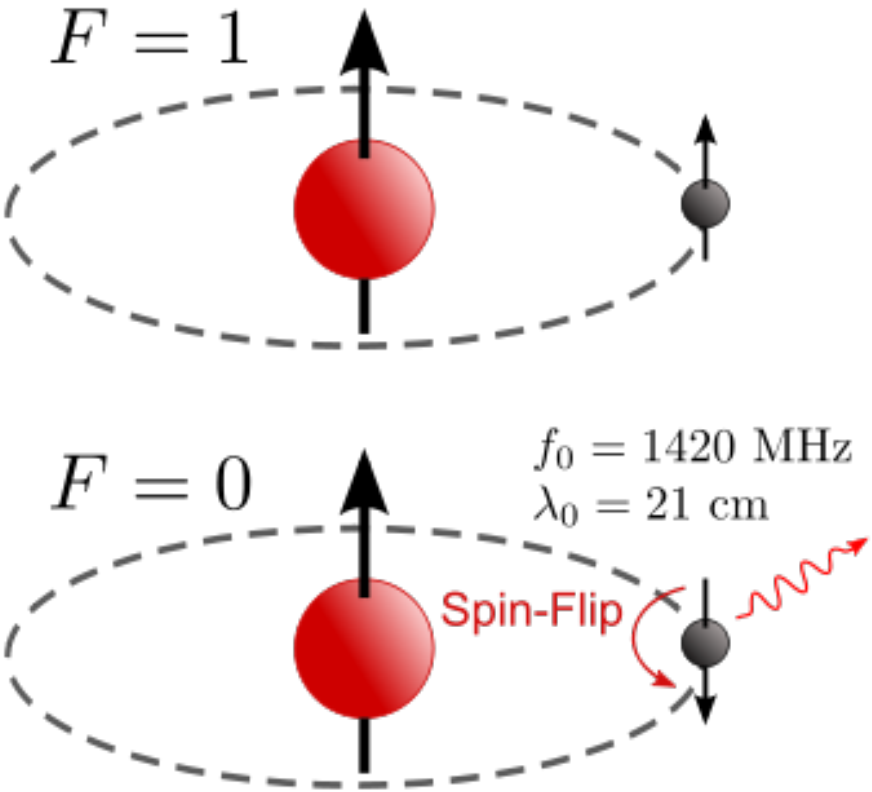


An H atom in upper energy state (parallel spins)

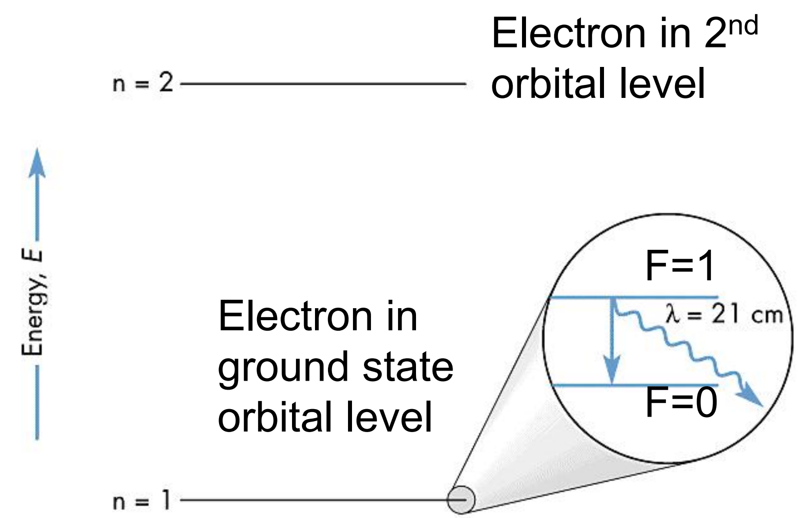
will ***spontaneously*** change to

lower energy state (anti-parallel spins), emitting a photon with λ=21cm in the process

Neutral Hydrogen (HI): λ=21cm spectral line from “spin-flip transition”



Hydrogen energy level diagram



Electron in ground state orbital level is split into 2 hyperfine levels

Why 21cm HI line is important

It is easy to excite upper energy level

- Upper energy level is only $E = 5.9\times10^{-6}$ eV or $T = E/k = 0.07$ K above ground state!

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- Tiny amount of energy required to excite upper state – it is easy to do this with low energy collisions, which happen almost anywhere in universe!

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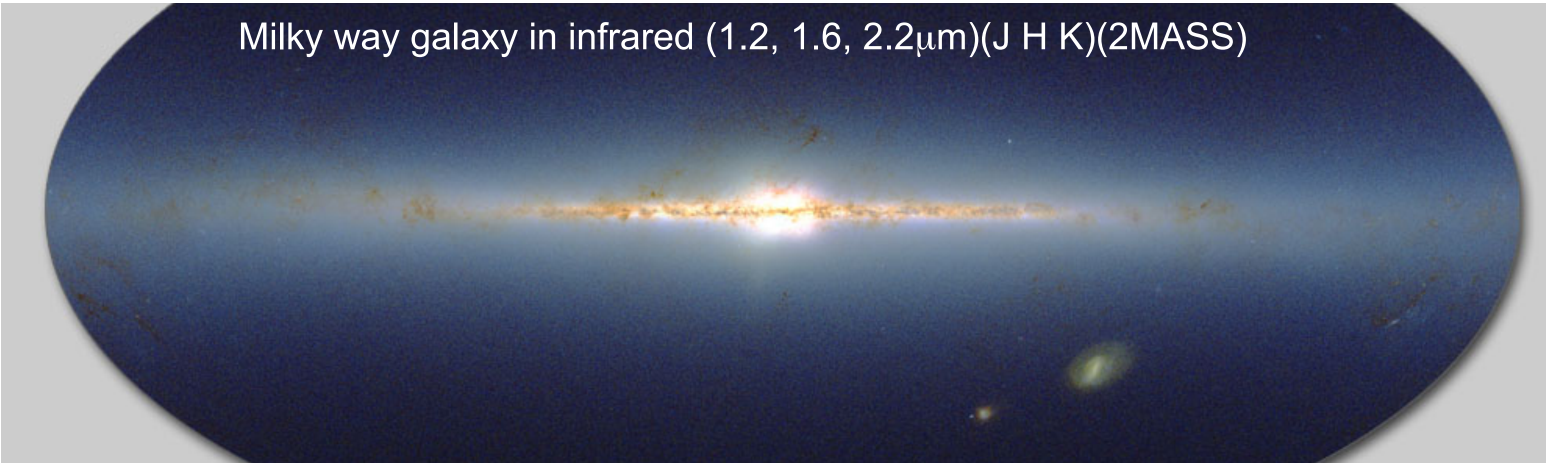
- Upper energy level is only $E = 5.9 \times 10^{-6}$ eV or $T = E/k = 0.07$ K above ground state!
- Tiny amount of energy required to excite upper state – it is easy to do this with low energy collisions, which happen almost anywhere in universe!
- 21cm HI line is excellent probe of neutral hydrogen gas throughout universe

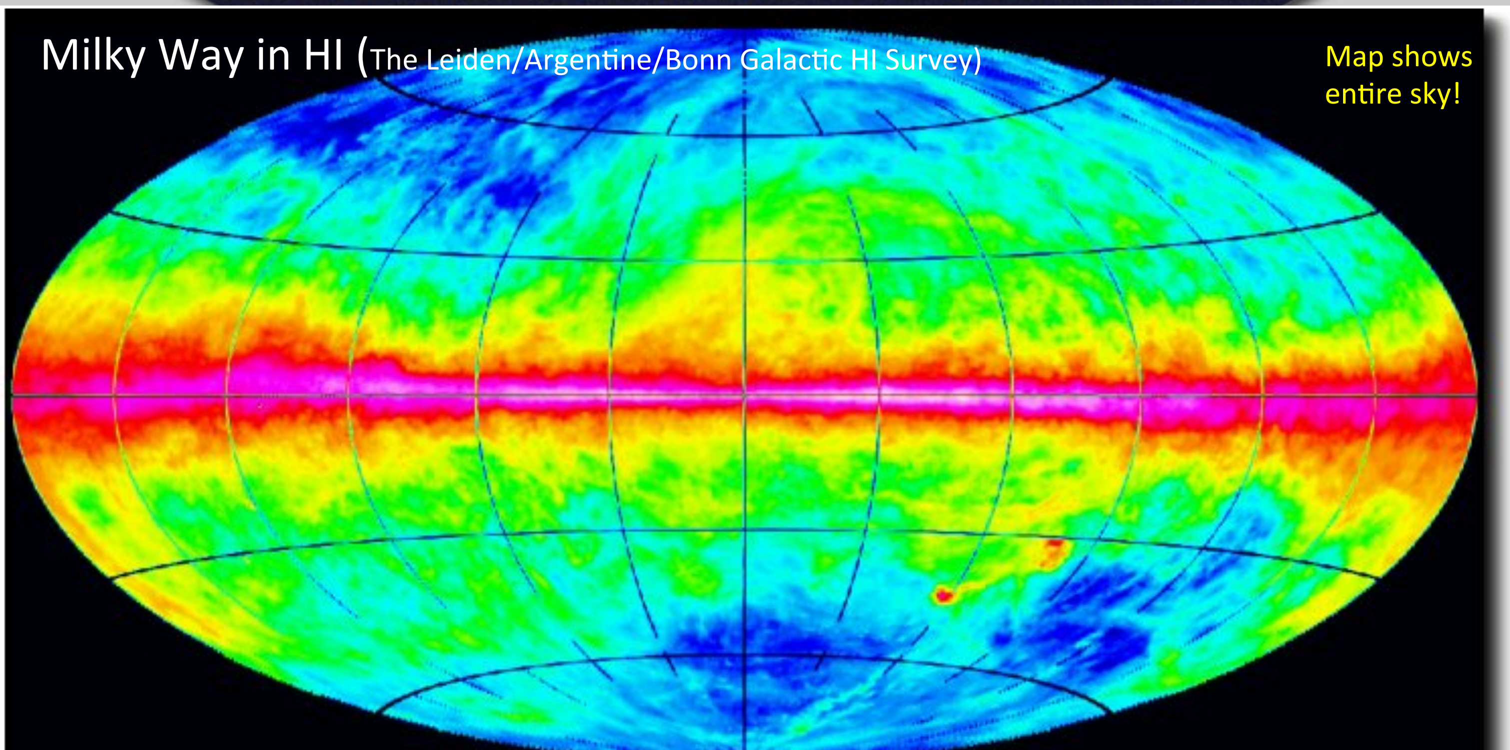
2 most important radio telescopes for HI studies of galaxies

Very Large Array (VLA)
New Mexico, US
27 dishes with 25m diameter
interferometer

Arecibo Telescope
Puerto Rico
305m diameter
Single dish

Milky Way in stars (NIR) and neutral gas (HI)



180°  180°

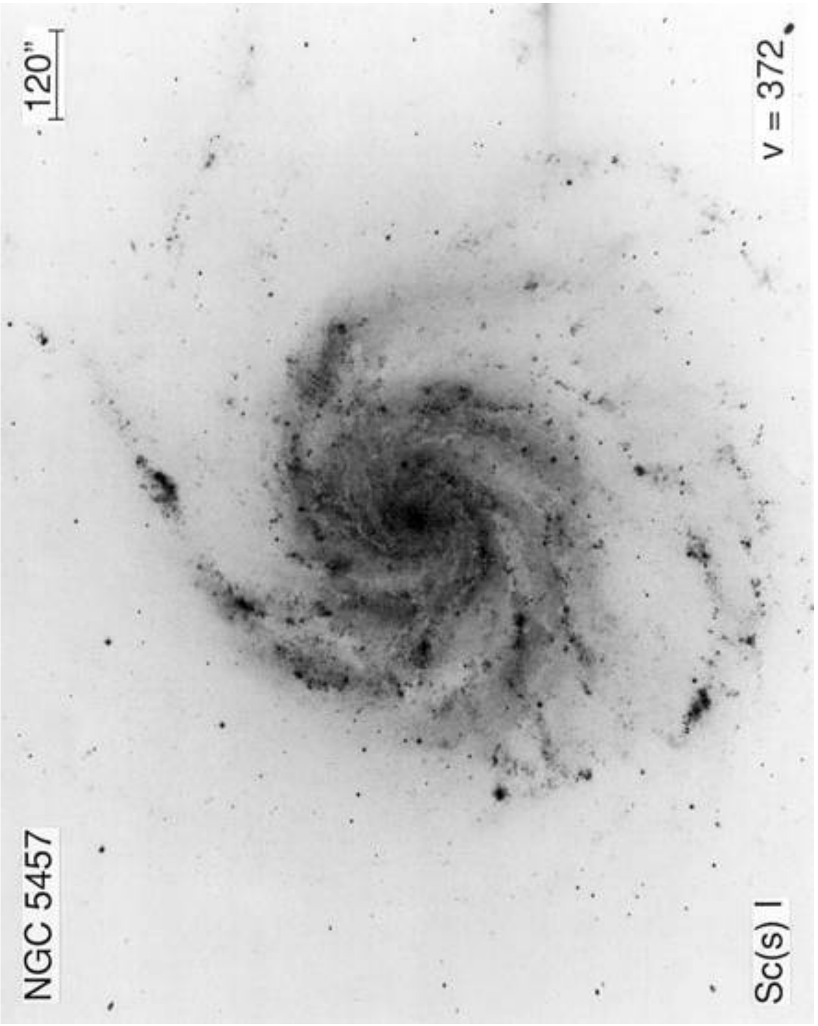
A disk component (not bulge) but some HI clouds extend up into the halo

HI gas is associated with the disk not the bulge

Blue: stars   Red: heated dust (distribution like HI gas)

Sc galaxy M101

“Negative” Optical Image of M101

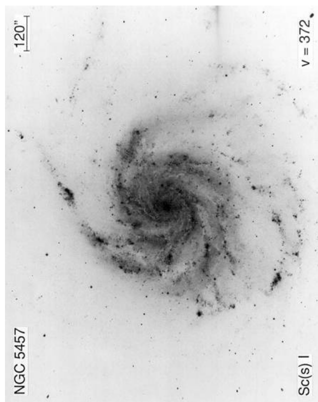


Sandage & Bedke

M101 is one of largest nearby spirals

2 different images of M101 to same scale

Optical starlight In M101



HI gas in M101

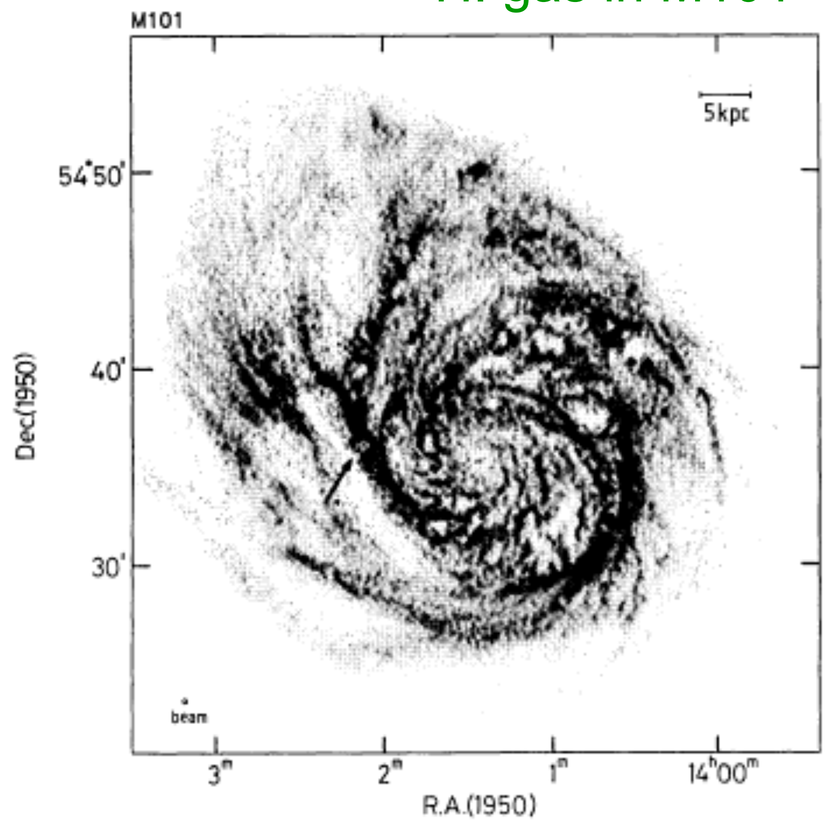


Fig. 1. Grey-scale picture of the total HI column density distribution of M 101. The column densities range from 1 10^{20} (white) to 3.8 10^{21} cm^{-2} (dark). The resolution is 13″×16″ (~ 500 pc). The arrow indicates the position of the superbubble.

Kamphuis etal 1991

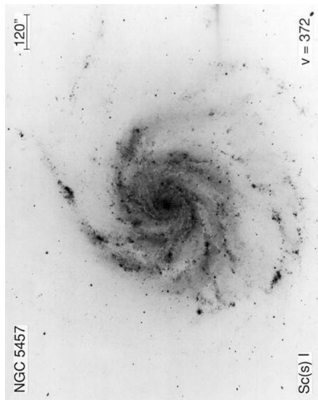
HI gas much more extended than optical starlight

Why are the outer parts of most spiral galaxies gas-rich?

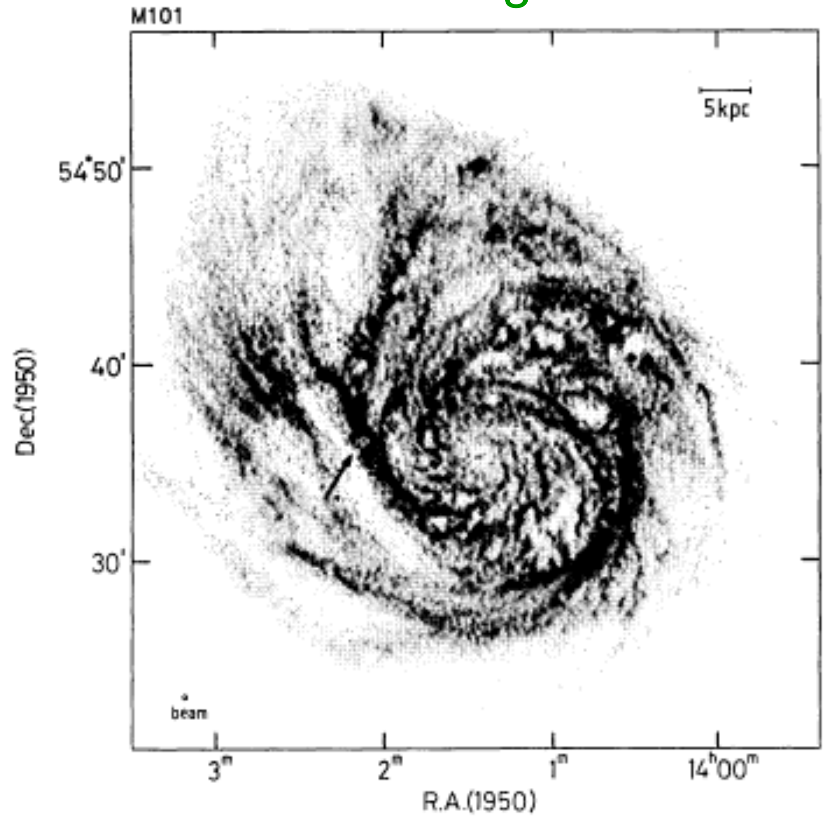
A. Gas is blown outwards by lots of supernovae during starburst phase of evolution
B. Stars don't form so easily in the gas of the outer galaxy
C. The gravitational force on the small gas particles is weak
D. Magnetic fields keep the gas from settling to center
E. Gas is bound to the Dark Matter

2 different images of M101 to same scale

Optical starlight In M101



HI gas in M101



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- HI gas much more extended than optical starlight

-> Gas inefficient in forming stars in outer parts of galaxy because of low gas density

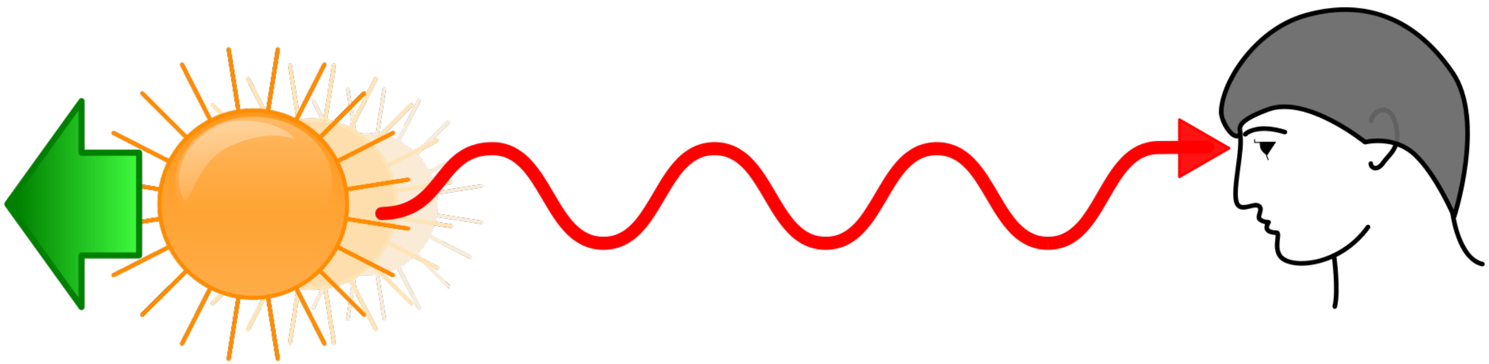
Kamphuis etal 1991

having lots of HI gas in the outer parts of galaxies is great 😃 because it gives us a way to measure the masses of galaxies far from the center…

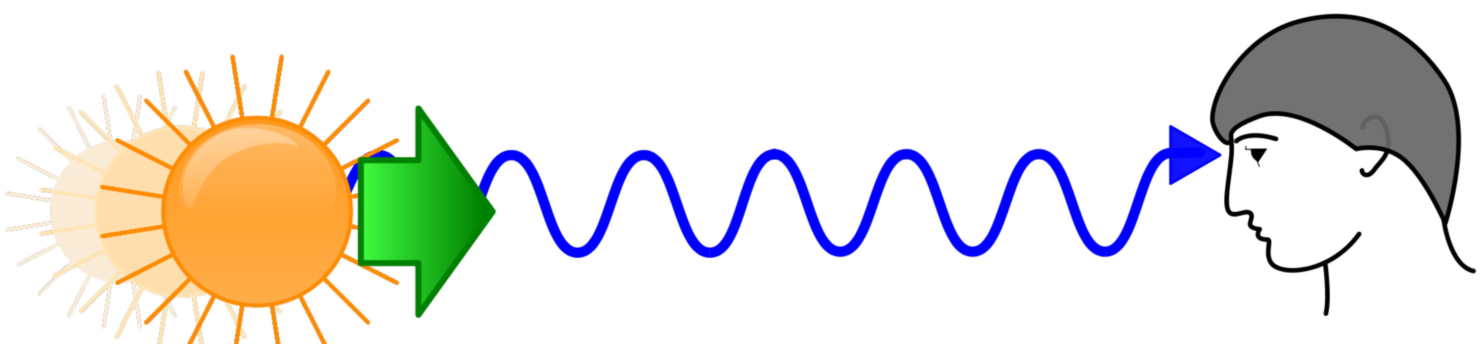
by ***measuring the Doppler shift of the HI emission line at 21cm*** .. with radio telescope → ***provides evidence for Dark Matter!***

Doppler shift

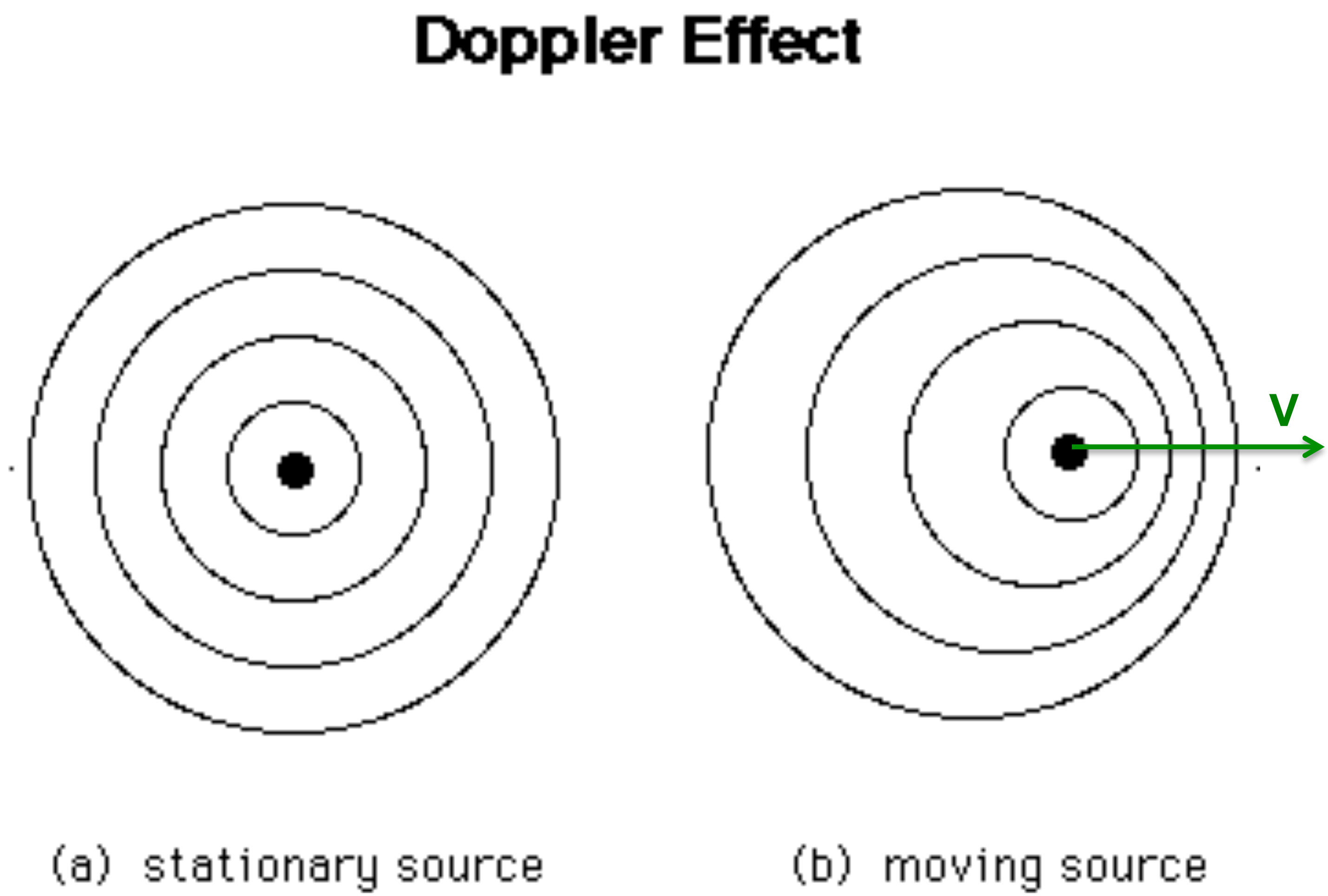
Apparent change in wavelength (and frequency) of wave due to relative motion between source & observer



redshifted photon from star moving away from observer

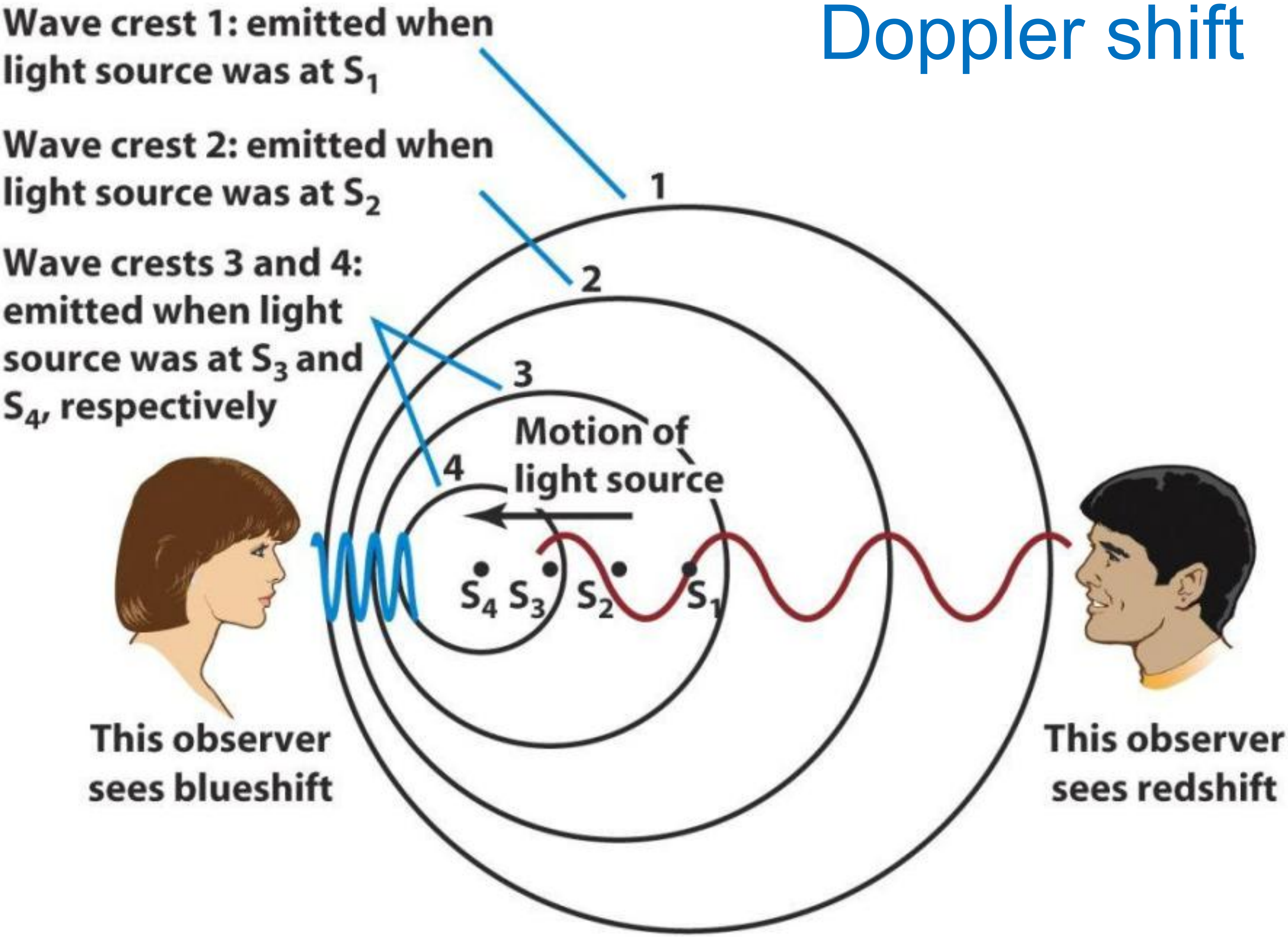


blueshifted photon from star moving toward observer

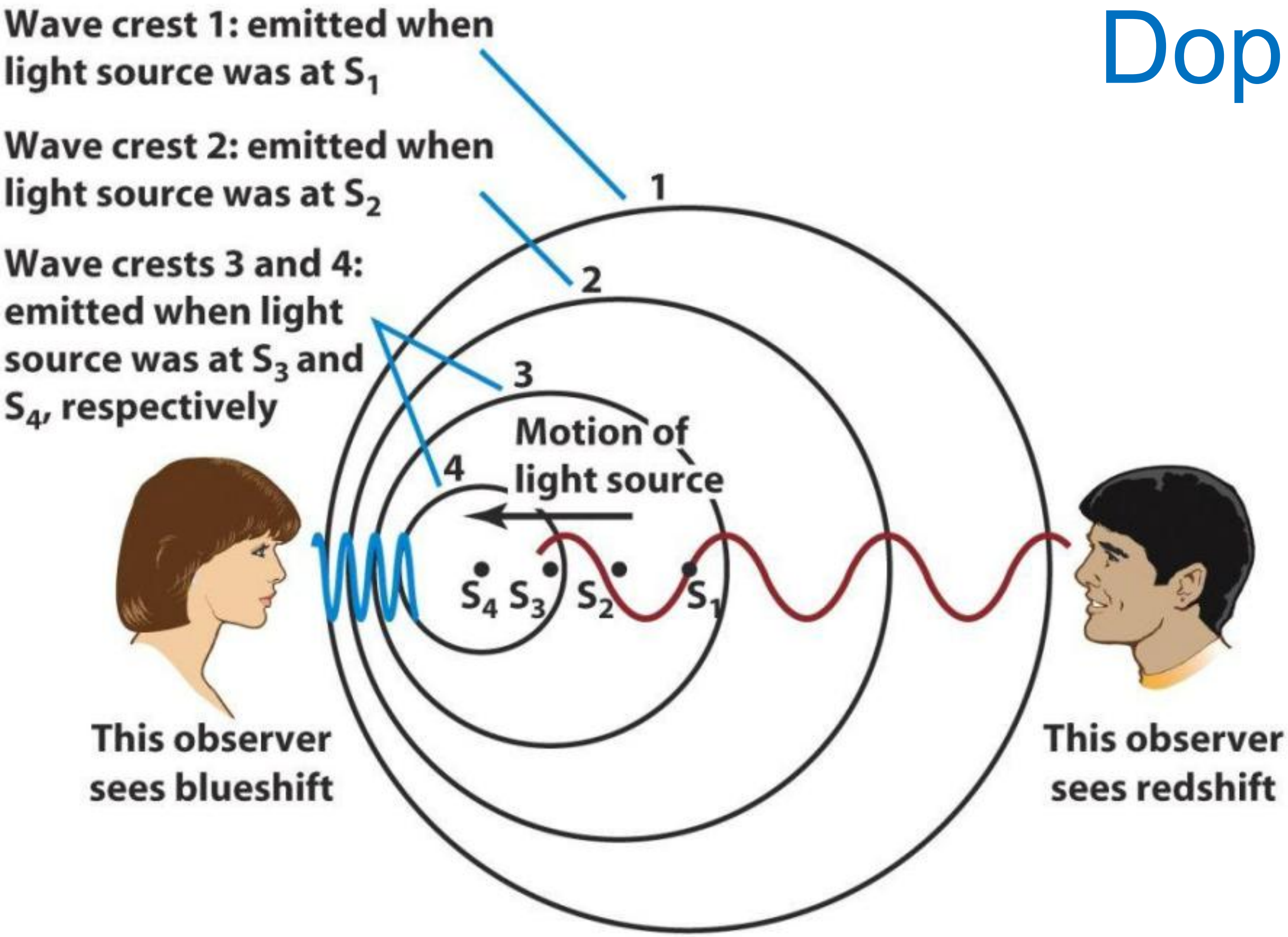


wavecrests for stationary & moving sources

Doppler shift



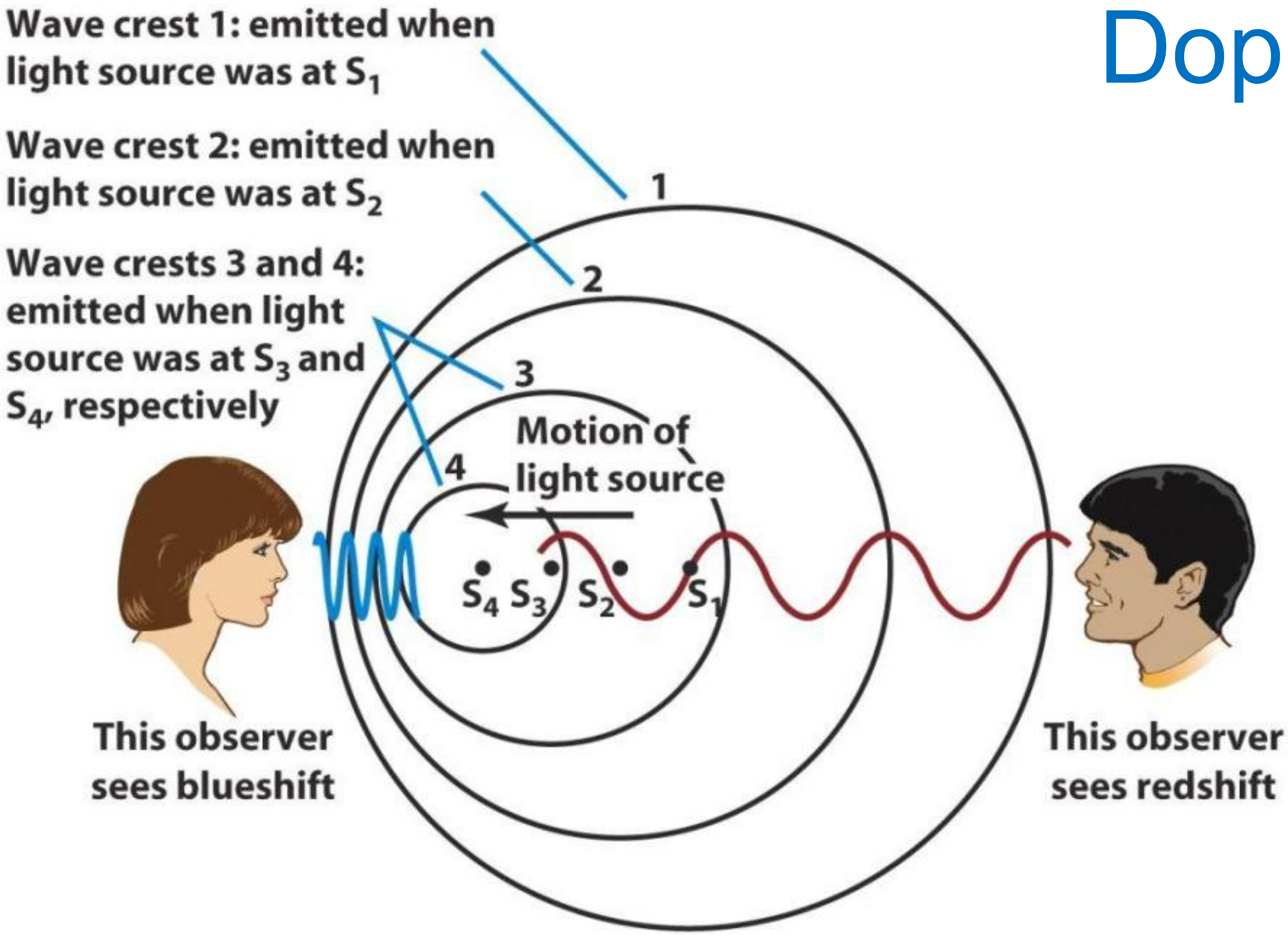
Doppler shift



Motion along line-of-sight toward observer (v<0) causes blueshift ($\lambda<\lambda_o$)

Wavecrests ***squashed together*** so wavelengths shorter

Doppler shift



Motion along line-of-sight away from observer ($v>0$) causes redshift ($\lambda>\lambda_o$)

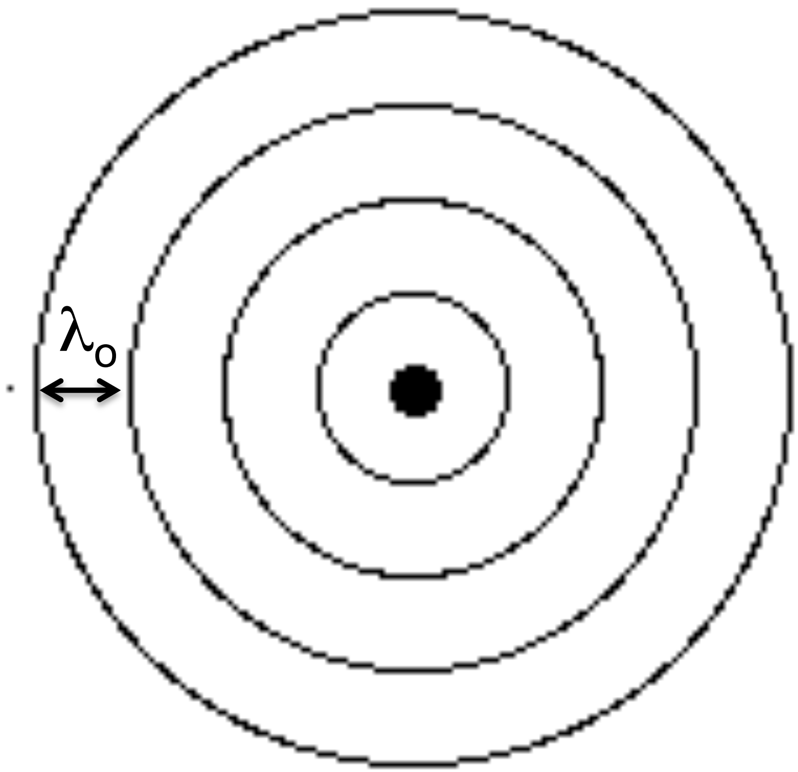
Wavecrests ***stretched out*** so wavelengths are longer

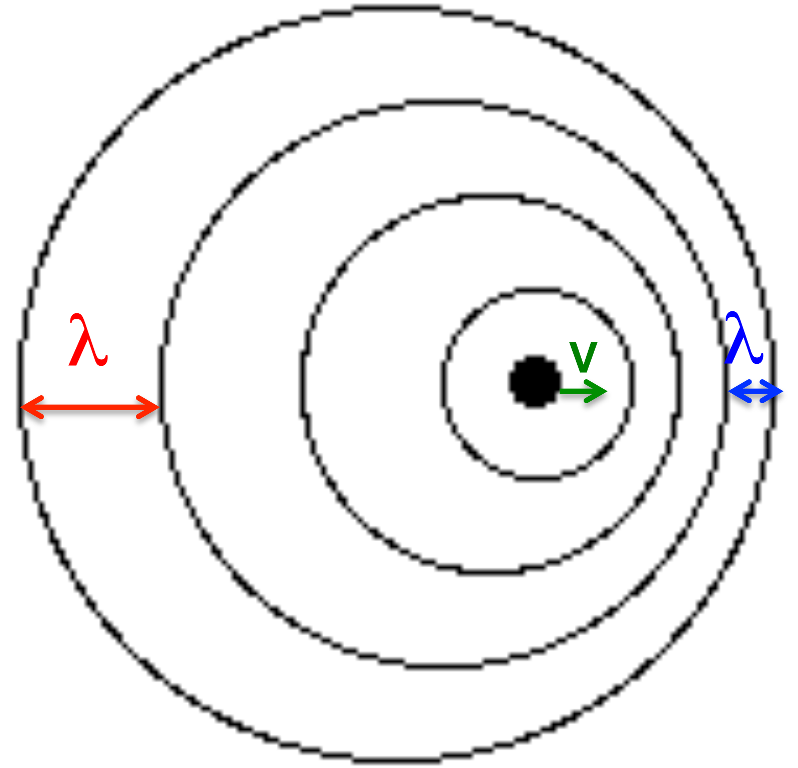
Doppler shifts

redshifted wavelength λ for source moving **away**

blueshifted wavelength λ for source moving **toward**

wavelength λ_o for stationary source





$$(\lambda - \lambda_o) / \lambda_o = \Delta\lambda / \lambda_o = v/c$$

doppler shift for light

convention: away is positive v, toward is negative v

3 things which cause λ of light to shift:

Doppler shift, Cosmological redshift, Gravitational redshift

In general shift defined by z:

$$z = (\lambda - \lambda_o) / \lambda_o = \Delta\lambda / \lambda_o$$

λ_o = rest wavelength

λ = detected wavelength

$$\lambda / \lambda_o = (1+z)$$

e.g., if $\lambda = \lambda_o$, $\Delta\lambda = 0$, $z = 0$ no shift

for Doppler shifts:

$$z = \Delta\lambda / \lambda_o = v / c \quad \text{(for } v \ll c\text{)}$$

Jen is stopped for going through a red light in her Hummer. She tells the cop that the Doppler effect caused the red light to appear green.
How fast would she need to be going?

A. 200 mph
B. 100 km/sec
C. 1% of speed of light
D. 33% of speed of light
E. 99% of speed of light

why can you ***hear*** the Doppler shift of the moving buzzer, but not ***see*** it?

doppler shift for sound

$\Delta\lambda/\lambda = v/v_s$ v_s=340 m/s

speed of sound

doppler shift for light

$\Delta\lambda/\lambda = v/c$ $c=3.00\times10^8$ m/s

speed of light

For doppler buzzer, v ~3 m/s

doppler shift for sound

$\Delta\lambda/\lambda = v/v_s = (3 \text{ m/s})/(340 \text{ m/s}) = 10^{-2}$

doppler shift for light

$\Delta\lambda/\lambda = v/c = (3 \text{ m/s})/(3.00\text{x}10^{8} \text{ m/s}) = 10^{-8}$

For doppler buzzer, v ~3 m/s

doppler shift for sound

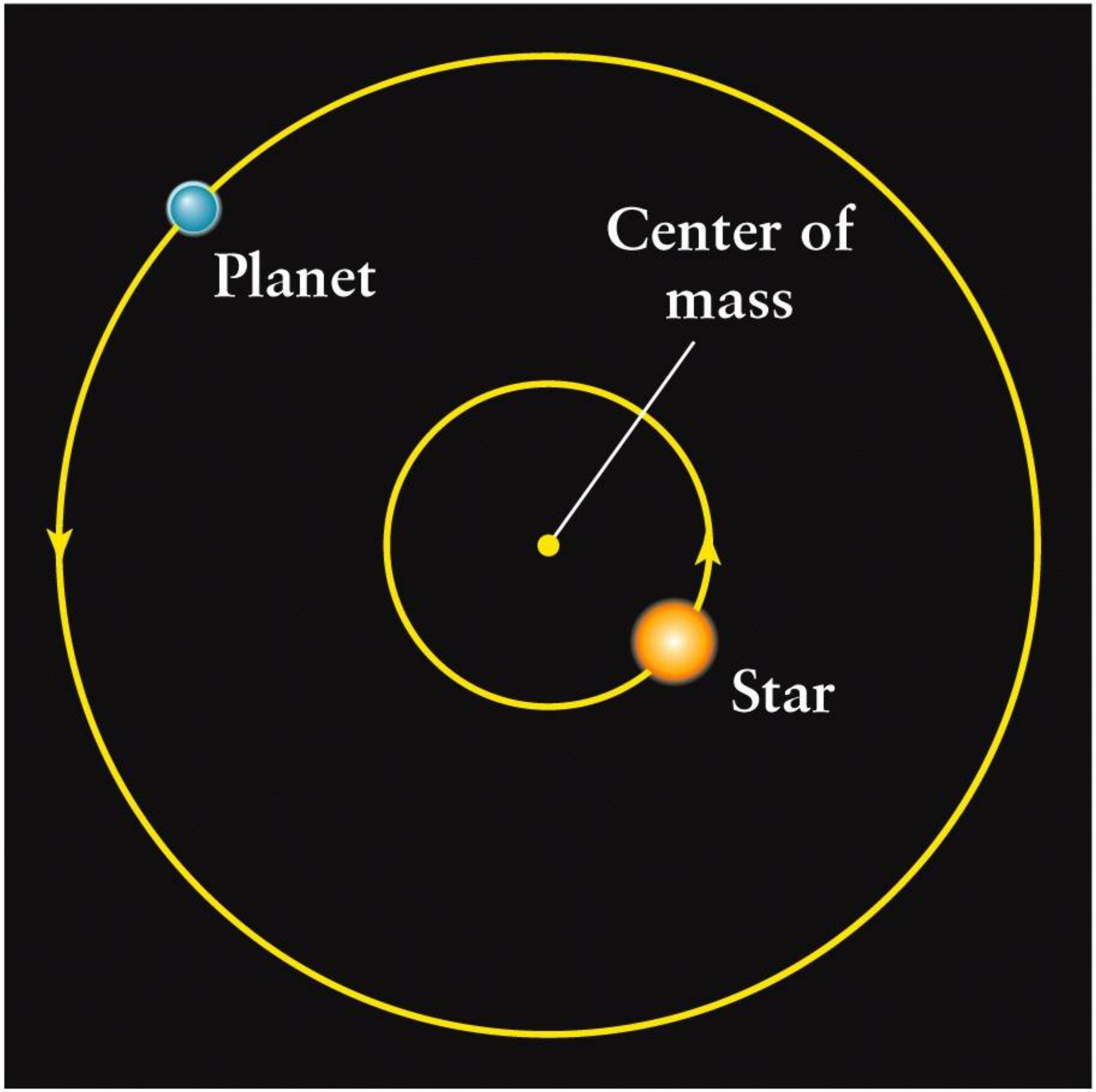
$\Delta\lambda/\lambda = v/v_s = (3 m/s)/(340 m/s) = 10^{-2}$

We can hear a pitch change of 1% !!

doppler shift for light

$\Delta\lambda/\lambda = v/c = (3 m/s)/(3.00 x 10^{8} m/s) = 10^{-8}$

We can't see such a small change in the wavelength of light (but sensitive instruments can detect)



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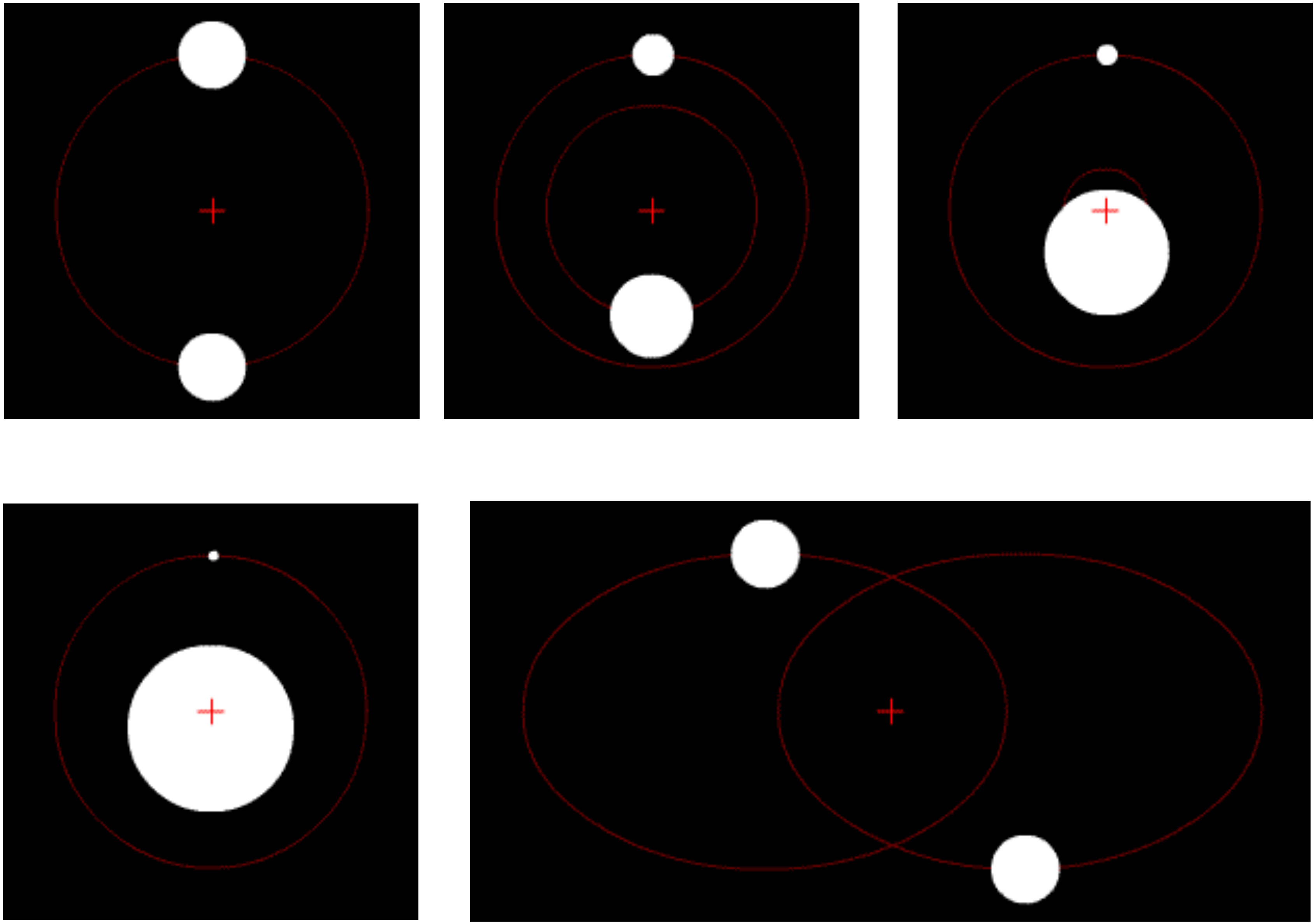
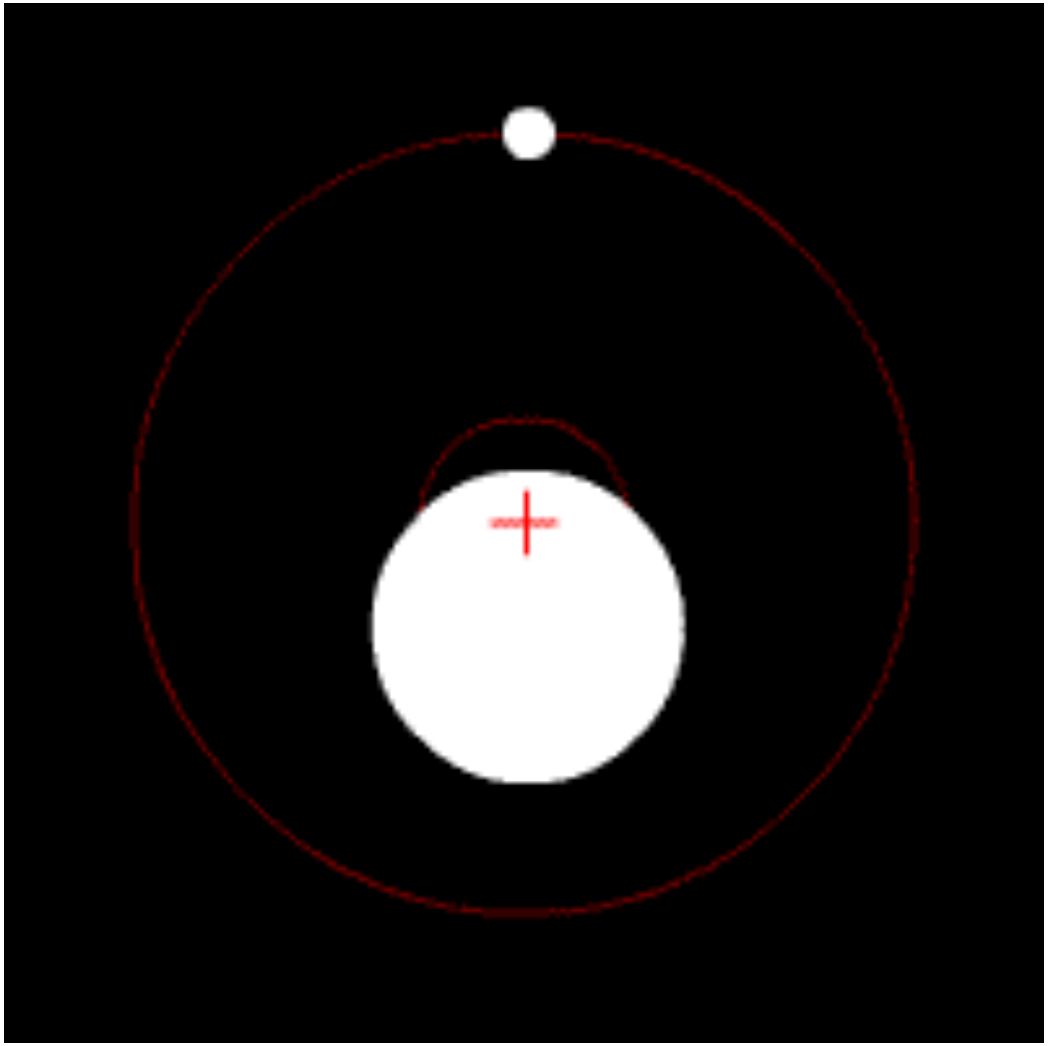
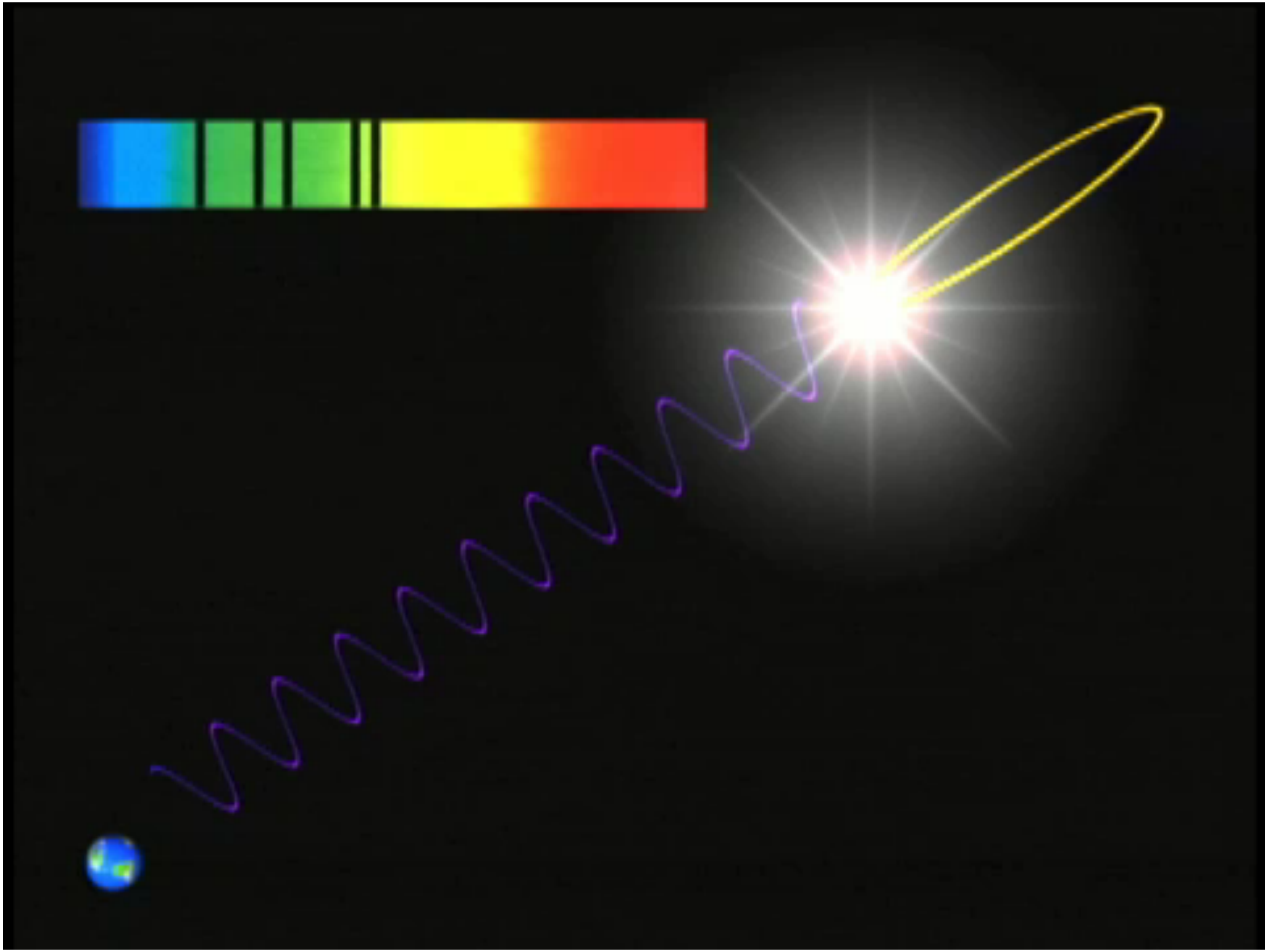
Star and planet both orbit around center of mass

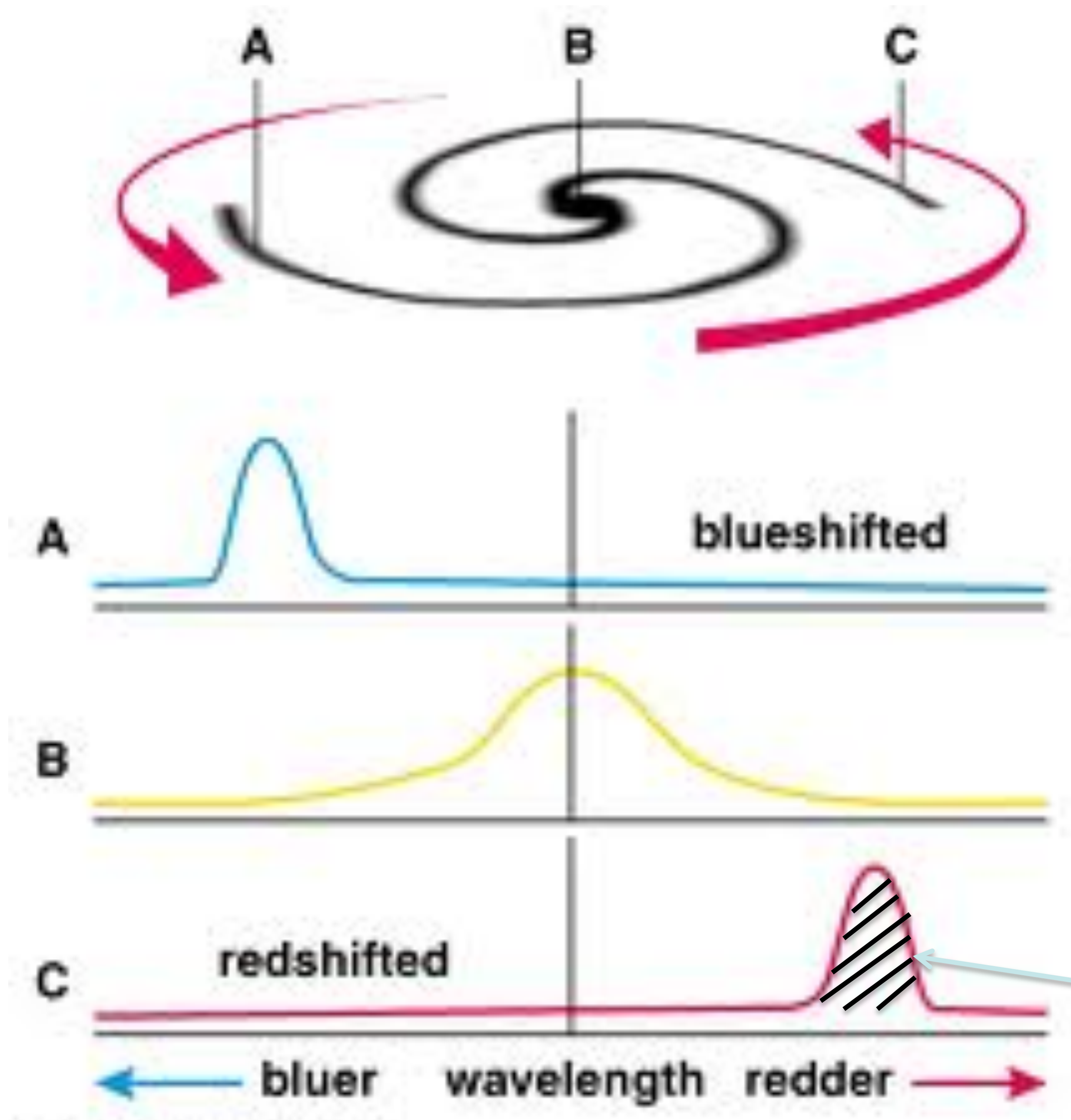


Planet and star orbiting center of mass

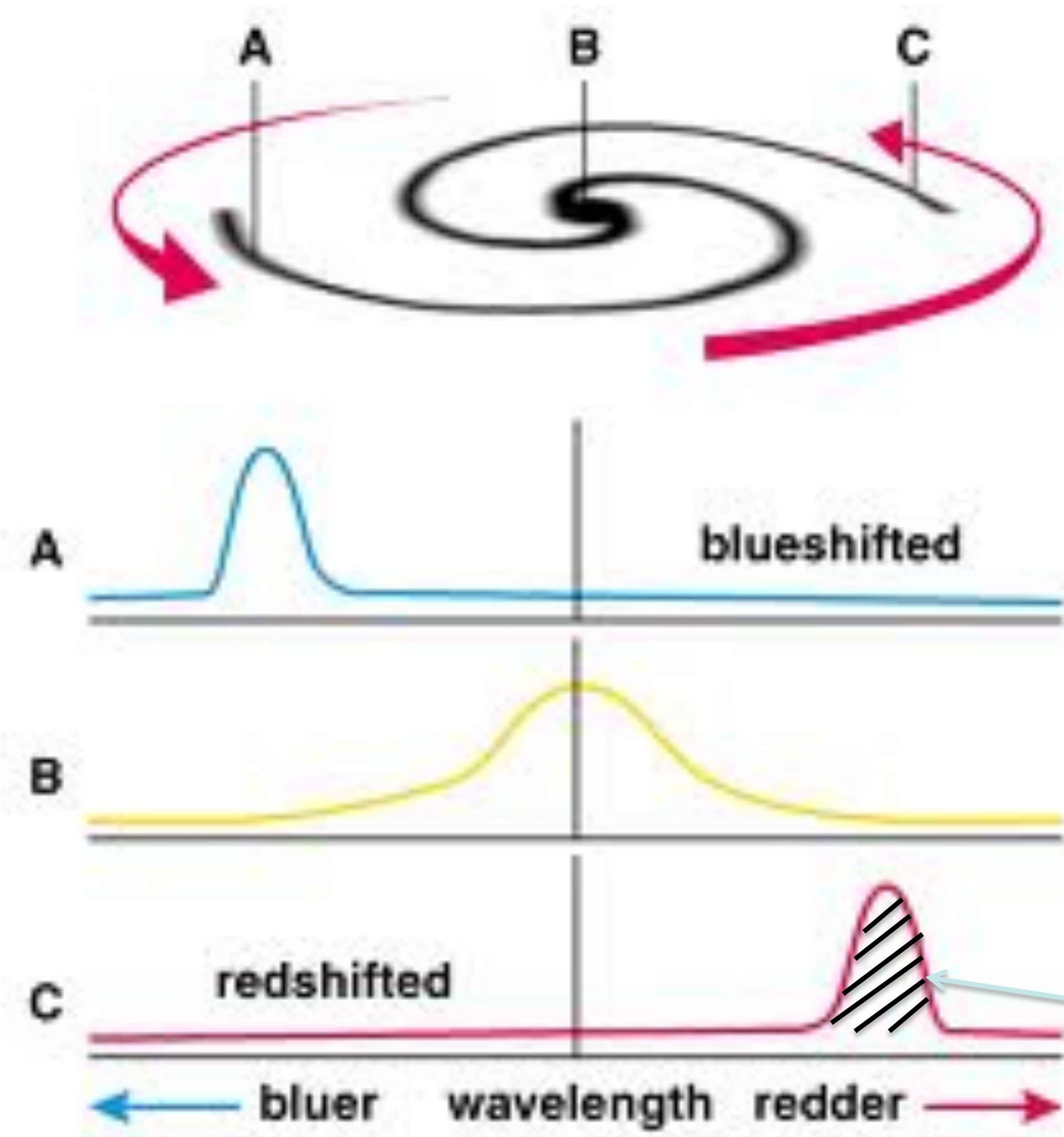


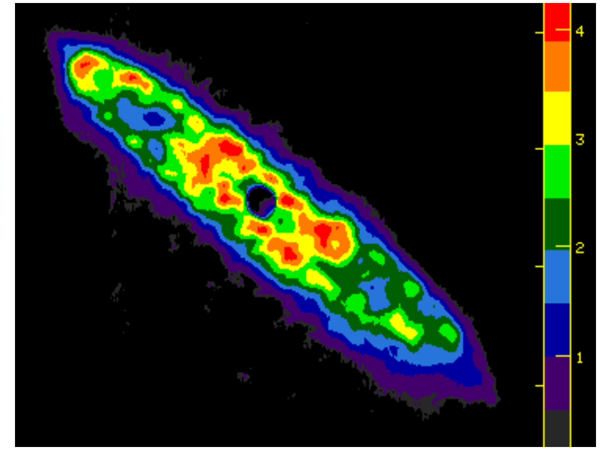
Center of mass can be inside one of the bodies!





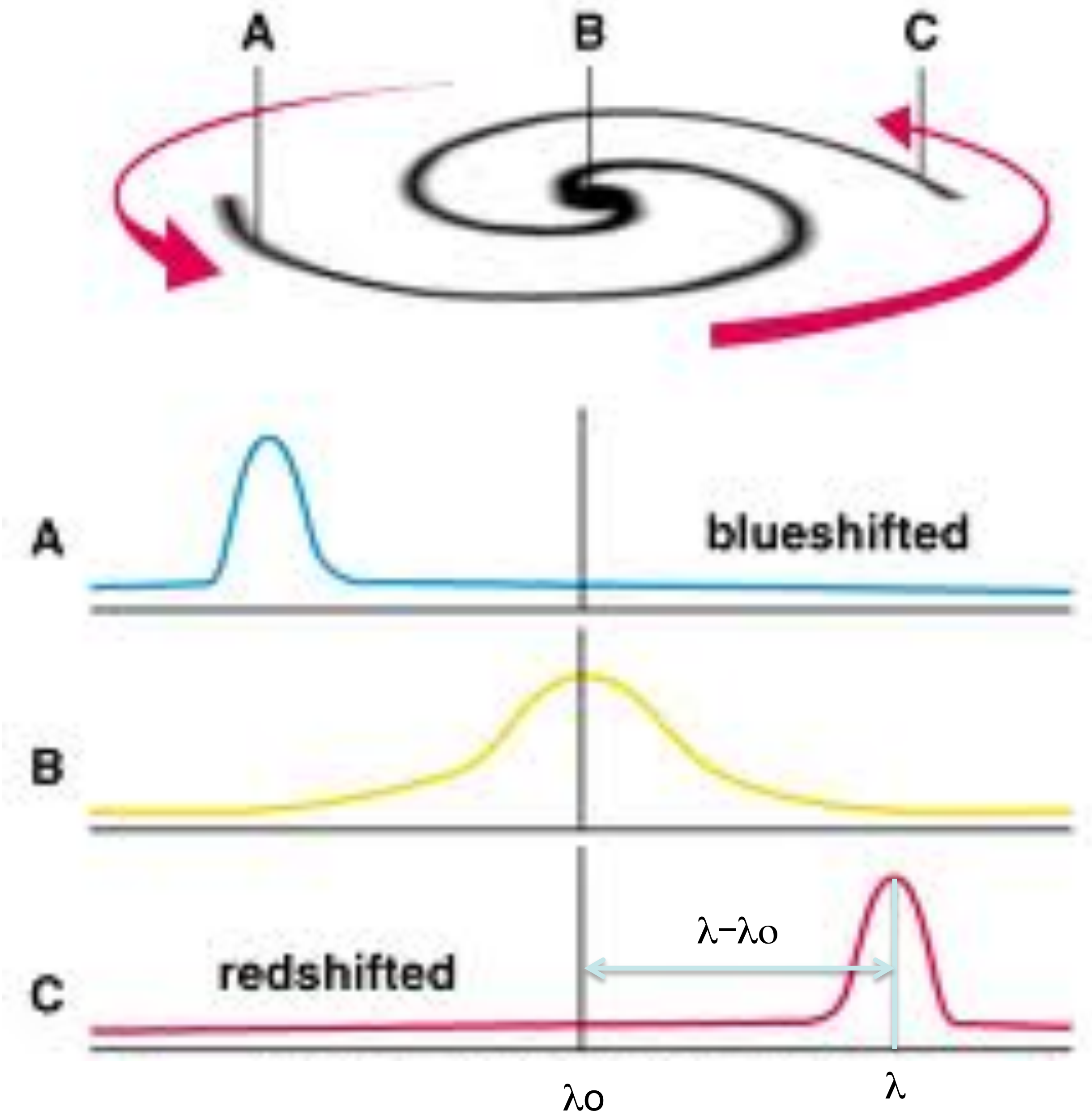
Line intensity (flux) gives
HI mass per area (surface density)



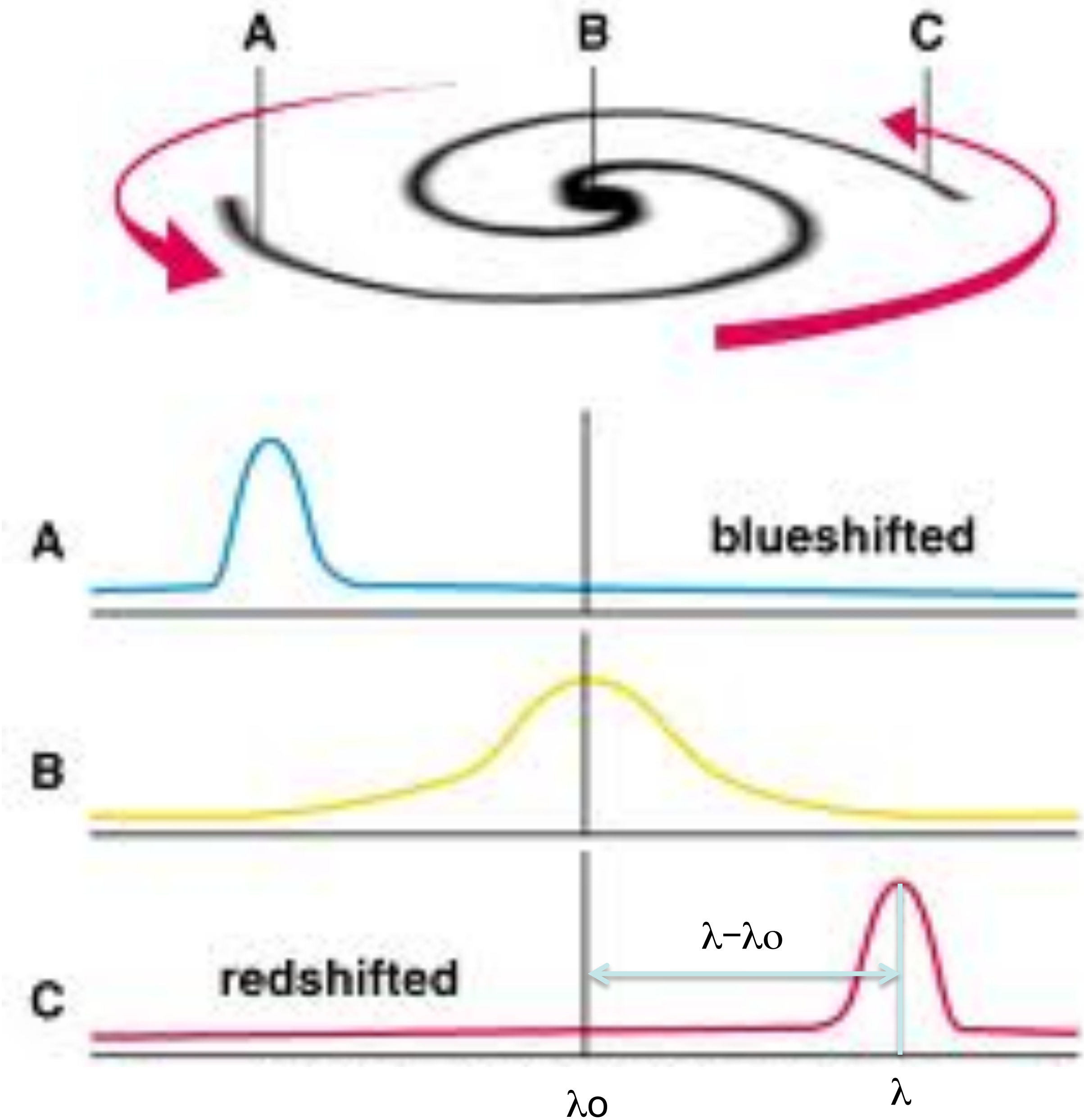


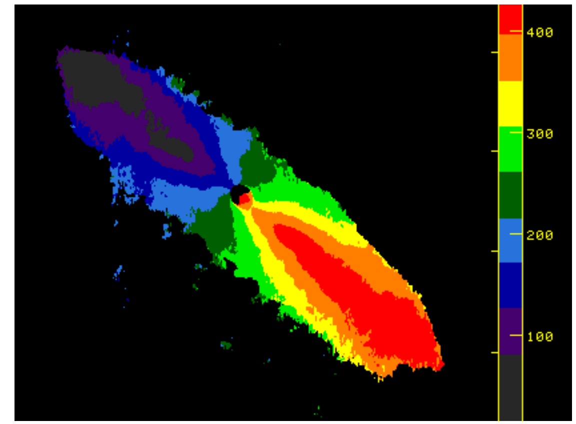
HI surface density map of spiral galaxy NGC 2903 (color → intensity = amount of HI gas)

Line intensity (flux) gives HI mass per area (surface density)



Wavelength shift gives velocity by Doppler shift
$(\lambda - \lambda_o)/\lambda_o = v/c$

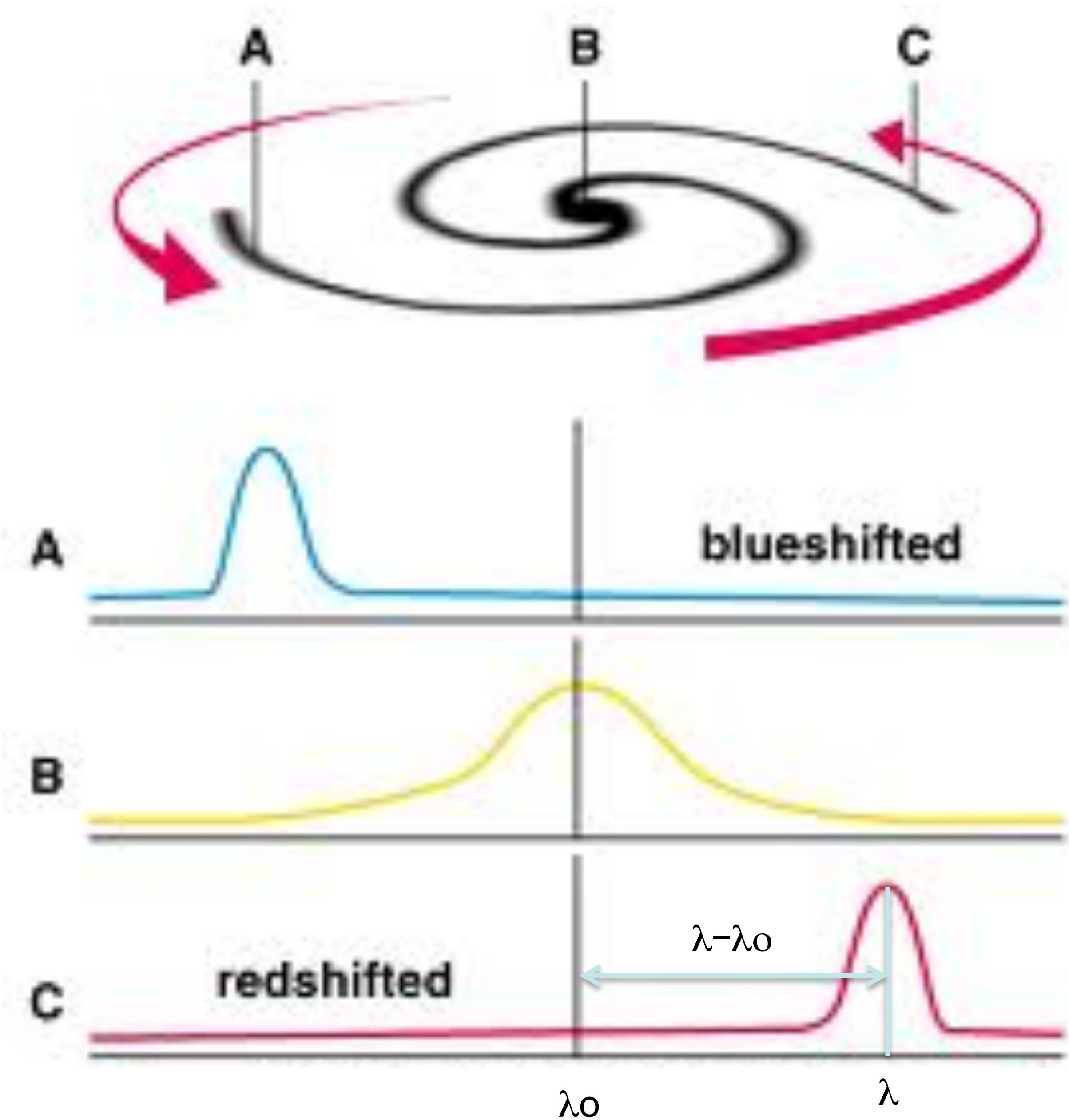


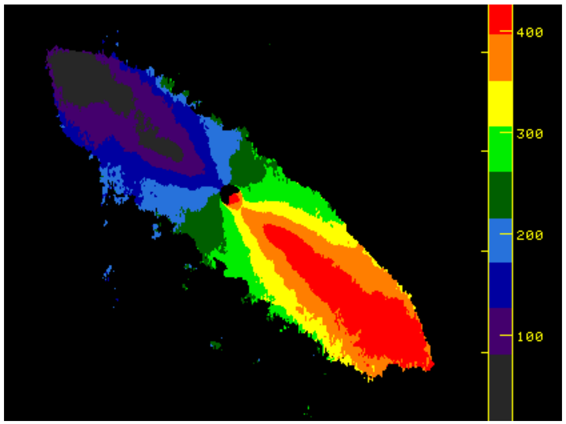


HI velocity map of
spiral galaxy NGC 2903
Color= velocity of HI gas

Wavelength shift gives velocity by Doppler shift

$$(\lambda - \lambda_o)/\lambda_o = v/c$$





HI velocity map of
spiral galaxy NGC 2903
Color= velocity of HI gas

Wavelength shift gives velocity by Doppler shift

$$(\lambda - \lambda_o)/\lambda_o = v/c$$

and these velocities provide evidence for Dark Matter in galaxies !