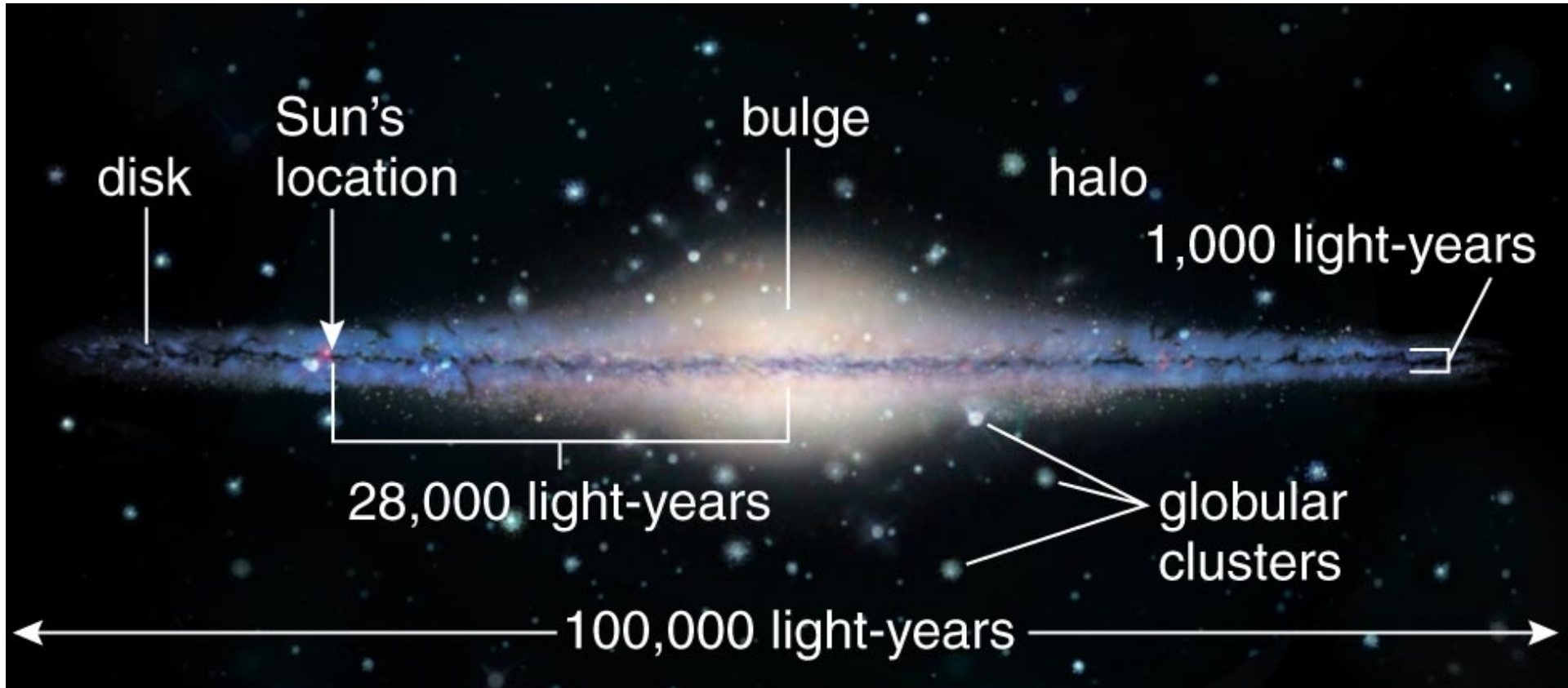
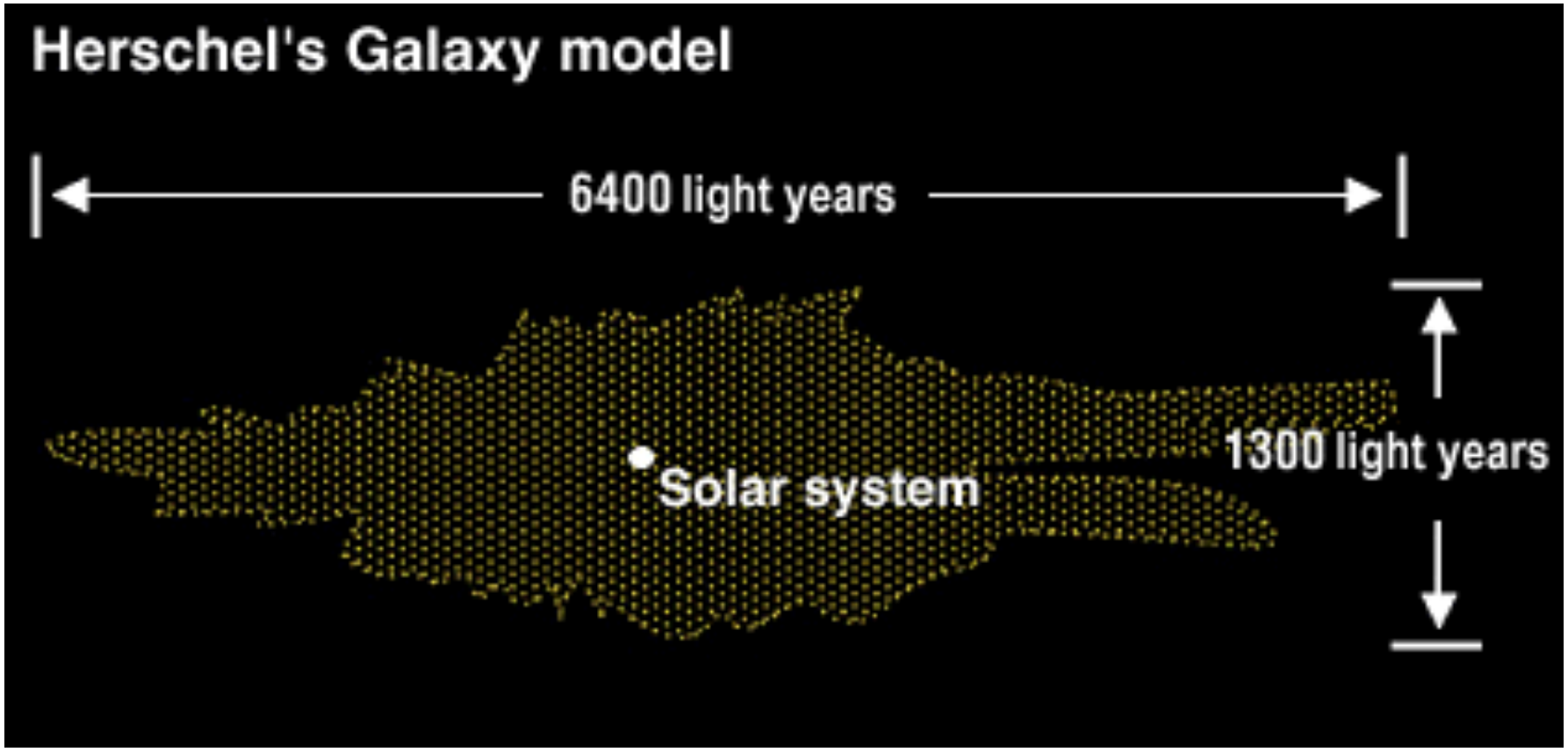
Face On and Edge On Views of **Milky Way Galaxy**

- **Galactic Disk**: 1000ly thick&100,000ly dia
- **Galactic Bulge** ~3000 ly thick; 6X18,000 ly=elongated bar
- **Galactic Halo** is ~300,000 ly diameter sphere of faint stars



Herschel's Star Counts

- ~1800 William and Caroline counted stars
- Found there were many more stars in the plane
- Grindstone model

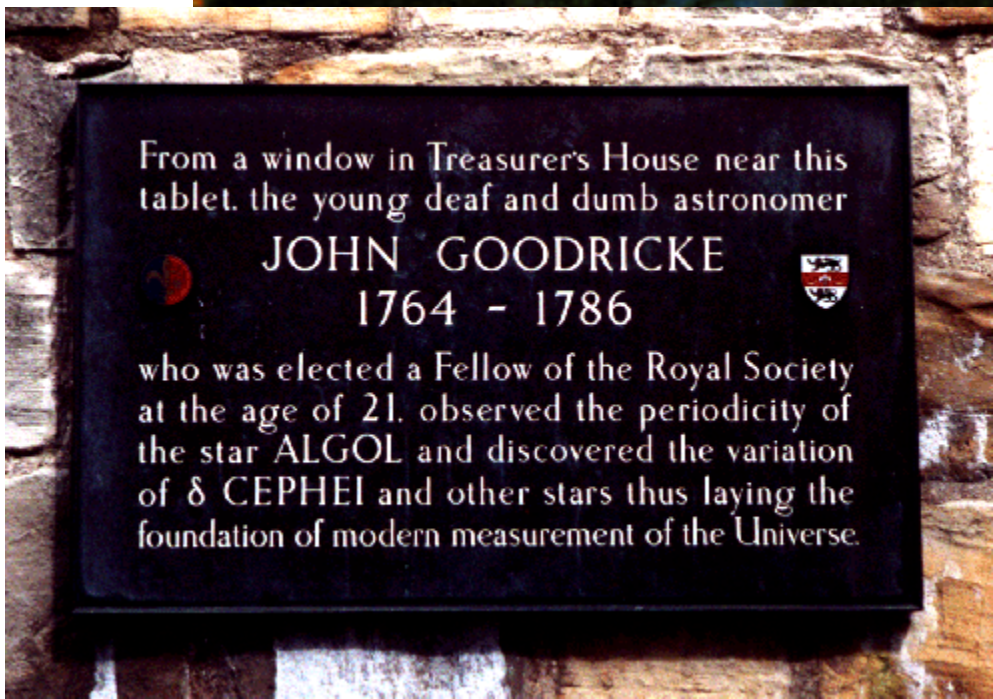


Milky Way Galaxy

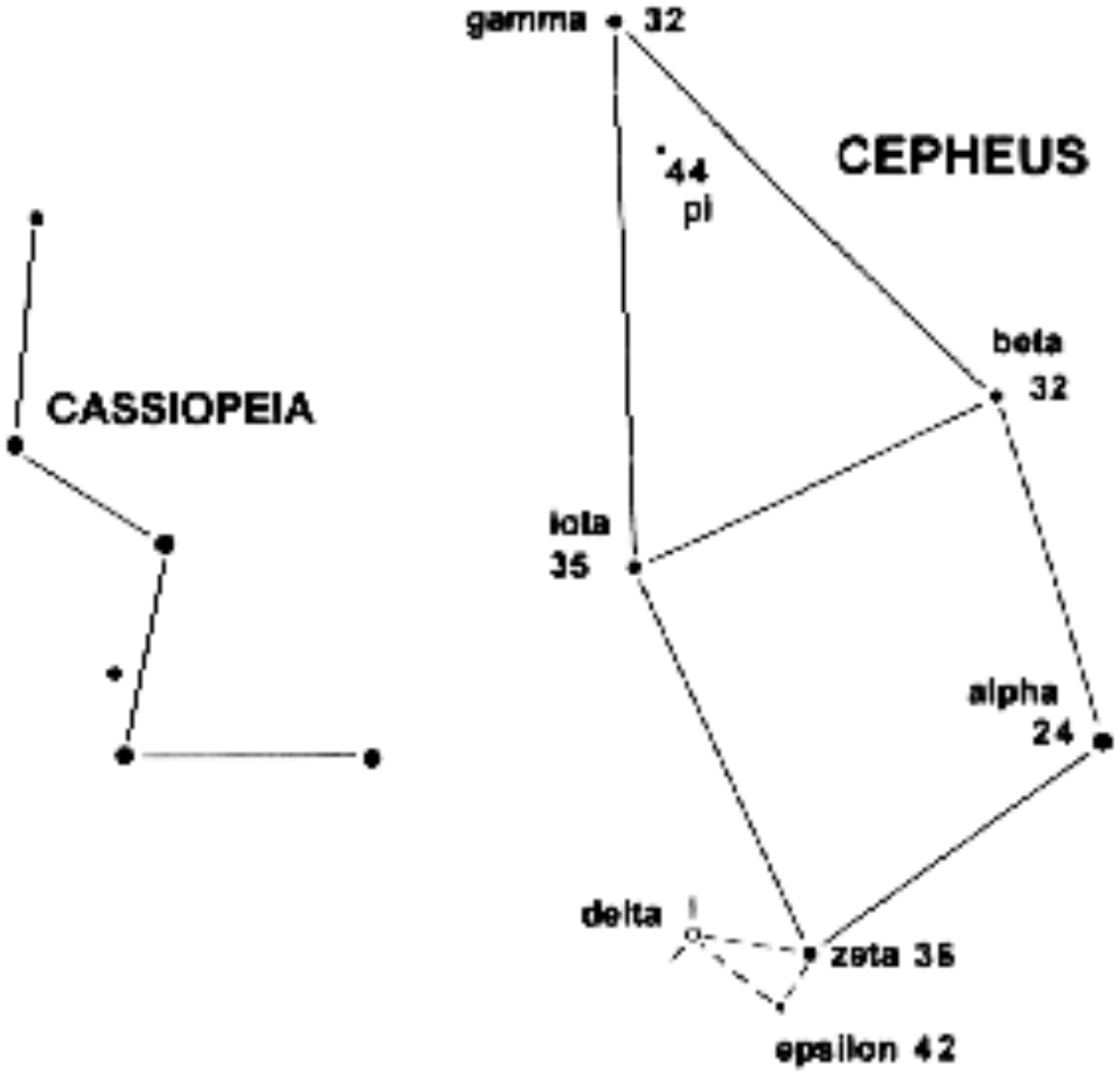
- Centre of Milky Way from VLT in Chile
- Dust clouds ruin star counts

John Goodricke

- Deaf Mute – 19 years old
- Discovered first variable star = Delta Cephei in 1784
- Variable Stars Change in brightness due to pulsations or flares or spots or eclipses



δ Cephei Star Chart

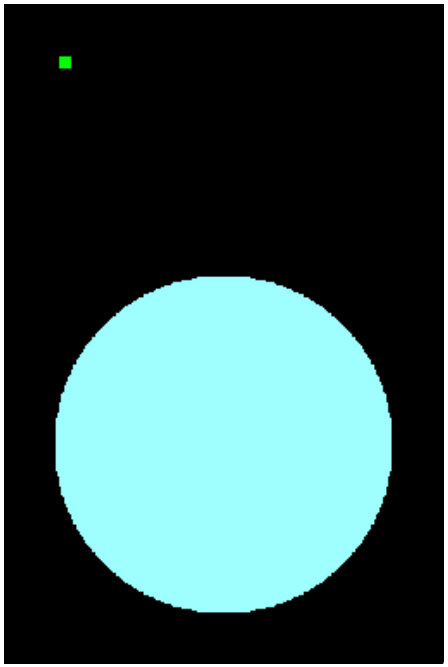


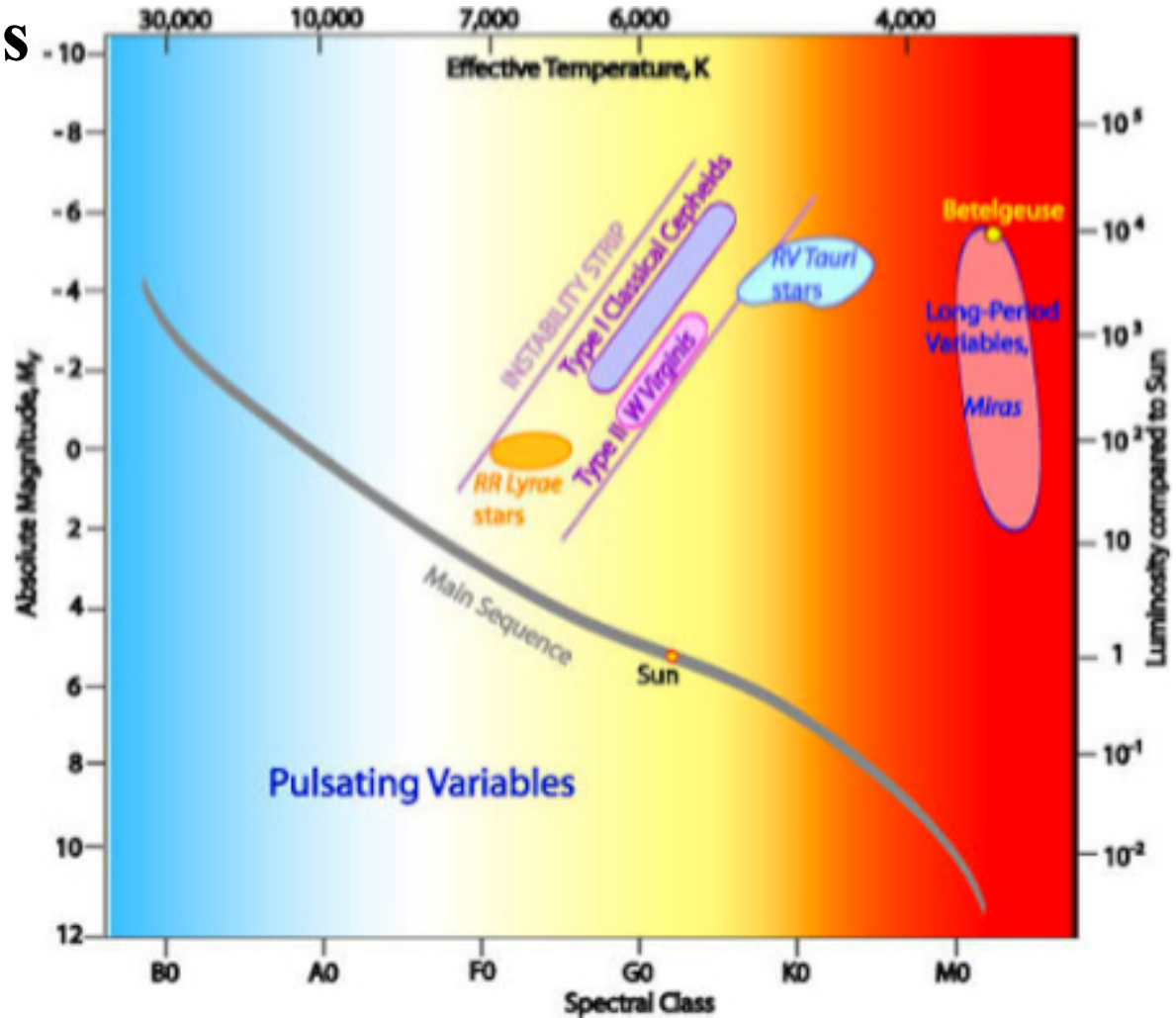
Henrietta Leavitt 1868-1921

- Harvard College 1902
- Discovered 2400 variable stars
- Discovered by observing Cepheids in Magellanic clouds
- Size of Galaxy and Size of Universe

Pulsating Variable Stars

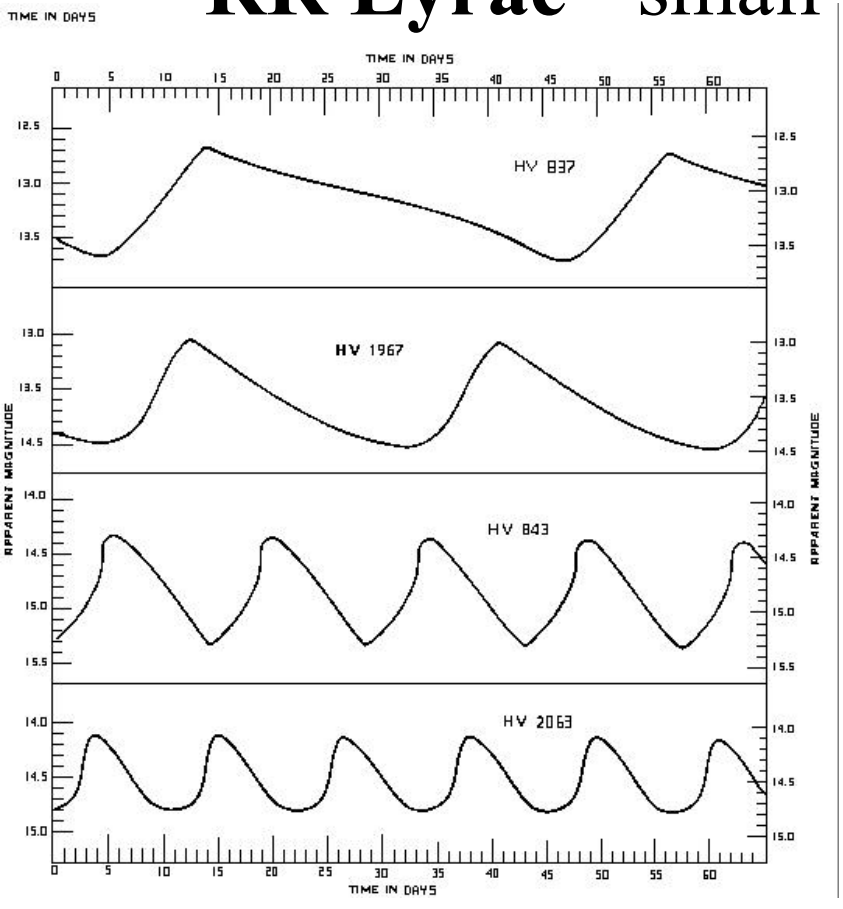
- At some temperatures/pressures stars become unstable to pulsation = **Instability Strip**
- **RRLyr & Cepheids**

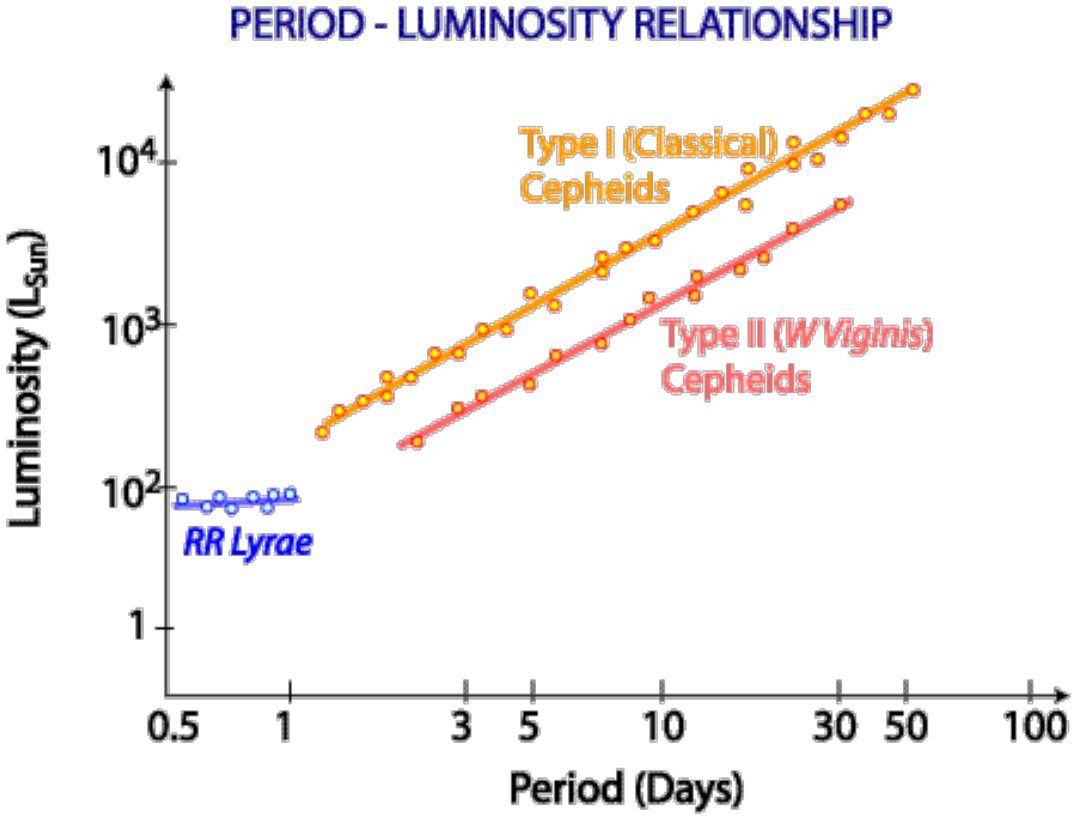




Period-Luminosity Relationship

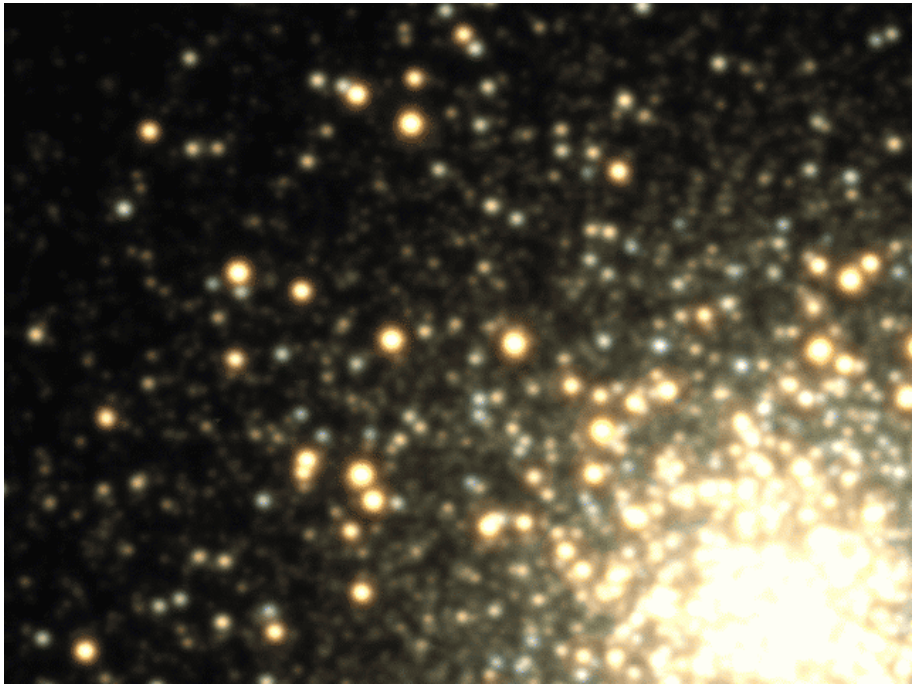
- The bigger the star the slower it pulsates
- The bigger the star the brighter it is
- **RR Lyrae** =small & **Cepheids** =Large

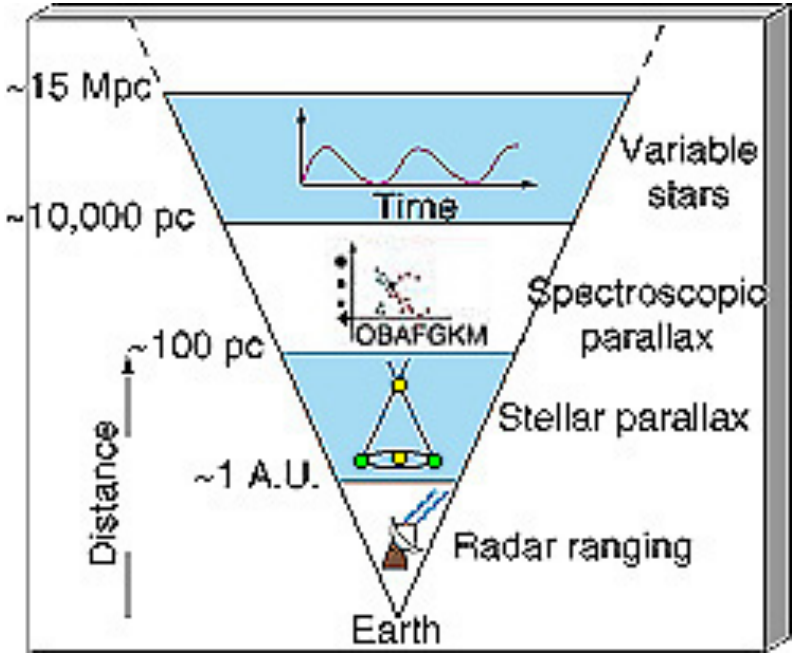




Distance Indicators

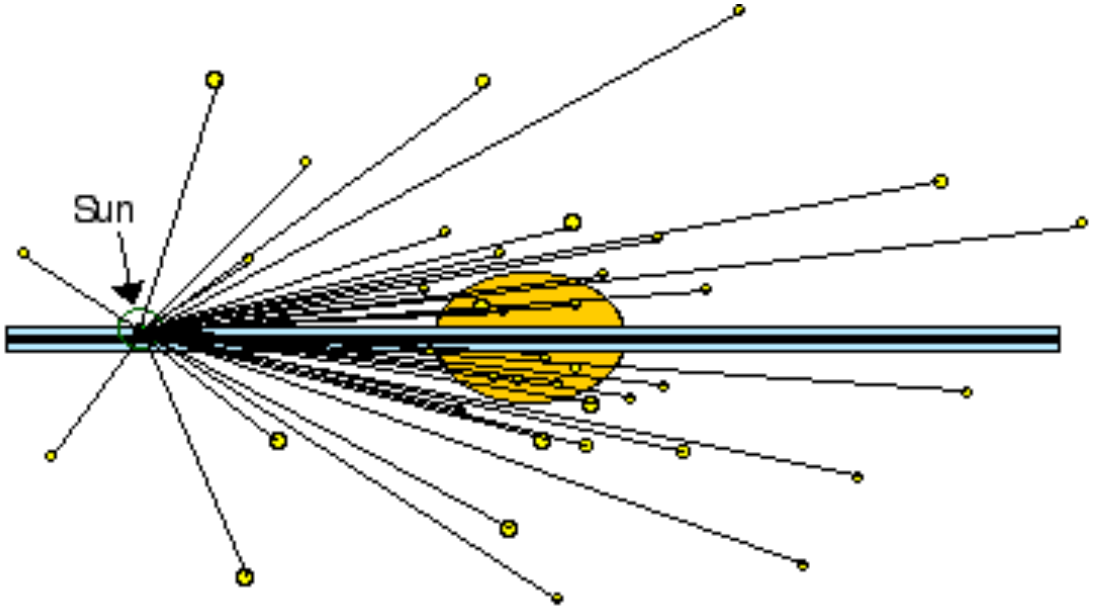
- **RR Lyrae** pulsating on horizontal branch in instability strip
- Have known absolute magnitude = Luminosity
- Are found in globular clusters - give distances to globulars



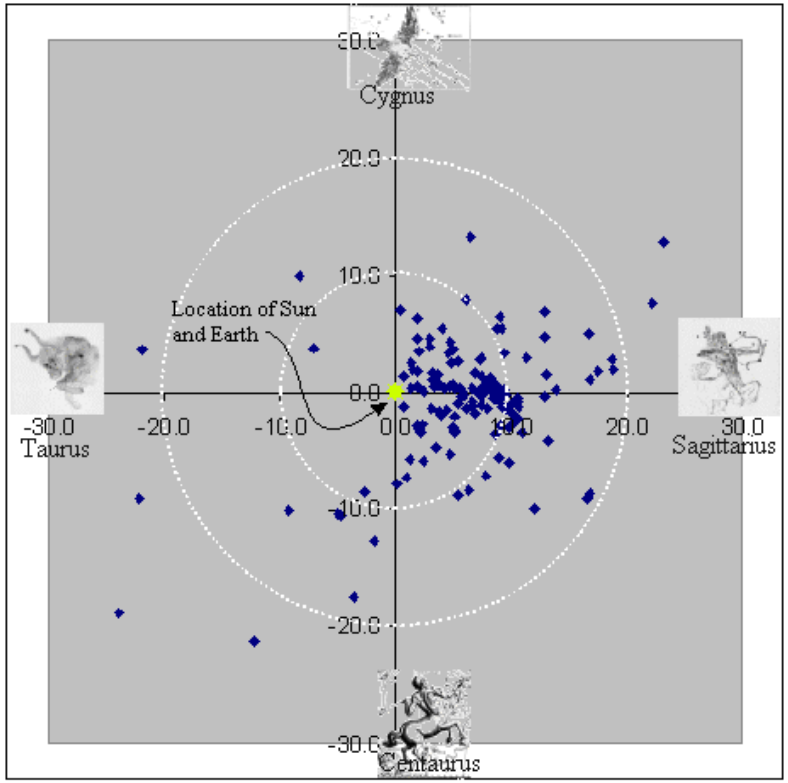


Size of the Galaxy

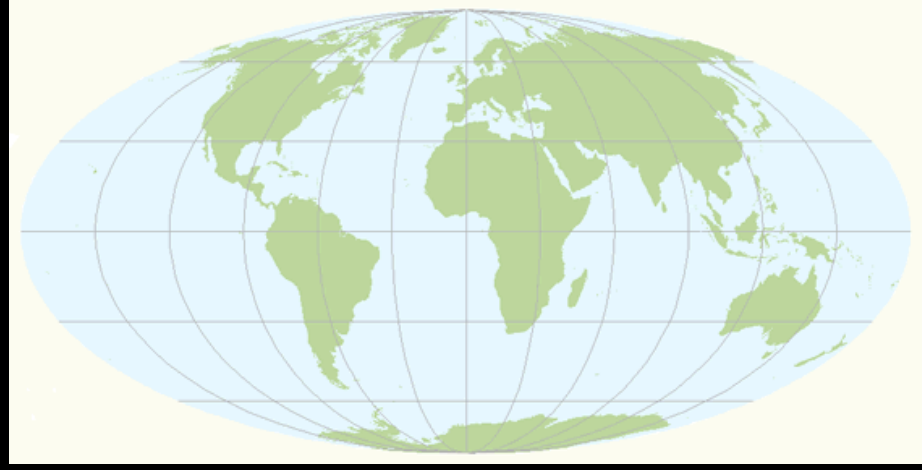
- Harlow Shapely used globular clusters 1920
- To find the distance=8kiloparsecs = 26,000light years and
- Direction to the **Galactic Center**

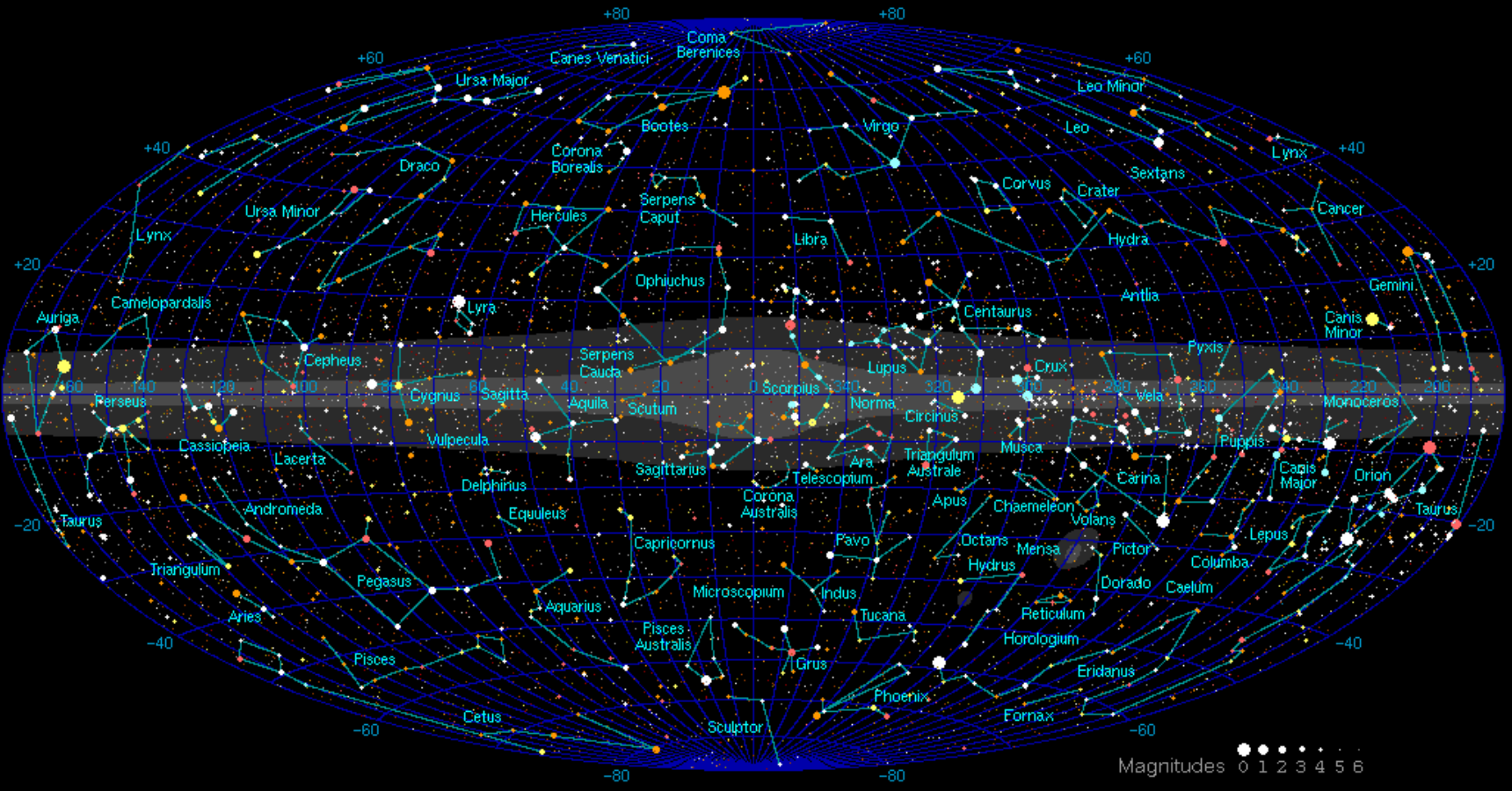


Find the distance and direction to each globular cluster to find the direction to the center of the Galaxy and how far away the center is from us.



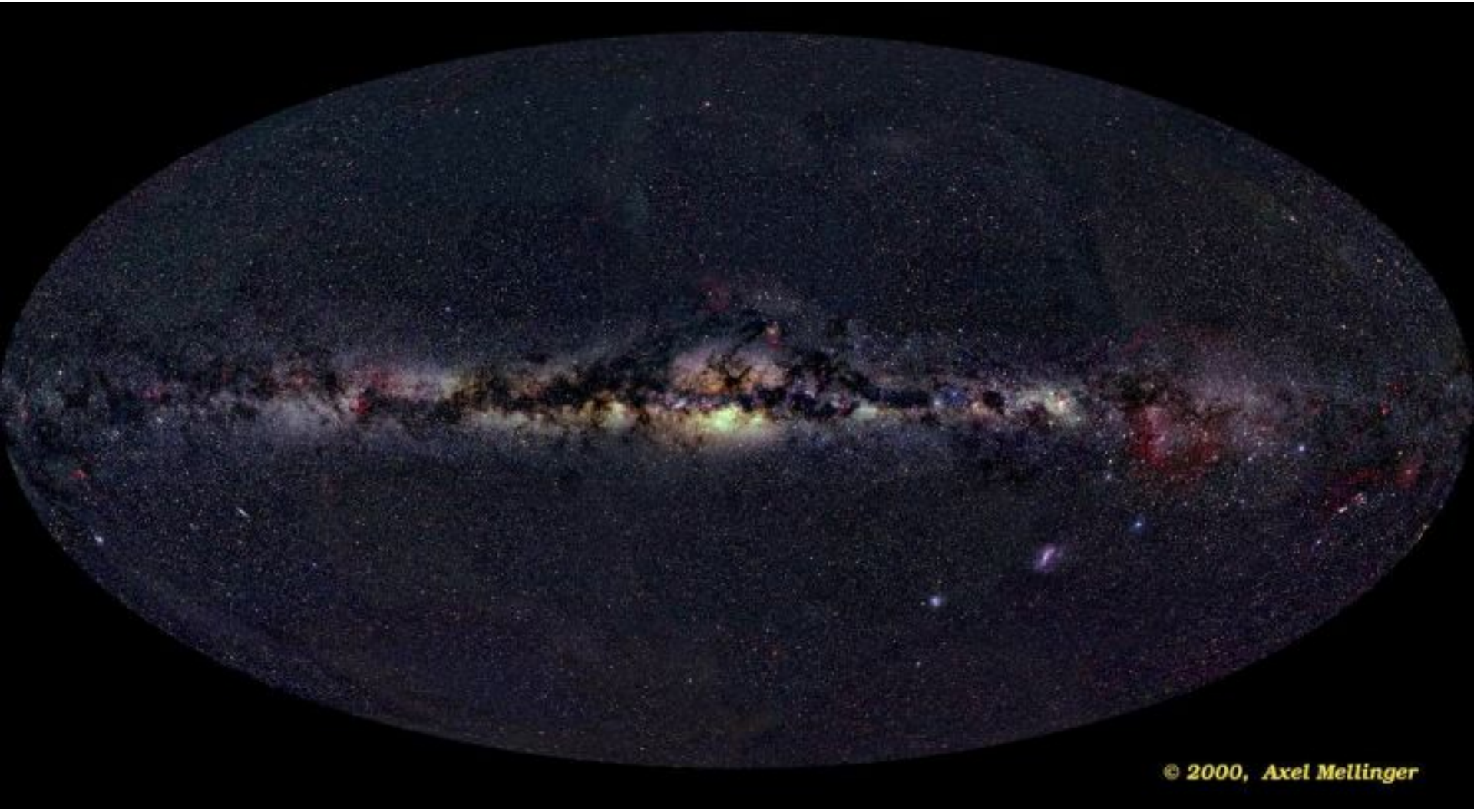
Galactic Coordinates





Interstellar Extinction

- Dust is concentrated to plane of galaxy
- Use Globular clusters just above and below plane



See Thru Dust - Near-Infrared Light

- Longer wavelength near-infrared light "sees" through dust
- Clear view of **bulge** and **disk** of Milky Way Galaxy

Population I = Disk Components

- **Disk** contains most stars ~100Billion
- All the gas=10^{10} & dust=10^{8} M_{sun}
- Young stars - O&B & T associations
- Type I Cepheids
- H II regions
- Dark Nebulae
- Giant Molecular Clouds's
- Open Clusters

Population II
Components

- **Halo**

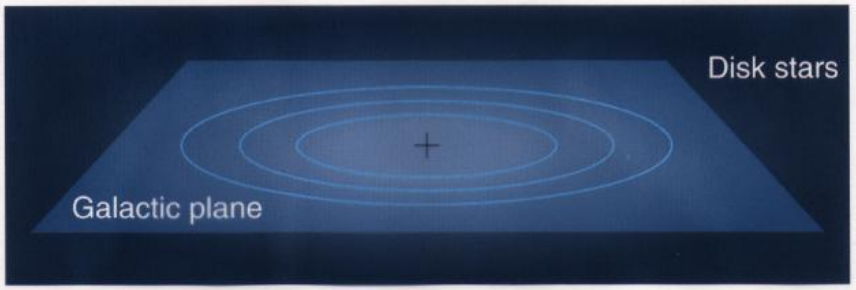
1. 150 Globular clusters
2. A Billion old red stars
3. No gas or dust; no new stars

- **Bulge:**

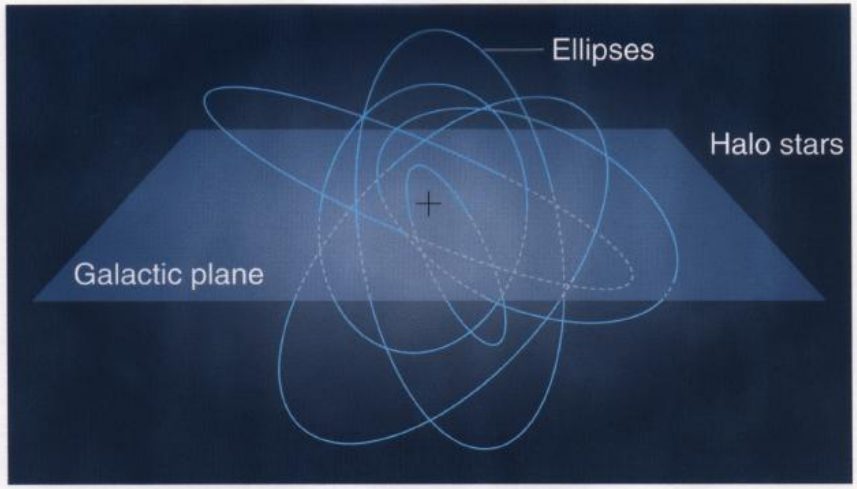
1. Old Pop I and Pop II stars
2. Young stars in centre

Disk and **Halo** Orbits

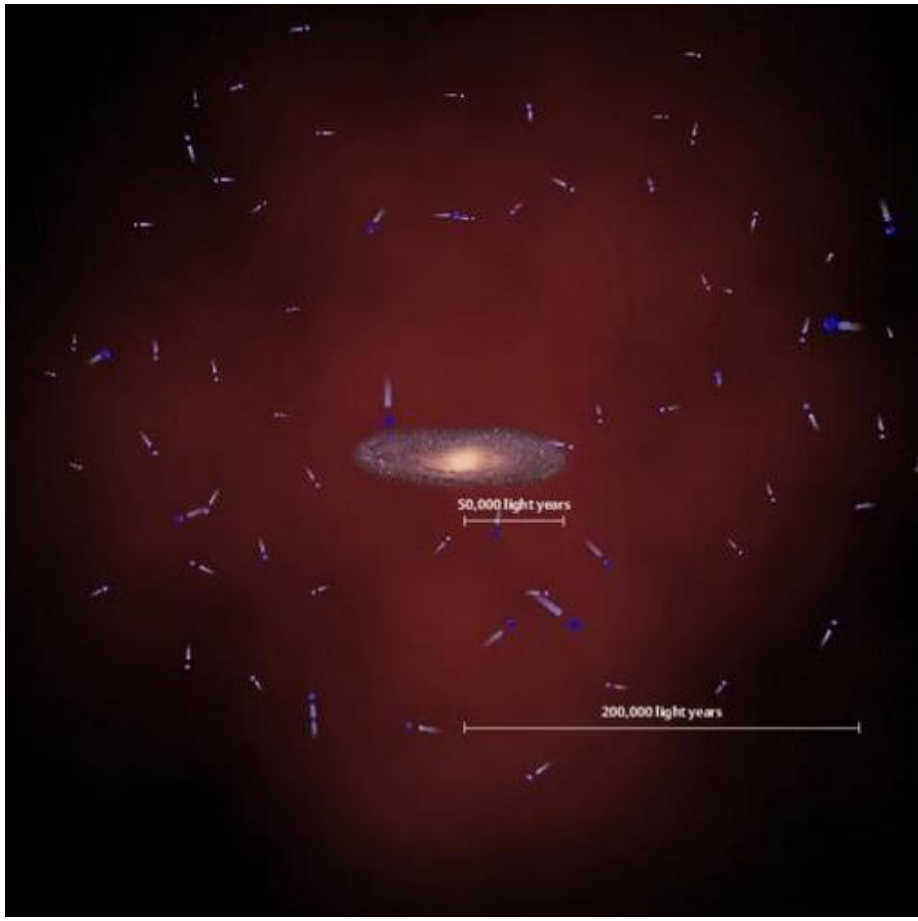
- Halo=Pop II objects have elliptical /plunging orbits which make them appear to have high velocity
- Disk=Pop I objects orbit in the plane of the Galaxy



a Circular orbits

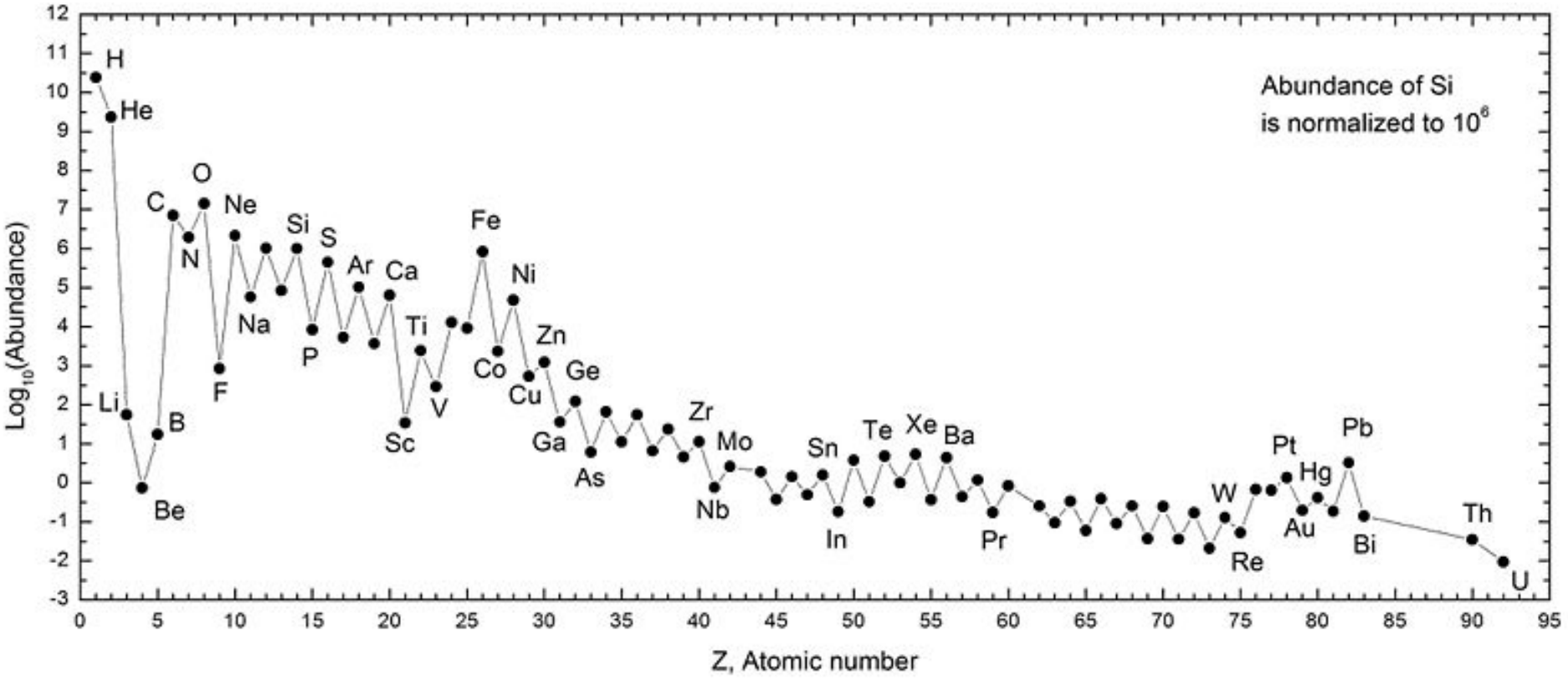


b Randomly oriented, highly elongated orbits



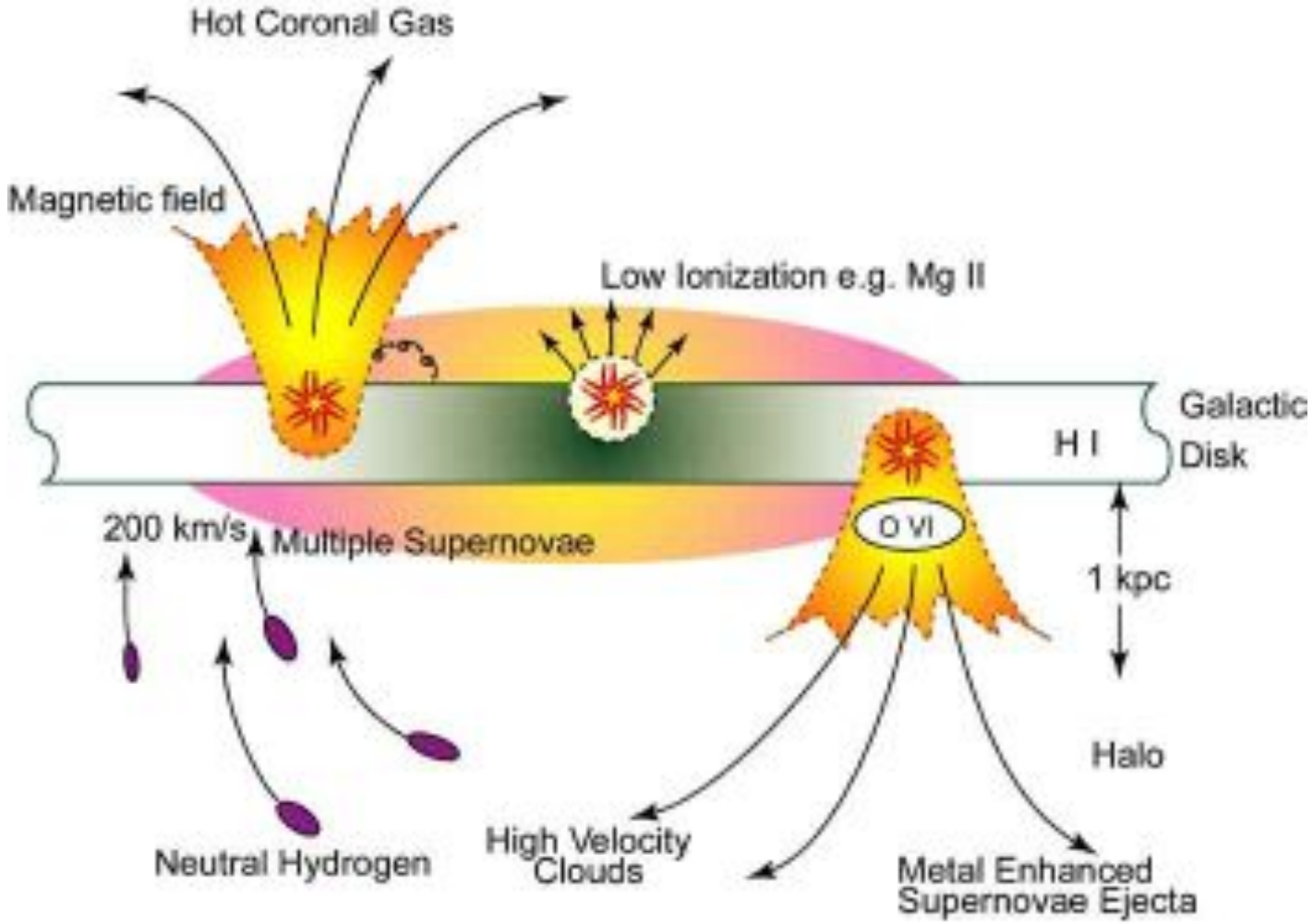
Nucleosynthesis

- Universe started with 75% Hydrogen and 25% Helium
- All other elements are called "metals" by astronomers
- Beyond Iron formed by neutron capture in supernova



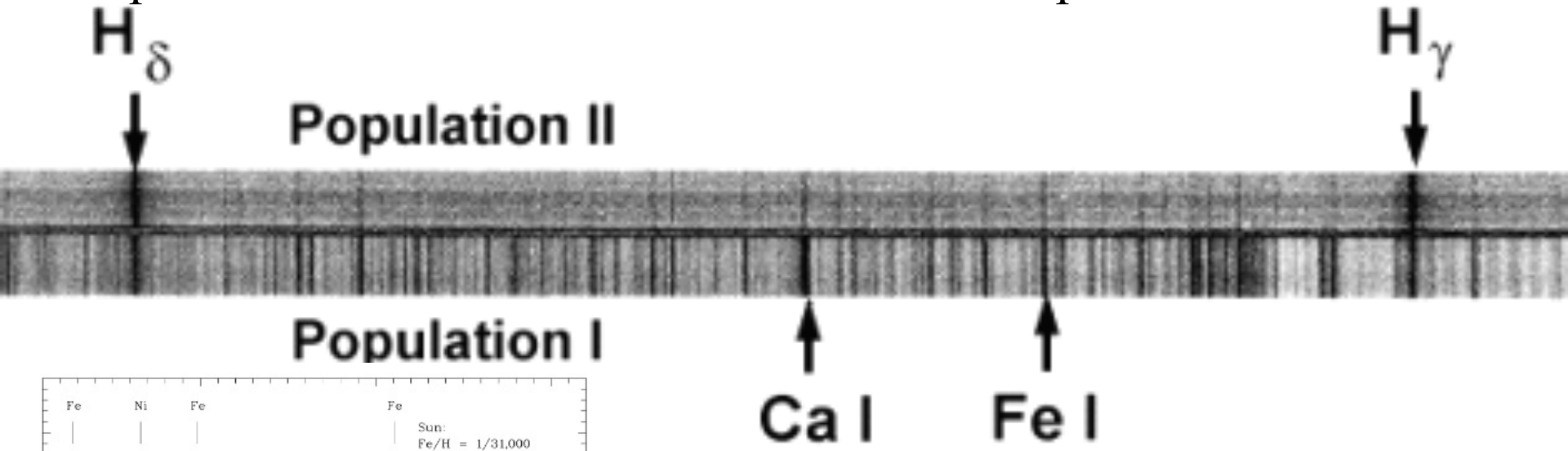
Galactic Fountains

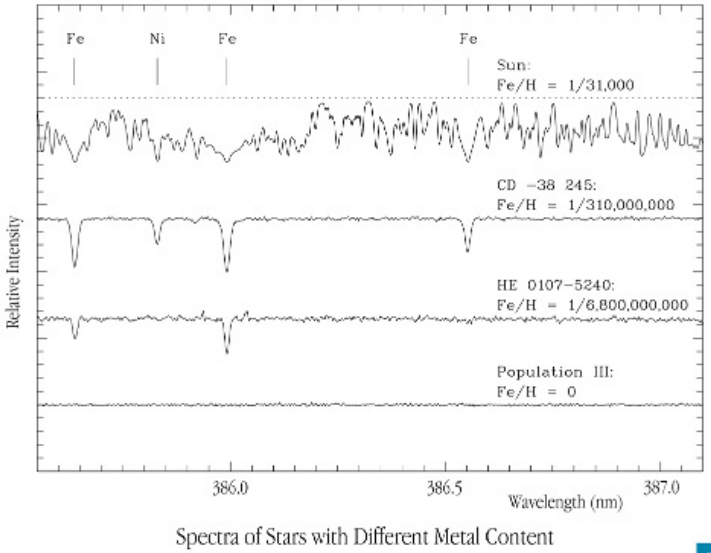
- Supernovae blast out the enriched material from which
- Succeeding generations of stars are formed



Spectra of Pop I and II Stars

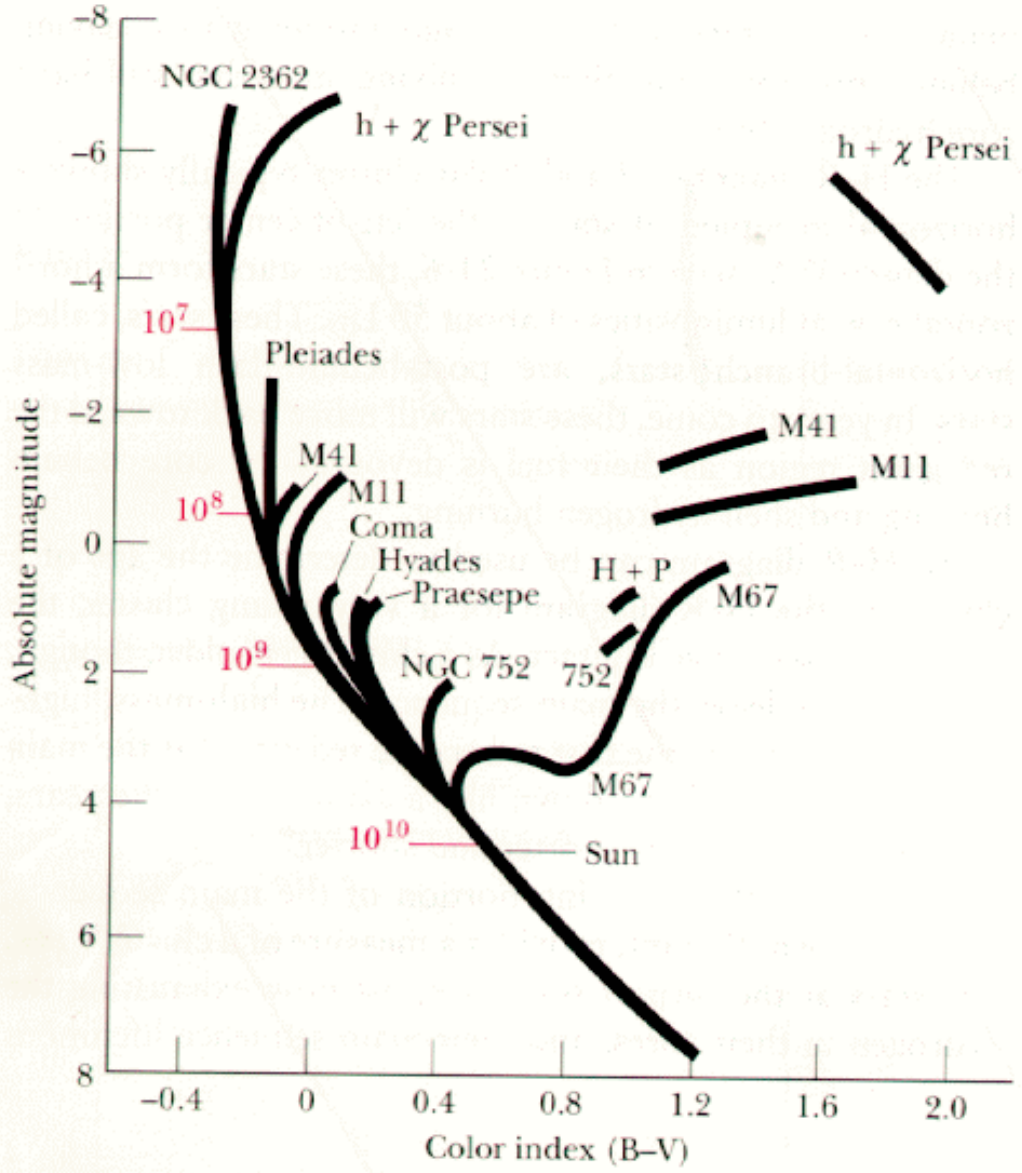
- Lines of Hydrogen are about equal => same temperature
- Lines of heavier elements are much weaker in Pop II stars
- Pop I stars like sun contain ~2% metals and Pop II ~0.2%





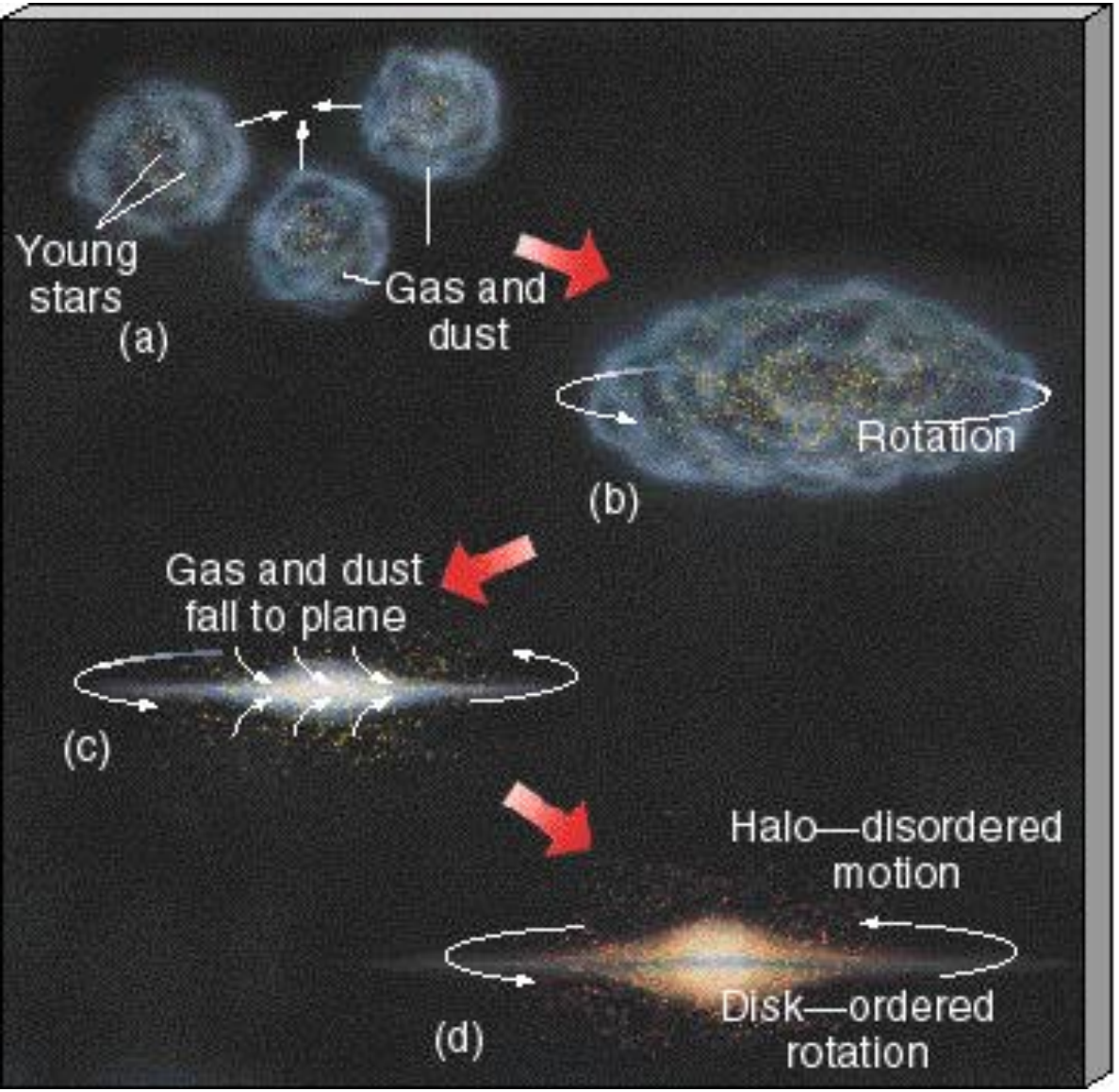
Spectra of Stars with Different Metal Content

Clusters Give the Age of Pop I & II

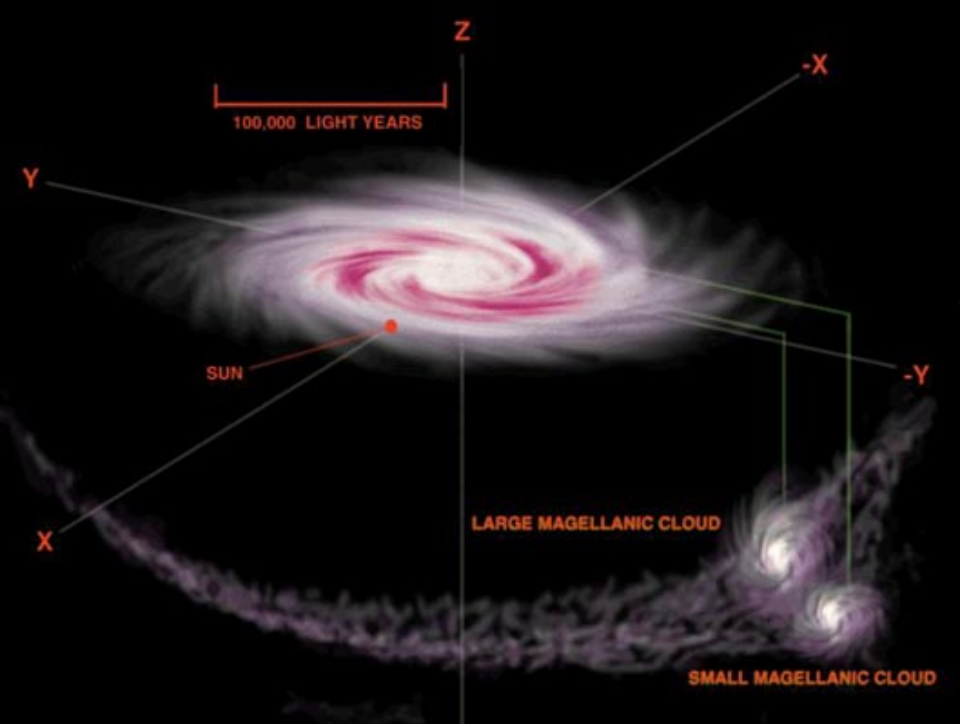


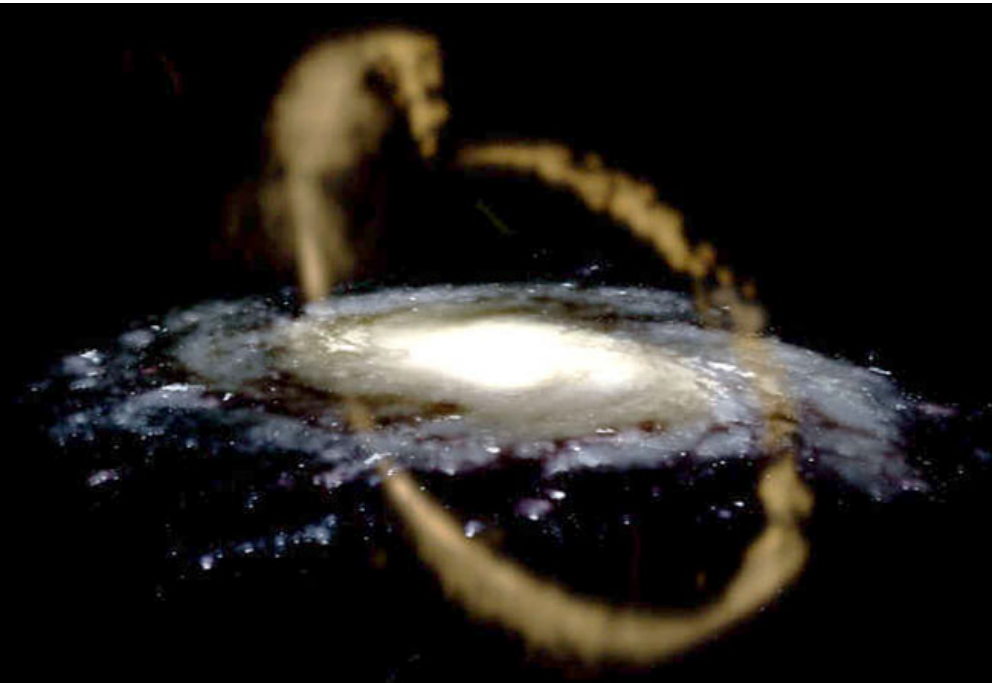
- Oldest open clusters in the disk are ~ 10 Billion years old
- Oldest globular clusters in halo are ~13 Billion

Monolithic Collapse Hypothesis



- First stars form in halo
- Then stars form in disk
- From gas enriched in heavy elements
- So old metal poor stars in halo and young metal rich stars in disk
- But no Pop III?, discrepant globular cluster/halo star ages?
- Old metal rich stars in bulge?

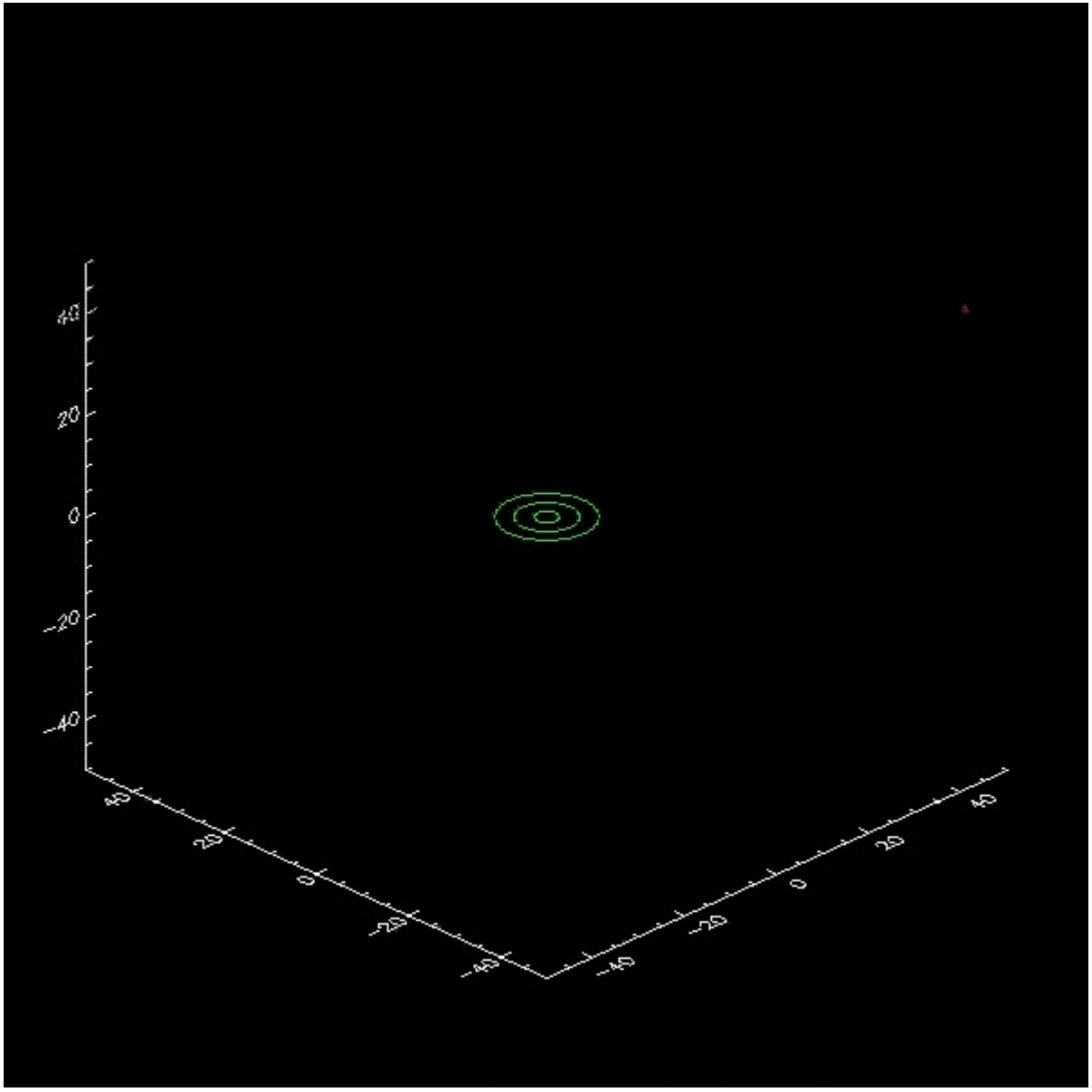




The Milky Way: The Cannibal

- Galaxy mergers explain discrepant globular cluster ages
- The Milky Way is merging with LMC and SMC
- Sagittarius dwarf's orbit takes it through galaxy
- **Tidal streams** torn from merging galaxies

Formation of Milky Way?

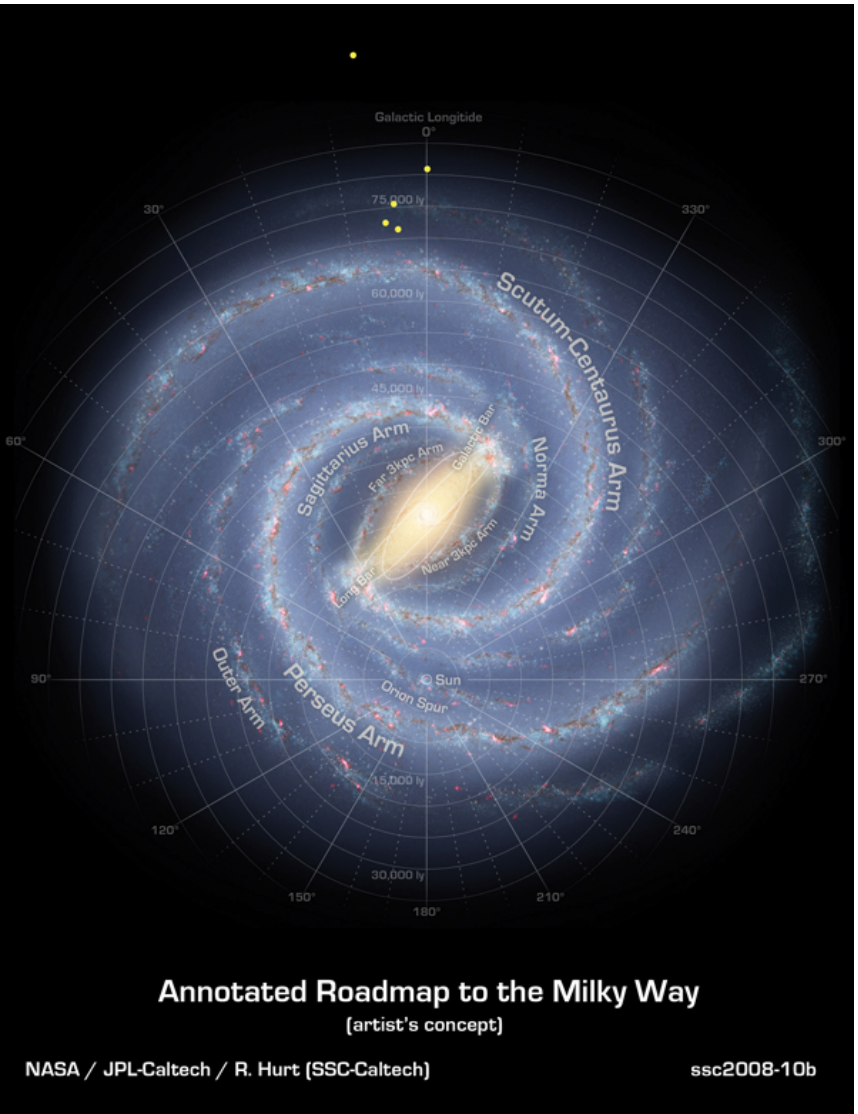


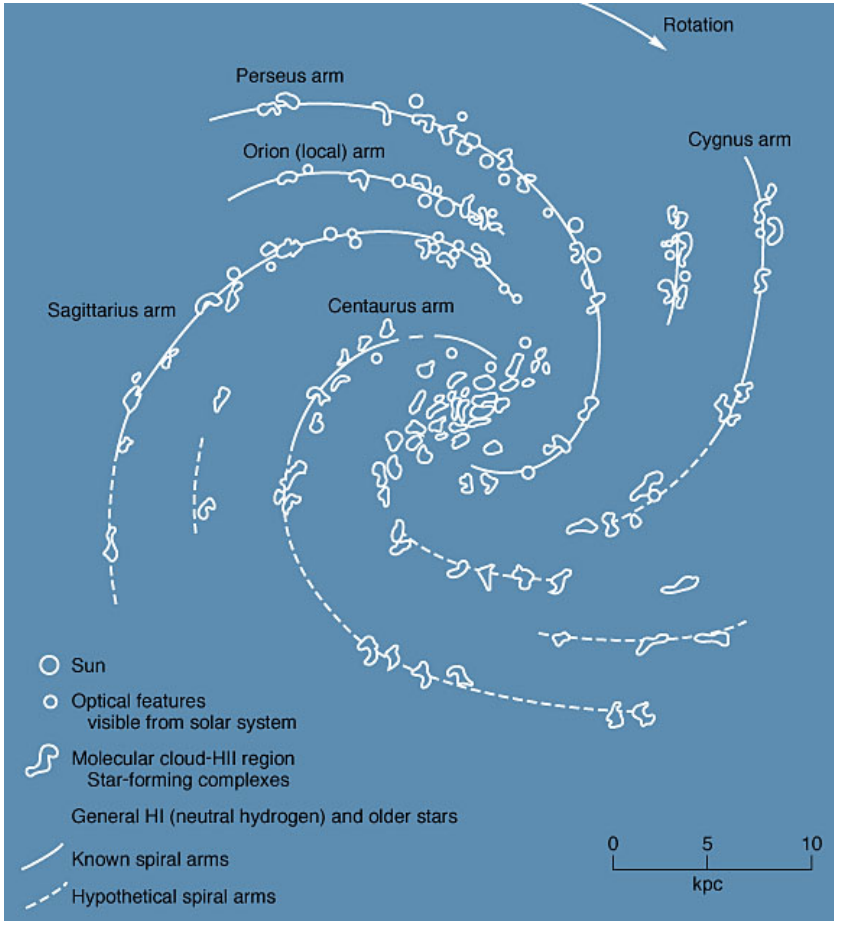
Spiral Arms: M51

- Pop I objects found in spiral arms
- Dust lanes on inside of arms
- Followed by H II regions and blue stars
- Which live for a million years ~1degree in orbit around galaxy

To Map **Spiral Arms** Use Pop I Tracers:

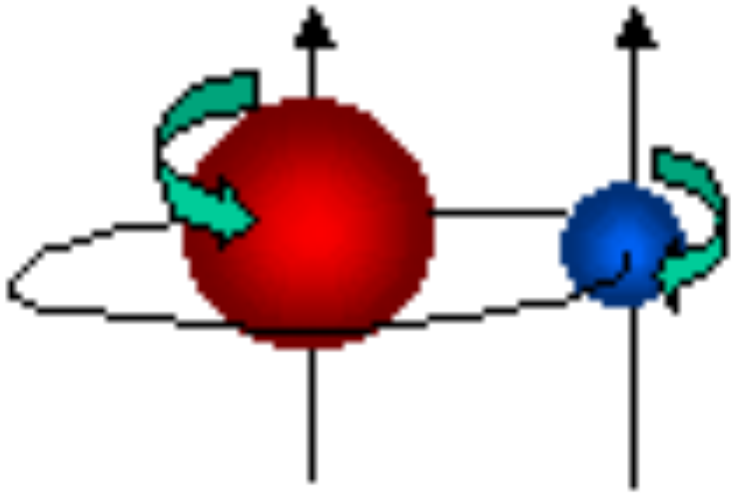
- 5 Cepheids on far side
- OB Associations & Open Clusters
- HI & H II regions
- Molecular clouds CO, H_2





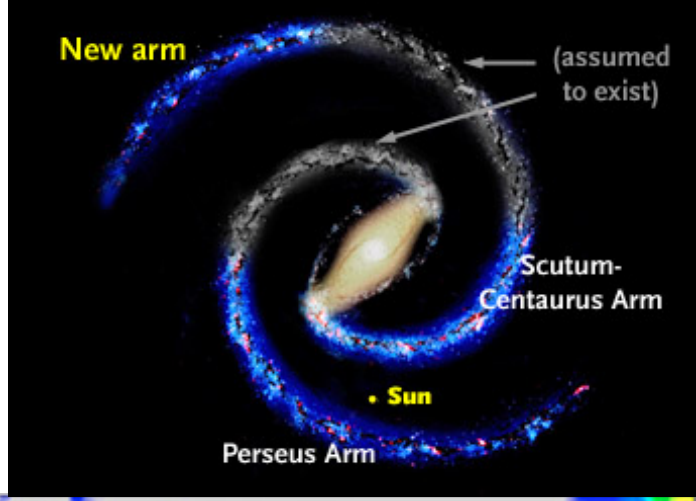
H I Region = Clouds of Neutral Hydrogen Atoms

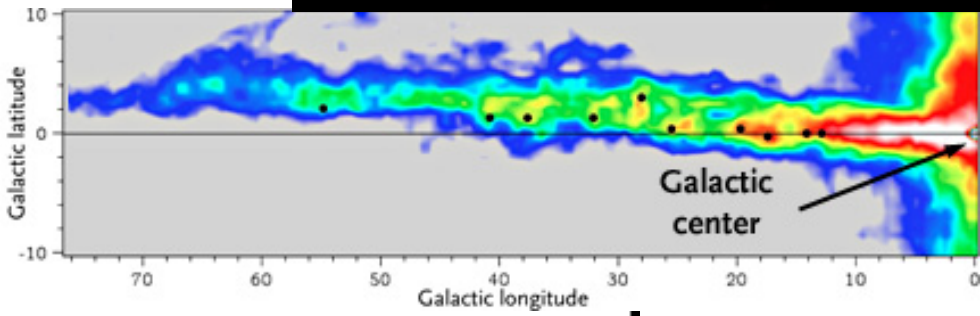
- Charged proton & electron spin generating magnetic field
- Magnetic fields aligned has a higher energy
- Energy of spin-flip transition equals **21-cm radio** photon

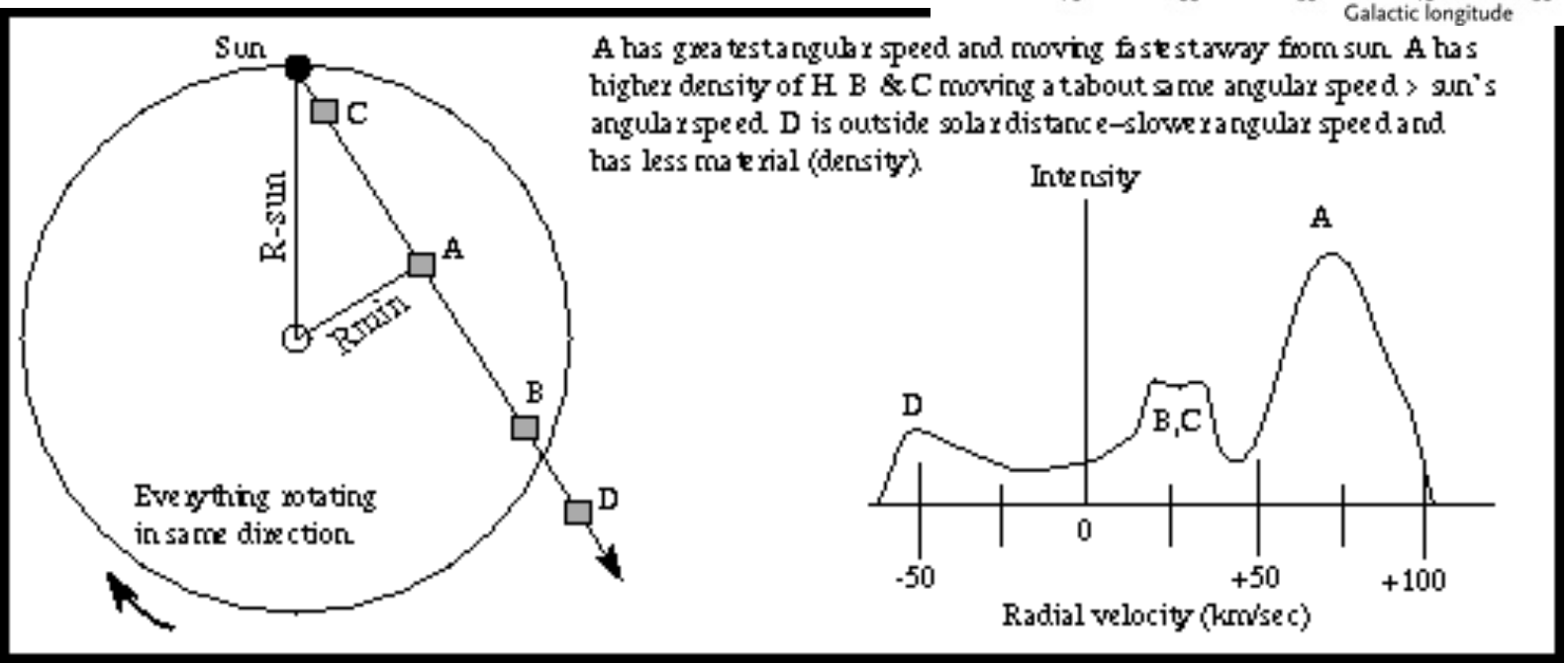


Map of Milky Way's Hydrogen Clouds

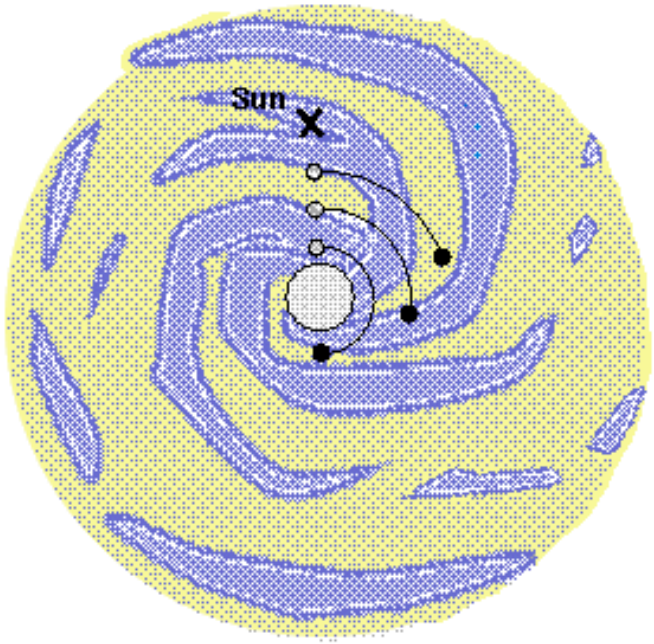
- Interstellar medium is transparent to 21 cm radio radiation
- Can see "New Arm" on far side of Milky Way







Differential Rotation

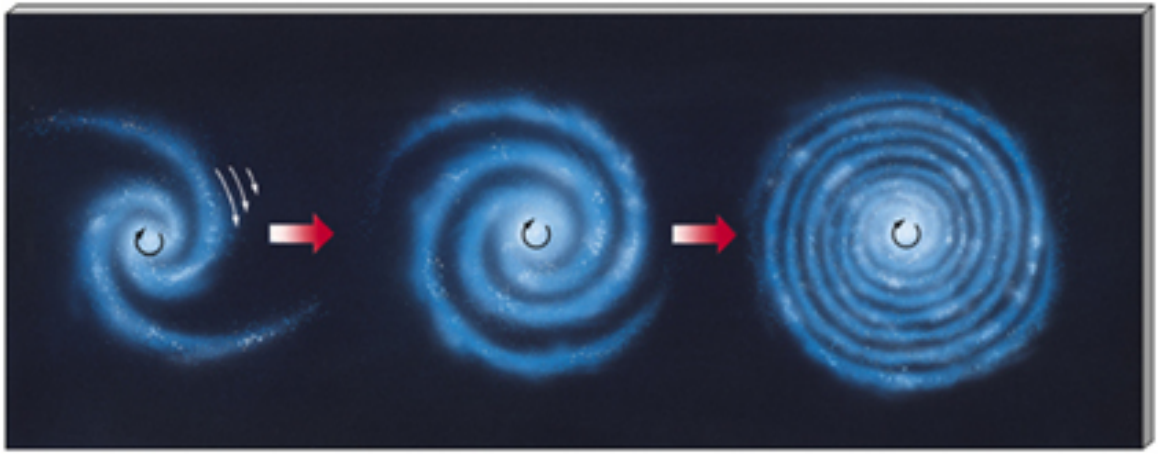


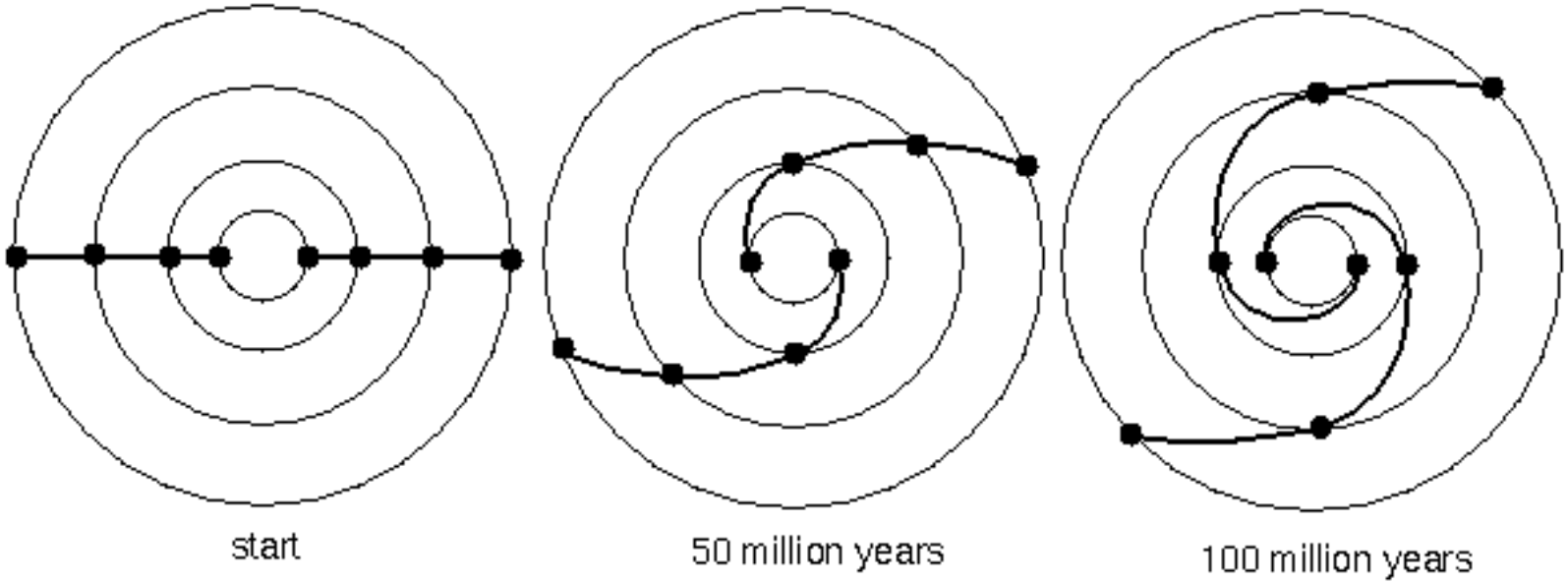
Differential rotation: greater **angular** speeds closer to the galactic center.

- Not solid body rotation
- Not Keplerian orbits
- Stars are all orbiting at same velocity
- Outer stars have farther to go so they get lapped by stars on inside track
- And trail off behind

Winding Dilemma

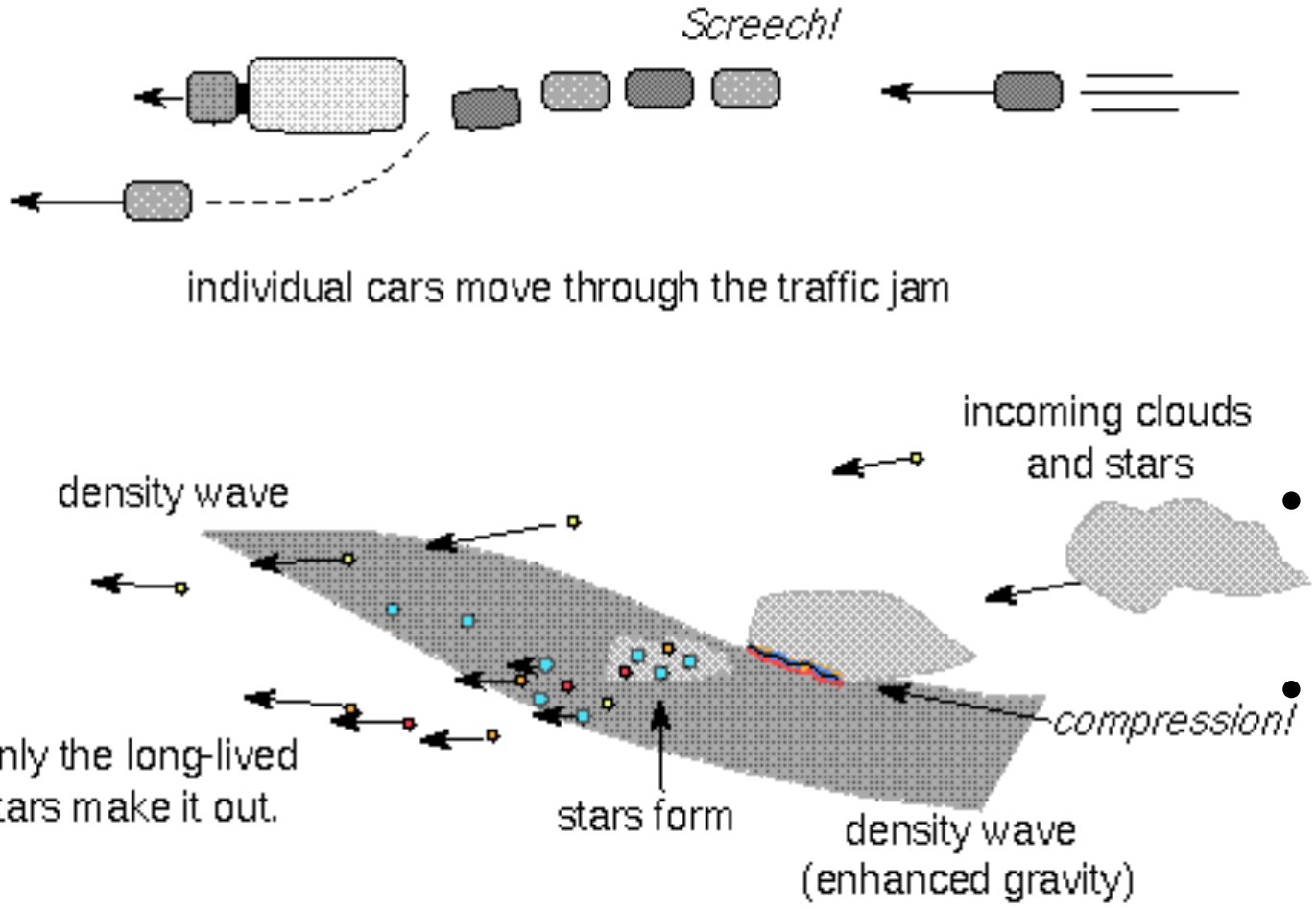
- Arms wind up in a few rotations





Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

Spiral Density Wave

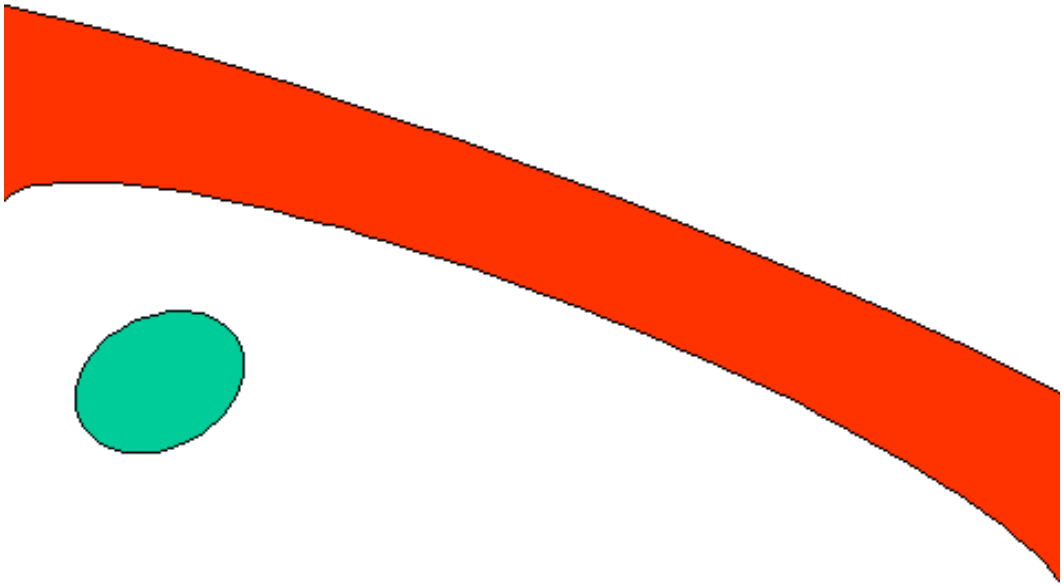


- Like the wave at Vikes games
- Pattern speed different from rotation speed of stars

Spiral density waves are like traffic jams. Clouds and stars speed up to the density wave (are accelerated toward it) and are tugged backward as they leave, so they accumulate in the density wave (like cars bunching up behind a slower-moving vehicle). Clouds compress and form stars in the density wave, but only the fainter stars live long enough to make it out of the wave.

Spiral Density Waves Form Stars

- Green Giant Molecular Cloud encounters the Red Spiral Arm and forms Stars which then Supernovae Type II
- Animation by G. Rieke

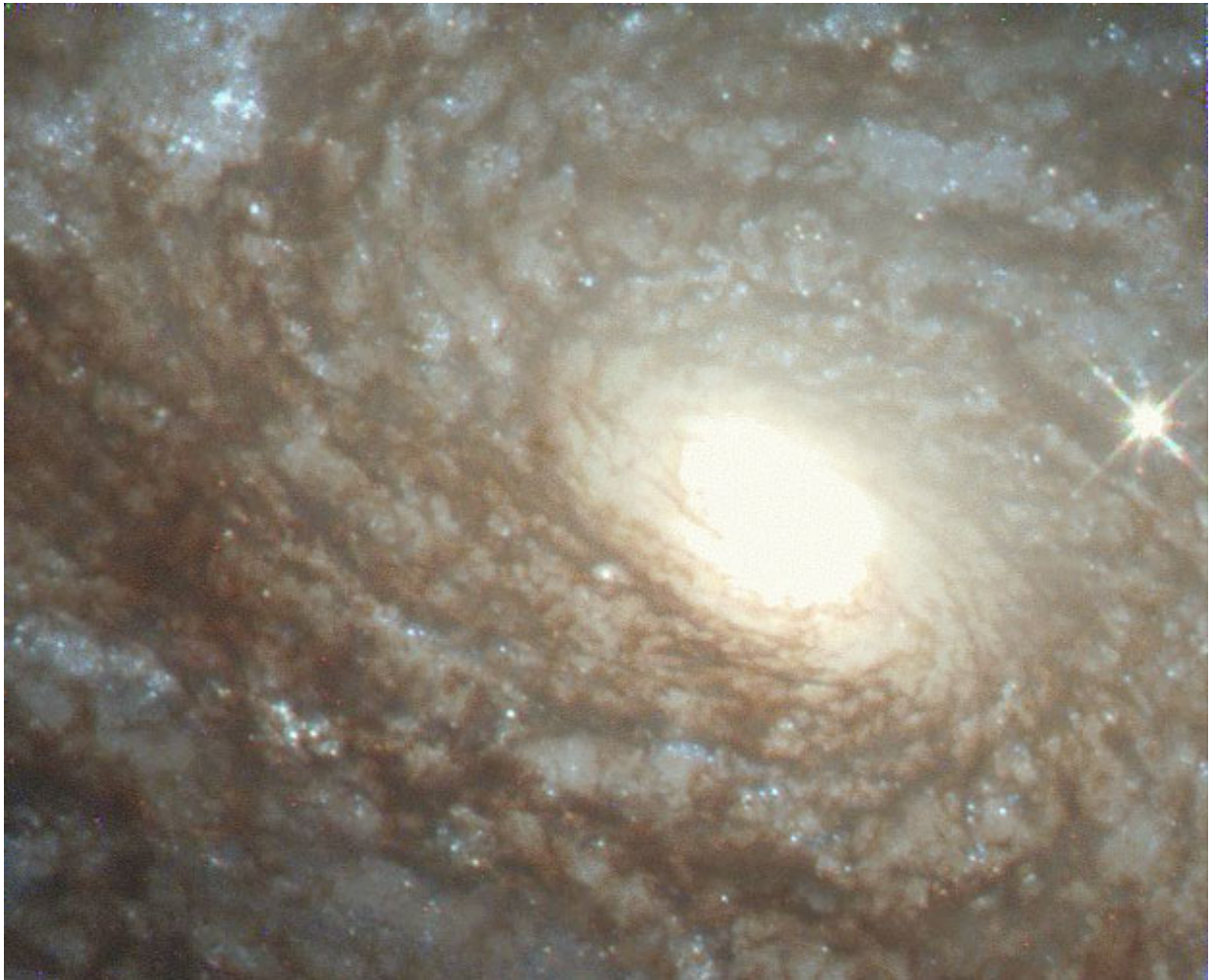


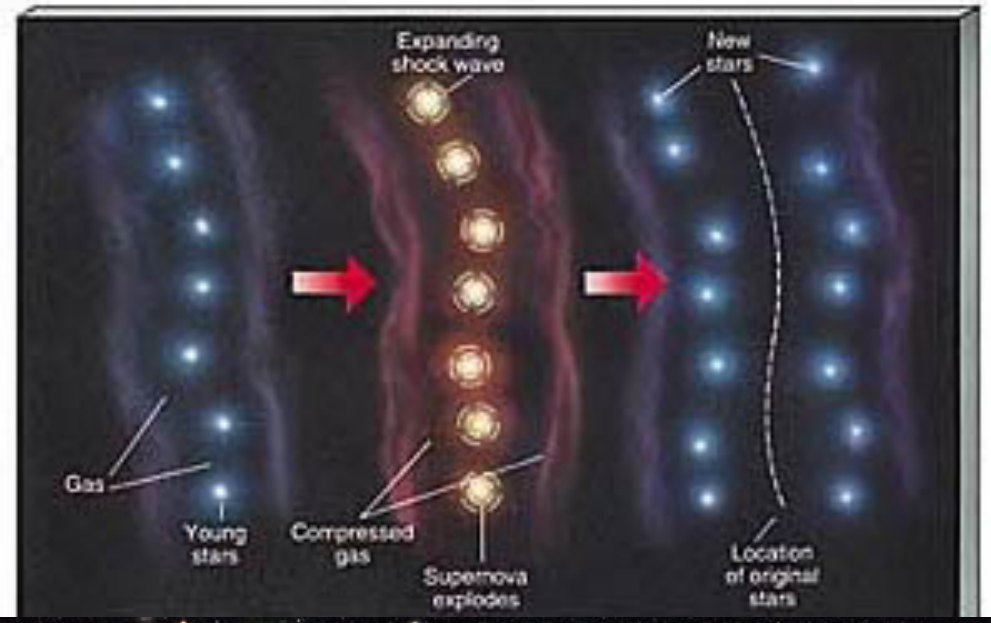
Grand Design Spiral Galaxy

- 10% of galaxies are Grand Design spirals
- Die out after a billion years so they need kick to restart

Flocculent Spiral NGC 4414

- Fluffy or wooly appearance – 30% of spirals
- Not produced by Density waves





Self-Propagating Star Formation

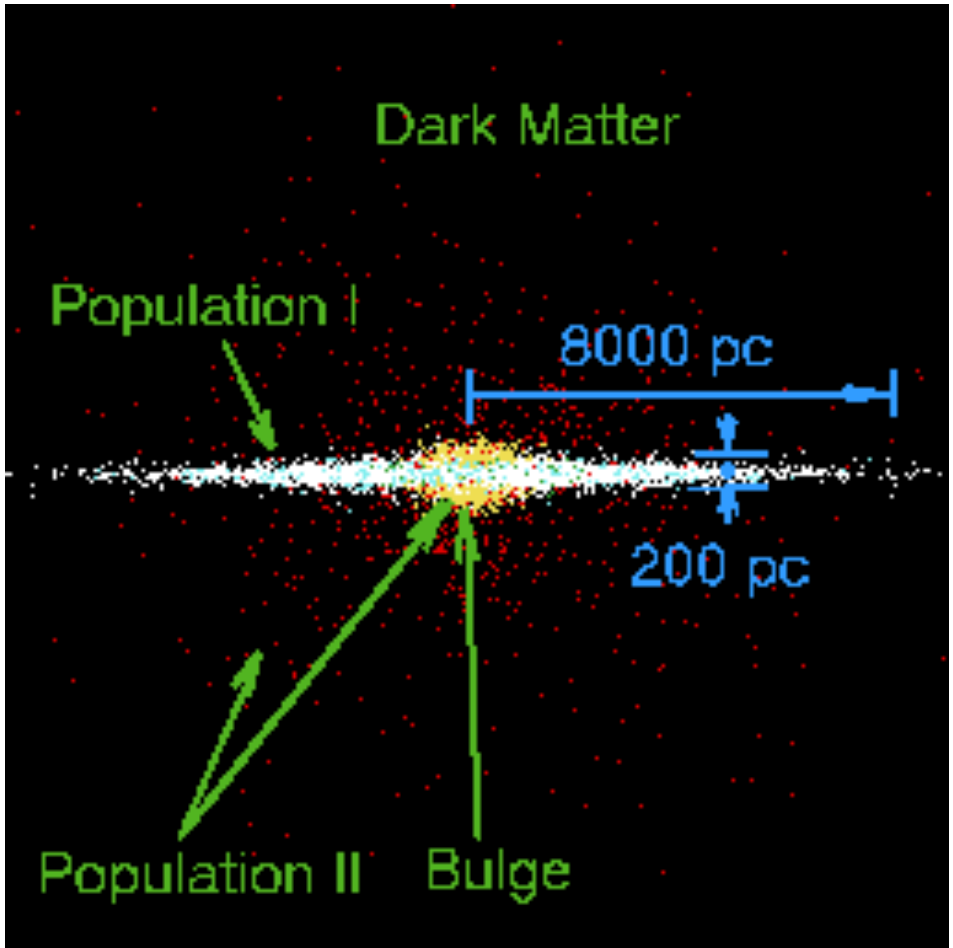
- Supernovae and stellar winds compress GMC
- Differential rotation smears into spiral arm
- But not grand design spirals

Which of the following is not correct?

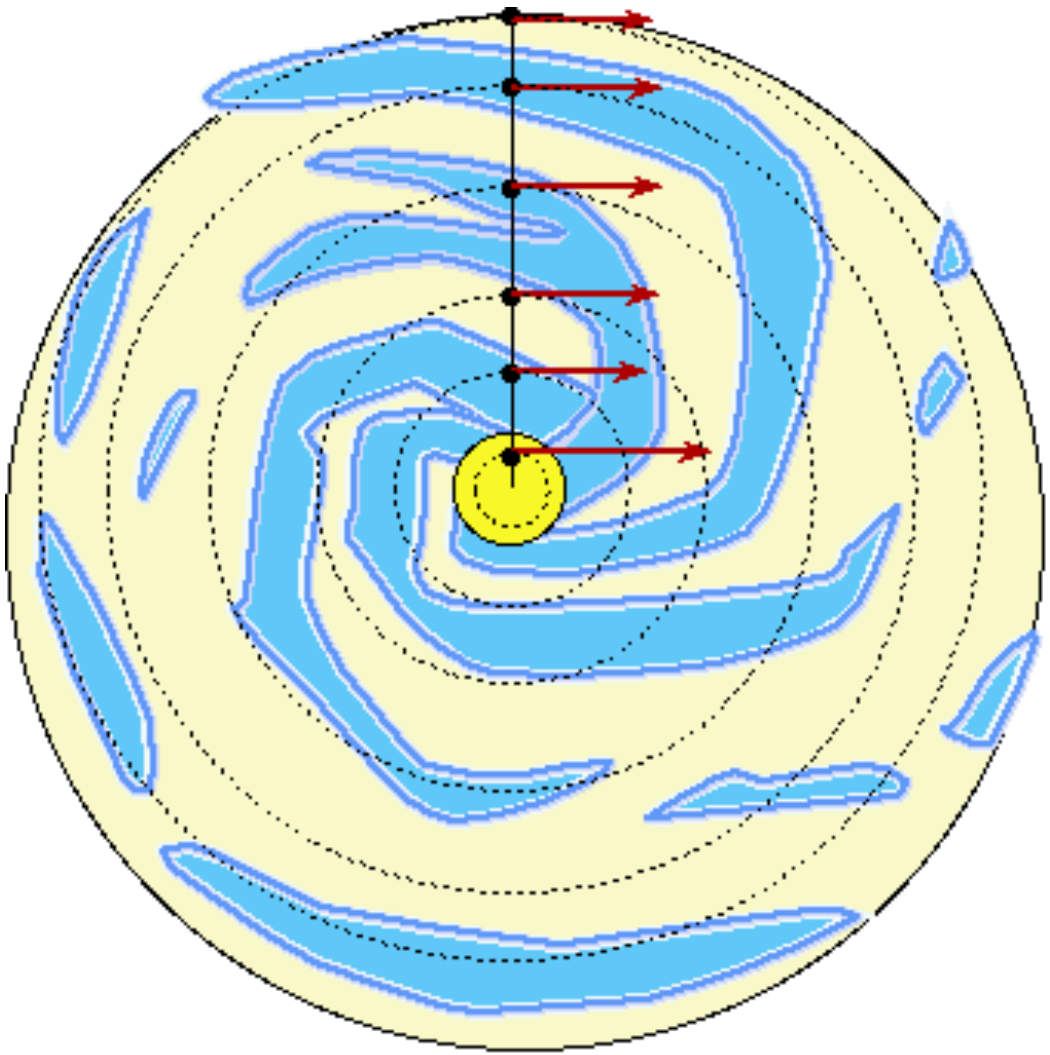
a. The Milky Way Galaxy contains billions of stars in a disk, bulge and halo
b. The bigger the pulsating variable star (Cepheid) the longer its period and the brighter it will be
c. Young, blue, metal-rich stars in circular orbits (Population I stars) are found in the Galaxy's disk
d. The Galaxy's spiral arms are probably produced by spiral density waves or self-propagating star formation
e. All of these are correct.

Review POP I and POP II

- Pop I stars are young, hot, blue, metal rich, found in disk, low velocity, Type II supernovae, all masses, open clusters, Cepheids, gas
- Pop II stars are old, red, metal poor, halo, high velocity, Type Ia supernovae, only low mass stars left, globular clusters, RR Lyrae



To Find the Mass of the Galaxy

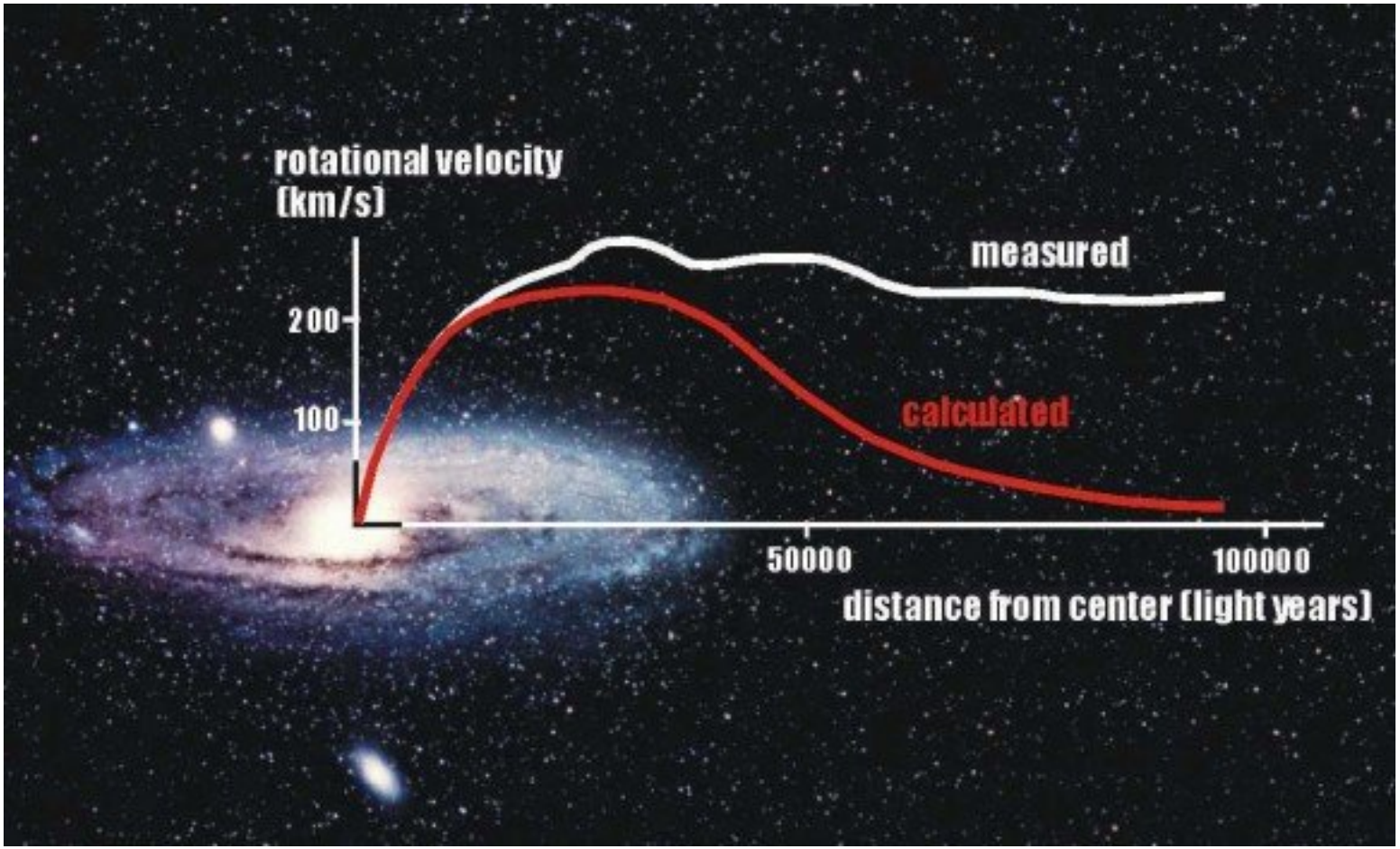


The mass inside an orbit can be found using the size of the orbit and the orbital speed. The arrows show the speeds for certain points on the **rotation curve** for this galaxy.

- Need the Period P and the semimajor axis A
- Mass=A^3 /P^2
- Gives the mass interior to the orbit

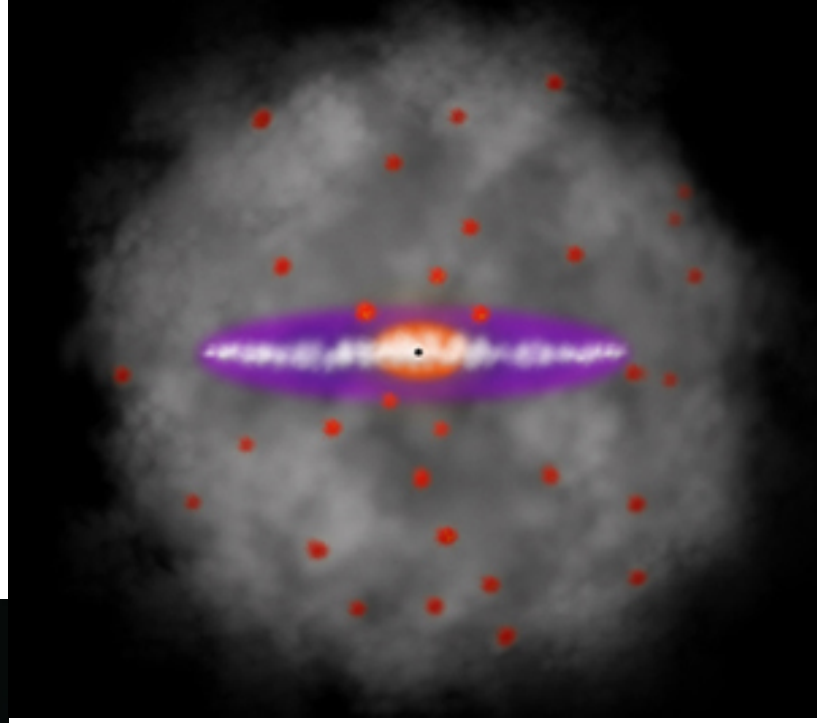
Galactic **Rotation Curve**

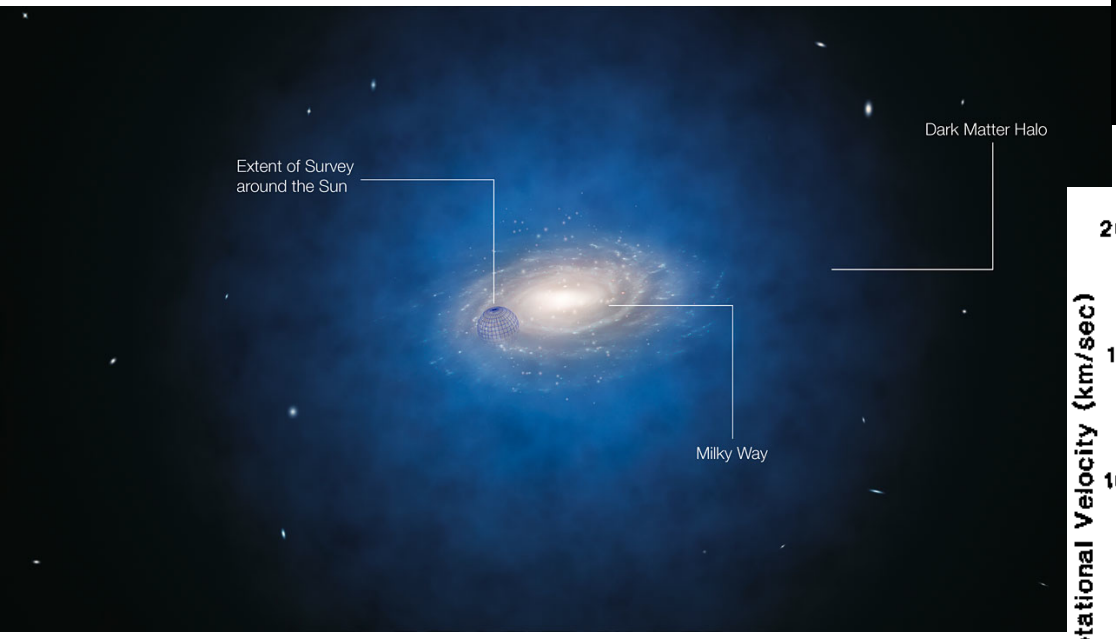
- Rotation speed does not decrease like solar system
- Stars beyond luminous “edge” still have high velocity

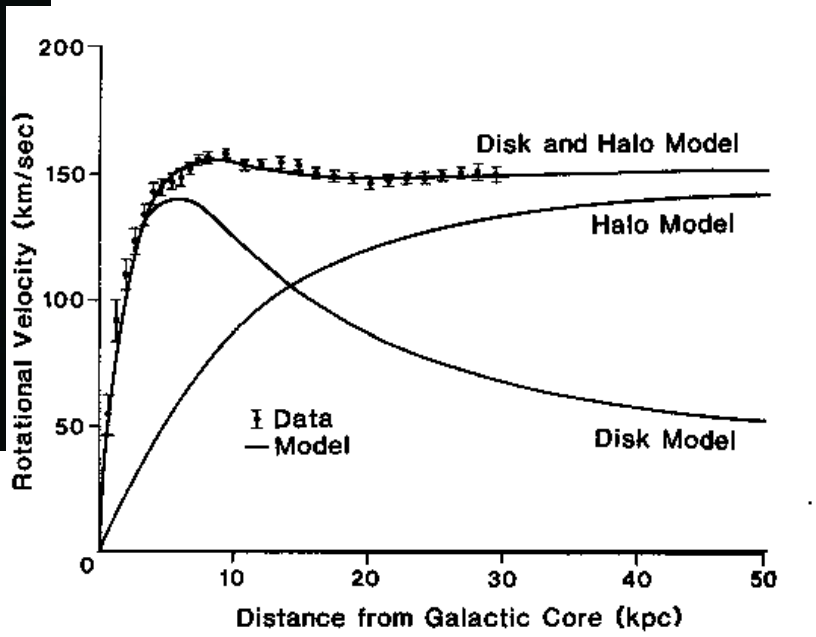


Dark Halo

- Must be more mass beyond luminous edge of galaxy

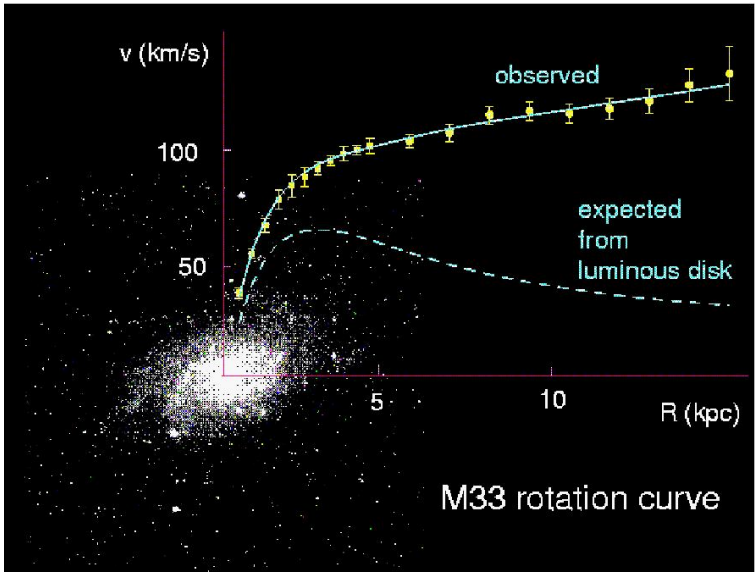




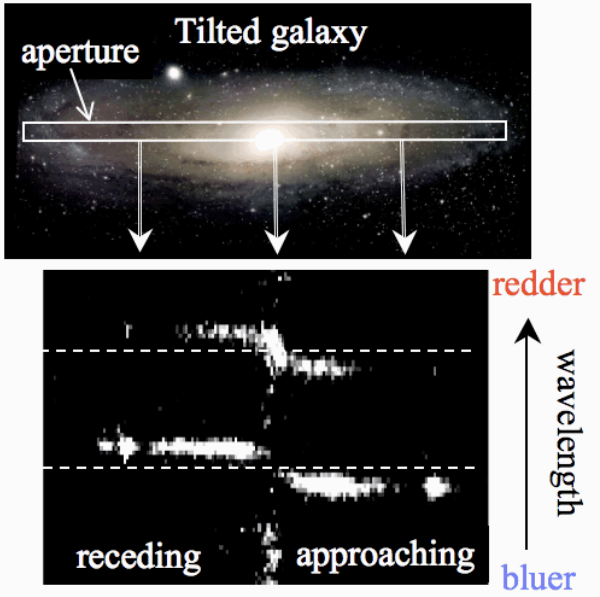


Dark Matter

- Non-luminous matter in Dark Halo is called **Dark Matter**
- Seen in other galaxies
- Galaxies are the white caps on the waves of Dark Matter

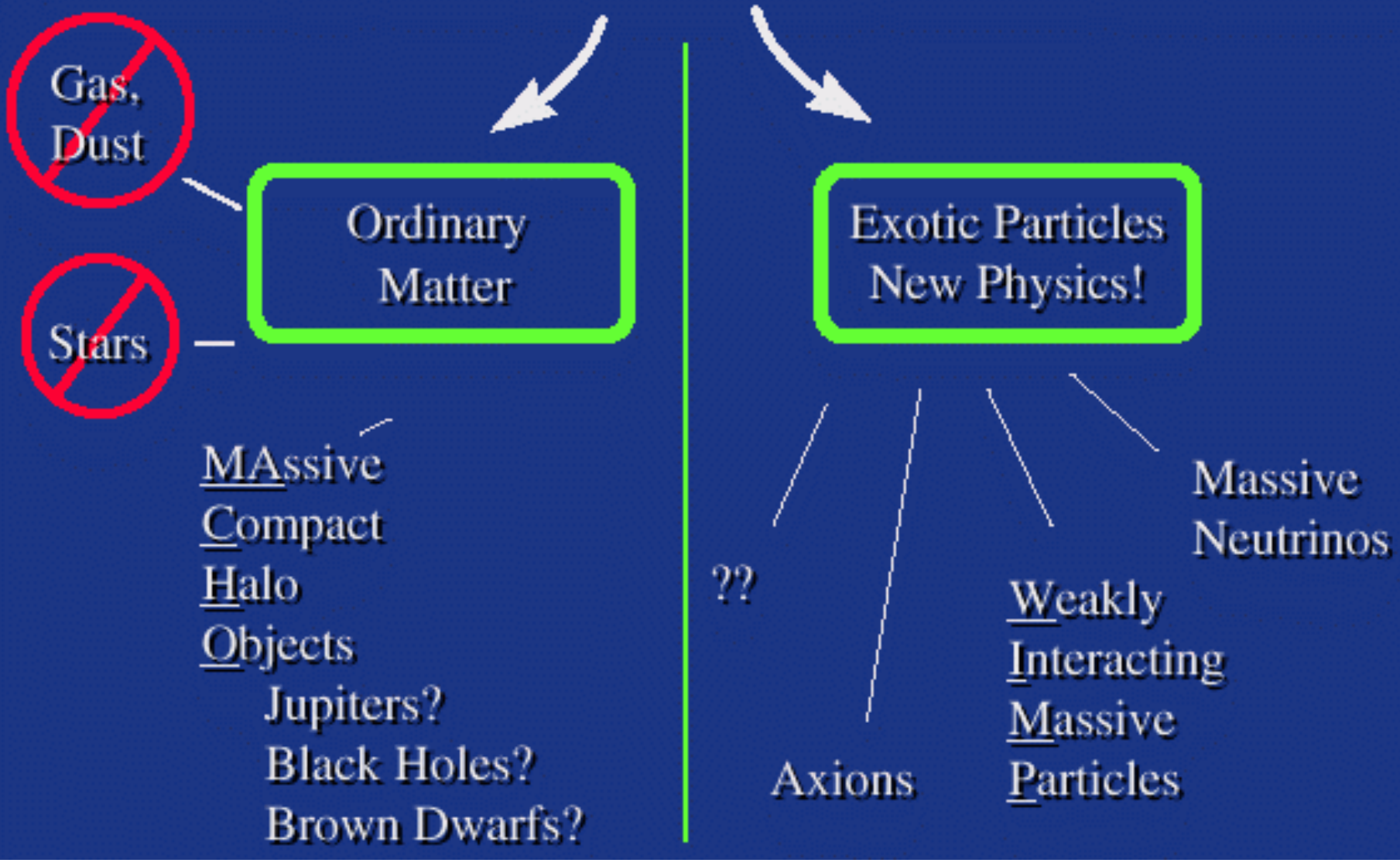


Vera Rubin measuring galaxy rotation curves (~1970)



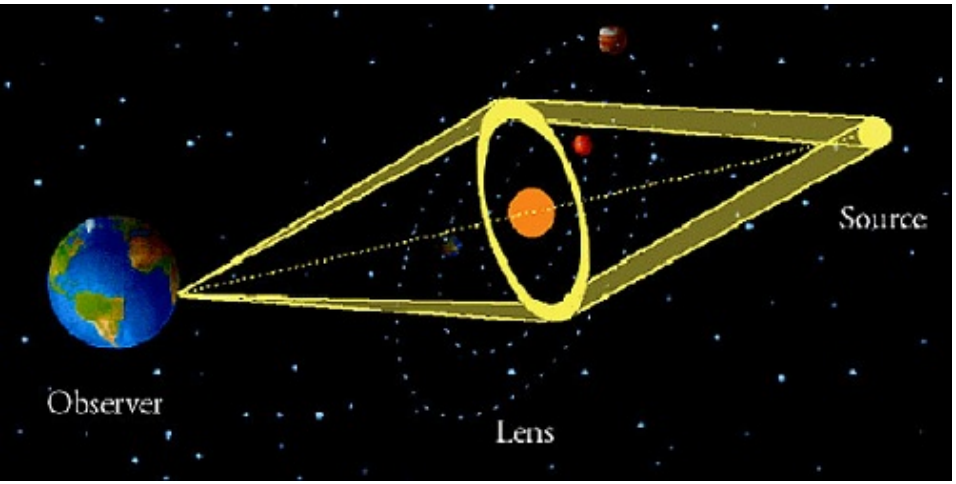
Resulting spectrum of light within aperture

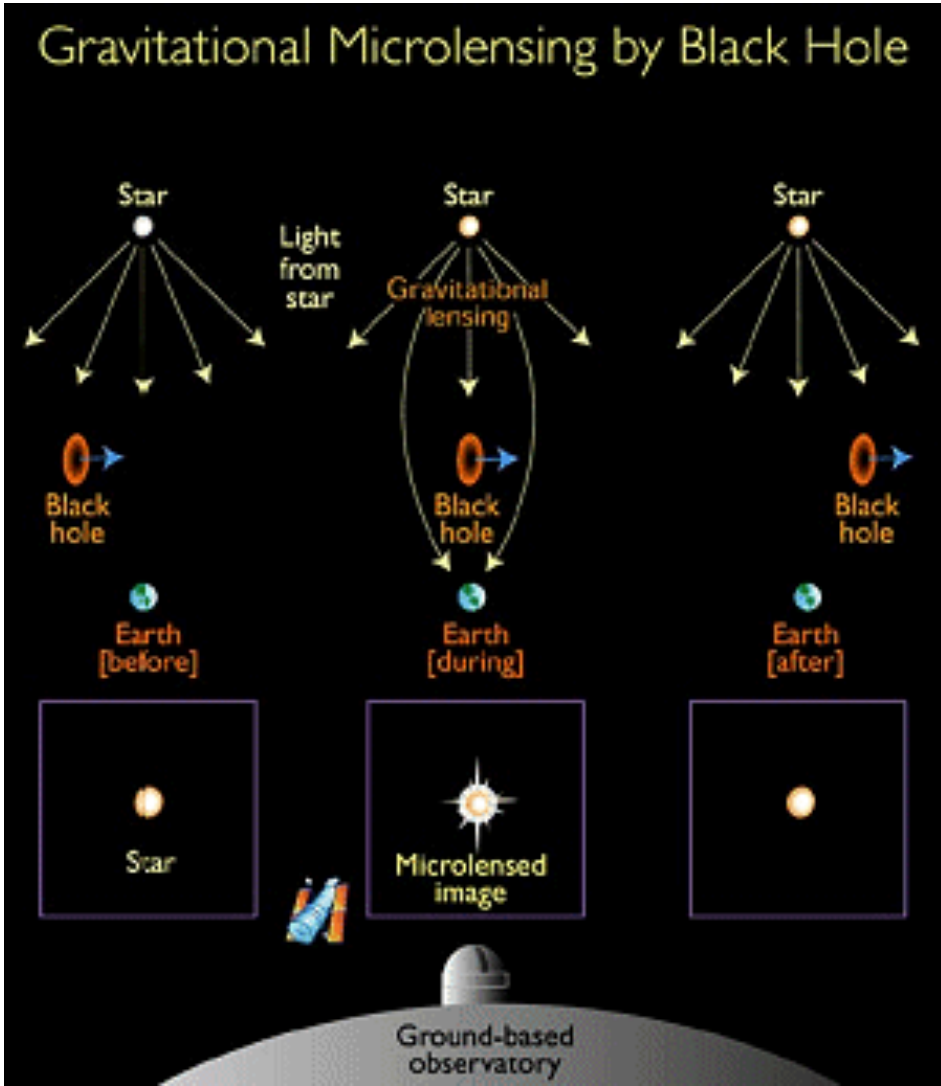
What is the Galactic Dark Matter?



Gravitational Lensing/Microlensing

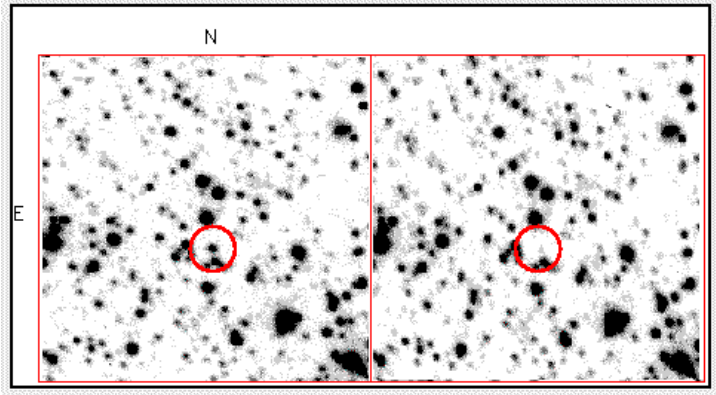
- General Relativity predicts bending of light
- Large mass – Large bending
- Exact alignment makes ring
- Great distance = brightening

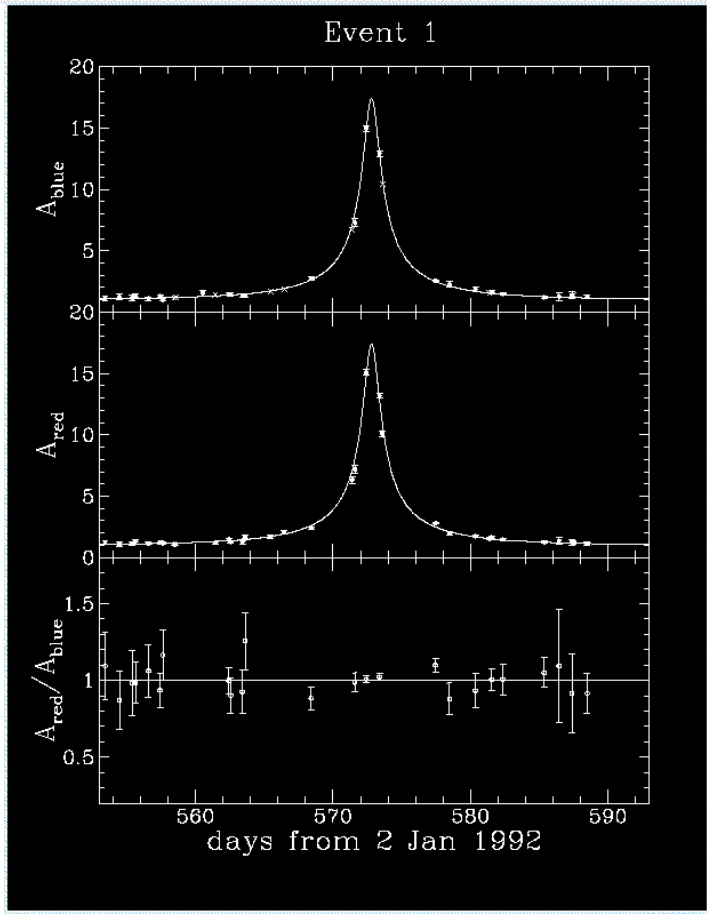


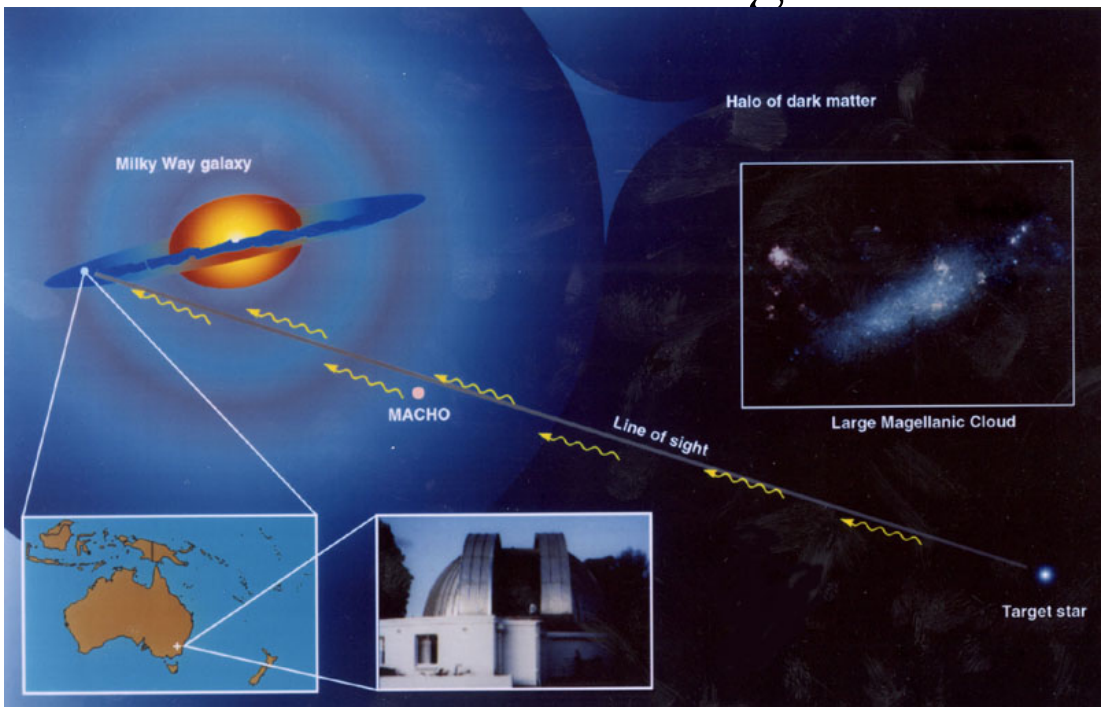


MACHO's

- Search for MACHO's by looking for a star brightening amongst 10 million others
- Not enough MACHO's = White Dwarfs & Black Holes etc
- Dark Matter is something else??

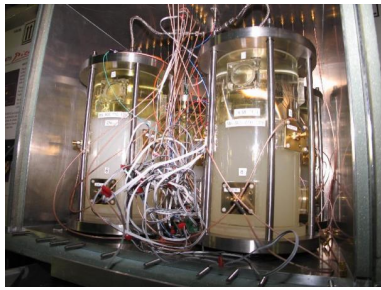


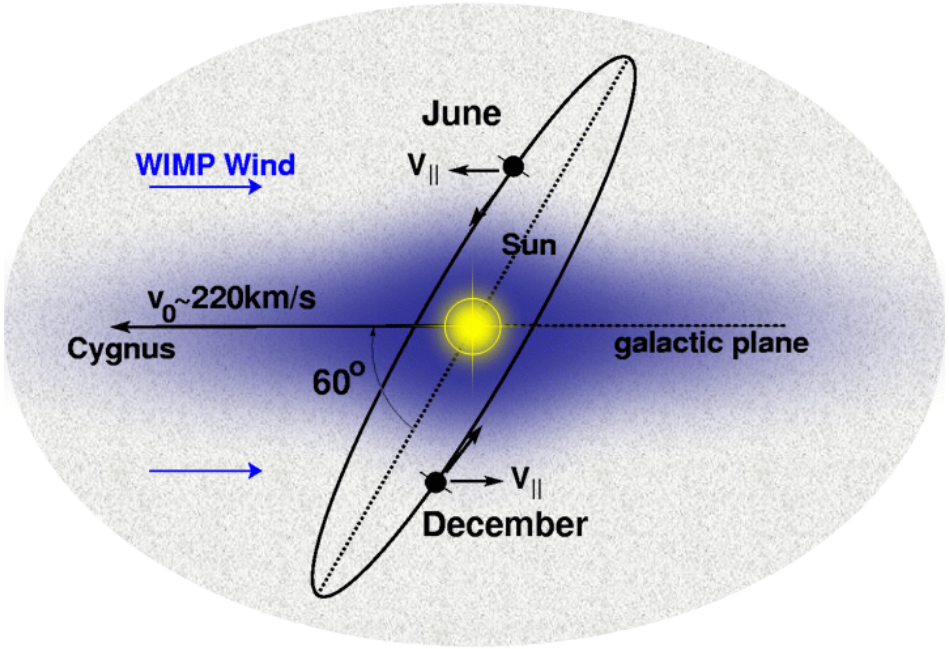




Detecting **WIMP**s/Nonbaryonic Matter

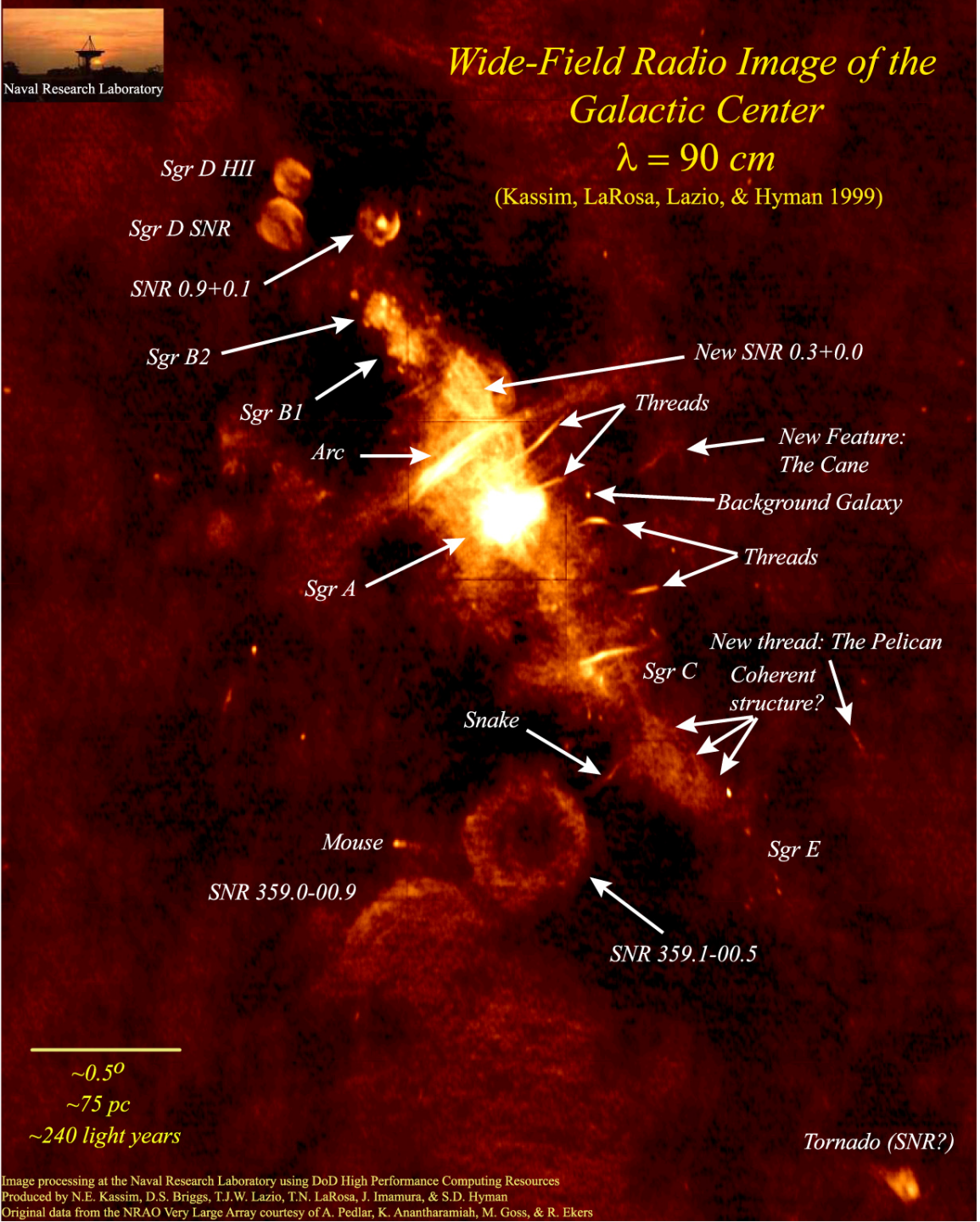
- Billions of WIMPs pass through you every second
- Shield detector: put it 2km down at the bottom of the mine
- WIMP hits atom making flash or ionized trail
- More energetic collisions in summer/winter
- Most of the mass in universe is Dark Matter





Center of Milky Way in Visible 40°

- Visible blocked by dust cloud ~1000pc: observe in IR, Radio, X-Ray

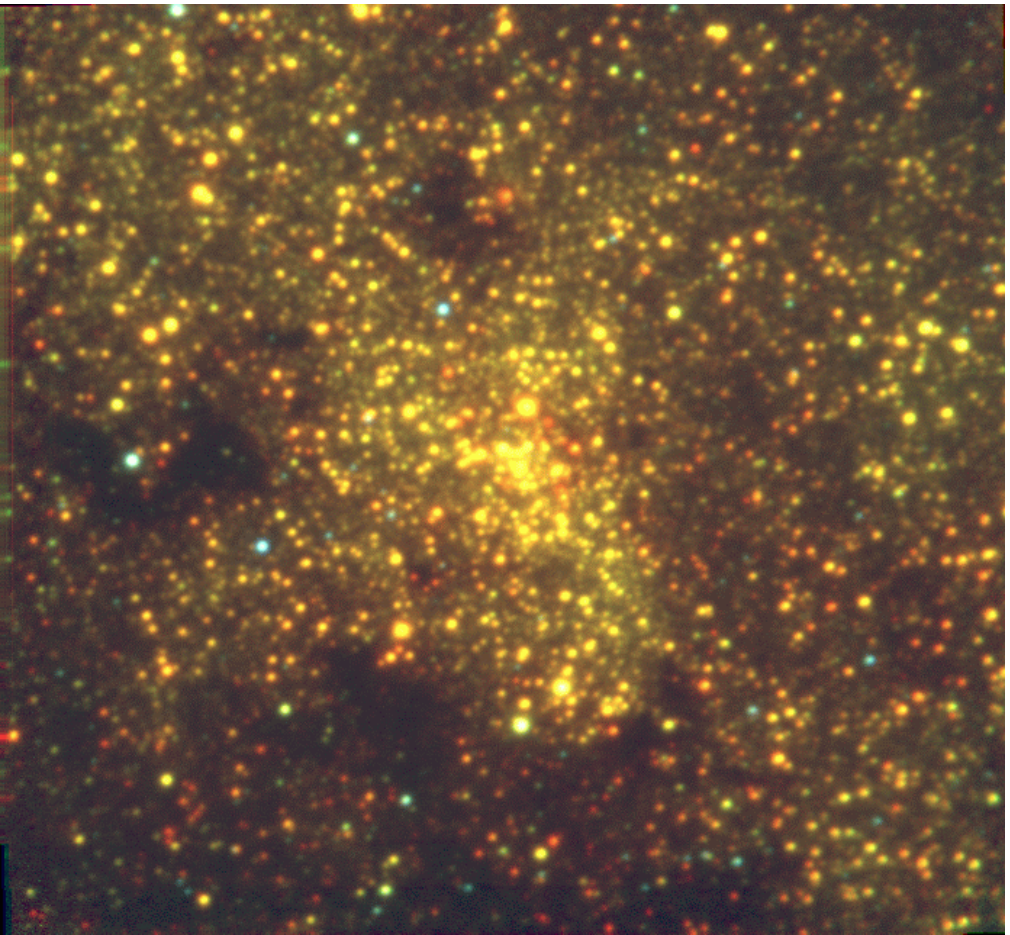


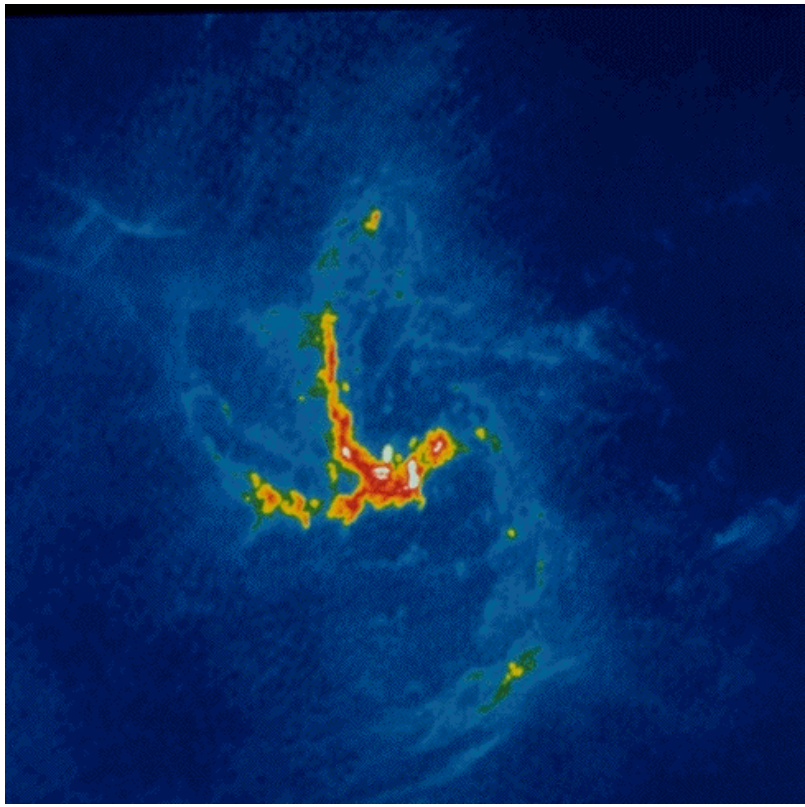
Galactic Center in Radio 4°

- Sagittarius A is powerful radio source
- Magnetic fields
- Lots of star formation
- Supernovae Remnants

Central 10 light years=60”

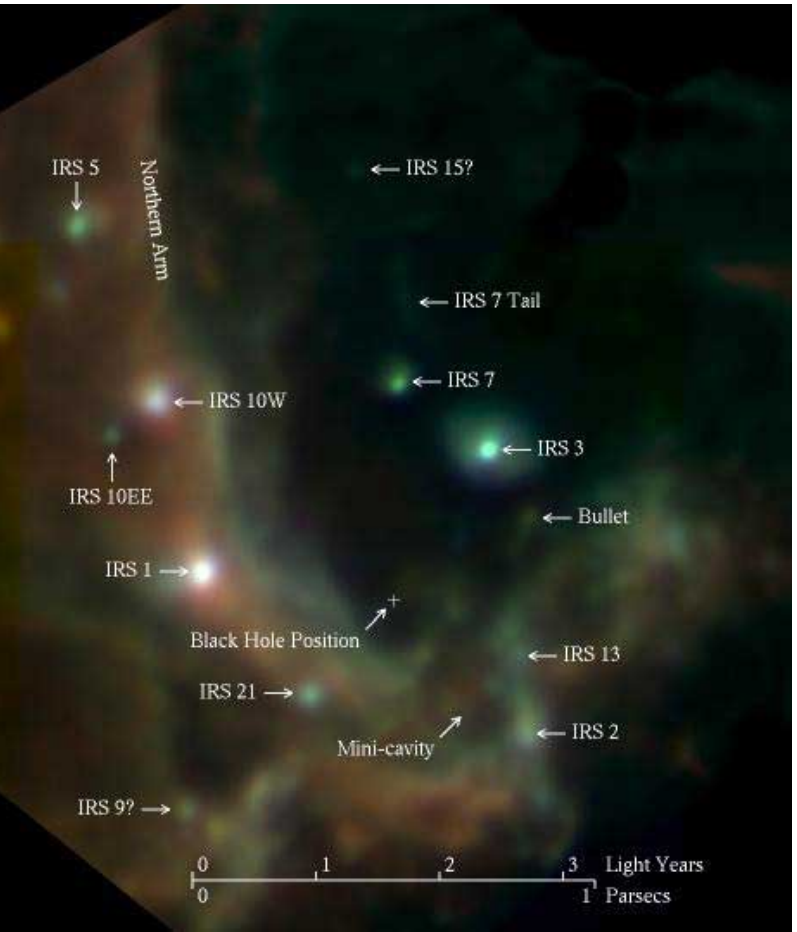
- Radio shows Mini-Spiral of molecular cloud falling into black hole
- Infrared => crowded central star cluster
- A million stars as bright as Sirius

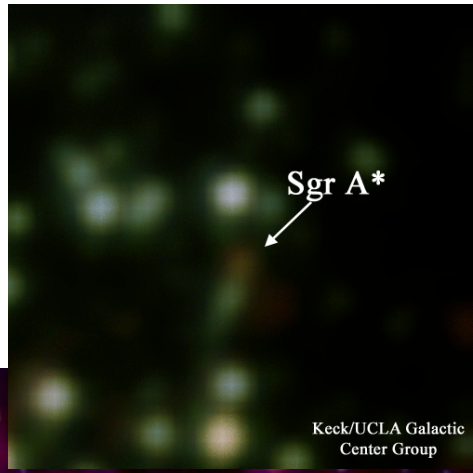


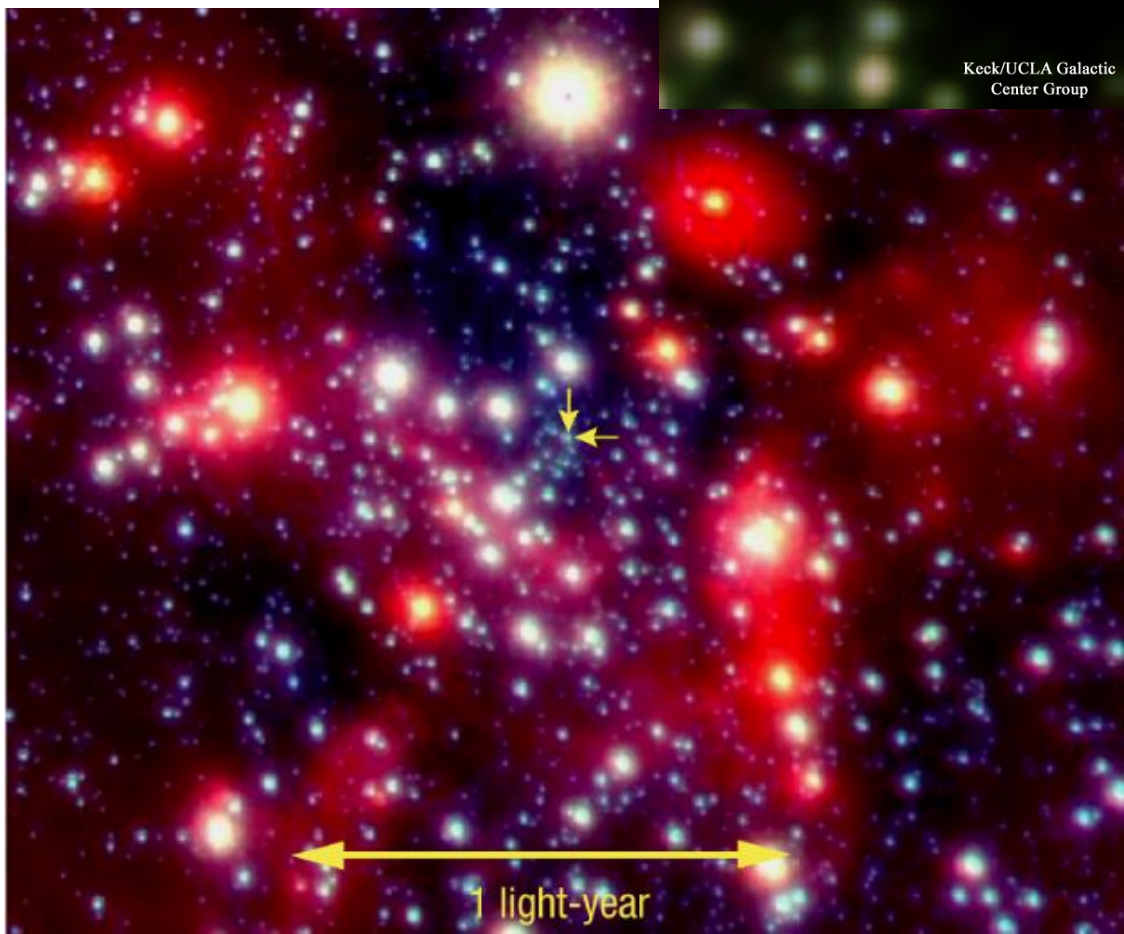


SGR A* Mid & Near IR 10”

- Stars warm the dust falling into BH
- Near IR shows many stars
- **SgrA*** IR brightness varies in 2hours=15AU

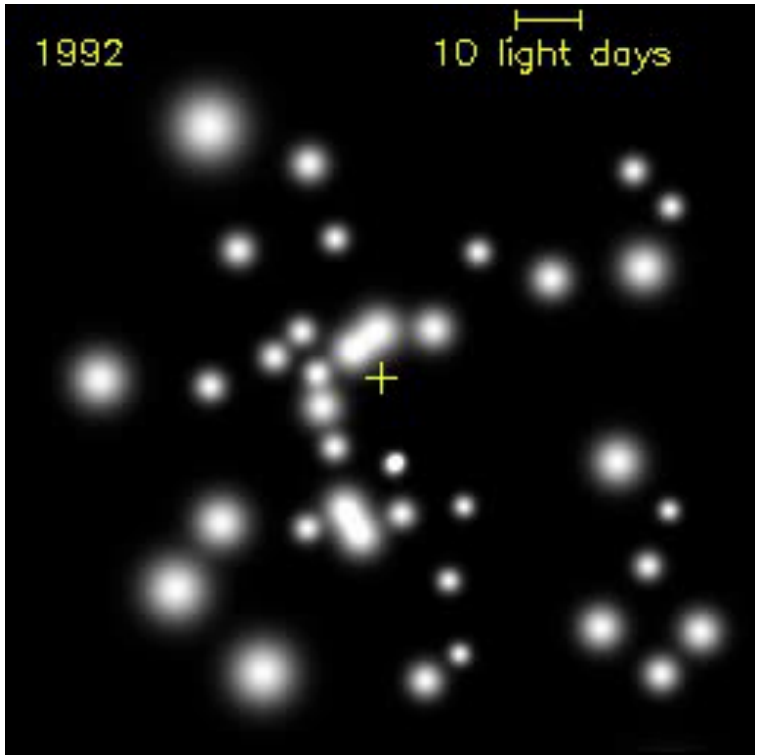






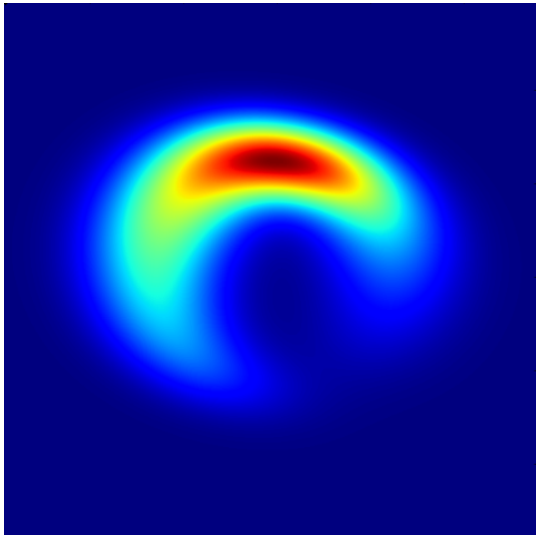
Galactic Nucleus=SGR A* 0.5” IR

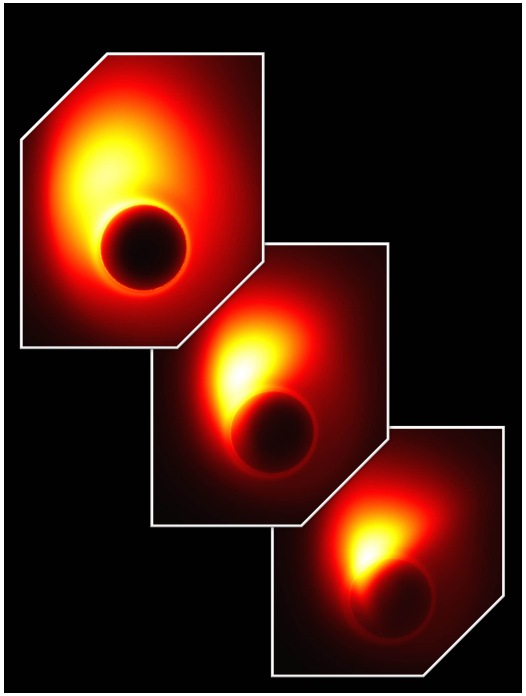
- Visual Binary - Period=15years Semi Major Axis=900AU
  Mass=A^3/P^2 =3.7 million solar masses
- Closest approach =120AU = 17 light hours
- Diameter of BH would be 10 million km (<1AU) = 13 times sun’s diameter



Event Horizon Telescope 2020?

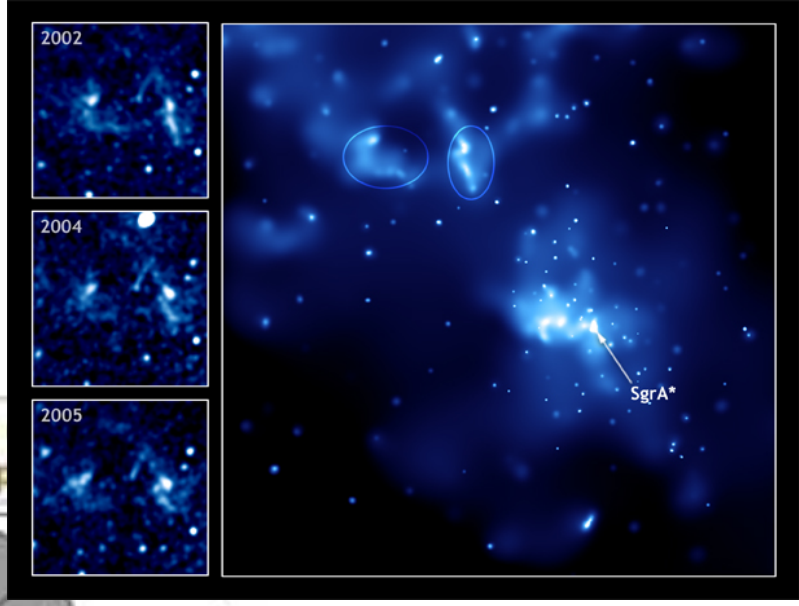
- Combines many small telescopes to resolve inner ring of accretion disk of Black Hole
- Calculations of what disk will look like

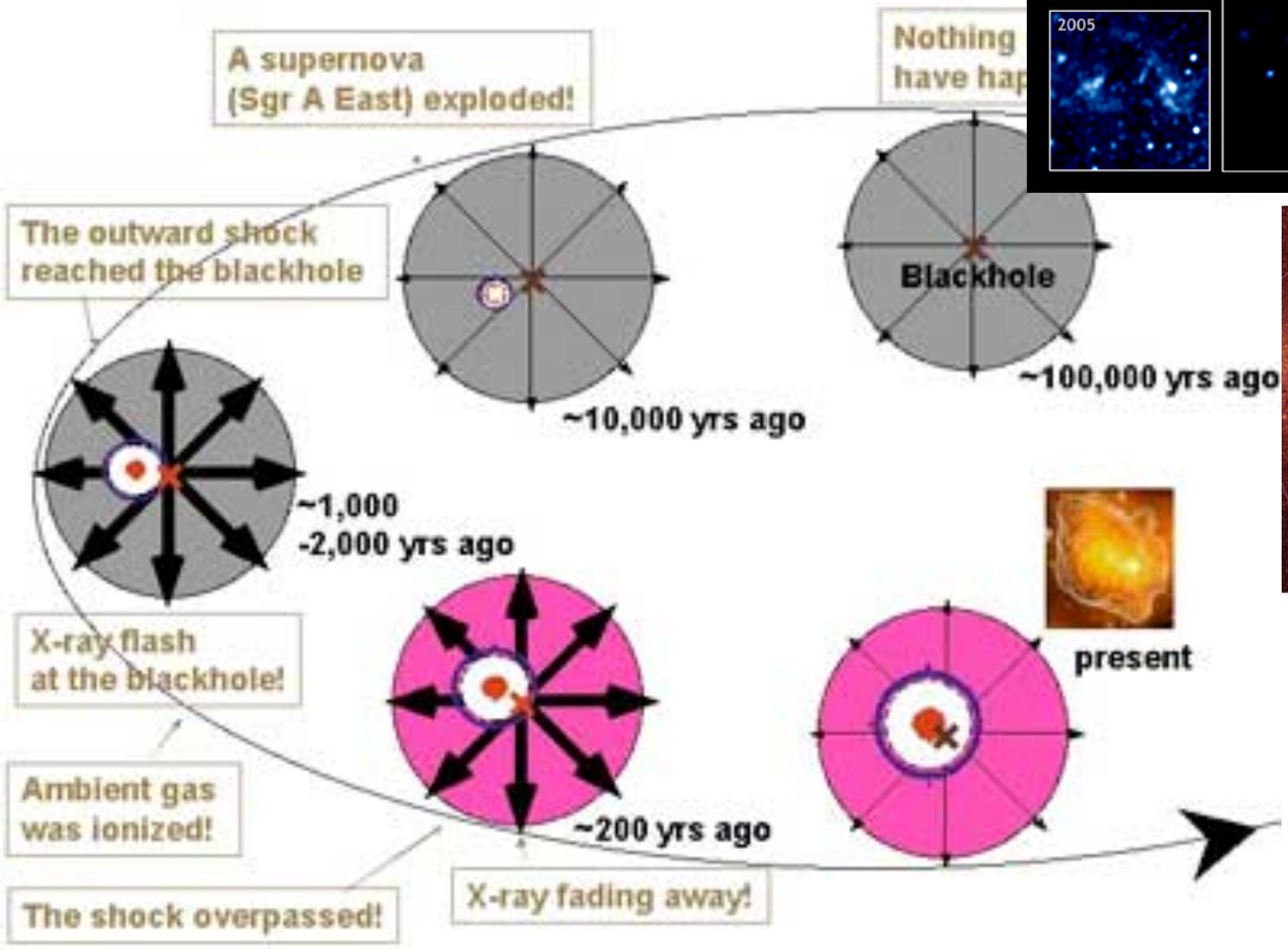


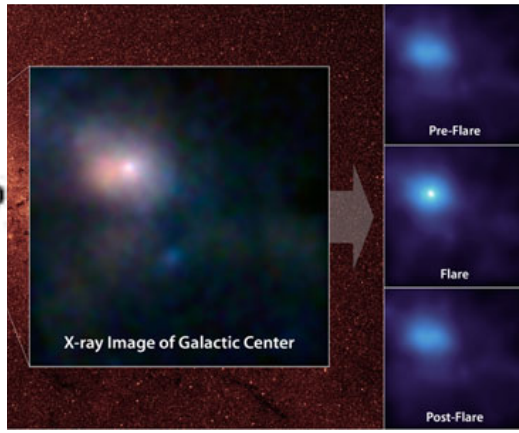


A Quiet Black Hole?

- 0.0002 solar masses/year for brightness
- Light echo of past greatness

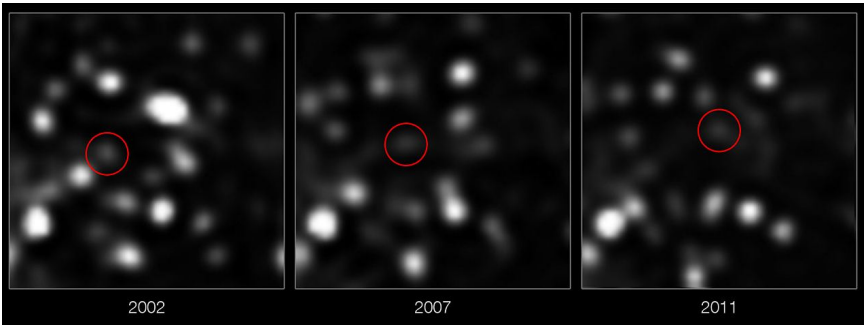


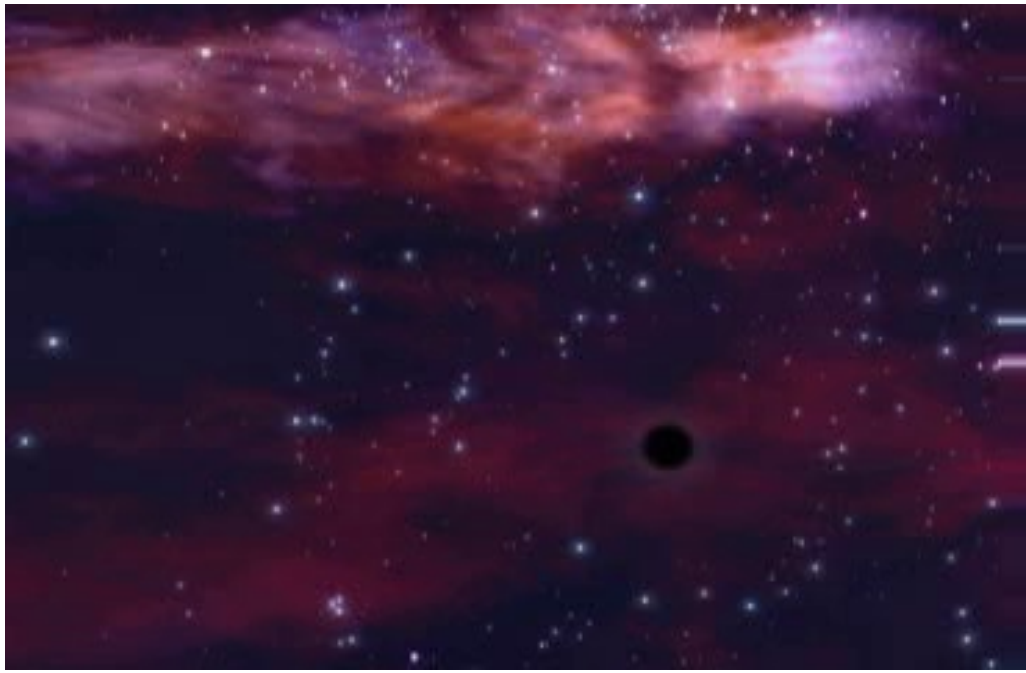


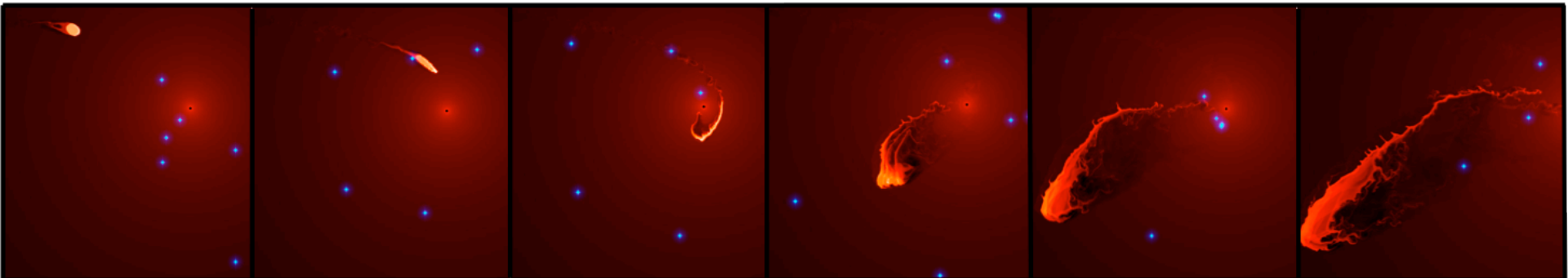


If/When Star/Cloud G2 Gets Too Close

- The black hole's tides pull it apart mid-2014??
- Some of the gas would fall in glowing in X-rays







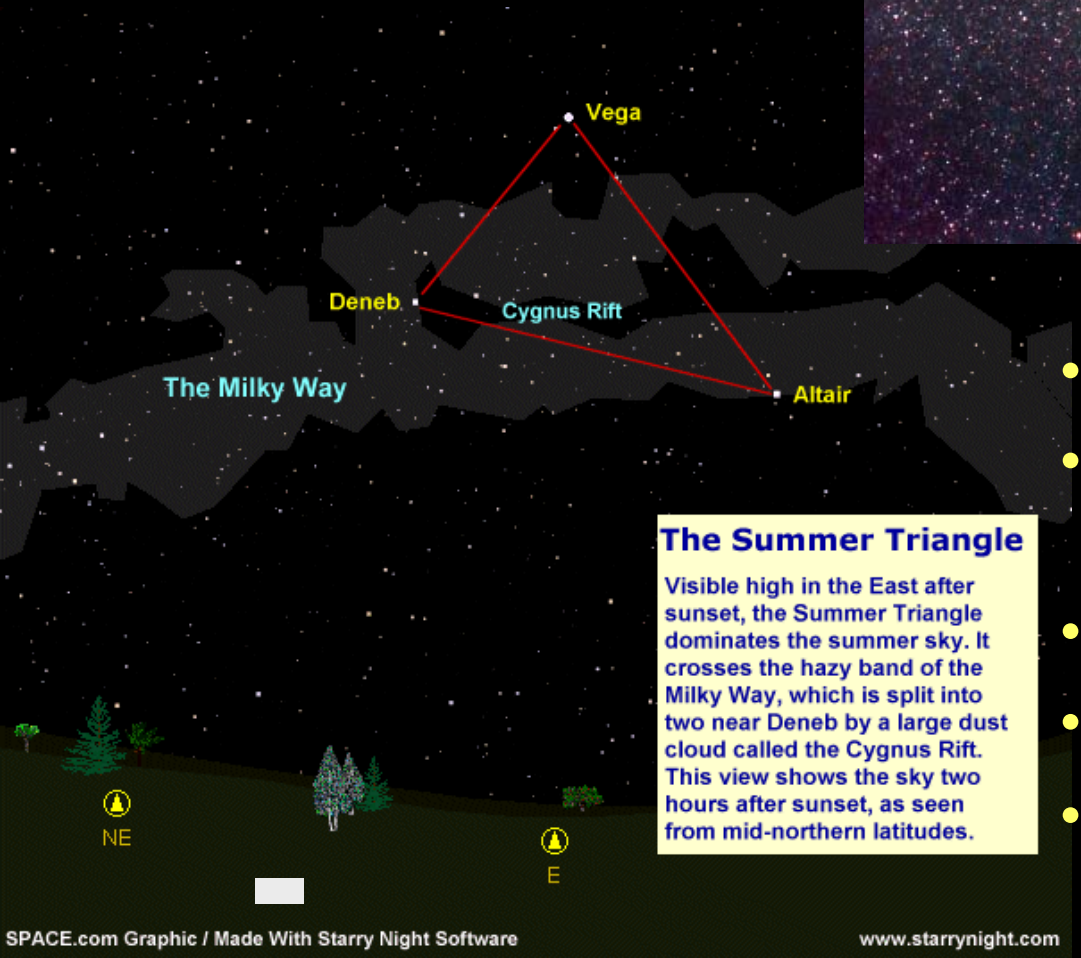
Which of the following statements in NOT correct?

a. The rotation curve of our Galaxy indicates that most of the mass of the Galaxy is Dark Matter
b. At the Galactic Nucleus (Sgr A*) is a million solar mass black hole
c. Galaxies are Spiral, Elliptical or Irregular types
d. The more distant a galaxy, the faster it seems to be moving away from us
e. All of these are correct

Milky Way Center in IR

- 2° =900light year - Spitzer data

Chinese Valentines Day



The Summer Triangle

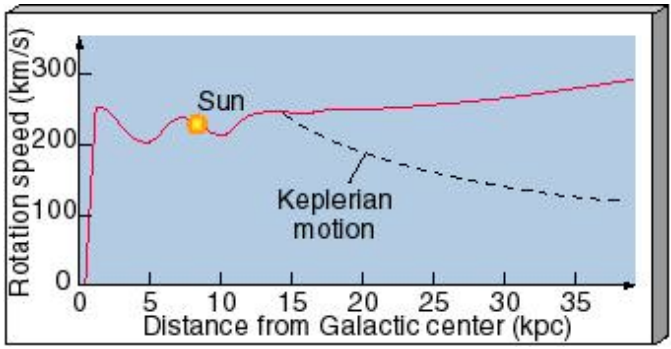
Visible high in the East after sunset, the Summer Triangle dominates the summer sky. It crosses the hazy band of the Milky Way, which is split into two near Deneb by a large dust cloud called the Cygnus Rift. This view shows the sky two hours after sunset, as seen from mid-northern latitudes.

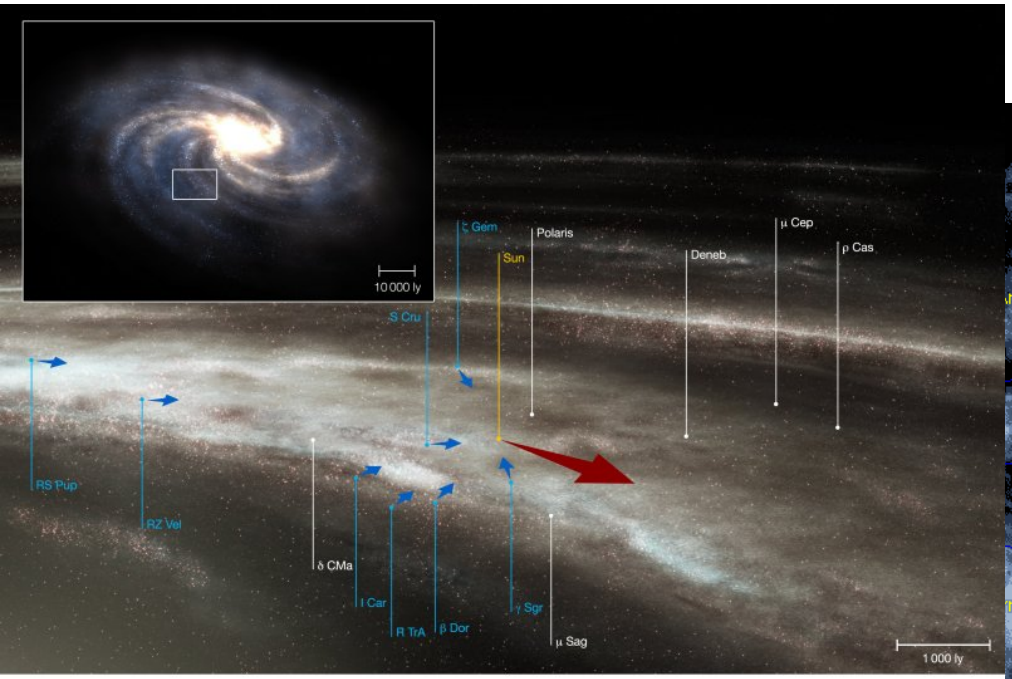
- On the 7th day of the 7th month
- Cowherd (Altair) loved & married Princess (Vega)
- Separated by Mother
- Can cross bridge of magpies
- Over Milky Way (River)

1° Center of Milky Way

- Near IR (Hubble Telescope) spans 300ly

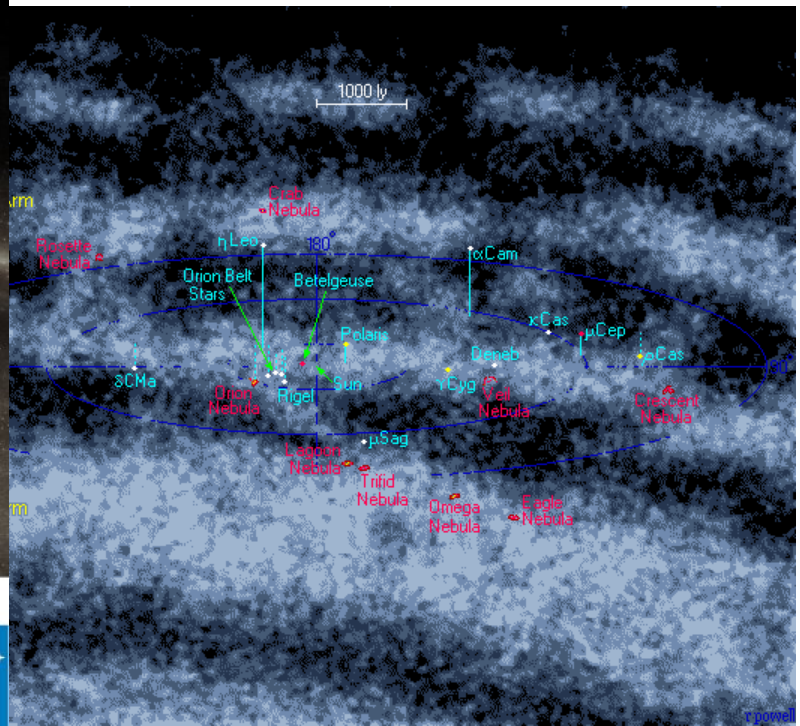
Pop I Traces Nearby Parts





Cepheids in the Solar Neighbourhood

(Artist's impression)

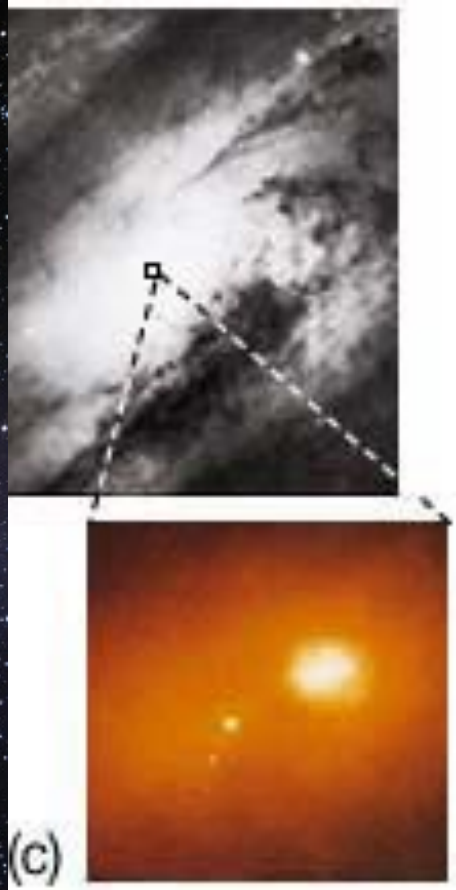


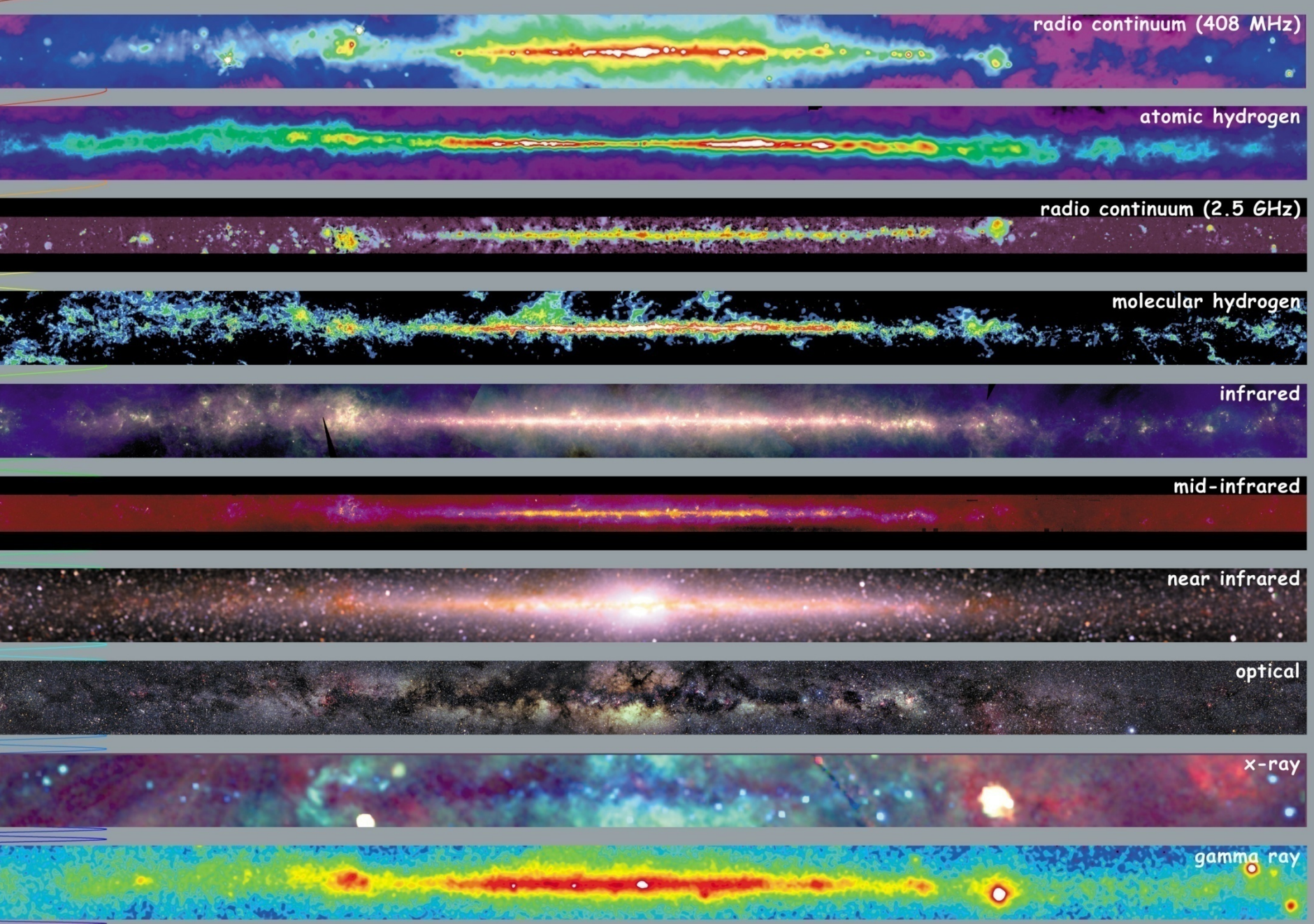
ESO PR Photo 30/08 (19 September 2008)

Milky Way Over Paranal

M31 Andromeda Galaxy

- Milky Way looks like Andromeda galaxy
- With **Disk**, **Bulge**, **Halo**, **Galactic Nucleus**



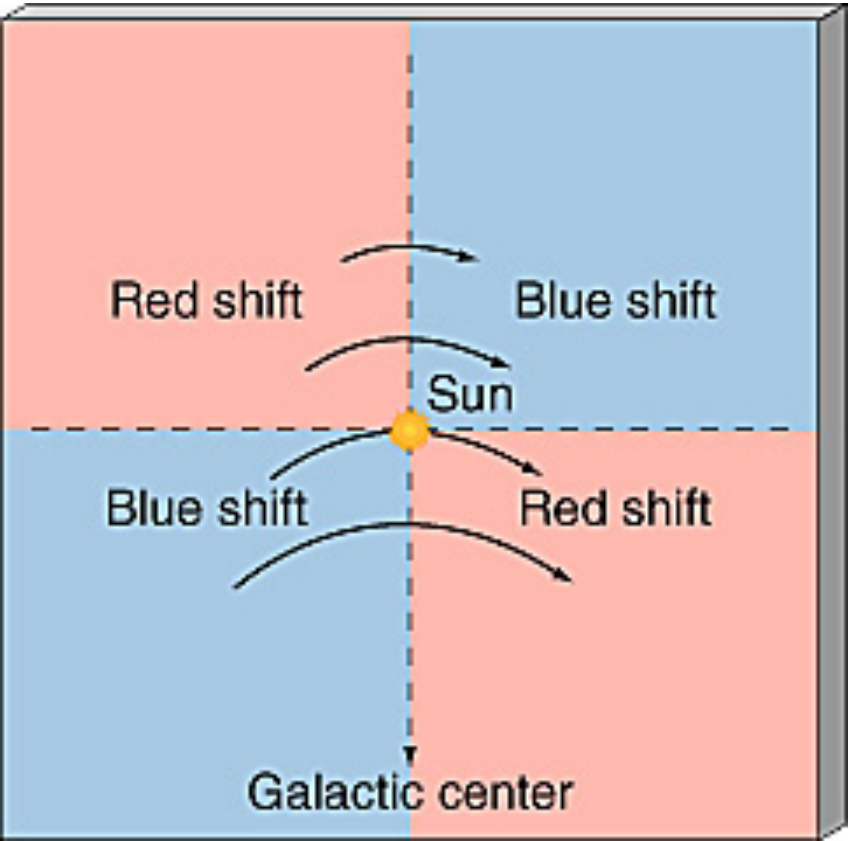


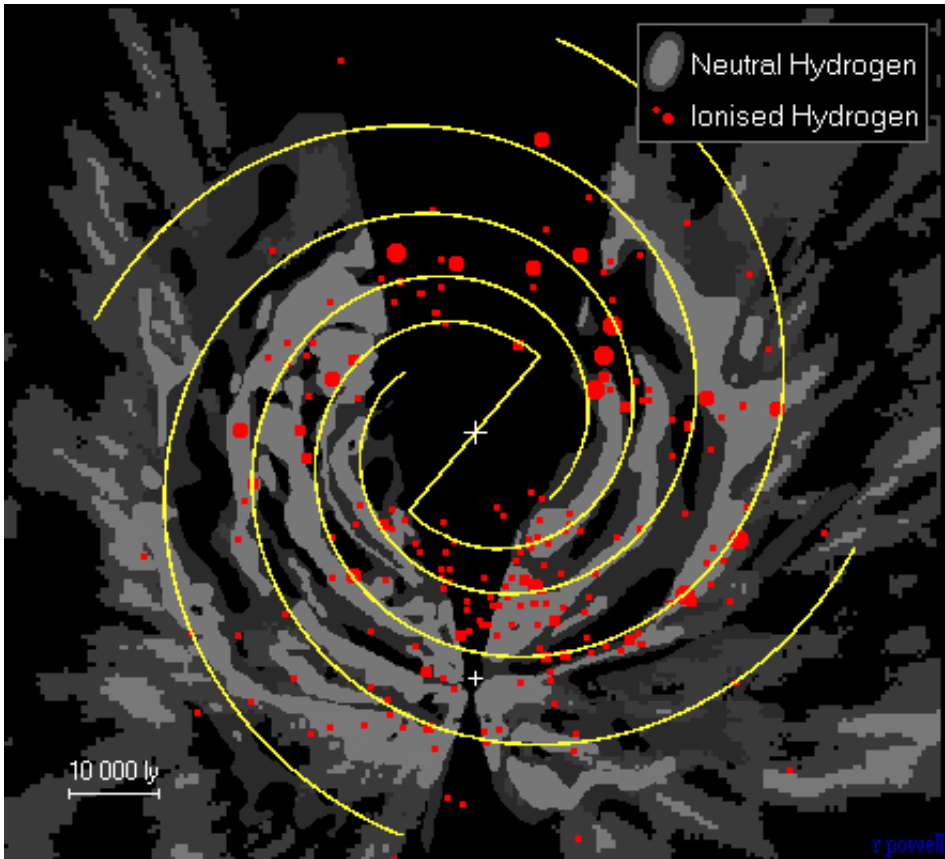
http://adc.gsfc.nasa.gov/mw

Multiwavelength Milky Way

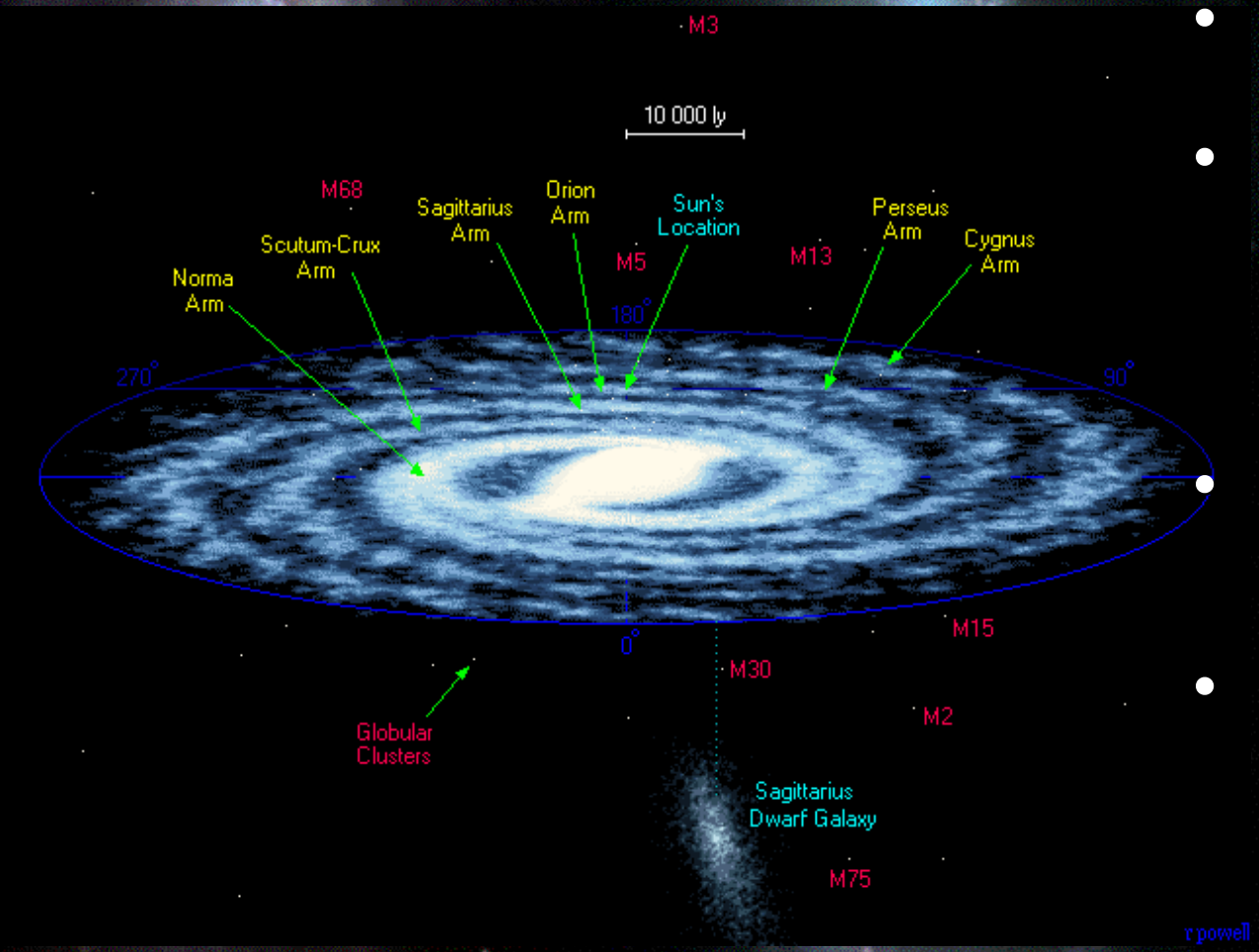
Radial Velocity Relative to Sun

- Sun approaches stars in some sectors
- Radio will see through dust (21-cm)
- Some sectors have no radial velocity difference – Galactic center and anticenter





50,000 Light Years



- Our Sun is ~26,000 ly from centre.
- Towards centre of Galaxy stars are packed together much closer than they are near Sun.
- Globular clusters lie well outside the plane of the Galaxy
- Nearby Sagittarius dwarf galaxy is slowly being swallowed up by our own galaxy.

Number of stars within 50 000 light years = 200 billion

Spiral Galaxy and Comet Ikeya-Zhang

- The comet is very near and M31 is 2 million light years away
- Can we find the Milky Way's shape by counting foreground stars?

Stars, Milky Way & Zodiacal Light

- Herschel assumed all stars same brightness and no dust

Canadian Galactic Plane Survey 21cm

- ~100K, 1-1000 atoms/cc, neutral hydrogen atoms, HI clouds
- Shows size of neutral Hydrogen clouds; frothy, turbulent motions