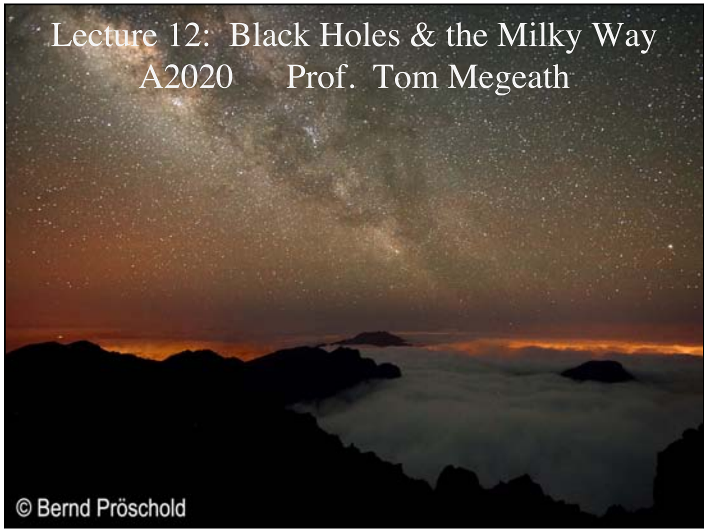
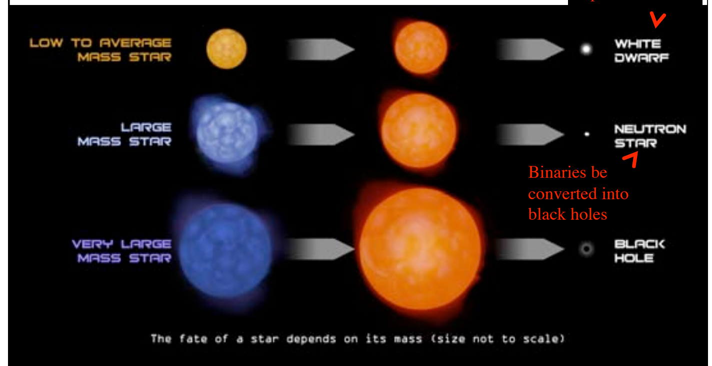
Lecture 12: Black Holes & the Milky Way
A2020 Prof. Tom Megeath



Review: Creating Stellar Remnants

Binaries may be destroyed in white dwarf supernova



Review: Stellar Remnats

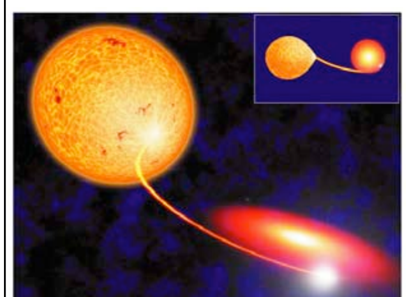
Cores of low mass stars (carbon) --> white dwarfs (size of the Earth)

Cores of high mass stars (left over from collapse of iron core and resulting supernova) --> neutron stars (size of Toledo)

White dwarfs:
1. supported by electron degeneracy pressure
2. Maximum mass 1.4 solar masses
3. In binary systems, if they accrete enough mass so mass exceeds 1.4 solar masses - white dwarf supernova.

Neutron stars
1. Supported by neutron degeneracy pressure
2. Maximum mass 3 solar masses

Accretion Disks



- Mass falling toward a white dwarf or neutron stars from its close binary companion has some angular momentum.
- The matter therefore orbits the white dwarf in an *accretion disk*
- Friction between orbiting rings of matter in the disk transfers angular momentum outward and causes the disk to heat up and glow

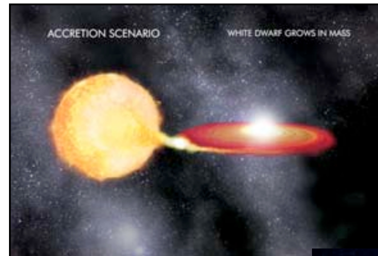
Two Types of Supernova

Massive star supernova:

Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion

White dwarf supernova:

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing total explosion



Triggering White Dwarf Supernova

White dwarf fed by accretion disk until it exceeds 1.4 solar masses

White dwarf binary combines and exceeds 1.4 solar masses

http://chandra.harvard.edu/photo/2010/type1a/animations.html

Black Holes

A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.

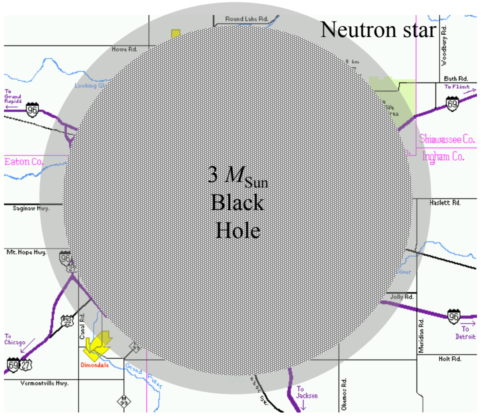
Initial Kinetic Energy = Final Gravitational Potential Energy

$$\frac{(\text{escape velocity})^2}{2} = \frac{G \times (\text{mass})}{(\text{radius})}$$

"Surface" of a Black Hole

- The "surface" of a black hole is the radius at which the escape velocity equals the speed of light.
- This spherical surface is known as the ***event horizon.***
- The radius of the event horizon is known as the ***Schwarzschild radius.***

Radius = 2 G M / c^2 where M = mass of the black hole, c is the speed of light, G is the gravitational constant.



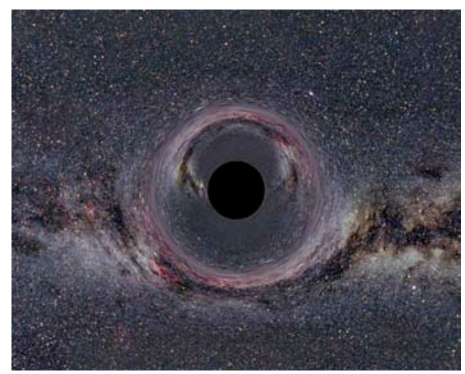
The event horizon of a $3\ M_{Sun}$ black hole is also about as big as a small city

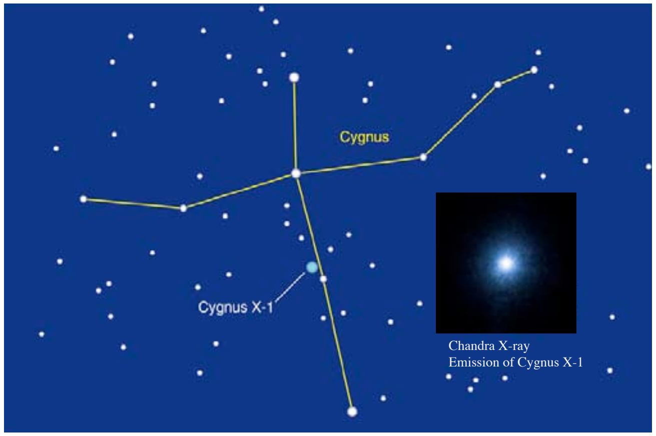
Neutron Star Limit

- Quantum mechanics says that neutrons in the same place cannot be in the same state
- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about $3\ M_{sun}$
- Some massive star supernovae can make black hole if enough mass falls onto core

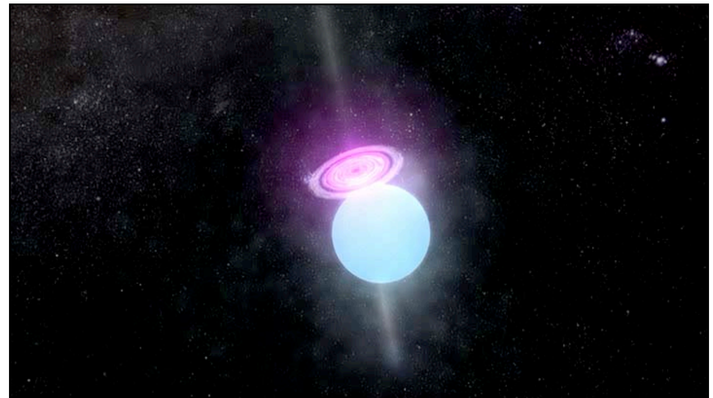
How do you find a black hole?

Gravitational Lenses





X-ray binaries may also harbor black holes



- Need to measure mass
  - Use orbital properties of companion
  - Measure velocity and distance of orbiting gas
- It's a black hole if it's not a star and its mass exceeds the neutron star limit (~3 M_{Sun})

The Galactic Center in the Near-Infrared (seeing stars through the dust)

Galactic Center in Mid-Infrared Light

Spitzer space telescope, infrared image, S. Stolovy

The Galactic Center in Radio Waves

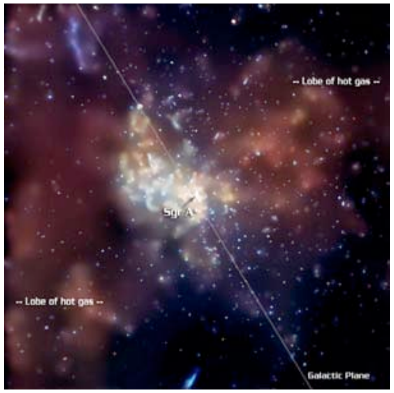
The Galactic Center in X-rays

Lots of hot gas and X-ray binaries. What is creating the hot gas?

Galactic center in X-ray (blue), near-IR (green) and mid-IR (red)

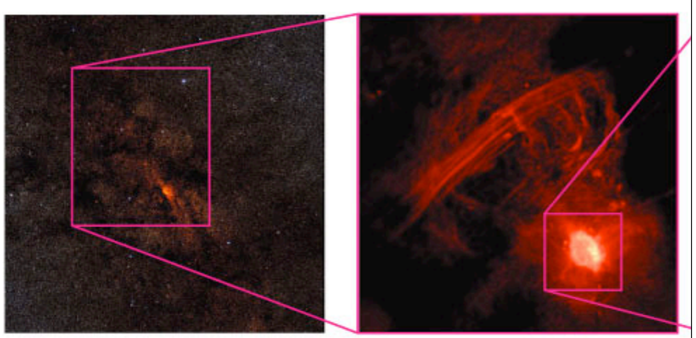
Zooming in on the Galactic Center with X-rays

The Center of the Galaxy In X-rays



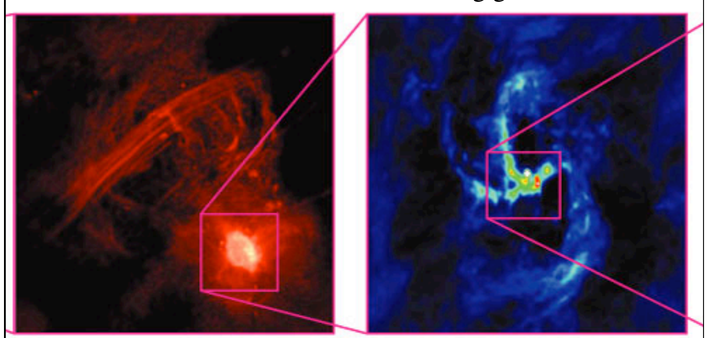
Infrared light from center

Radio emission from center



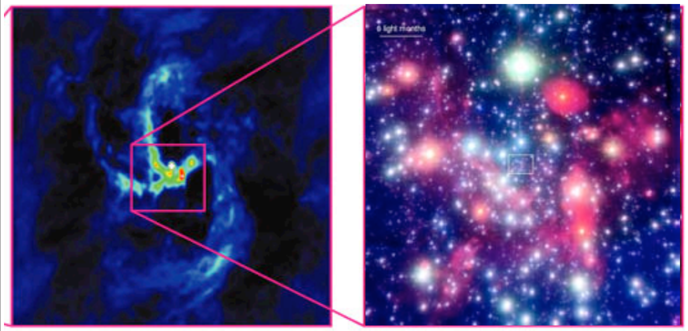
Radio emission from center

Swirling gas near center

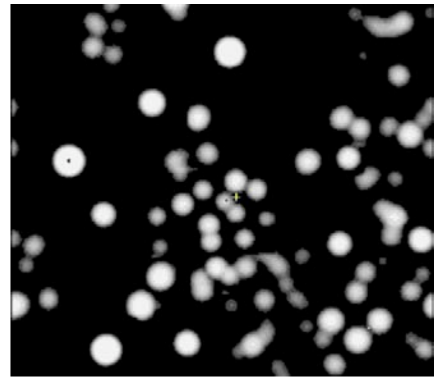


Swirling gas near center

Orbiting star near center



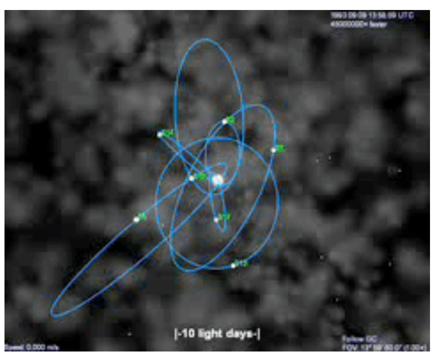
Black Hole in the Galactic Center



This is an infrared image of the stars in the galactic center.

In the center, at the position of the cross, is a source emitting radio waves - this might be the black hole.

Orbits of stars around black hole

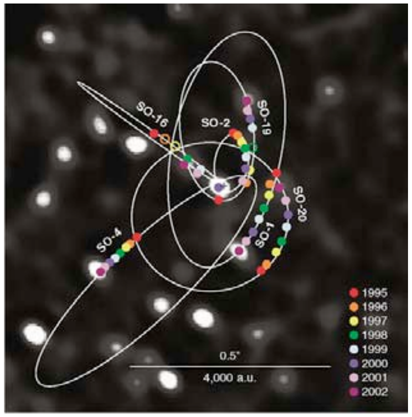


http://www.mpe.mpg.de/ir/GC/index.php

Orbital Velocity Law

$$M_r = \frac{r \times v^2}{G}$$

- The orbital speed (v) and radius (r) of an object on a circular orbit around the black hole tells us the mass (M_r) within that orbit



Stars appear to be orbiting something massive but invisible … ***a black hole?***

Orbits of stars indicate a mass of about 4 million M_{sun}

The closest star is 17 light hours from the black hole - moving 5000 km/s

Best evidence for a supermassive black hole: the center of our galaxy

The motions of stars in the center show the presence of a compact dark mass with a total mass of 4 million suns.

The mass, small size and darkness of this object all point to a black hole.

X-ray emission is occasionally emitted by this black hole (eating up a star or gas cloud)

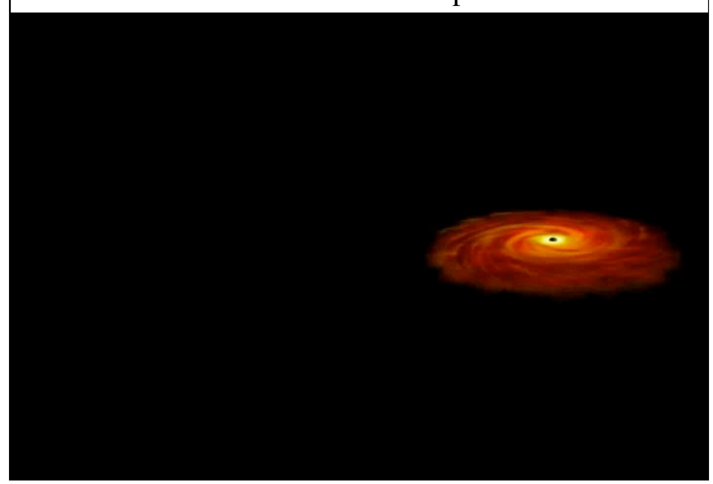
Where does the cluster of massive stars come from?

•High mass stars have short life times

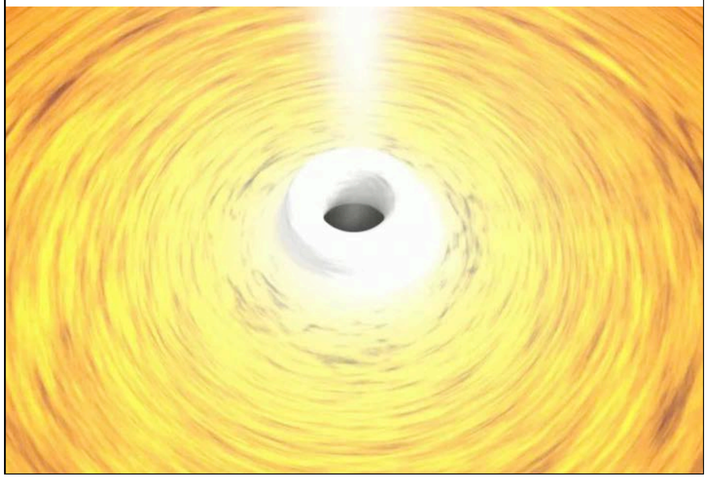
•How do you get young stars near a supermassive black hole?

•There are two popular scenarios.

Scenario 1: The black hole captures a cluster

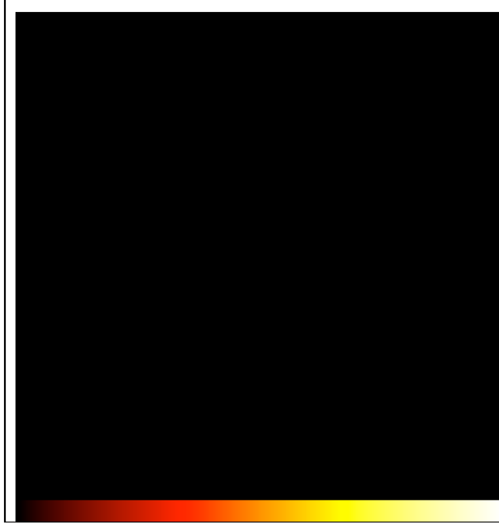


Scenario 2: Stars form in the gas orbiting the black hole.



Clue: We find high mass star but no low mass stars.

Star formation in a disk would produce primarily high mass stars.



Simulation of star formation around a black hole (Bonnell & Rice)

Ingredients:

Black hole
Infalling cloud of gas

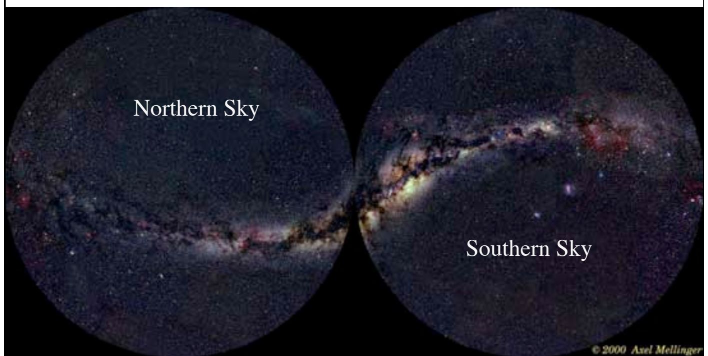
Result

Star formation

The Structure of the Milky Way Galaxy

The Milky Way galaxy appears in our sky as a faint band of light

The Milky Way in the Night Sky



We live inside the Milky Way galaxy. Every star you see in the night sky is part of the Milky Way galaxy. The Milky Way itself – which is only seen on a dark night – is the combined glow from distant stars.

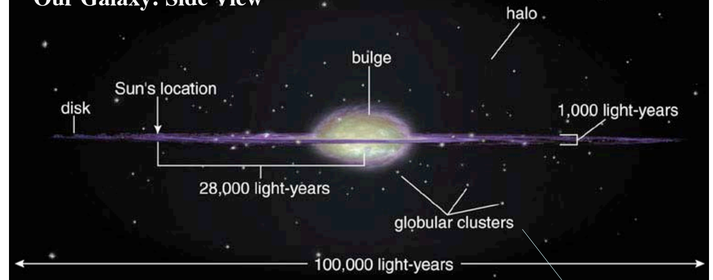
The Milky Way in Visible Light

View from the Earth: *Edge On*

The Milky Way in the Infrared

View from the Earth: *Edge On*

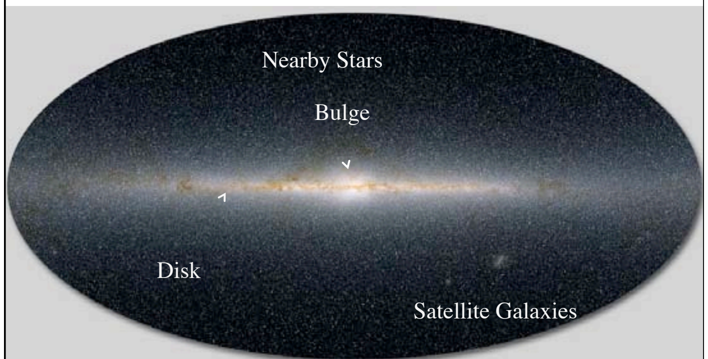
Our Galaxy: Side View



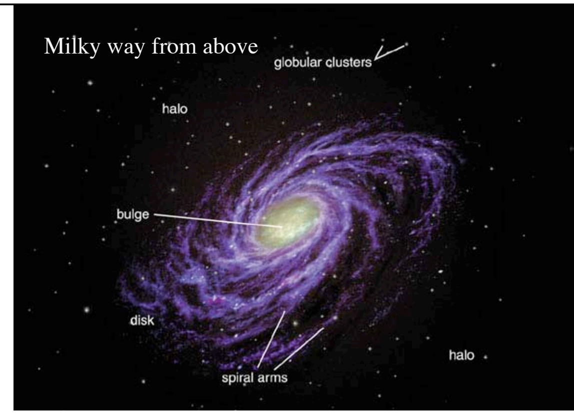
We see our galaxy edge-on

Primary features:
Disk: young and old stars – where we live.
Bulge: older stars
Halo: oldest stars, globular clusters, dark matter

The Milky Way in the Infrared



View from the Earth: *Edge On*



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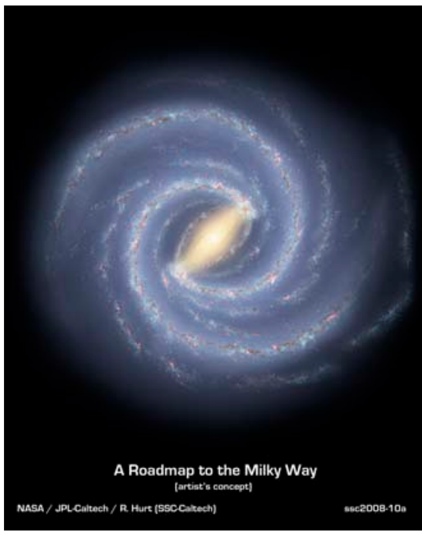
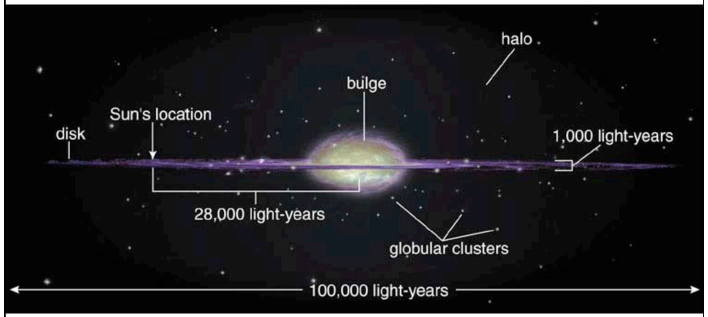


The center of the Galaxy has a bar!

Such bars are seen in the bulges of other galaxies.

This was only confirmed by in our Galaxy by Spitzer in recent years.

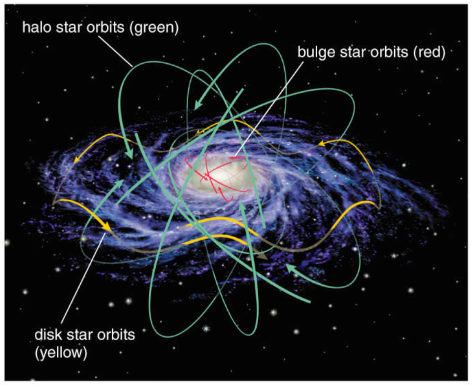
Two of the spiral arms start at the end of the bar.

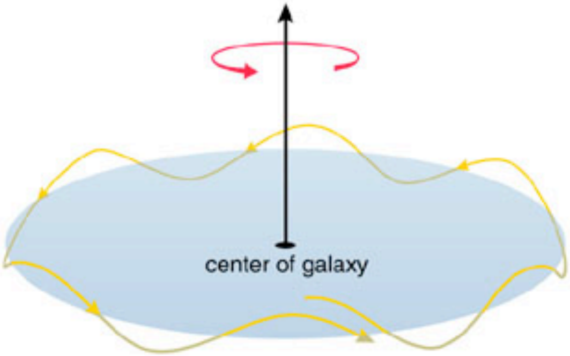


We see our galaxy edge-on

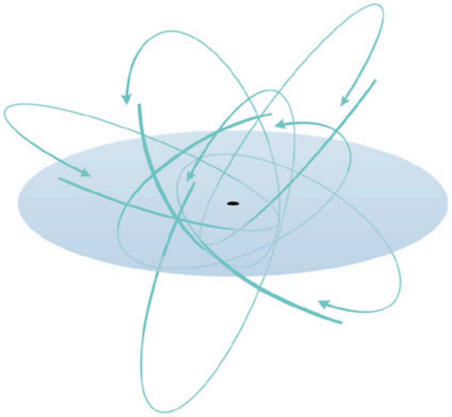
Primary features: disk, bulge, halo, globular clusters

How do stars orbit in our galaxy?

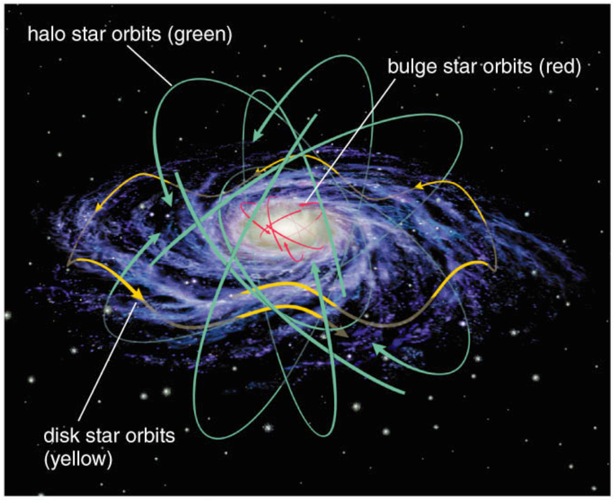




Stars in the disk all orbit in the same direction with a little up-and-down motion



Orbits of stars in the bulge and halo have random orientations



Thought Question

Why do orbits of bulge stars bob up and down?

A. They're stuck to interstellar medium
B. Gravity of disk stars pulls toward disk
C. Halo stars knock them back into disk

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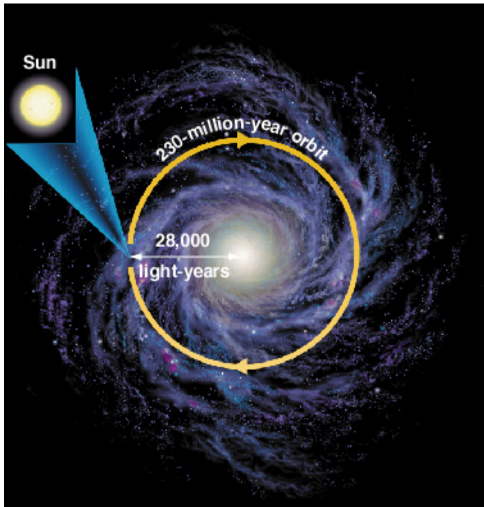
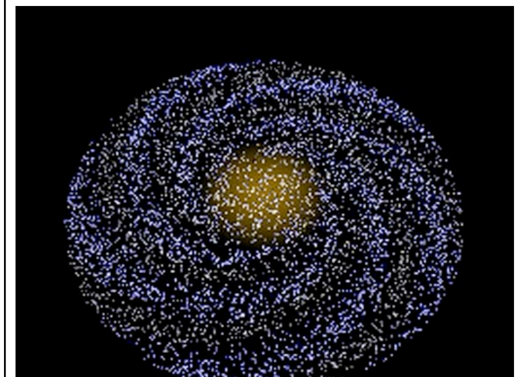


Sun's orbital motion (radius and velocity) tells us mass within Sun's orbit:

$1.0 \times 10^{11}\ M_{Sun}$

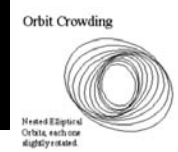
Spiral Density Waves

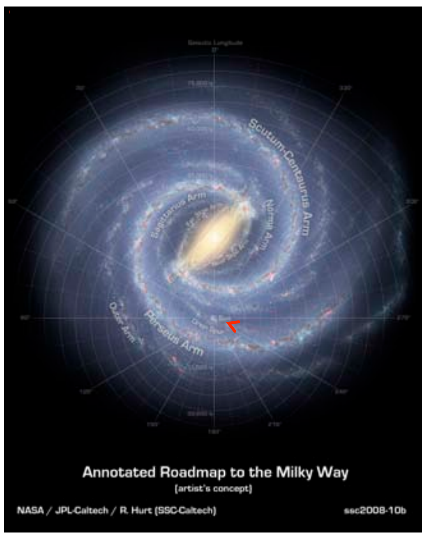


What causes spiral density waves?

Why don't spiral arms wrap up into tighter and tighter configurations?

Spiral density waves are gravity induced "traffic jams"



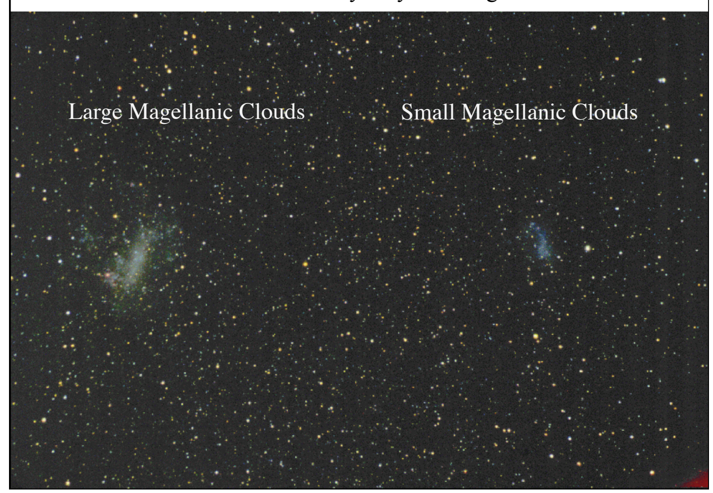


Spiral Arms & Where is the Sun?

Most stars are formed in the spiral arms of a galaxy, where gas is collected and compressed.

You are here!

Satellite Galaxies of the Milky Way: the Magellanic Clouds



Satellite Galaxies of the Milky Way: the Magellanic Clouds

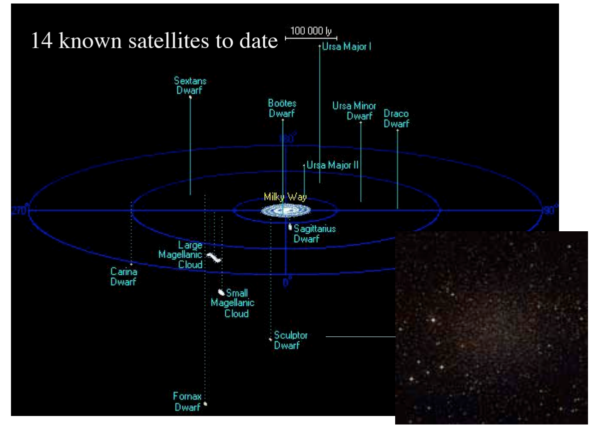
The Large Magellanic Clouds

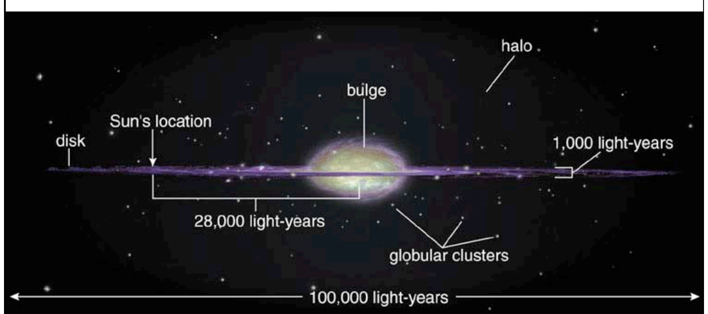
•160,000 light years away
•1/10 mass of Milky Way
•28000 light years across.

The Small Magellanic Clouds

•200,000 light years away
•1/50 mass of Milky Way
•14000 light years across.

Satellites Galaxies to the Milky Way





Thus, in the last 10 years we have learned that the disk & bulge of our galaxy is the center of a much larger, chaotic system that extends several hundred thousand light years.

Thought Question

What happens to satellite galaxies as they pass by the Milky Way?

A. The stars in the two galaxies collide
B. Nothing
C. Satellite galaxy is disrupted by tides

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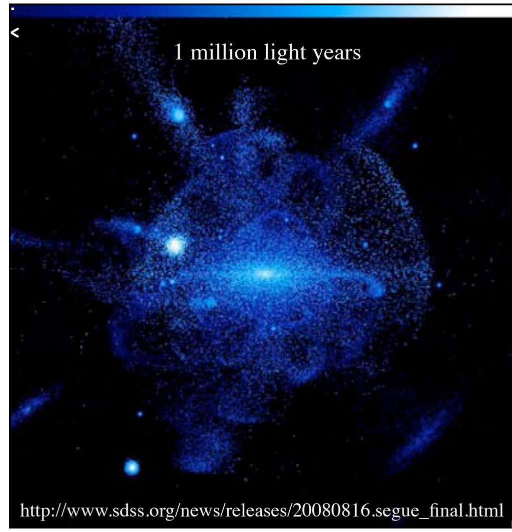

Surrounding the Milky Way are numerous small galaxies being torn apart and "eaten" by the Milky Way.

Johnston
Bullock

What clues to our galaxy's history do halo stars hold?

Halo Stars:
0.02-0.2% heavy elements (O, Fe, …),
only old stars

Disk Stars:
2% heavy elements,
stars of all ages

Halo Stars:
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Halo stars formed first, then stopped

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2% heavy elements, stars of all ages

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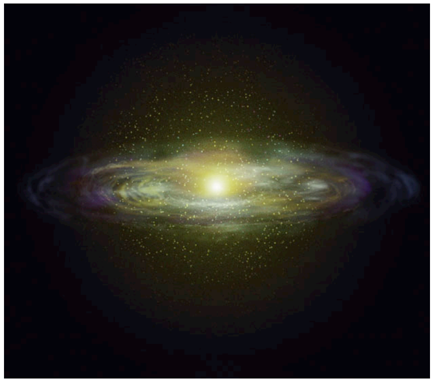
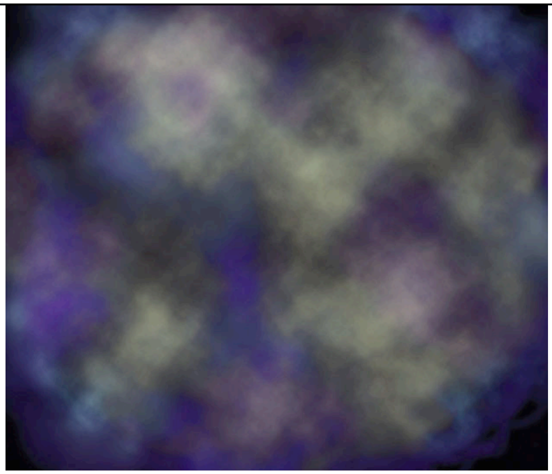
Disk Stars:
2% heavy elements, stars of all ages

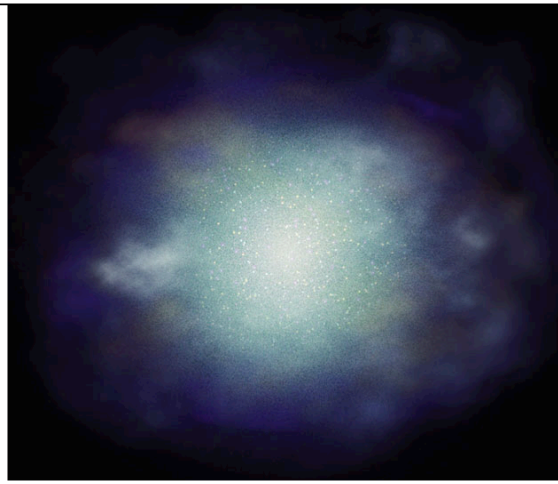
Disk stars formed later, kept forming

How did our galaxy form?

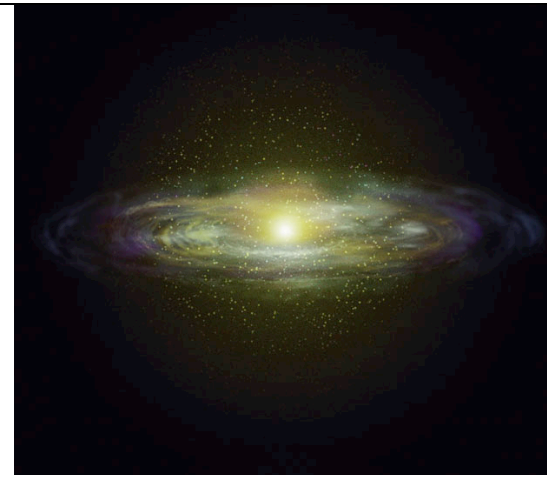




Our galaxy probably formed from a giant gas cloud

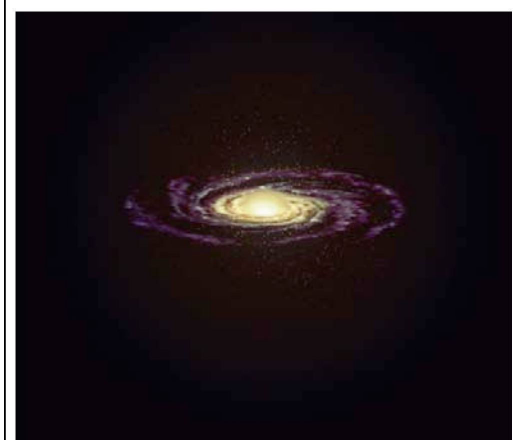


Halo stars formed first as gravity caused cloud to contract



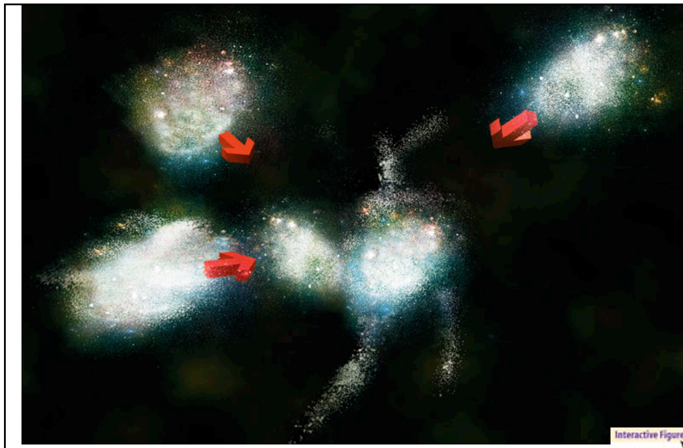
Remaining gas settled into spinning disk

Stars continuously form in disk as galaxy grows older



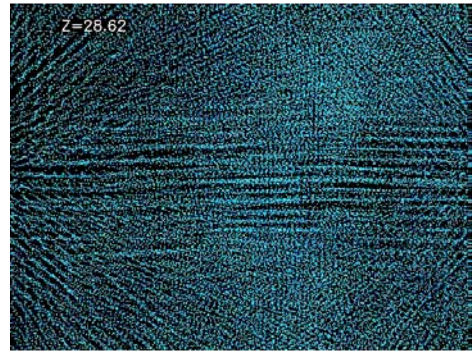
Warning: This model is oversimplified

Stars continuously form in disk as galaxy grows older



Detailed studies: Halo stars formed in clumps that later merged

February -December: Formation and Evolution of Local Group

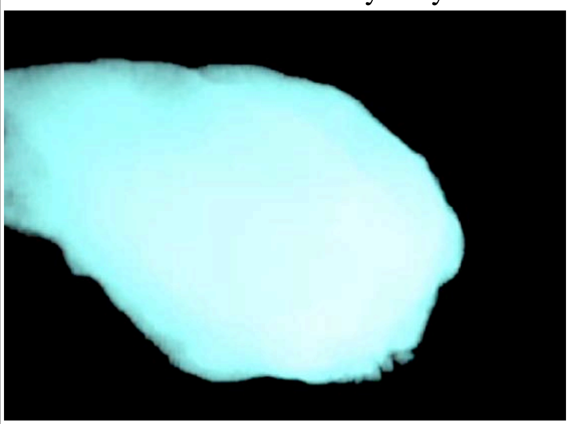


Formation of a group of galaxies like the local group:

Galaxy formation is a dynamic process in which big galaxies cannibalize smaller galaxies.

http://cosmicweb.uchicago.edu/filaments.html

The Formation of the Milky Way and other Spirals



Grey: Gas

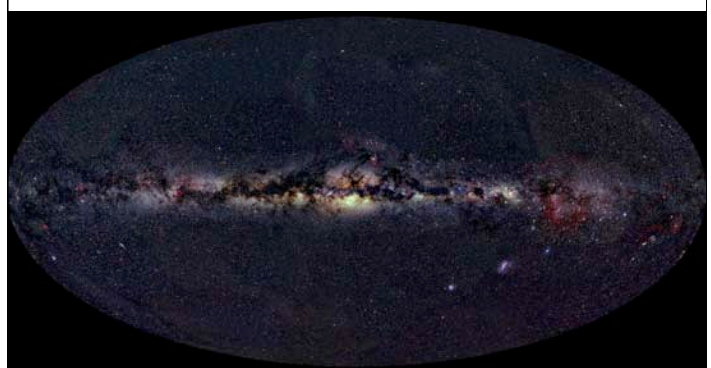
Red: older and low mass stars

Blue: young stars

This gives you 12 billion years of history

Simulation by NBodyShop and Fabio Governato (http://www.youtube.com/Nbodyshop)

The Interstellar Medium



View from the Earth: *Edge On*

© 2000, Axel Mellinger

Thought Question

What are the dark areas in the milky way?

A. Areas devoid of stars.
B. Clusters of black holes.
C. Clouds of dust and gas.

Thought Question

What are the dark areas in the Milky Way?

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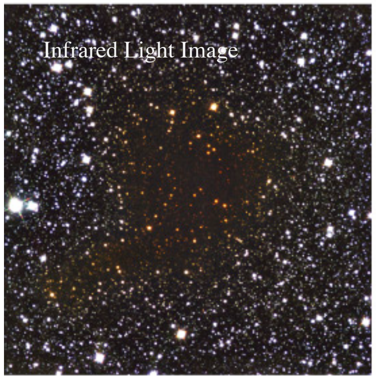
B. Clusters of black holes.
C. *Clouds of dust and gas.*

Interstellar Dust

- Clouds of gas and dust are found in the milky way.
- In these clouds, tiny solid particles of *interstellar dust* block our view of stars on the other side of a cloud

Interstellar Reddening



- Long-wavelength infrared light passes through a cloud more easily than visible light
- Observations of infrared light reveal stars on the other side of the cloud

The Universe is Mainly Hydrogen

73% Hydrogen

25% Helium

2% Everything else

But hydrodgen can have many forms:

Atomic hydrogen (electron and proton bound)

Ionized hydrogen (electrons and protons separated)

Molecular Hydrogen (two hydrogen atoms bound together)

The Interstellar Medium

The space between the stars is not empty, but filled with a very low density of matter in the form of:

•Atomic hydrogen

•Ionized hydrogen

•Molecular Hydrogen

•Cosmic Rays

•Dust grains

•Many other molecules (water, carbon monoxide, formaldehyde, methanol, etc)

•Organic molecules like polycyclic aromatic hydrocarbons

How do we detect the interstellar medium?

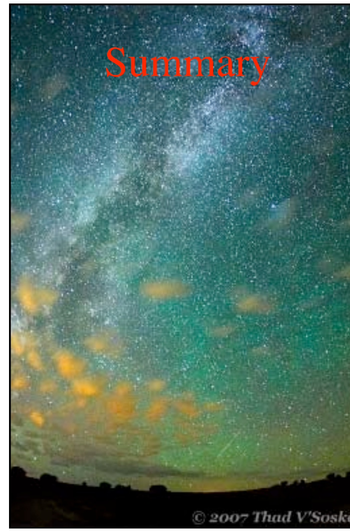
Hot ionized gas: visible light telescopes (nebula), radio telescopes

Really hot ionized gas (supernovae remants): visible light, radio telescopes, X-ray telescopes

Warm atomic gas: radio telescopes

Cold molecular gas (with dust mixed in): visible light (dark clouds) and radio telescopes

Dust and Large Molecules: visible light (dark clouds), visible light (reflection nebula), infrared light (glowing dust clouds!!)



Evidence for a black hole in the center of the galaxy.

Star formation around that black hole

Why the Milky Way appears as it does in the sky (seeing our galaxy edge on).

The parts of the Milky Way

The halo older than the disk.

Satellite Galaxies.

The formation of galaxies through cannabalism

The Universe is mainly Hydrogen.

The interstellar medium is the gas and dust (mostly hydrogen) that floats between the stars.

Hydrogen can be molecular, atomic and ionized.