How Big is Space, and What is Fills it?

No such thing as “empty” space

- Space may be much less dense than our atmosphere, but it is far from empty
- Looking at the night sky, if you live in a city or suburb, not much to see
- Far from city lights the universe emerges
- We see that we are a part of something much bigger, a galaxy
- We will see that filling space in a galaxy is an ISM that our suns protects us from

Night sky

Answering this weeks question:

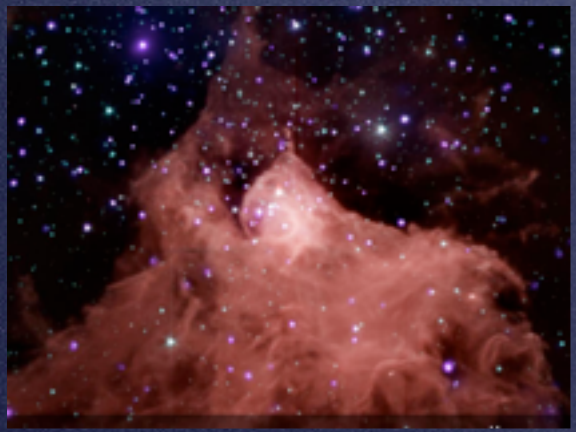
1. What exists between stars in galaxies?
2. How do we measure large distances?
3. What are the different types of galaxies?
4. What exists between galaxies?
5. Are there large scale structures bigger than galaxies?
6. If so, what fills those structures?

Interstellar Medium

Interstellar Medium (ISM)

- Gas and dust in the region between stars (outside their heliospheres)
- Not empty, but 100 trillion times less dense than Earths atmosphere (10^6 vs 10^{19} particles per cm^3)
- Enough material in the galaxy to make billions of suns like our own!
- Dense enough to support sound waves and shock waves

Types of ISM gas clouds

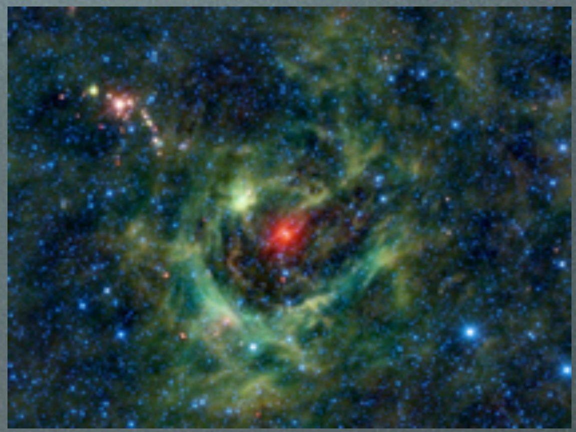


Molecular Cloud

- violet dots are newly forming stars
- low temp (≈10K) and high density (10^3-10^6 atoms per cm^3) allow molecules to form

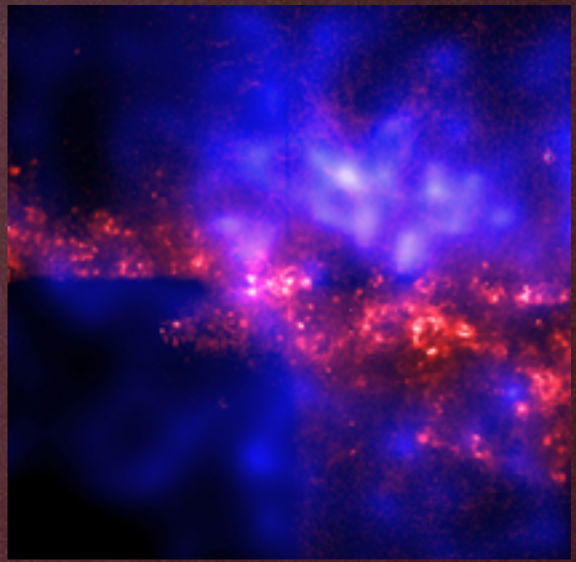
HI Cloud

- Clouds of atomic H



HII Region

- Clouds of ionized H



Coronal Gas

- Hot dense gas originating with supernova blast
- similar in density and temp to suns corona

- All 4 types of clouds have roughly the same pressure
- The still mix and interact due to turbulent winds inside of them
- Turbulence: think of smoke

smoke is a form of turbulence

ISM Dust

- ranges from .1 to 10 microns (1micron=10^{-6} m)

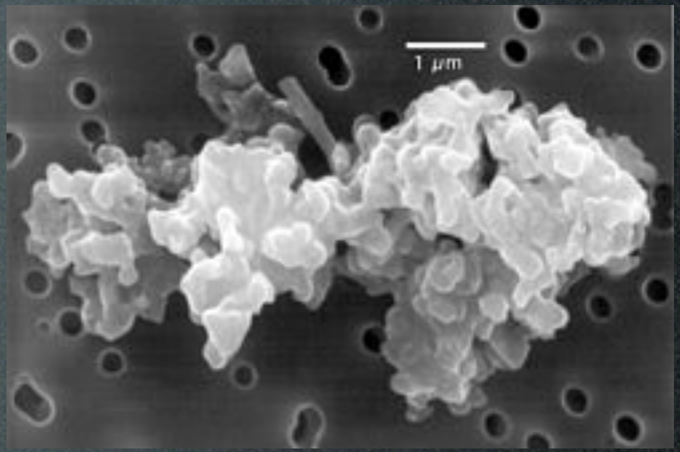
- Right size to absorb and scatter optical light

- Absorption makes objects dimmer then they really are

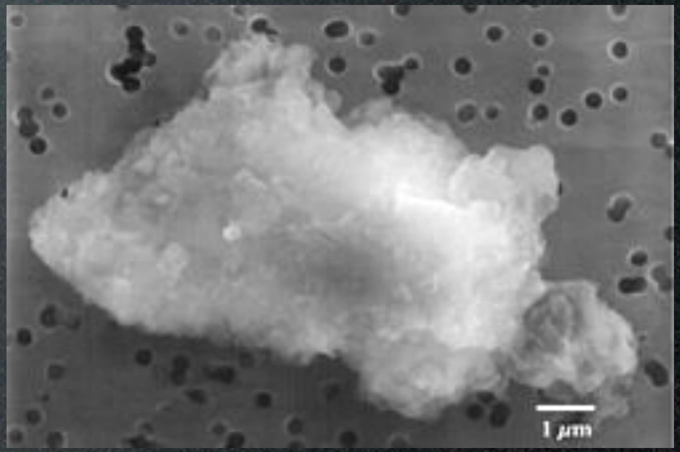
- More blue light is scattered, making objects appear redder

- ≈1 dust particle for every 100 gas particles

- Acts like flypaper, causes dust grains to stick together and form molecules



Cosmic Dust



Cosmic Dust

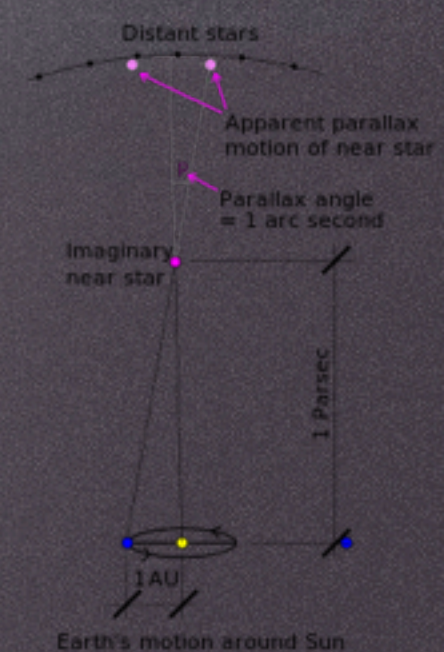
Galactic Distances

Light Year

- Measuring in our solar system we typically used the AU b/c 10^5 km starts to add up
- That's ok, for everything in our system, even the Oort cloud is only a few 1000 AU (some estimates have the size of the cloud as much as 100,000 AU)
- 1 ly = distance light travels in a year
- earth-moon distance=1.3 light seconds
- earth-sun distance=8 light minutes
- distance to the nearest star (Proxima Centauri)=4.2 ly
- This means we see what the star looked like 4.2 years ago

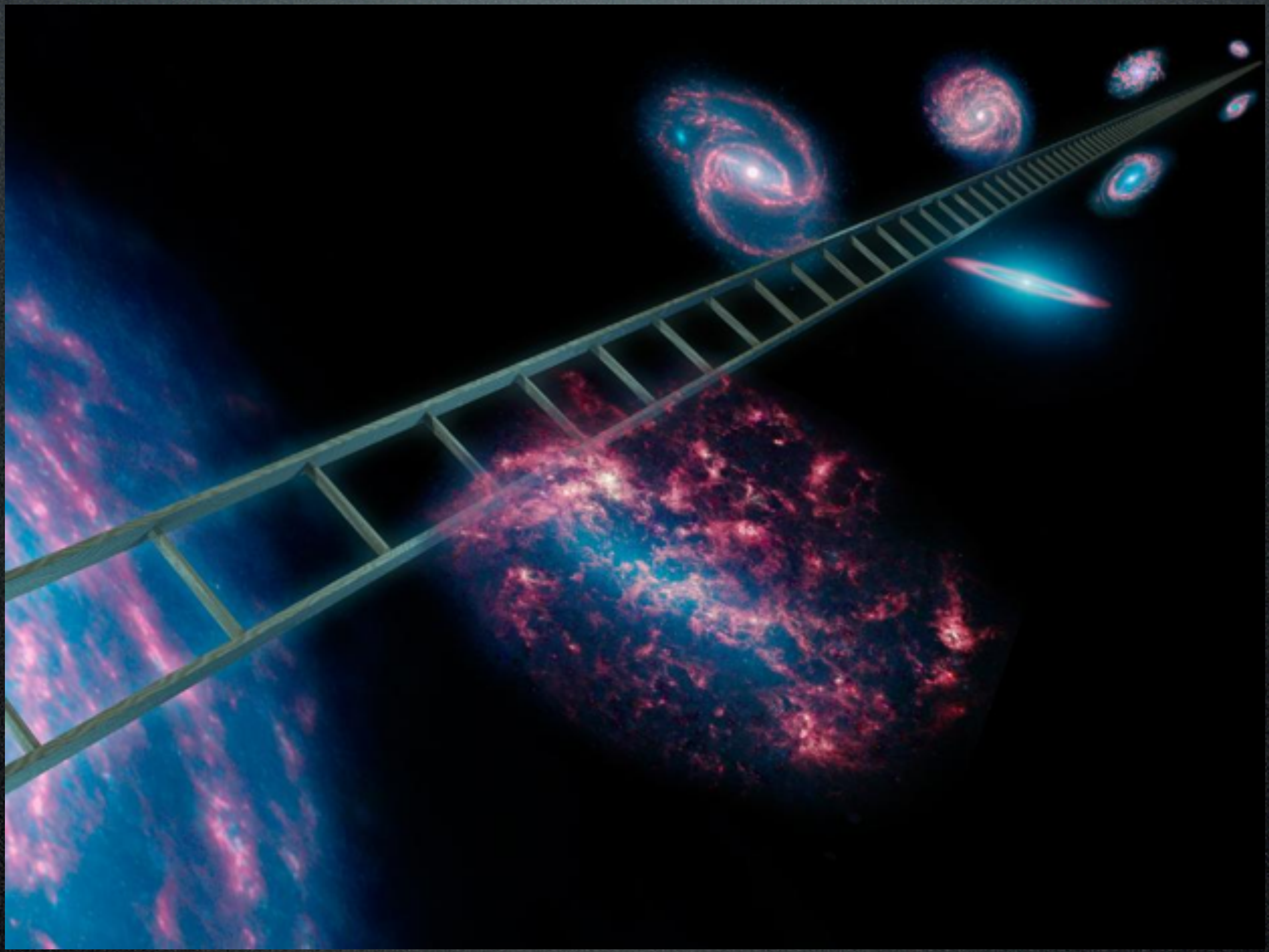
Parsec

- Another common unit for long distance
- Using the earths orbit as a baseline, an object at 1 pc has a parallax of 1 arc sec in the sky
- Distance to nearest star is 1.3 pc



Parsec definition

Climbing the Cosmic Distance Ladder

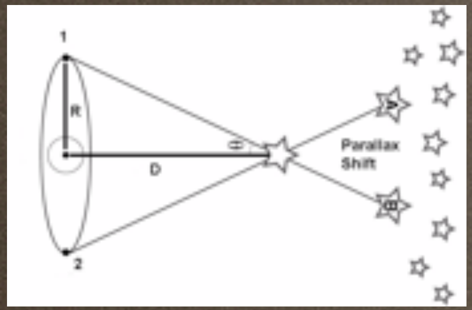


Cosmic Distance Ladder

Review from last week

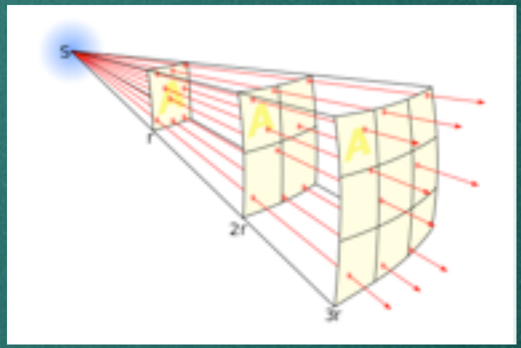
Parallax

- See last week for review
- Used for stars up to
500pc ≈ 1600 ly



The same works for earth, only our eyes become opposite sides of our orbit

Standard Candles



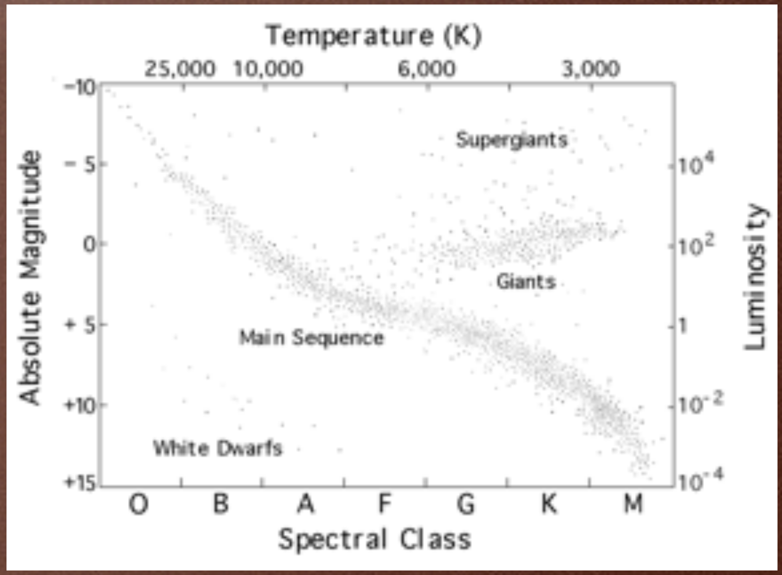
Inverse Square Law describes light observed

- Luminosity (brightness)
$L_{measured}=L_{intrinsic}/d^2$
- For objects where we know $L_{intrinsic}$ we can calculate the distance to the object
- Standard Candle: class of objects that all have roughly the same brightness, allowing us to calculate distance

Standard Candles

Spectroscopic Parallax

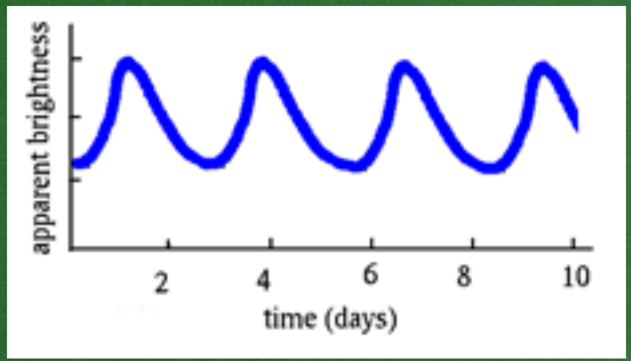
- Not really parallax
- Position on the HR diagram gives an approximate absolute (intrinsic) magnitude
- Using a similar formula to the one shown earlier, we can derive the distance
- Accurate up to 10 kpc ≈ 32,600 ly (still only the Milky Way galaxy)



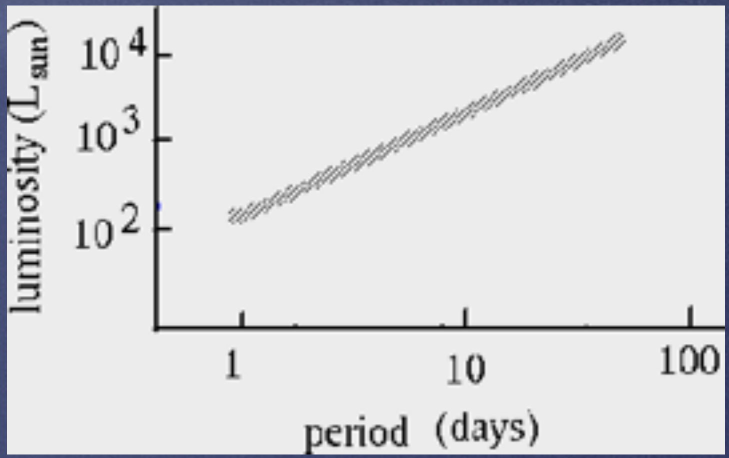
HR Diagram

Cepheid Variables

- Yellow Super-Giants 4-20 M_{sun}
- Brightness changes by a factor of 10 over a period of months or days



Period/apparent brightness for a cepheid



Relationship b/w period and luminosity

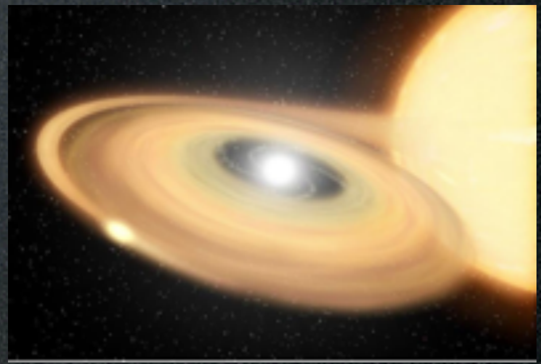
- Useful up to 20 Mpc ≈ 65 million ly (other galaxies)

Type Ia Supernova

Nova

- ≈ half of all star systems are binary (or more)
- If the stars are close enough they can gravitationally interact
- A more massive white dwarf can pull some of the mass from a larger but less massive companion
- If the accretion rate is slow (1 M_{sun} per 1 billion yr) then only 10^{-5} M_{sun} will accrete before a runaway nuclear reaction is triggered
- The shell of H and He is ignited and blows off the star
- The white dwarf is still intact, and will begin accreting from the companion again, only to have another nova explosion later in time

binary stars over time
<click for video>



<click for nova video>

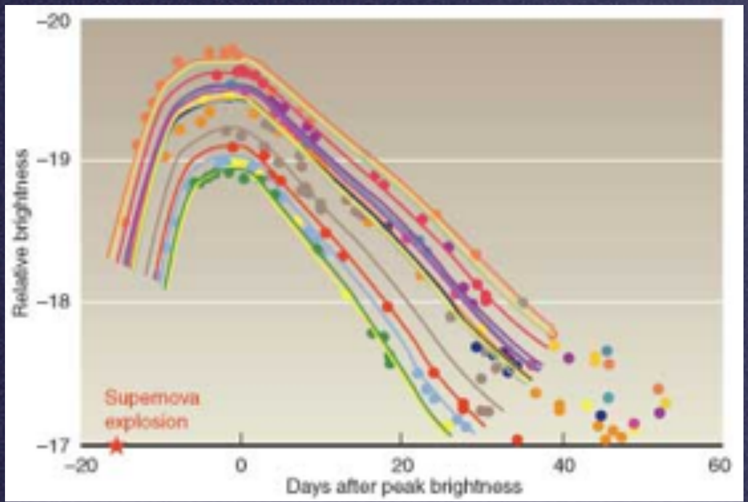
Type Ia Supernova

- If the accretion rate is faster (≈1 M_{sun} per 10 million yr) the white dwarf mass increases to almost the Chandrasekhar limit (1.44 M_{sun})
- This triggers the fusion of C at the core
- In a matter of seconds the core burns from C all the way up to Fe, heating the star up to billions of degrees
- This high temp gives the core enough energy to tear itself apart (and its companion)
- Bright enough to be seen halfway across the observable universe

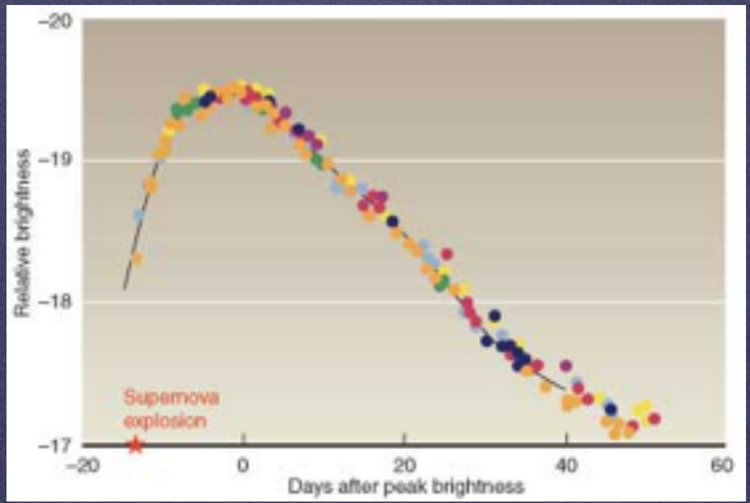
Type Ia Supernova
<click for video>

Another type Ia supernova
<click for video>

Calculating Distance



Type Ia SN have a distinctive light curve



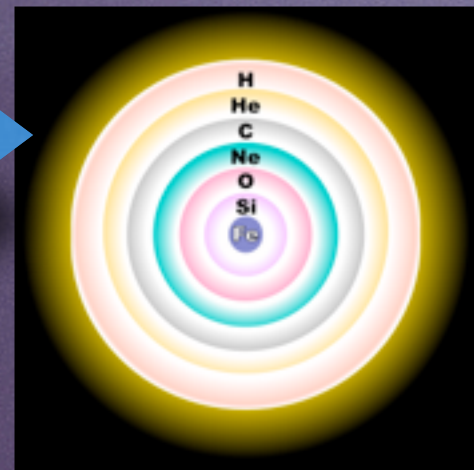
Normalized type Ia SN light curves all have the same relative brightness

- Knowing the intrinsic luminosity allows astronomers to calculate distance

Metallicity

Metallicity

Stars are created from a cloud of mostly H and He

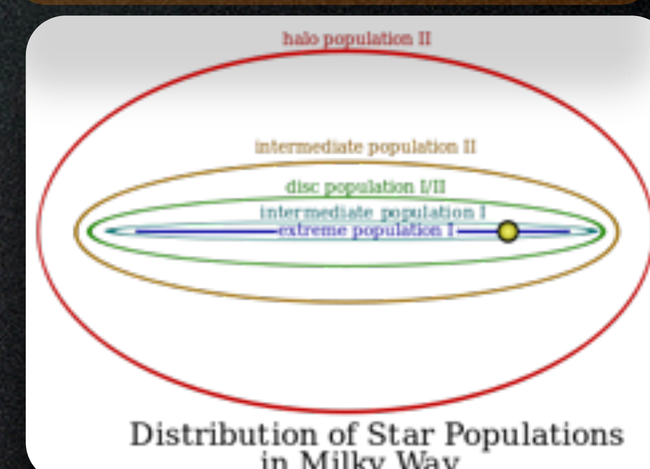


Inside stars, heavier elements up to Fe are created by fusion

All matter heavier than Fe is created in super nova explosions

The next generation of stars will form from a cloud with a larger amount of "metals", all elements higher than He

- Metallicity: fraction of "metals" in a star
- Pop I stars: newly formed, metal rich stars
- Pop II stars: older, metal poor stars
- Pop III stars: the 1st generation of stars, almost all H and He



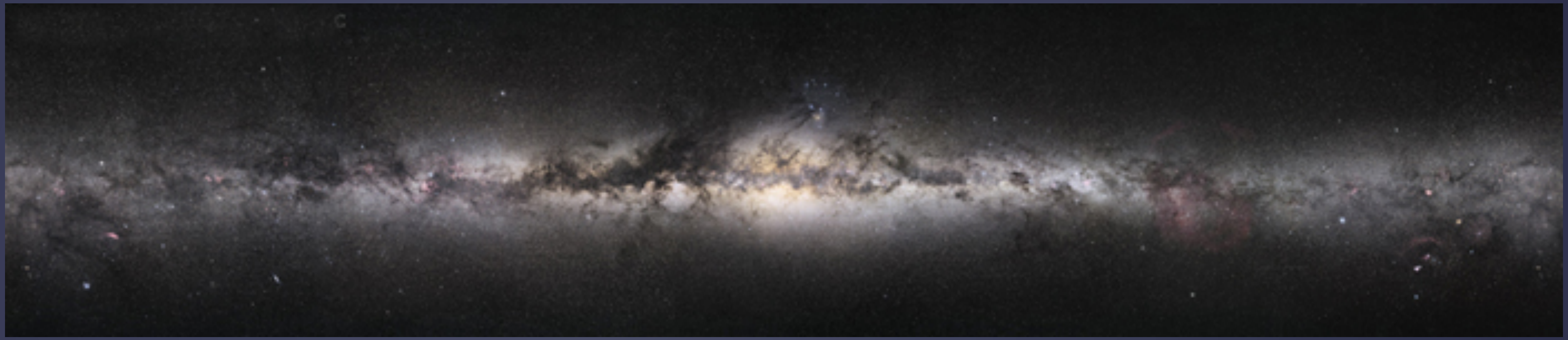
Metallicity in the MW

The Milky Way

<click for video>

Intro

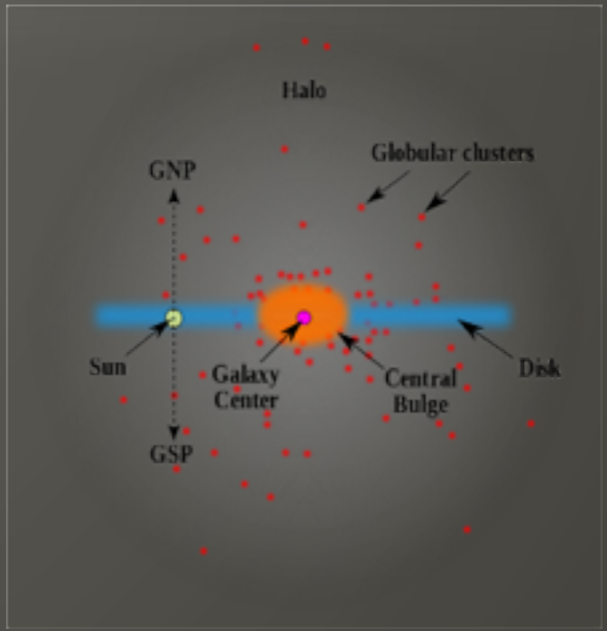
- Galileo first realized that the fuzzy band in the sky was actually a city of stars
- We now know that there are 100's of billions of stars in the Milky Way
- Next several video about the anatomy of the Milky Way
- Then we will look at the variety of galaxies observed in the universe



360 degree panorama

Anatomy

- The Milky Way is a bared spiral galaxy consisting of
- a disk containing spiral arms
- a halo of globular clusters
- a bulge
- a galactic center
- a super massive black hole
- a mysterious form of matter that dominates the universe that we are still struggling to understand
- Over the next few lectures we will be investigating the different features of the galaxy

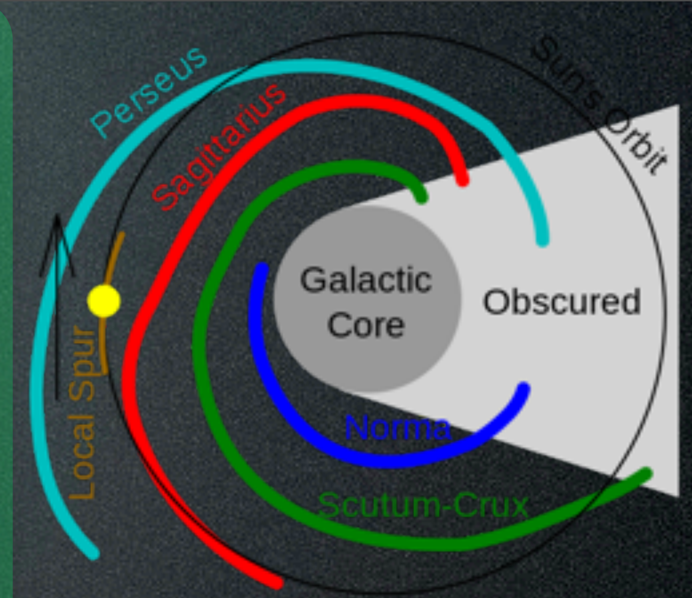


Milky Way

The Galactic Disk

Galactic Disk

- Flattened distribution of stars with a 25 kpc radius and height of 300 pc
- Contains 200-400 billion stars (mostly Pop I)
- Metallicity decreases (in stars and ISM) from galactic center
- Rotational period of a star (on avg) ≈ 233 million years
- Gravitational interactions cause stars to oscillate up and down in the disk (oldest stars scattered the most)
- Evidence of spiral arms

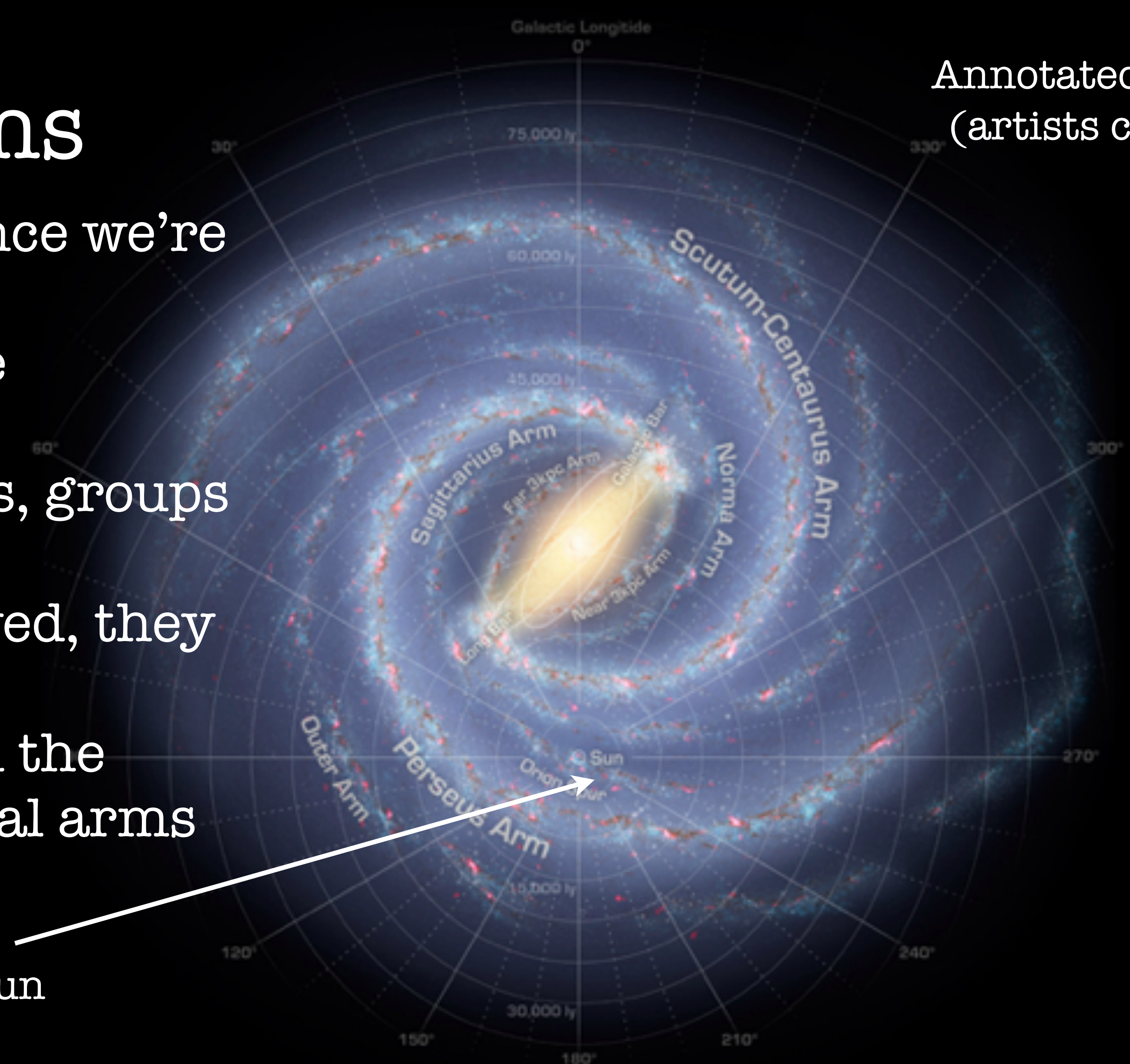


Observed Structure

Observing Spiral Arms

- Hard to find in the Milky Way since we’re in it
- In other galaxies spiral arms are contained in the disk
- Astronomers see OB associations, groups of massive stars
- Since massive stars are short lived, they mark star forming regions
- These regions are not uniform in the galaxy, imply the existence of spiral arms
- We are in the Orion-Spur

Annotated Milky Way (artists conception)



Our sun

Why spirals aren’t stellar structures

- Stick/string analogy
- Age of the galaxy ≈ 13 billion yr
- Rotational period of the disk ≈ 200 million yr
- Implies 50 orbits=tightly wound galaxy
- This is NOT observed

Spiral arms have not been wrapped around the galaxy 50 times

Spirals as Density Waves

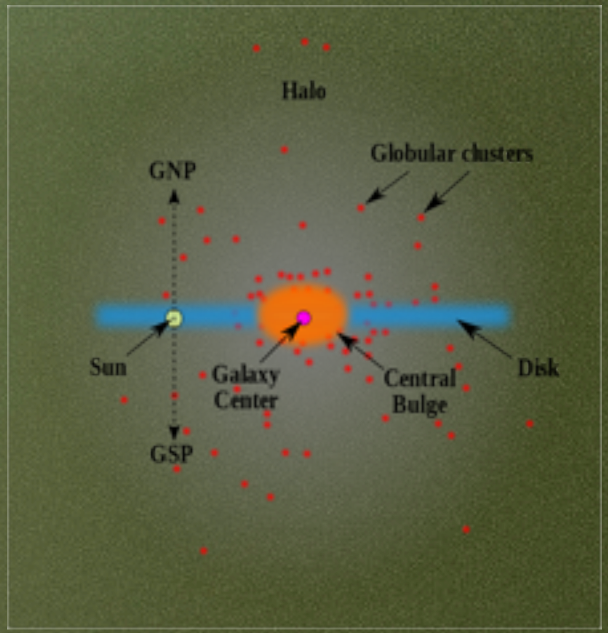
- Instability: smoke rising from incense or a candle
- Spiral density waves are a form of instability, compression waves in the IGM (like sound or traffic at a light)
- Explains why OB associations are in the arms:
- Density waves trigger star formation but OB stars only live a few million yr

Incense
(note: perhaps we could film this to show a growing instability in the smoke)

The Stellar Halo and the Bulgy Bar

The Stellar Halo

- Spherical region around the galactic center w/ 30 kpc radius (some clusters and stars located as far as 72 kpc)
- Most halo stars located in 1 of ≈ 150 globular clusters
- Filled with a hot ≈ 1 million K gas (almost 100’s of times hotter than the surface of the sun)
- Mass of halo gas and stars about the same as the disk
- Pop II stars with no star formation ever observed



Milky Way

Plunging Orbits

- Halo clusters dive toward the galactic center and pas through to the other side
- Indicates they weren’t rotating much during formation
- Halo orbits have slower retrograde motion around the galactic center

Galactic Bulge

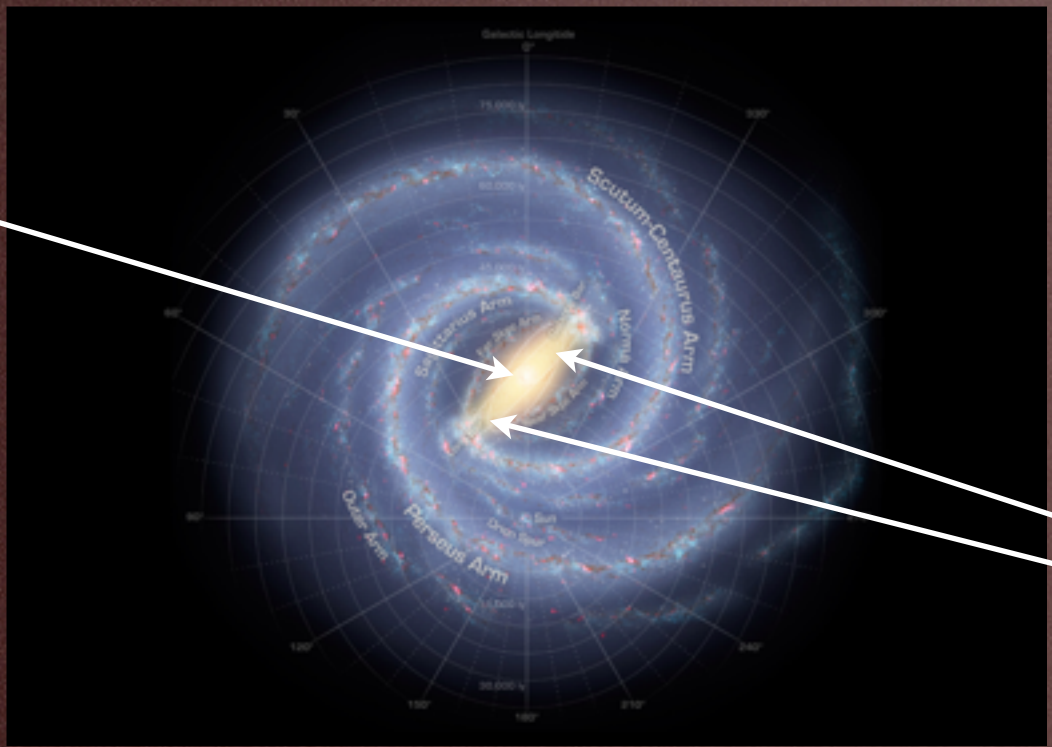
- Quasi-spherical distribution of stars with 5 kpc radius
- Densities as high as 1600 stars/pc^3 (100,000 times more dense than the disk)
- Mostly Pop II stars
- Contains dense gas and star forming regions
- Gas and dust obstructs most of our view

Bulge
(artists conception)

The Bar

- Rectangular region attached to the bulge

bulge



bar

Annotated Milky Way
(artists conception)

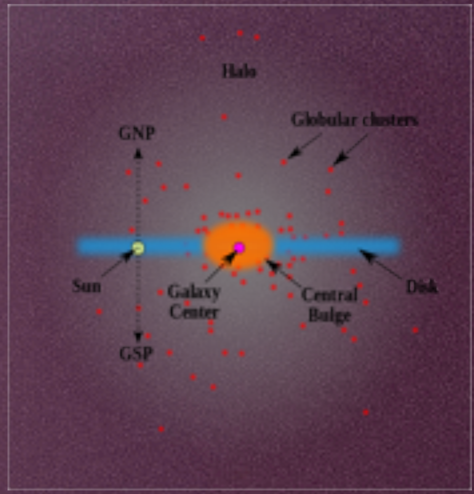
The Galactic Center

Galactic Center

- Central 1 pc of the galaxy contains about 10 million stars
- 100 million times more dense than our region of the galaxy

(Recall, Proxima Centauri is ≈ 1.3 pc from us!)

- Molecular ring at 2 pc orbits the center



Milky Way

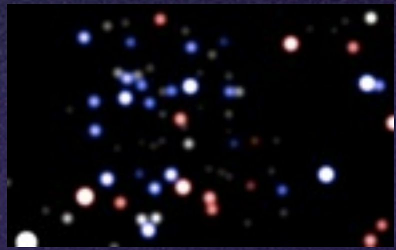
Starbursts

- Period of rapid star formation
- Observed in the center of other spiral galaxies
- Expected in the galactic center in the next 200 million yr
- Conundrum of Old age/Paradox of Youth: OB stars found in the galactic center (was not expected)
- Possibly due to gas collapsing toward the center
- Magnetic arcs 50 pc in length (similar to solar prominences)

Starburst galaxy (artists rendition)

Galactic Black Hole

- An abundance of rapidly rotating stars is located at the center of the galaxy
- Using Newtons laws, the mass they are orbiting must be about $4.3\times10^6\ M_{sun}$
- Mass is contained in 45 AU (slightly larger than Neptunes orbit)
- Must be a massive black hole
- Also explains xray flares, gamma ray emissions, and other oddness in the galactic center



Rapid Rotation

Galactic Black Hole <click for video>

This wraps up our tour of the Milky Way... for now

Later we will see we have omitted a huge piece of the puzzle... Dark Matter... But that is a tale for another day

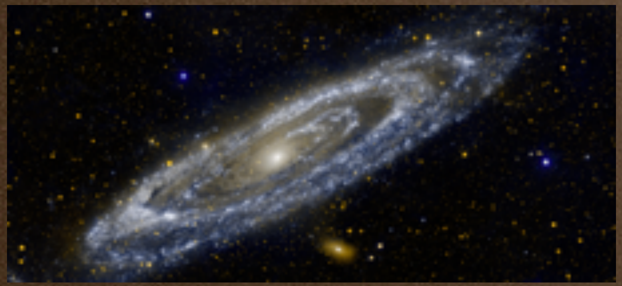
Galactic Zoology

Spirals

- We've already looked in depth at 1 spiral, the Milky Way
- Closest galaxy to us is M31 (Andromeda), and is also a spiral
- Arms of a spiral tell us about the density waves in the galaxy
- size range: 5 kpc to 100 kpc
- mass range: 10^9 M_{sun} to 10^{12} M_{sun}
- No "dwarf" spirals

IC 342

Grand Design Spirals

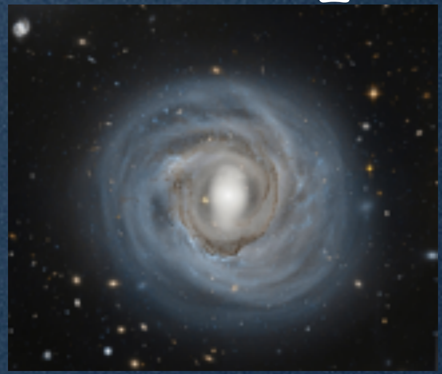


M31:Andromeda

M81

M51:Whirlpool

Barred Sprals



- 33% of spirals have a bar
- Bar has high star formation
- spiral arms begin at the bar
- bars are density waves
- transient of Gyr

No Arm Spirals

Sombrero Galaxy

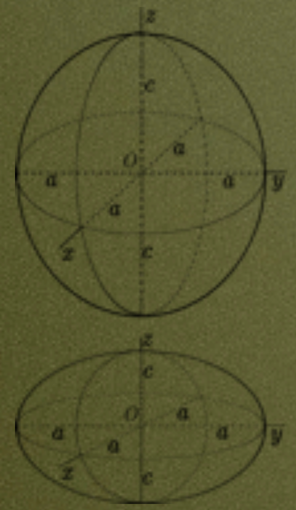
Flocculent Spirals

M101:Pinwheel Galaxy

Elliptical Galaxies

- 15% of galaxies
- No disk
- Triaxial
- Very little ISM and star formation
- Low density halo of 10^7 K gas
- Stars have mostly plunging orbits
- Contain more globular clusters than spirals
- Large mass/size range:
- Dwarf Galaxies: 10^6 M_{sun}/1 kpc
- Giant Galaxies: 10^{13} M_{sun}/150 kpc

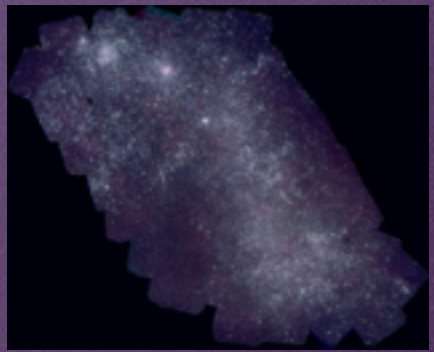
NGC 1132



triaxial

Irregular Galaxies

- Galaxies with irregular shapes
- Irr I type: truly amorphous
- Irr II type: retain some features of a disk
- Mass range: 10^7 M_{sun} to 10^{10} M_{sun}
- Rare in the universe today
- Usually satellites of larger galaxies (more later)
- LMC and SMC are Irr I satellites of the Milky Way



Small Magellenic Cloud

Large Magellanic Cloud

Milky Way, SMC and LMC

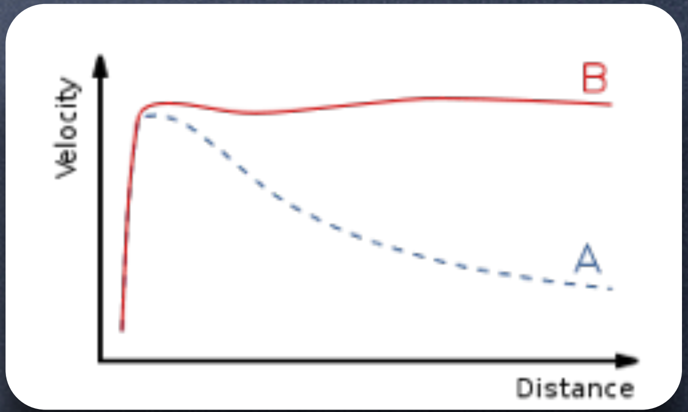
Introduction to Dark Matter

Dark Matter

- Recall that everything we know about space (outside the solar system) is a result of absorbing light at some range of wavelengths
- What about matter that doesn't interact with light?
- We'll go into more detail next week, but here's an introduction

Evidence for Dark Matter

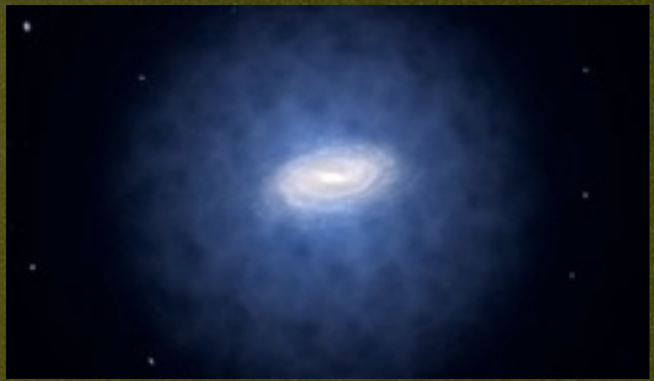
- Orbits: each radius from the central object has a different rotational speed
- Increased radius=decreased orbital speed
- Problem: This is not true for orbits in the galaxy!
- Orbital speeds are constant, all the way out to the edges of the galaxy
- Conclusion: either GR is wrong or there is some type of non-luminous matter



Galaxy Rotation Curves
A:predicted
B:actual

Observational Calculations

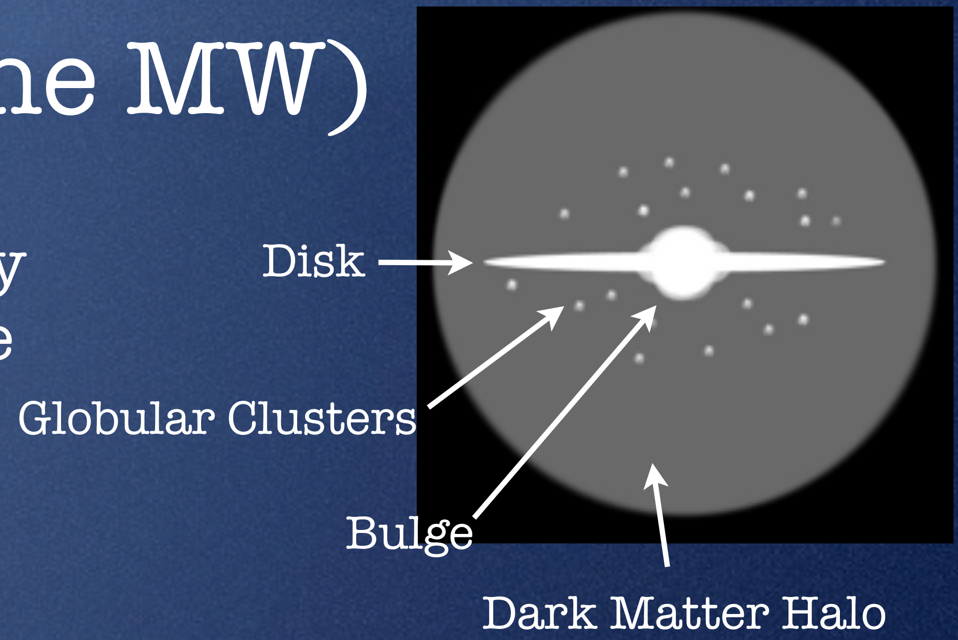
- DM out weighs luminous matter by a factor of 5!
- The galaxy is mostly dark!
- DM must be located in a halo around the galaxies
- Estimated radius of DM halo ≈ 100 kpc



Milky Way DM halo
(artists interpretation)
(click for video)

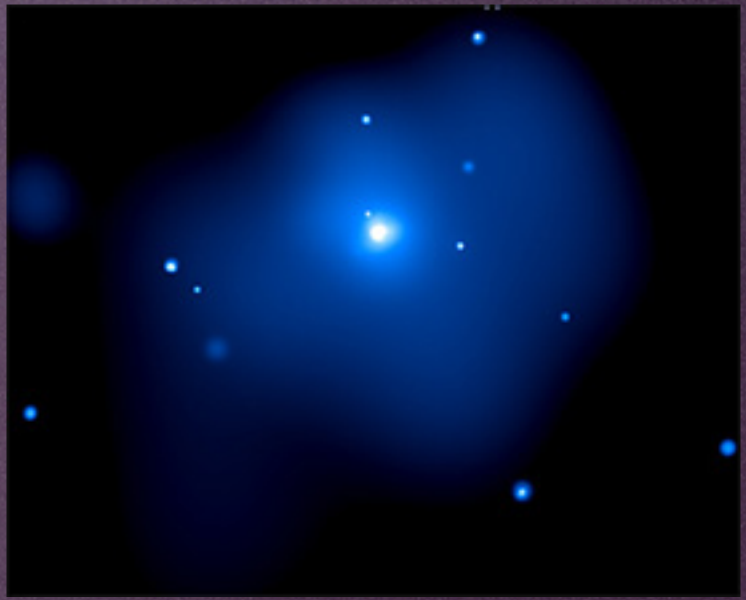
Dark Matter in Spirals (outside the MW)

- Still detected using rotation curves in the disk
- Mass and size of DM halo varies from galaxy to galaxy
- The shape of the DM halo for spirals is about the same



Dark Matter in Ellipticals

- Measuring the avg velocity of stars in elliptical galaxies shows $v_{avg} > v_{esc}$
- There isn't enough luminous matter to hold galaxies together
- 90% of mass in ellipticals is DM



18 million K gas cloud in NGC 4555 that should escape into space, if not for dark matter

Conclusion: The universe is mostly dark matter!

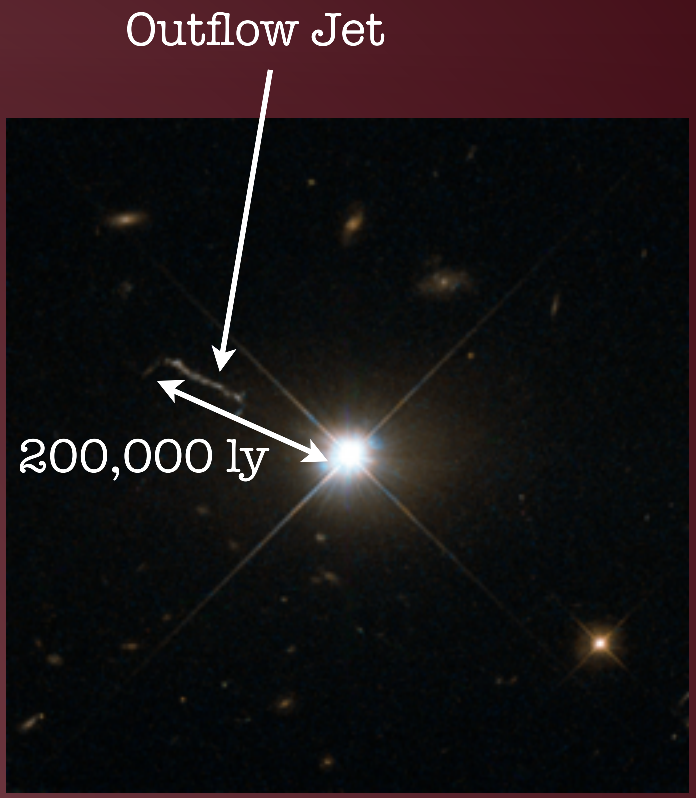
Types of Active Galactic Nuclei

Quasars (Quasi-Stellar Radio Source)

- 1st discovered in the 1960's

3C 273

- 1st Quasar discovered
- 2.5 billion ly from earth
- 1000's of times the energy output of our galaxy
- At 30 ly from Earth (7 times distance to the nearest star) it would be as bright in our sky as the sun!
- Unlike SN, the output never died down
- Output powerful from x-ray to IR

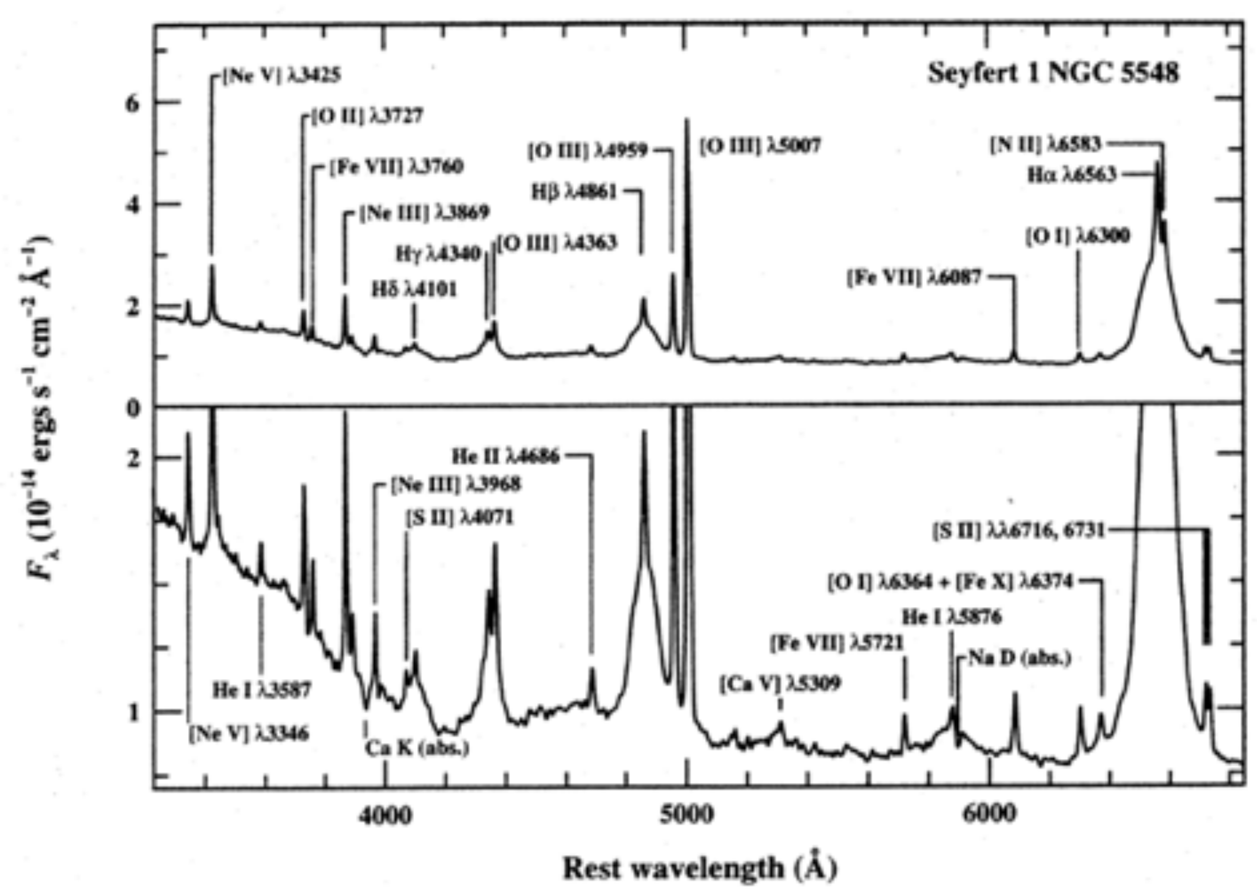


3C 273

Seyfert Galaxies

- Some quasars are in resolved galaxies
- Highly ionized elements in gas (e^{-}'s stripped by high x-ray and uv radiation)
- Broad emission lines=high speeds (≈10,000 km/s)
- Rapid changes in brightness
- Type I:Bright UV and x-ray
- Type II:Bright radio

NGC 1275 Image

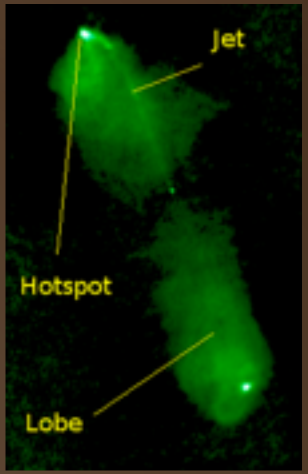


NGC 1275 Spectum

Radio Galaxies

- Powerful Radio jets from galactic nuclei extending 100's of kpc into the IGM
- Tend to be found in elliptical galaxies

3C 348



3C 98

Blazars

- Very compact, high energy quasars
- High output in full spectrum, from radio to gamma rays
- Show rapid variability
- 3C 273 (first observed quasar) is actually a blazar

3C 273

Next Time: Unifying AGN

Unified Model for AGN

Characteristics of AGN

- 1% of galaxies have AGN
- Compact in size
- Relativistic outflow jets at very high energies
- Strong emission at a variety of wavelengths
- Detected at the center of galaxies

Conclusion

- Since jets are relativistic, they must have been moving near c before being launched into space
- Due to compactness and speed, they likely come from supermassive black holes at galactic centers
- As the gas falls into the black hole, gravitational energy is turned into heat and kinetic energy
- Compactness creates higher energy from accreted material
- Only galaxies with enough gas accreting will have AGN

Quasar video

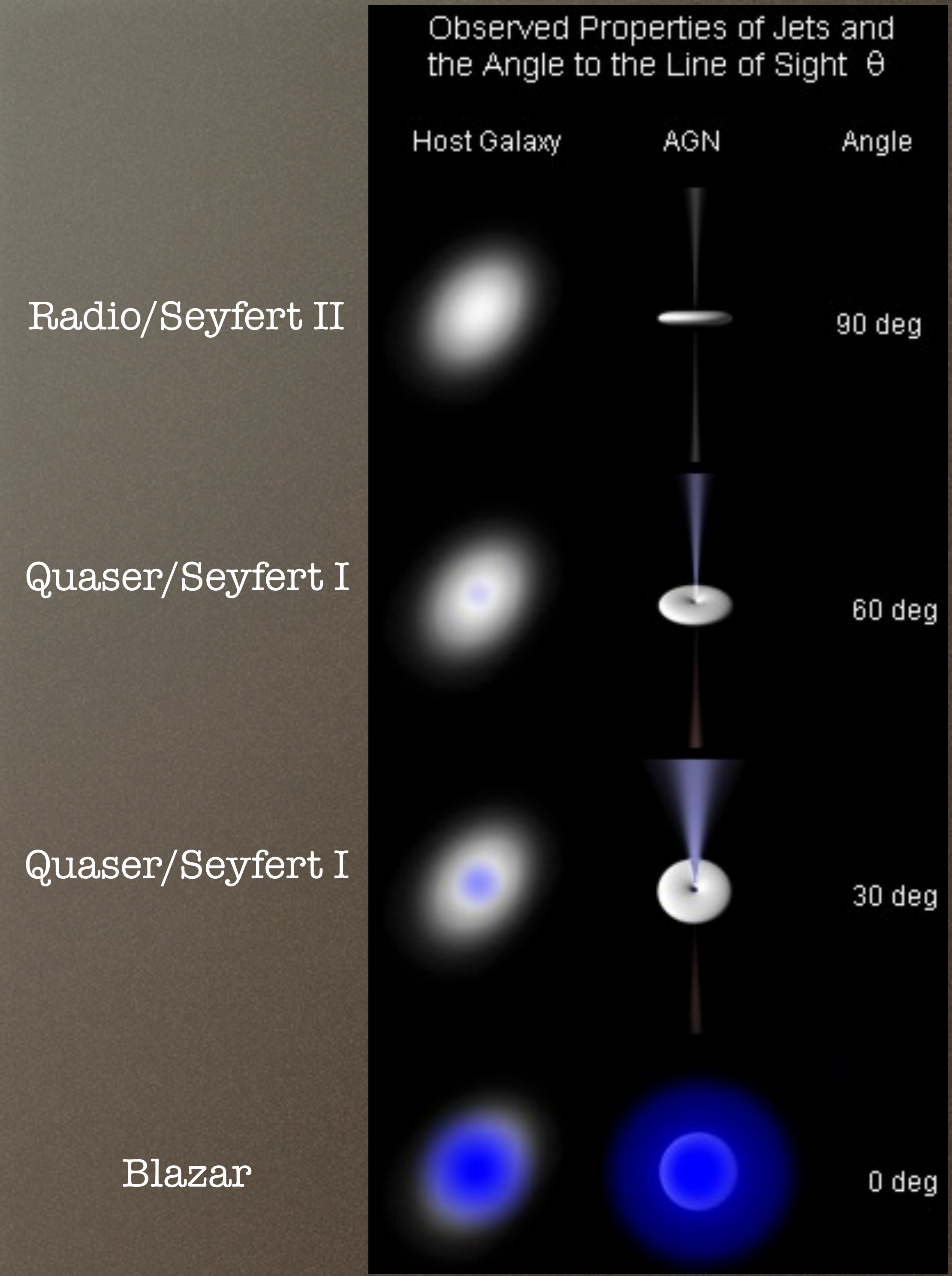
Quasar video

Another quasar video

Distinguishing AGN

- SMBH has a 1pc accretion disk
- Further out is a 100 pc torus of molecular gas
- A small halo surrounds the SMBH, disk and the torus
- All types of AGN are the same outflow
- The viewing angle of the system determines which type of AGN we see (see graphic on right)

Dusty torus surrounding SMBH



AGN type based on viewing angle

Which came first, SMBH or Galaxy?

- Correlation in spirals of bulge mass to BH mass (≈700:1)
- Correlation between the avg roation speed in the outer regions of the galaxy and SMBH mass (M-σ relation)
- M-σ not explained by direct effect
- Theory: Collapse of gas into SMBH before the bulge has turned into stars=SMBH and bulge form together
- Still not well understood

Galaxies are Colliding

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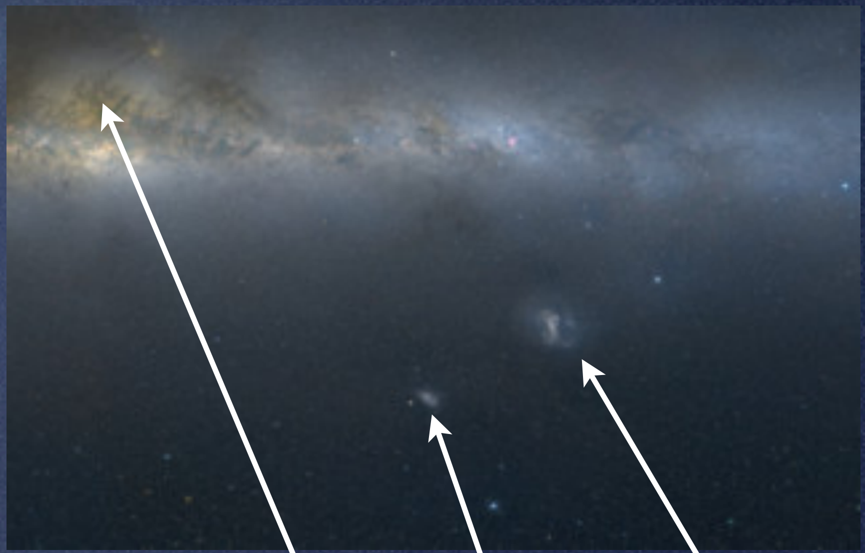
Satellite Galaxies and Collisions

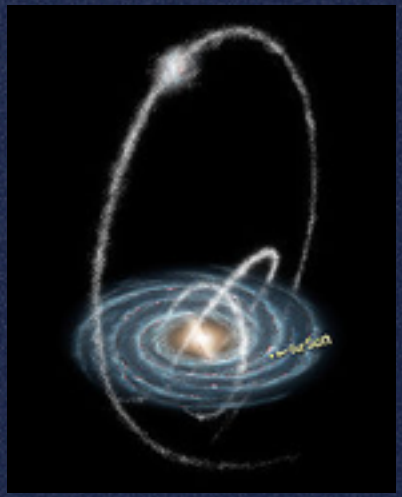
- All large galaxies have smaller satellite galaxies
- Galaxy collisions are an important part of galaxy evolution
- Almost every galaxy is an agglomeration of smaller galaxies
- Milky Way has at least 14 satellites: 2 Irr, 1 elliptical, 8 dwarf elliptical, and 2 dwarf spheroids
- Tidal streams are leftovers of past collisions/fly bys
- Satellite galaxies can also collide (SMC and LMC tidal disrupted each other 2.5 billion yr ago)



Milky Way, SMC and LMC

Click for simulation

NGC 2207 and IC2163



Tidal streams

Galaxy Groups and Galaxy Clusters

Galaxy Groups

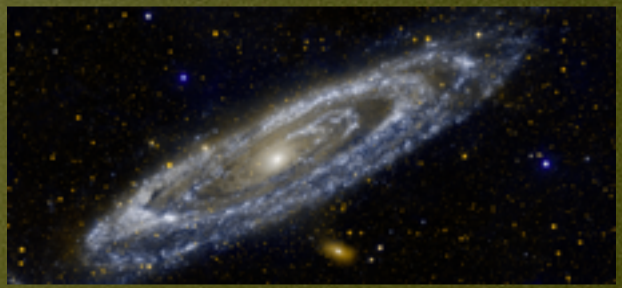
- Gravitationally bound galaxies orbiting a common center of mass
- Most groups have < 50 galaxies
- Avg diameter: 2Mpc with mass ≈ $10^{13} M_{sun}$
- DM appears to be present, binding groups together
- Ratio of DM to matter ≈ 5.5:1

Hickson Compact Group 59

Local Group

- 3 galaxies and their satellites in our local group: M33,Milky Way, M31 (increasing size order)
- MW has more mass than M31 due to more dark matter
- Size: 3.1 Mpc
- Mass: $10^{12} M_{sun}$
- In ≈ 4 billion yr, M31 will collide with MW

Annotated Milky Way (artists conception)

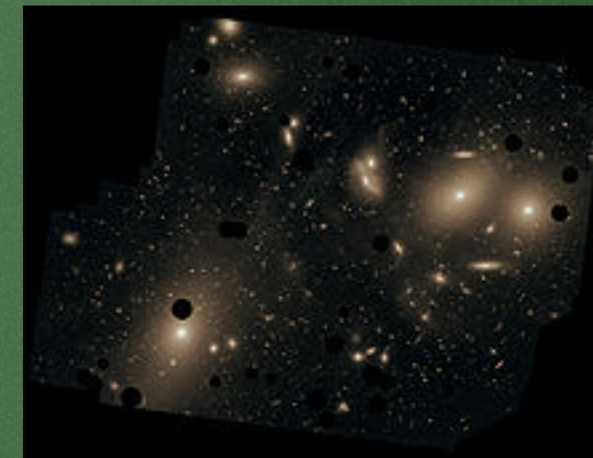


M31:Andromeda

M33:Triangulum Galaxy

Galaxy Clusters

- 100’s to 1000’s of galaxies gravitationally bound, stretching from 2 to 10 MPC in space
- ex. Virgo cluster is the size of our local group (3.1 Mpc) but has 1300-2000 galaxies!
- Each galaxy in the cluster has its own halo of hot x-ray emitting gas (Inter Cluster Medium or ICM)
- Not enough mass due to LM to hold the gas in the cluster, indicates dark matter

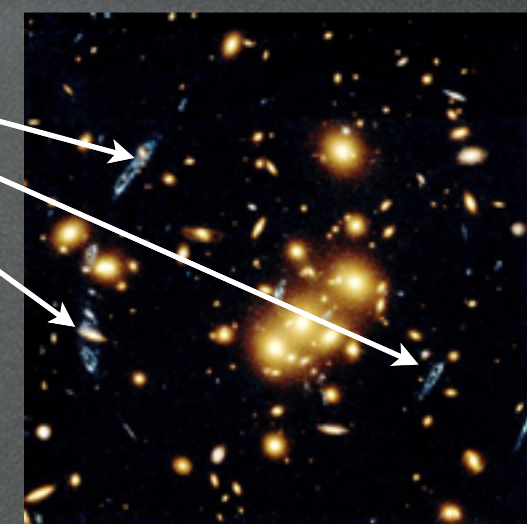


Virgo Cluster

Gravitational Lensing

- Recall that mass warps the shape of space
- Just like a telescope or microscope bends light, so does matter
- Rings or arcs are created by the abundance of matter in a galaxy cluster
- The shape of the image tells us about DM in the cluster
- Beyond GR theories cannot explain these effects
- Cluster have DM to matter ratios ≈ 10:1

same galaxy,
behind cluster



Gravitational Lensing

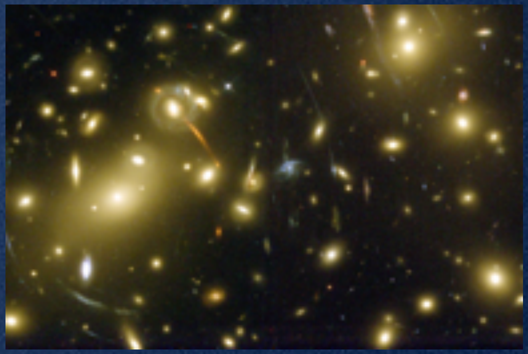
DM in galaxy cluster

Superclusters

Galaxy Superclusters

- All-sky surveys allow astronomers to make 3D maps of the universe
- Result: Distribution is not uniform (as expected)
- Galaxies are arranged in long filaments with enormous voids (100's of millions of ly across), containing no galaxies
- Supercluster: chain of clusters and groups bound by mutual gravitational attraction
- Milky Way part of Virgo (or local) supercluster, with about 100 galactic groups and clusters
- Typical cluster mass: 10^{15} M_{sun}
- Typical Luminosity: 10^{12} M_{sun}
- Lensing from superclusters also indicates the presence of DM

Virgo Supercluster



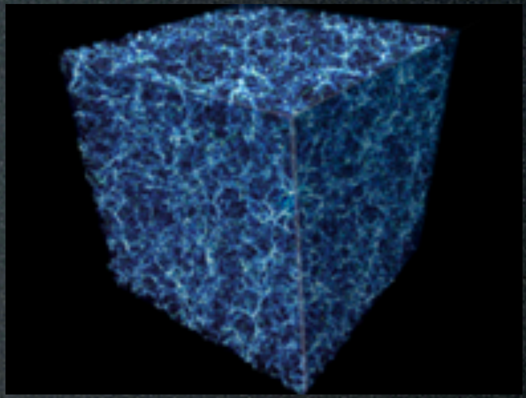
Abel 2218 and lensing

Rivers of Galaxies

- As the universe expands (more next week), galaxies are moving with space, and through space
- Motion in excess of expansion are called peculiar velocities
- Great Attractor: peculiar velocities of galaxies moving toward a central region in excess of 700 km/s
- Rivers of galaxy (including the MW) are flowing toward even larger superclusters
- DM needed to explain these movements

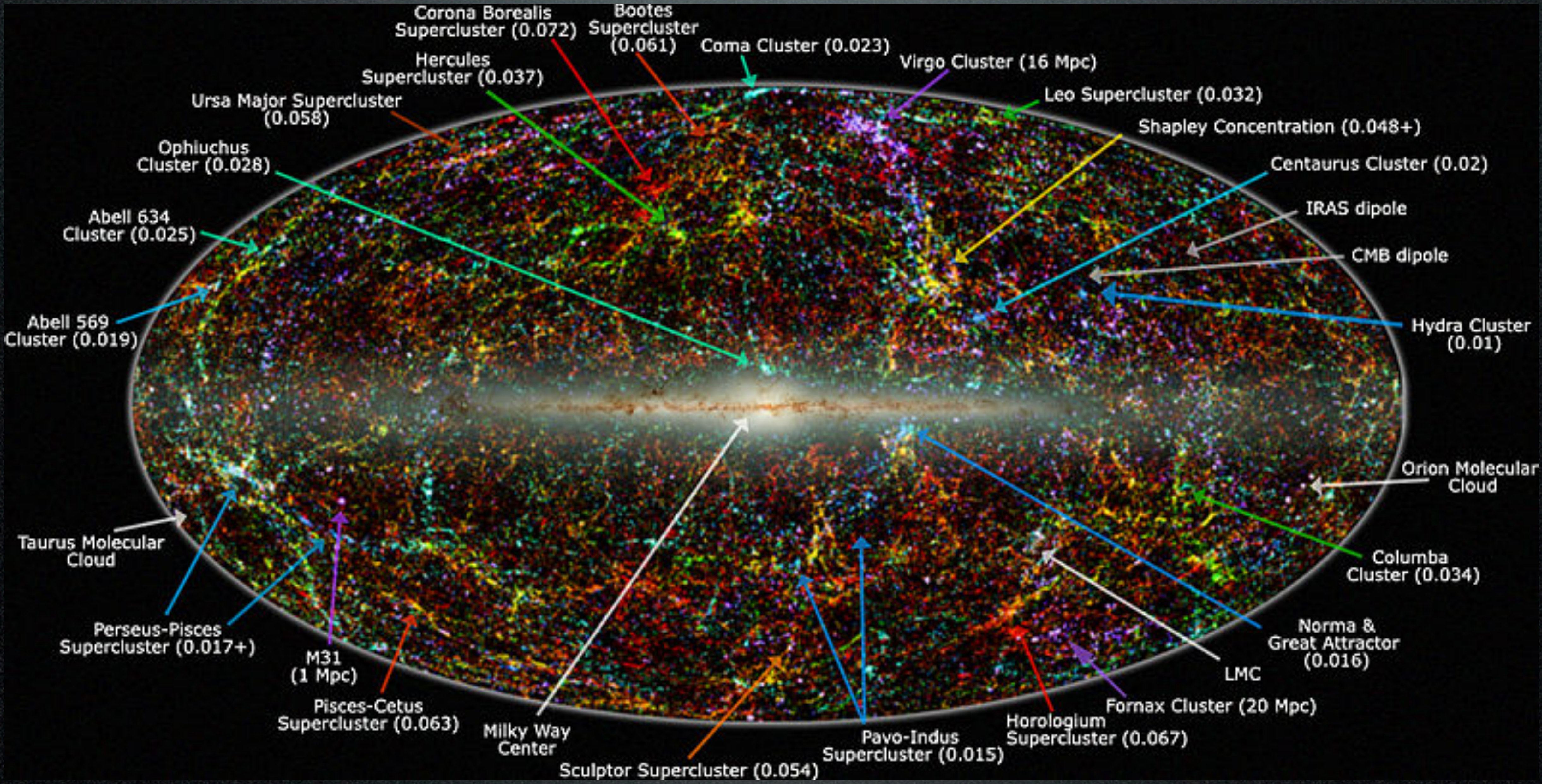
Great attractor

The Cosmic Sponge



Cosmic Foam

- On the largest scales, the structure of the universe is smooth
- Ie. the pattern of superclusters and voids repeats
- The universe begins to look like a sponge, or foam
- Meaning: on the largest scale the universe is homogeneous
- The universe looks the same no matter which direction you look (isotropic)
- We are lucky the universe is homogeneous and isotropic, it means we can do cosmology (which we'll do next week)



All-sky map

Answering the Question

How big is space, and what fills it?

- We have seen that space is far from empty

- In galaxies there is an ISM, made of different gas clouds dense enough for sound and shock waves to propagate

- There are several different types of galaxies, each with a super massive black hole at it's center, sometimes blasting enormous jets of energy into the space around it

- Galaxies arrange themselves in groups and clusters, with hot gaseous ICM's filling them that can be hotter than the sun

- Filaments of galaxies called superclusters fill space like an enormous foam with vast voids of empty space between them

- The universe is about 87% dark matter, 13% "normal" matter: we don't even know what most of the universe is made out of

- If we look at all the matter that makes up the observable universe, we see that it covers a space roughly 91 billion light years in diameter

Next week: we investigate the origin and fate of the universe, learn more about what makes dark matter dark, and hypothesize about what might be outside the observable universe