

Astronomy 12

*Stars, Stellar Evolution, and
High Energy Astrophysics*

<http://apod.nasa.gov/apod/astropix.html>

- Stan Woosley

The Nature of Astronomy

- *The scientific study of objects beyond earth (here with emphasis on stars and physics)*
- *A progress report. Our views of the cosmos change daily (but the new theories often include the old ones as subsets)*
- *The universe and all its constituents are evolving*
- *A novel aspect of astronomy is its ability to carry out direct studies of the past*

See also Fraknoi, Morrison and Wolff
Prologue

*The scientific mind does not so much
provide the right answers as ask the
right questions*

Claude Levi-Strauss
French philosopher
1908 - 2009

*One thing I have learned in a long life is
that all our science, measured against reality,
is childlike - and yet it is the most precious
thing we have.*

Albert Einstein
Physicist
1879 - 1955

“Astrophysics”

The universe obeys physical laws and those laws do not vary with space or time

It is best understood on the basis of physical “models” and mathematics

Scientific notation

$$1 = 1.0 \times 10^0$$

$$0.10 = 1.0 \times 10^{-1}$$

$$10 = 1.0 \times 10^1$$

$$0.00000010 = 1.0 \times 10^{-7}$$

$$1,000,000 = 1.0 \times 10^6$$

$$0.00346 = 3.46 \times 10^{-3}$$

$$3,450,000 = 3.45 \times 10^6$$

$$0.002356347 \approx 2.36 \times 10^{-3}$$

$$(1.0 \times 10^{-2})(2.0 \times 10^4) = 2.0 \times 10^2 = 200$$

$$(1.0 \times 10^{-2}) / (2.0 \times 10^4) = \frac{1}{2} \times 10^{-6} = 5.0 \times 10^{-7}$$

In Ay12 (e.g. homework), use only the precision justified by the statement of the problem. The default is 3 figures of accuracy.

Logarithms

$$\log(1) = 0$$

$$\log(10) = 1$$

$$\log(0.1) = -1.$$

$$\log(10^{-6}) = -6$$

$$\log(52.3) = 1.72\dots$$

$$\log(a)(b) = \log(a) + \log(b)$$

$$\log(a^b) = b \log(a)$$

$$\text{e.g. } \log(10^2) = 2 \log(10) = 2$$

$$\log(10^x) = x \log(10) = x$$

$$\log(100) = \log(10)(10) = \log(10) + \log(10) = 2$$

logarithms are used extensively in the stellar magnitude system because of the need to describe brightnesses that span many orders of magnitude.

Angular Measure

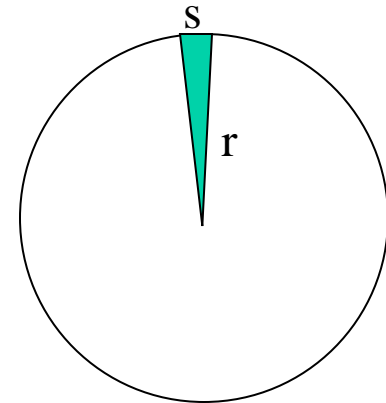
(used, e.g., for distance determination)

1 full circle = 360 degrees

1 degree = 60 arc minutes

1 arc minute = 60 arc seconds

http://mintaka.sdsu.edu/GF/explain/atmos_refr/angles.html



2π radians = 360 degrees

A *radian* is the angle subtended by a length of arc equal to the radius of the circle

1 radian = $360/2\pi = 57.29\dots$ degrees = 206,265 arc seconds

Length of arc, s , subtended by angle θ

$$s = r \theta$$

if θ is measured in radians

Thumb at arm's length ~ 2 degrees

Little finger at arm's length ~ 1 degree

hand spread ~ 20 degrees

Smallest angle with naked eye ~ 1 arc min

Sun or moon ~ $\frac{1}{2}$ degree

Units

The basic units in Ay12 are cm, gm, and sec.

How many cm in a light year? $1 \text{ ly} = c * 1 \text{ yr}$

$$c = 2.99 \times 10^5 \text{ km s}^{-1}$$

$$\text{Julian year} = 365.25 \text{ days}$$

$$\text{day} = 24 \text{ hours}$$

$$\text{km} = 10^3 \text{ m}$$

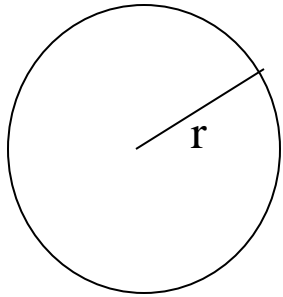
$$\text{hour} = 60 \text{ minutes}$$

$$\text{m} = 10^2 \text{ cm}$$

$$1 \text{ ly} = c \times 1 \text{ year}$$

$$\begin{aligned} &= \left(\frac{2.99 \times 10^5 \text{ km}}{\text{s}} \right) (1 \text{ yr}) \left(\frac{10^3 \text{ m}}{\text{km}} \right) \left(\frac{10^2 \text{ cm}}{\text{m}} \right) \left(\frac{365 \text{ day}}{1 \text{ yr}} \right) \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{60 \text{ min}}{1 \text{ hr}} \right) \left(\frac{60 \text{ s}}{1 \text{ min}} \right) \\ &= 9.44 \times 10^{17} \text{ cm} \end{aligned}$$

Spherical Geometry



Circumference of a circle = $2\pi r$

Surface area of a sphere = $4\pi r^2$

Volume of a sphere = $\frac{4}{3}\pi r^3$

Mass of a sphere with *constant density* ρ

$$M = \left(\frac{4}{3}\pi r^3 \right) \rho$$

To a good approximation stars are spheres

Mass of a sphere with radius r and constant density ρ (gm cm^{-3})

$$M = \frac{4}{3}\pi r^3 \rho$$

E.g., How much does a (spherical) asteroid with radius 5 km and density 5 gm cm^{-3} weigh?

$$\begin{aligned} M &= \frac{4}{3}(3.14)(5 \times 10^5 \text{ cm})^3 \left(5 \frac{\text{gm}}{\text{cm}^3}\right) \\ &= (4.19)(125 \times 10^{15})(5) \text{ gm} \\ &= 2.62 \times 10^{18} \text{ gm} \end{aligned}$$

Calculus

$$\frac{d}{dx} x^n = n x^{n-1}$$

$$\int x^n dx = \left(\frac{x^{n+1}}{n+1} \right)$$

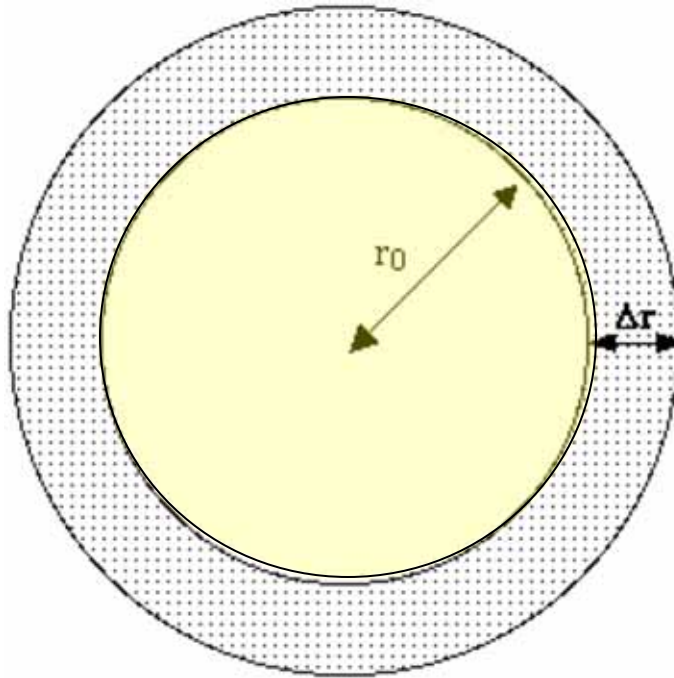
$$\frac{d}{d\theta} (\text{Cos } \theta) = -\text{Sin } \theta$$

$$\frac{d}{d\theta} (\text{Sin } \theta) = \text{Cos } \theta$$

Binomial expansion theorem

$$(1 + \varepsilon)^n \approx (1 + n\varepsilon) \quad \text{if } |\varepsilon| \ll 1$$

$$\text{e.g. } (1 + 0.01)^{\frac{1}{2}} \approx 1.005 \quad (\text{actually } 1.0049876\dots)$$



Eg. Volume of a sphere

$$\text{Area of a shell} = 4 \pi r_0^2$$

$$\text{Thickness} = \Delta r_0 \approx dr_0$$

Add up a whole bunch of shells

$$\int 4 \pi r_0^2 dr_0 = \frac{4}{3} \pi r_0^3$$

ANGULAR MEASURE

$\pi = 3.14159\dots$
 $2 \pi \text{ radians} = 360^\circ$
 $1 \text{ radian} = 57^\circ.296$
 $1 \text{ degree} = 60' = 60 \text{ arc min}$
 $1 \text{ arc min} = 60'' = 60 \text{ arc sec}$
 $1 \text{ radian} = 206265''.806$
 Number of square degrees on sky = 41,252.961

PHYSICAL CONSTANTS

Speed of light	c	$2.99792 \times 10^{10} \text{ cm s}^{-1}$
Constant of gravitation	G	$6.672 \times 10^{-8} \text{ dyne cm}^2 \text{ g}^{-2}$
Planck's constant	h	$6.626 \times 10^{-27} \text{ erg s}$
Boltzmann's constant	k	$1.381 \times 10^{-16} \text{ erg (deg K)}^{-1}$
Mass hydrogen atom	m_H	$1.673 \times 10^{-24} \text{ g}$
Avogadro's number	N_A	$6.022 \times 10^{23} \text{ g}^{-1}$
Mass electron	m_e	$9.1095 \times 10^{-28} \text{ g}$
Charge on the electron	e	$4.803 \times 10^{-10} \text{ electrostatic units}$
Stefan-Boltzmann radiation constant	σ	$5.670 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ (deg K)}^{-4}$
Radiation energy density constant	$a = 4\sigma/c$	$7.56 \times 10^{-15} \text{ erg cm}^{-3} \text{ (deg K)}^{-4}$
Constant in Wien's Law	$\lambda_{\max} T$	$0.28979 \text{ cm (deg K)}^{-1}$
Electron volt	eV	$1.6022 \times 10^{-12} \text{ erg}$
Million electron volts	MeV	10^6 eV
Angstrom	Å	10^{-8} cm
1 Megaton of TNT	MT	$4.2 \times 10^{22} \text{ erg}$

ASTRONOMICAL CONSTANTS

Astronomical Unit	AU	$1.495978707 \times 10^{13}$ cm
Parsec	pc	206265 AU
		3.262 ly
		3.086×10^{18} cm
Light year	ly	9.4605×10^{17} cm
		6.324×10^4 AU
(siderial) year	yr	3.155815×10^7 s
Mass of Earth	M_E	5.977×10^{27} g
(Equatorial) radius of Earth	R_E	6.378×10^8 cm
Mass of sun	M_\odot	1.989×10^{33} g
Radius of sun	R_\odot	6.960×10^{10} cm
Luminosity of sun	L_\odot	3.83×10^{33} erg s ⁻¹
Solar constant at Earth	S	1.37×10^6 erg cm ⁻² s ⁻¹

MISCELLANEOUS

Area circle	$A = \pi R^2$
Area of a sphere	$A = 4\pi R^2$
Volume of a sphere	$V = \frac{4}{3}\pi R^3$
Latitude of Santa Cruz	36.9998 degrees N
Longitude of Santa Cruz	122.0624 degrees W
Temperature in K	Temperature in C + 273.15
Temperature in F	(Temperature in C)*9/5 + 32
5 magnitudes	factor of 100 in flux
For very small $\theta \ll 1$ radian	$\sin \theta \approx \tan \theta \approx \theta$

*Our location in the
Universe*

“Spaceship Earth”



From Apollo 11

1969

The Earth as a planet

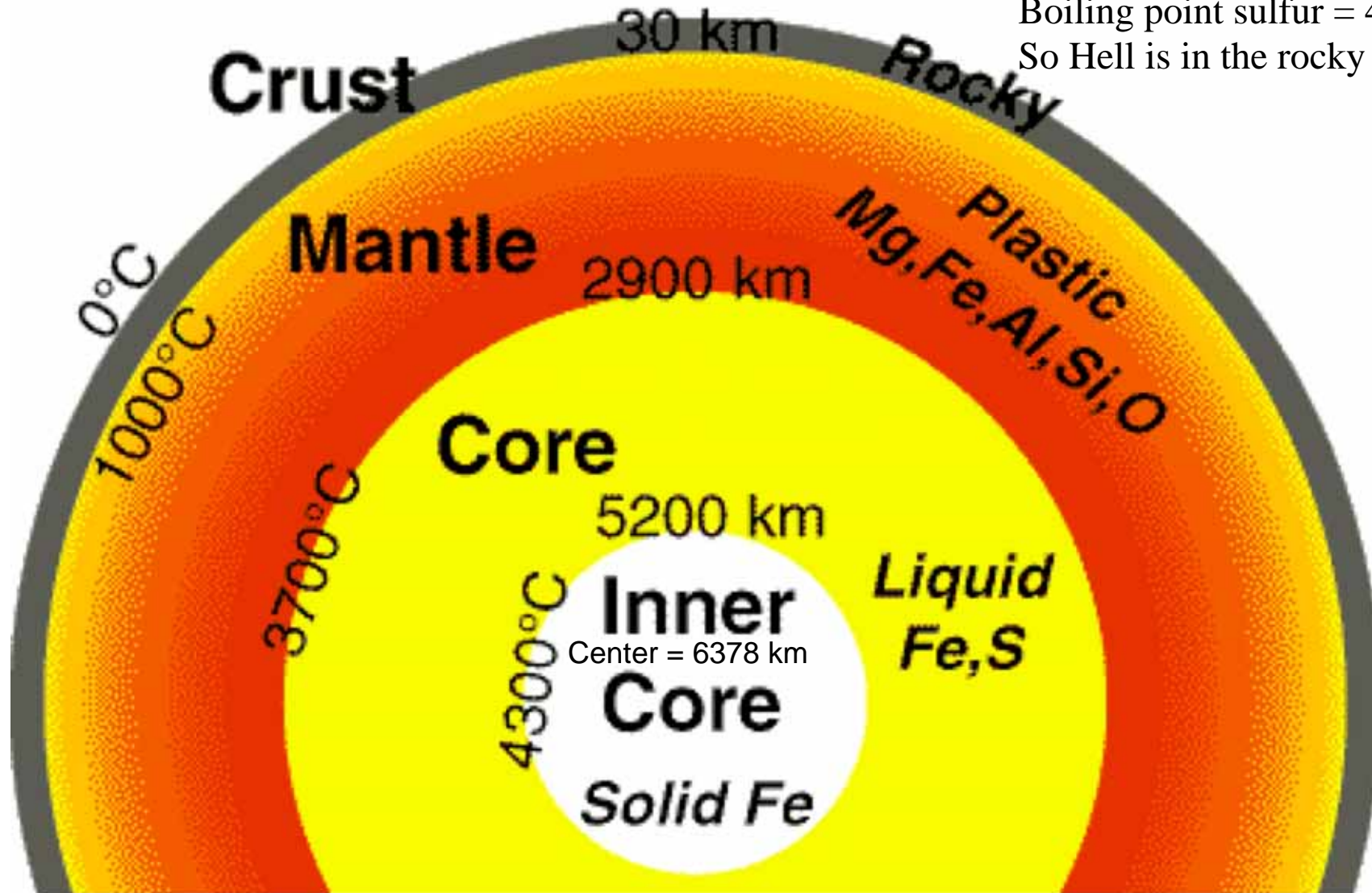
- $M_{\text{earth}} = 5.997 \times 10^{27} \text{ gm}$
- $R_{\text{earth}} = 6.378 \times 10^8 \text{ cm}$
- Age \sim 4.54 billion years (U,Th dating - close to age of sun)
- Orbit sun = $1.496 \times 10^{13} \text{ cm}$ (\sim average distance) = **AU**
(93 million miles) [prior to 1976 was semi-major axis; now radius of circular orbit with the equivalent period]
- Period around the sun = 365.256363... days
(Julian year = 365.25 days)

- Average density = 5.52 gm/cm^3

$$\rho \approx \left(\frac{M}{4/3\pi r^3} \right)$$

densest planet in the solar system,
barely beats Mercury

Boiling point sulfur = 445 C
So Hell is in the rocky crust



or a big, rusty, sandy rock....

34.6% Fe

29.5% O

15.2% Si

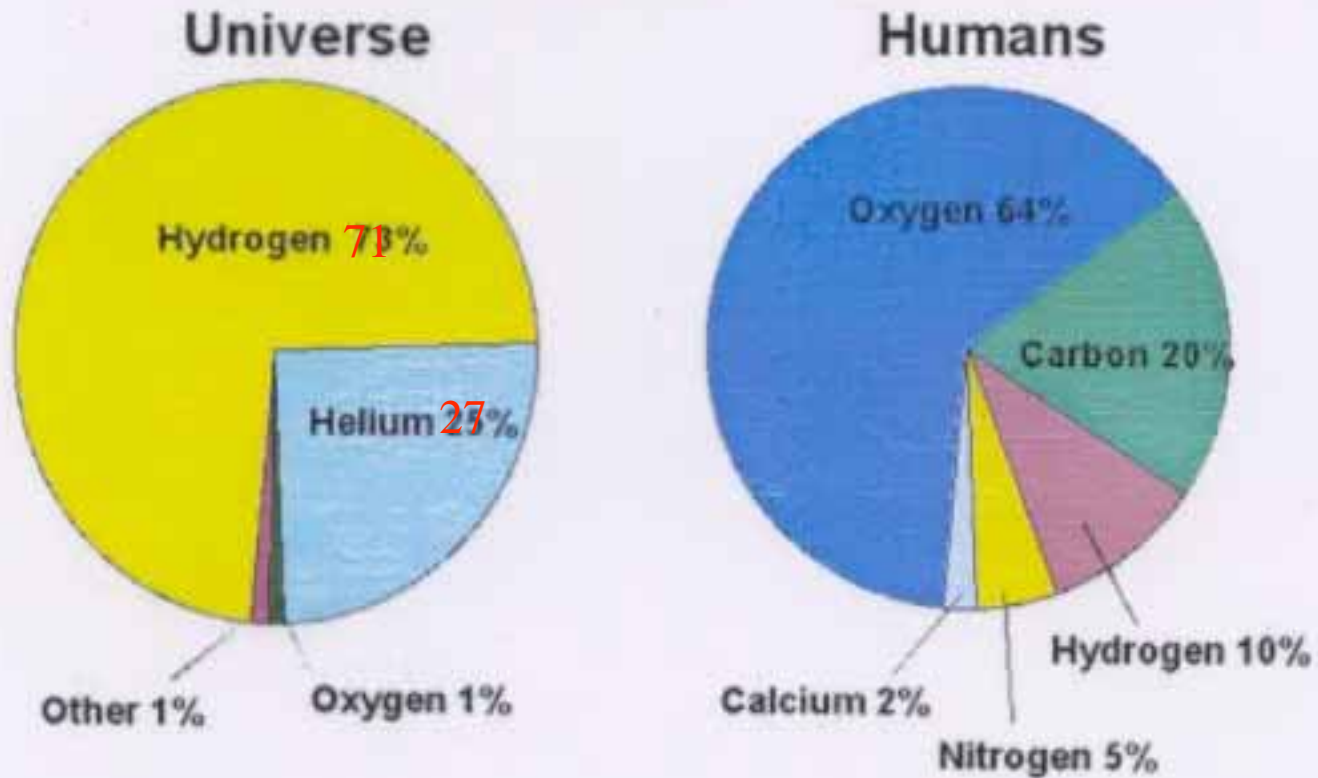
12.7% Mg

2.4% Ni

1.9% S

In contrast to

Relative Abundance by Weight



Where did these elements come from?

*This rusty sandy rock orbits
the nearest star, the sun....*

The Sun

The only star we can study in great detail

Mass = 1.989×10^{33} gm; about 300,000 Earth masses

Radius = 6.96×10^5 km; almost 100 Earth radii

Average density 1.41 gm/cm^3

Age = 4.567×10^9 years

Luminosity = 3.90×10^{33} erg/s

(world's armament in 10^{-5} seconds)

$1.37 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$
at earth

Central temperature = 15.7 million K

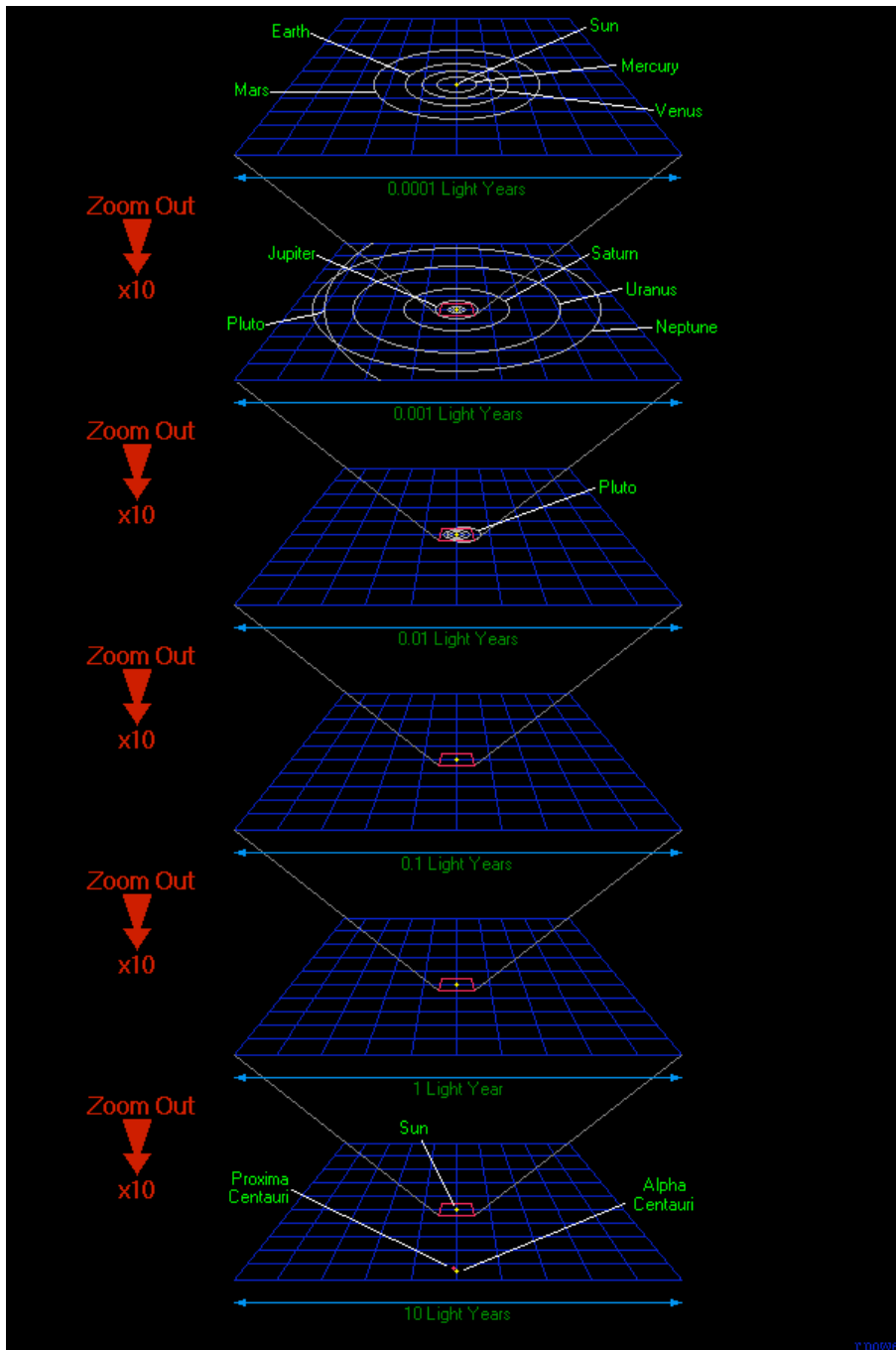
Photospheric temperature about 5700 K

$K = C + 273$

Rotation period 24.47 days at the equator
slower near poles

Surface composition (by mass) 70.6% H
27.5% He, 1.9% C, N, O, Fe, Si, etc
(like “universe”)

A typical star. A little on the heavy side.

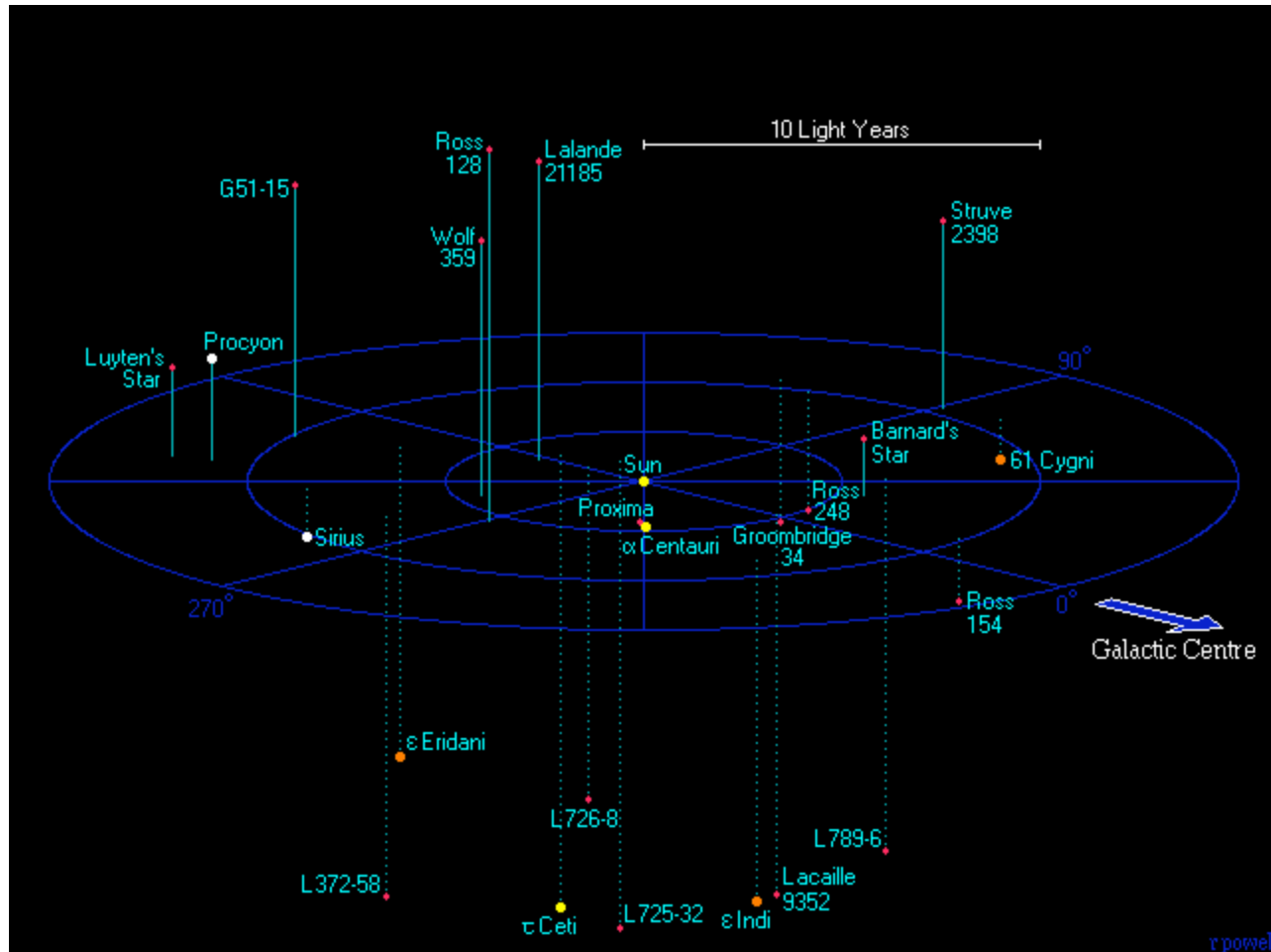


The figure at the left shows the effect of zooming out in distance from our solar system by a total factor of 100,000 (10^5).

At this scale the next star system over, alpha-centauri, becomes visible.

Most of the universe, even within galaxies, is empty.

12.5 ly
www.atlasoftheuniverse.com



circles indicate plane of Milky Way galaxy

The nearest (24) stars within 12.5 light years of the earth. The closest star system – Alpha Centauri – is about 7000 times the radius of Pluto's orbit, 270,000 times the radius of the Earth's orbit,

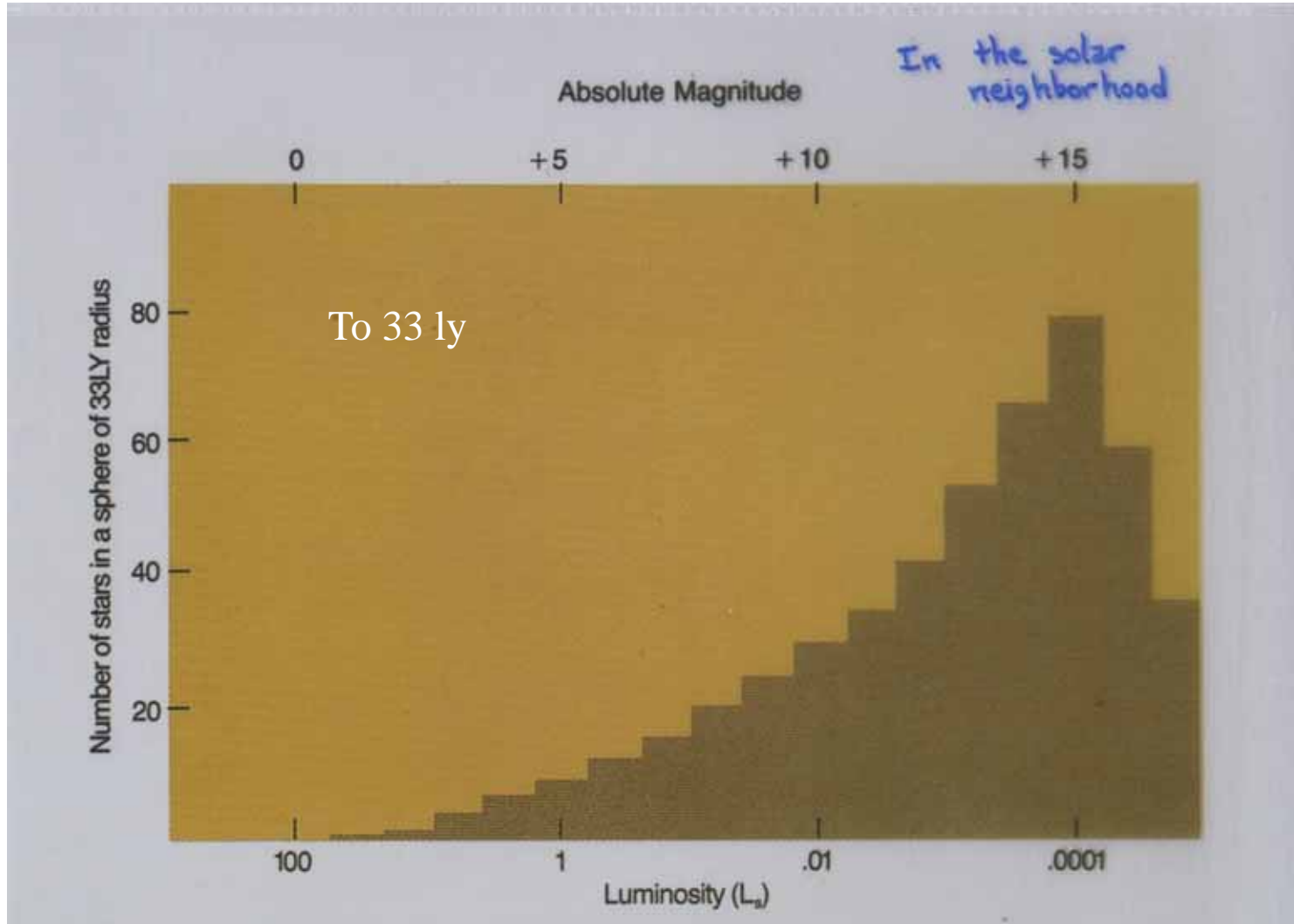
Some specific nearby stars:

- *The sun* – a typical yellow dwarf star. Type G2 with 8 planets
- *Proxima Centauri* – closest of the triplet of stars loosely known as “alpha-Centauri”
Proxima Centauri is a faint red star that orbits Alpha-Centauri A and B with a period of about one million years. Proxima Centauri is 4.22 light years from the Earth (now) and about 0.24 light years from Alpha-Centauri A and B.
- *Alpha-Centauri A and B* – a double star system with a period of about 80 years. Component A is a near twin of the sun (Type G2). Component B is a little fainter and orange. Alpha-Centauri A and B are 4.39 light years from the Earth.
- *Barnard's star* – highest proper motion of all stars. 5.9 light years away. It moves 0.29 degrees per century. In another 8000 years Barnard's star will be the closest star to us (3.8 ly in 11700 AD). M star, faint, red, about 11 Gyr old. No big planets.
- *Lalande 21185* – One of the brightest red dwarfs in the sky but still requires binoculars to see it. In 1996 a couple of Jupiter sized planets were discovered here
- *Epsilon Eridani* – 10.5 light years away. Searched for life by radio searches in the 1960's. May have a Jupiter sized planet orbiting at a distance of 3.2 AU. Young star (1Gyr?). K2
- *Procyon A,B* – 11.41 light years away. Another multiple star system. 8th brightest star in the sky has a white dwarf companion
- *Sirius A,B* – At a distance of 8.60 light years Sirius A is the brightest star in the sky. Sirius B is a white dwarf

Brightest stars		Nearest Stars	
Star name	Apparent magnitude	Star name	distance (ly)
Sun	-26.8	Sun	-
Sirius	-1.46	Proxima Centauri	4.2
Canopus	-0.72	Alpha Centauri AB	4.3
Arcturus	-0.04	Barnards stars	6.0
Alpha Centauri	-0.01	Wolf 359	7.7
Vega	0.00	BD 36+2147	8.2
Capella	0.08	Luyten 726-8AB	8.4
Rigel	0.12	Sirius A B	8.6
Procyon	0.38	Ross 154	9.4
Betelgeuse	0.41	Ross 248	10.4

most nearby stars are too faint to see without a telescope

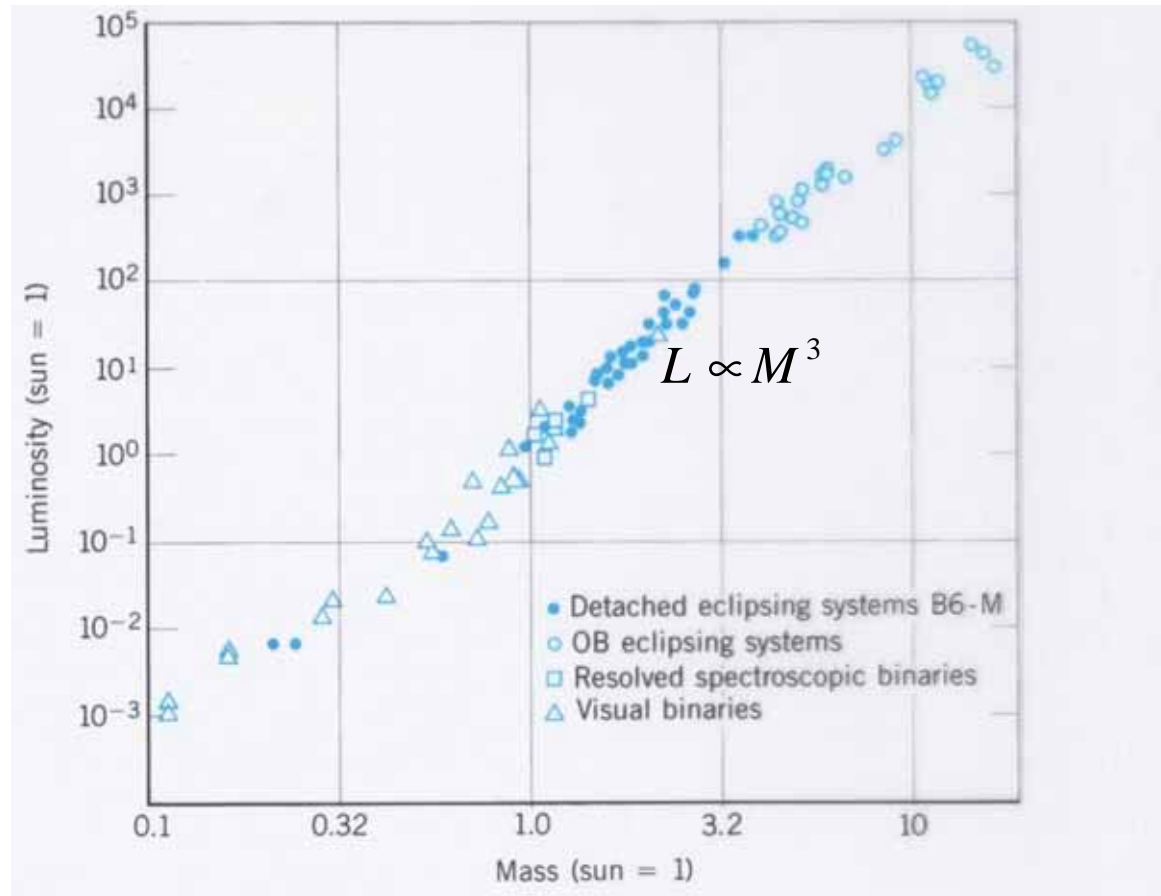
In a volume limited sample – counting all stars...



Most stars are less luminous than the sun, only a few are brighter.

Masses and luminosities

In binary star systems we can determine the mass of the star. For stars that are spectroscopically “main sequence” the star’s luminosity is correlated with its mass.



e.g., 10 solar masses is between 10³ and 10⁴ times more luminous than the sun. 0.1 solar masses is down by 10³

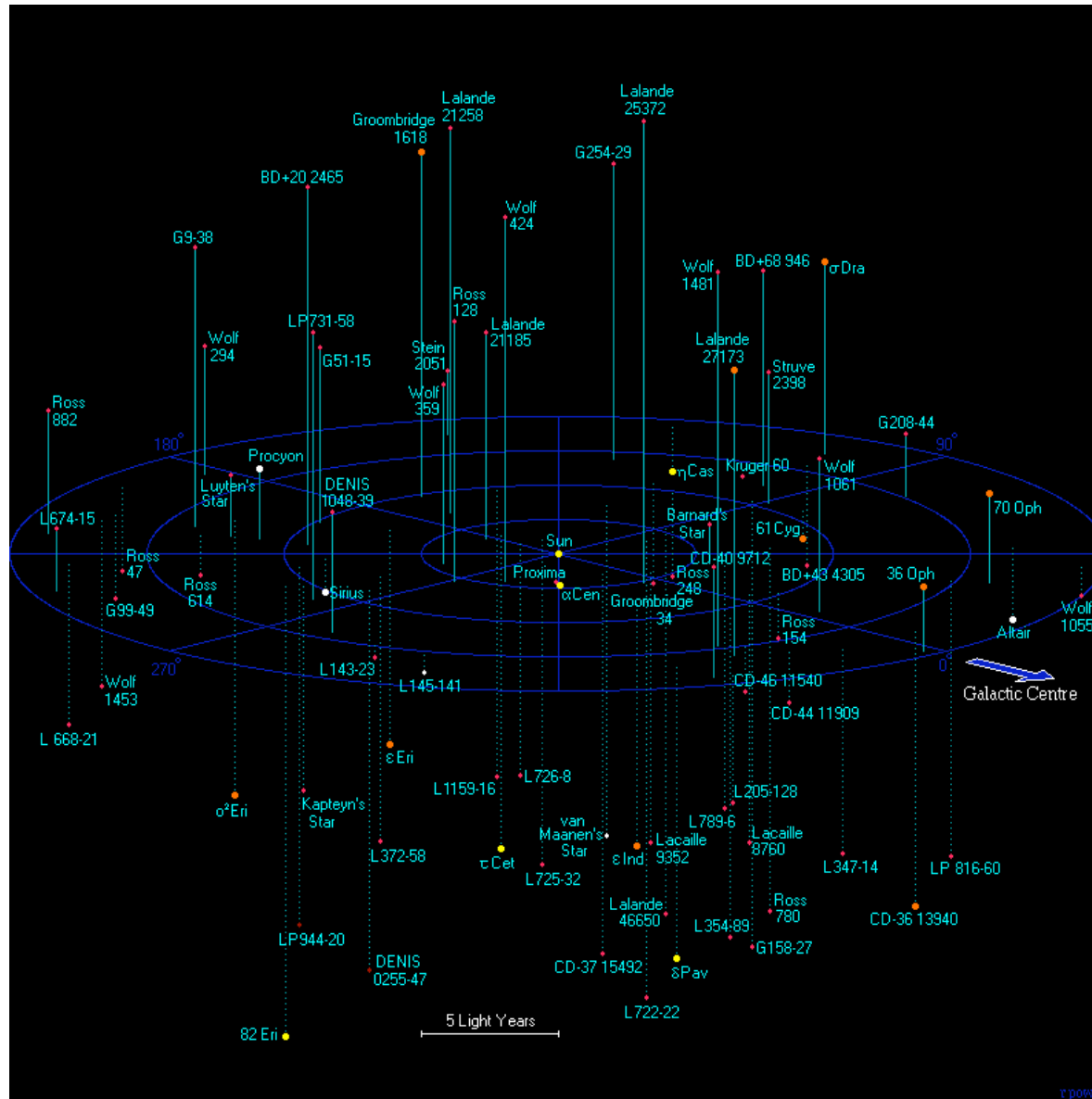
To summarize:

- There are many more faint stars than bright ones
- Faint stars also have low mass
- Low mass stars live a long time

The converse is also true:

- Bright (high luminosity) stars are rare
- Bright stars are more massive (exception red giants)
- Massive stars have short lives

20 light years – 78 systems – 109 stars



isotropic distribution

50 ly
~2000 stars

250 light years

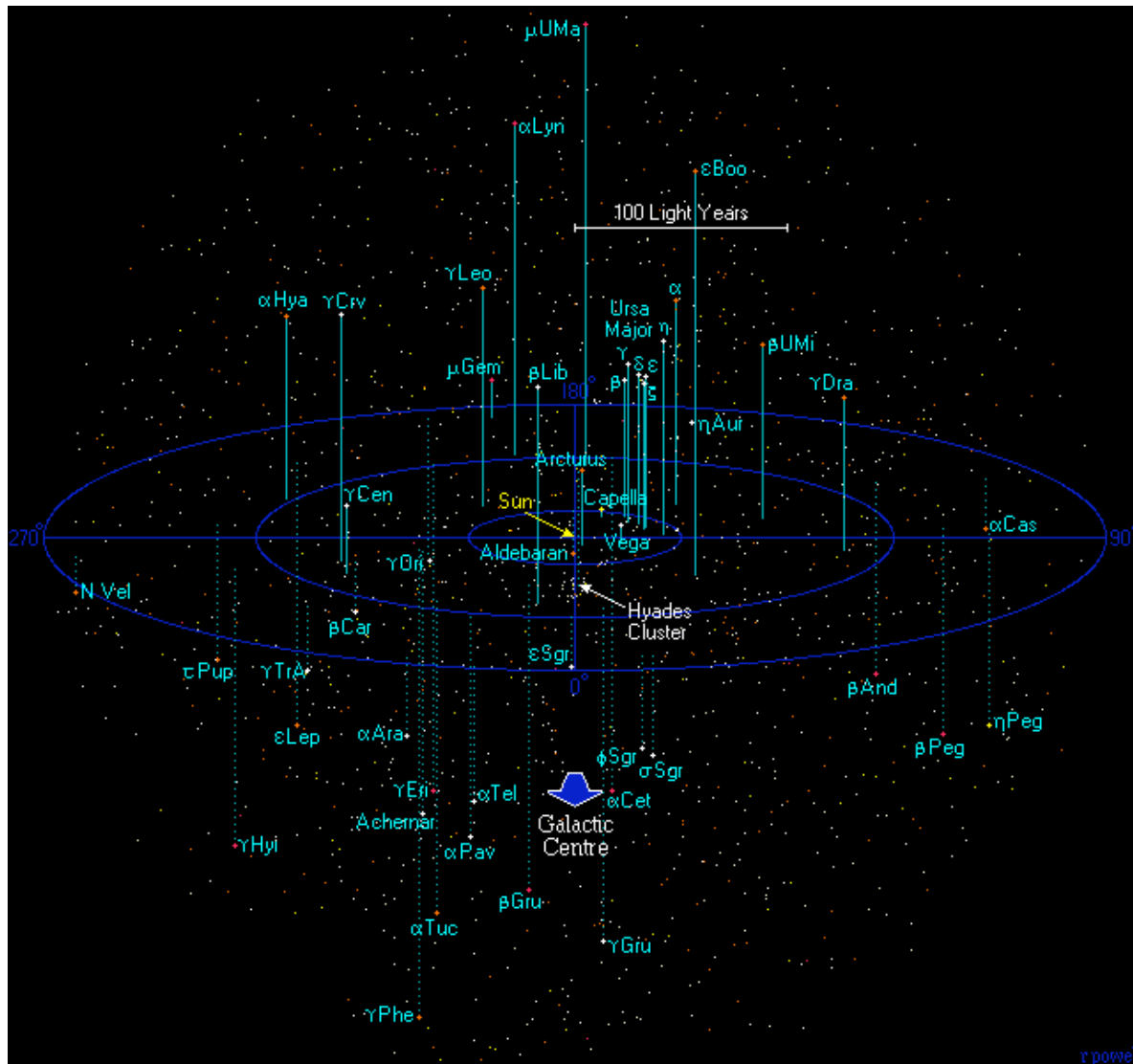
Number for isotropic
distribution and constant density

$$n \propto d^3$$

About 250,000 stars lie within 250 light years of the Earth. Beyond this distance it becomes difficult to see all the stars in the plane of the Milky Way Galaxy because of the presence of dust.

Only the 1500 most luminous of these stars are plotted. Most of these are visible to the unaided eye.

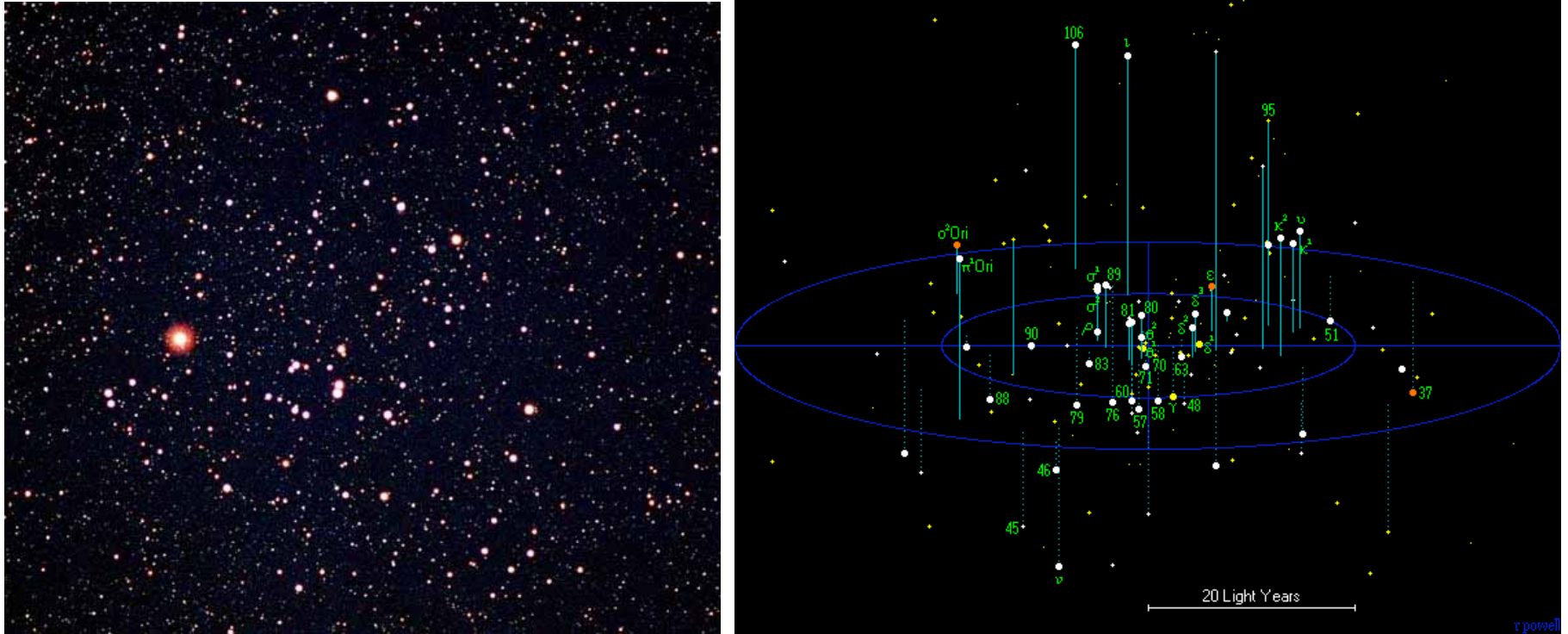
Note the presence of the Hyades cluster.



Starting to see some preference for Galactic plane for distances beyond this.

< 1500 stars are visible to the unaided eye. More often it's a few hundred.

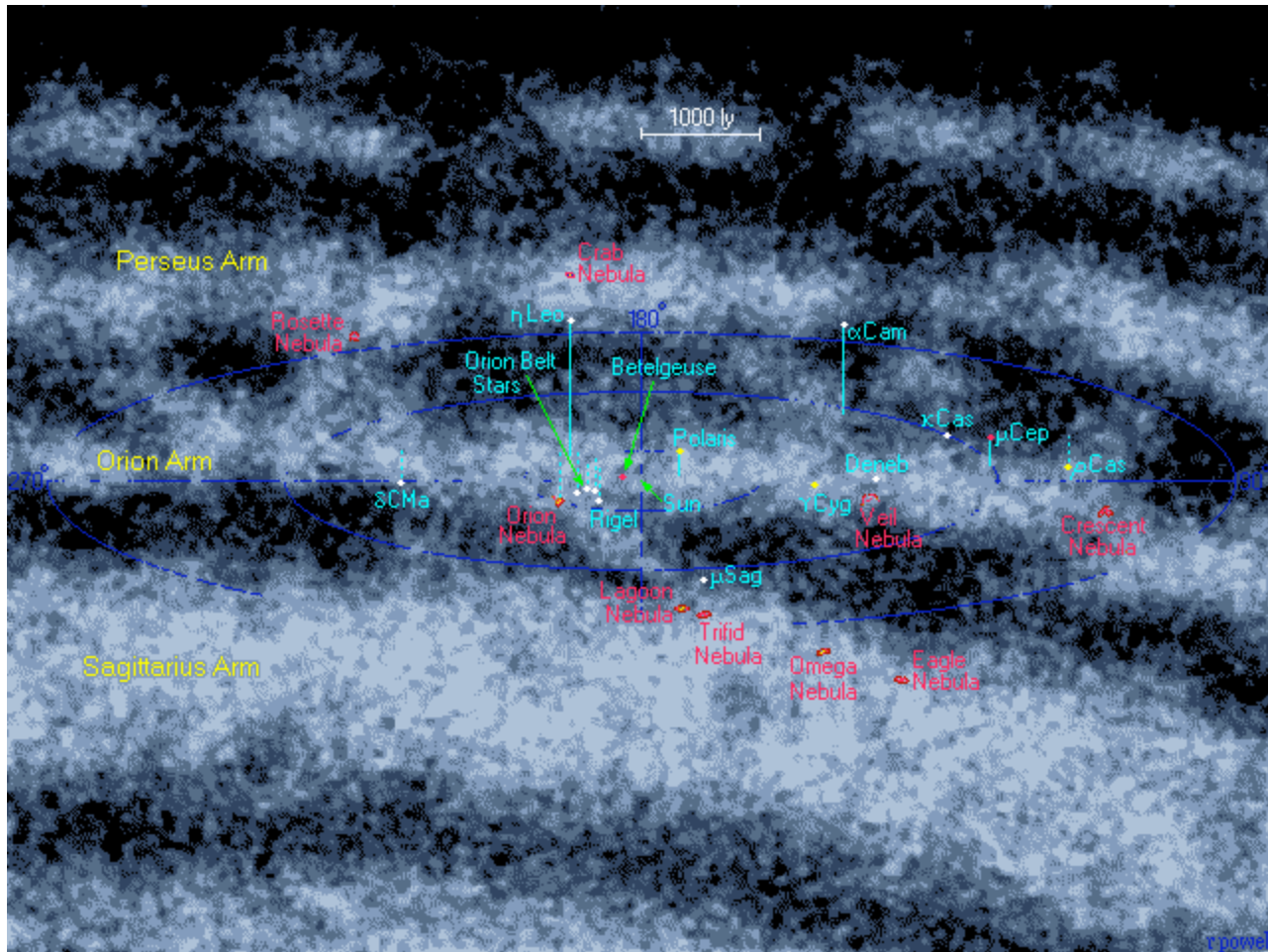
The Hyades Open cluster of stars (151 light years)



*The bright red star Aldebaran
is not in the Hyades*

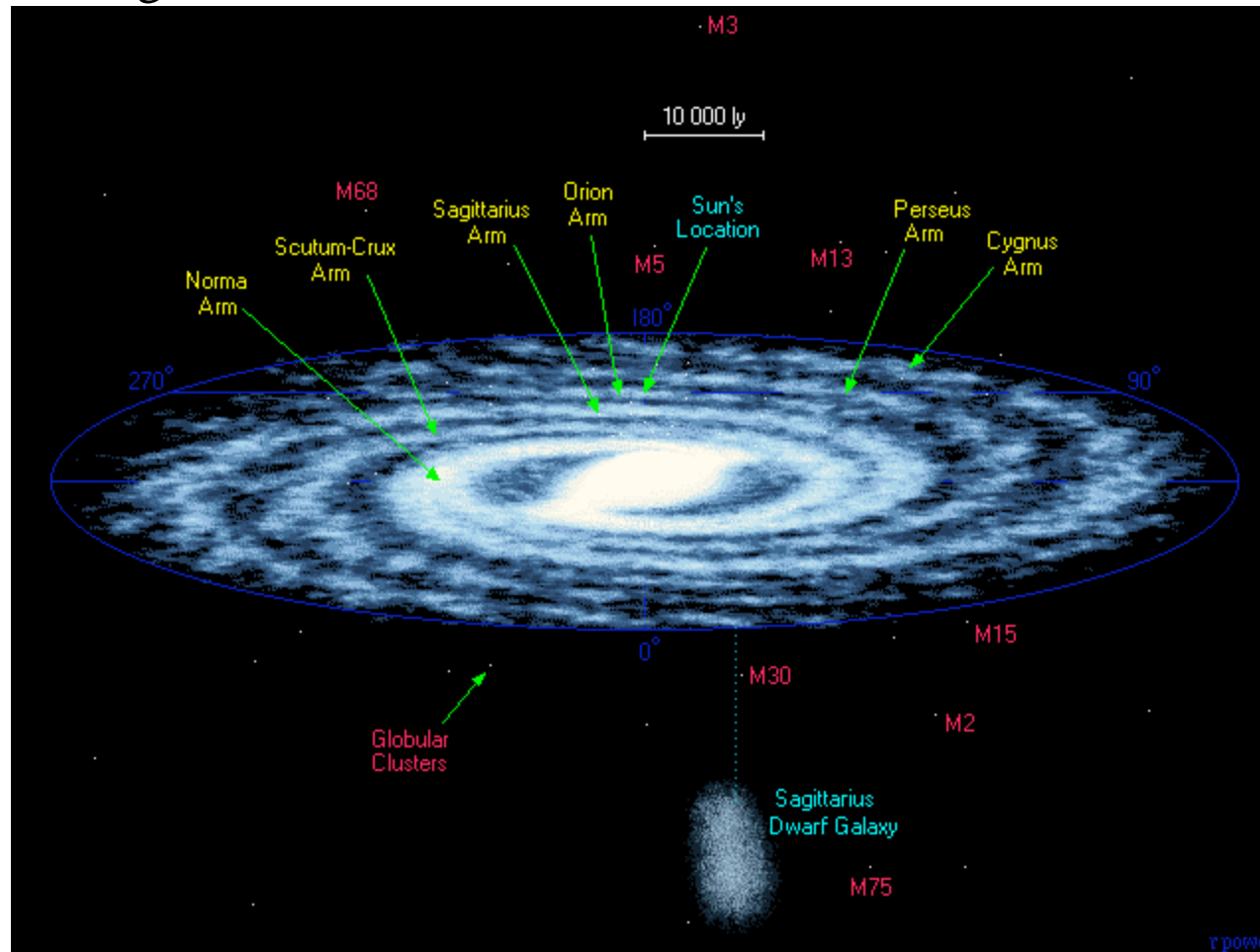
This cluster of stars is only about 625 million years old and is in the process of coming apart. Stars like this are born together from a giant cloud of molecular gas, most of which is blown away by the young stars. About 200 stars are catalogued at http://en.wikipedia.org/wiki/List_of_stars_in_Hyades

5000 light year view – Galactic spiral arm structure is becoming apparent. The sun is on the “Orion Arm” a lesser arm of the Milky Way compared e.g., to the Sagittarius Arm. There is also a lot of gas and dust.



Betelgeuse 650 ly; Orion 1350 ly

The entire visible galaxy is about 80,000 light years across. Note orbiting galaxy and globular clusters



<http://www.atlasoftheuniverse.com/galaxy.html>

Globular Clusters



47 Tuc

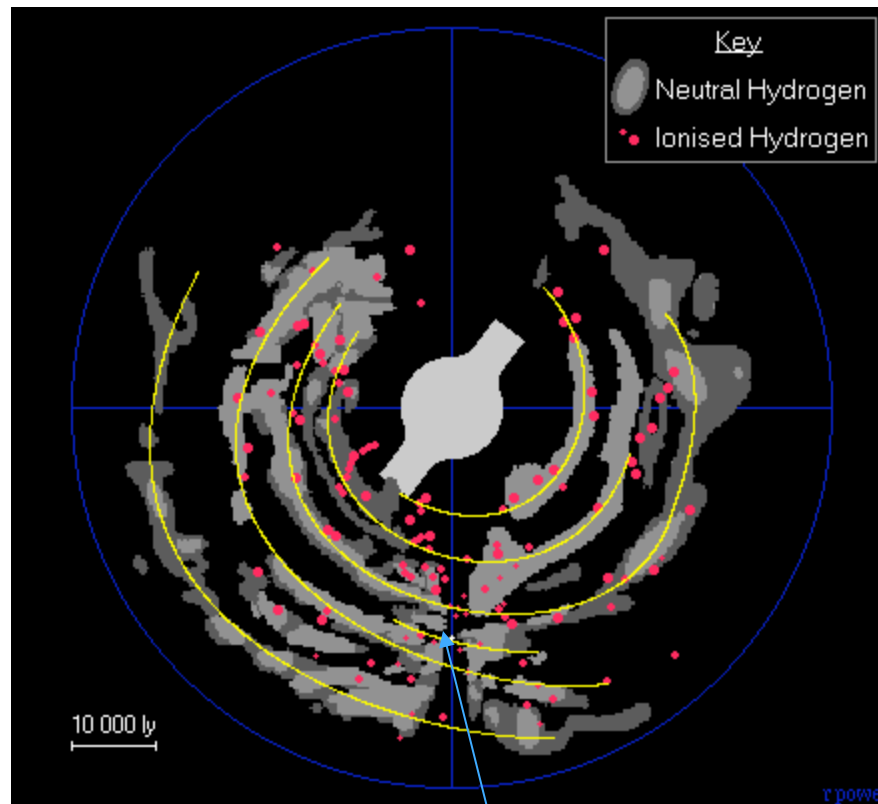
Second brightest globular cluster (behind Omega Cen). There are about 200 globular clusters altogether. This one is near the direction of the SMC in the sky and about 20,000 ly distant. Lots of red giants visible here.



M13

This globular cluster in Hercules is 22,000 ly distant and contains $10^5 - 10^6$ stars. Age \sim 12 to 14 billion years. It is about 150 light years across.

The clearest experimental evidence for spiral structure in our own galaxy comes from radio observations. The galaxy is transparent in the 21 cm line of atomic H.

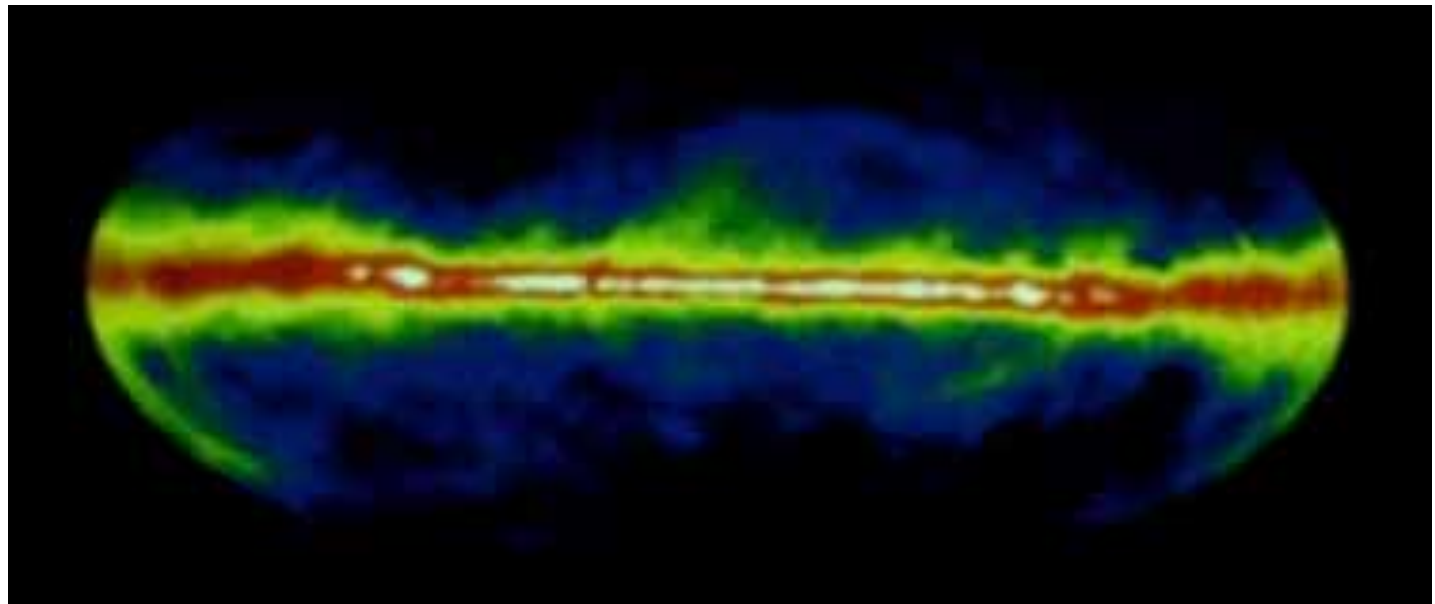


the sun

Radio View of the Milky Way

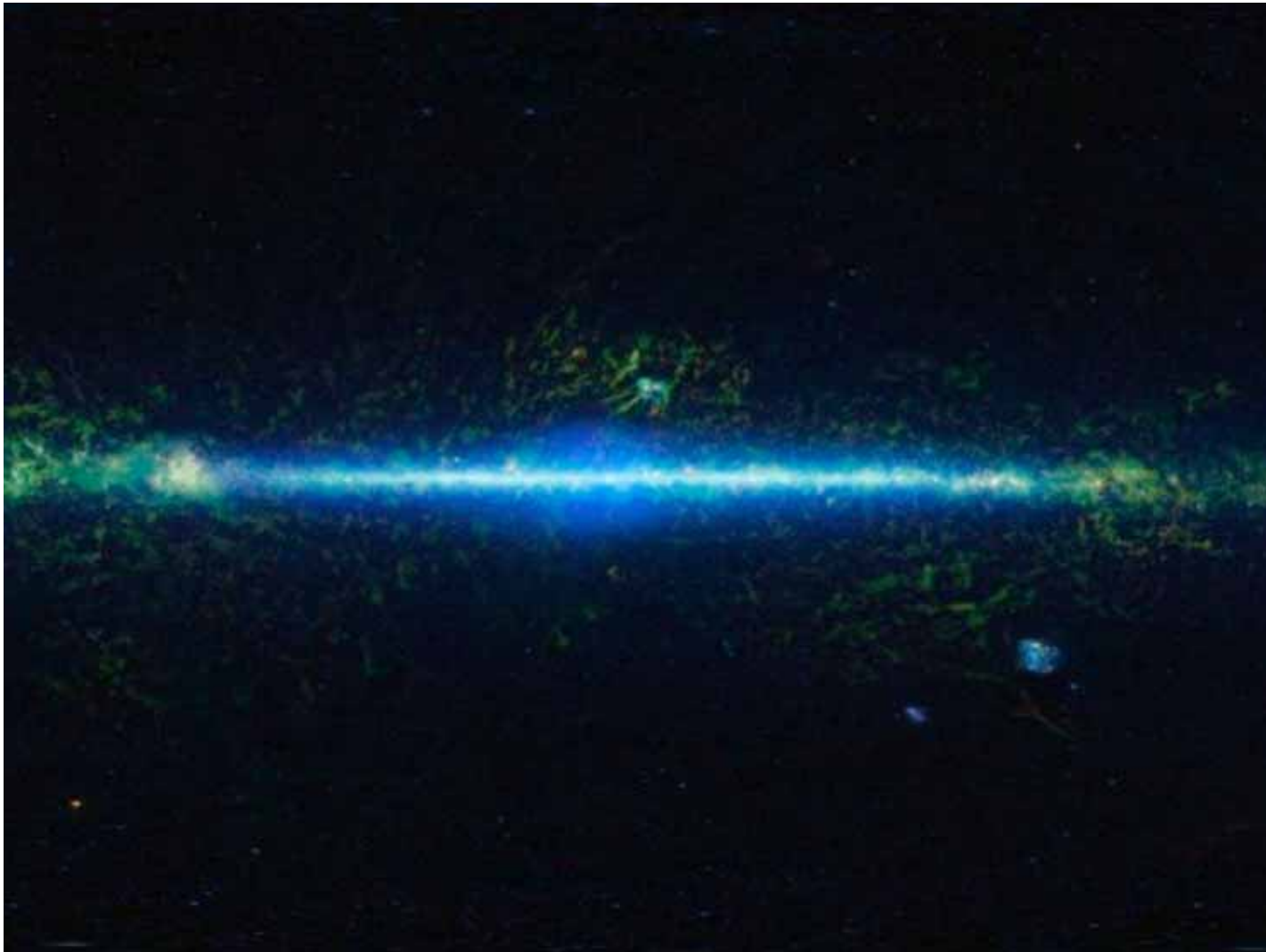
Interstellar dust does not absorb radio waves

We can observe any direction throughout the Milky Way at radio waves



Radio map at a wavelength of 21 cm, tracing neutral hydrogen

<http://www.geekosystem.com/wise-all-sky-atlas/>

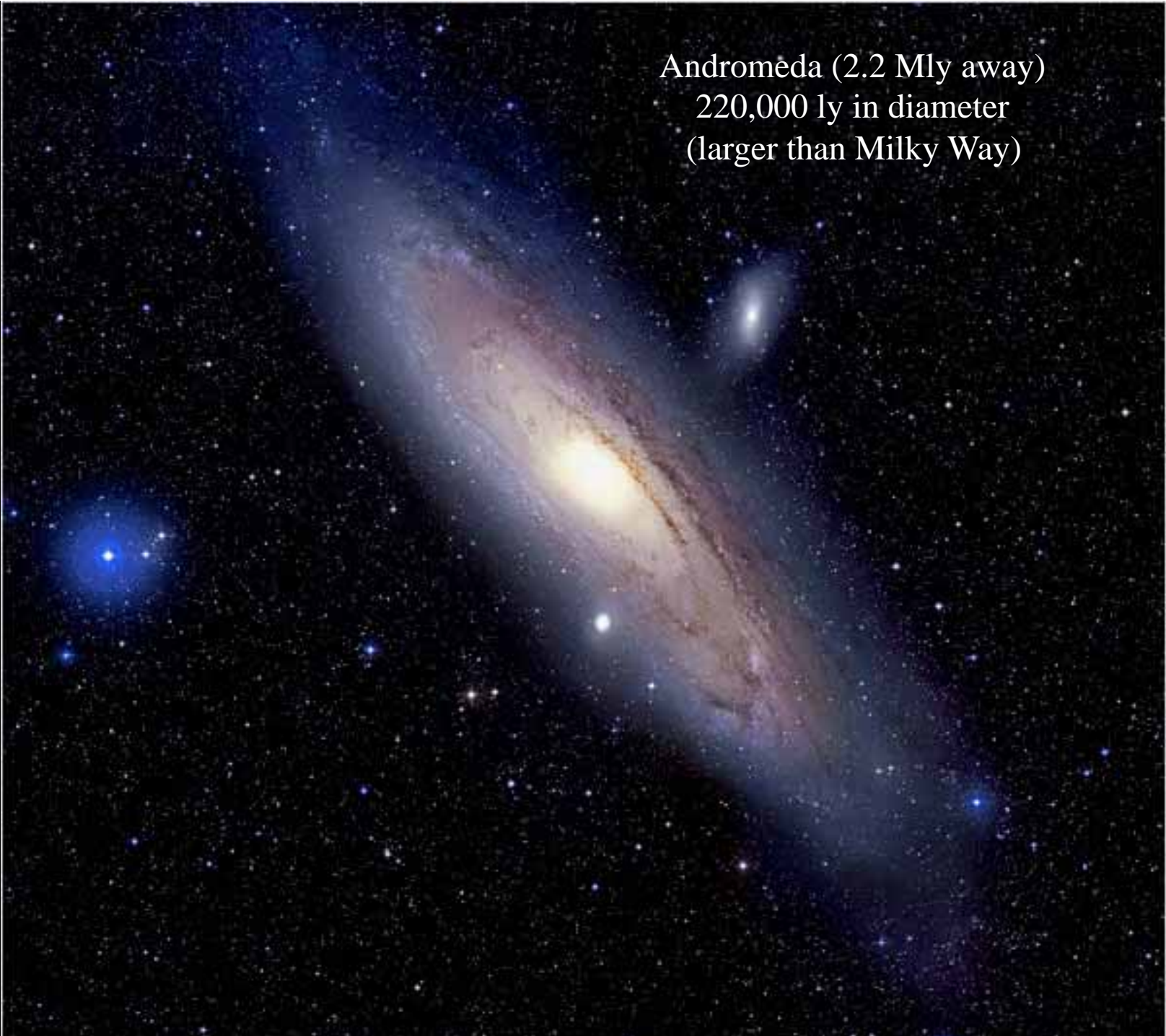


Released 2012. Wide Field Infra-Red Survey Explorer (WISE) composite photograph of the entire sky.
Over 500 million individual stars catalogued

Other *spiral* galaxies are thought to look very similar to our own Milky Way.



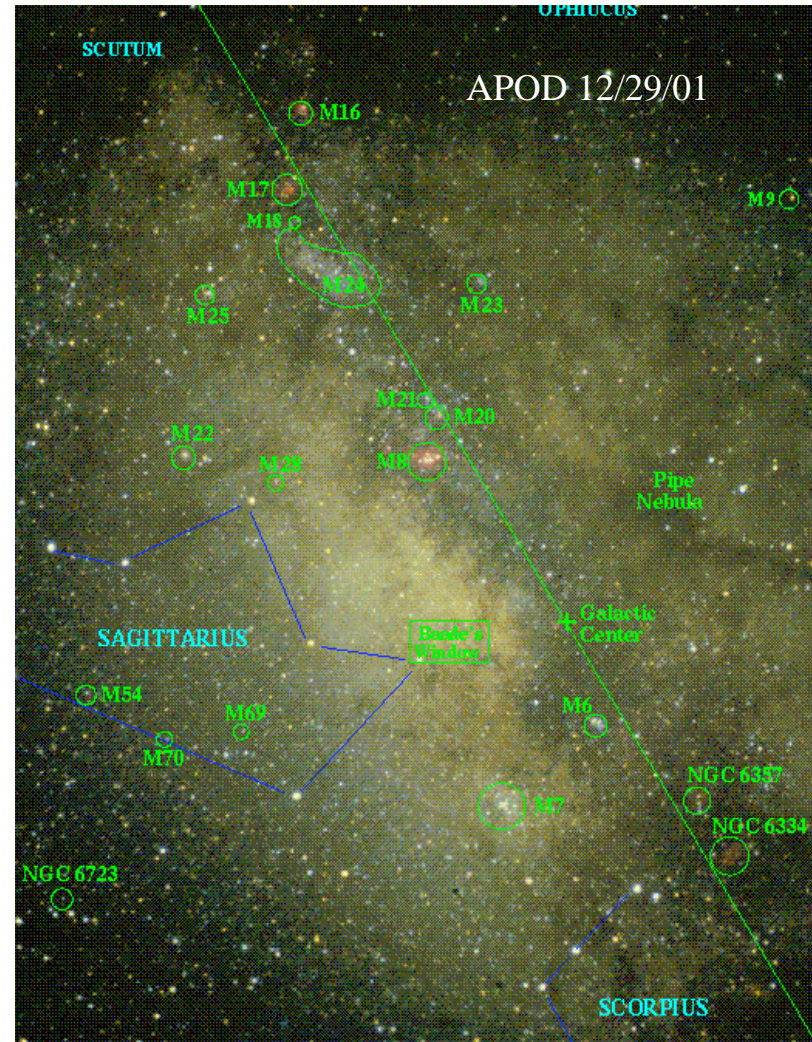
Andromeda (2.2 Mly away)
220,000 ly in diameter
(larger than Milky Way)



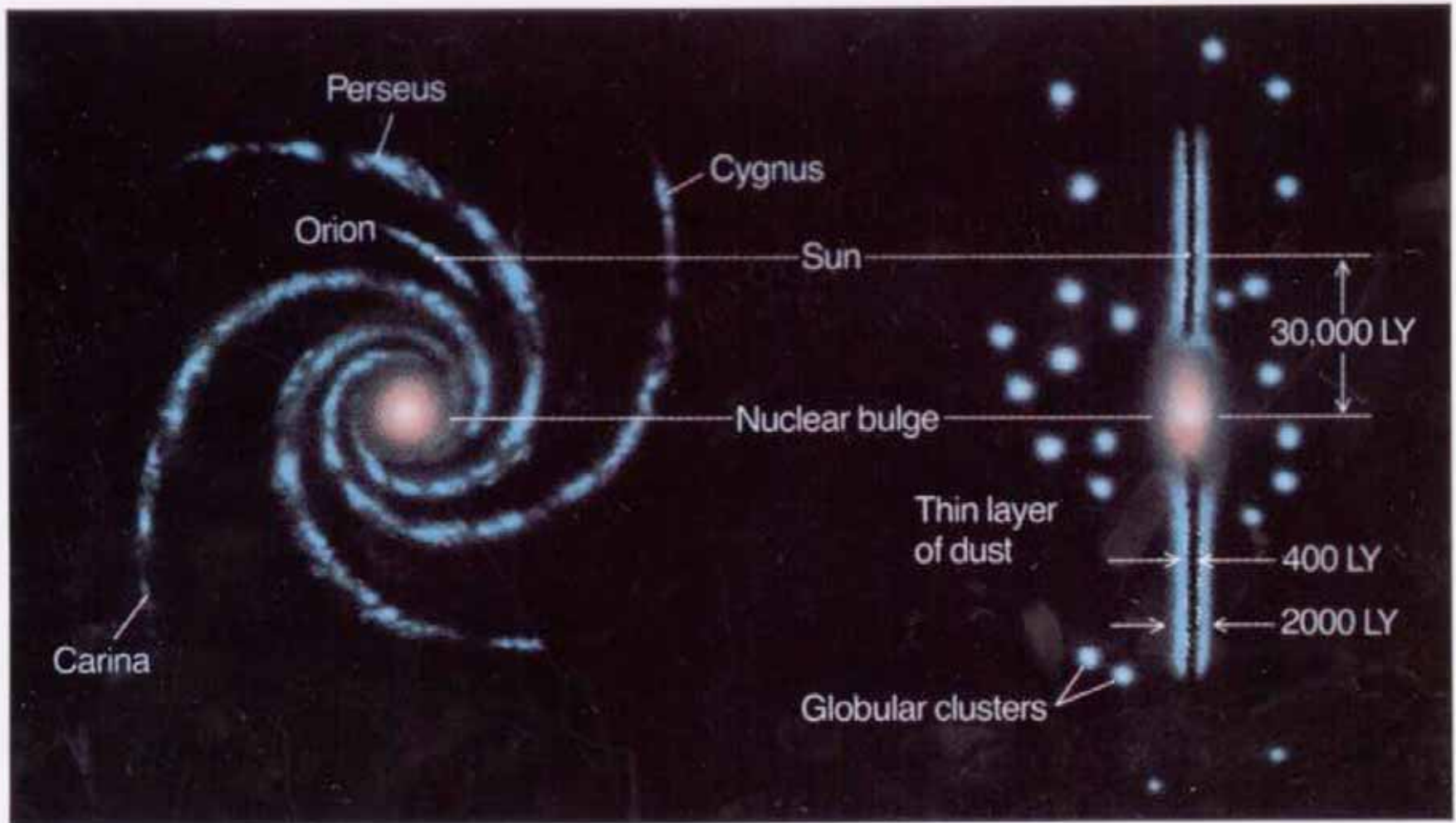
The center of our galaxy is towards the constellation Sagittarius



Infrared observation (2MASS) towards center of the Milky Way - dust glows in IR

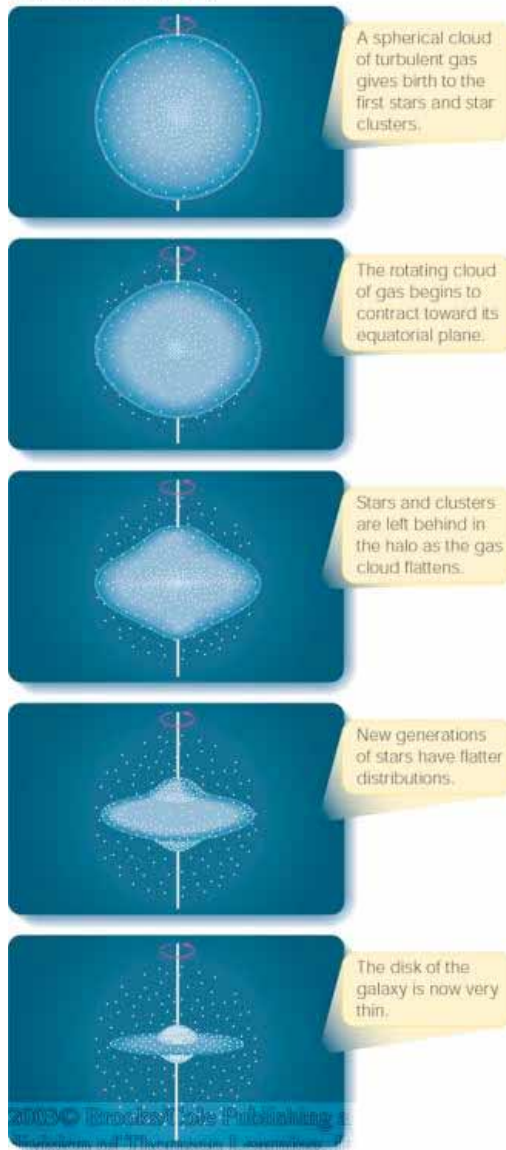


Optical - M 6,7,18,21,23,24,24 = open clusters; M 16,17,20 = nebulae; M 9, 22,28,54,69,70 = globular clusters



History of the Milky Way

Origin of the Halo and Disk



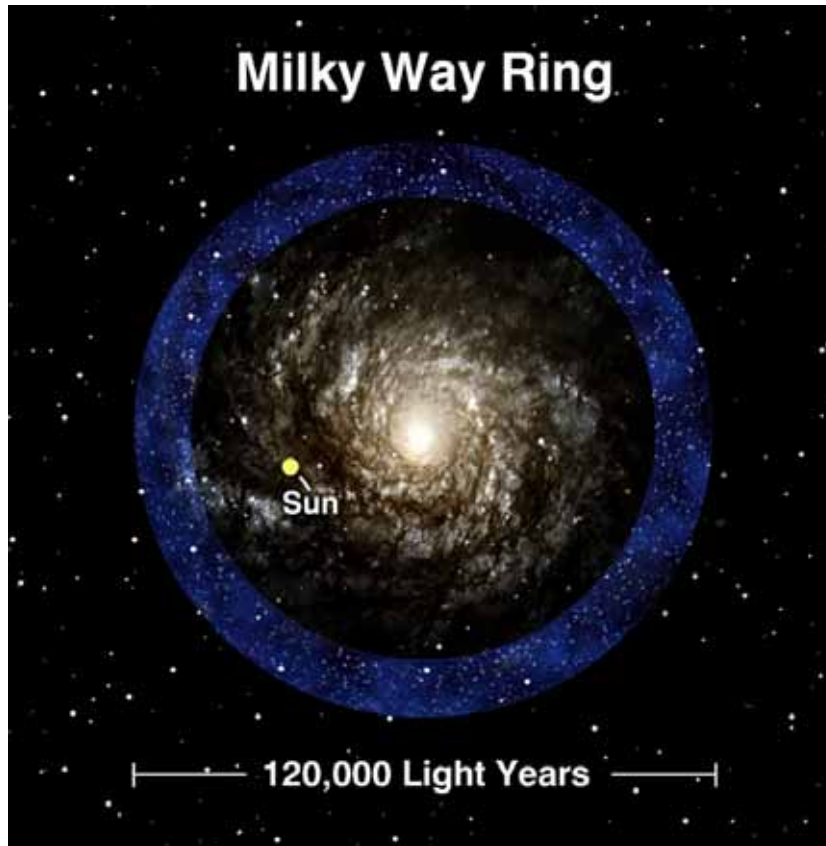
The traditional theory:

Quasi-spherical gas cloud fragments into smaller pieces, forming the first, metal-poor stars (pop. II);

Rotating cloud collapses into a disk-like structure

Later populations of stars (pop. I) are restricted to the disk of the Galaxy

Changes to the Traditional Theory



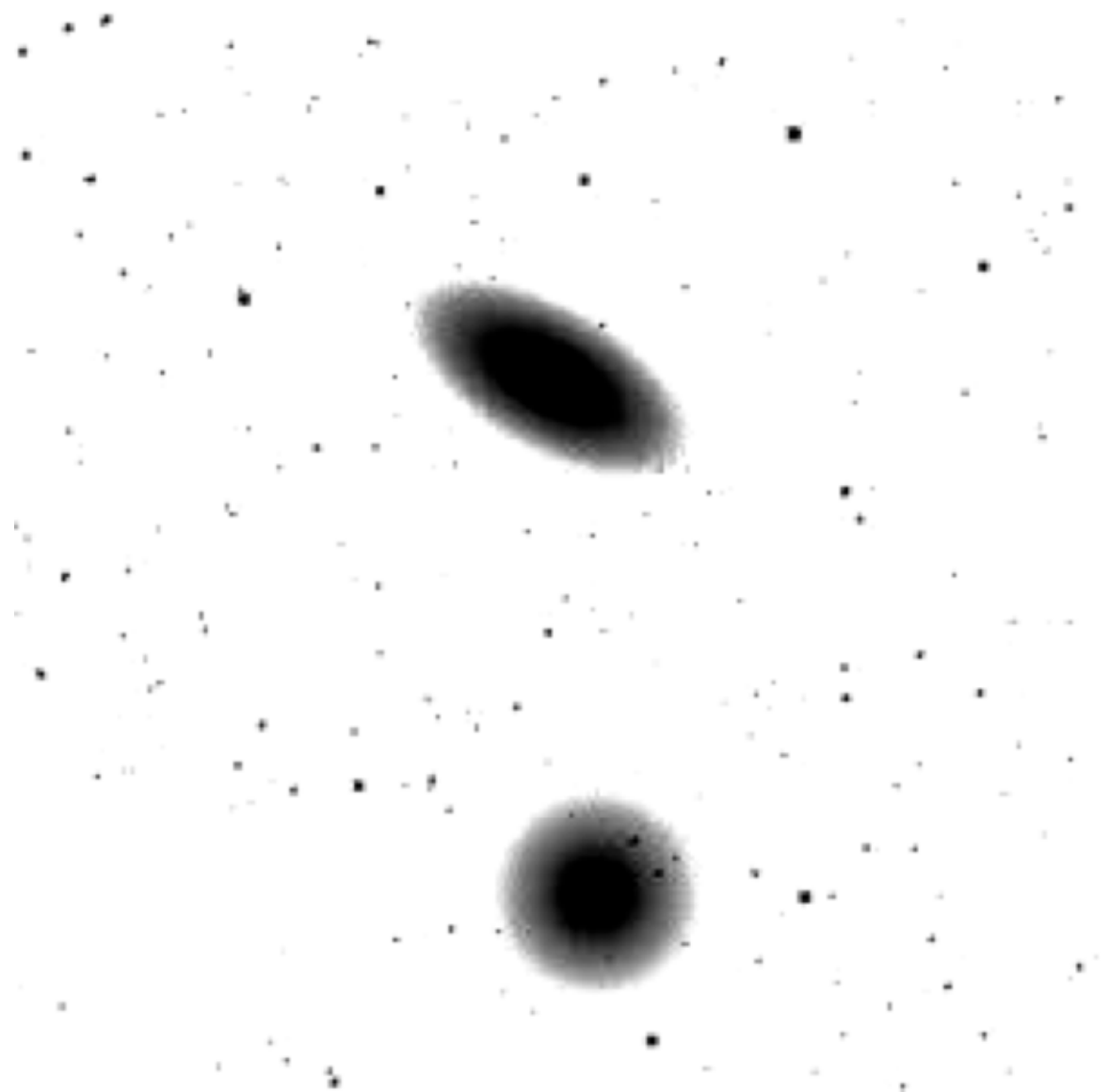
Ages of stellar “populations” may pose a problem to the traditional theory of the history of the Milky Way

Possible solution: Later accumulation of gas, possibly due to mergers with smaller galaxies

Recently discovered ring of stars around the Milky Way may be the remnant of such a merger

<http://www.sdss.org/news/releases/20030106.milkyway.html>

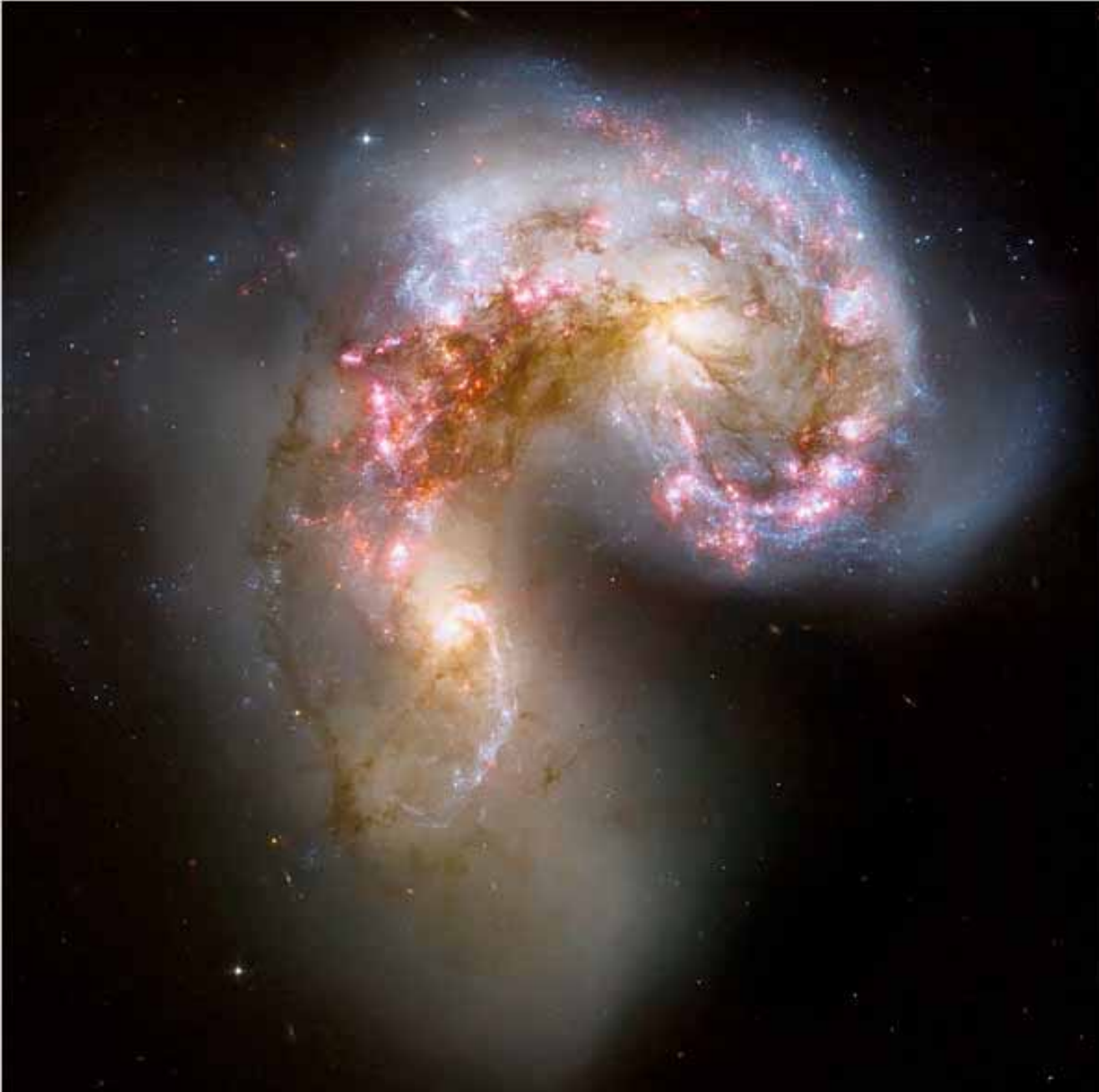
Sloan Digital Sky Survey



*About 3 billion years in
the future, our galaxy and
Andromeda will merge.*

*Calculation by John Dubinsky
at CITA.*

Galaxies collide



The Antenna Galaxy is not one but two galaxies in the process of merging.

New generations of stars are being born, even new globular clusters, in the blue regions. Note also the presence of a lot of dust.

Besides spiral galaxies like Andromeda ...
(2.2 Mly)



Similar to but somewhat larger and brighter than the Milky Way (has about 250 globular clusters and many orbiting dwarf ellipticals)

There are also Elliptical galaxies



For example, the massive elliptical galaxy M87 at the center of the Virgo cluster of galaxies.

Such galaxies are oval in shape, have no discernible spiral structure, and little gas or dust.

Reddish in color. Very few new stars being born.

Elliptical galaxies come in all sizes from just a little larger than globular clusters to 10 times the mass of the Milky Way.

The most common kind of galaxy nowadays are the dwarf ellipticals.

Gas used up long ago making stars or stripped by galactic collisions and encounters.

Irregular and other galaxies

The SMC contains several hundred million stars



Small Magellanic Cloud
AAO ref UKS 17



IC 5152
AAO ref AAT 43



NGC 1313 starburst galaxy
AAO ref AAT 64



Large Magellanic Cloud
AAO ref UKS 14



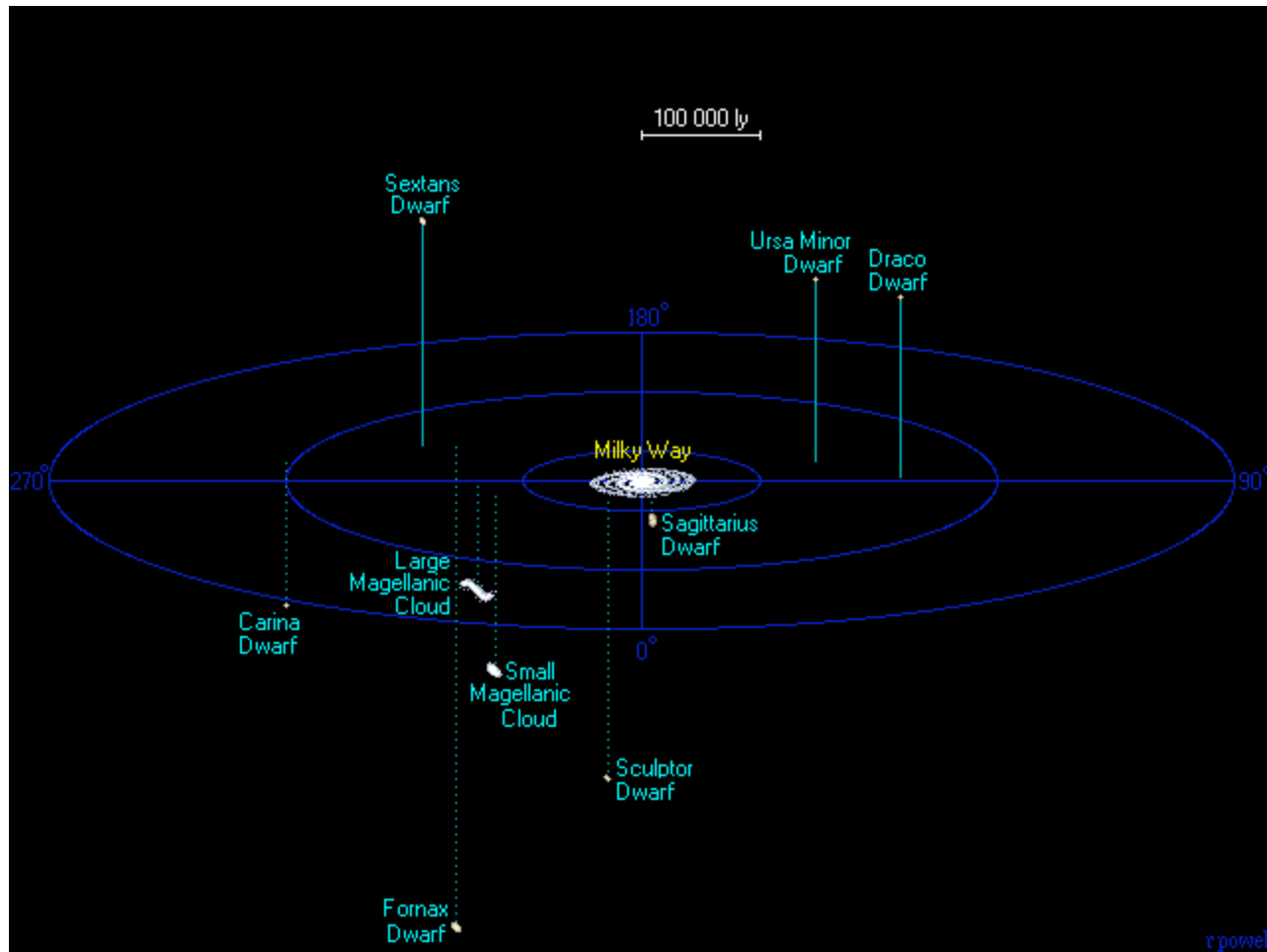
NGC 6822
AAO ref AAT 26

The LMC (157,000 ly) is the fourth largest galaxy in the local group and contains about 10 billion solar masses

- 1) Andromeda
- 2) Milky Way
- 3) Triangulum Galaxy (M33)
- 4) LMC



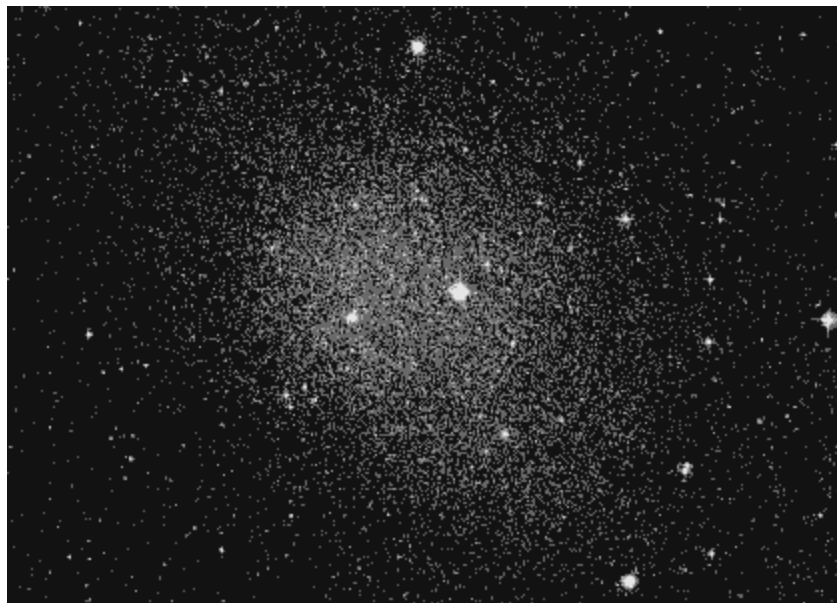
*The nearest members of the
Local Group of Galaxies
orbit our Milky Way*



(500,000 ly)

Fornax dwarf galaxy

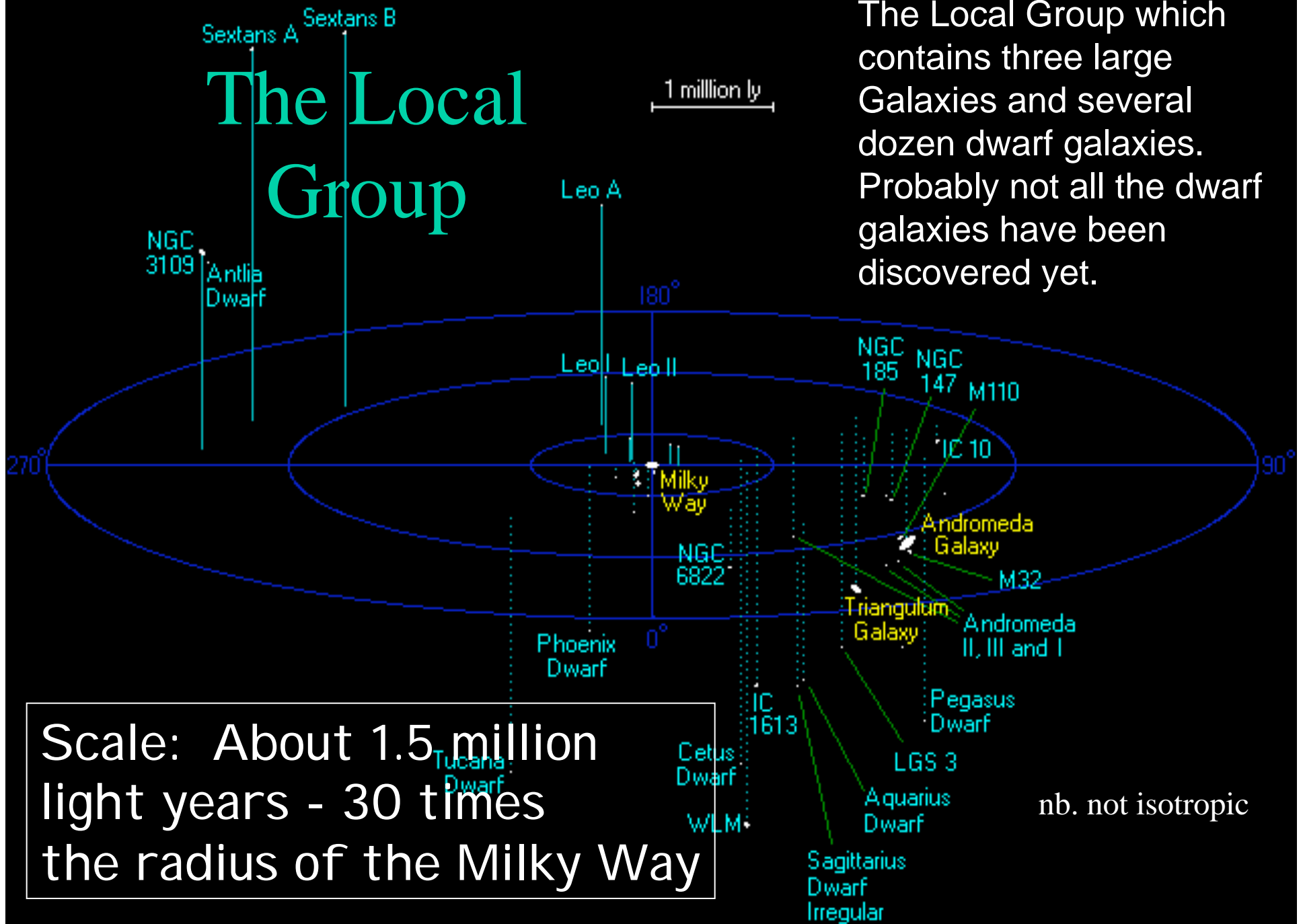
460,000 ly distant, discovered in 1938



Like most dwarf galaxies it doesn't look very impressive. Contains only a few million stars. Orbiting by six globular clusters

The Local Group

The Local Group which contains three large Galaxies and several dozen dwarf galaxies. Probably not all the dwarf galaxies have been discovered yet.



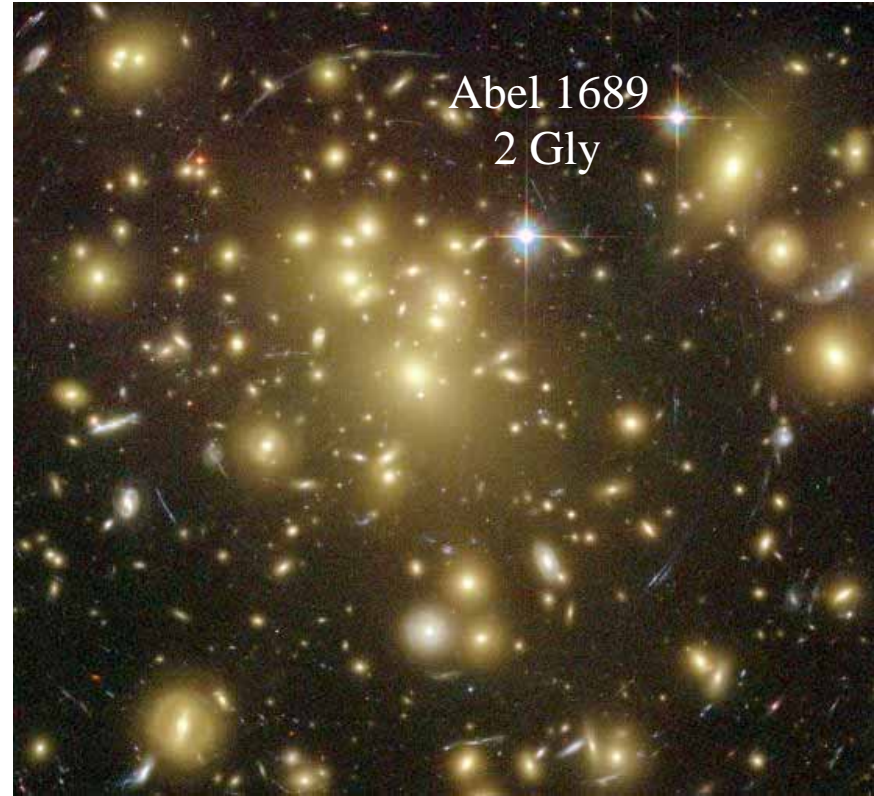
Scale: About 1.5 million light years - 30 times the radius of the Milky Way

nb. not isotropic

Clusters of Galaxies

Rich clusters of galaxies

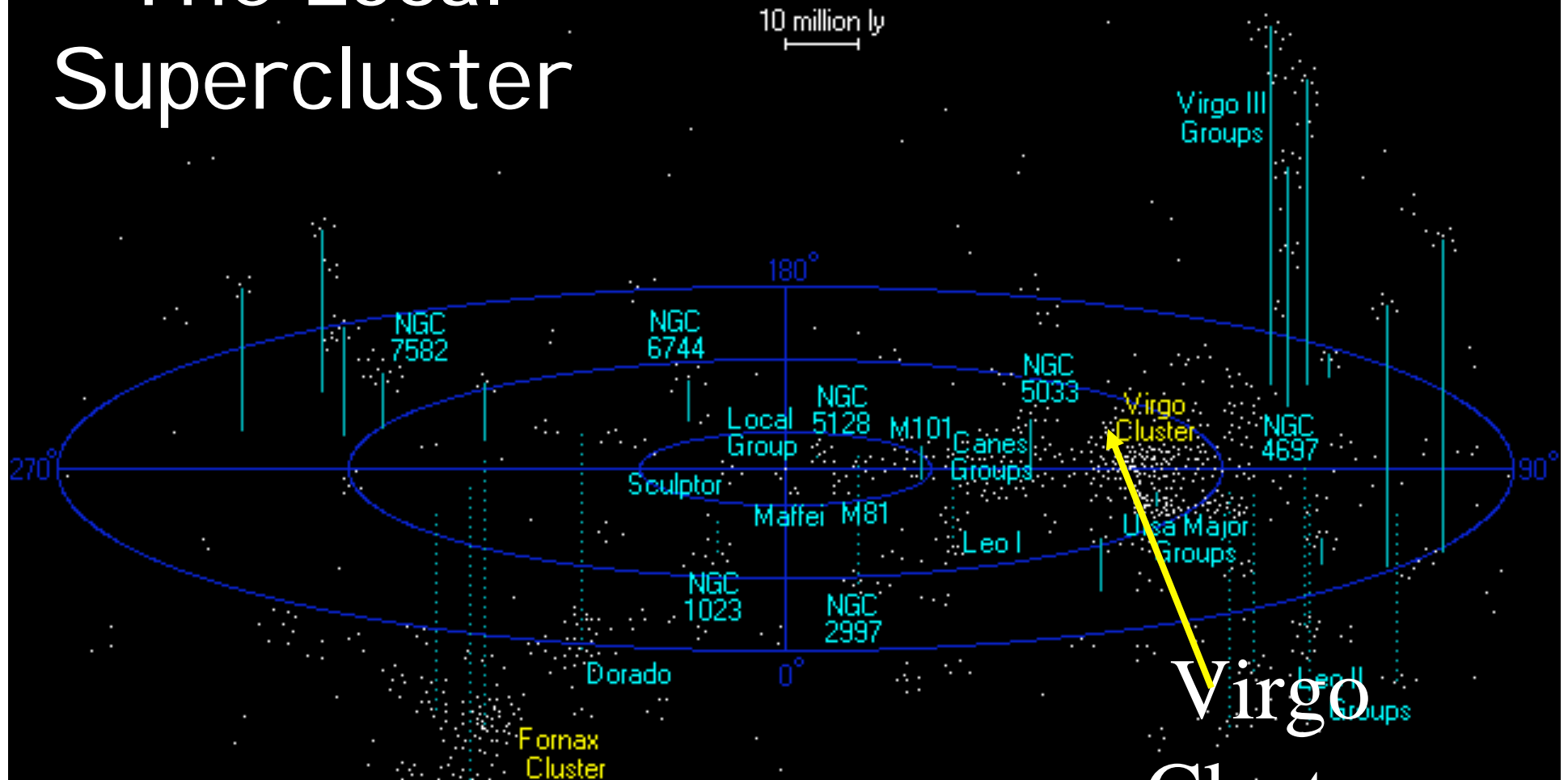
- thousands of galaxies
- concentrated toward the center
- more ellipticals
- hot gas
- lots of mergers



Poor clusters of galaxies

- just a few galaxies
- ragged shapes
- more spirals,
- fewer ellipticals

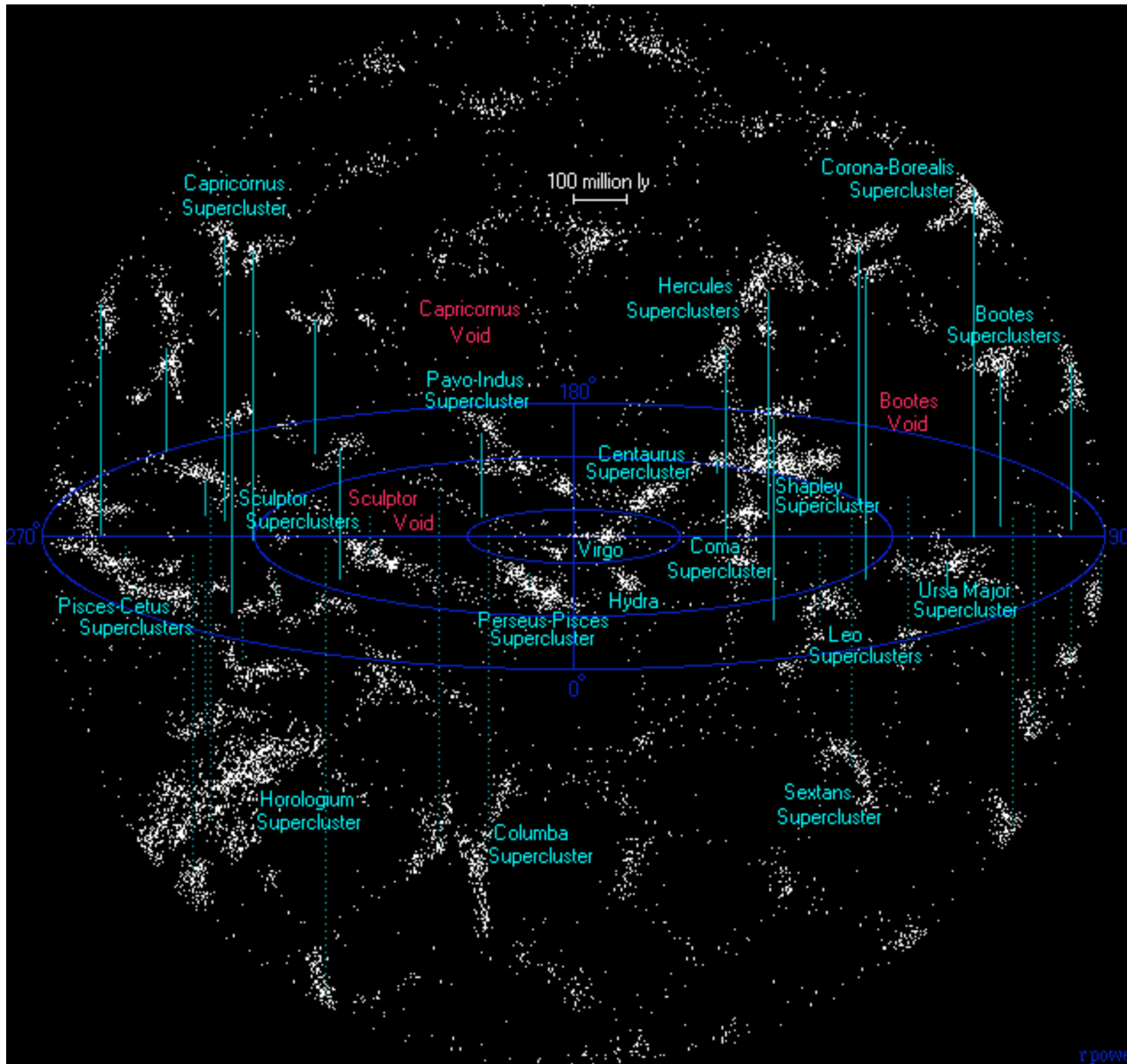
The Local Supercluster



Virgo
Cluster
54 Mly

Scale: about 60 million ly –
30 times the radius of the
Local Group

One Billion Light Years



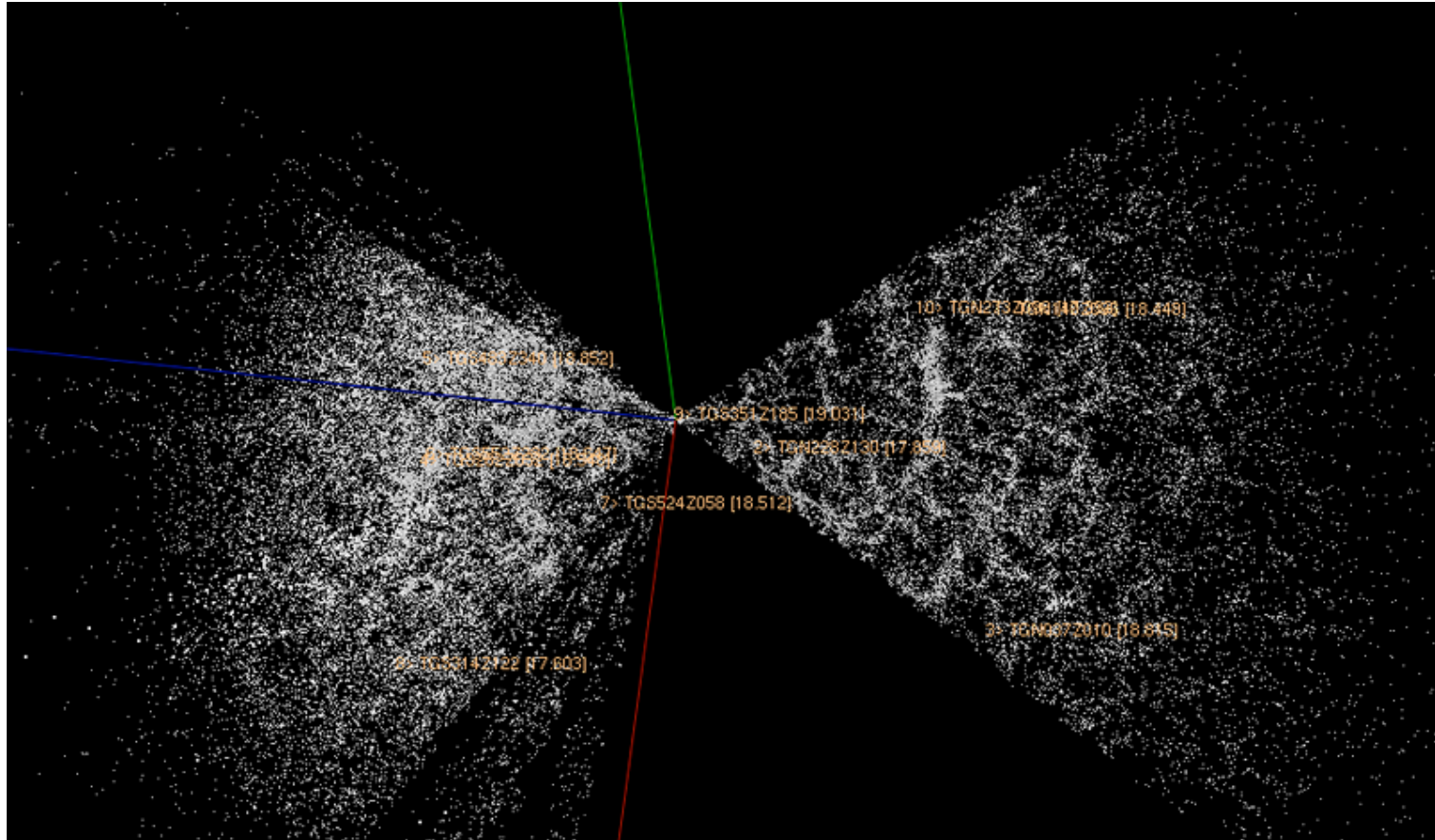
7% of the radius of the visible universe

- 80 superclusters
- 160,000 galaxy groups
- 3 million large galaxies
- 30 million dwarf galaxies
- 500 million billion stars

The nearest really large supercluster is in Centaurus. Virgo is small by comparison.

Structure starting to be filamentary with walls and voids.

2dF Galaxy Redshift Survey - AAT (2003) closest 3 billion light years



Survey obtained spectra for 232,155 galaxies over 272 nights of observation. 1500 square degrees. Did not sample the whole sky. On the whole the universe is *homogeneous and isotropic*. Note cellular structure.

<http://www.mso.anu.edu.au/2dFGRS/>

Size of Hubble eXtreme Deep Field on the Sky

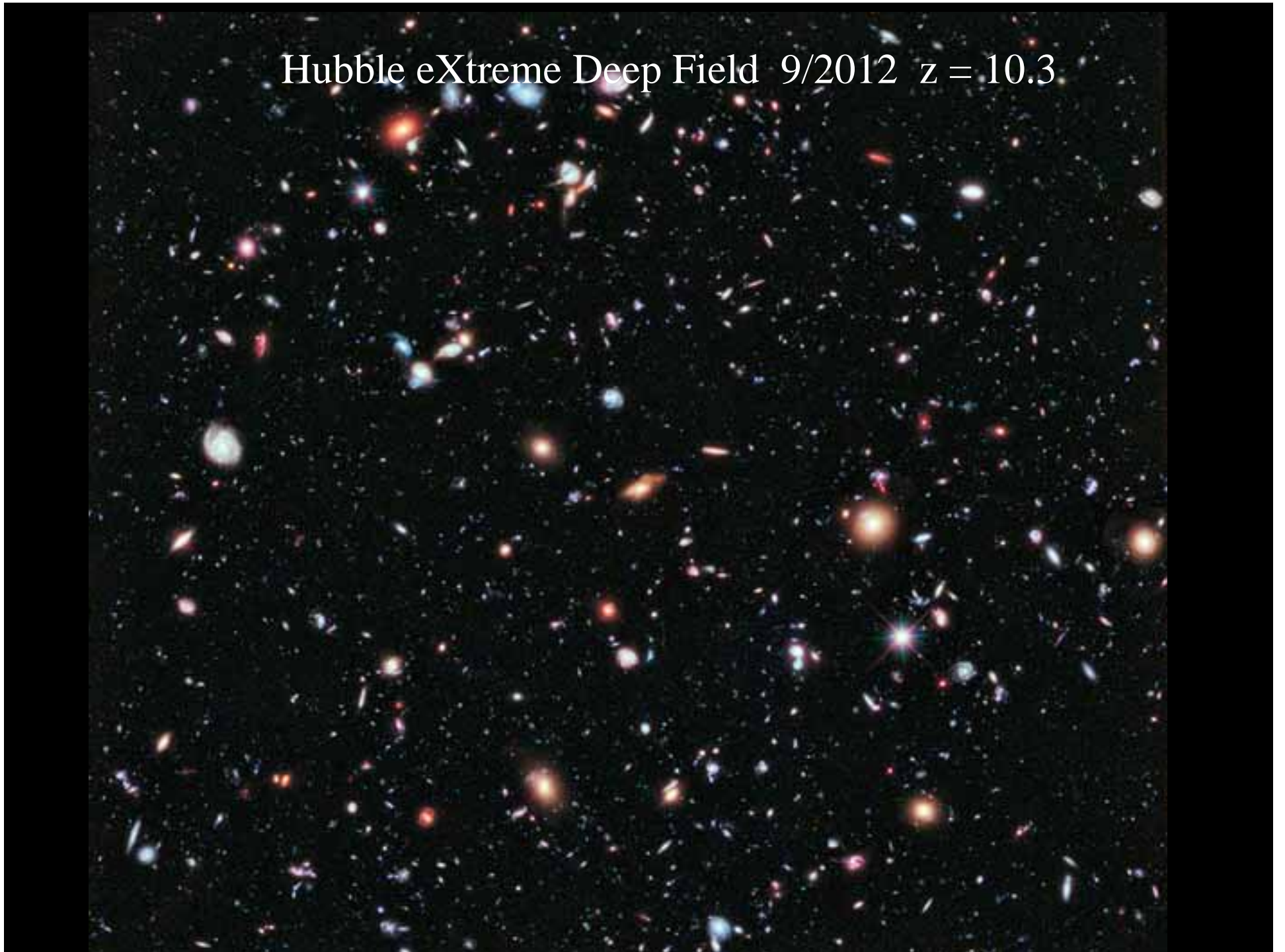


*The Hubble eXtreme
Deep Field photo
made from a composite
of 2000 images taken
over a decade. Like
a 23 day time
exposure*

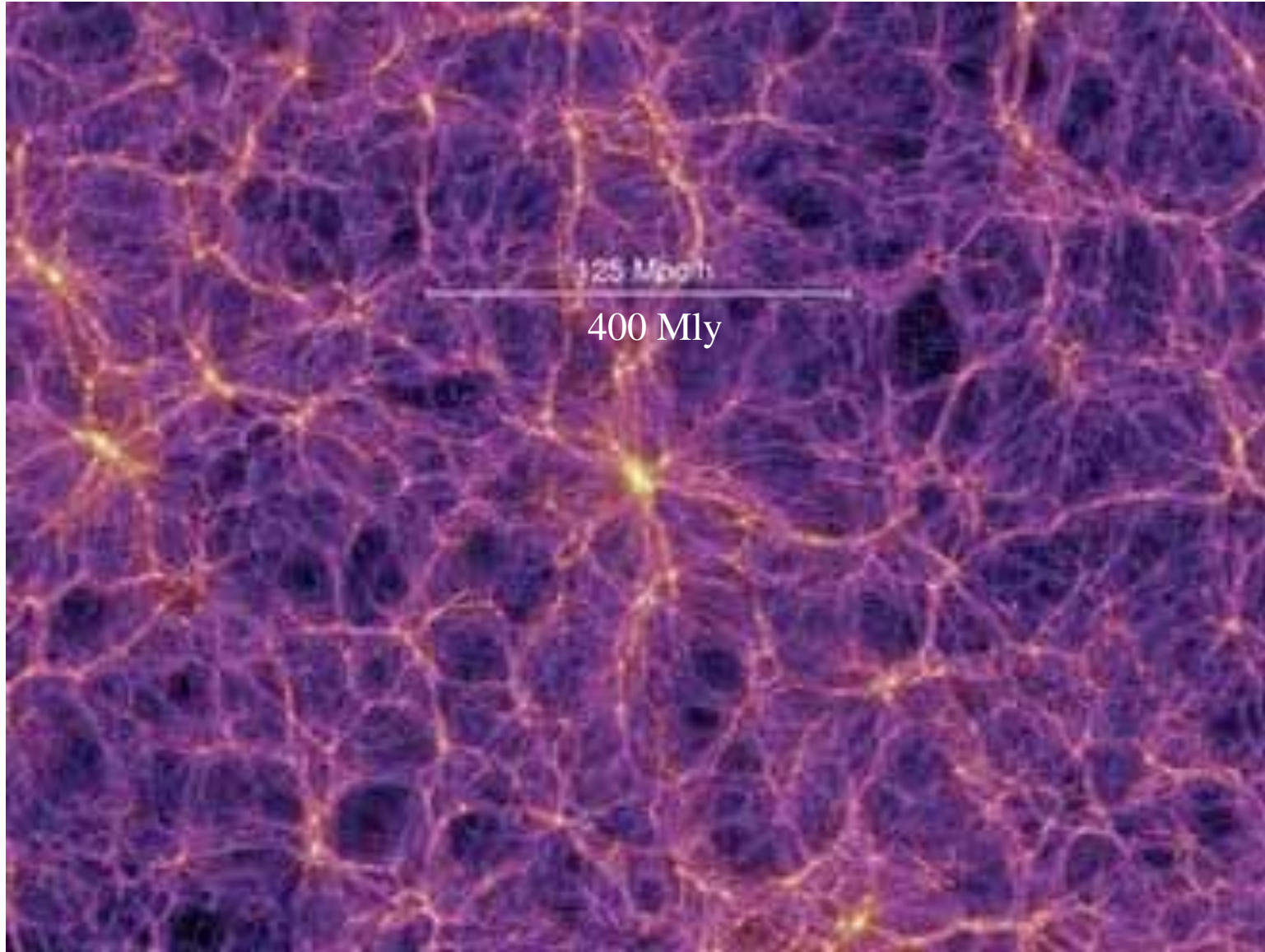
*Shows a piece of the
universe when it
was “only” 400
million years old.
5500 galaxies*

*The current age
is 13.7 billion years*

Hubble eXtreme Deep Field 9/2012 $z = 10.3$



<http://www.mpa-garching.mpg.de/galform/virgo/millennium/>

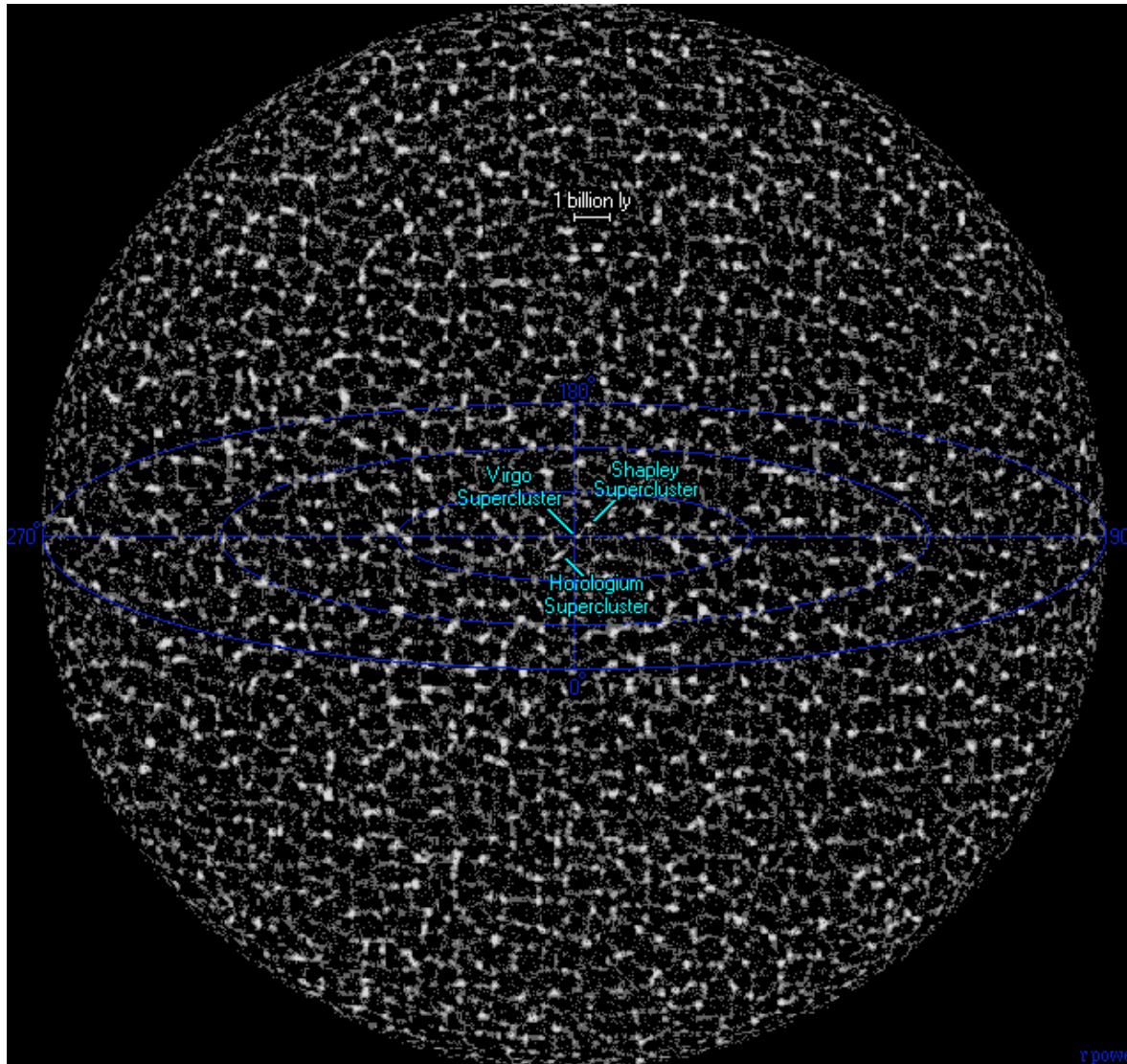


Numerical simulation of cosmic structure
“The millenium simulation project”

<http://www.mpa-garching.mpg.de/galform/virgo/millennium/>

Approximately 15 Billion Light Years

(a sketch)



~300,000 superclusters

~ 10^{10} large galaxies

~ 2000 billion billion stars

*The end of the road
(for now) ...*