Astronomy 12

Stars, Stellar Evolution, and High Energy Astrophysics

http://www.ucolick.org/~woosley/

- Winter 2016
- Physical Sciences 110

- Stan Woosley

UCSC Dept of Astronomy and Astrophysics

Astronomy 12 -- Stars and Stellar Evolution

WHEN AND WHERE:
Jan 5 - Mar 10, 2016

LECTURES
Tu Th 12 - 1:45
Physical Sciences 110

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Section: TBD

Tutoring from LSS

Cameron Wehrfritz
Learning Support Services
webpage:
http://lss.ucsc.edu/programs/small-group-tutoring/index.html

signup:
<://eop.sa.ucsc.edu/OTSS/tutorsignup/

ANNOUNCEMENTS:

signup: <://eop.sa.ucsc.edu/OTSS/tutorsignup/

ANNOUNCEMENTS:

Handouts from Class

- Astronomy 12 Syllabus
- Constants Sheet

Astronomy Links

- Links directly related to lectures
- Other Interesting Links

Notes from Class

- Class notes from last year
- Current class notes

Homework and Review for Exams

Astronomy 220C

- Class notes from graduate Ay220C class

Astronomy 112

- Class notes from upper division class

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Comments and suggestions to: woosley@ucolick.org Last update: 1/1/16

PHYSICAL CONSTANTS

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

Astronomy 12 Links

General Links

Textbook site	Los of background material for our class textbook
http://www.astronomynotes.com/	An excellent hypertext astronomy textbook
http://www.freebookcentre.net/Physics/Astronomy-Books-Download.html	Many free online astronomy texts.
http://heasarc.gsfc.nasa.gov/docs/www_info/webstars.html http://heasarc.gsfc.nasa.gov/docs/objects	Gateway to all sorts of astronomical images and resources
http://imagine.gsfc.nasa.gov/docs/science/know_12/	Science Section of "Imagine the Universe". Mostly high energy astrophysics
http://antwrp.gsfc.nasa.gov/apod/astropix.html	Astronomy Picture of the Day

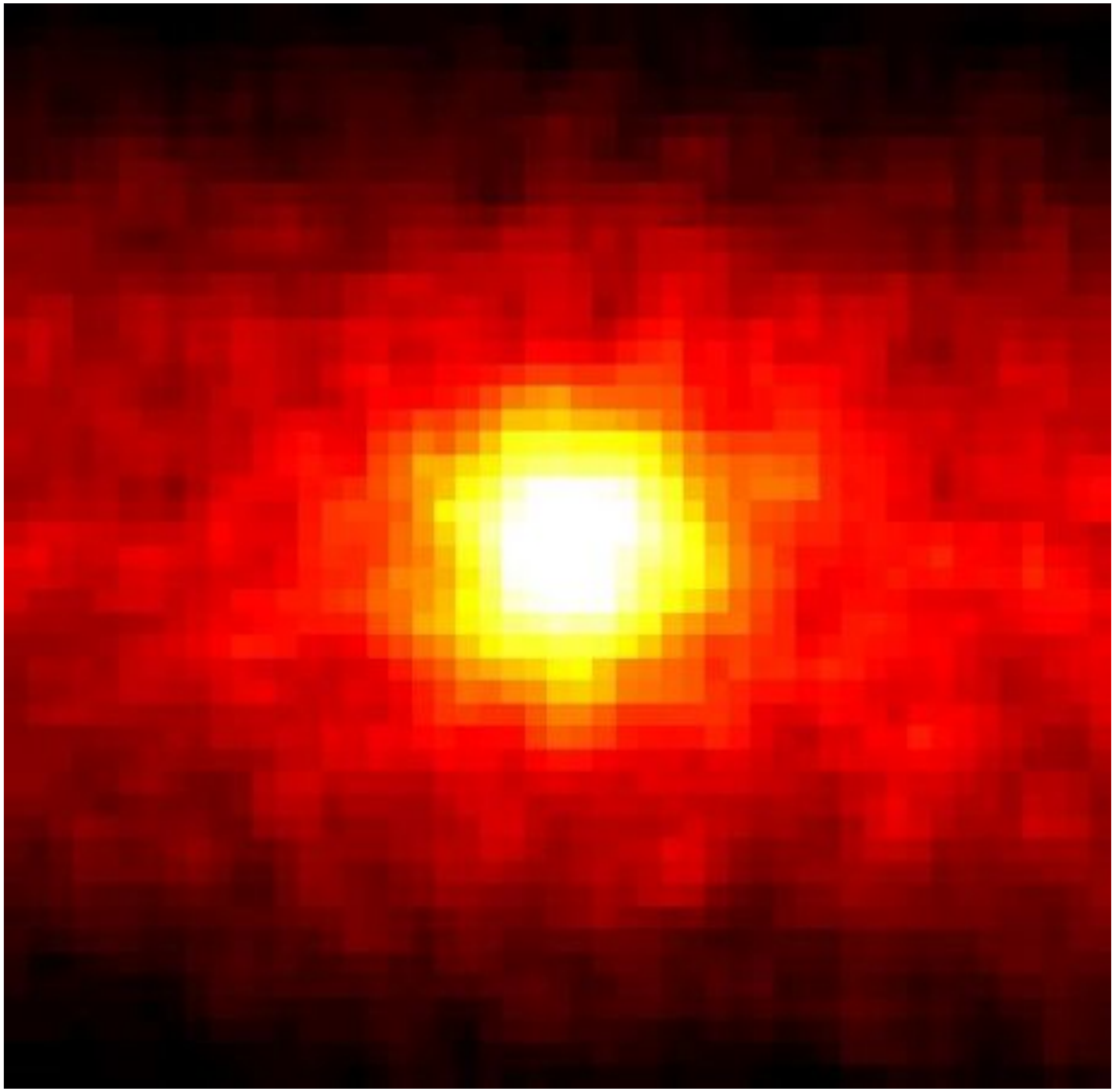
The Nature of Science

- *Science is most successful at addressing the "how" of the universe, not so much its purpose.*

- *Science endeavors to understand the universe with a minimal set of assumptions – physical laws, fundamental particles, fundamental forces, initial conditions, and mathematics.*

- *.In most cases science is tested against observations and its ability to correctly predict outcomes, though sometimes our ability to observe is limited and we must rely on mathematical theory.*

The Sun - 1999
(First picture in neutrinos)



This "picture" was taken using data from the Kamiokande 2 neutrino observatory. It contains data from 504 nights (and days) of observation. The observatory is about a mile underground.

Each pixel is about a degree and the whole frame is 90^o x 90^o.


Who says you can’t
crack open a star?

The Nature of Astronomy

- *The scientific study of objects beyond earth (here with emphasis on stars)*
- *A progress report. Our views of the cosmos change daily (but the new theories often include the old ones as subsets)*
- *The cosmos itself changes; all of its constituents are evolving.*
- *A novel aspect of astronomy is its ability to carry out direct studies of the past*
- *Interesting experiments are set up for us, but we have no control over them. Everyone is an observer!*

See also Fraknoi, Morrison and Wolff *Prologue*

"Astrophysics"

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

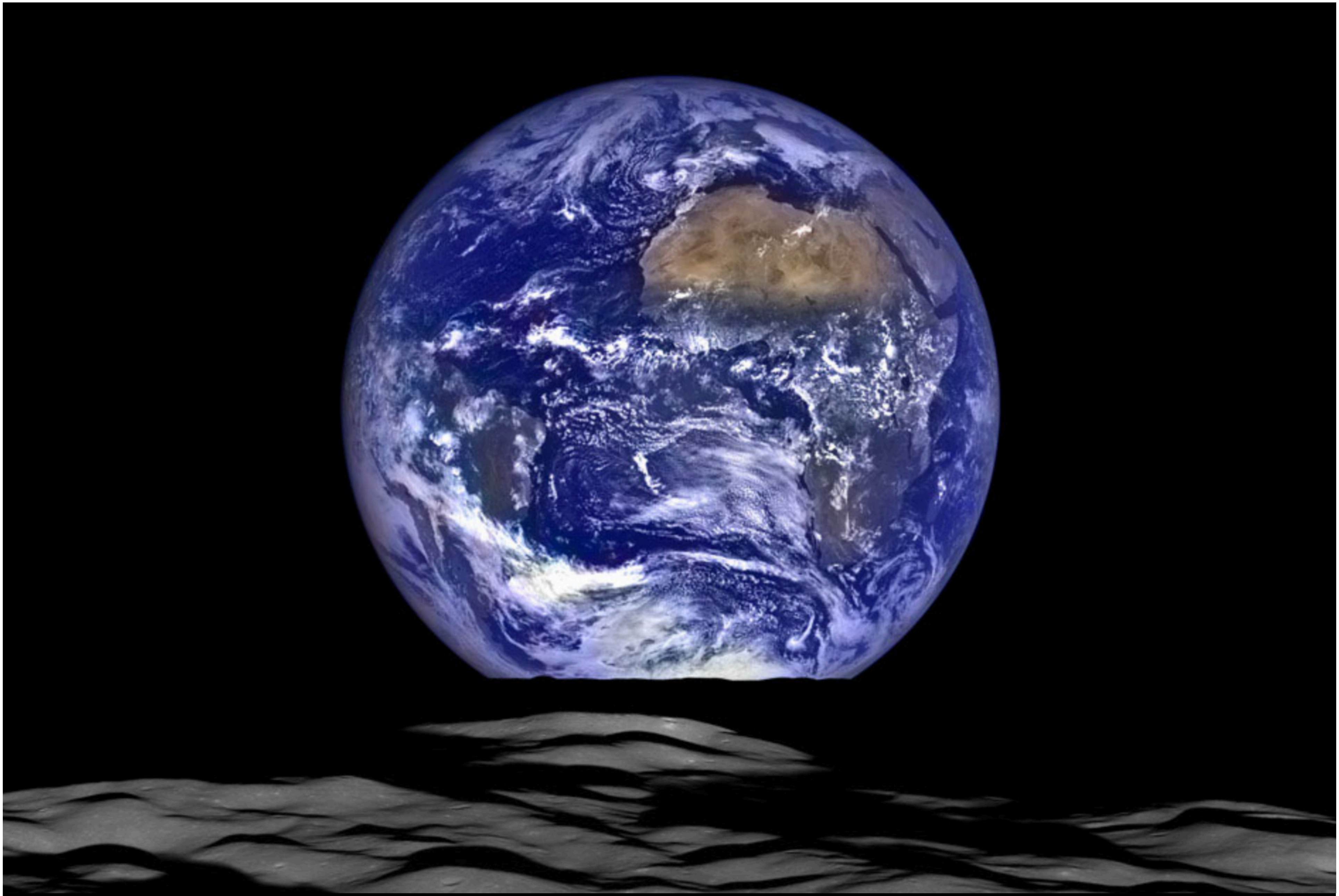
It is best understood on the basis of physical "models" and mathematics

Our location in the Universe

“Spaceship Earth”

From Apollo 11

1969



More recently from the Lunar Reconnaissance Orbiter
(APOD 1 – 4 – 2016)

The Earth as a planet

- M_{earth} = 5.997 x 10^{27} gm $(3 \times 10^{-6}\ M_\odot)$
- R_{earth} = 6.378 x 10^{8} cm
- Age ~ 4.54 billion years (U,Th dating - close to age of sun)
- Orbit sun = 1.496 x 10^{13} cm (~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 = 365.242199… days
  (Julian year = 365.25 days; 86,400 s; exactly)
- 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

aside – leap year

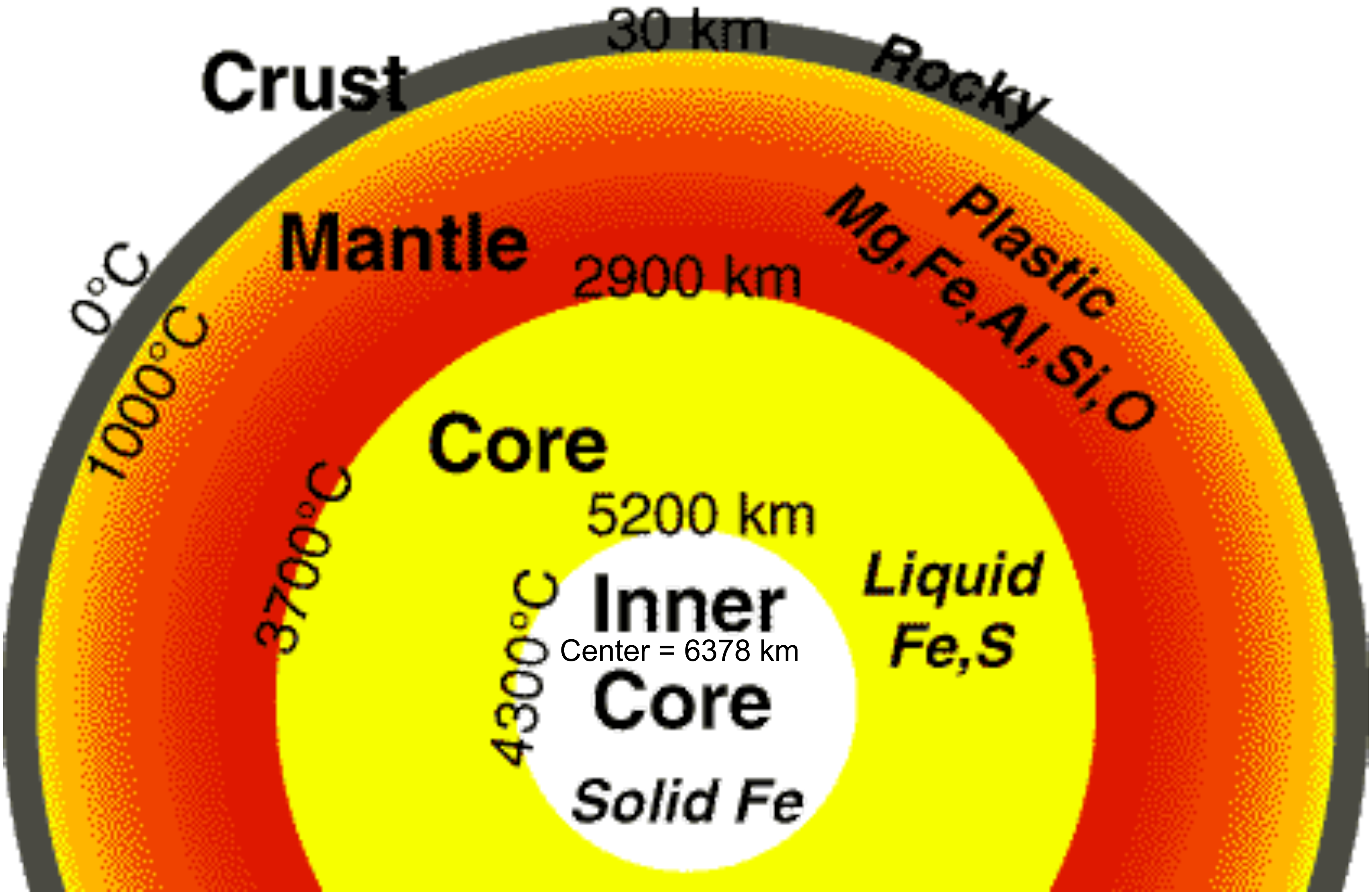
Every year that is divisible by 4

but not years divisible by 100 unless they
are divisible by 400

e.g., 2100 will not be a leap year
2000 was a leap year

After 8000 years this system will be off by a day

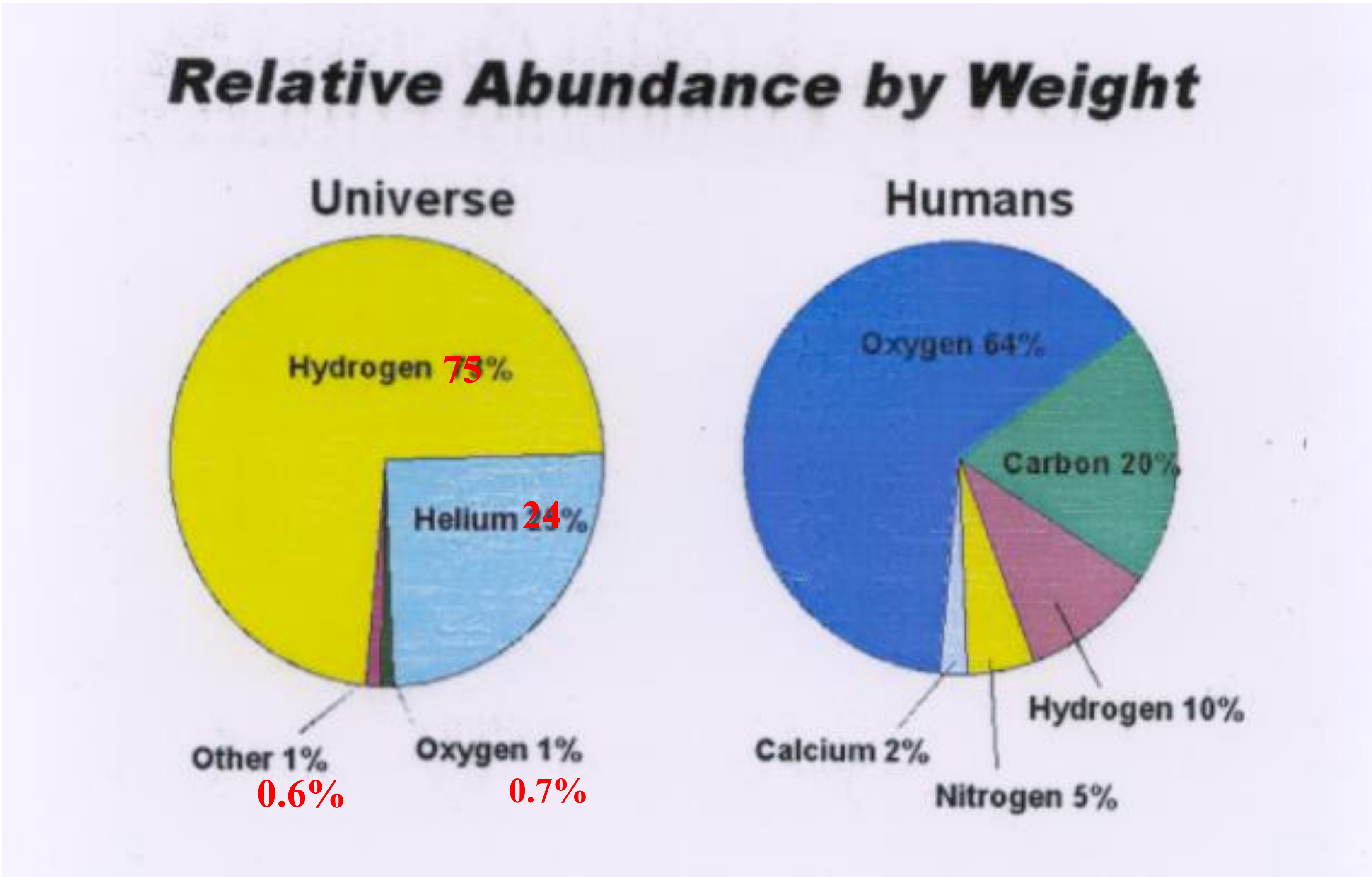
The Earth in Greater Depth



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 …….



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 x 10^{33} gm; about 300,000 Earth masses
Radius = 6.96 x 10^{5} km; almost 100 Earth radii
Average density 1.41 gm/cm^3 (central density 100 x greater)
Age = 4.56 x 10^{9} years
Luminosity = 3.90 x 10^{33}erg/s
(world's armament in 10^{-5} seconds)

1.37 x 10^{6} erg cm^{-2} s^{-1} at earth

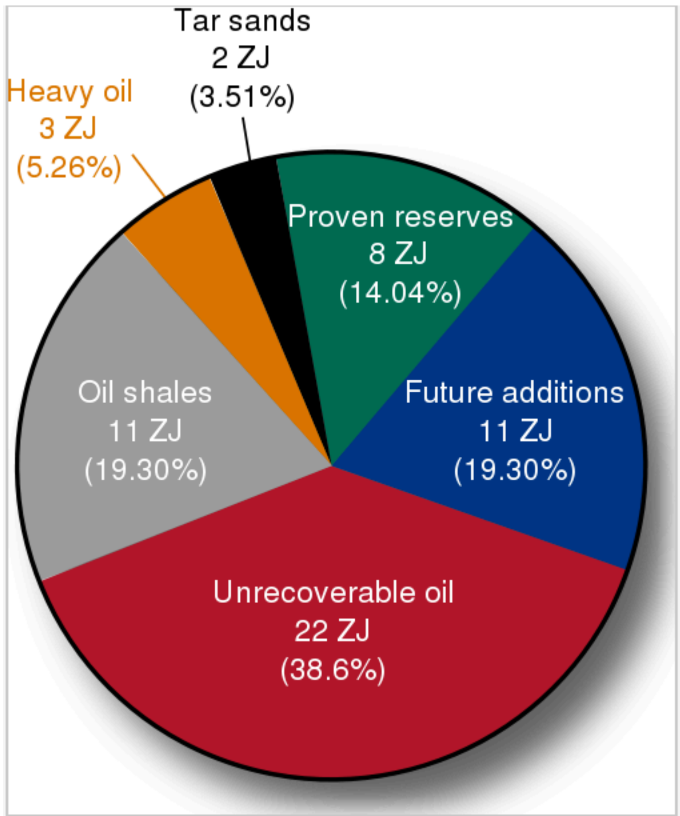
Central temperature = 15.7 million K
Photospheric temperature about 5700 K

K = C +273

Rotation period 24.47 days at the equator
slower near poles

Initial composition (by mass) 74.9% H
23.8% He, 1.3% C, N, O, Fe, Si, etc
(like "universe")

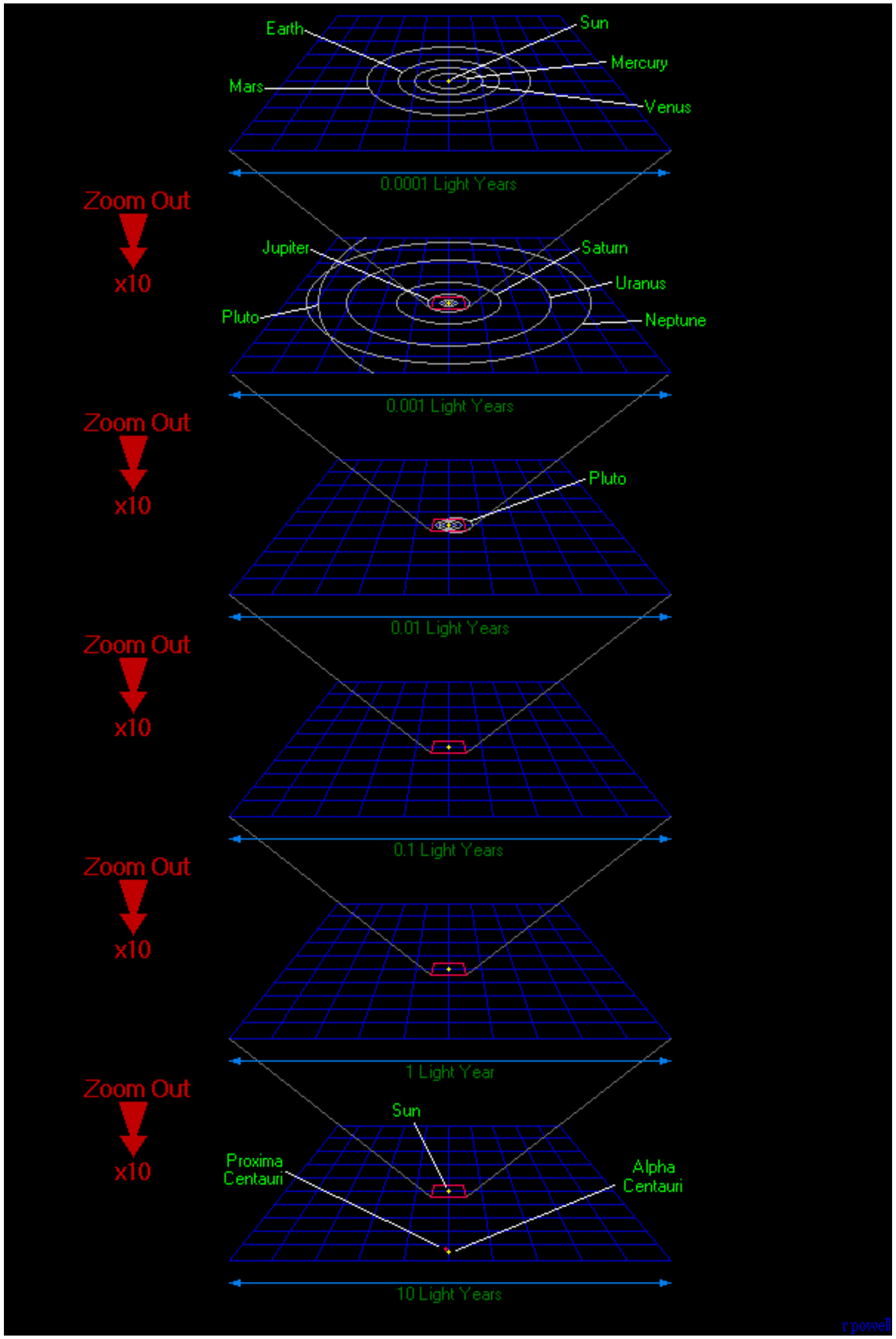
A typical star. A little on the heavy side.



Worlds total energy reserves 57 ZetaJoules = 57 x 10^{21} joules = 5.7 x 10^{29} erg

$$L_{\odot} = 3.9 \times 10^{33} \text{ erg s}^{-1}$$

https://en.wikipedia.org/wiki/World_energy_resources



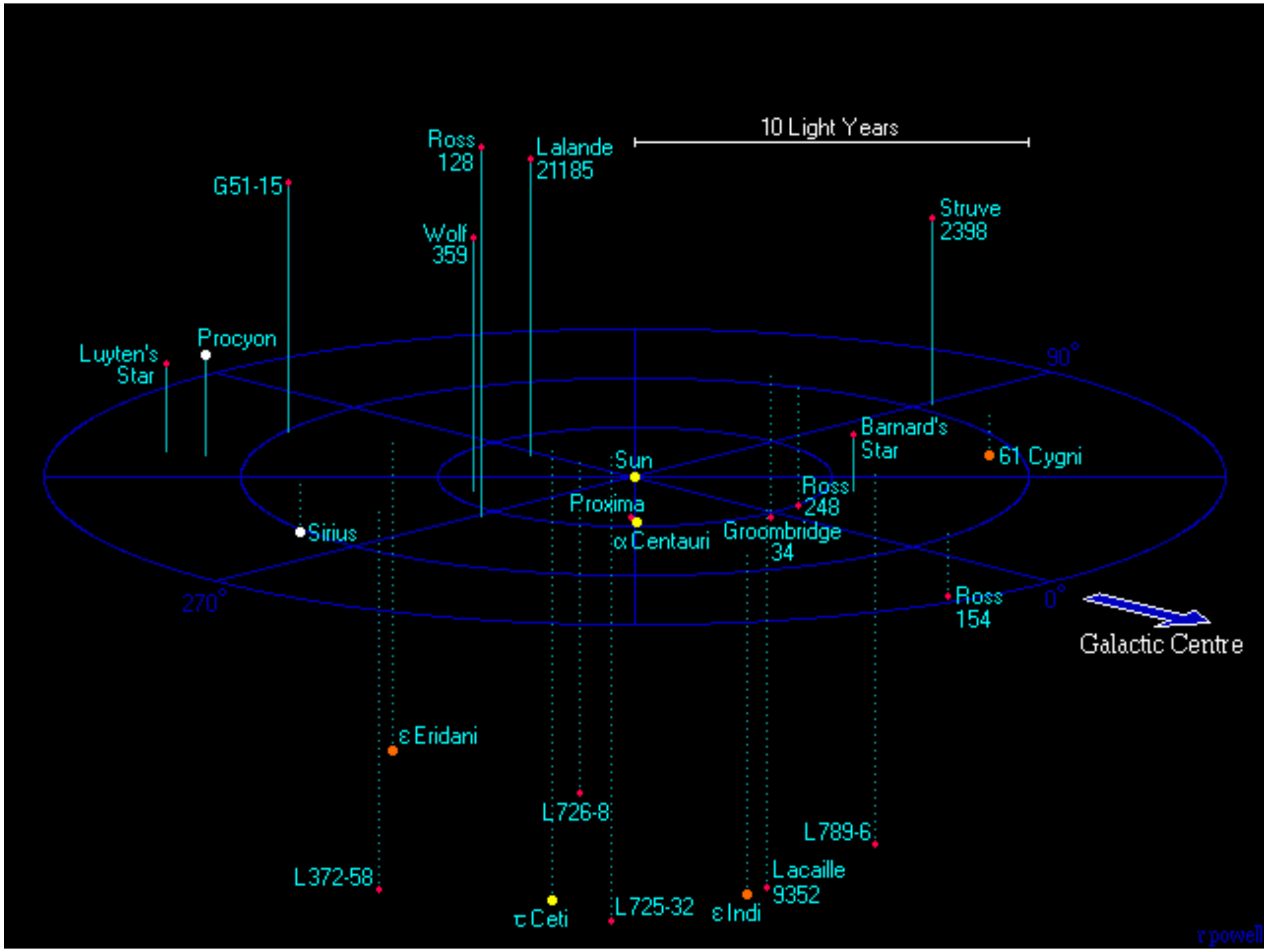
The figure at the left shows the effect of zooming out in distance from our solar system by a total factor of 100,000 (10^5).

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

Most of the universe, even within galaxies, is empty. Between galaxies it is emptier still.

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. *May* have planets.

- *Barnards star* – highest proper motion of all stars. 5.9 light years away. 1/7 Msun. 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 3.4 AU. Young star (1Gyr?). K2

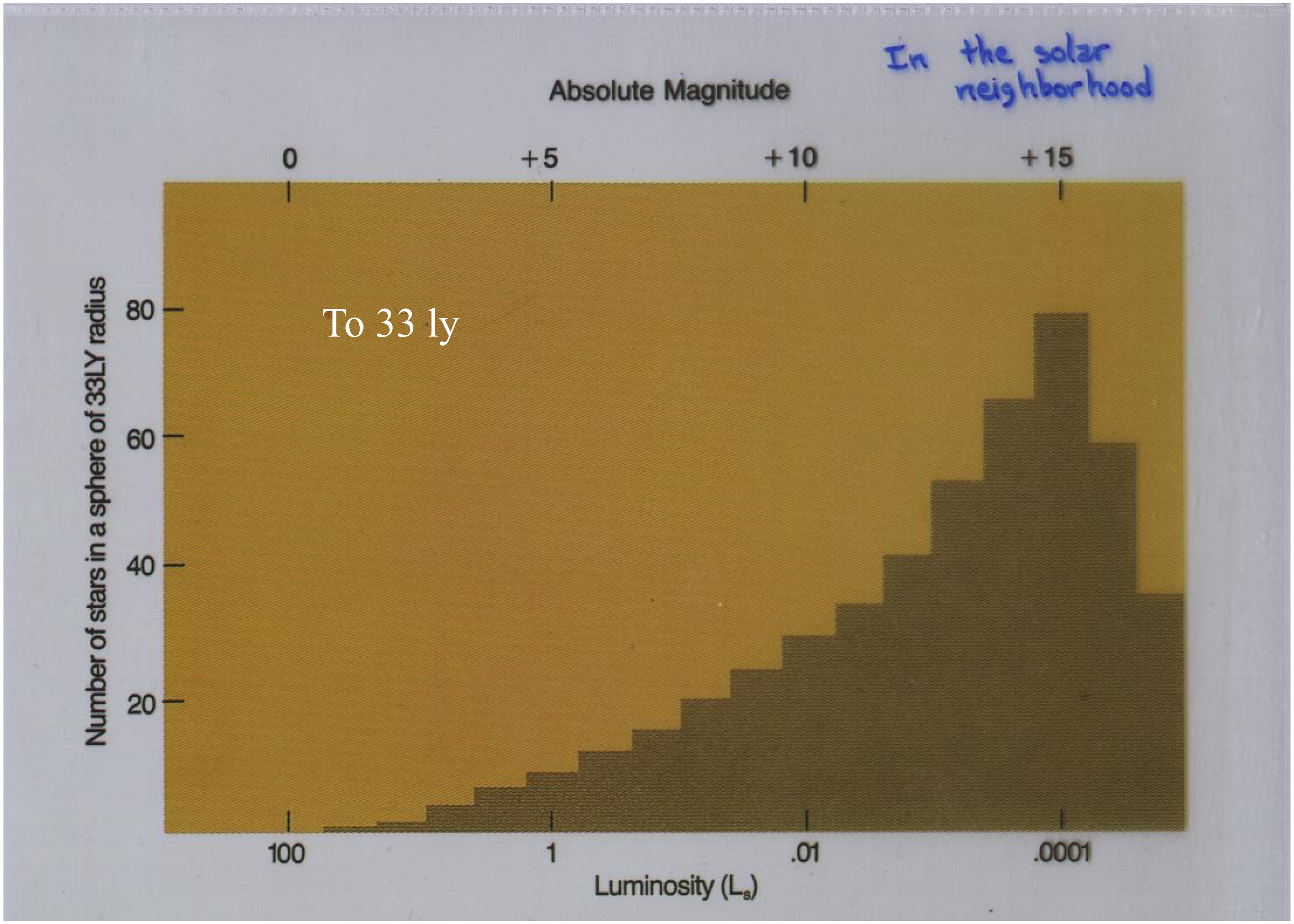
- *Procyon A,B* – 11.41 light years away. Another multiple star system. 8^{th} brightest star in the sky has a white dwarf companion

- *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

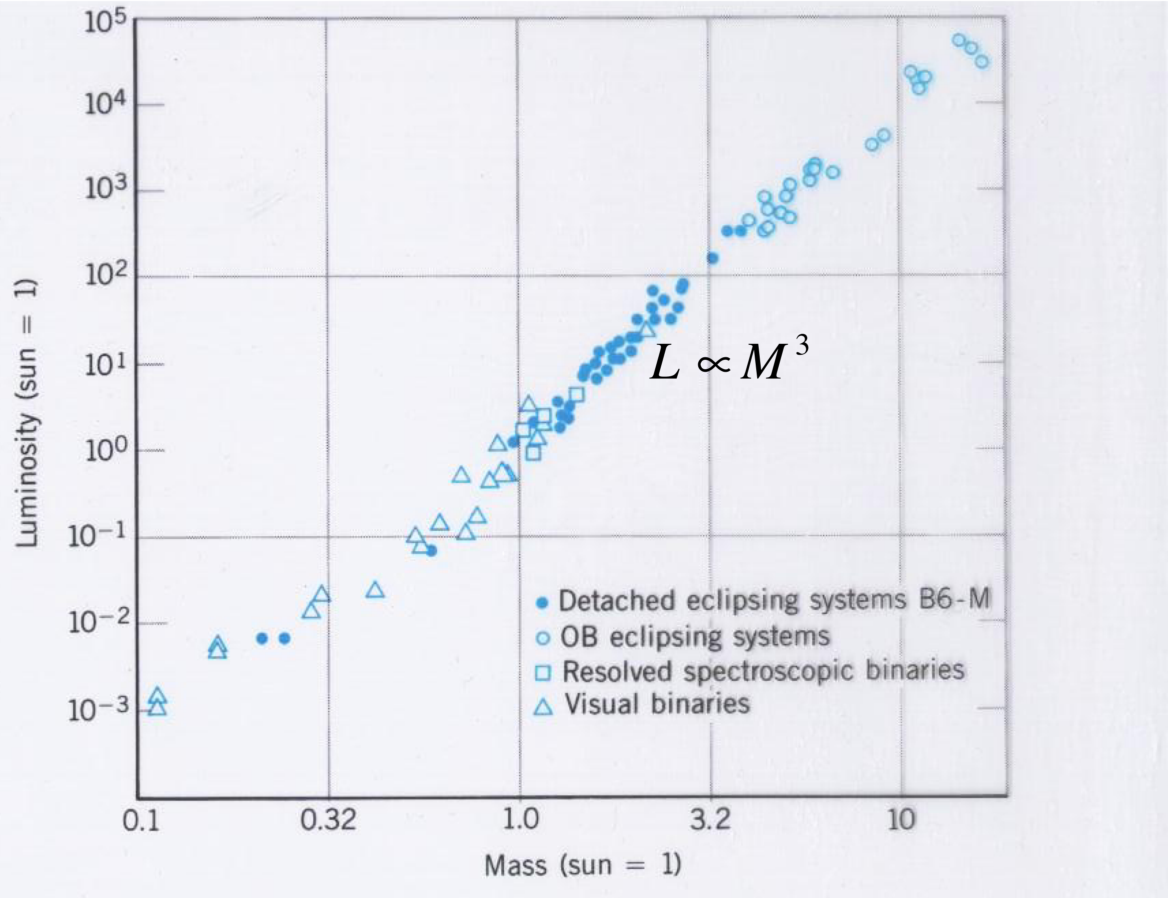
In a volume limited sample – counting all stars…



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 thar are spectroscopically "main sequence" the star's luminosity is correlated with its mass.



e.g., 10 solar masses is between 10^3 and 10^4 times more luminous than the sun. 0.1 solar masses is down by 10^3

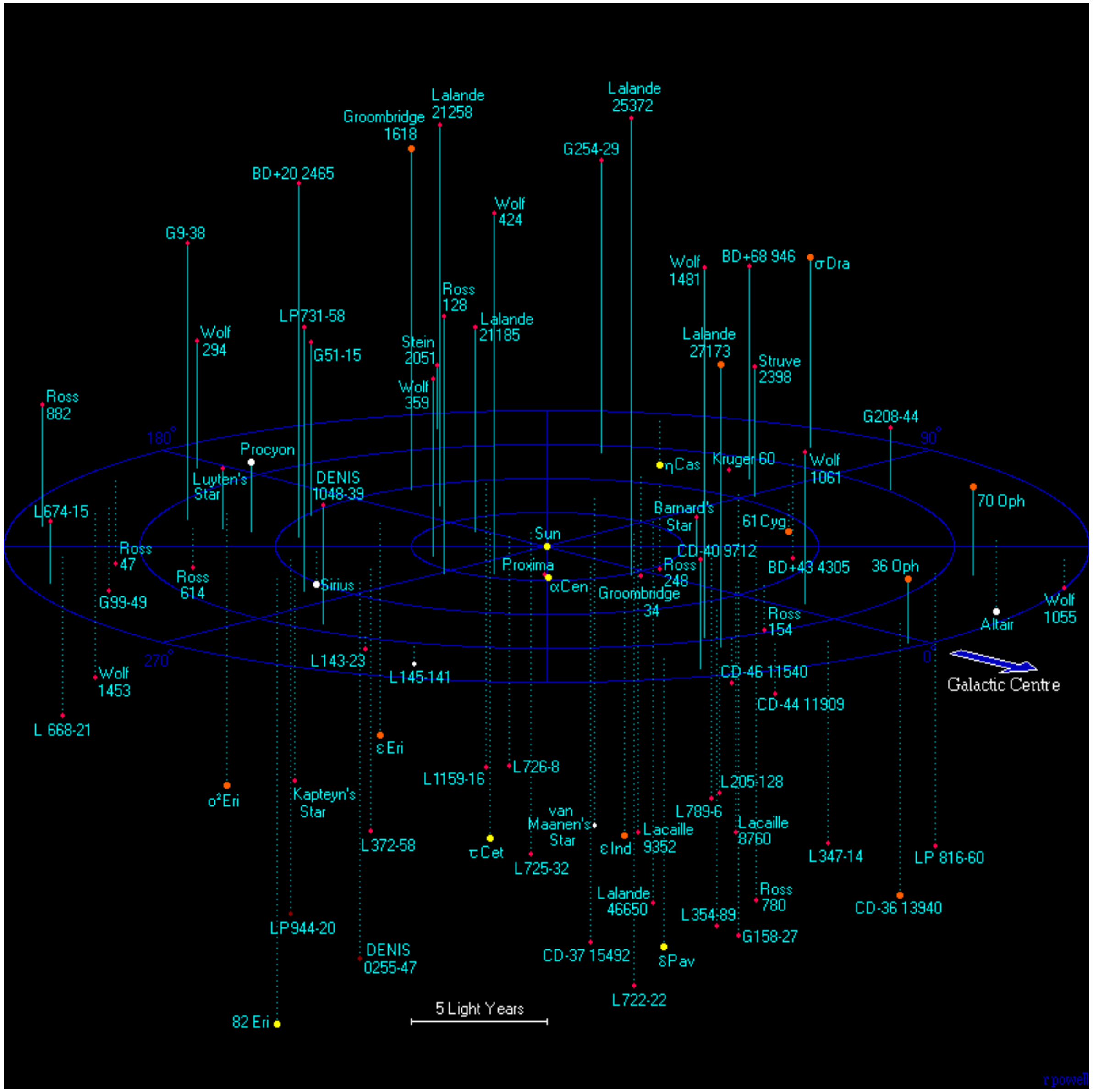
To summarize:

- 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

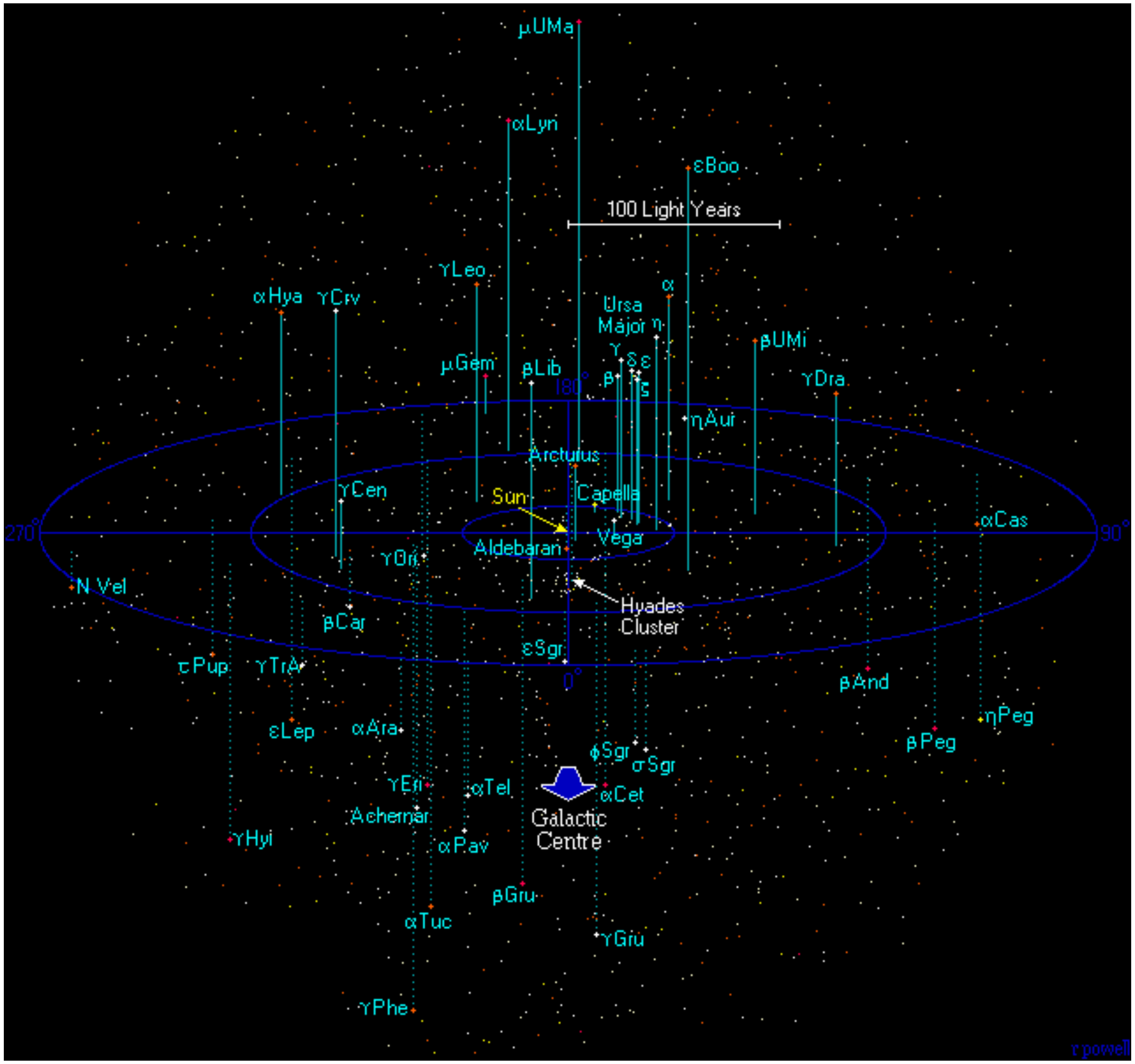
20 light years – 78 systems – 109 stars



isotropic distribution

50 ly
~2000 stars

250 light years



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

Number for isotropic distribution and constant density

$n \propto d^3$

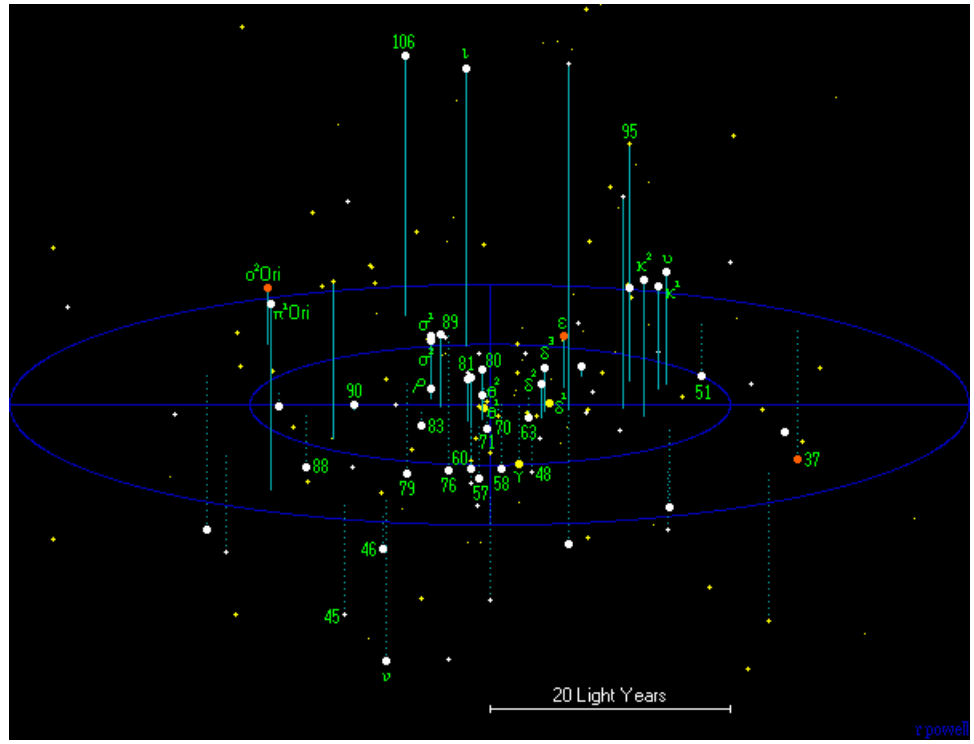
About 250,000 stars lie within 250 light years of the Earth. Beyond this distance it becomes difficult to see all the stars in the plane of the Milky Way Galaxy because of the presence of dust.

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.

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

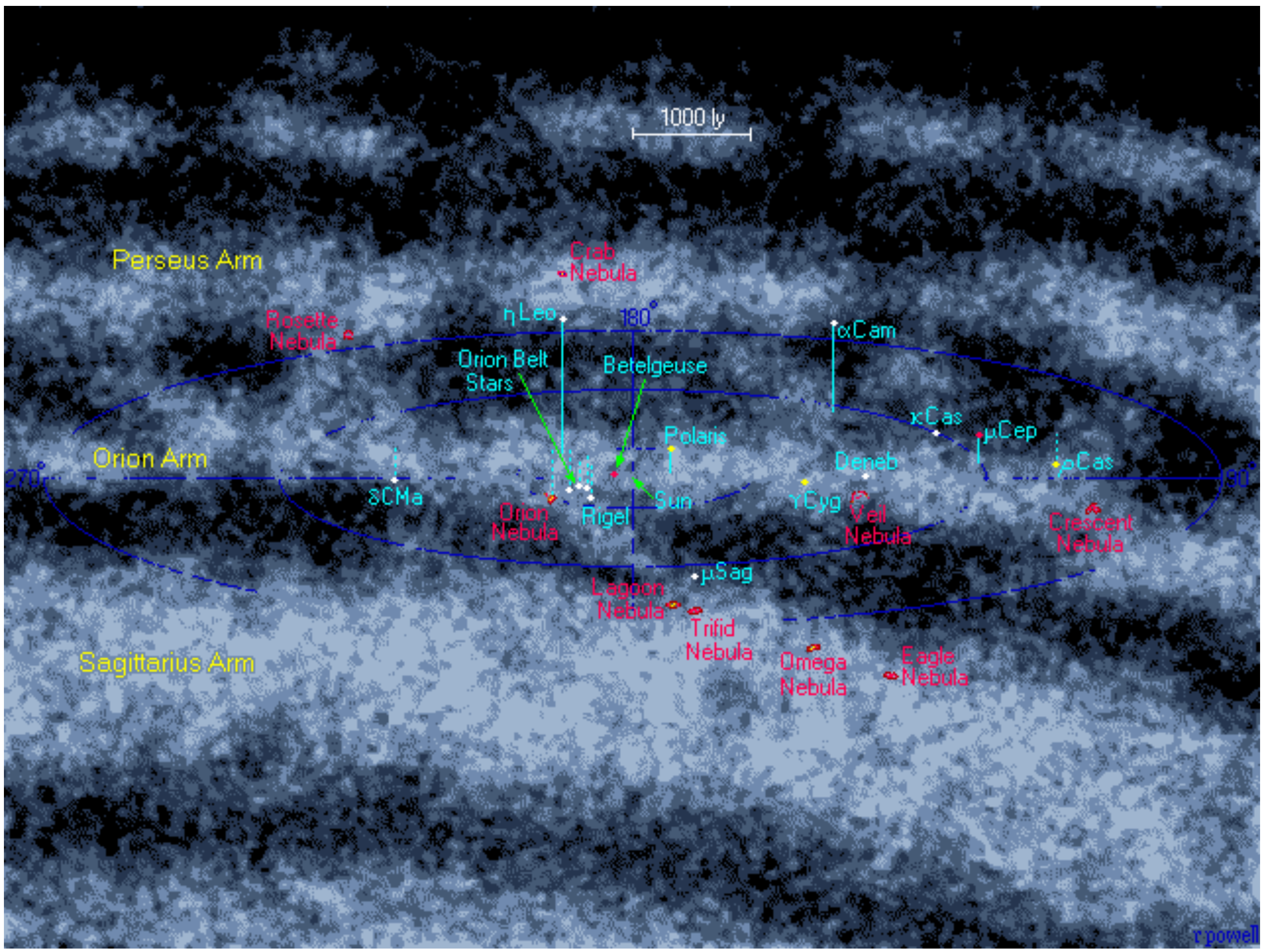
The Hyades Open cluster of stars (151 light years)



The bright red star Aldebaran is not in the Hyades

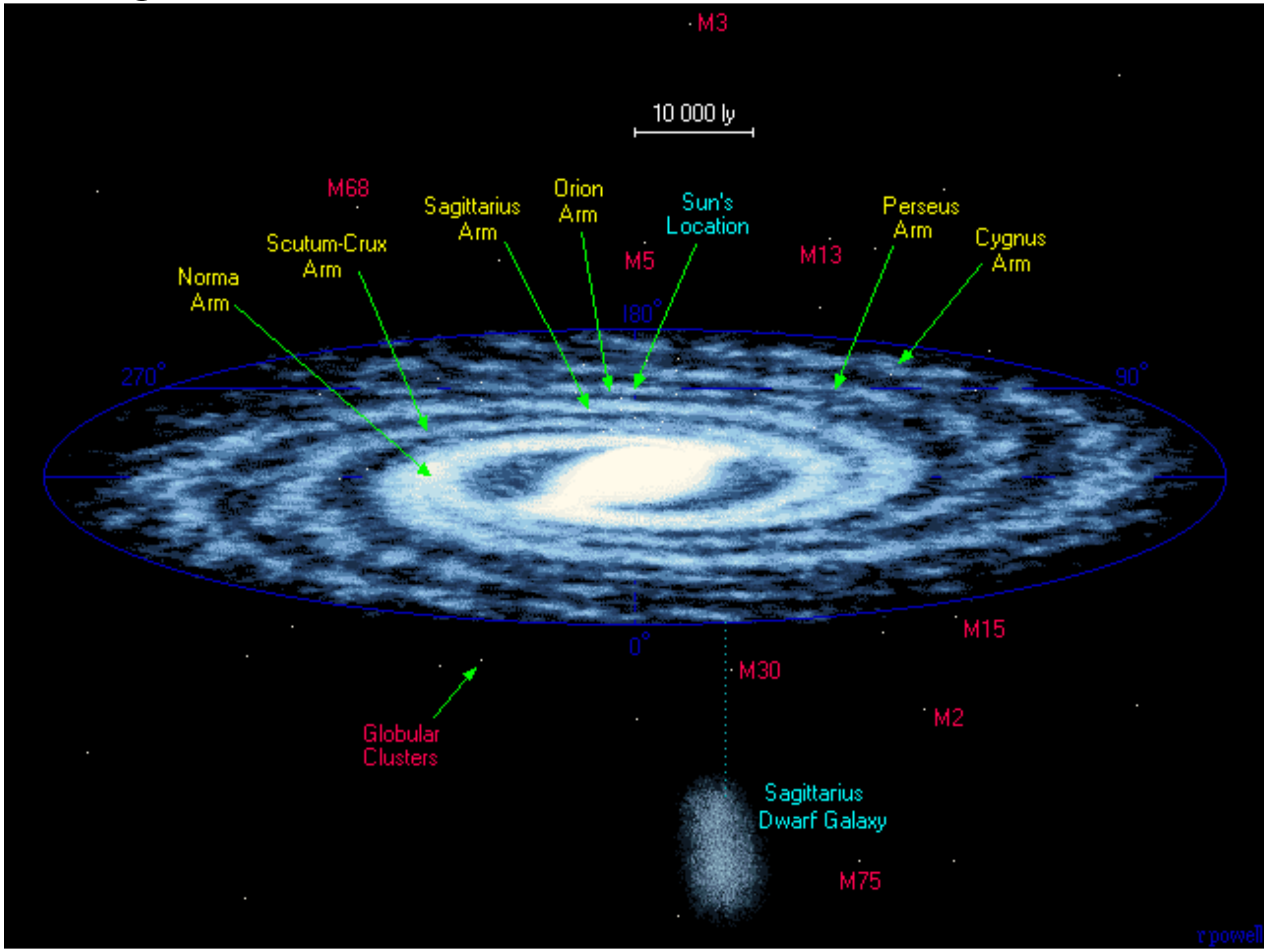
This cluster of stars is only about 625 million years old and is in the process of coming apart. Stars like this are born together from a giant cloud of molecular gas, most of which is blown away by the young stars. About 200 stars are catalogued at http://en.wikipedia.org/wiki/List_of_stars_in_Hyades

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 Sagitarius Arm. There is also a lot of gas and dust.



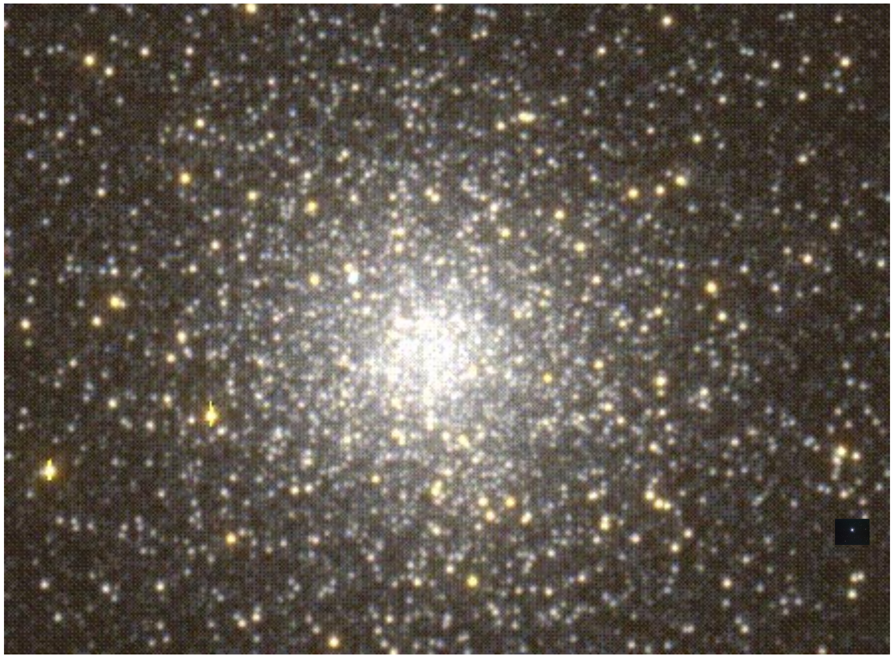
Betelgeuse 650 ly; Orion 1350 ly

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



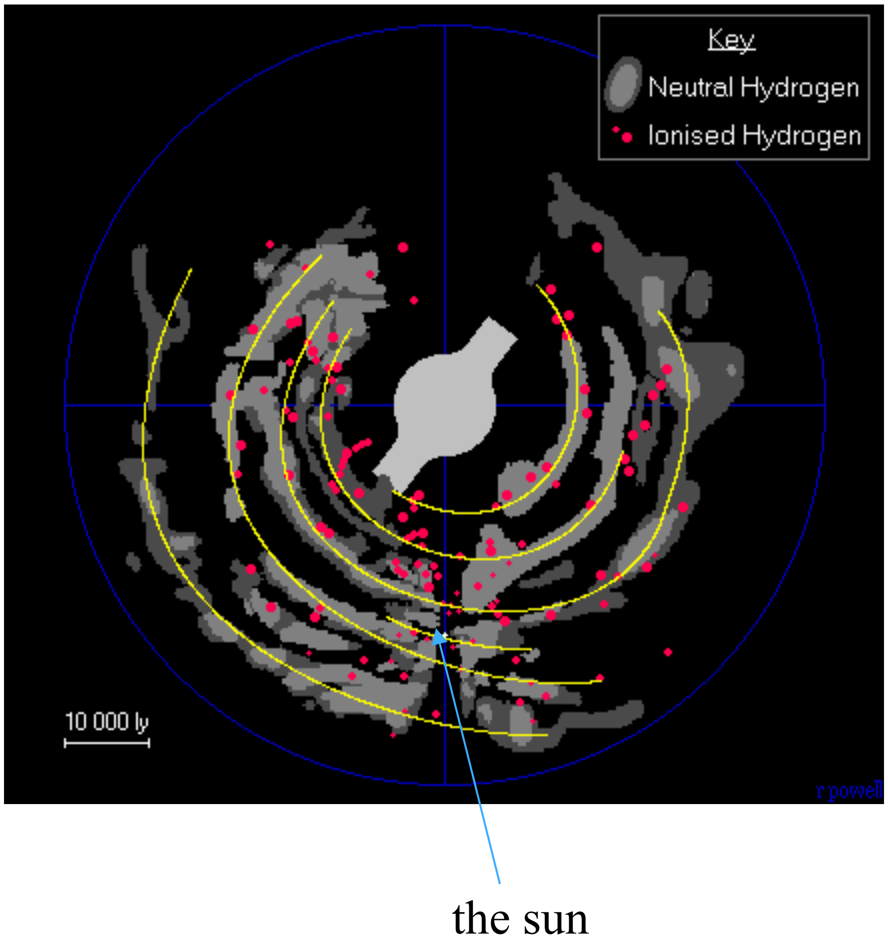
47 Tuc

M13

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.

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

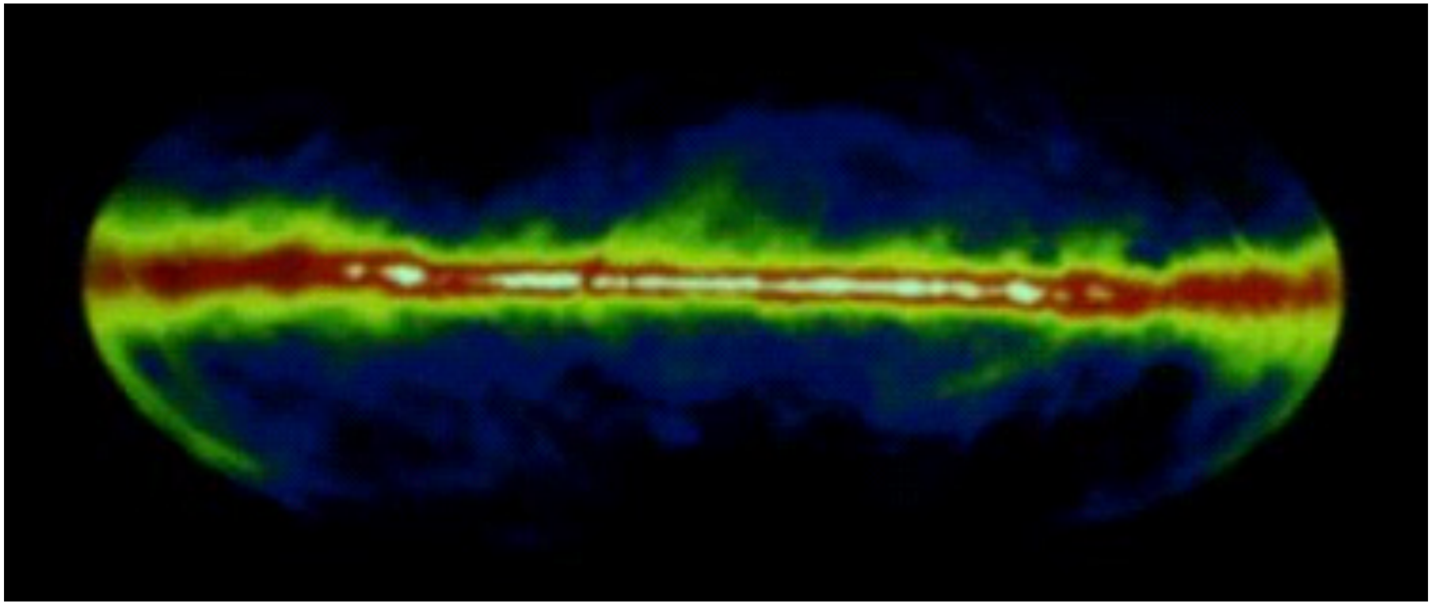
The clearest experimental evidence for spiral structure in our own galaxy comes from radio observations. The galaxy is transparent in the 21 cm line of atomic H.



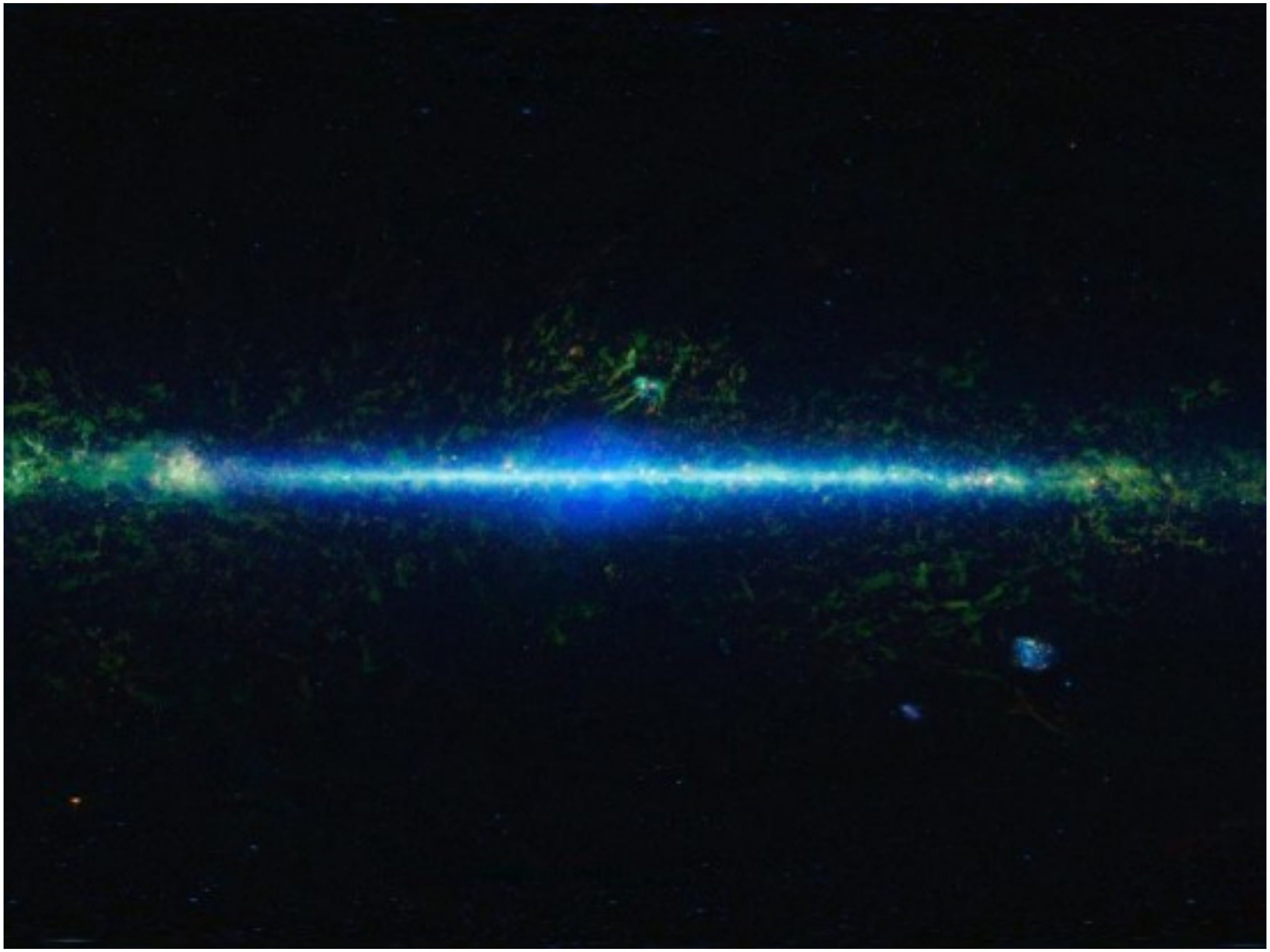
Radio View of the Milky Way

Interstellar dust does not absorb radio waves

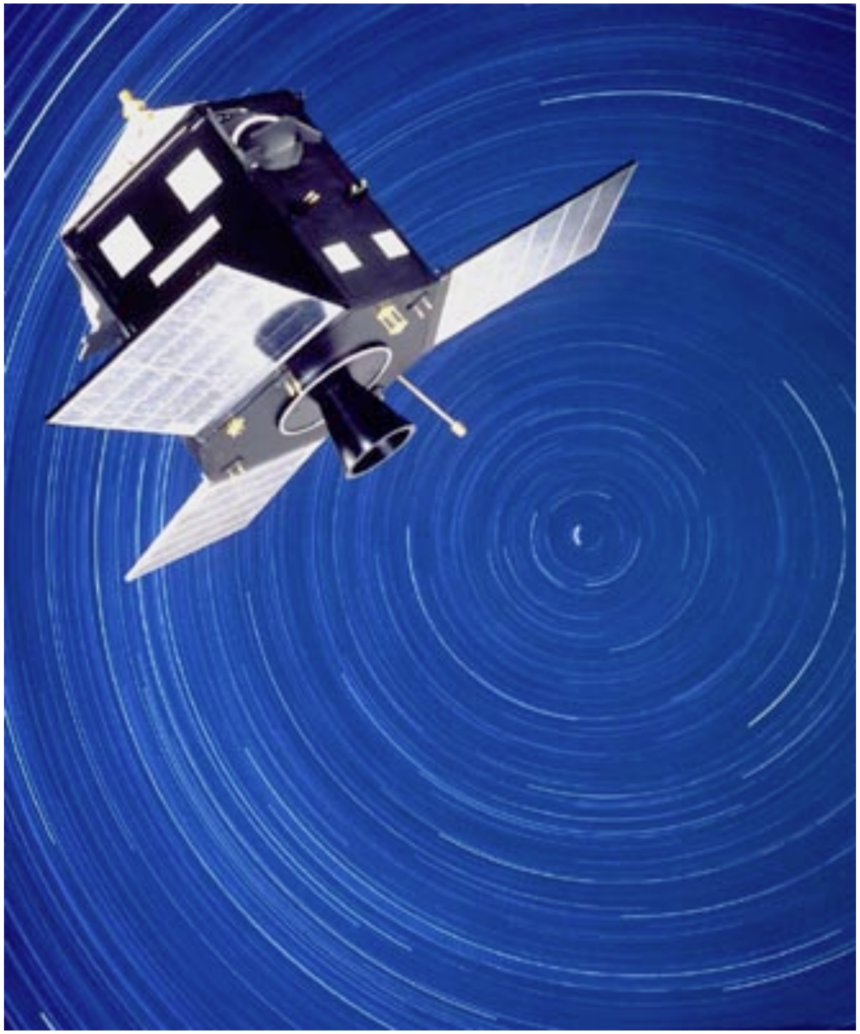
We can observe any direction throughout the Milky Way at radio waves



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, though not with great precision.



Aside: In AD 150 Ptolemy in his Almagest catalogued 1,022 of the brightest stars.

Hipparcos Space Astrometry Mission (1989 – 1993)

Catalogue of accurate distances (1 milli arc s angular resolution)

118,218 stars

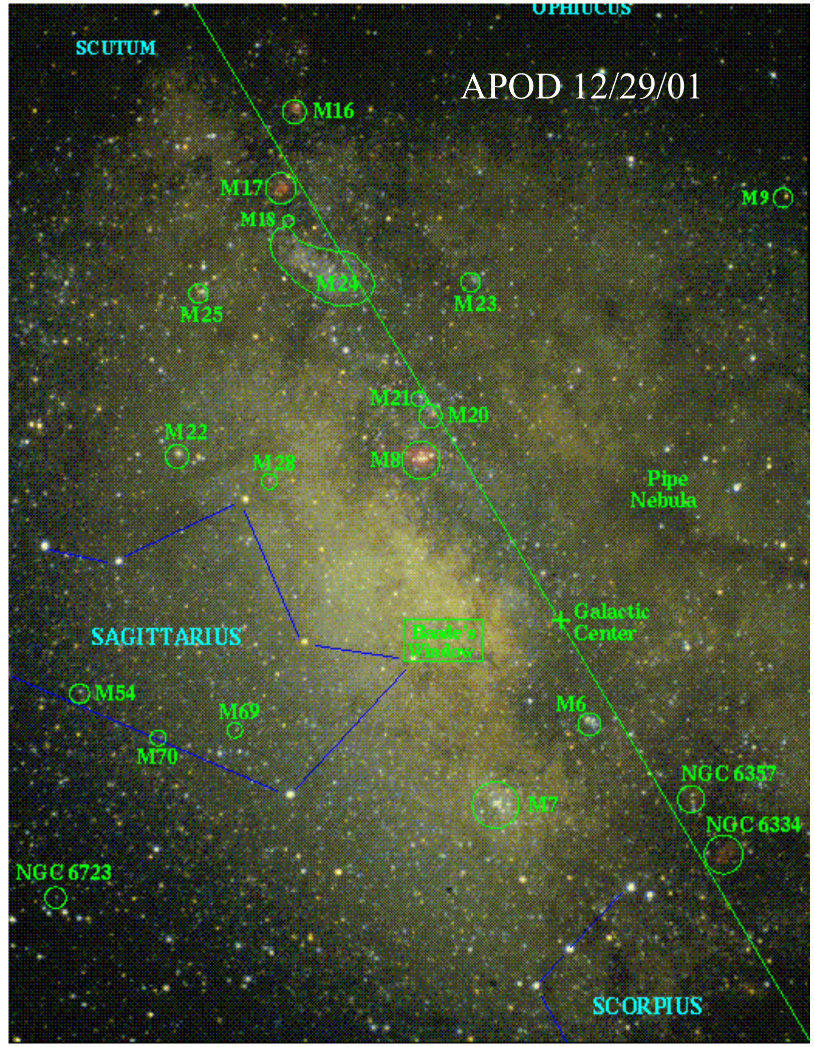
Total stars observed (Tycho 2 Catalogue; 25 mas)

2,539,913 stars

Including 99% of all stars brighter than 11^{th} magnitude

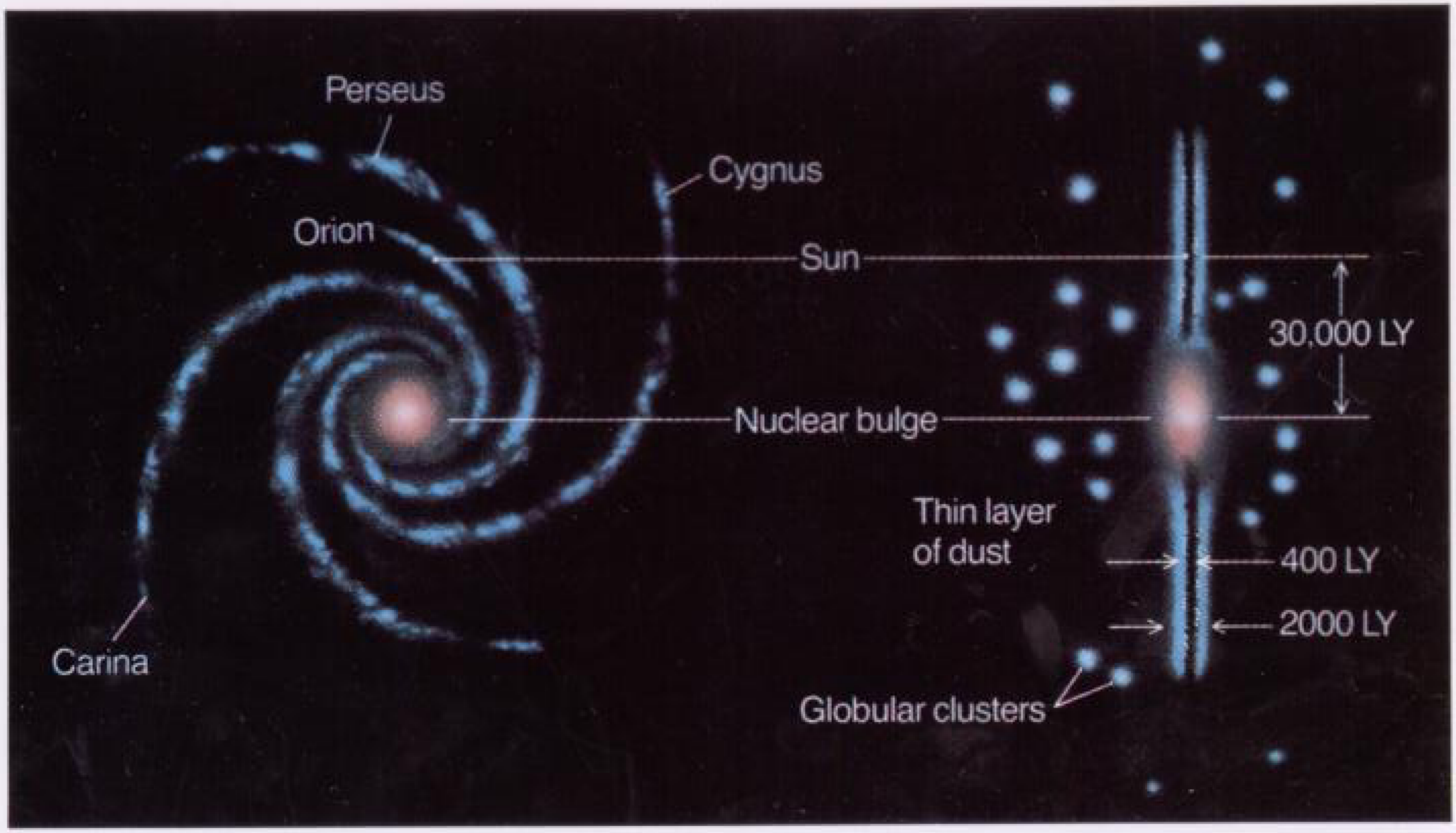
GAIA – launched 12/19/13 is studying the properties of *one billion* stars. Each will be observed 70 times during its 5 year mission. Will obtain accurate distances for 100,000 stars, less accurate distances for one million. First data release coming soon. 20 micro arc sec resolution at 15^{th} magnitude.

The center of our galaxy is towards the constellation Sagitarius

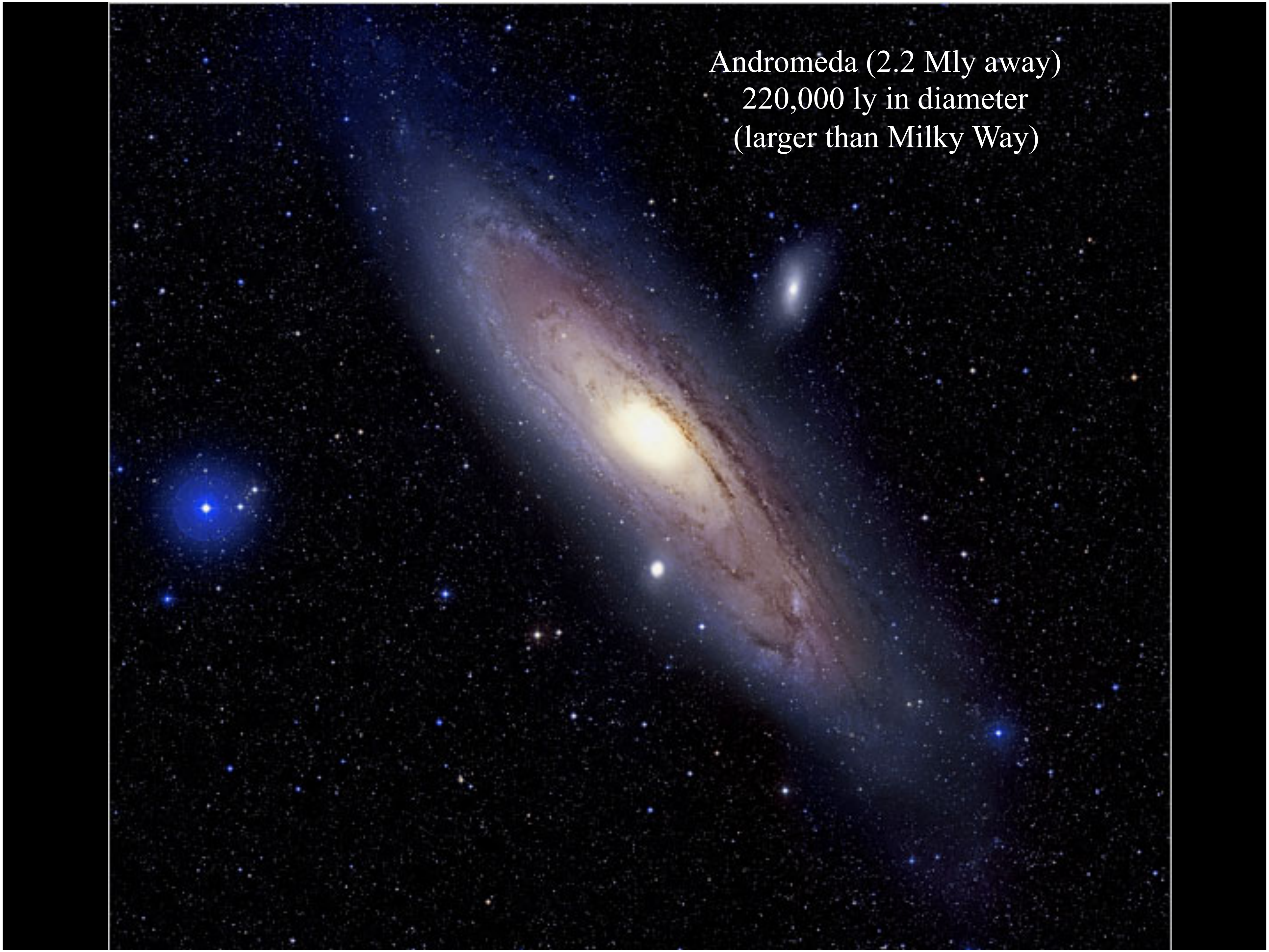


Infrared observation (2MASS) towards center of the Milky Way - dust glows in IR

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


Perseus
Cygnus
Orion
Sun
30,000 LY
Nuclear bulge
Thin layer of dust
400 LY
2000 LY
Carina
Globular clusters

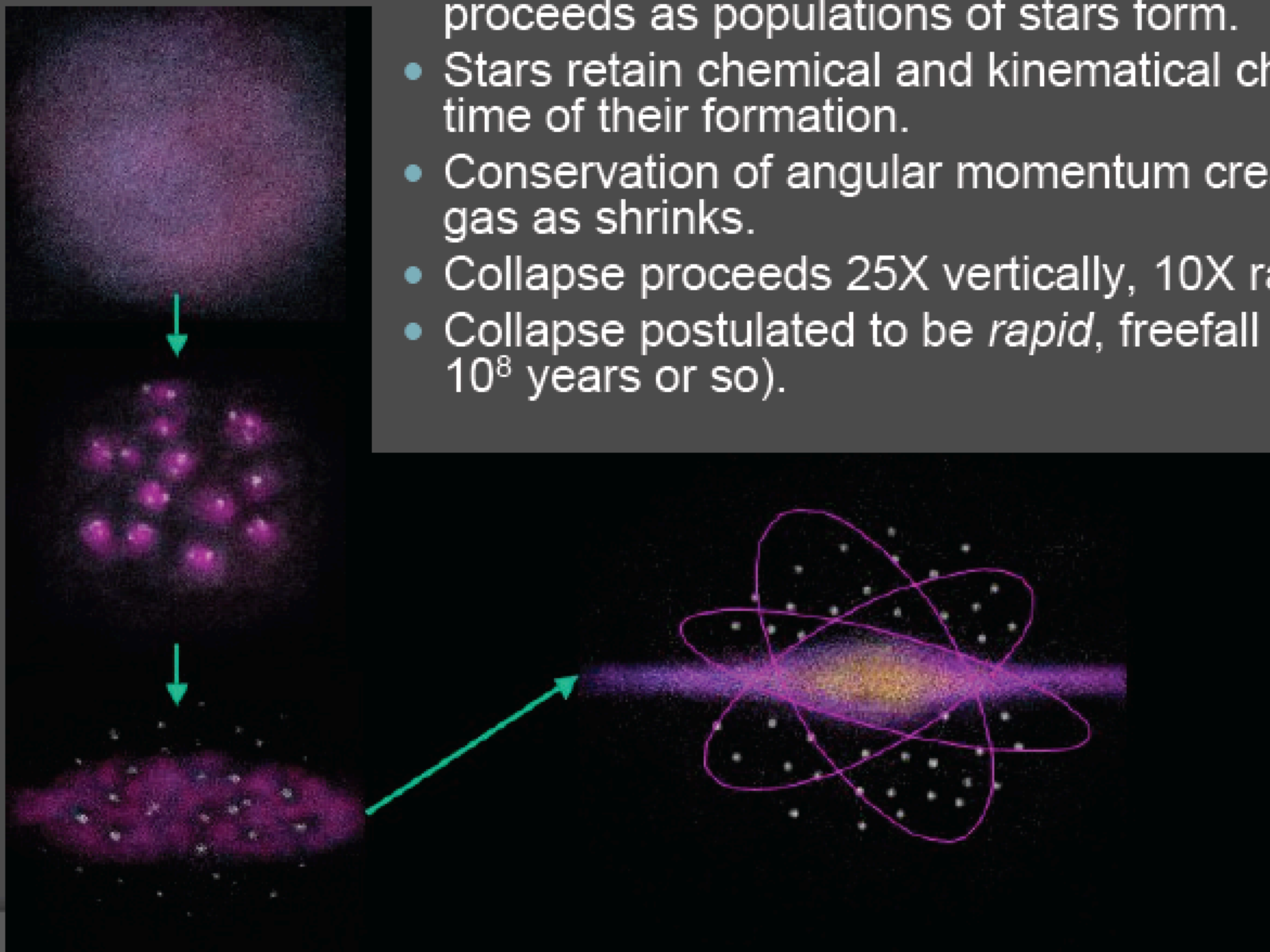
Other *spiral* galaxies are thought
to look very similar to our own Milky Way.


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

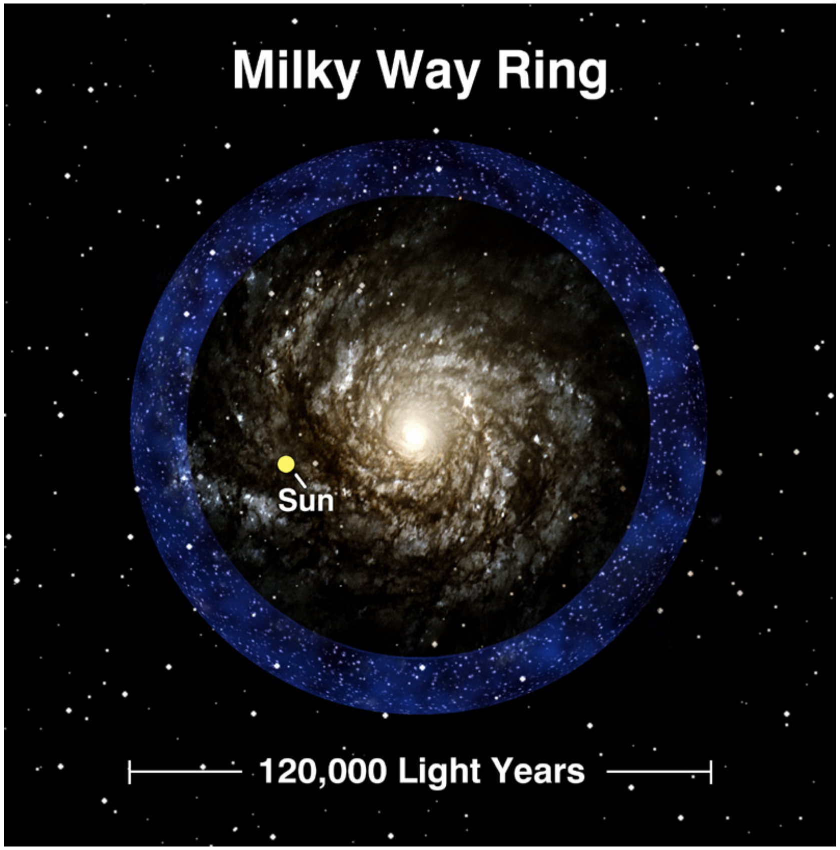
- ELS <u>formulated</u> a physical model to account for continuum of trends:

1962

  - Galaxy starts as ball of unenriched gas.
  - Self-gravity, spherical collapse begins.
  - Stars form during collapse, chemical enrichment of gas proceeds as populations of stars form.
  - Stars retain chemical and kinematical character of gas at time of their formation.
  - Conservation of angular momentum creates ``spin-up" of gas as shrinks.
  - Collapse proceeds 25X vertically, 10X radially into a disk.
  - Collapse postulated to be *rapid*, freefall timescale (10^7-10^8 years or so).



Changes to the Traditional Theory

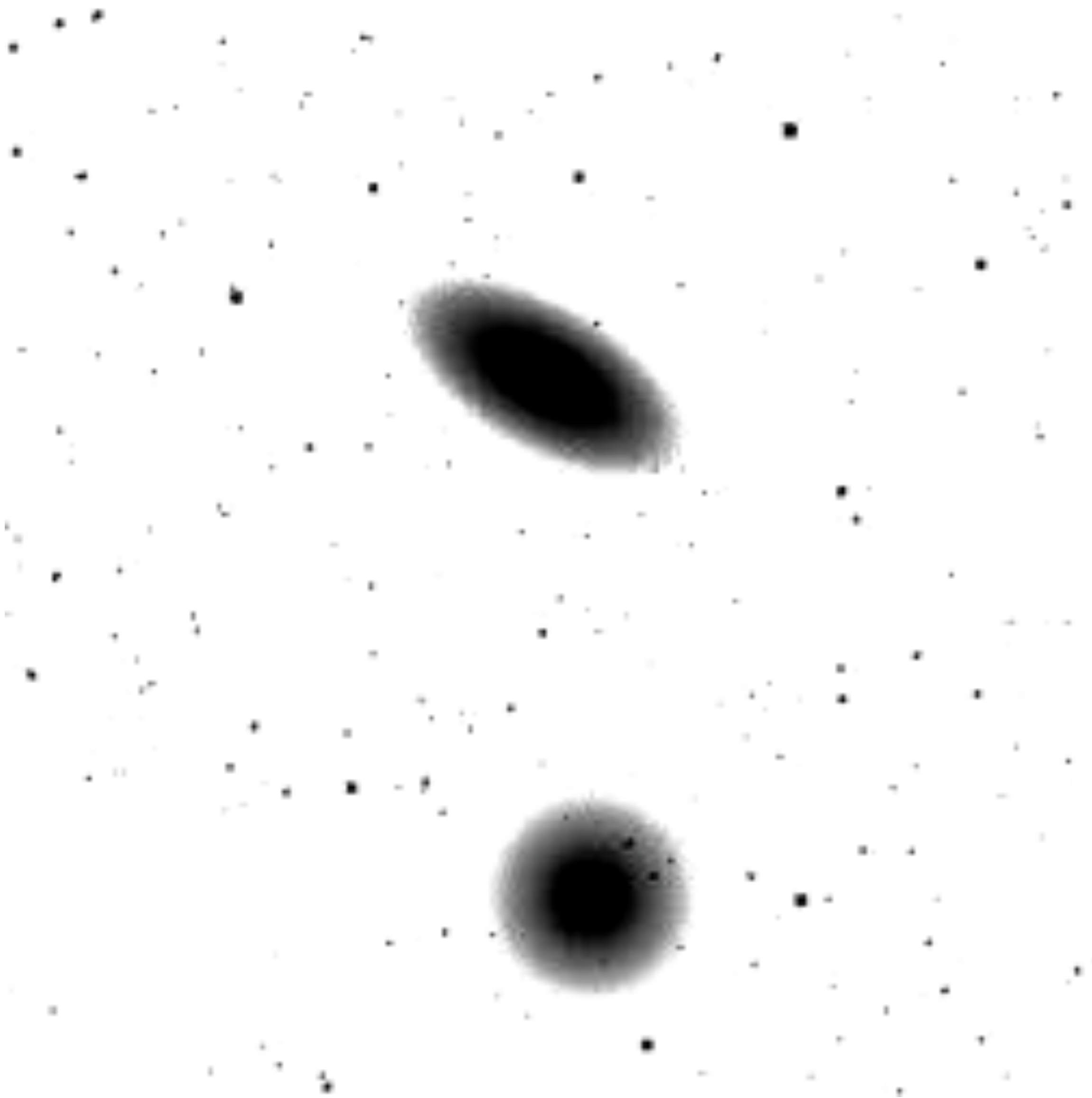


Sloan Digital Sky Survey (2003)

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

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

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



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 …
(2.5 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

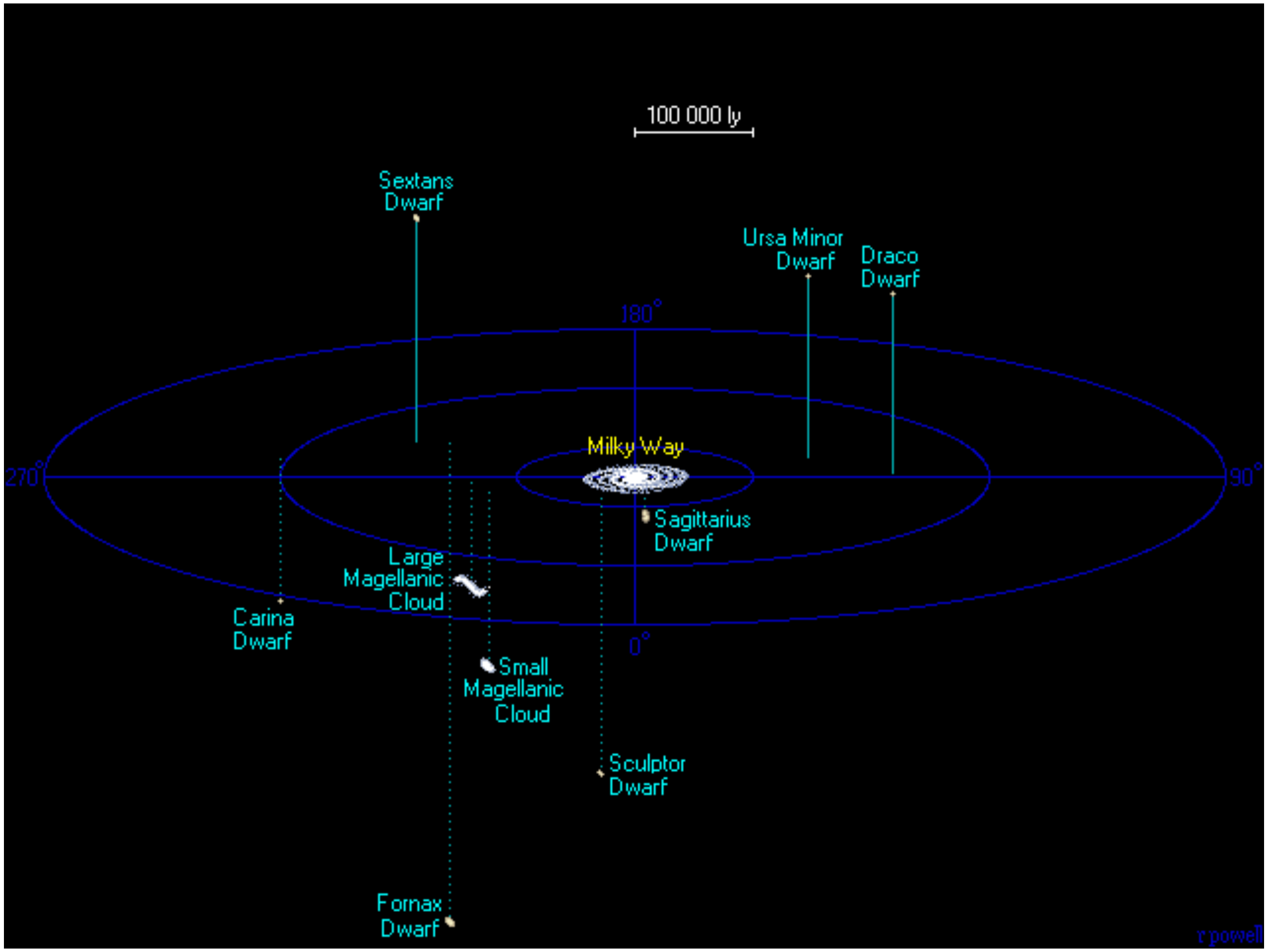
Large Magellanic Cloud
AAO ref UKS 14

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

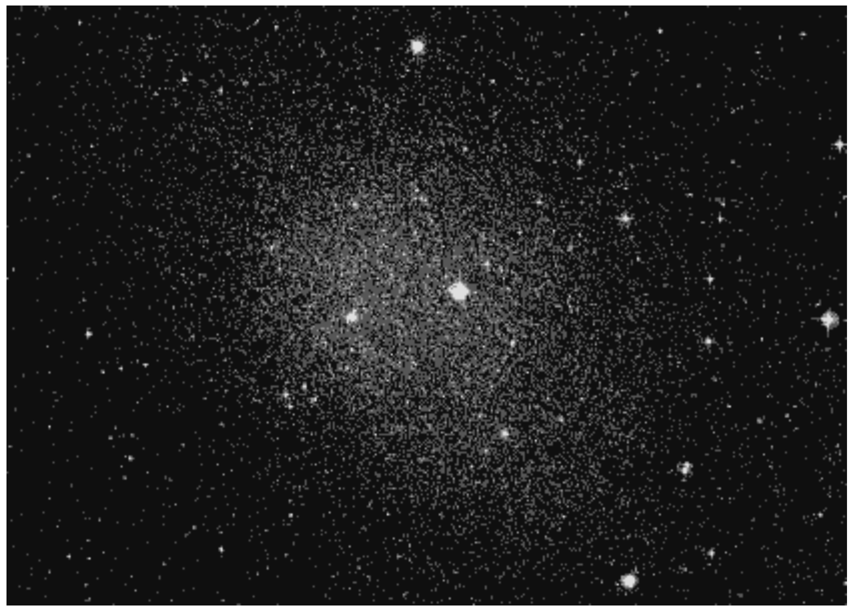
The nearest members of the Local Group of Galaxies orbit our Milky Way



(500,000 ly)

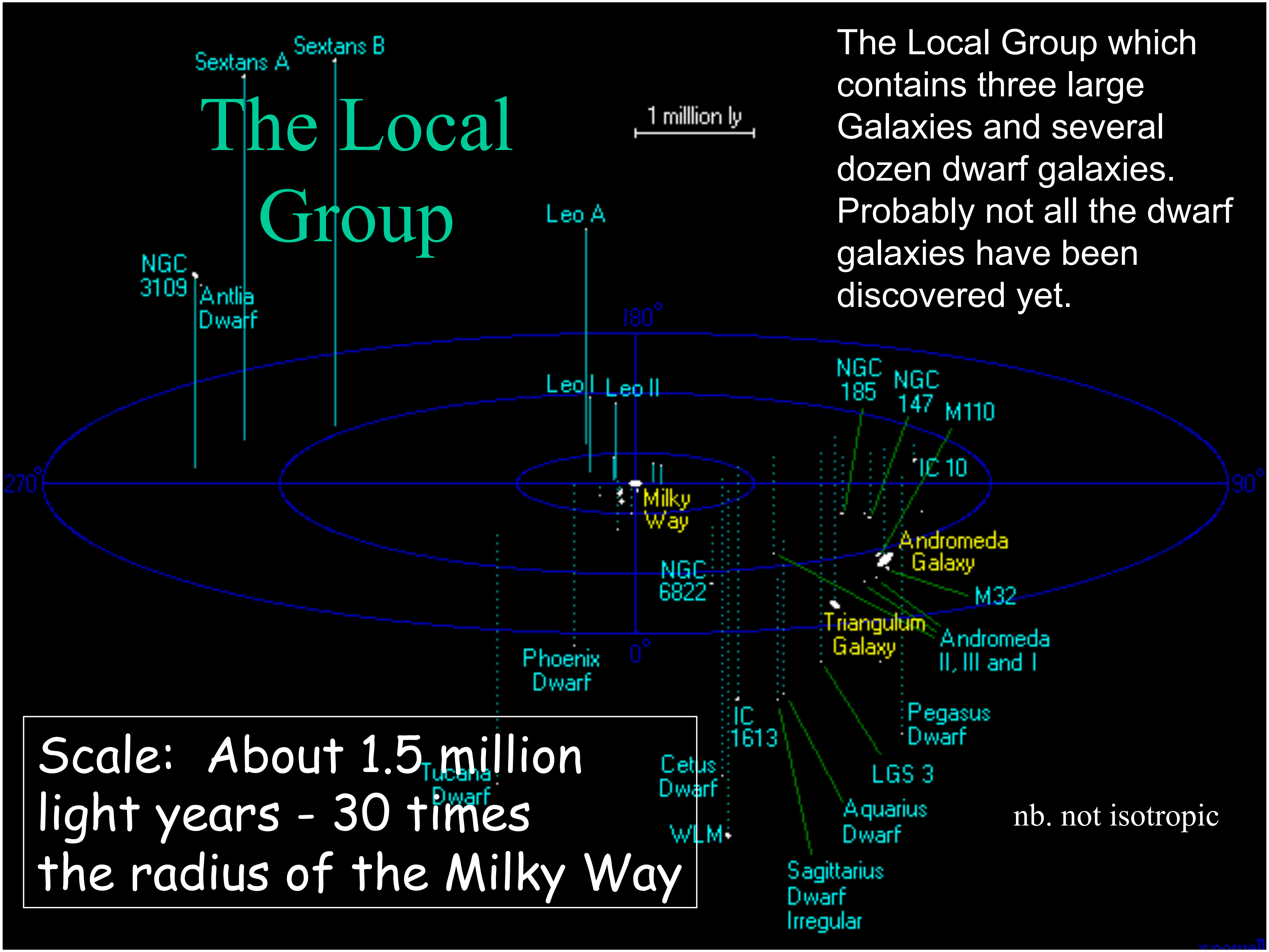
Fornax dwarf galaxy

460,000 ly distant, discovered in 1938



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

The Local Group

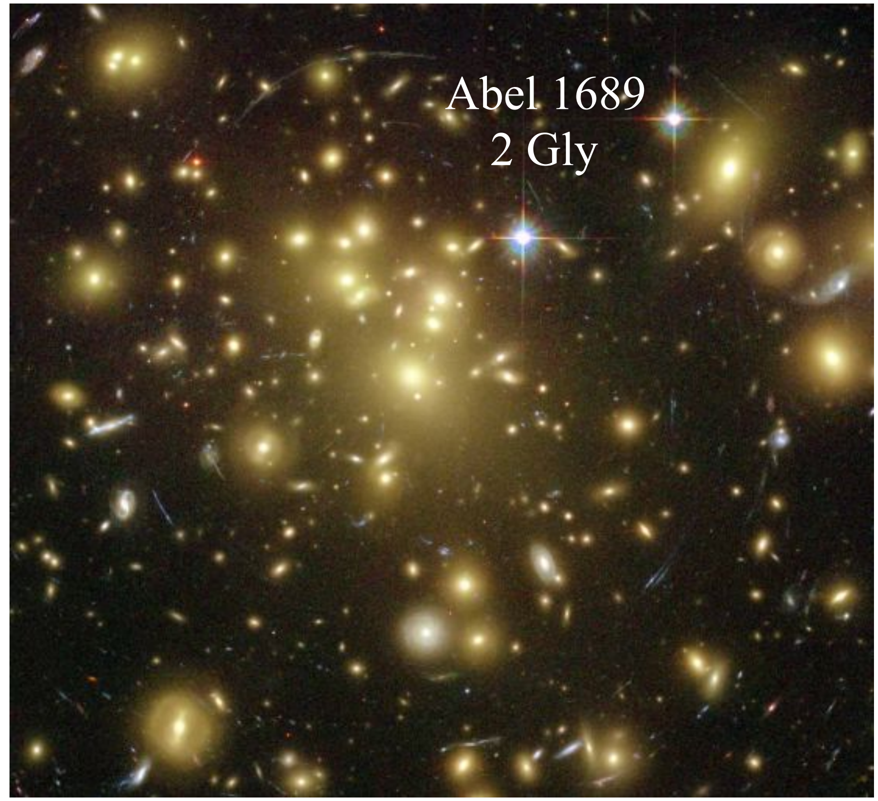


The Local Group which contains three large Galaxies and several dozen dwarf galaxies. Probably not all the dwarf galaxies have been discovered yet.

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

nb. not isotropic

Clusters of Galaxies



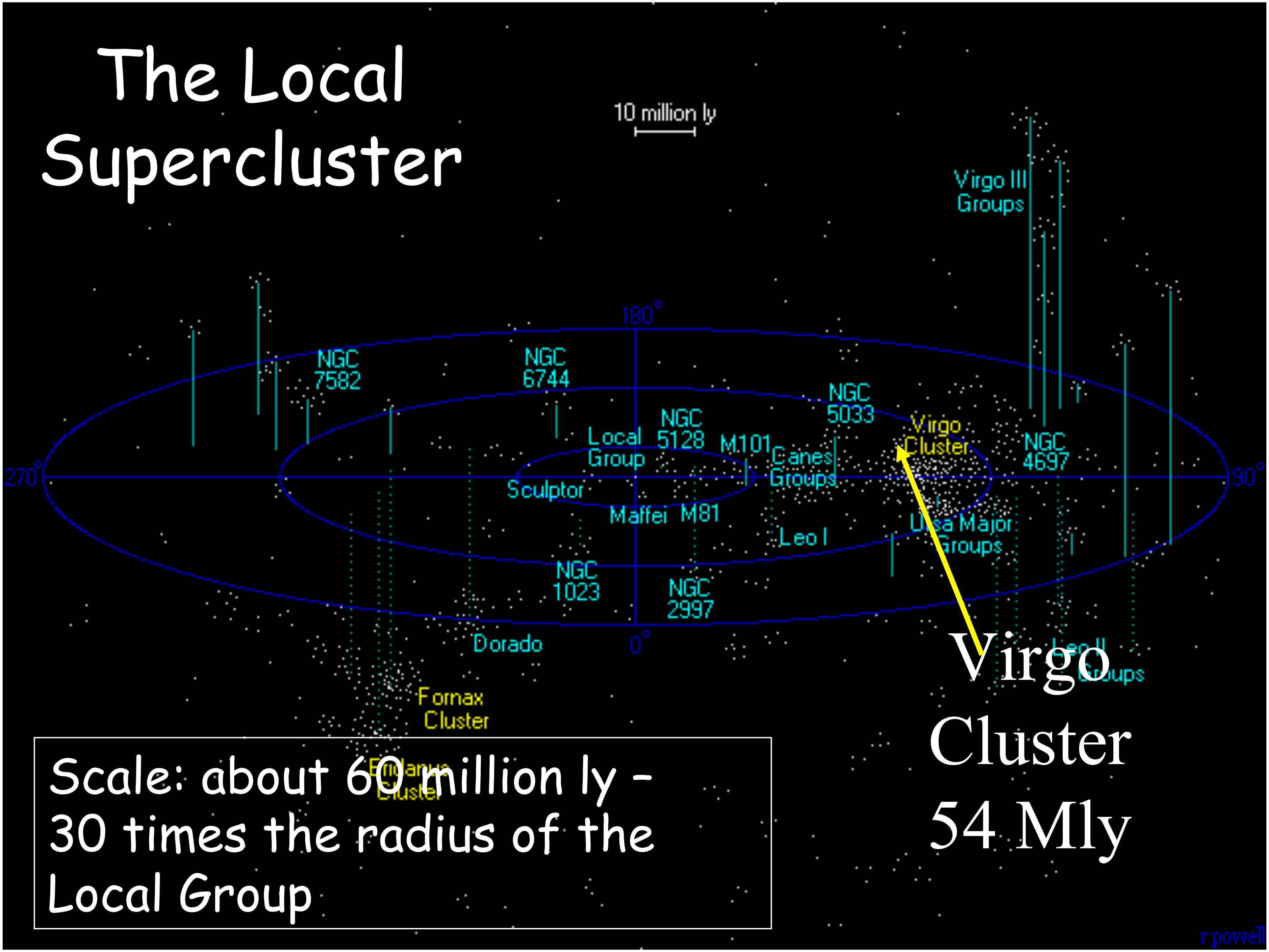
Rich clusters of galaxies

- 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

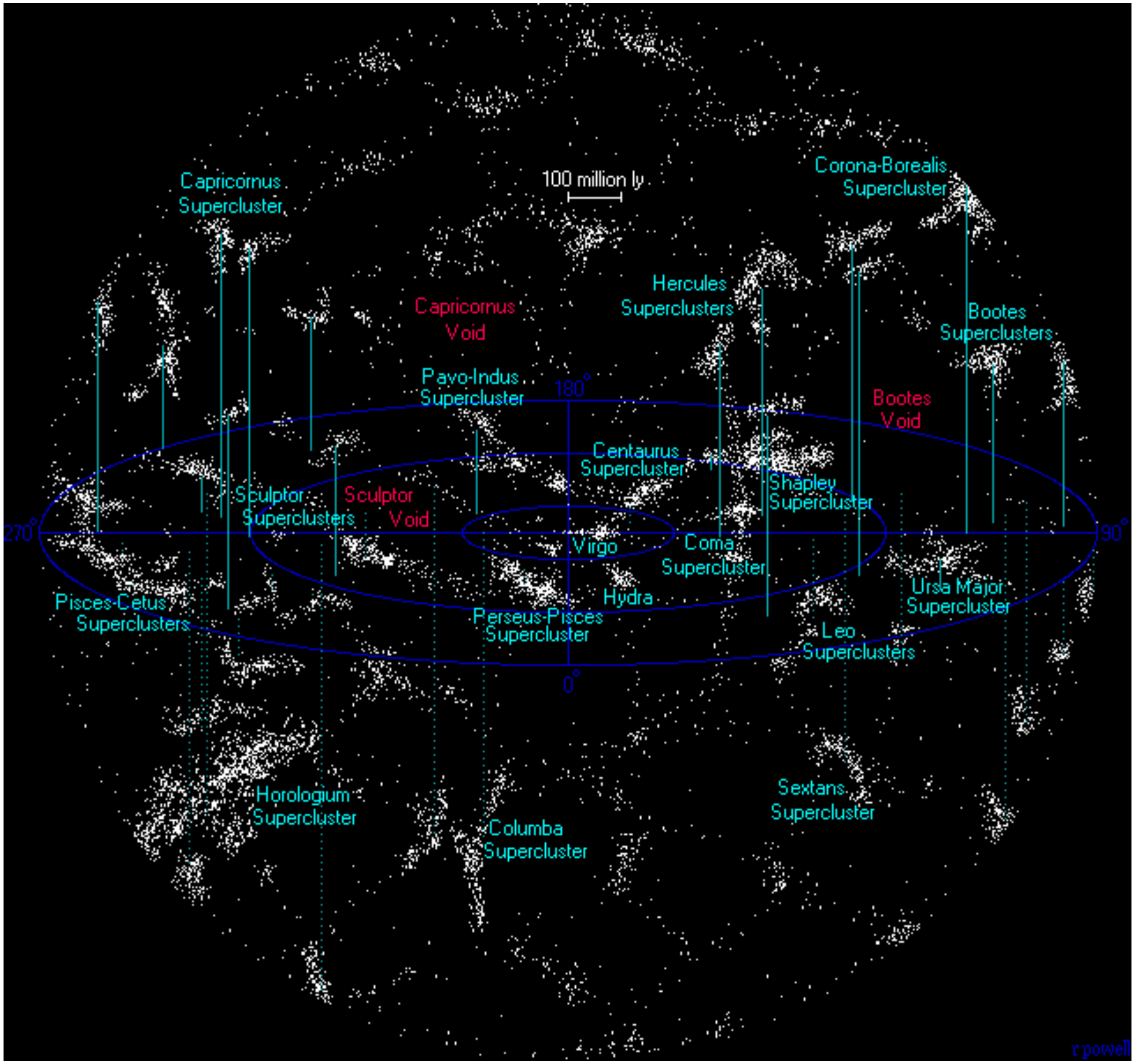
The Local Supercluster



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

Virgo Cluster 54 Mly

One Billion Light Years



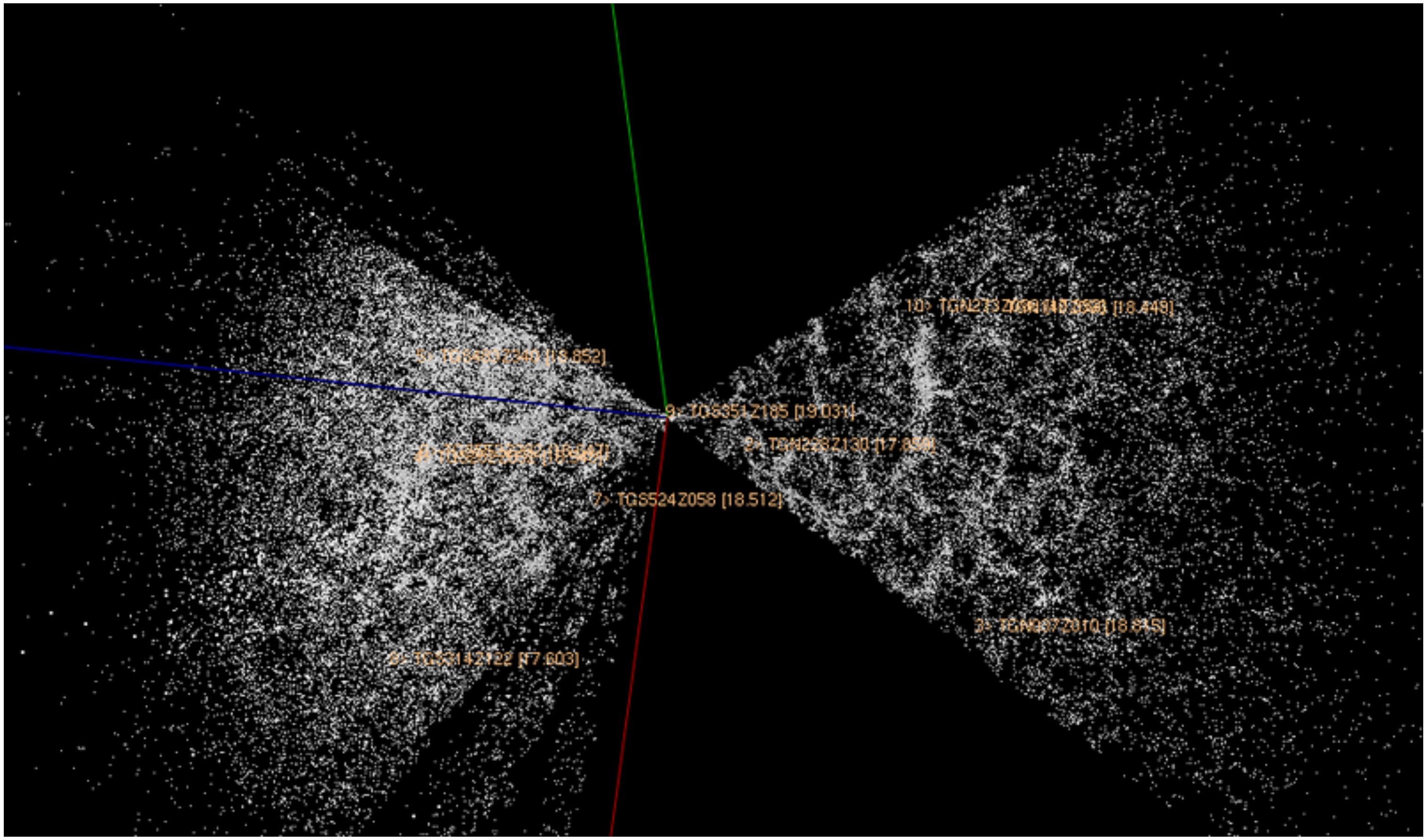
7% of the radius of the visible universe

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.

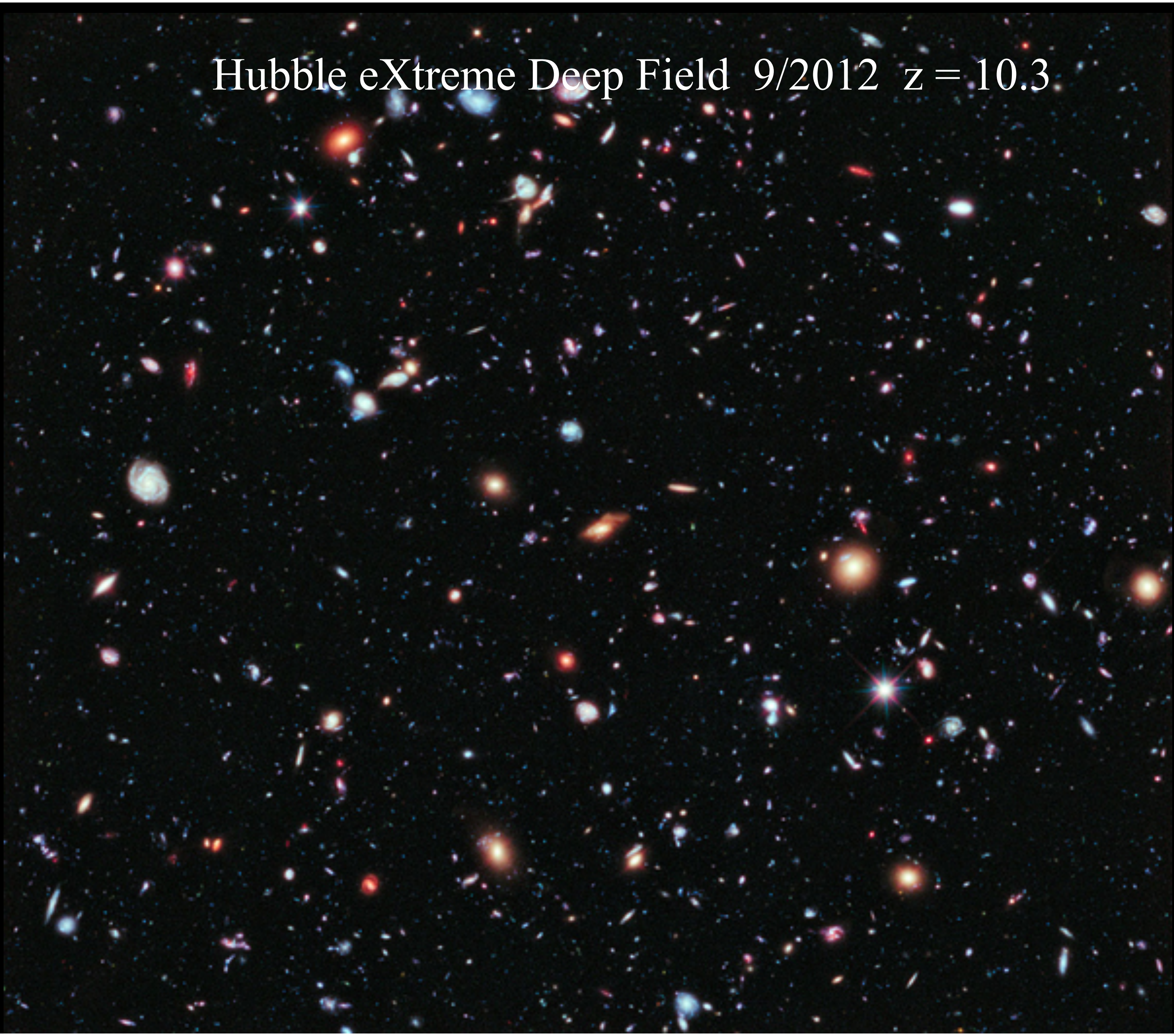
http://www.mso.anu.edu.au/2dFGRS/

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

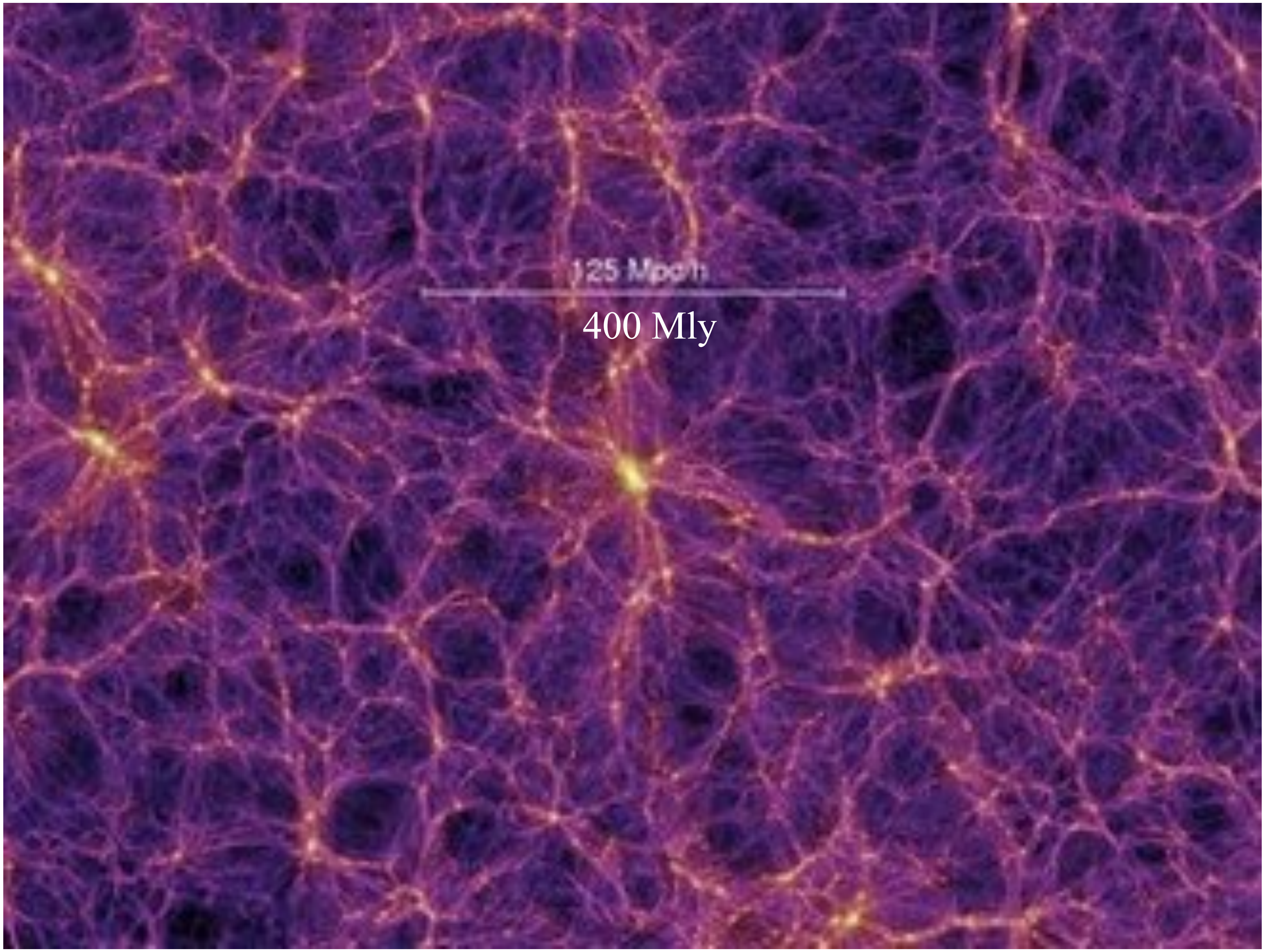
Shows a piece of the universe when it was "only" 400 million years old. 5500 galaxies

The current age is 13.8 billion years

Hubble eXtreme Deep Field 9/2012 z = 10.3

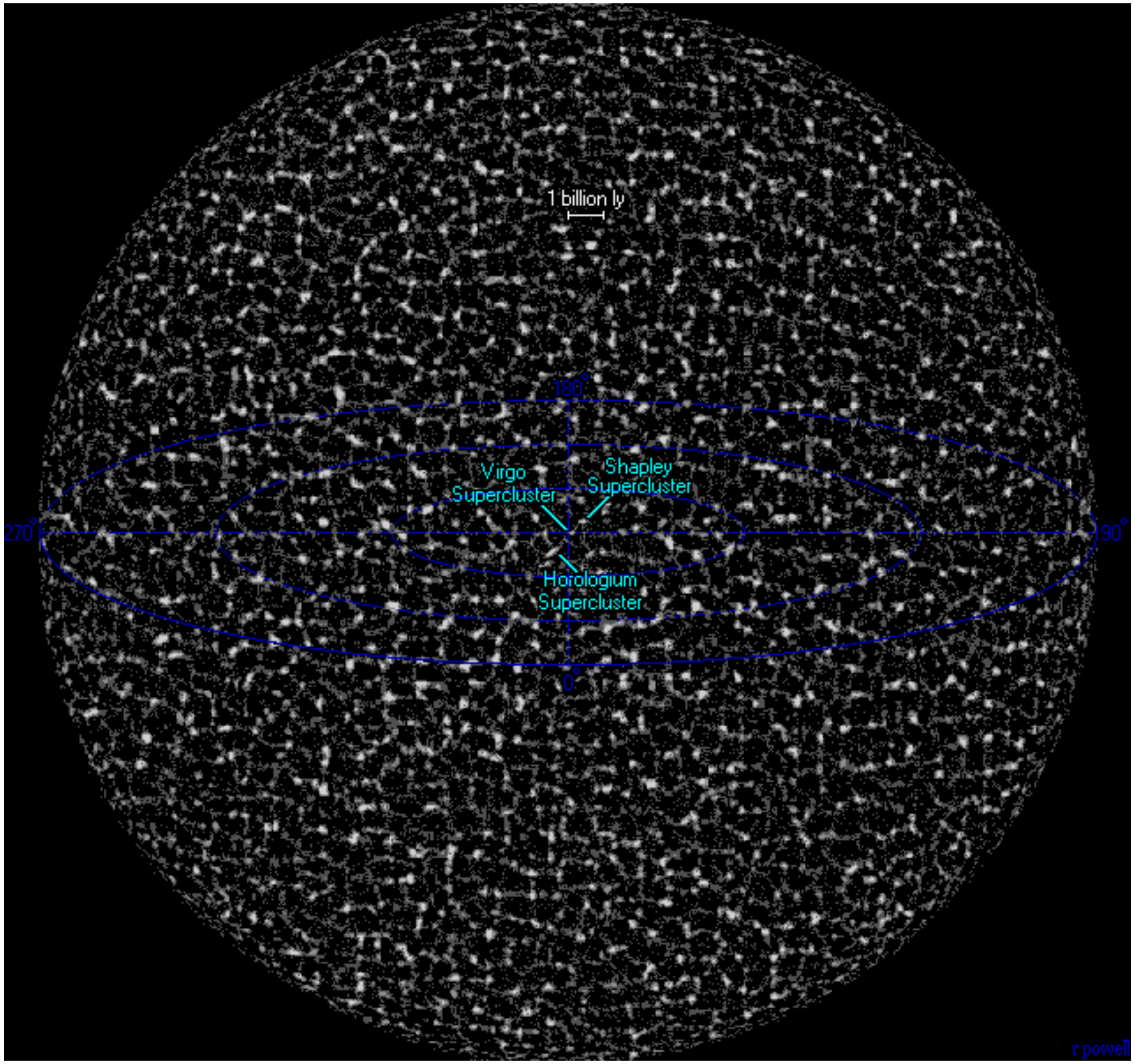


http://www.mpa-garching.mpg.de/galform/virgo/millennium/



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) ...

Appendix: Math and Constants

Scientific notation

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

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

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

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

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

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

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

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

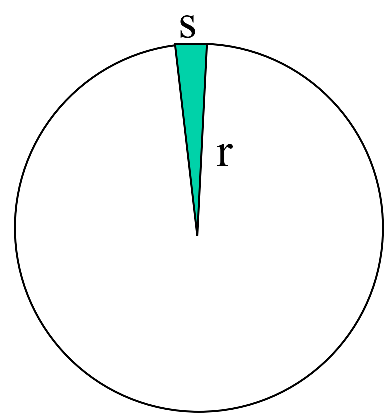
$$\left(1.0 \times 10^{-2}\right)\left(2.0 \times 10^{4}\right) = 2.0 \times 10^{2} = 200$$

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

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

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 citcle

1 radian = $360/2\pi$ = 57.29.... 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 ~ ½ degree

HST ~ 0.4 milli-arc-seconds (0.01 pixel – for astrometry)

GAIA ~ 10 – 20 μas (1 foot at 2 million miles)

Units

The basic units in Ay12 are cm, gm, and sec (with apologies to the physicists).

How many cm in a light year? 1 ly = c * 1 yr

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

based on Julian year = 365.25 days (exactly)

day = 24 hours

hour = 60 minutes

km = 10^3 m

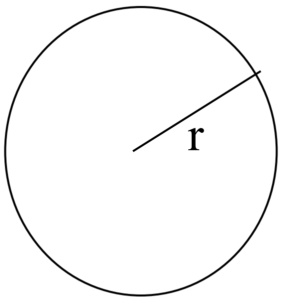
m = 10^2 cm

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

$$\simeq \left(\frac{2.99\times10^5 \text{ km}}{\text{s}}\right)(1 \text{ yr})\left(\frac{10^3 \text{ m}}{\text{km}}\right)\left(\frac{10^2 \text{ cm}}{\text{m}}\right)\left(\frac{365 \text{ day}}{1 \text{ yr}}\right)\left(\frac{24 \text{ hr}}{1 \text{ day}}\right)\left(\frac{60 \text{ min}}{1 \text{ hr}}\right)\left(\frac{60 \text{ s}}{1 \text{ min}}\right)$$

$$\approx 9.44 \times 10^{17} \text{ cm}$$

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”?

$$M = \frac{4}{3}(3.14)(5\times10^5 \text{ cm})^3 (5 \frac{\text{gm}}{\text{cm}^3})$$

$$= (4.19)(125\times10^{15})(5) \text{ gm}$$

$$= 2.62 \times 10^{18} \text{ gm}$$

Calculus

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

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

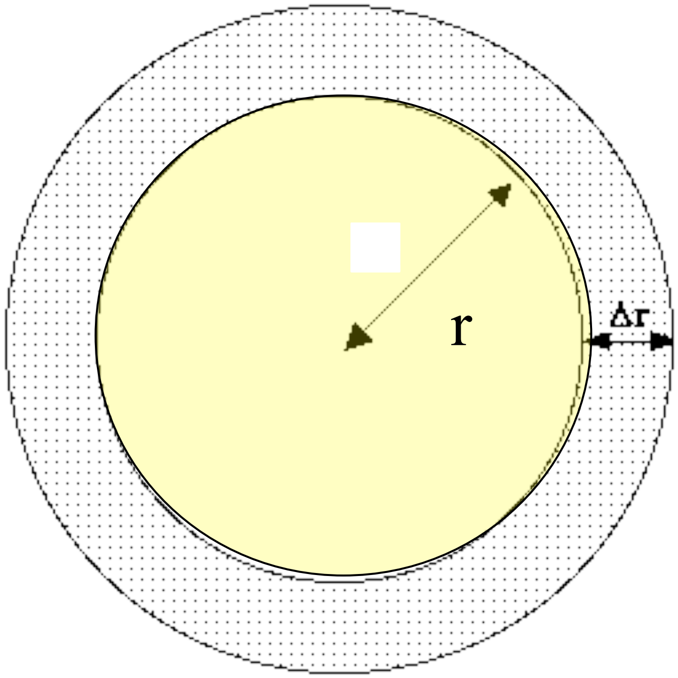
$$\frac{d}{d\theta}(Cos\,\theta) = -Sin\,\theta$$

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

Binomial expansion theorem

$$(1+\;\varepsilon\;)^{\mathrm{n}} \approx (1+n\varepsilon) \qquad if\ |\varepsilon| \ll 1$$

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



Eg. Volume of a sphere

Area of a shell = 4 π r^2

Thickness = Δr $\approx$ dr

Add up a whole bunch of shells

$$\int_0^{r_0} 4\pi r^2 \, dr = \frac{4}{3}\pi \, r_0^3$$

ANGULAR MEASURE

$\pi = 3.14159....$

$2\ \pi$ radians $= 360^o$

1 radian $= 57^o.296$

1 degree = 60' = 60 arc min

1 arc min = 60" = 60 arc sec

1 radian = 206265".806

Number of square degrees on sky = 41,252.961

PHYSICAL CONSTANTS

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

ASTRONOMICAL CONSTANTS

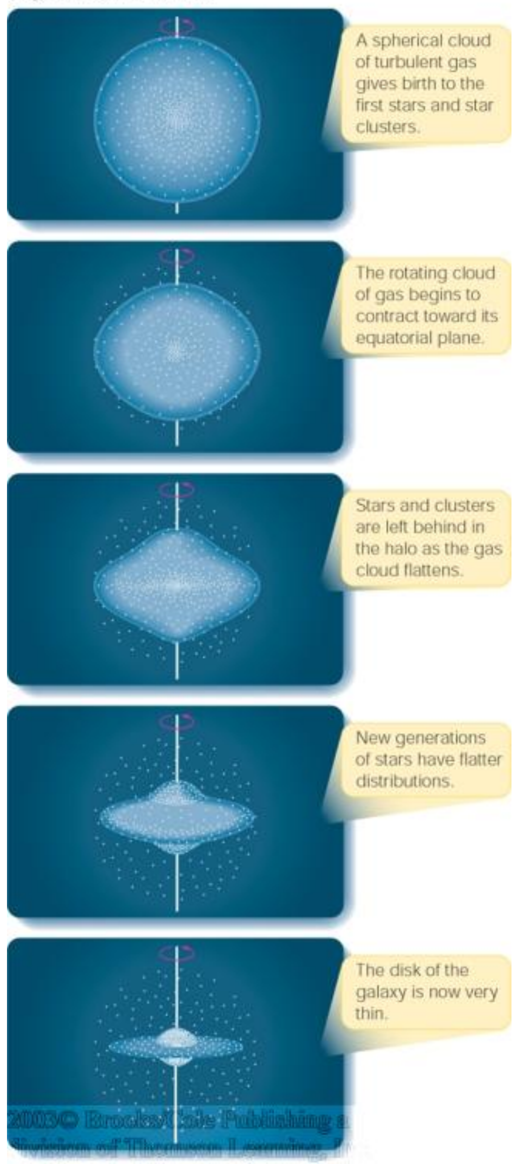
Astronomical Unit	AU	$1.495978707 \times 10^{13}$ cm
Parsec	pc	206265 AU
		3.262 ly
		3.086×10^{18} cm
Light year	ly	9.4605×10^{17} cm
		6.324×10^{4} AU
(siderial) year	yr	3.155815×10^{7} s
Mass of Earth	M_E	5.977×10^{27} g
(Equatorial) radius of Earth	R_E	6.378×10^{8} cm
Mass of sun	$M_\odot$	1.989×10^{33} 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 $\theta << 1$ radian	$\sin\theta \approx \tan\theta \approx \theta$

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

Eggen, Lyndon-Bell, and Sandage (1962)