

Masses of Galaxies

Measure mass by:

- motion within a galaxy
- motion of different galaxies about each other
- gravitational lensing
- Gives
 - most mass isn't in stars and “normal” matter

→ **DARK MATTER**

See M31 and a Brief History of Dark Matter, M.S. Roberts, Frontiers of Astrophysics: A Celebration of NRAOs 50th Anniversary, 2008.

Mass of Galaxy – stars move around center

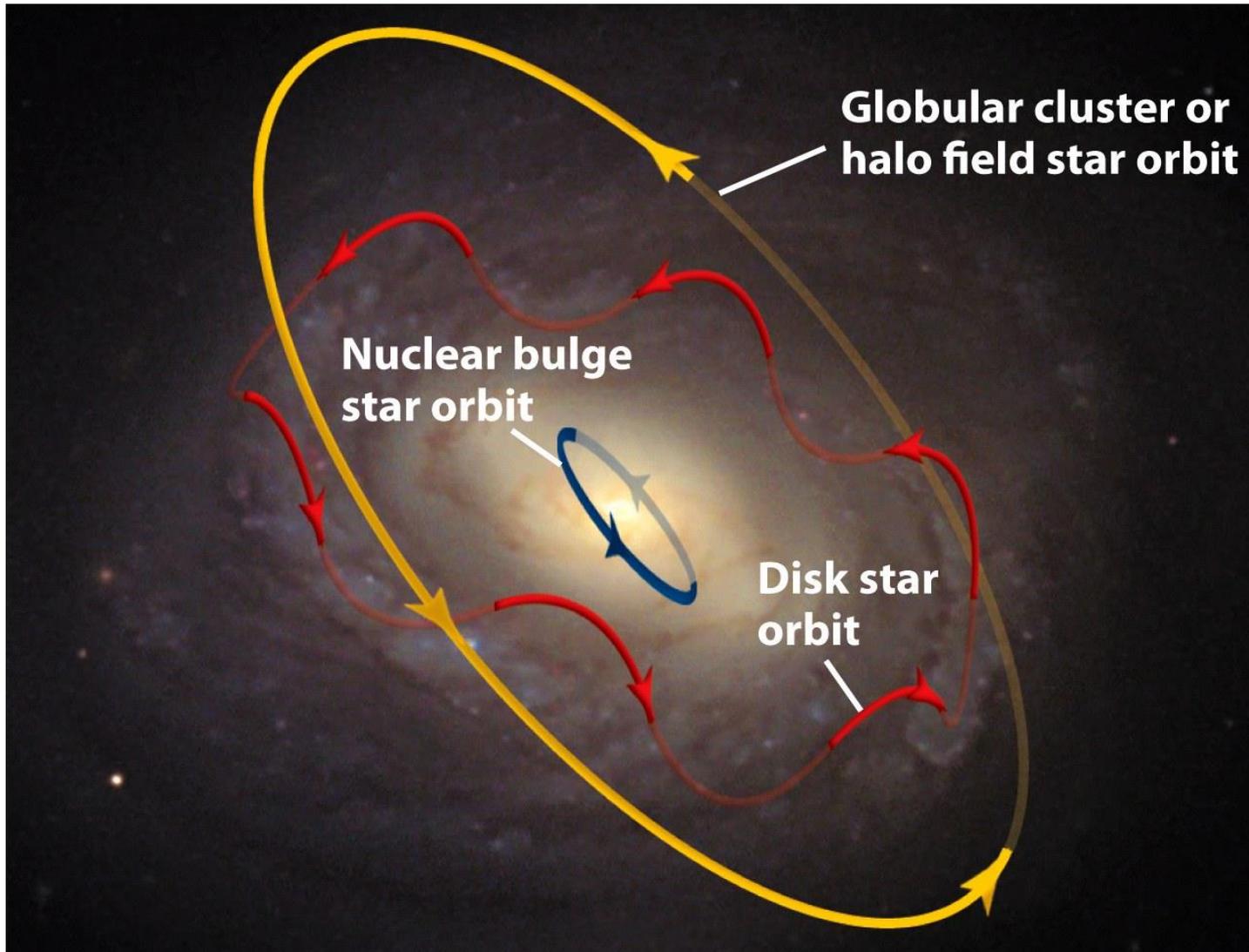
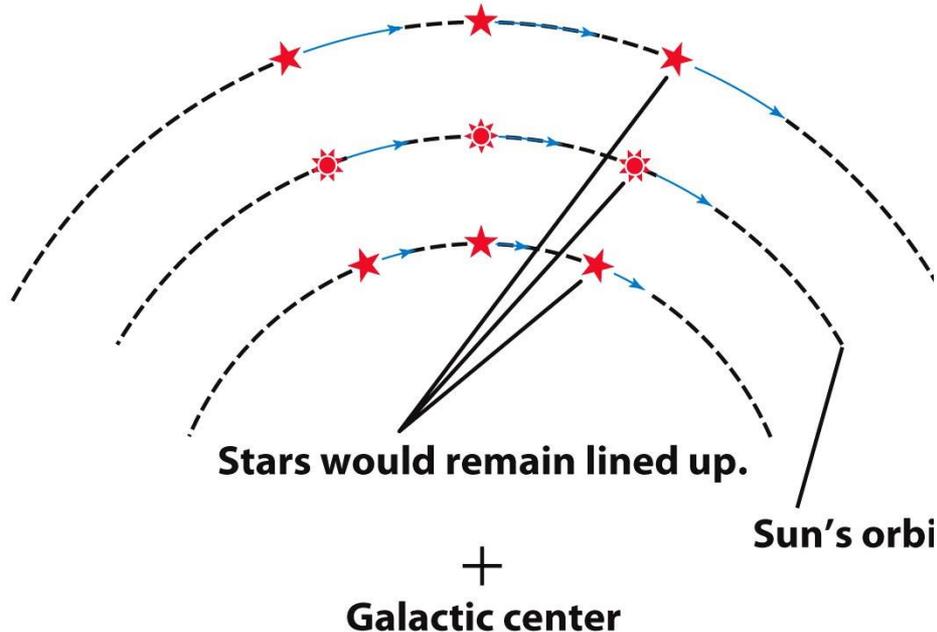


Figure 11-15
Discovering the Essential Universe, Fourth Edition
© 2009 W. H. Freeman and Company

Differential Rotation of Galaxy

If our Galaxy rotated like a solid disk, the orbital speed would be greater for stars and gas in larger orbits.



Because the Sun and stars obey Kepler's third law, the orbital speed is less for stars and gas in larger orbits.

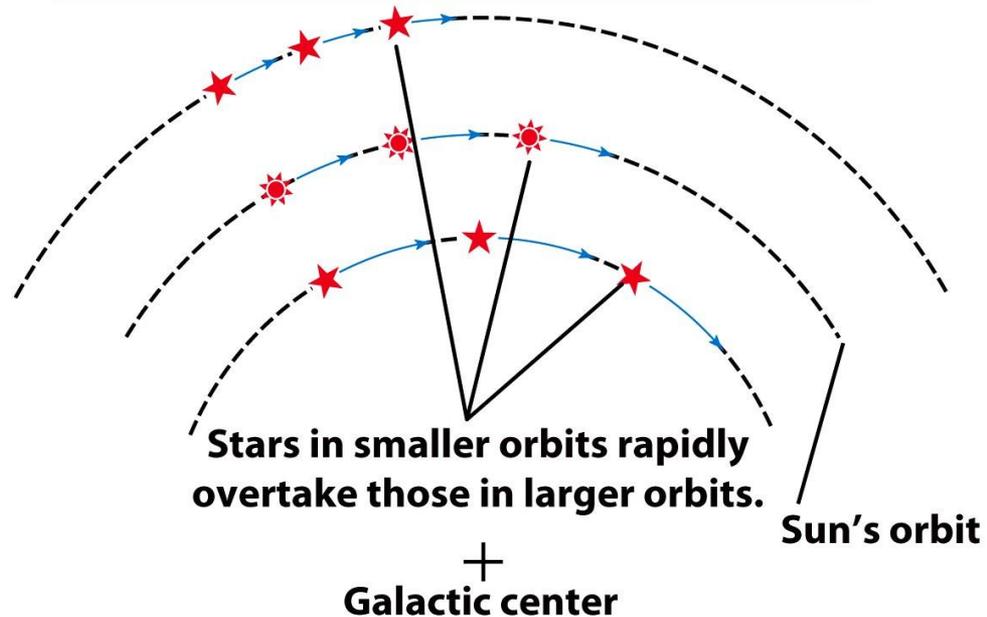


Figure 11-17a
Discovering the Essential Universe, Fourth Edition
© 2009 W. H. Freeman and Company

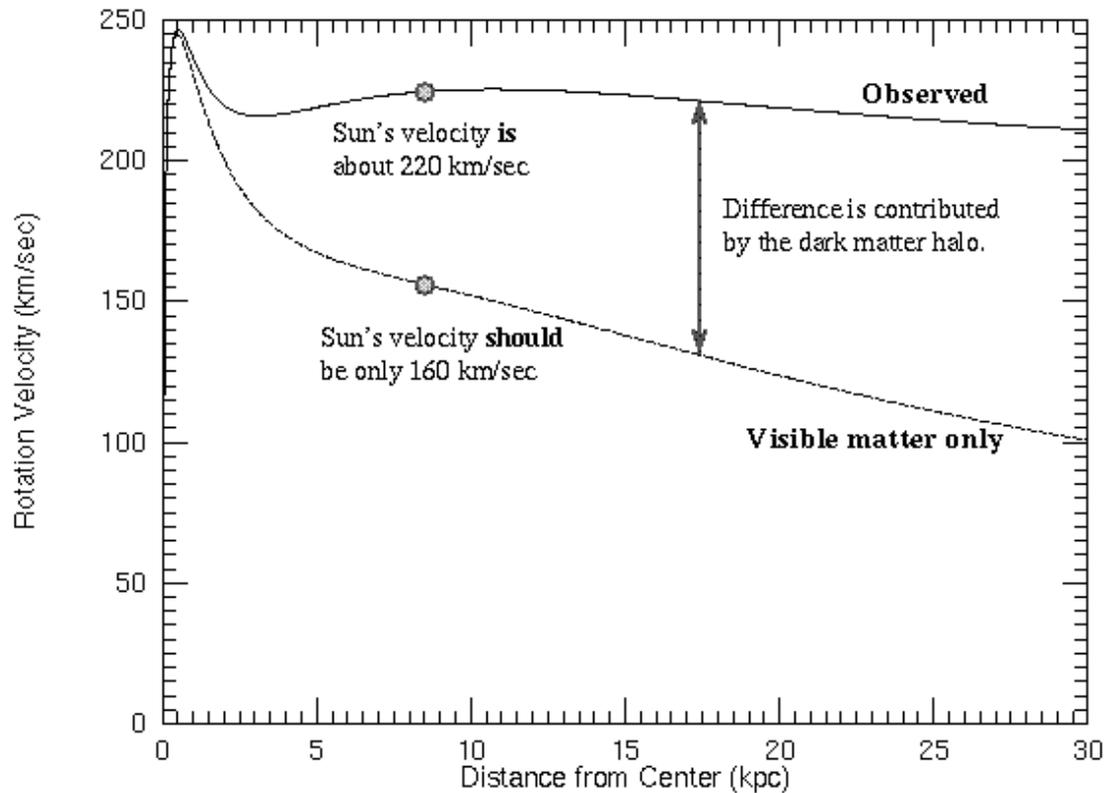
Figure 11-17b
Discovering the Essential Universe, Fourth Edition
© 2009 W. H. Freeman and Company

Recall while it takes 1 year for the Earth to orbit the Sun, it takes Jupiter 12 years

Mass of Milky Way

- Sun is 30,000 light years from center (2,000,000,000 AU); period of 200,000,000 years
- same as for planets:
$$\text{Dist}^3 / \text{Period}^2 = M \text{ (inside)}$$
 giving 200 billion Mass(Sun) inside the Sun's radius
- repeat for 150,000 LY from center \rightarrow >1000 billion Mass(Sun) for Galaxy mass inside that distance

Differential Rotation of Galaxy



At larger distances from the center, the Galaxy is moving faster than what would be expected from the amount of “normal” matter

The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo**.

Milky Way moving “too fast” 1932 J. Oort and others.

Verna Rubin and others 1965-75 showed in other galaxies

Mass of Galaxies

- mass doesn't match observed amount of matter
- unseen “dark matter” unknown composition
- extends beyond visible part of Milky Way
- observed in other Galaxies (1939-1975). Vera Rubin pioneered though no Nobel Prize as (partially) she wasn't a male (she was first female allowed to use some telescopes)

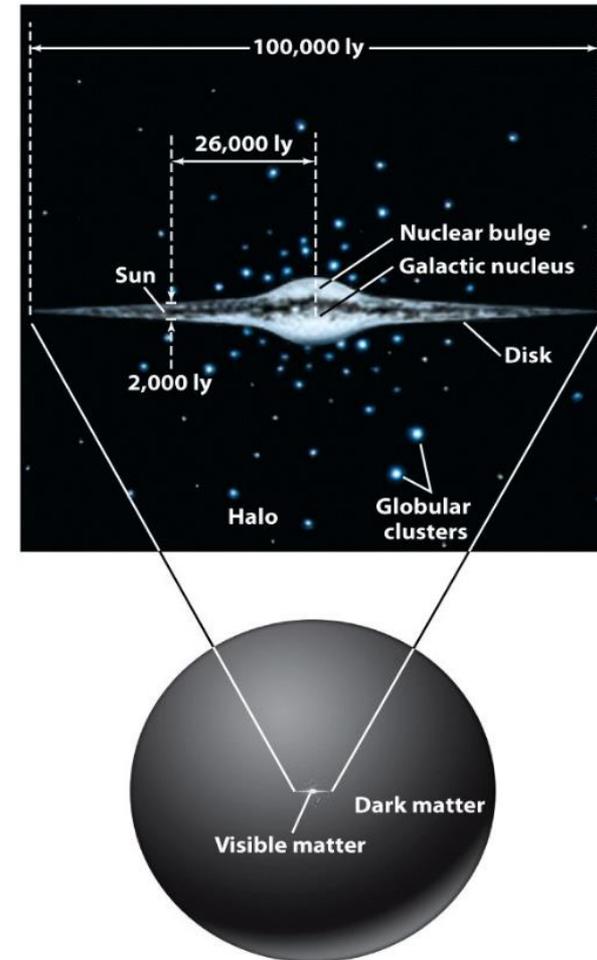
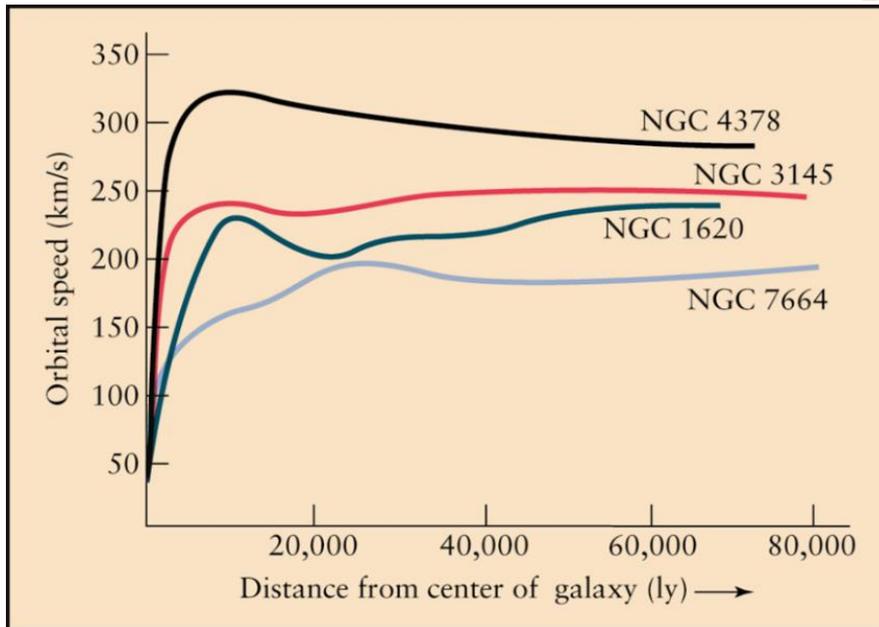
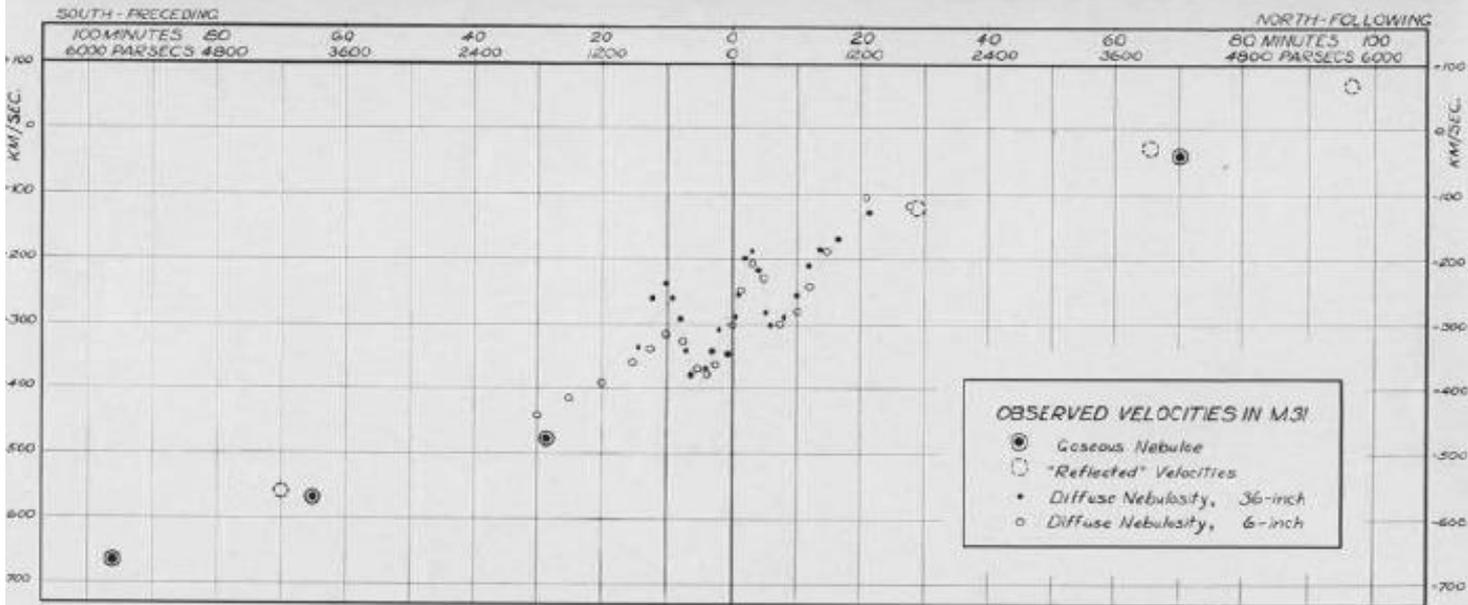


Figure 11-11
Discovering the Essential Universe, Fourth Edition
© 2009 W.H. Freeman and Company

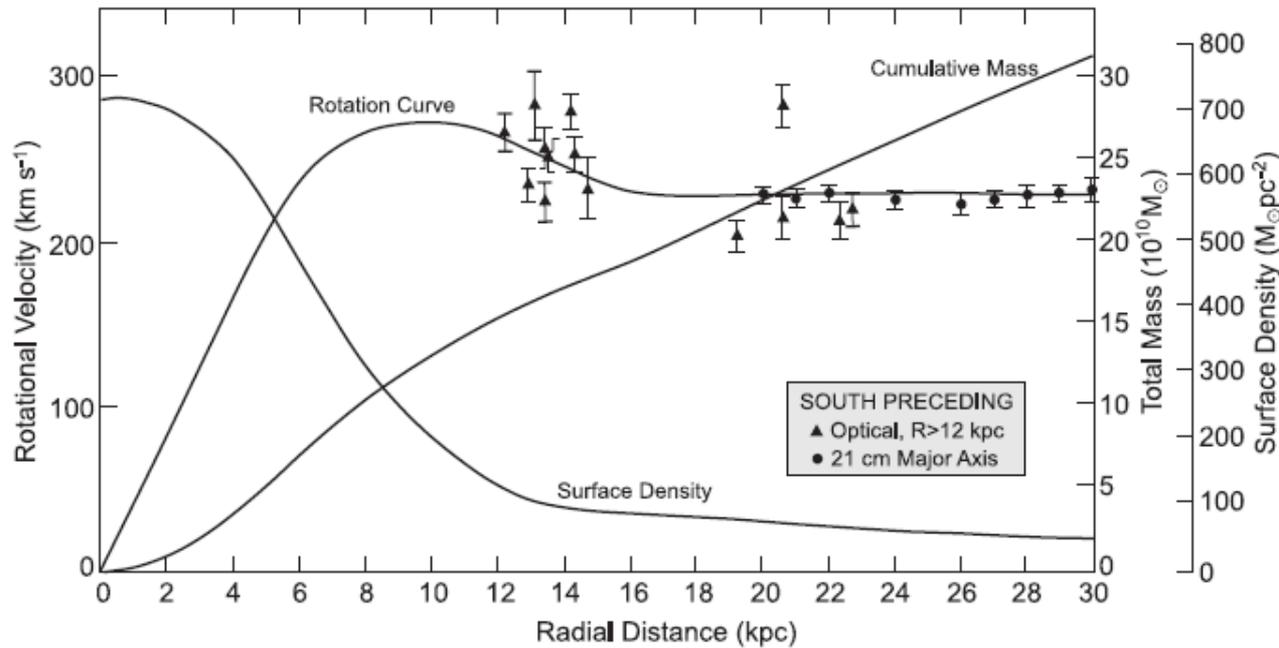
Andromeda Galaxy Rotation - 1939



The Andromeda Nebula, with observed velocities plotted below. Smoothed mean velocities of the unresolved central portion are represented by small dots for observations with the Crossley reflector, and by small open circles for observations with the 6-inch mirror. In the photograph, the bright-line emission nebulosities are circled, and their velocities, with the exception of the one on the minor axis, are plotted as ringed dots. (Photograph by Mayall)

H.W.
Babcock,
1939 PhD
thesis,
Univ. of
California.
Velocities
vs distance
from center
→ moving
too fast at
larger
distances

Andromeda Galaxy Rotation – 1970s



Vera
Rubin
data are
filled
triangles

Figure 2. A smoothed rotation curve of M31 (Roberts and Whitehurst 1975). The filled triangles are based on optical observations (Rubin and Ford 1970). The filled circles are from 300 foot telescope HI measurements extending to 150'.

The H1 measurements used the Aricebo telescope in Puerto Rico and measured the spin-flip 21 cm line from Hydrogen. Too much velocity at large radius → missing mass compared to what could be seen (the “surface density” curve)

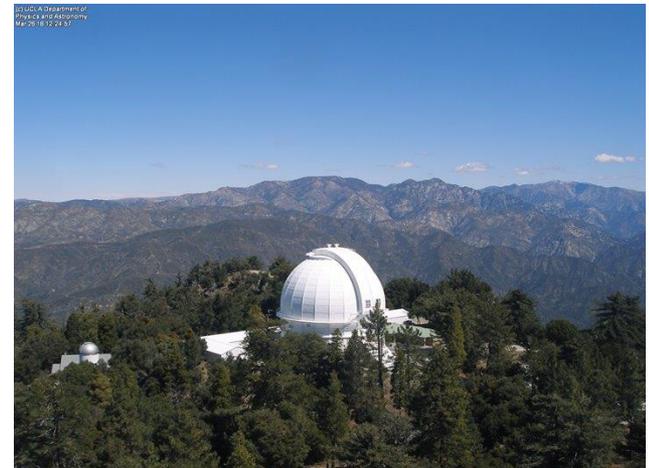
Other Dark Matter Observations

- Observations ignored until 1970s when astrophysics community started to realize measurements consistently indicated the presence of dark matter
- look at velocities of individual galaxies in a cluster about each other; find too large → due to “missing mass” first observed by Fritz Zwicky in 1932 (Caltech; he also introduced names “dark matter” and “supernova”) and Sinclair Smith in 1936 (Mt. Wilson, LA)
- look at gravitation lensing by a nearby galaxy of a more distant galaxy (many including NIU students Donna Kubik and Matt Weisner. see their theses at

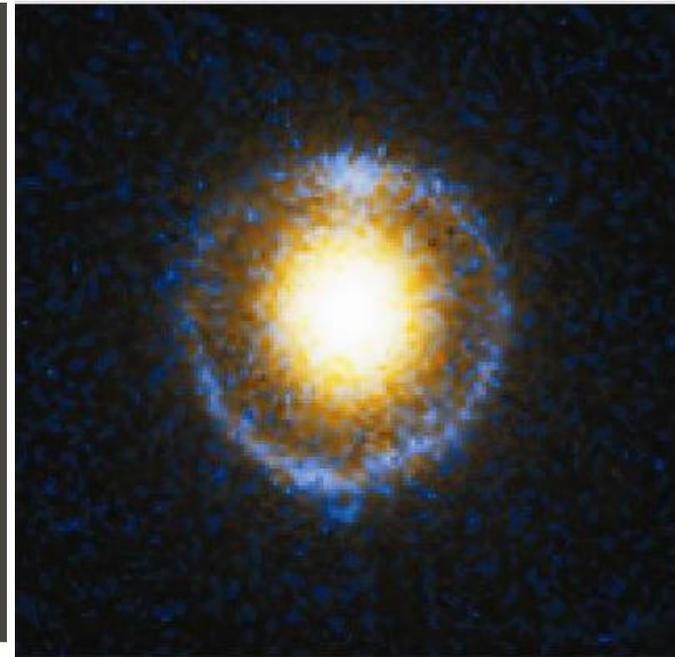
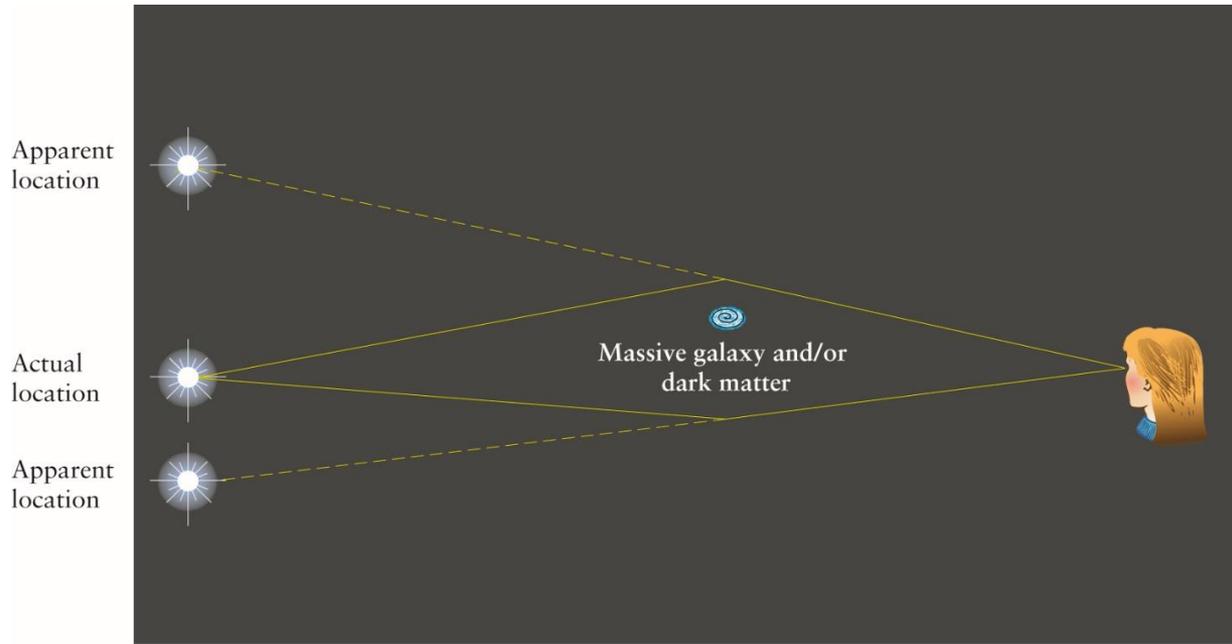
www.physics.niu.edu/physics/academic/grad/theses1.shtml)

Mt. Wilson Observatory

- Near Pasadena. Had 60 and 100 inch mirrors 1908-1950s. Good interferometry, meaning measured spectrum and Doppler shifts well
- Hubble worked there, measured distances to galaxies, determined Andromeda 2.2 MLY away and so a galaxy, obtained Hubble law.
- Fritz Zwicky studies galaxies in Coma Cluster, infers presence of dark matter. Later Sinclair Smith observes more galaxies
- In 1940s, Walter Baade realizes two type of stars, I and II, with type II just H and He



Gravitational Lensing by Galaxies



a

The ring (in blue) is light from the faraway galaxy and is called an “Einstein ring”. You can look at the spectrum of various parts and show they are all from the same galaxy, and also infer its distance using the Hubble Law. The size of the ring around the closer (in yellow) galaxy depends on the mass of the closer galaxy and so measures that galaxy’s mass

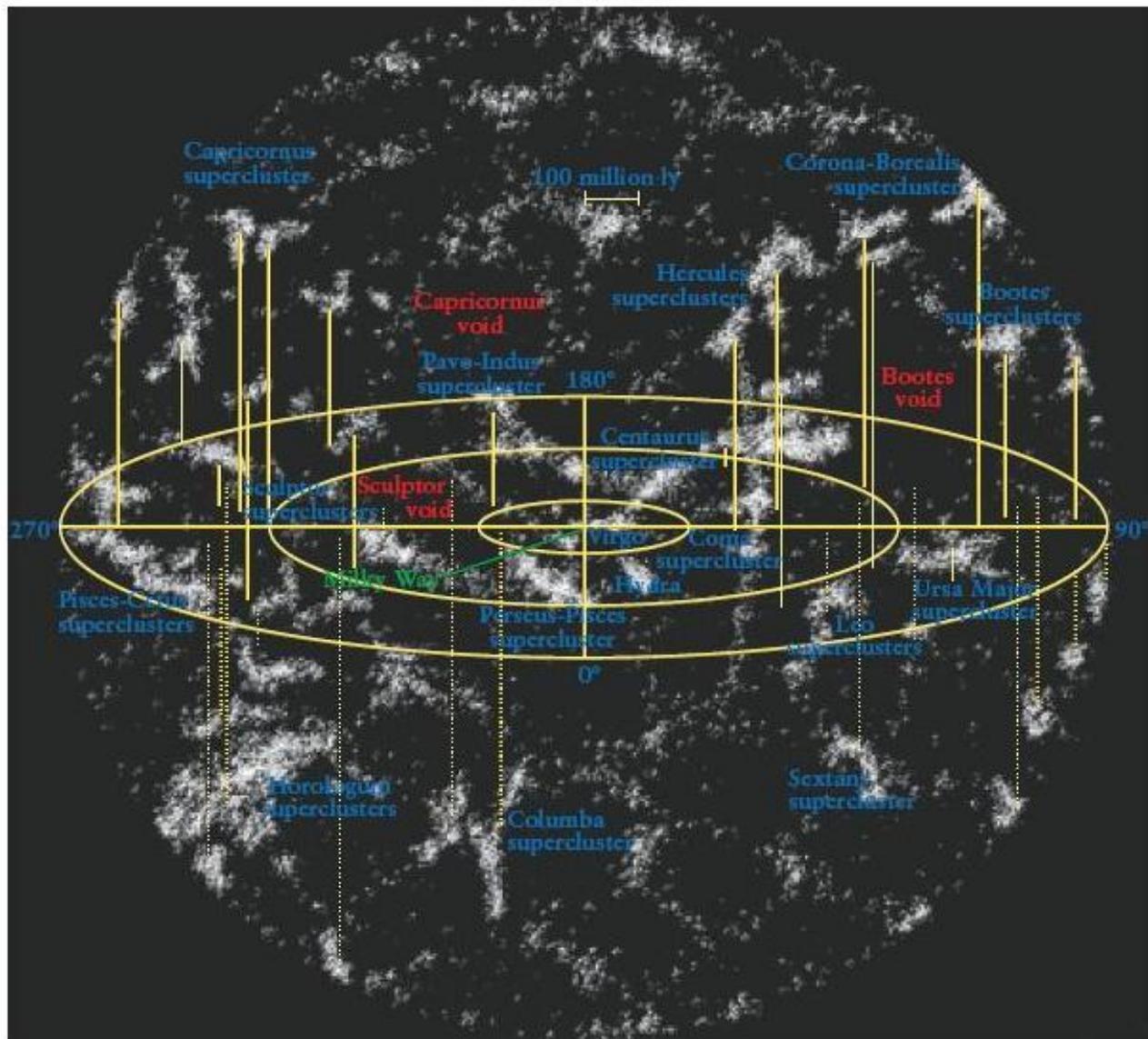
Galaxy Clusters and Superclusters

- galaxies come in clusters of 10-1000 galaxies: gravitationally bound, impacts formation. Motion about each other measures galaxies' masses
- clusters usually part of superclusters which reflect distribution of matter in early Universe



Formax Cluster 60
MLY from us

Superclusters of Galaxies. Not uniformly distributed. understanding “clumping” is another way to detect effect due to dark matter (how is complicated)



100s or 1000s of galaxies in a supercluster

Visible and Dark Matter

- “visible” matter - stars, gas, dust, neutron stars, black holes
- “dark” matter - not understood – Two Possibilities

Massive Astrophysical Compact Halo Objects

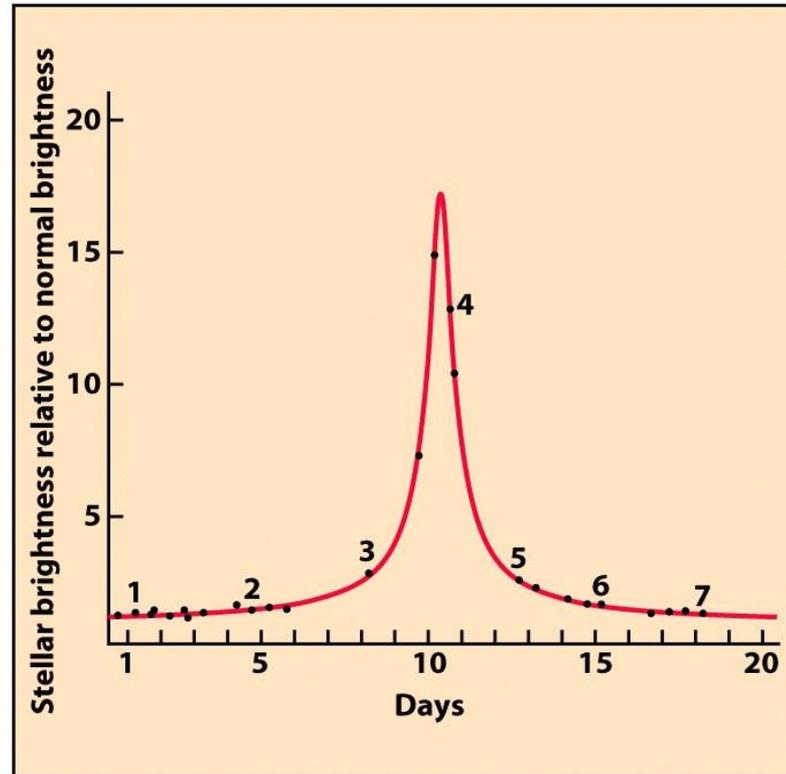
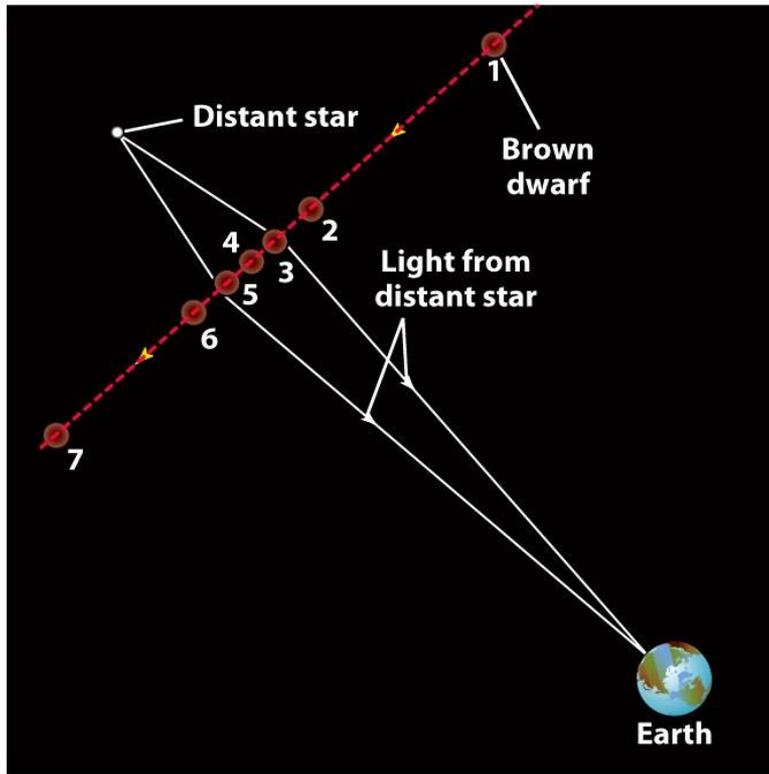
- cooled down white dwarves or black holes leftover from early universe (MACHO study) – not new physics -gravitational lensing studies - NO??

Weakly Interacting Massive Particles

- new physics - neutrinos having enough mass, new subatomic particles (WIMPS) YES?? Still have not identified. look for in high energy experiments at CERN and Fermilab (like Mu2e experiment) or in ultra cold experiments in deep underground mines

- more than 75% of mass is not understood - Dark Matter mystery → possible new physics. **Still not understood**

MACHO search

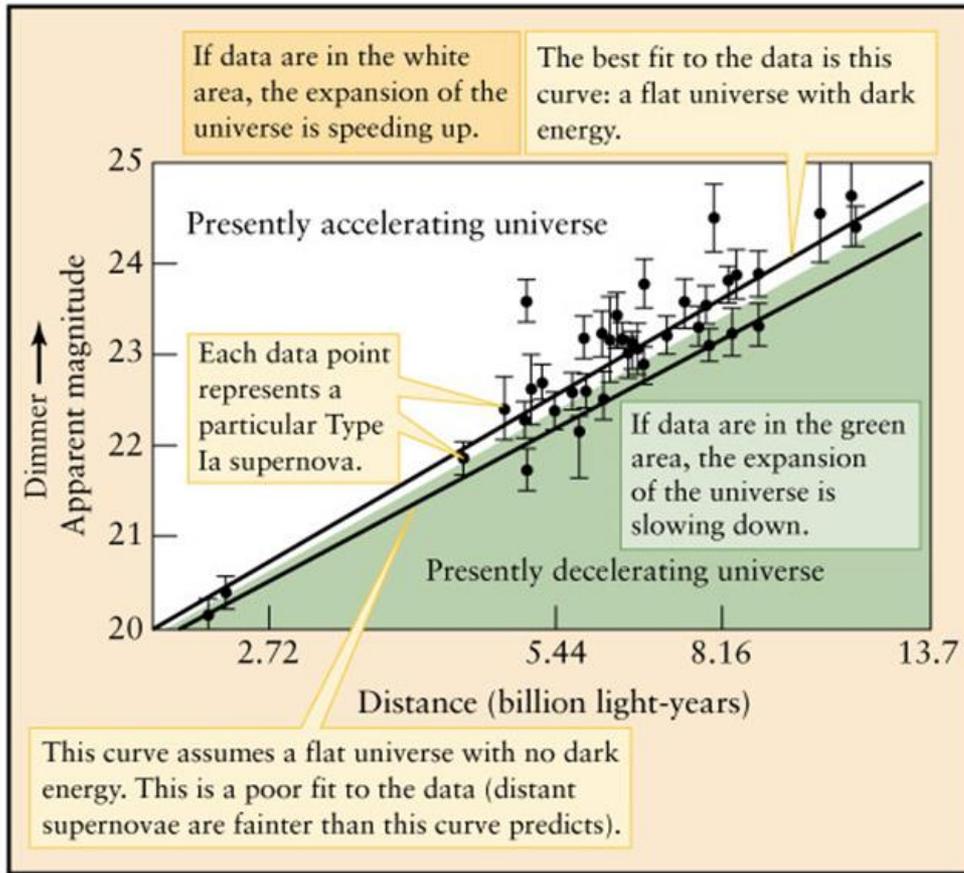


Look at a star from another galaxy and see if its luminosity increases due to gravitational lensing of “something” (cold white dwarf, neutron star, blackhole) on the outer part of our galaxy or in between galaxies. Some have been detected but not enough to account for the “missing mass”

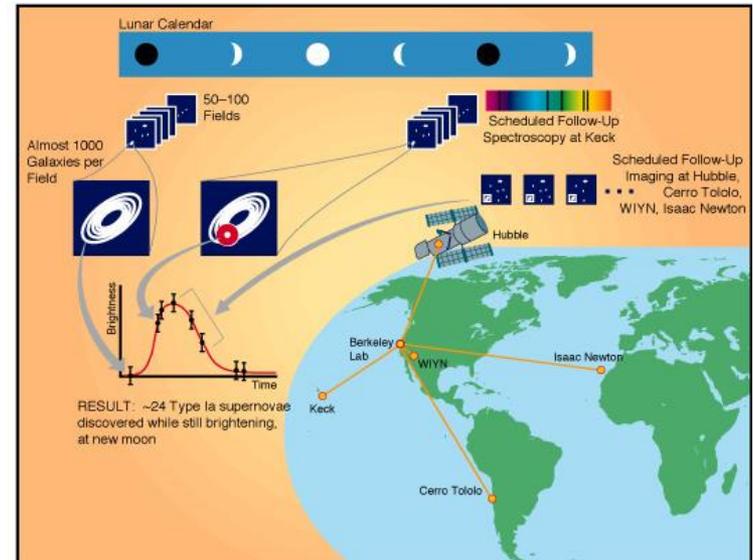
Expanding Universe

- Observation of galaxies all moving away from us gave the Hubble Law: $\text{velocity} = H \times \text{distance}$ → Universe is expanding → age about 13-14 billion years
- Age depends on how Hubble “constant” H is changing with time → amount of matter and energy. Matter slows up expansion due to gravity
- recent (1998) (perplexing) data indicated Universe is now accelerating. Like anti-gravity(?!?)
- Detect far distant Type Ia supernovas, up to 12 billion light years away. Use the Doppler shift to determine their recessional velocity v , and from $v = Hd$ their nominal distance. But when the SN brightnesses are measured they are dimmer than they should be, meaning they are further away. Explain by inferring that the Universe is now accelerating, caused by yet-to-be-understood “dark energy”

Accelerating Universe Discovery – complicated!!



1998: 2 groups. Use data from telescope in Chile to find supernovas, followup data with other telescopes



Detect most distant Type Ia supernovas. Formed at very early times. Distant supernovas are dimmer than expected shows they are further away than expected. Explanation is Universe is recently expanding. 1998 discovery and now very high priority. Dark Energy Survey in Chile searches for more supernovas.

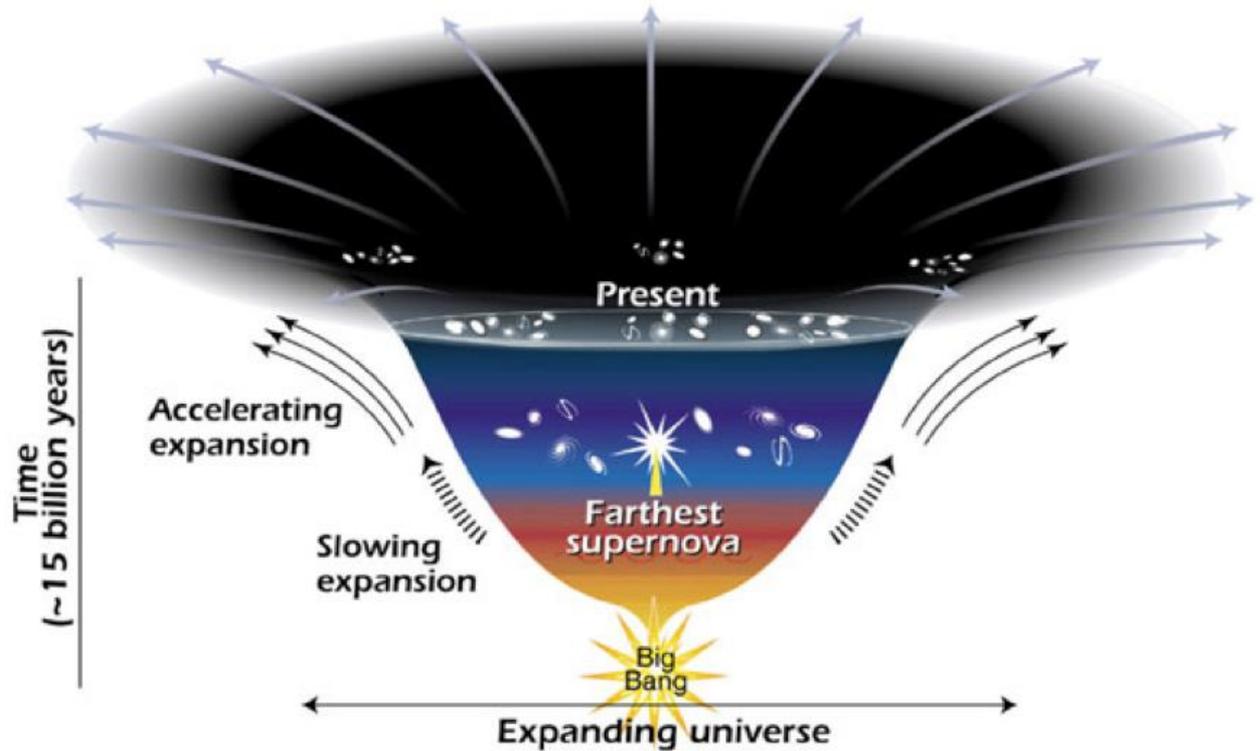
Expanding Universe

- As the Universe expands it cools down as the energy is spread out over a larger volume. At its earlier times it was much, much hotter.
- If expansion continues → cold (Open Universe)
- if the expansion somehow stops and a contraction begins → heats up (Closed Universe)
- we seem to be very close to the Critical Density which separates an Open from a Closed Universe (hint of underlying physics?)

Expanding Universe

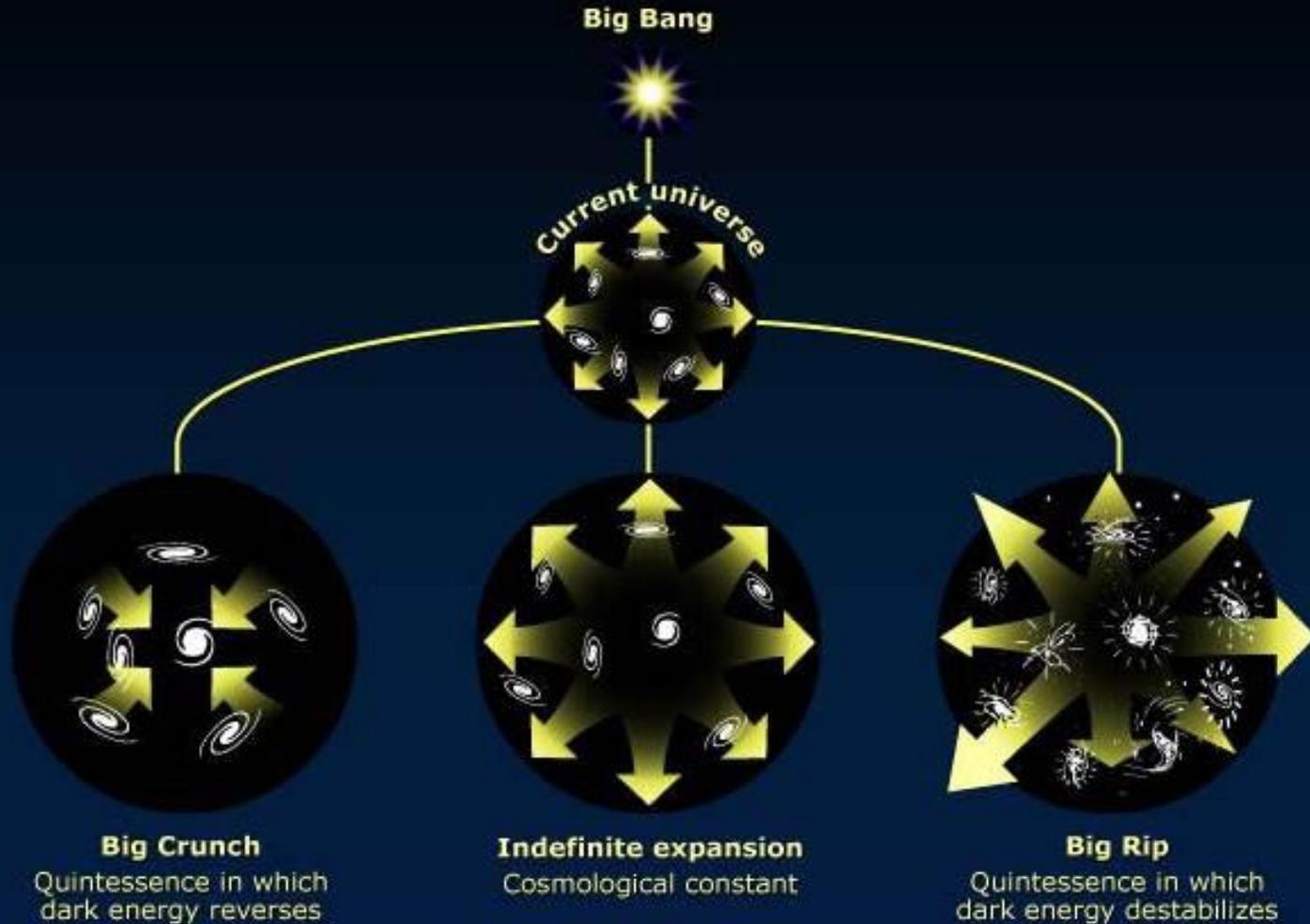
Gravity due to matter (mostly Dark Matter) slows up expansion in “early” Universe

“Dark Energy” (“empty space” energy though no one knows exactly what this is) increases expansion rate in “future” Universe



NASA/A. Riess

Future fates of the dark-energy universe



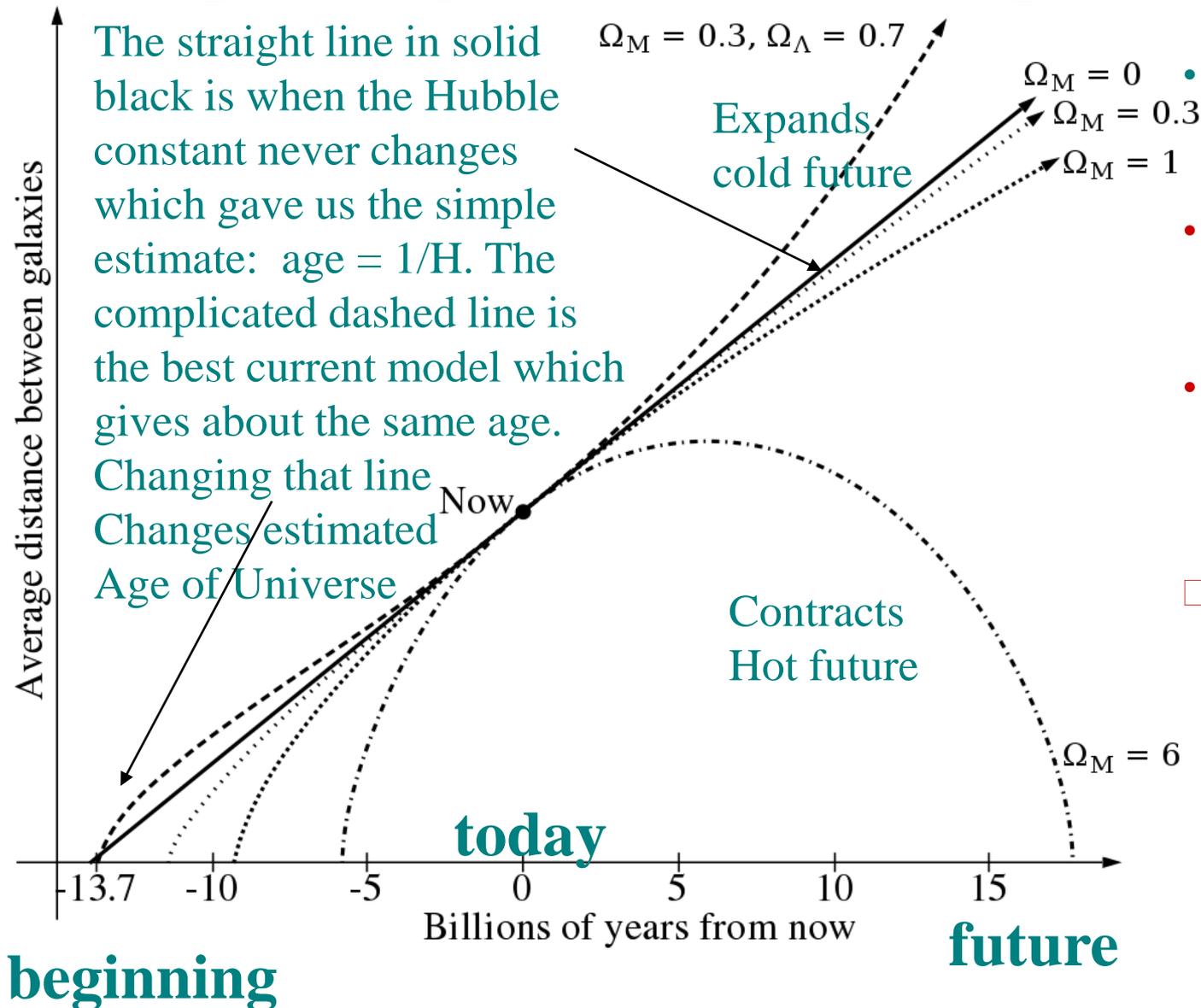
Very Hot

Very Cold

probably Very Cold

makes new Universes?

Expanding Universe – complicated slide!!



• Hubble constant H changes with time

• expand forever \rightarrow Open Universe

• stop expanding and then contracts \rightarrow Closed Universe

□ Ω is related to the mass and energy density of the Universe. Part of general relativity and complicated(!)

Fire and Ice

Robert Frost - 1923

Some say the world will end in fire,
Some say in ice.

From what I've tasted of desire
I hold with those who favor fire.

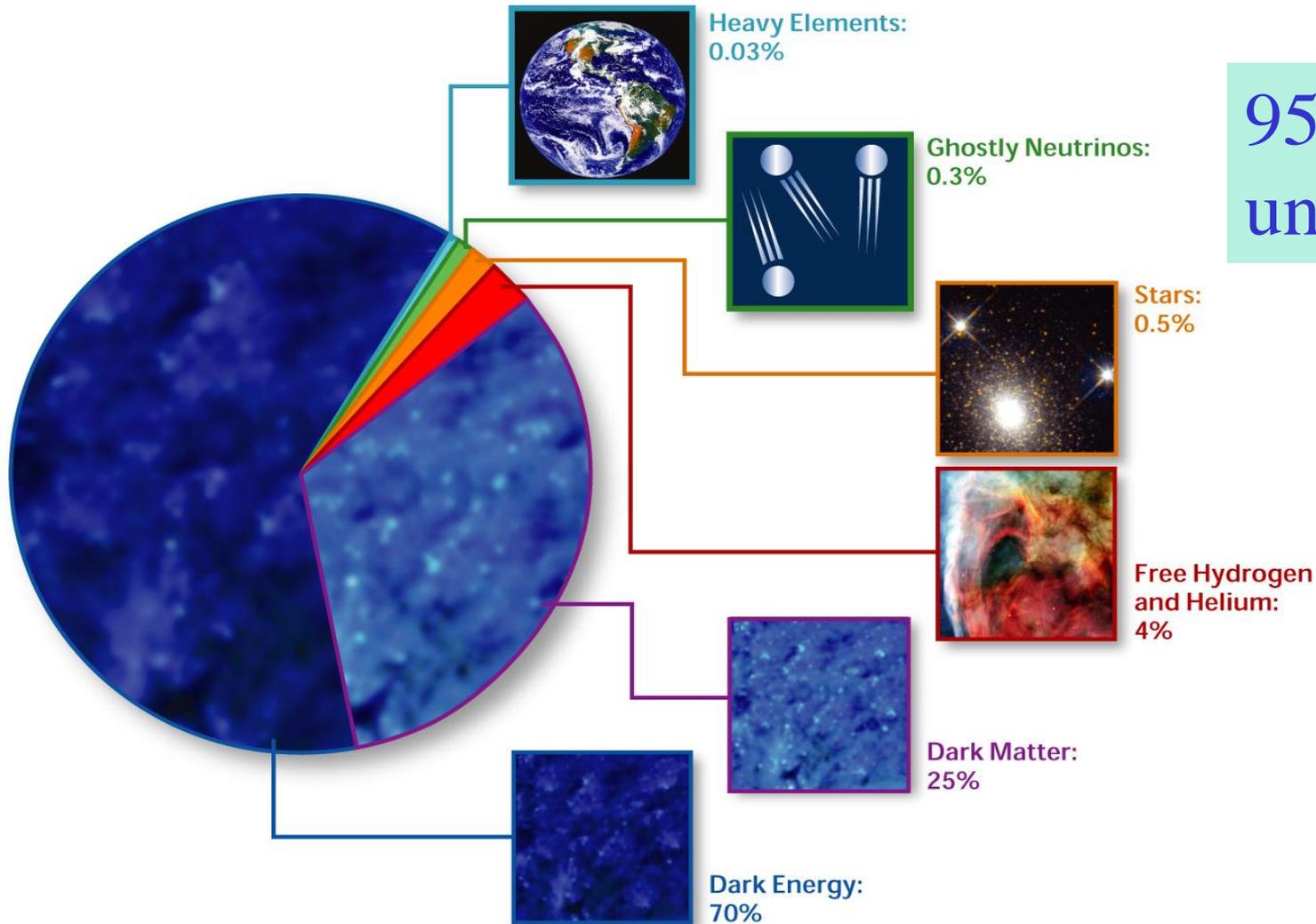
But if I had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

100-level gened classes should also contain items on history and culture. These are the poems for this course.

Physics for Poets Jeffrey Harrison

They sat in the last row of the lecture hall
cultivating a knowing remoteness
But with a secret satisfaction that the class
Had been named for the. The professor
Unwittingly provided them with phrases,
lines, metaphors, ideas for whole poems.
he spoke in the nasal cartoon voice
of someone who had been breathing helium,
and his bow tie led them to suspect
his head was a balloon: they imagined it
floating up to the ceiling, where it kept on
chattering about scattering patterns
Or how matter is mostly empty space...
How they sky should be purple and why it isn't.
They pictured a world under that purple sky
Populated by red giants and white dwarves
And tiny creatures of various colors
Called quarks. A world where the shortest distance
Between two points was a curve, where time
Slowed down and sped up, and where "wormholes"
Led to alternate realities. And all of it
Was made of string! They slurped up
That hypothetical vermicelli,
And thinking of these things, their minds
Achieved an asymptotic freedom.

Composition of the Universe



95% not understood

Graphics courtesy: NASA