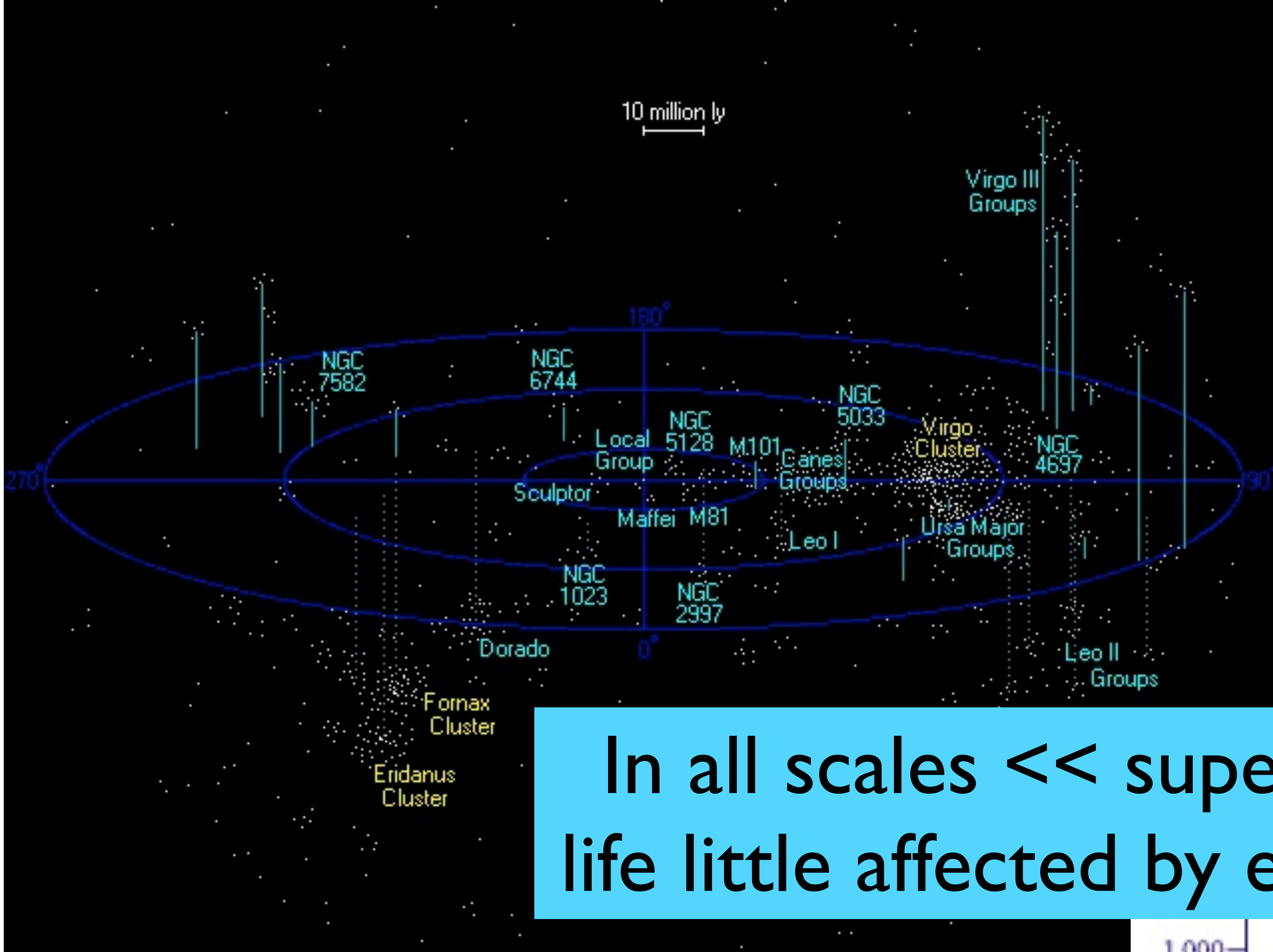
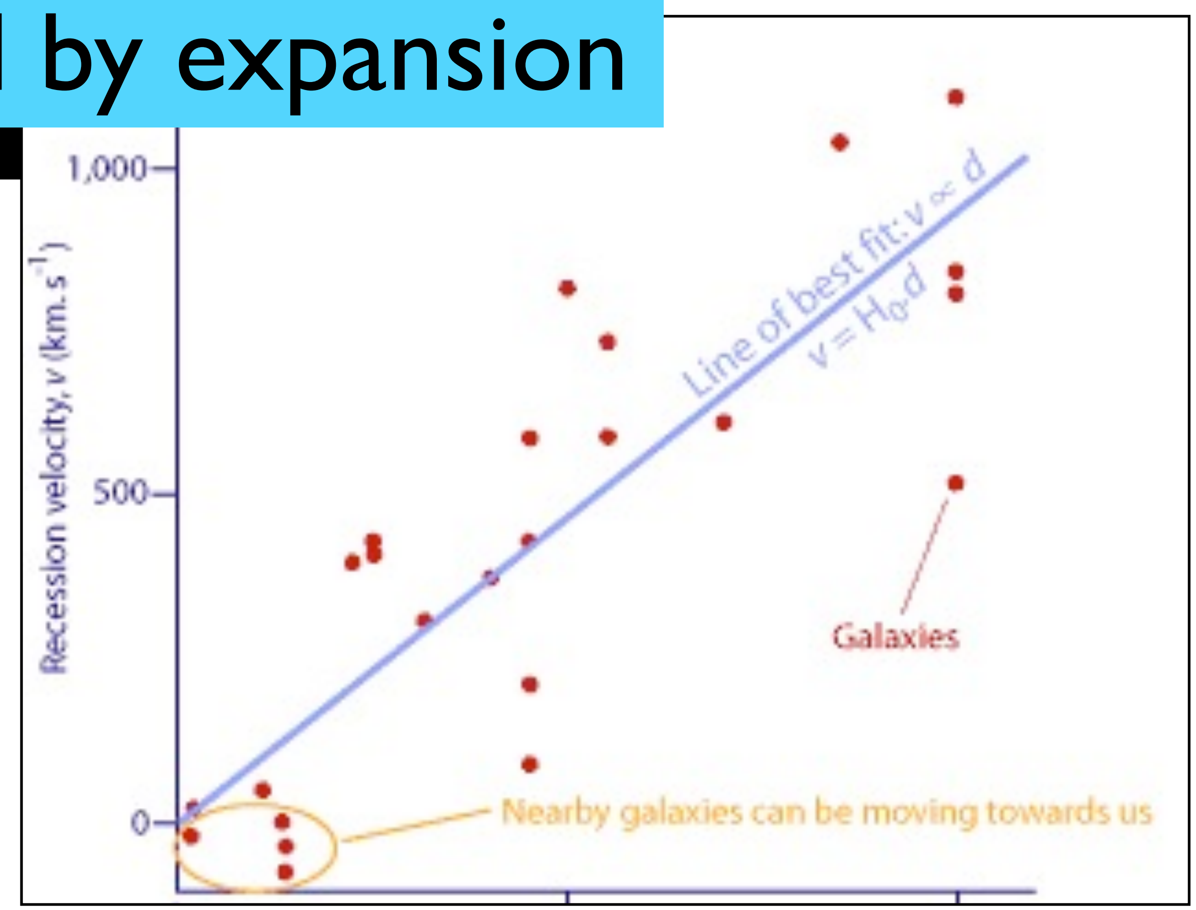


attractive force
within supercluster
counter-acted against
the cosmic
expansion, by ~ 20%

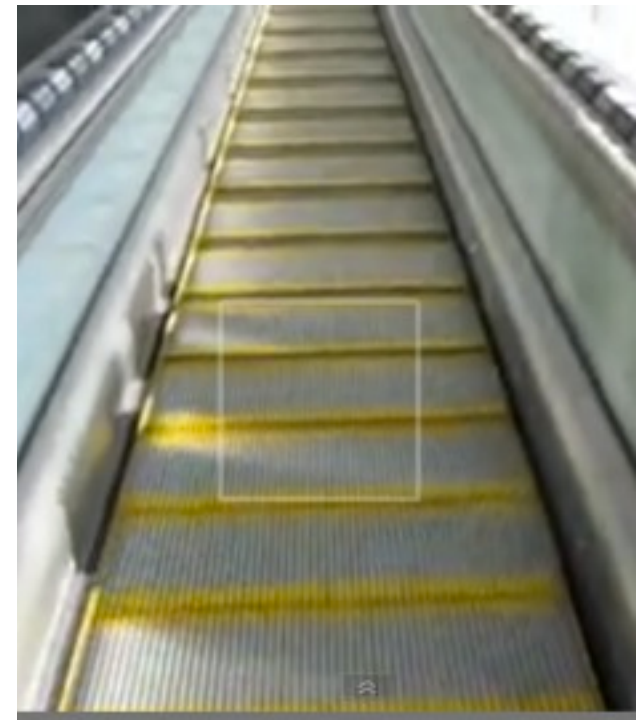
In all scales << supercluster,
life little affected by expansion

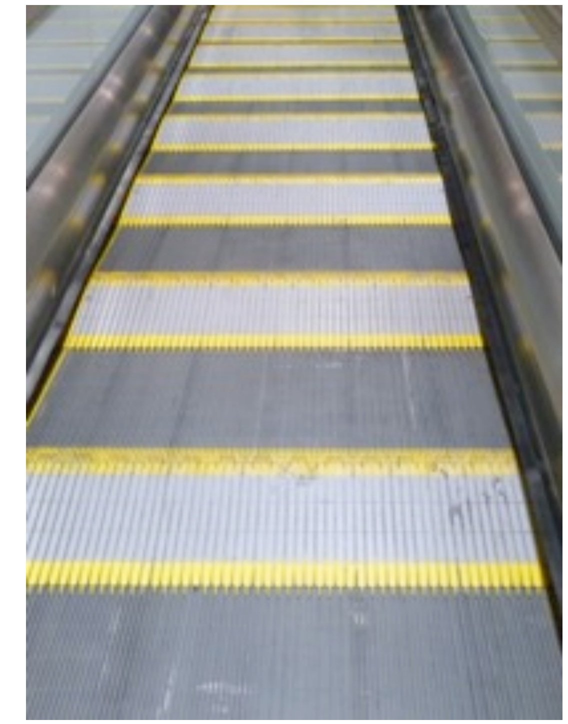


Virgo supercluster:
~ 100 million lyrs.
marginally bound

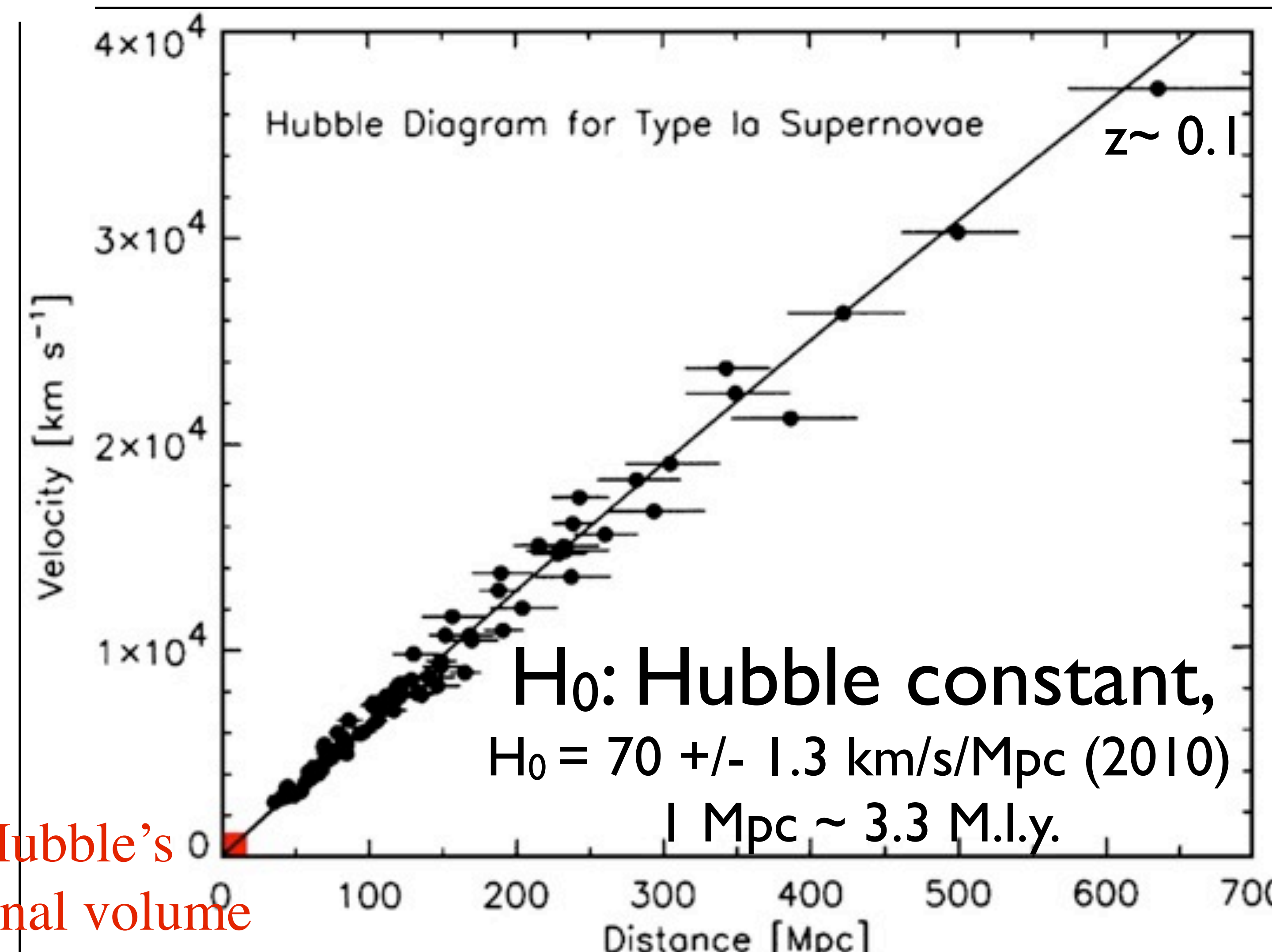
Hubble observed out to ~ 50 million lyrs (z < 0.003)

or





Thyssen Krupp Express Walkway, Toronto Airport



H$_0$: Hubble constant,

H_0 = 70 +/- 1.3 km/s/Mpc (2010)

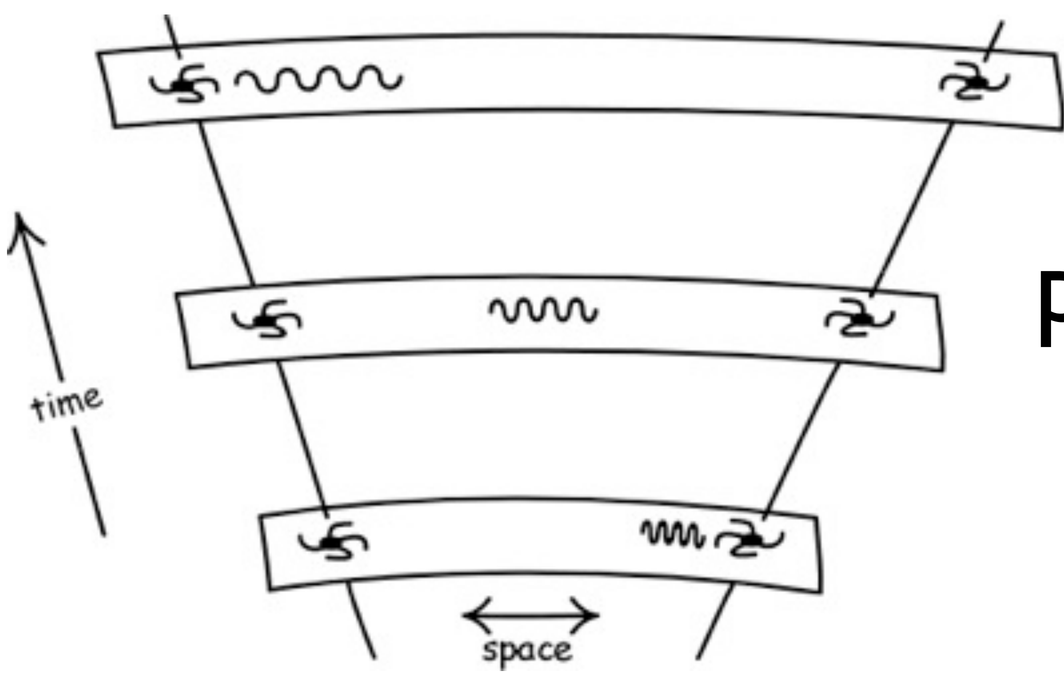
1 Mpc ~ 3.3 M.l.y.

Hubble's original volume

Cosmological Redshift:

light redshifted by **expansion**, **not** Doppler Effect

photon emitted with λ_0
when universe size a_0



photon stretched as it propagates toward us with speed of light

at reception, $\lambda(t)$
universe size $a(t)$

a=a(t) is also called the scale factor of the universe.

$$\boxed{1 + z = \lambda(t)/\lambda_0 = a(t)/a_0}$$

(where z is redshift)

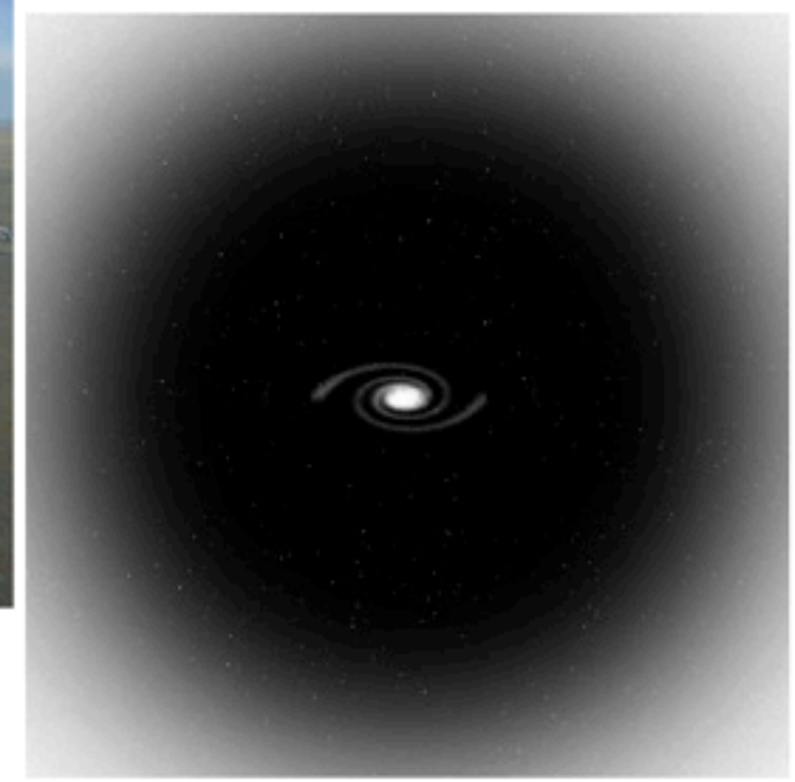
redshift tells about the size of the universe when the light was emitted. Or, the age of the universe.

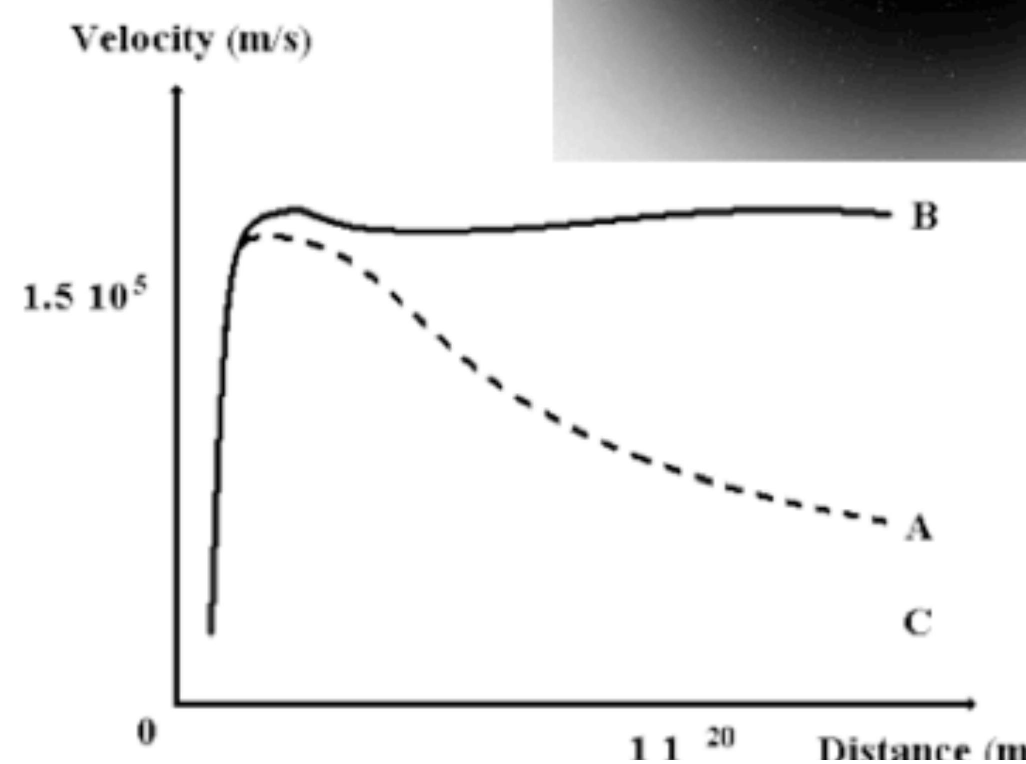
for $z=1$, $a(t) = 2\, a_0$

what holds galaxies, clusters of galaxies, superclusters together: gravity from...

Dark Matter

Readings: HH §15, Shu §12.1, §12.2, Allday §14

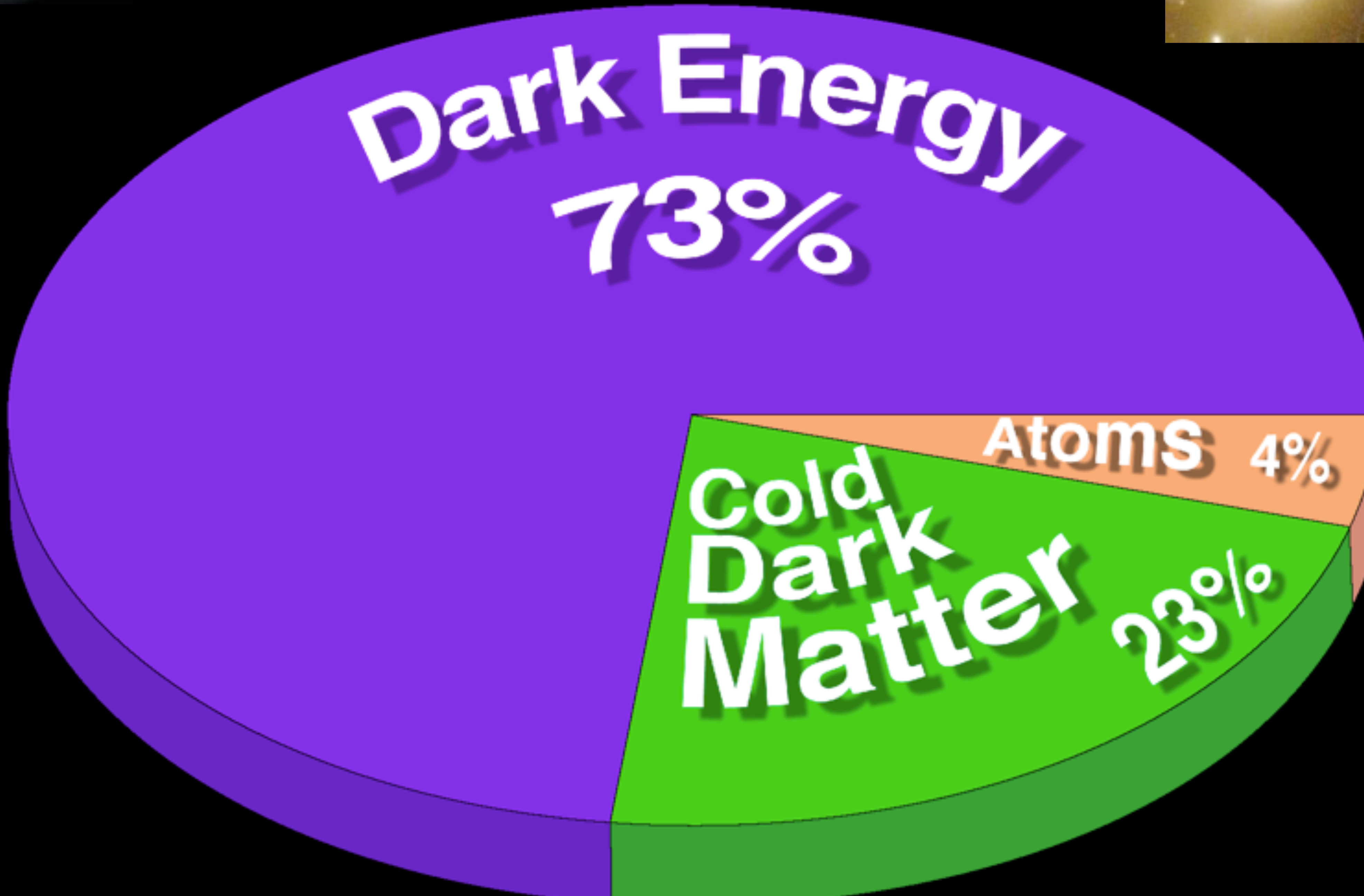


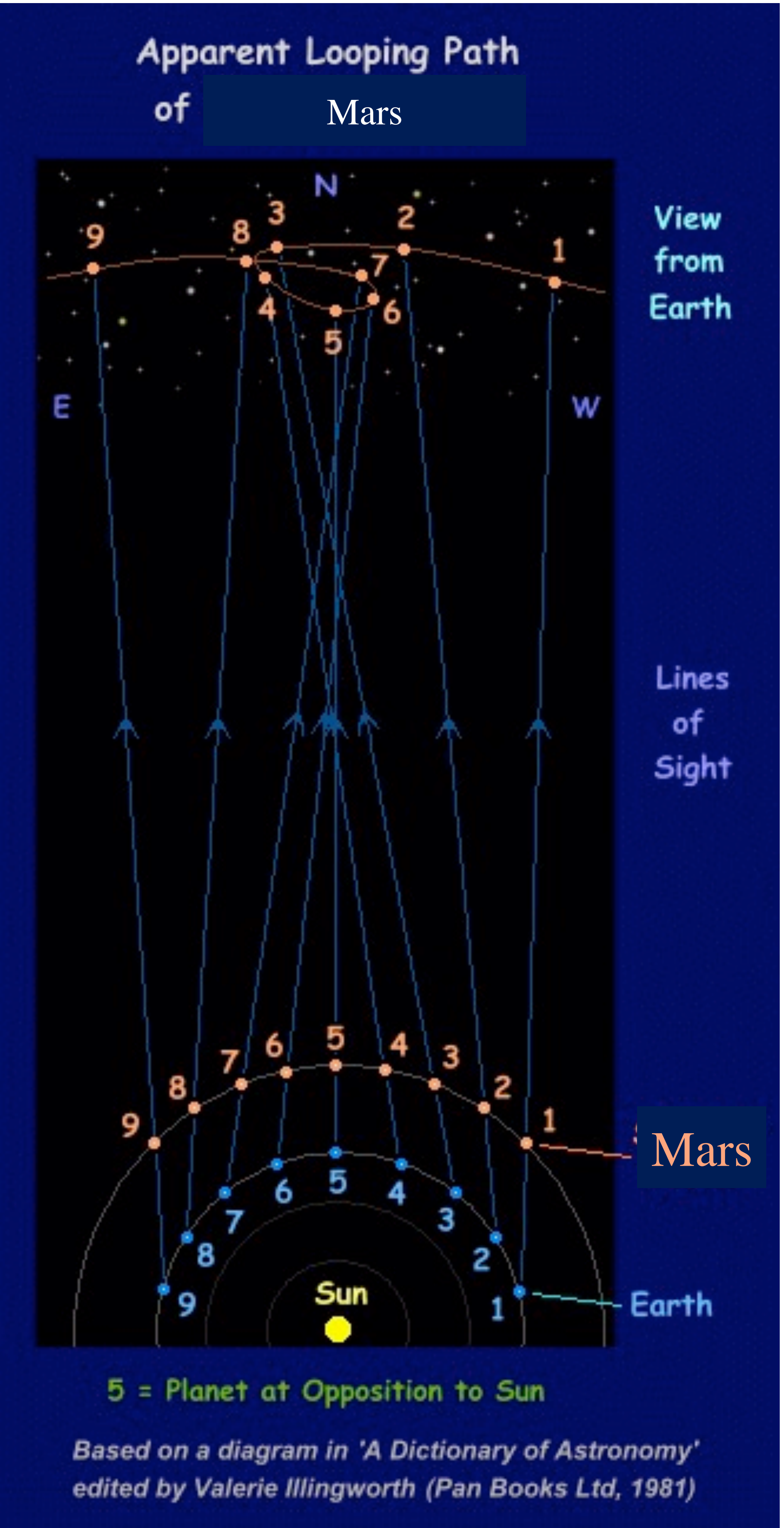


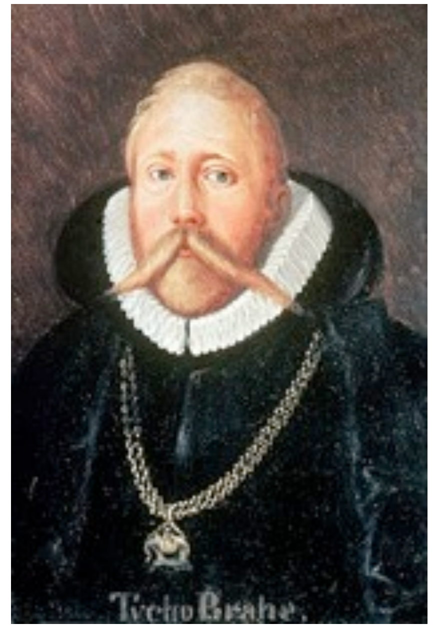
galaxy

galaxy cluster

gravitational lensing







Tycho Brahe
1546-1601

Johannes Kepler
1571-1630

From the vast amount of planetary positions collected by his predecessor, Tycho Brahe, Johannes Kepler was able to infer the three famous laws of planetary movements.

first law: the orbit of every planet is an ellipse with the Sun at one of the two foci.

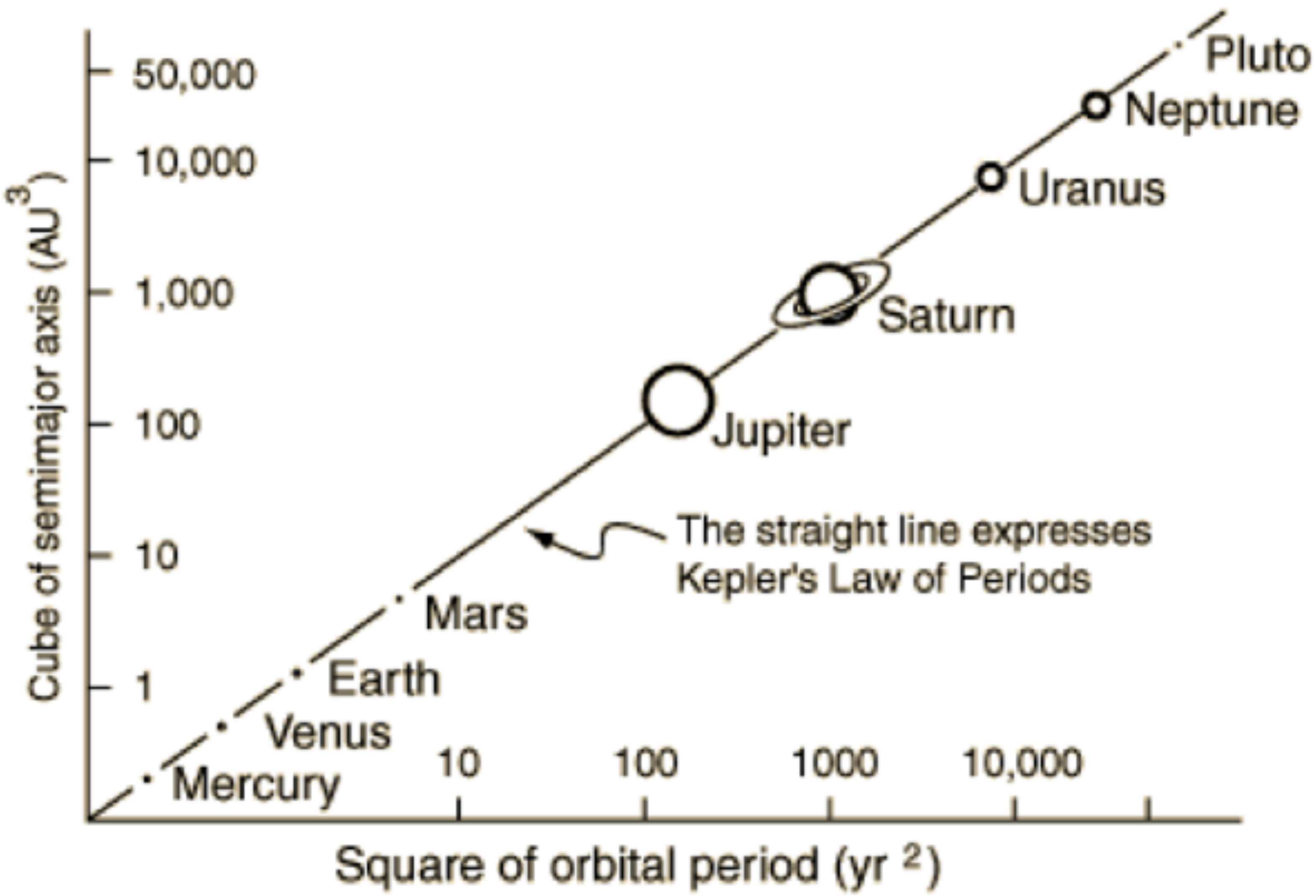
second law: a line joining a planet and the Sun sweeps out equal areas during equal intervals of time.

third law: the square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.

Third Law: the law of Periods

The square of the period of any planet is proportional to the cube of the semimajor axis of its orbit

Even if the Sun was completely invisible, we would still be able to infer its existence
and calculate its mass.



gravitational attraction between M and m: $F = \frac{GMm}{a^2}$

motion of the planet (m) prevents it from falling in to the Sun (M), a fictional 'centrifugal force': $F = \frac{mv^2}{a}$

balancing the two, we find, $\frac{GM}{a} = v^2$, where m drops out

now, for a planet moving in circular motion, we can relates its velocity to its orbital period, $v = \frac{2\pi a}{P}$,

and we end up with the Kepler's III law

$$\boxed{P^2 = \frac{4\pi^2}{GM} a^3} \tag{1}$$

for planets moving around our Sun, this specializes to $\left(\frac{P}{1\text{yr}}\right)^2 = \left(\frac{a}{1\text{AU}}\right)^3$

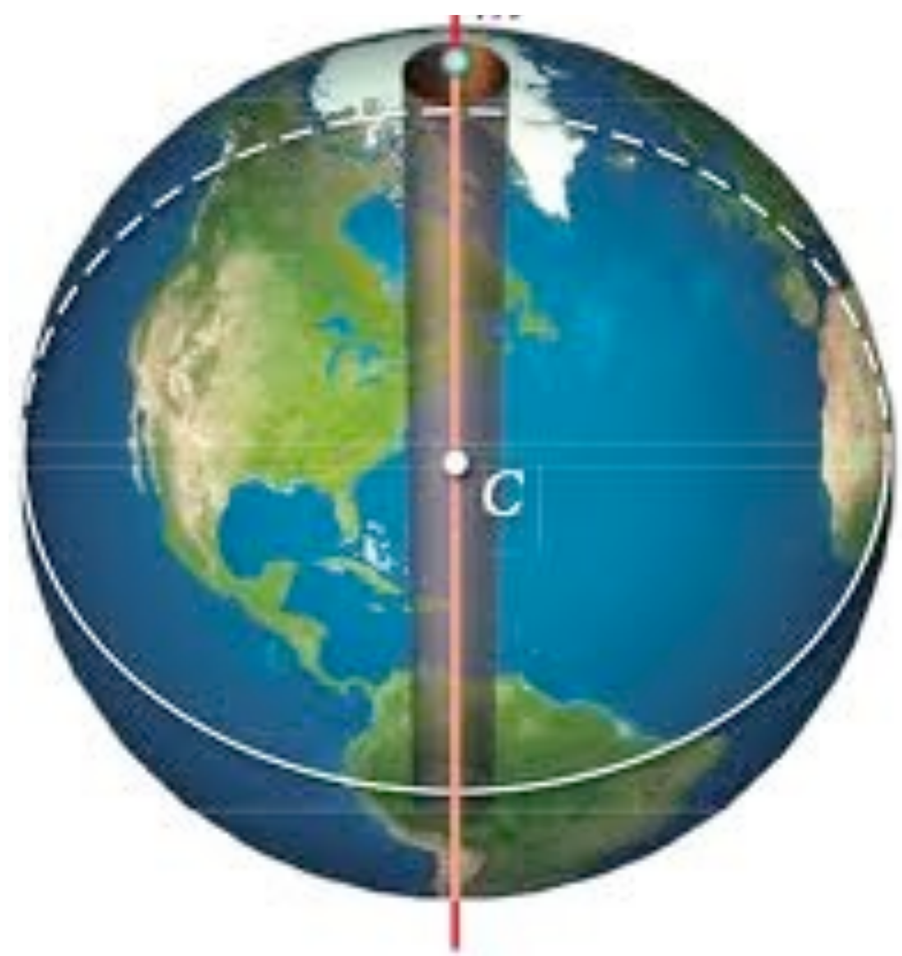
So what about galaxies?

Mass of the galaxy is extended.
How do we use Kepler's law? Two theorems by Newton.

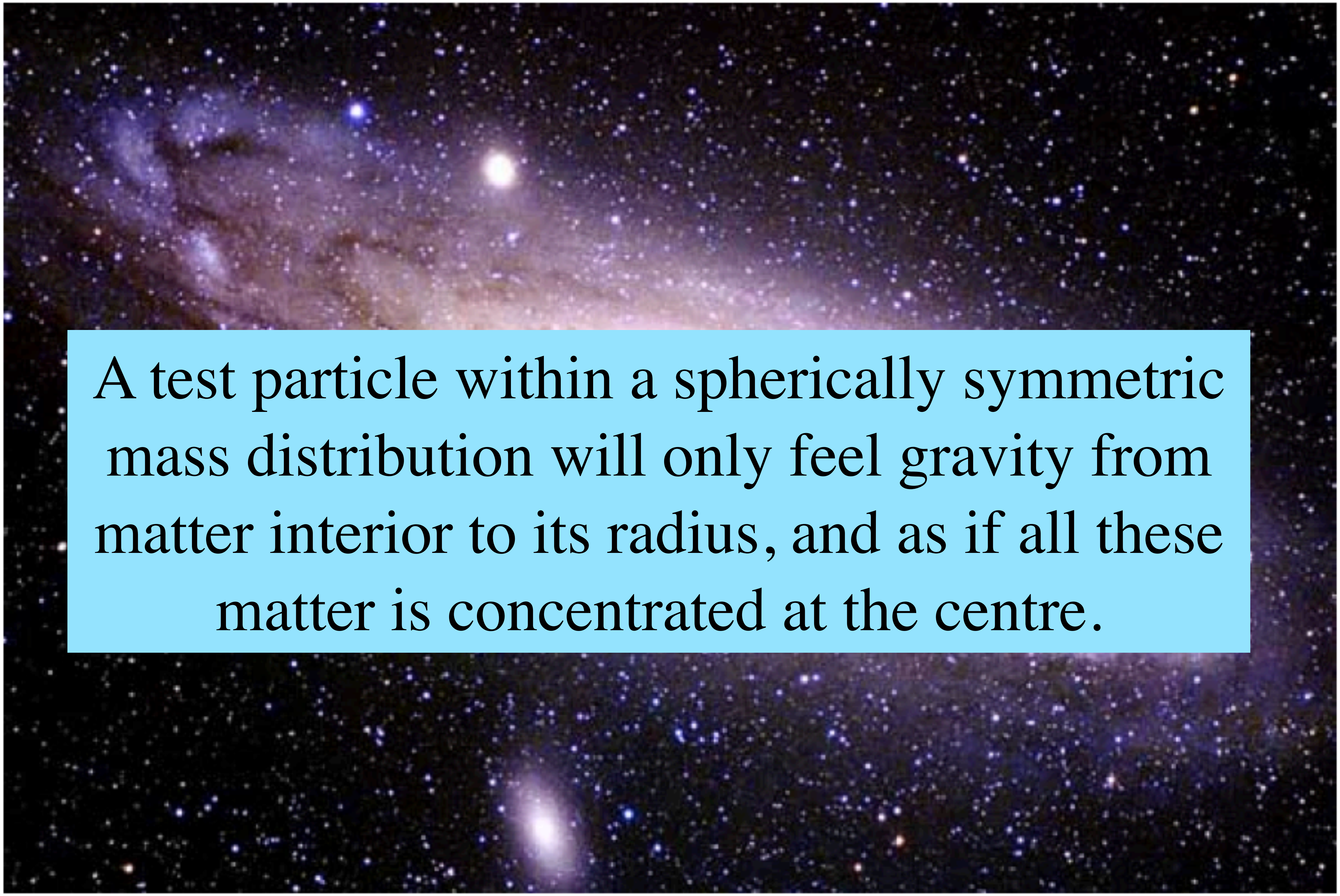
A spherically symmetric body affects external objects gravitationally as though all of its mass were concentrated at a point at its centre.

If the body is a spherically symmetric shell (i.e. a hollow ball), no net gravitational force is exerted by the shell on any object inside, regardless of the object's location within the shell.

$F = GMm/r$

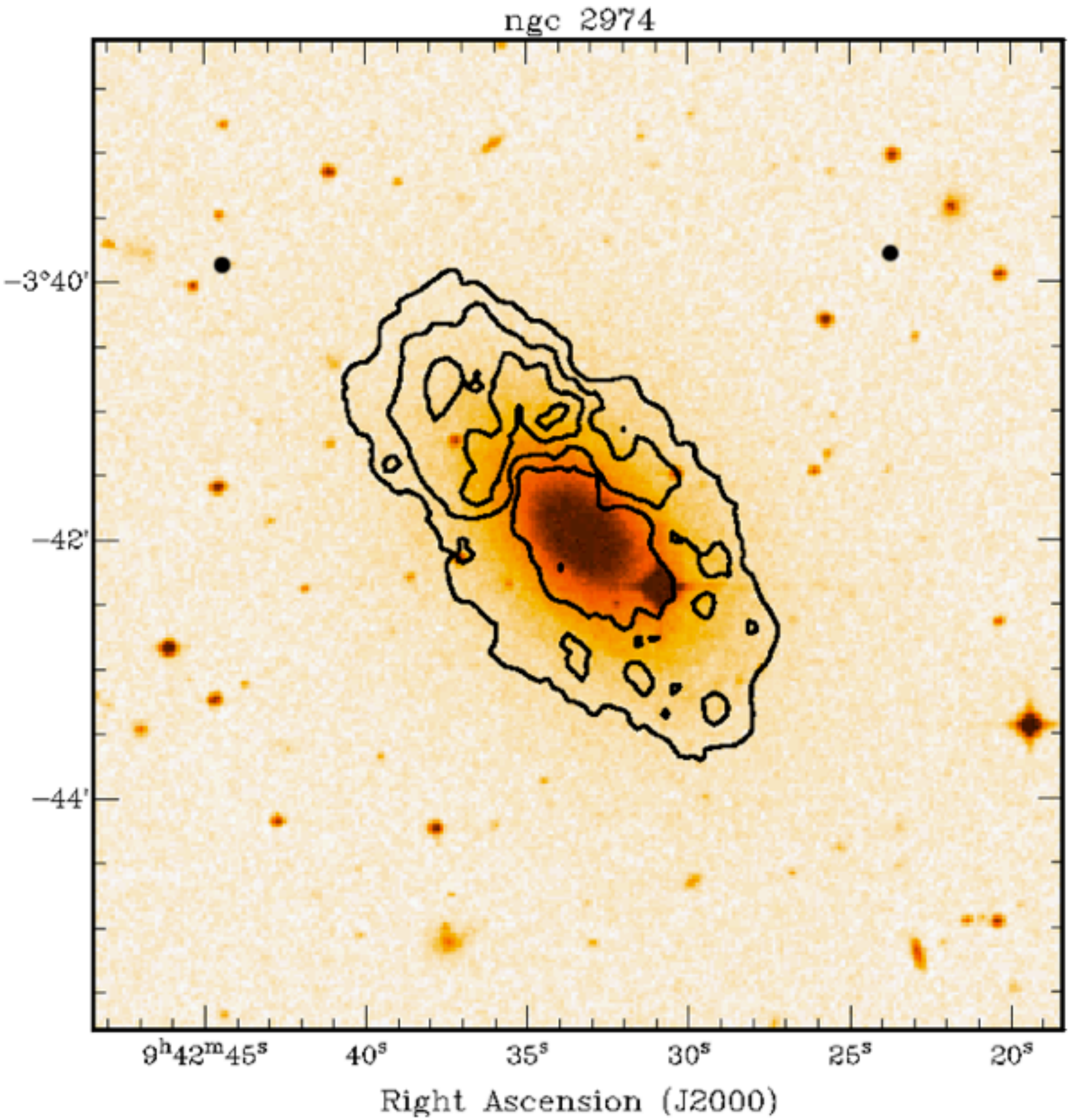


So what about galaxies?



A test particle within a spherically symmetric mass distribution will only feel gravity from matter interior to its radius, and as if all these matter is concentrated at the centre.

Problem set: NGC 2974



An elliptical
galaxy
with a gas ring!

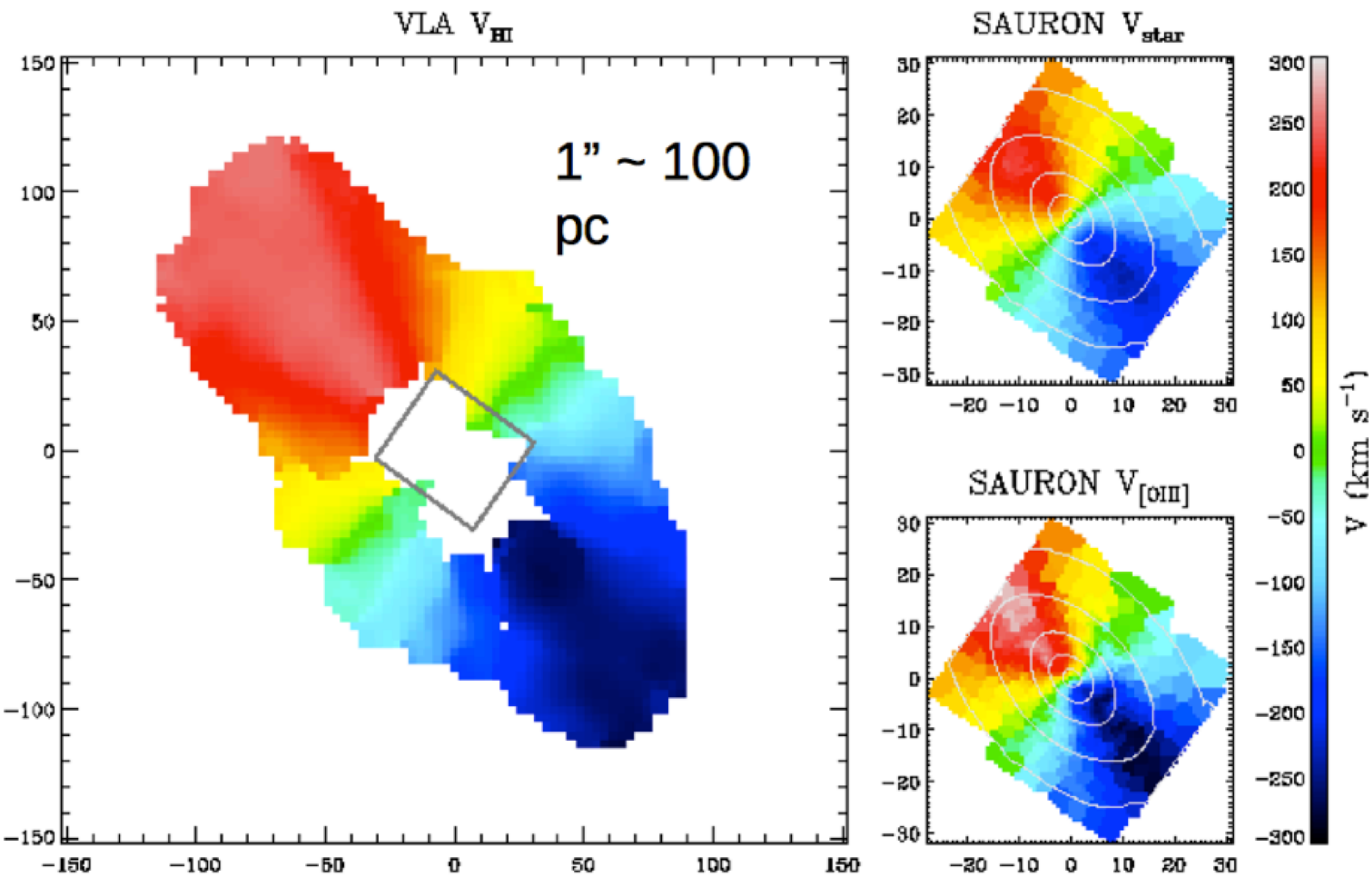
Weijmans et al.
2008

Very Large Array

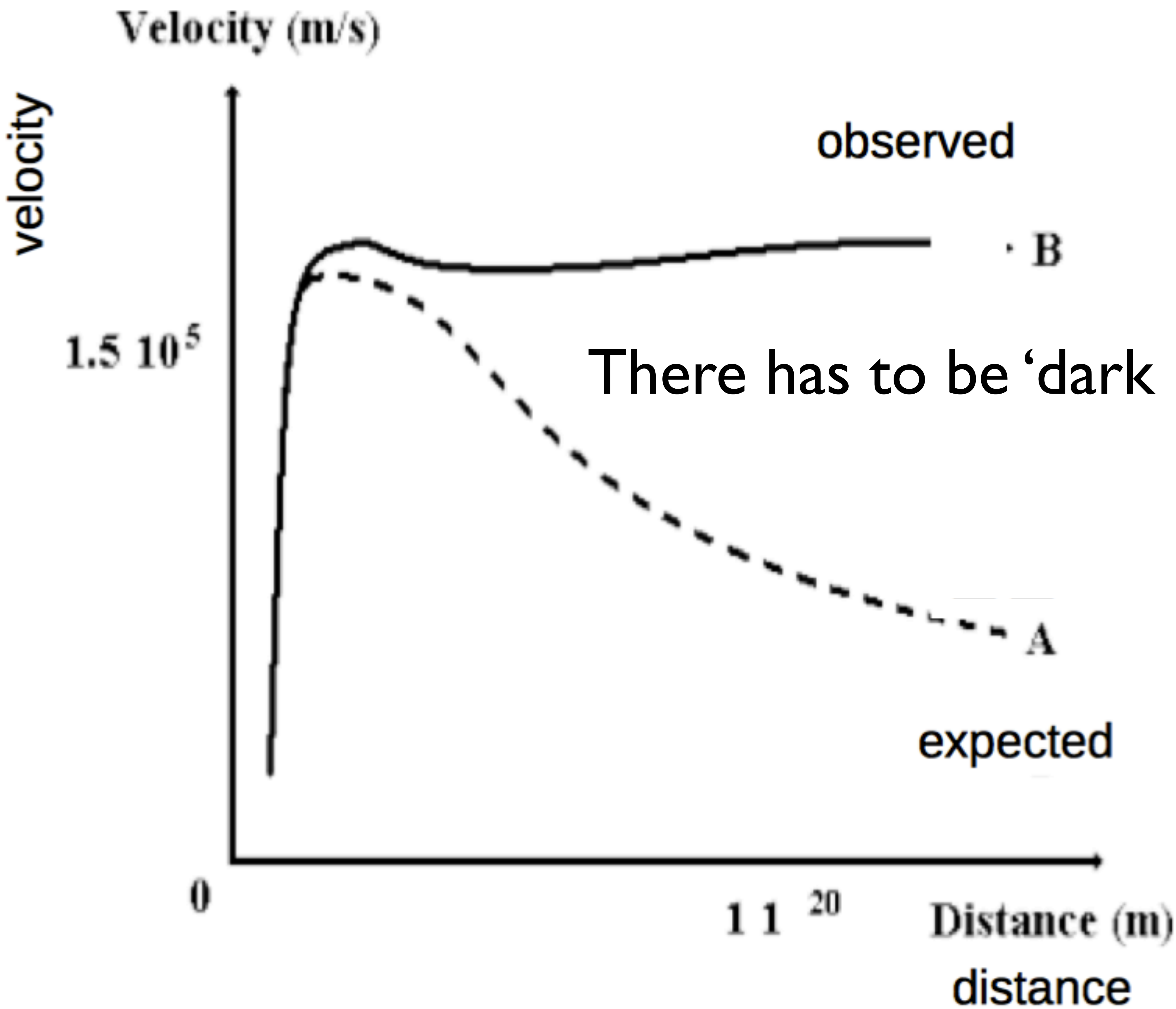
(New Mexico, radio, HI 21cm line, 27 x 25m dishes, along 23 km track, acting as a single lens)

Doppler shift seen in the gas ring

Velocity maps



Rotation curves of galaxies



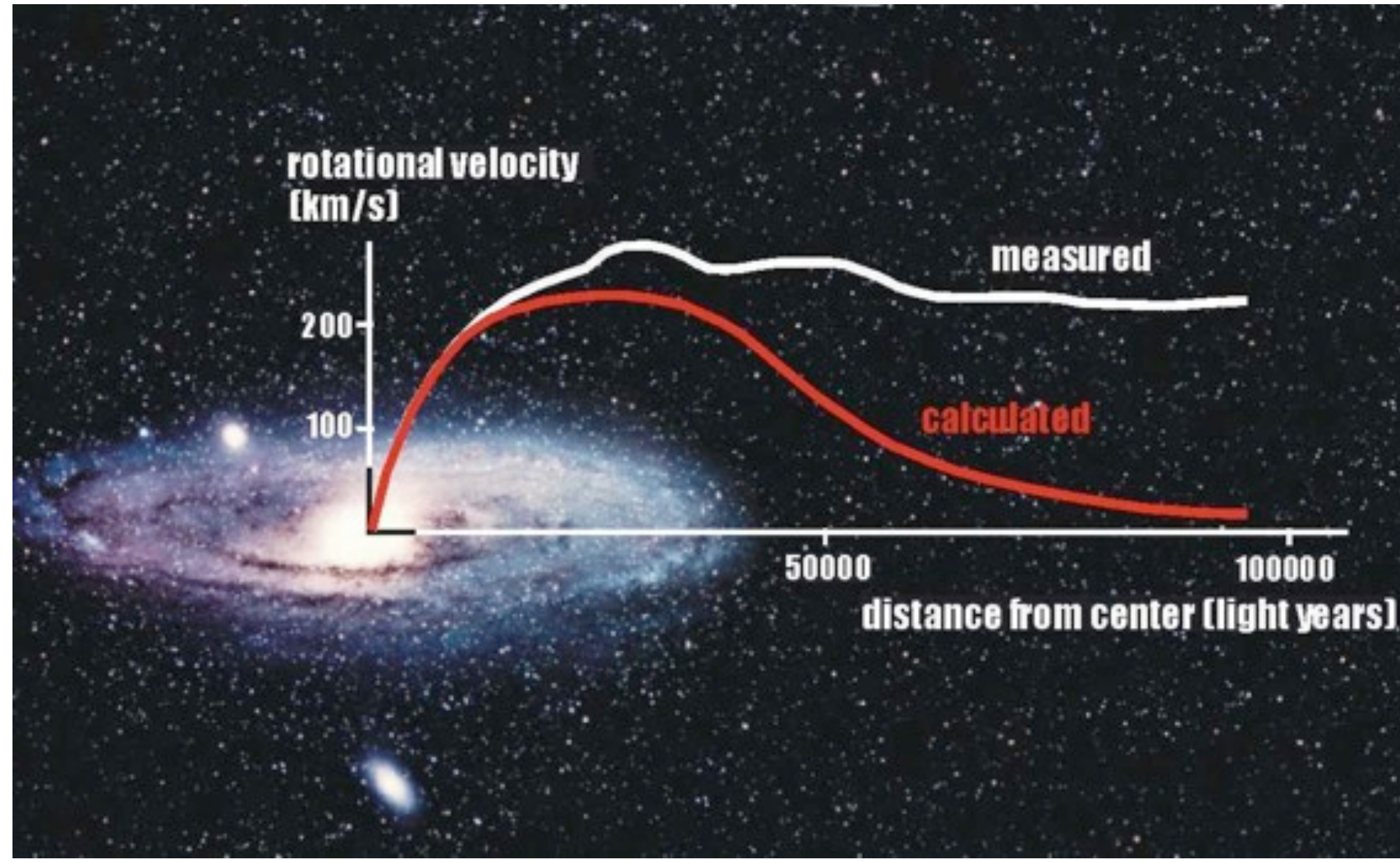
There has to be 'dark matter'!

Assume gas on circular orbit,
assume galaxy is spherical,
the measured v(r) yields enclosed mass within r: M(<r)

$$v^2 = \frac{GM(<r)}{r}$$

if $v(r) = v_0$,

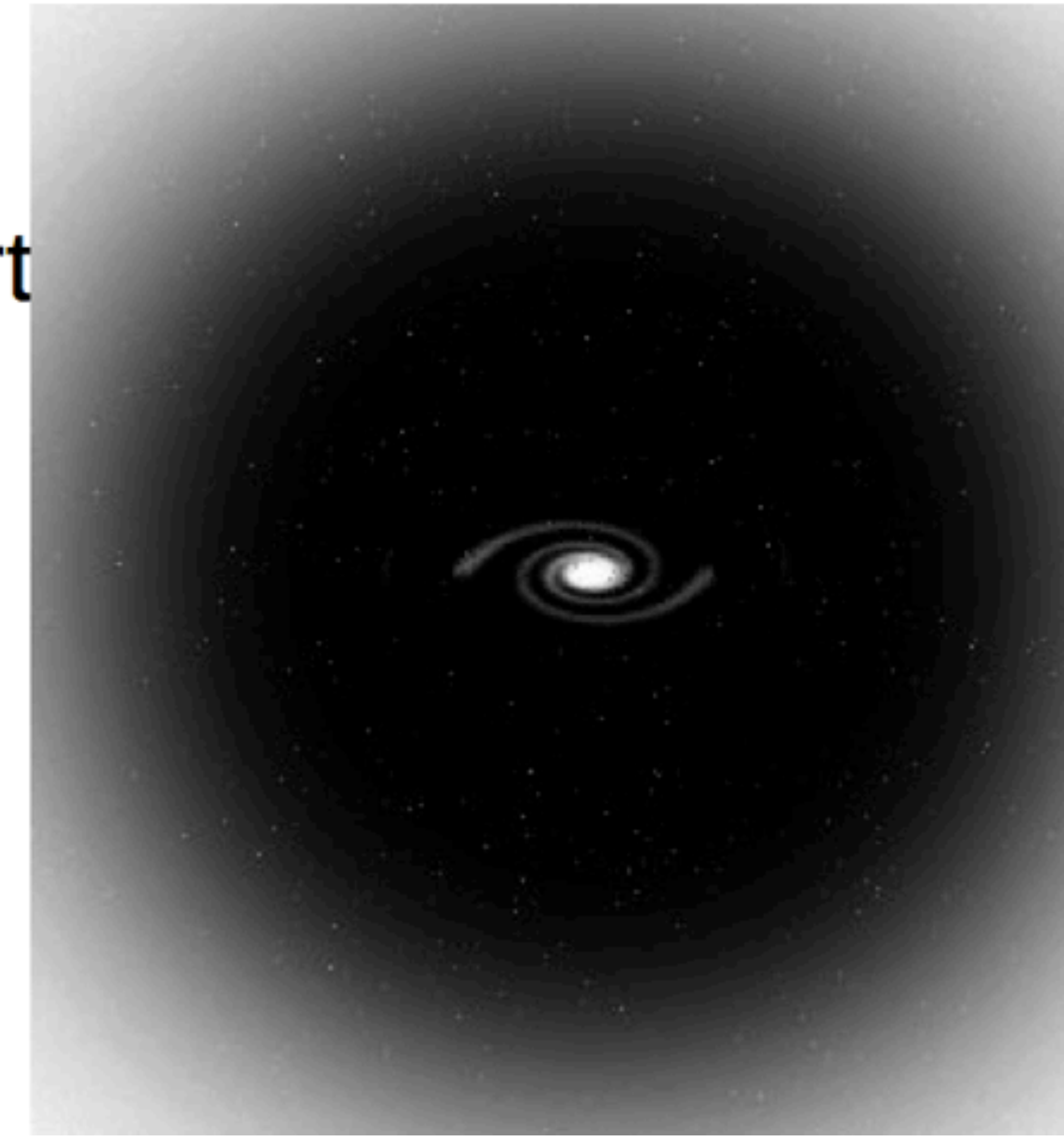
$$\rightarrow M(<r) = \frac{v_0^2}{G} \times r$$



if counting mass in stars and gas
$M(<r) =$ constant beyond about 50,000 light-years

Dark matter haloes

- Galaxy rotation curves are flat!
- Galaxies are embedded in a *halo* of dark matter
  - halo is much larger than the visible (luminous) part



The Milky Way is a typical ‘spiral’ galaxy

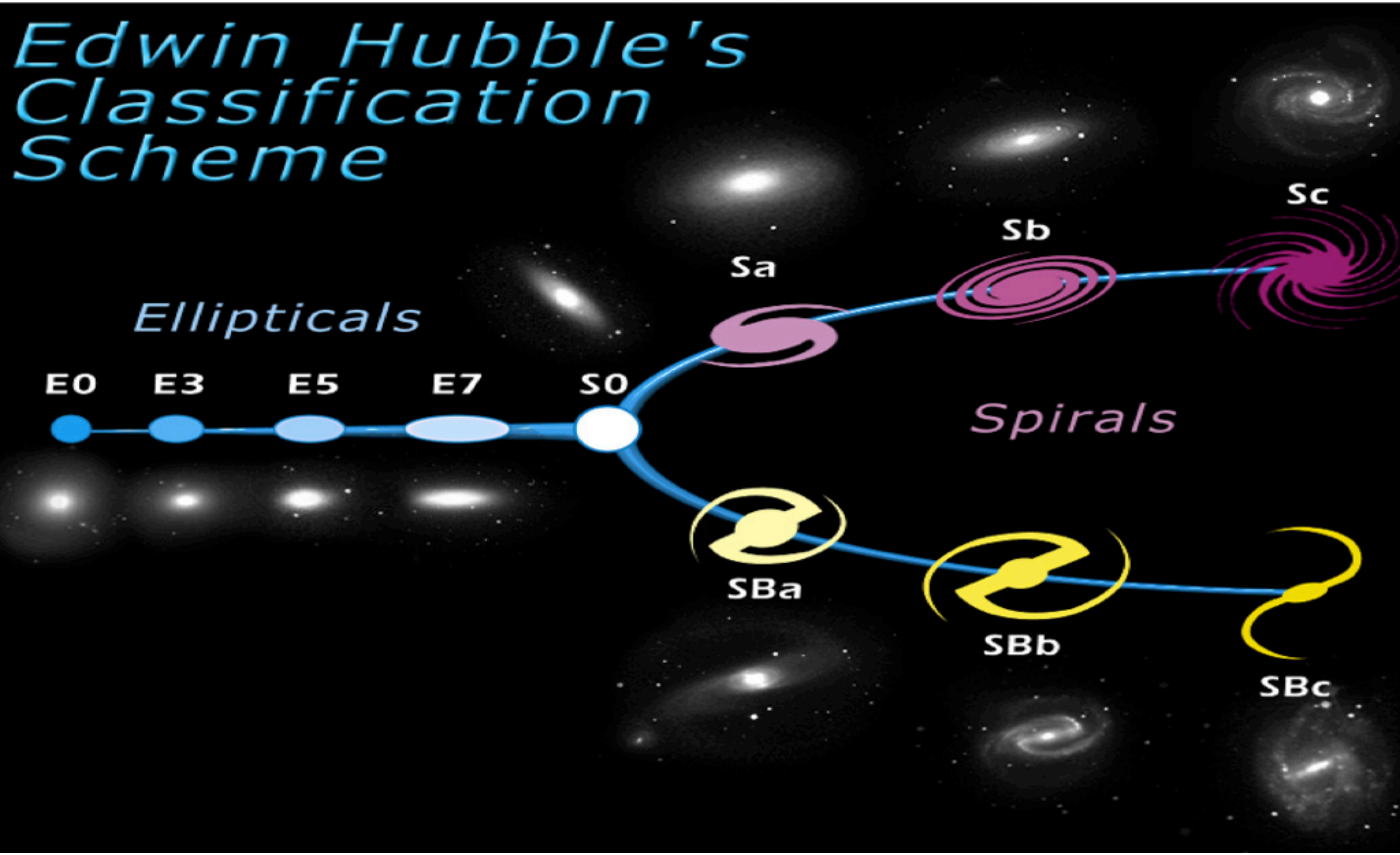
the Andromeda Galaxy

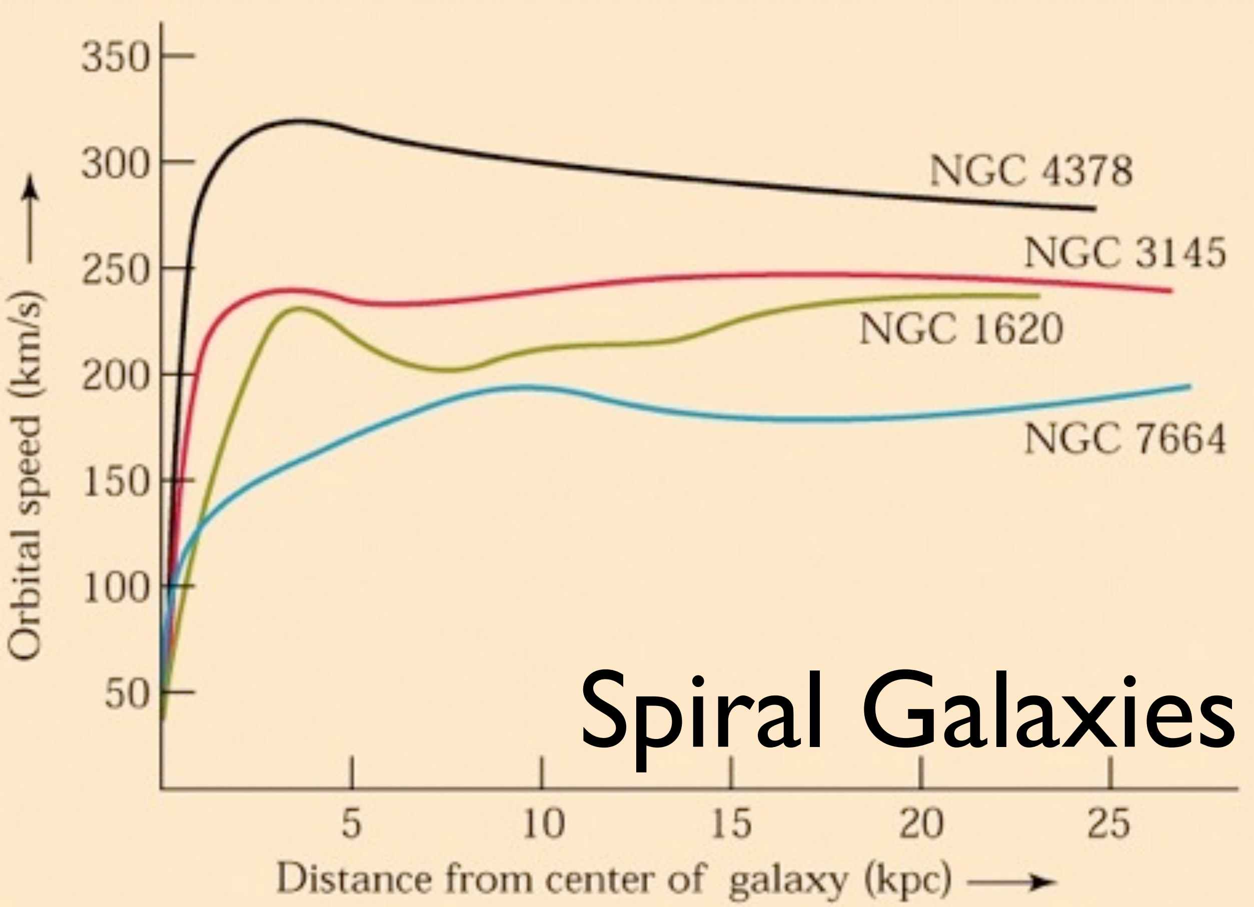
contain ~ 10^{11} stars,
stellar mass ~ 10^{11} M_{sun}
inferred total mass ~ 10^{12} M_{sun}

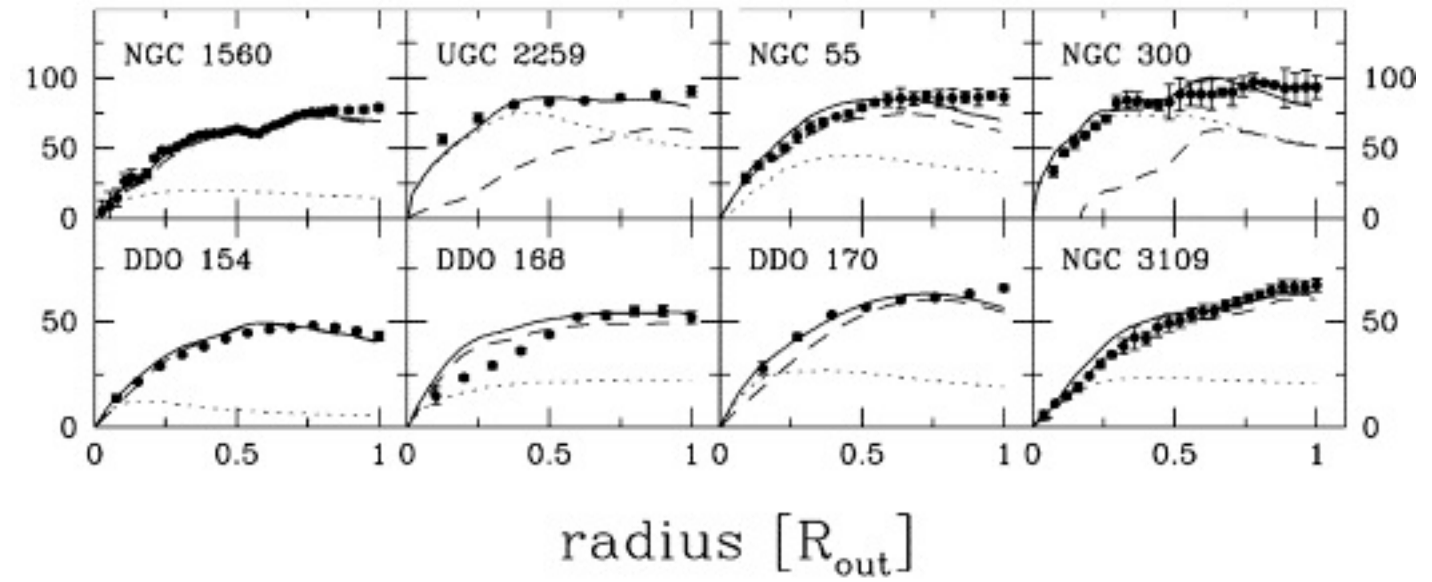
Milky Way Galaxy Mass Only Half As Large As Previously Thought, Astronomers Say

Science NOW | Posted: 01/11/2013 1:06 pm EST

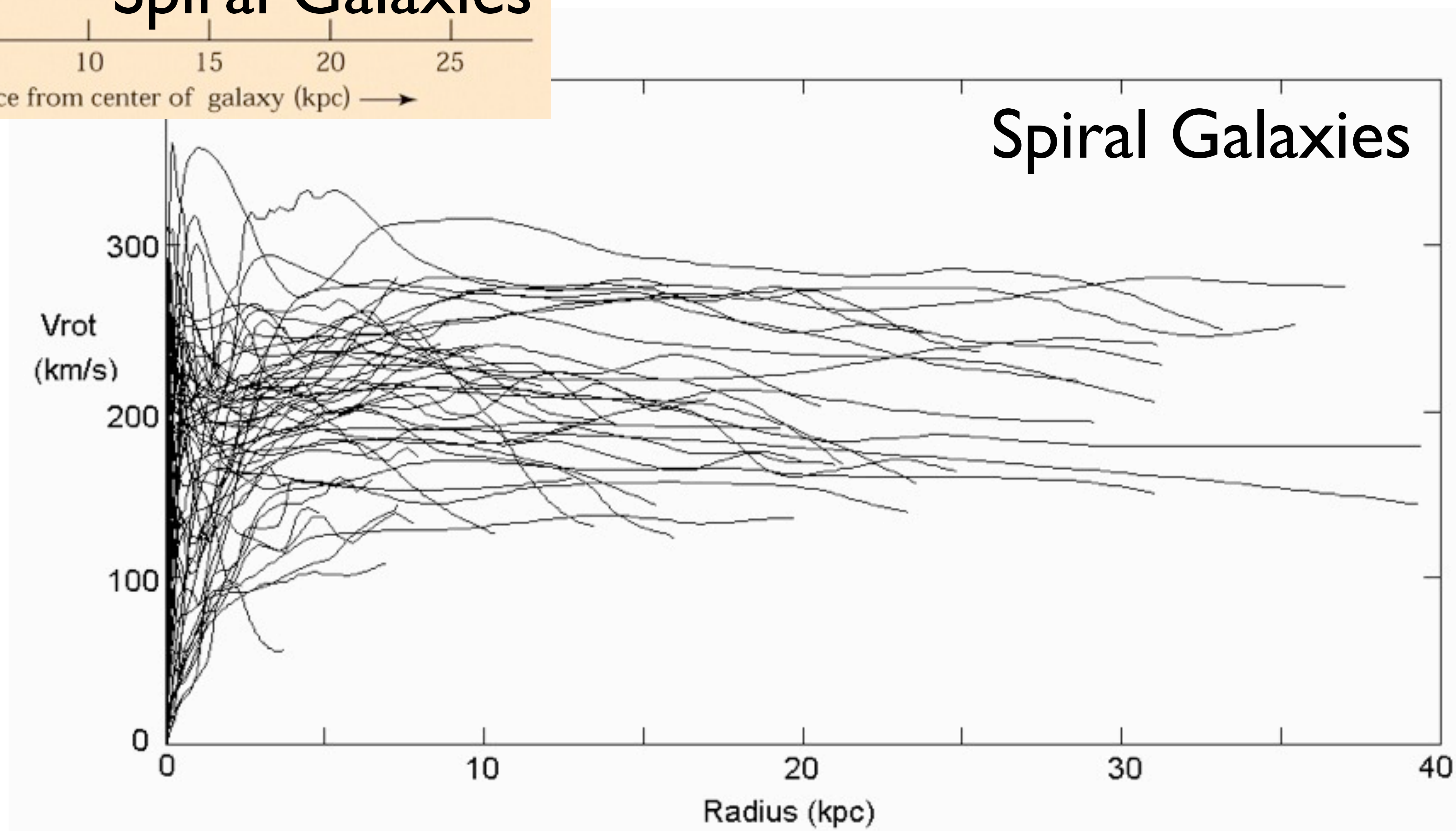
Do all galaxies have dark matter?







Dwarf Galaxies



Dark matter: only in galaxies?

- Galaxy clusters
  - discovery of dark matter (1930)
  - gravitational lensing
  - example: Bullet cluster
- The cosmic web: large scale structure
- Dark matter: what do we think it really is?

Guest Lecture: Dr. Anne-Marie Weijmans

See next lecture!