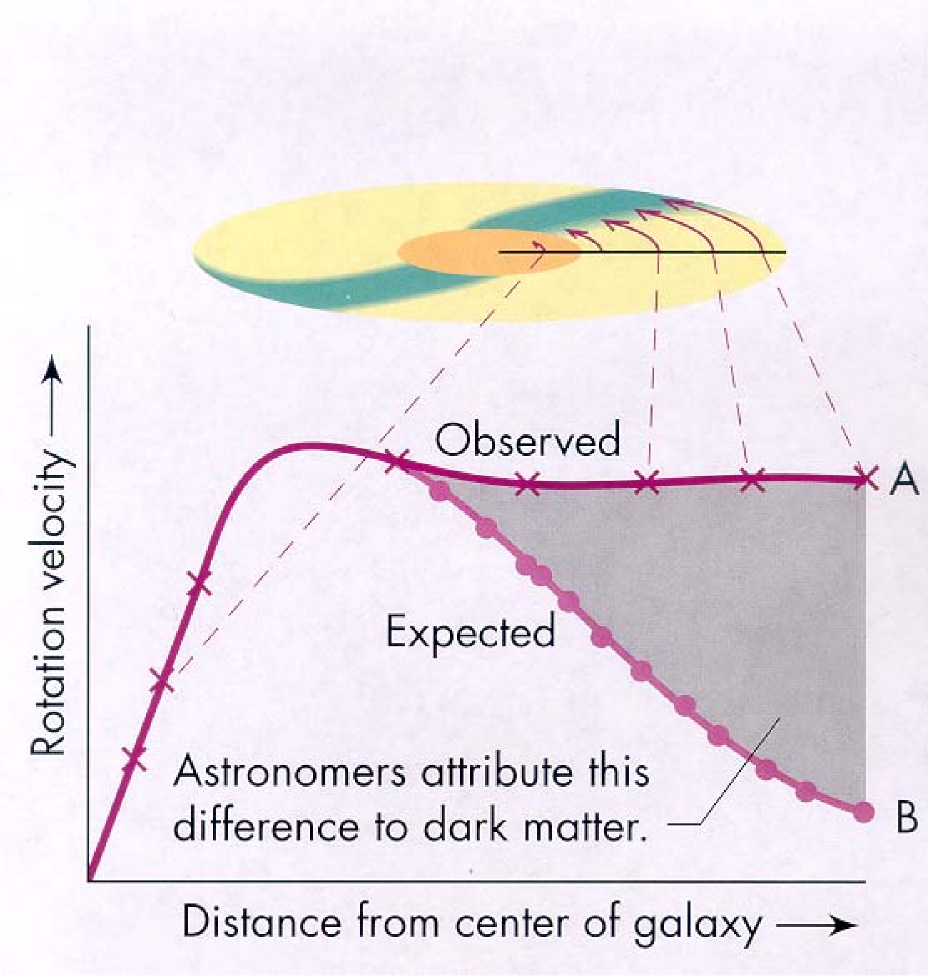
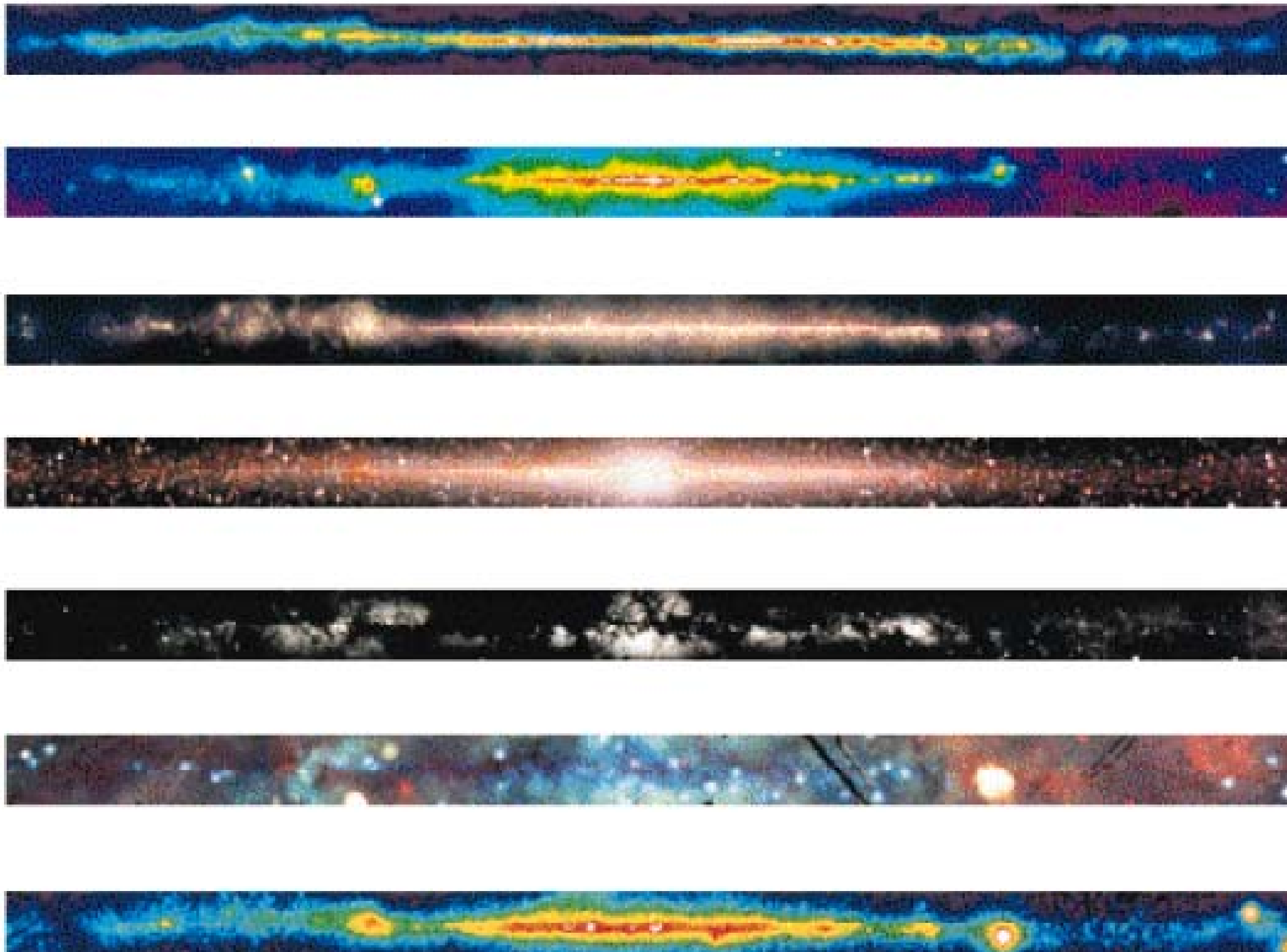
Lecture 6 Galaxy rotations

A schematic galaxy rotation curve (Fig. 15-17)



The matter in our Galaxy emits different kinds of radiation, depending on what stage of the star–gas–star cycle it is in.



(a) 21-cm radio emission from atomic hydrogen gas.

(b) Radio emission from carbon monoxide reveals molecular clouds.

(c) Infrared (60–100 μm) emission from interstellar dust.

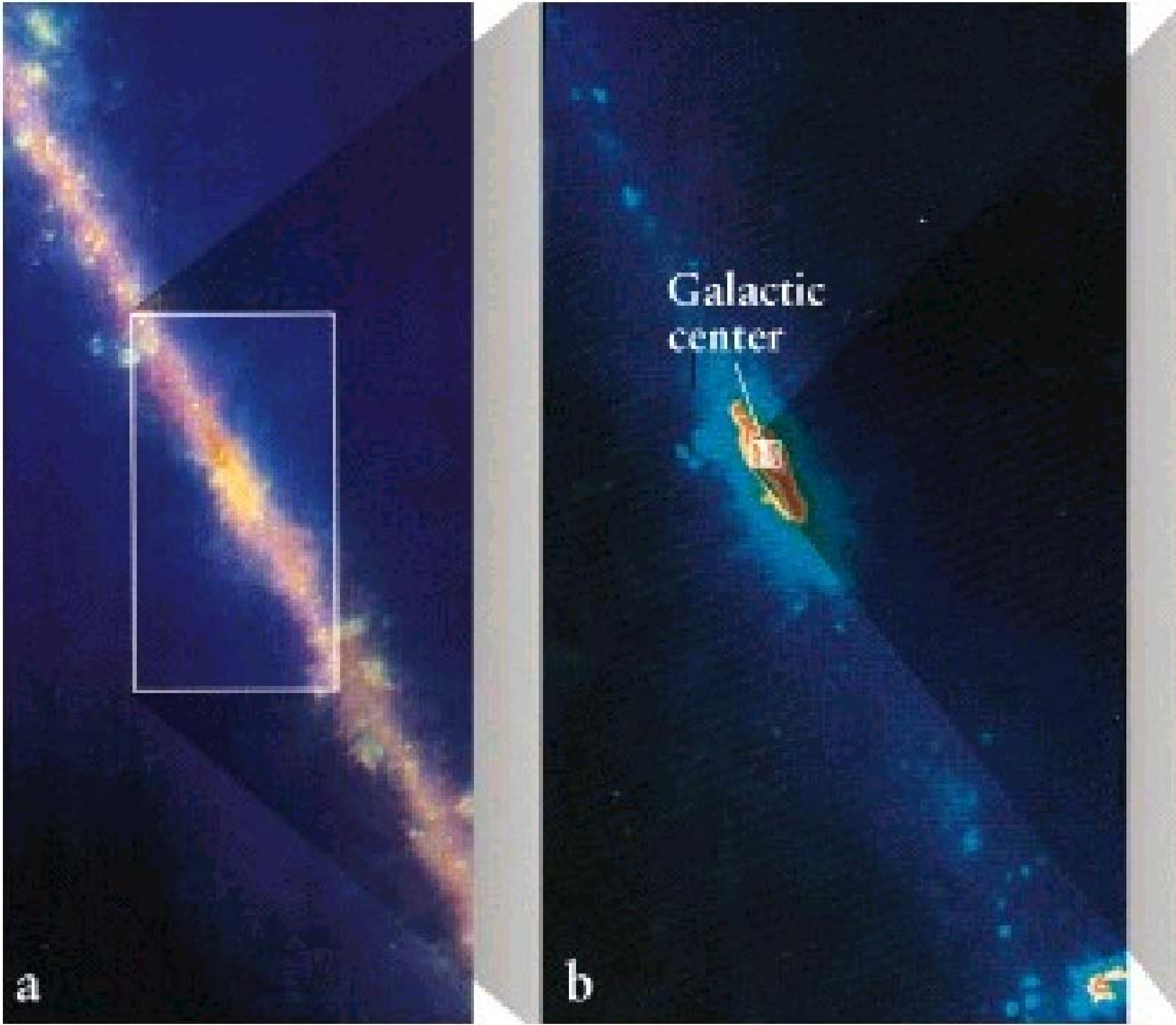
(d) Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

(e) Visible light emitted by stars is scattered and absorbed by dust.

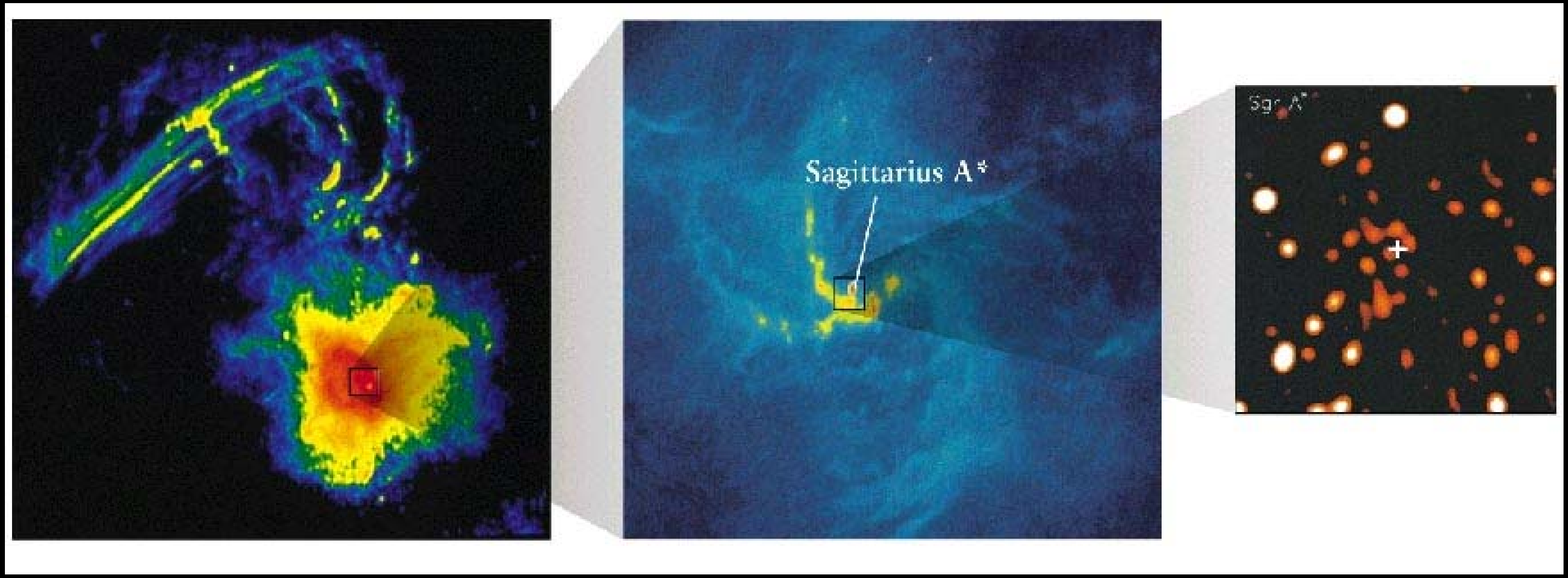
(f) X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

(g) Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

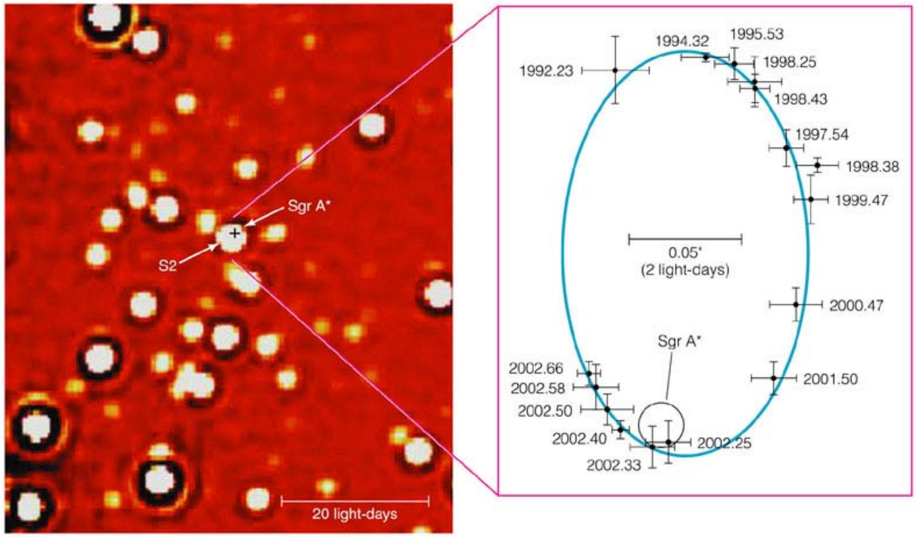
Infrared and radio observation are used to probe the galactic nucleus.



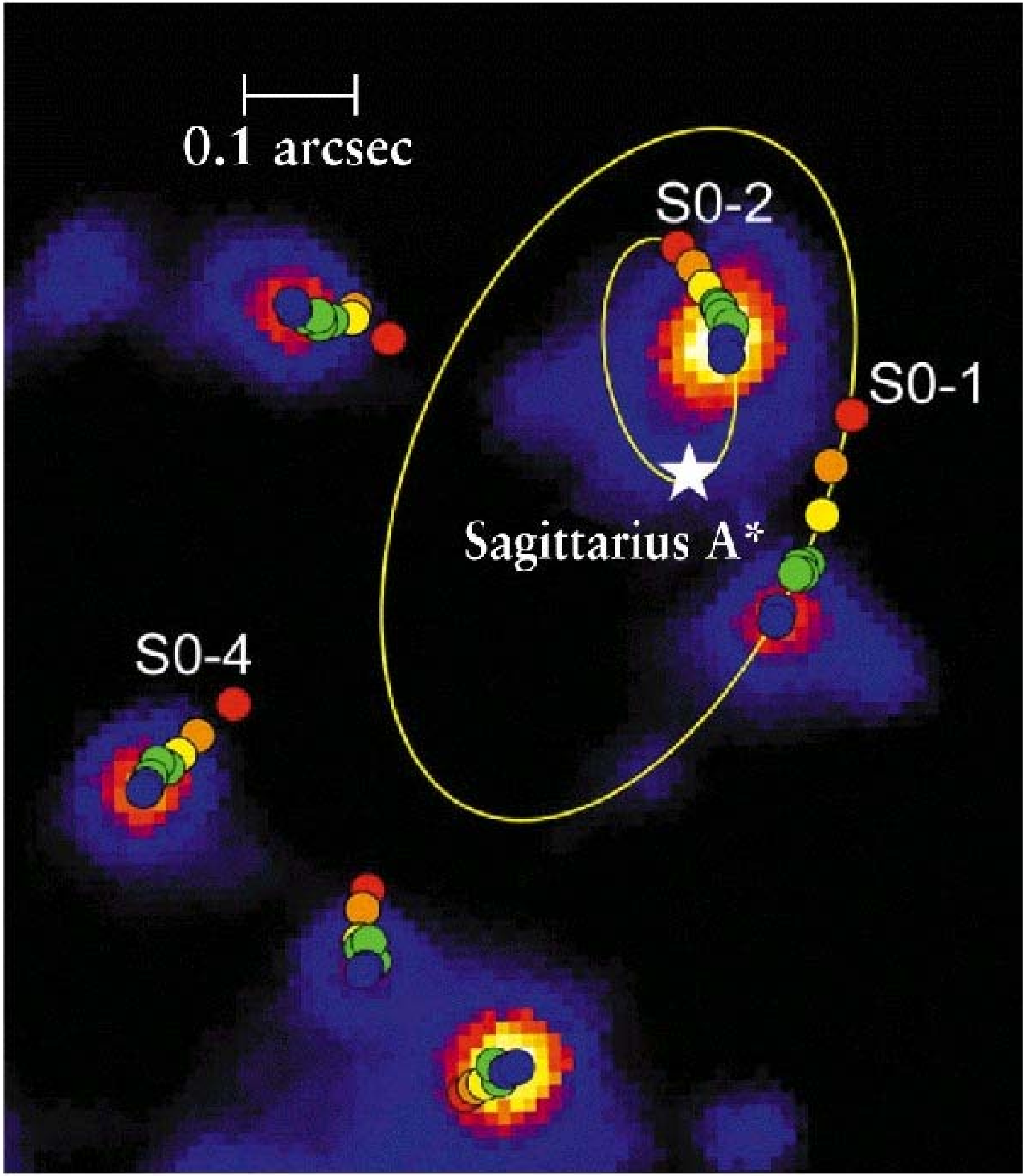
Infrared and radio observations are used to probe the galactic nucleus.



Center of the Galaxy

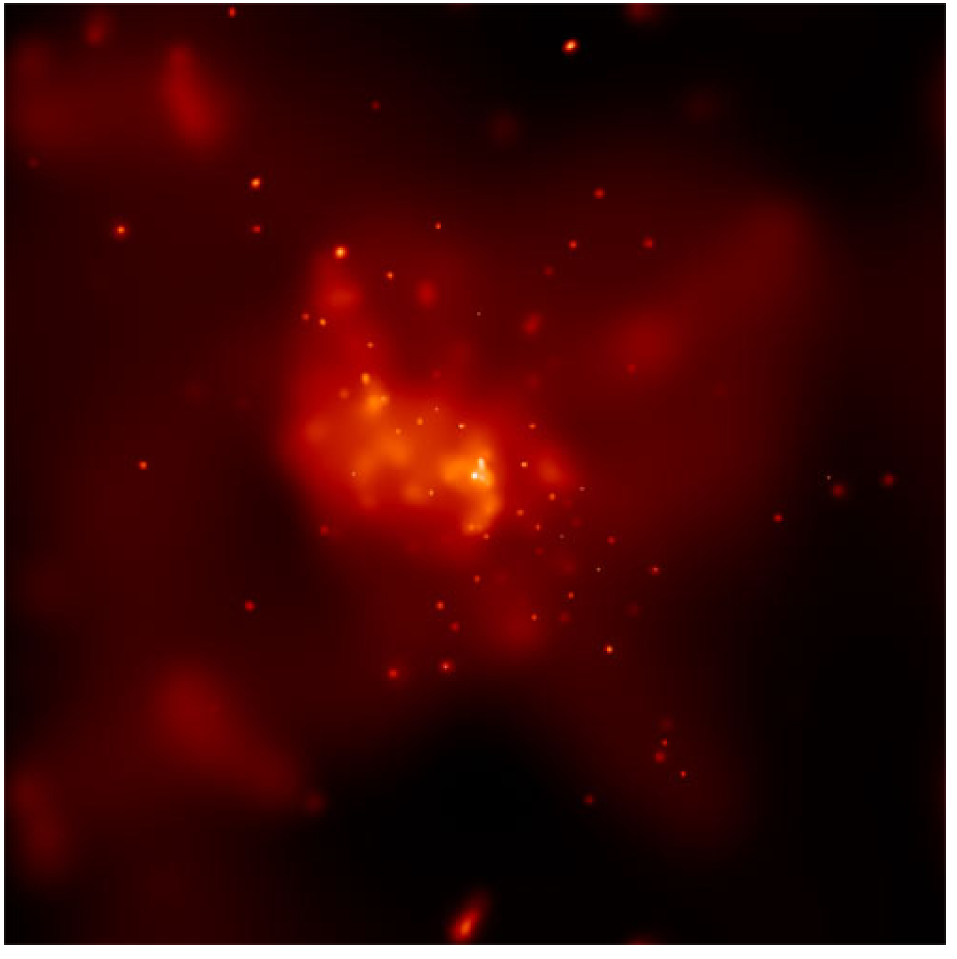


- Measure the orbits of fast-moving stars near the Galactic center.
  - using Kepler's Law, we infer a mass of 2.6 million $M_{\odot}$ for Sgr A*
- What can be so small, yet be so massive?



The colored dots superimposed on this infrared image show the rapid motions of stars around the galactic center. These can only be accounted for by *Sgr A** being an invisible supermassive black hole.

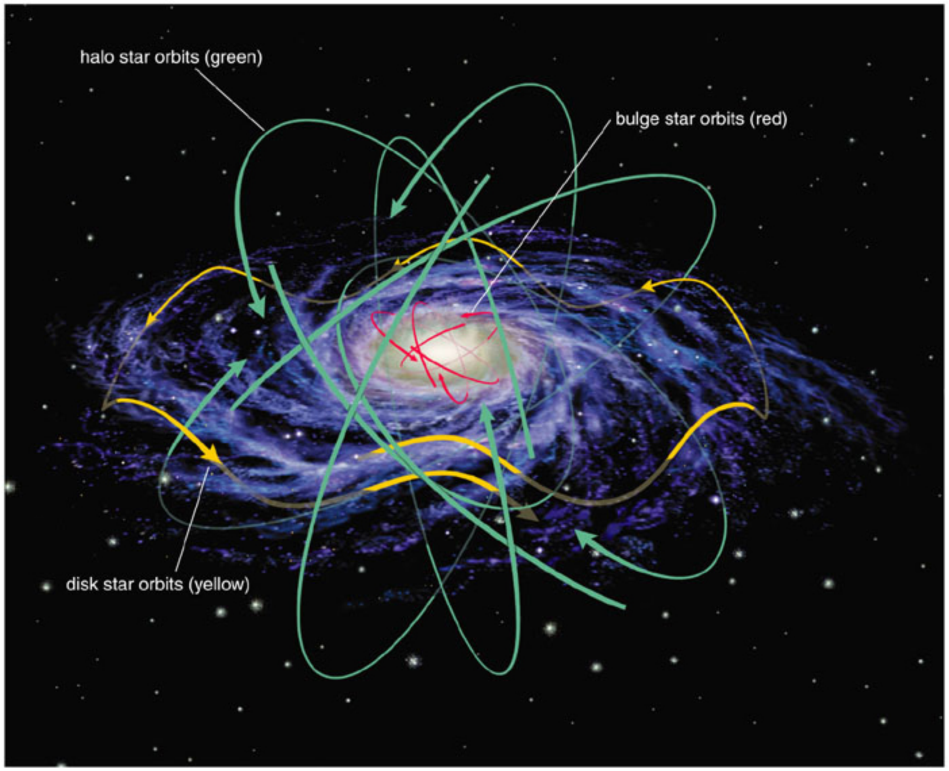
X-ray Flare from Sgr A*



*Chandra image of Sgr A**

- The rapid flare rise/drop time (< 10 min) imply that emission region is only 20 times the size of the event horizon of the 2.6 million $M_{\odot}$ black hole.
- Observations consistent with the existence of a supermassive black hole at the center of our Galaxy.
- Energy from flare probably came from comet-sized lump of matter…torn apart before falling inside event horizon!

Stellar Orbits in the Galaxy



Stars in disk all orbit the Galactic center:

- in same direction
- in same plane (like planets)
- “bobble” up and down
  - due to gravitational pull from the disk
  - this gives the disk its thickness

Stars in bulge and halo all orbit the Galactic center:

- in different directions
- at various inclinations to the disk
- have higher velocities
  - not slowed by disk as they plunge through it

The galactic year

- Observations indicate that for the Sun

  distance from GC = $D_\odot$ = 8 kpc (lab. 2)

  velocity about GC = $V_\odot$ = 220 km/s

Hence, rotation period of Sun about the GC is

$$P = \frac{2\pi D_\odot}{V_\odot} = 240 \times 10^6 \text{ years}$$

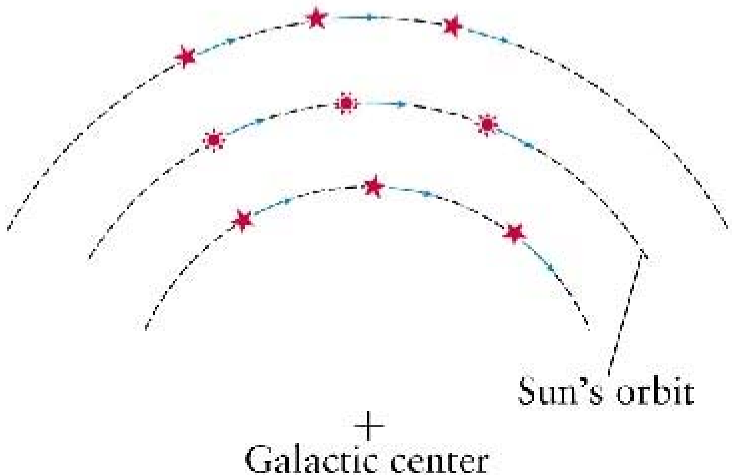
- Hence Kepler's 3rd law gives

$$\text{Mass of galaxy} = \frac{D_{\odot}^{3}}{P_{\odot}^{2}} = 10^{11}\ M_{\odot}$$

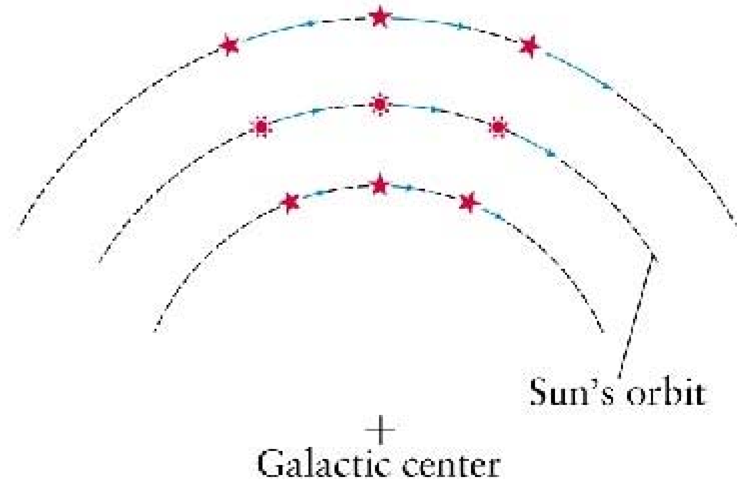
$$= \text{ mass interior to Sun's orbit}$$

Problem

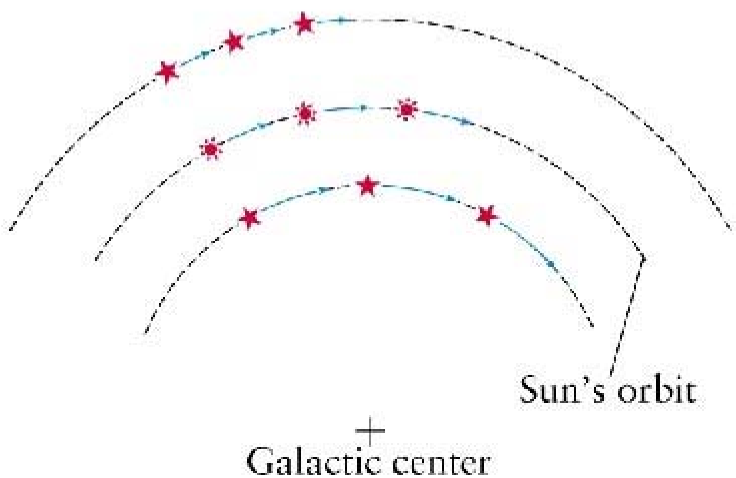
We cannot account for all of this mass in terms of the visible stars and the ISM



a Actual rotation of our Galaxy



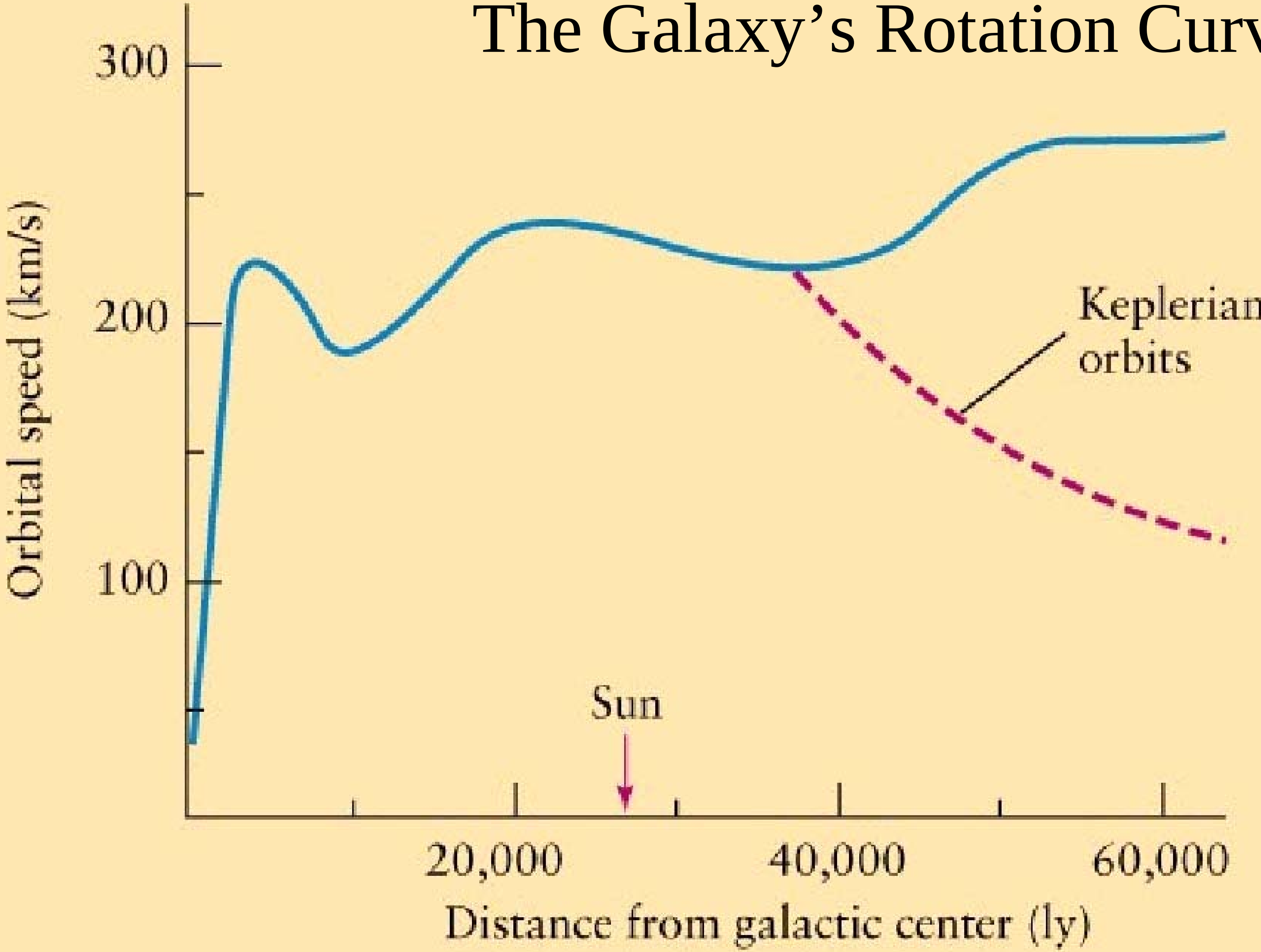
b If our Galaxy rotated like a solid disk



c If the Sun and the stars obeyed Kepler's third law

The rotation of our Galaxy reveals the presence of dark matter.

The Galaxy's Rotation Curve

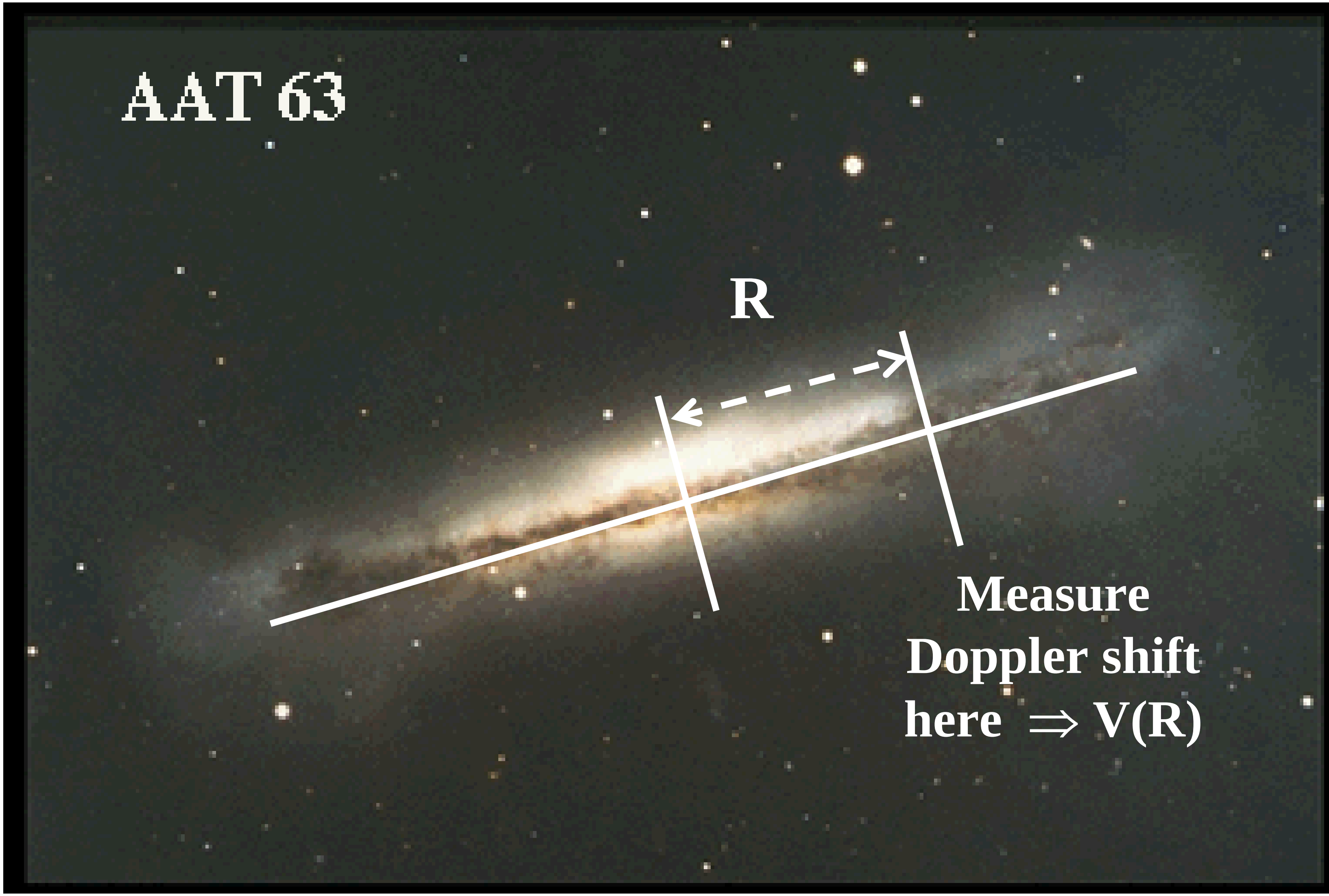


And not just in our Galaxy!

- Every galaxy studied to date shows evidence of containing dark matter
  - based upon galaxy rotation curves

Rotation curve = diagram of rotation velocity
against distance from GC

Determined from Doppler measurements of velocity V(R) and distance from galaxy center R


AAT 63
R
Measure
Doppler shift
here ⇒ V(R)

- Assume most of the mass is in the GC
- Kepler's 3rd law gives

$$P^2 = R^3 / M_{galaxy}$$

- and by definition

$$P = 2\pi R / V(R)$$

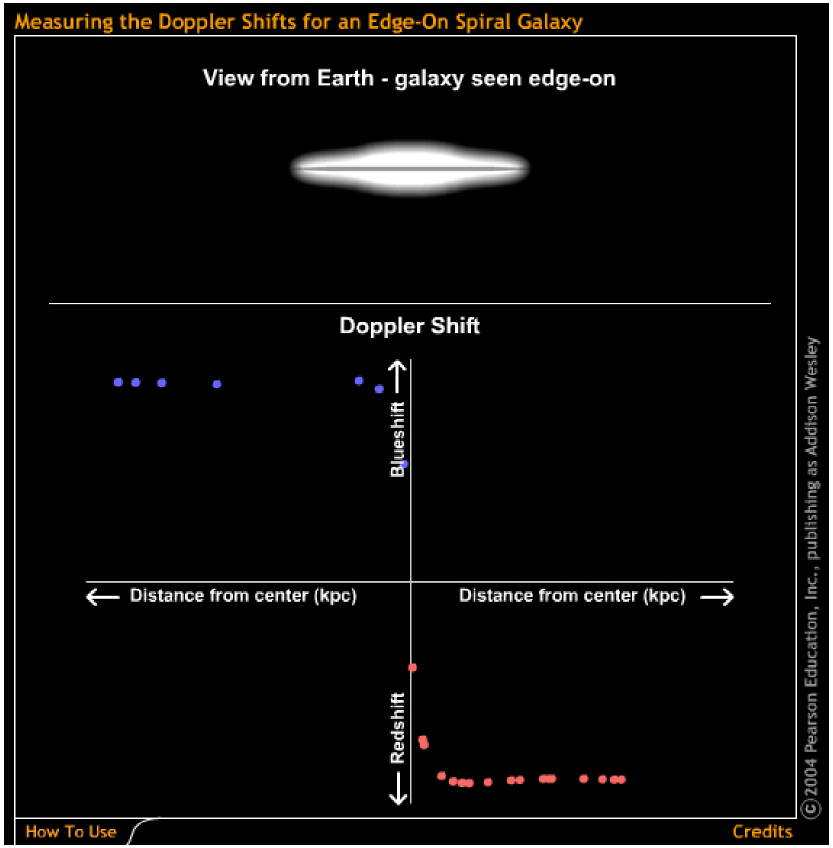
Hence: by combining equations

$$V(R) = \frac{\text{constant}}{\sqrt{R}} \quad \Leftarrow \textbf{Keplerian motion}$$

Plot V(R) against R

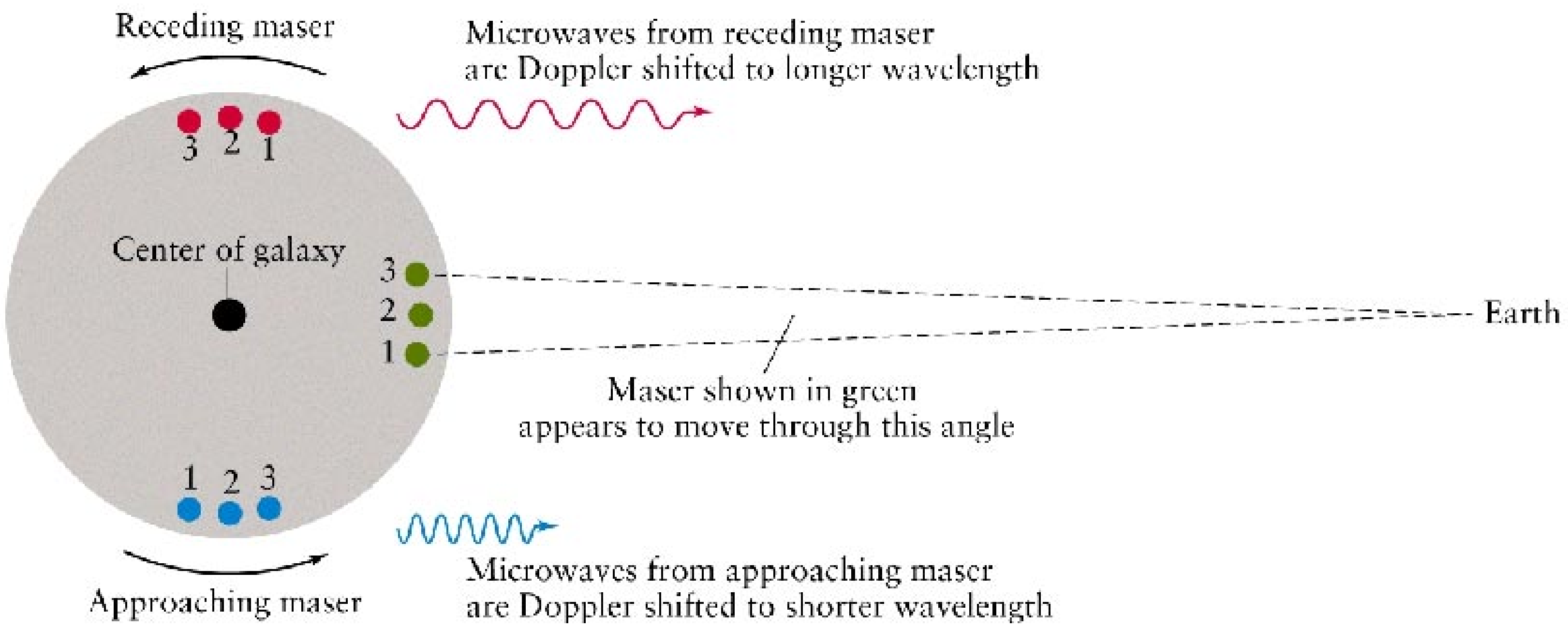
Determining Mass Distribution

- In Spiral Galaxies
  - measure the Doppler shift of the 21-cm radio line at various radial distances
  - construct a rotation curve of the atomic Hydrogen gas (beyond visible disk)
  - calculate the enclosed mass using Kepler's Law



A relatively new method is to use Masers.

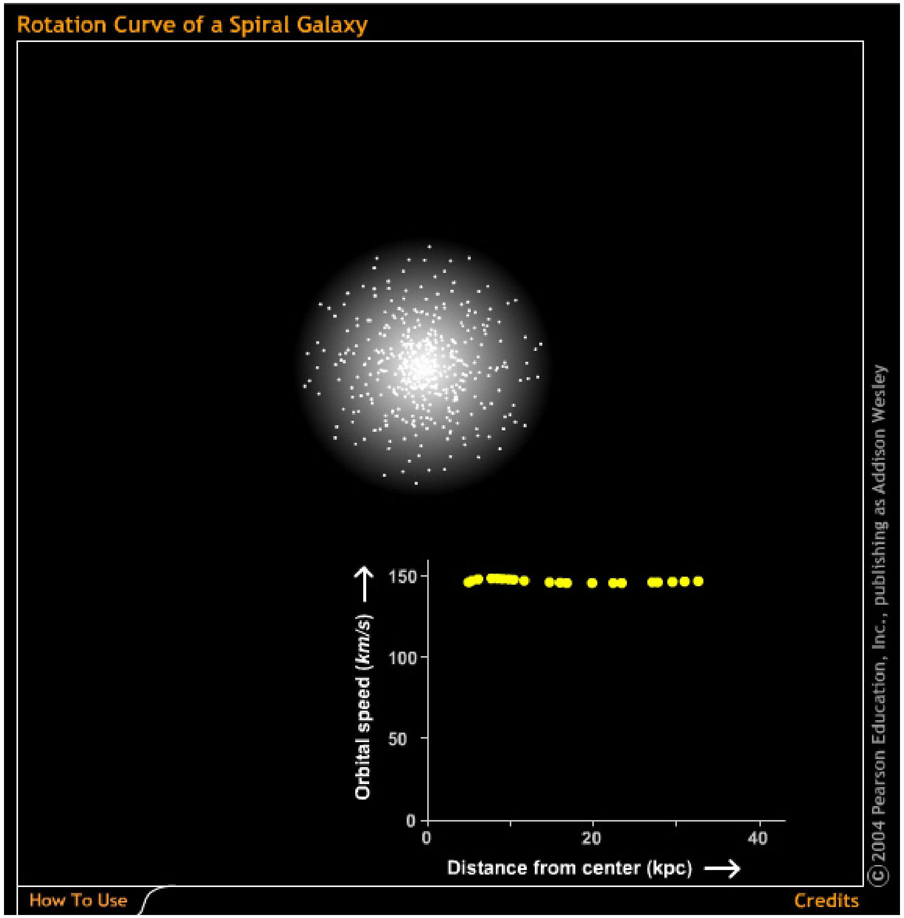
Masers are interstellar clouds that are easy to detect because they emit intense microwave radiation.



Orbital Velocities in the Disk

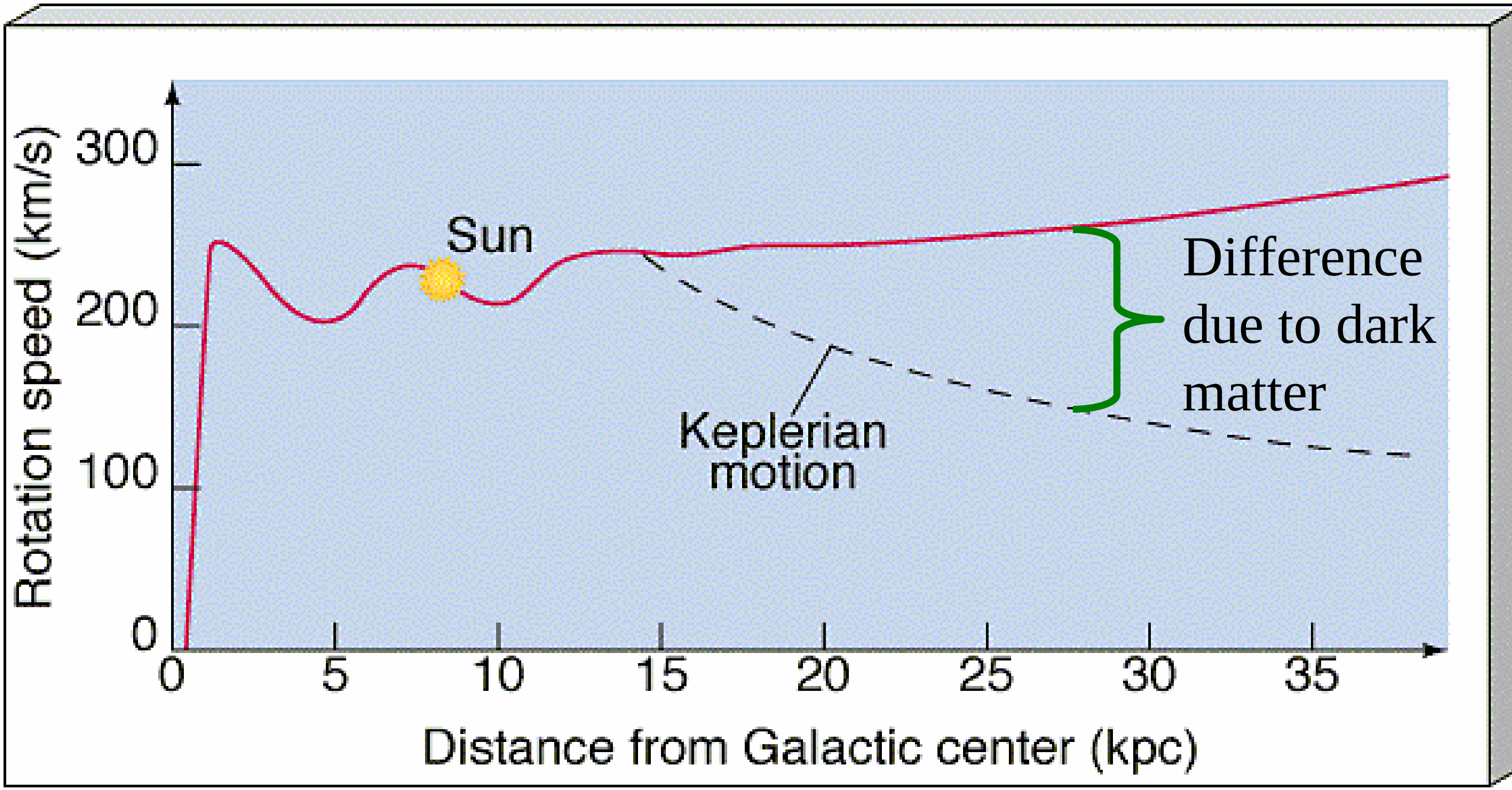
Stars in the Galactic disk should orbit according to Kepler's Laws

Here is what we observe:

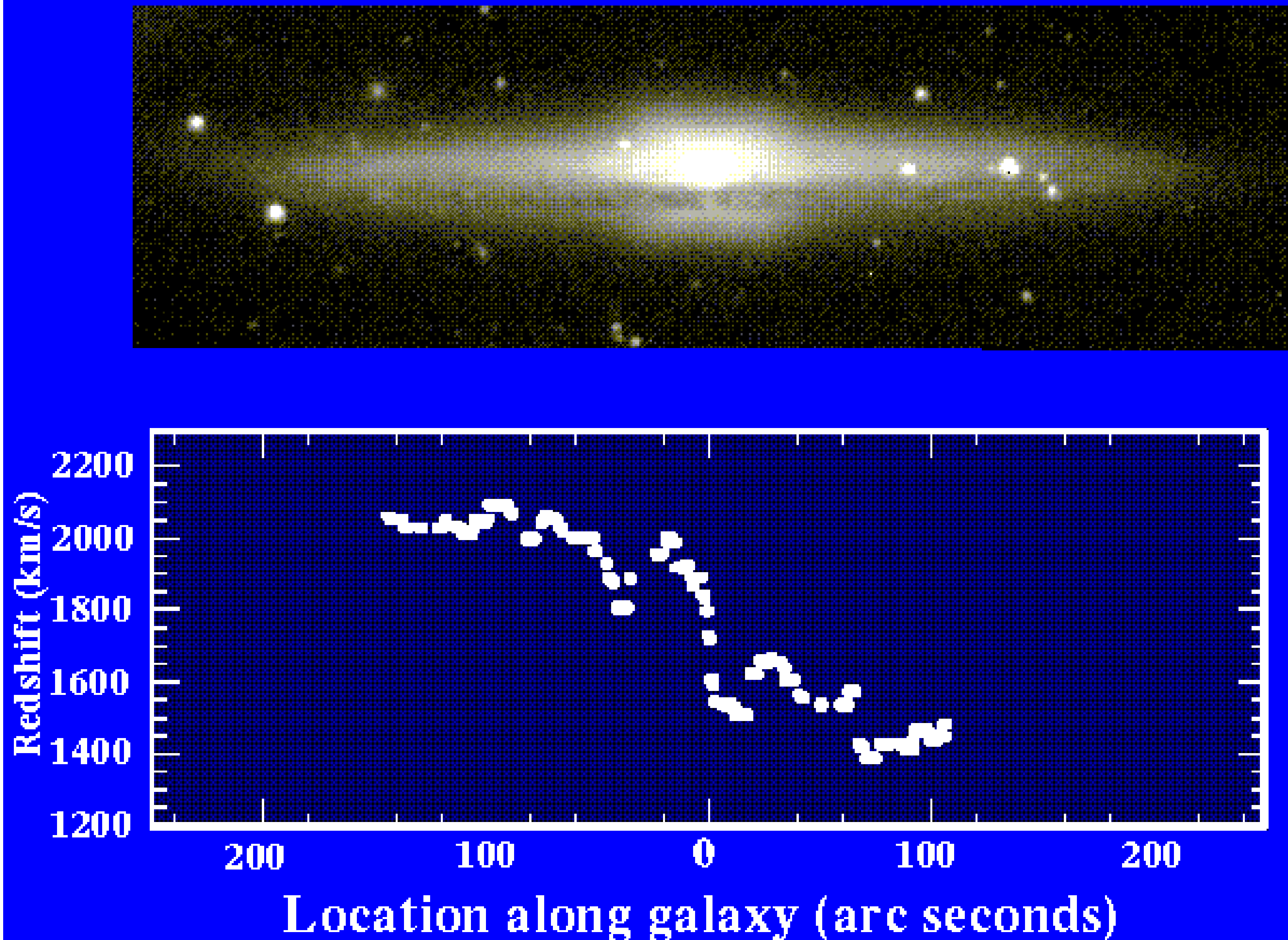


- The "flat rotation curve" of our Galaxy implies that:
  - its mass in **not** concentrated in the center
  - its mass extends far out into the halo
- But we do not "see" this mass
  - we do not detect light from most of this mass in the halo
  - so we refer to it as **dark matter**

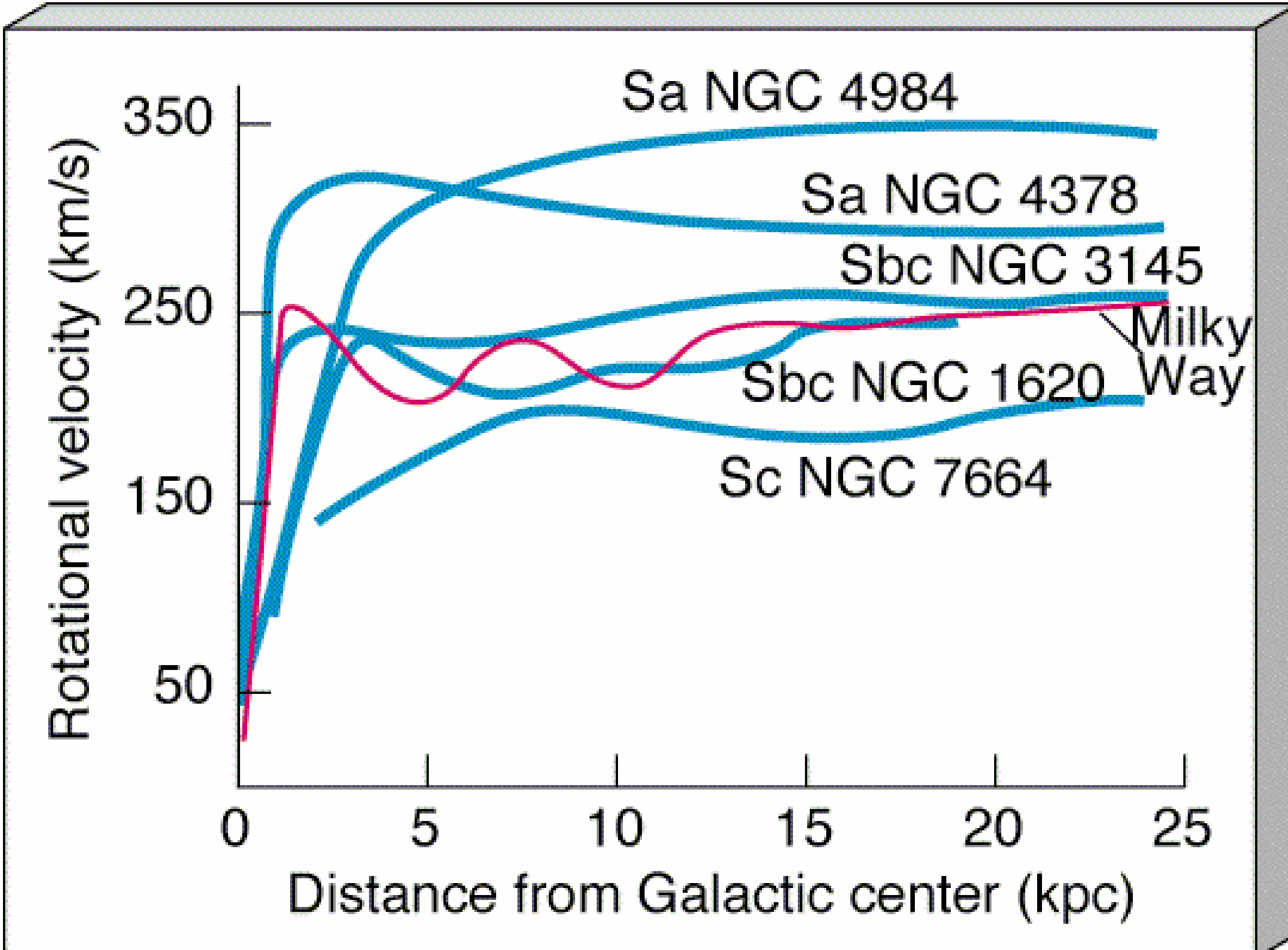
The Galactic Rotation Curve



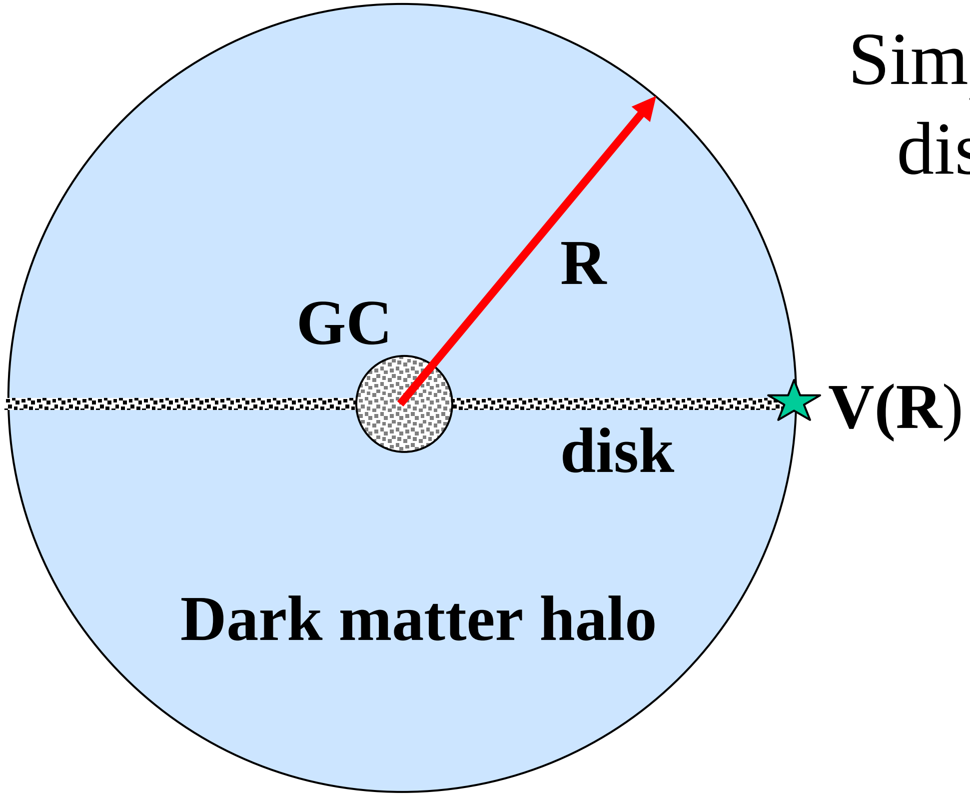
NGC 5746



2200
2000
1800
1600
1400
1200
Redshift (km/s)
200
100
0
100
200
Location along galaxy (arc seconds)


Sa NGC 4984
Sa NGC 4378
Sbc NGC 3145
Milky Way
Sbc NGC 1620
Sc NGC 7664
Rotational velocity (km/s)
350
250
150
50
0
5
10
15
20
25
Distance from Galactic center (kpc)

- Observations
  - Rotation curves for all observed galaxies remain flat to the extent of available observations
- Result
  - Point mass Keplerian theory doesn’t hold
- Hence:
  - Dark matter keeps V(R) constant with increasing distance from the galaxy center
  - Implies a spherical ‘halo’ of dark (gravitating) matter about galaxy



Simplest Dark Matter distribution model

From Kepler's third law: $$\frac{R^3}{P^2} = M_{DM}(R) + M_{disk} + M_{GC}$$

But, observations imply for R > R_{GC}, $M_{DM} >> M_{disk} + M_{GC}$

- For $R > R_{GC}$

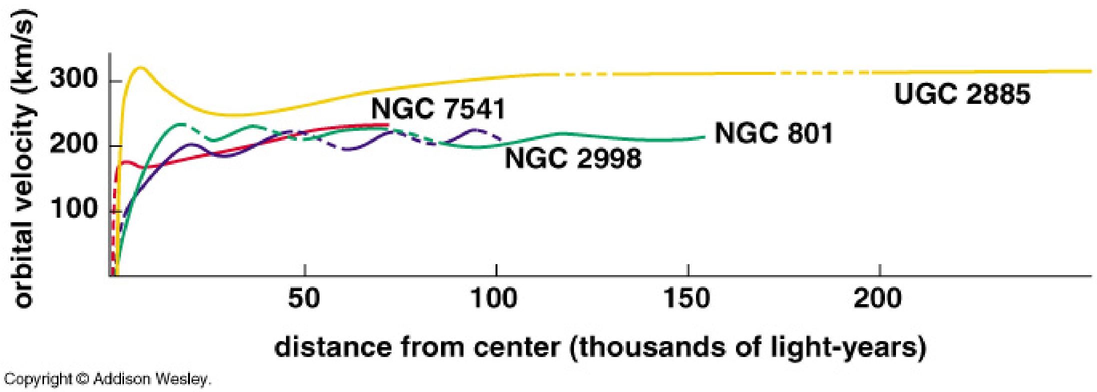
$$V^2(R) = 4\pi^2 \frac{M_{DM}(R)}{R} = \text{constant}$$

Hence $M_{DM}(R)$ = constant x R

And the density of dark matter must decrease as

$$\rho = \frac{M(R)}{\frac{4}{3}\pi R^3} = \frac{\text{constant}}{R^2}$$

Determining Mass Distribution



Rotation curves of spirals:

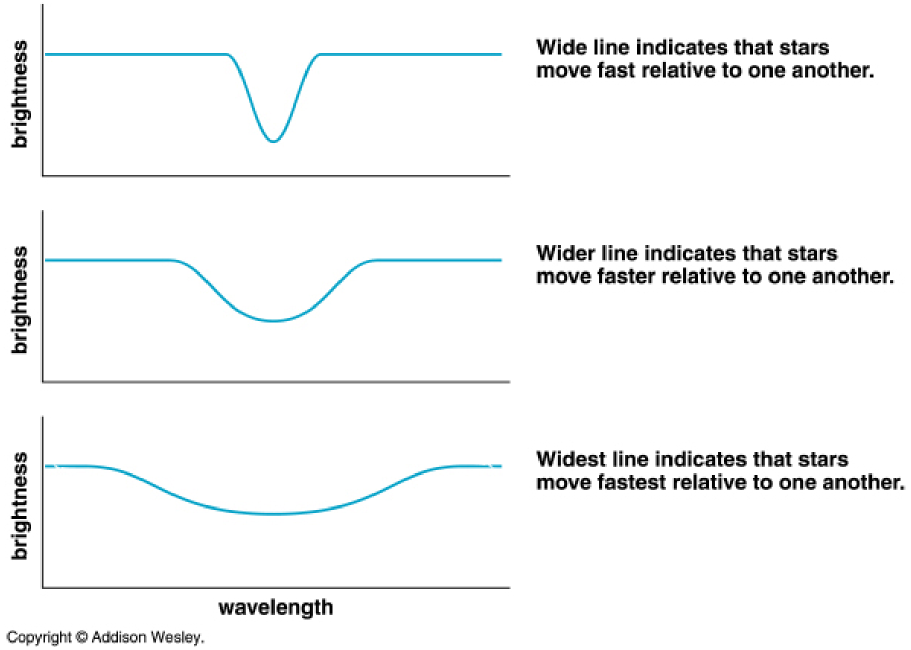
- flat at large distances from their centers
- indicates that (dark) matter is distributed far beyond disk

In Elliptical Galaxies:

- there is no gas
- measure the average orbital speeds of stars at various distances
- use broadened absorption lines

Results indicate that dark matter lies beyond the visible galaxy.

- we can not measure the total amount of dark matter, since we can see only the motions of stars



- Hence:
  - Simplest possible Dark Matter model
  - a spherical distribution of dark matter about GC
  - provided the density of dark matter decreases as $1/R^2$ then:
    - Dark Matter mass increases linearly with distance from the galactic center
    - And the rotation curve will be flat

What is Dark Matter made of?

Some dark matter could be made out of protons & neutrons:

- “ordinary” matter, the same matter **we** are made up of
- the only thing unusual about this type of dark matter is that it is dim

However, some or all of dark matter could be made of particles which we have yet to discover:

- this would be “extraordinary/exotic” matter

Physicists like to call ordinary matter **baryonic matter**.

Extraordinary matter = **nonbaryonic matter**.

Recall rotation curve of the Milky Way

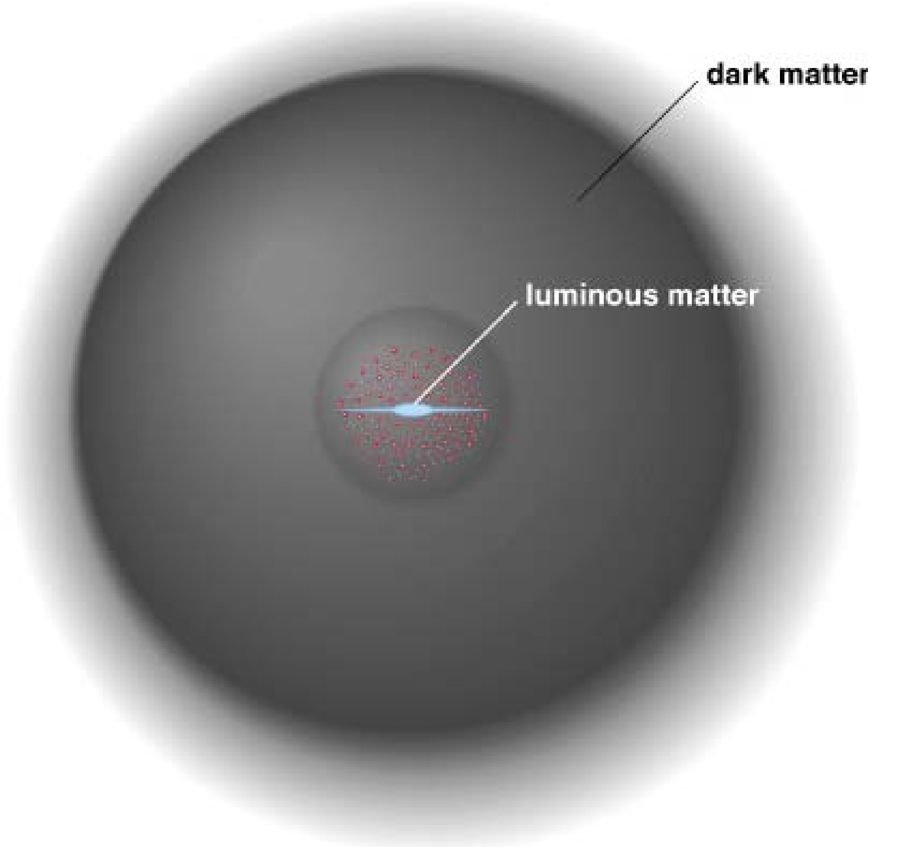
Atomic H clouds beyond our Sun orbit faster than predicted by Kepler's Law

- most of the Galaxy's light comes from stars closer to the center than the Sun

There are only two possible explanations for this:

1) we do not understand gravity on galaxy-size scales
2) the H gas velocities are caused by the gravitational attraction of unseen dark matter

- If we trust our theory of gravity...
  - there may be 10 times more dark than luminous matter in our Galaxy
  - luminous matter is mostly confined to the disk
  - dark matter is found in the halo and far beyond the luminous disk



So, what is it?

- MACHOs
  - Massive, compact halo objects
    - Planets, brown dwarfs, black dwarfs (?)
    - i.e., very low luminosity ordinary matter
- WIMPs
  - Weakly interacting massive particles
    - e.g., neutrinos (supported by solution to solar neutrino problem)

An Ordinary Matter Candidate

Our Galactic halo should contain baryonic matter which is dark:

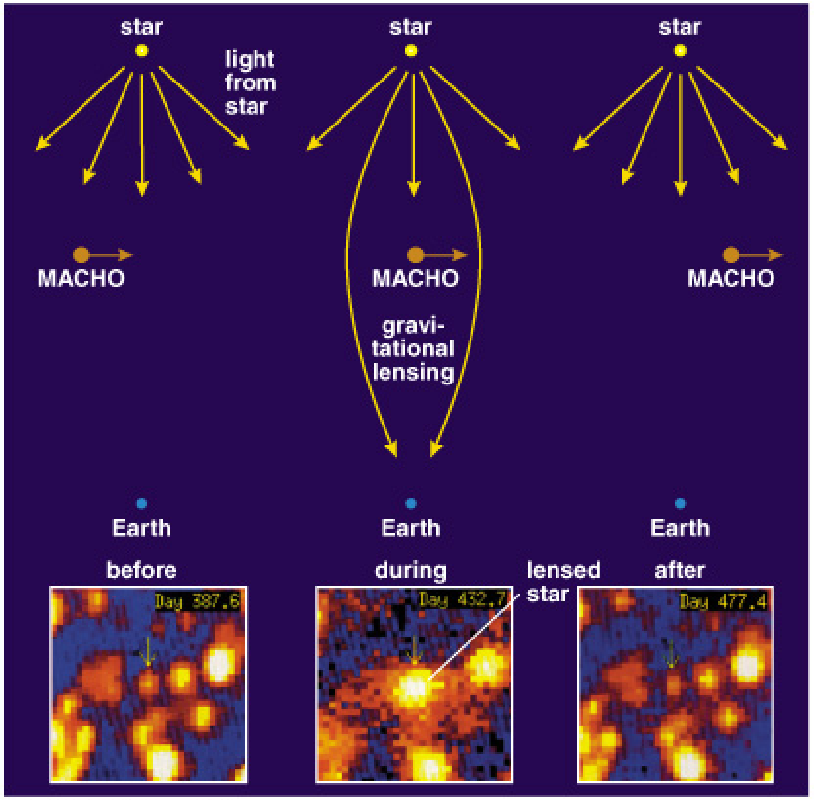
- low-mass M dwarfs, brown dwarfs, and Jovian-sized planets
- they are too faint to be seen at large distances
- they have been called “MAssive Compact Halo Objects” or **MACHOs**

We detect them if they pass in front of a star where

- they gravitationally lens the star’s light
- the star gets much brighter for a few days to weeks
- we can measure the MACHO’s mass

These events occur to only one in a million stars per year:

- must monitor huge numbers of stars
- # of MACHOs detected so far does not account for the Milky Way’s dark matter



An Extraordinary Matter Candidate

We have already studied a nonbaryonic form of matter:

- the **neutrino**…detected coming from the Sun
- neutrinos interact with other particles through only two of the natural forces:
  - gravity
  - weak force (hence we say they are "weakly interacting")
- their masses are so low & speeds so high, they will escape the gravitational pull of a galaxy…they can **not** account for the dark matter observed

But what if there existed a *massive* weakly interacting particle?

- physicists call them "Weakly Interacting Massive Particles" or **WIMPs**
- these particles are theoretical; they have not yet been discovered
- they would be massive enough to exert gravitational influence
- they would emit no electromagnetic radiation (light) or be bound to any charged matter which could emit light
- as weakly interacting particles, they would not collapse with a galaxy's disk
- yet they would remain gravitationally bound in the galaxy's halo

Mass-to-light ratio

Mass-to-Light Ratio = (mass of a galaxy) /(its luminosity)

- measure both mass and luminosity in Solar units

Within the orbit of the Sun, M/L = 6 $M_\odot / L_\odot$ for the Milky Way

- typical for the inner regions of most spiral galaxies
- for inner regions of elliptical galaxies, M/L = 10 $M_\odot / L_\odot$
    - natural since ellipticals contain dimmer stars

However, when we include the outer regions of galaxies:

- M/L increases dramatically
- for entire spirals, M/L can be as high as 50 $M_\odot / L_\odot$
- dwarf galaxies can have even higher M/L

We conclude that most matter in galaxies are not stars.

Measuring the Mass of a Cluster

There are three independent ways to measure galaxy cluster mass:

1. measure the speeds and positions of the galaxies within the cluster
2. measure the temperature and distribution of the hot gas between the galaxies
3. observe how clusters bend light as gravitational lenses

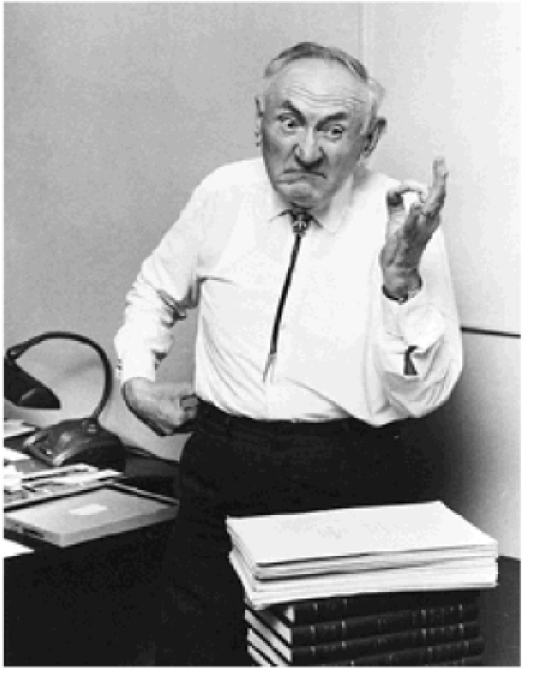
Orbiting Galaxies

This method was pioneered by Fritz Zwicky.

- assume the galaxies orbit about the cluster center
- measure the orbital velocities of the galaxies
- measure each galaxy's distance from the center
- apply Kepler's Law to calculate mass of cluster

Zwicky found huge M/L ratios for clusters.

- his proposals of dark matter were met with skepticism in the 1930s

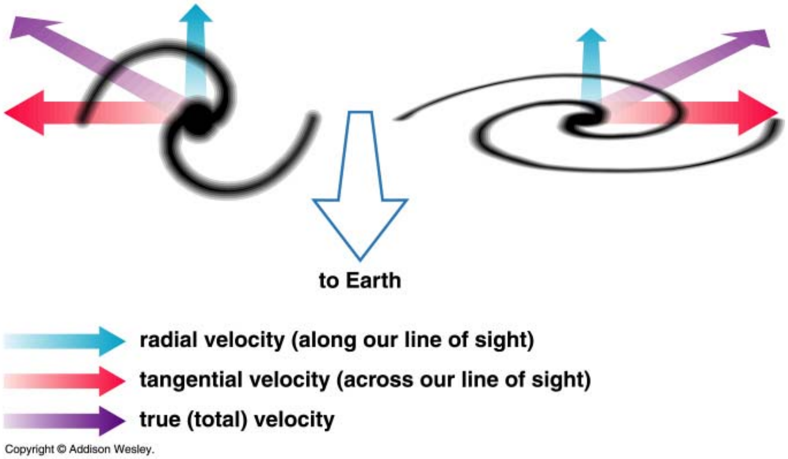


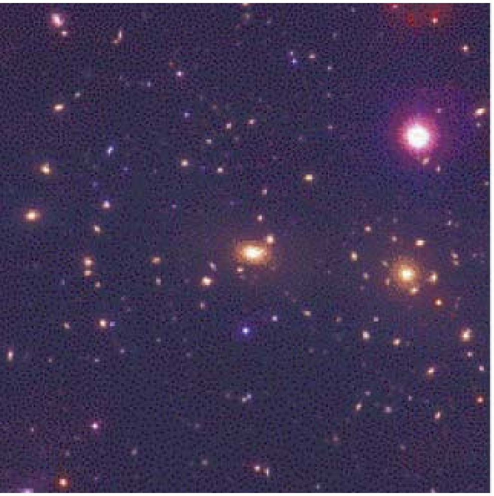
Fritz Zwicky

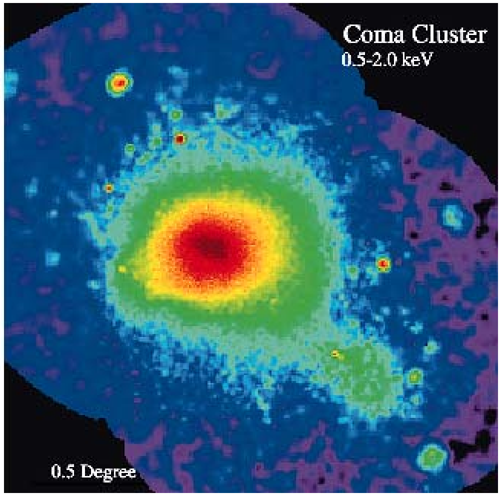
Measuring the Mass of a Cluster

Measuring galaxy orbits is not straightforward:

- we can only measure radial velocity
- must average all radial velocities to get the cosmological redshift (CR)
- subtract CR from each velocity







Coma cluster of galaxies

(optical) (X-ray)

Intracluster Medium:

the hot (10^7–10^8 K) gas between the cluster galaxies

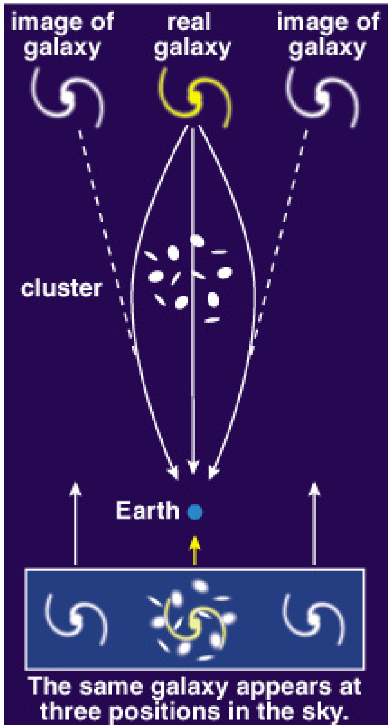
- this gas emits X-rays
- from the X-ray spectrum, we can calculate the temperature
- this tells us the average speed of the gas particles
- again, we can estimate mass

Measuring the Mass of a Cluster

This is a **gravitational lens**.

Einstein's Theory of Relativity states that massive objects distort spacetime.

- a massive cluster will bend the path of light which approaches it (like a lens)
- the blue arcs are the lensed images of a galaxy which is behind the cluster



The angle at which the light is bent depends on the mass of the cluster.

- by analyzing lensed images, we can calculate cluster mass

All previous methods for finding mass depended on Newton's Law of Gravity.

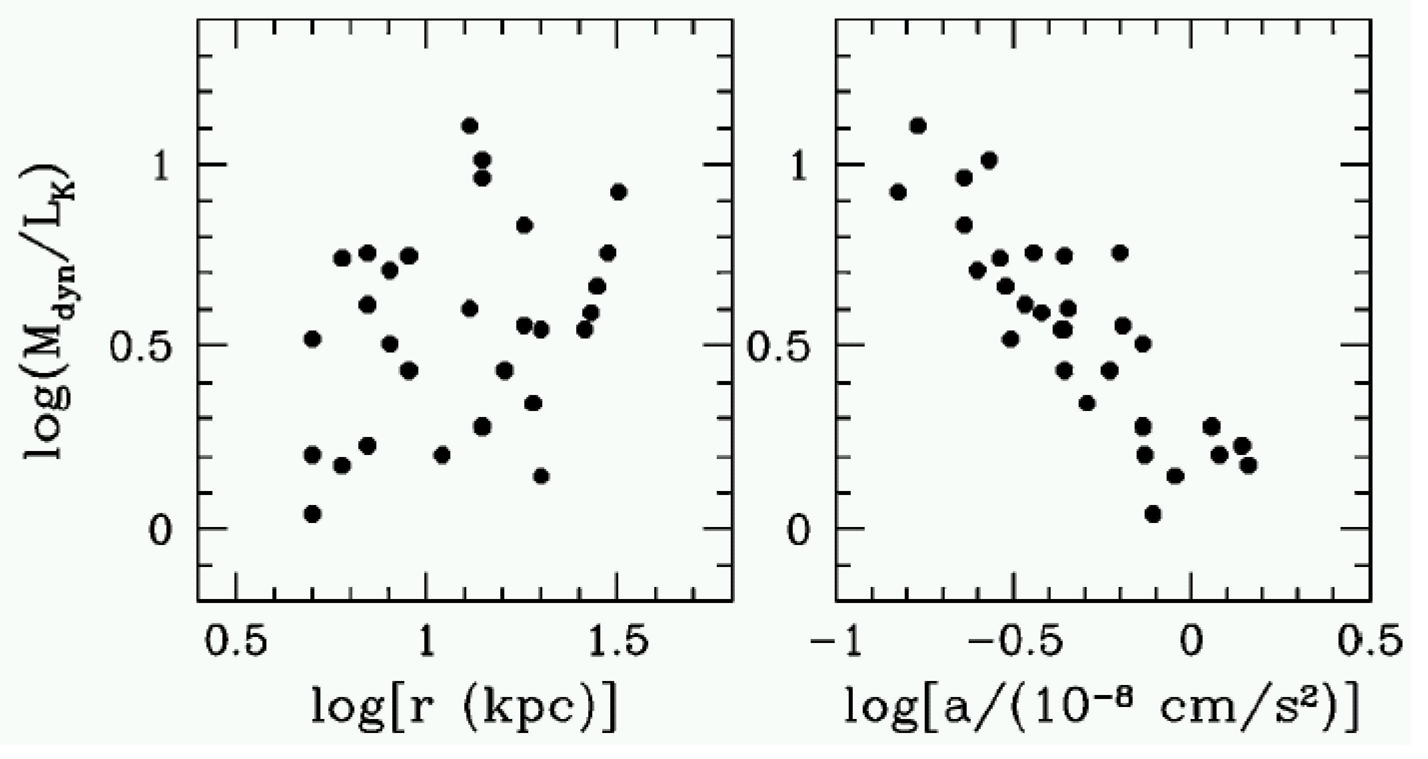
- this method uses general relativity

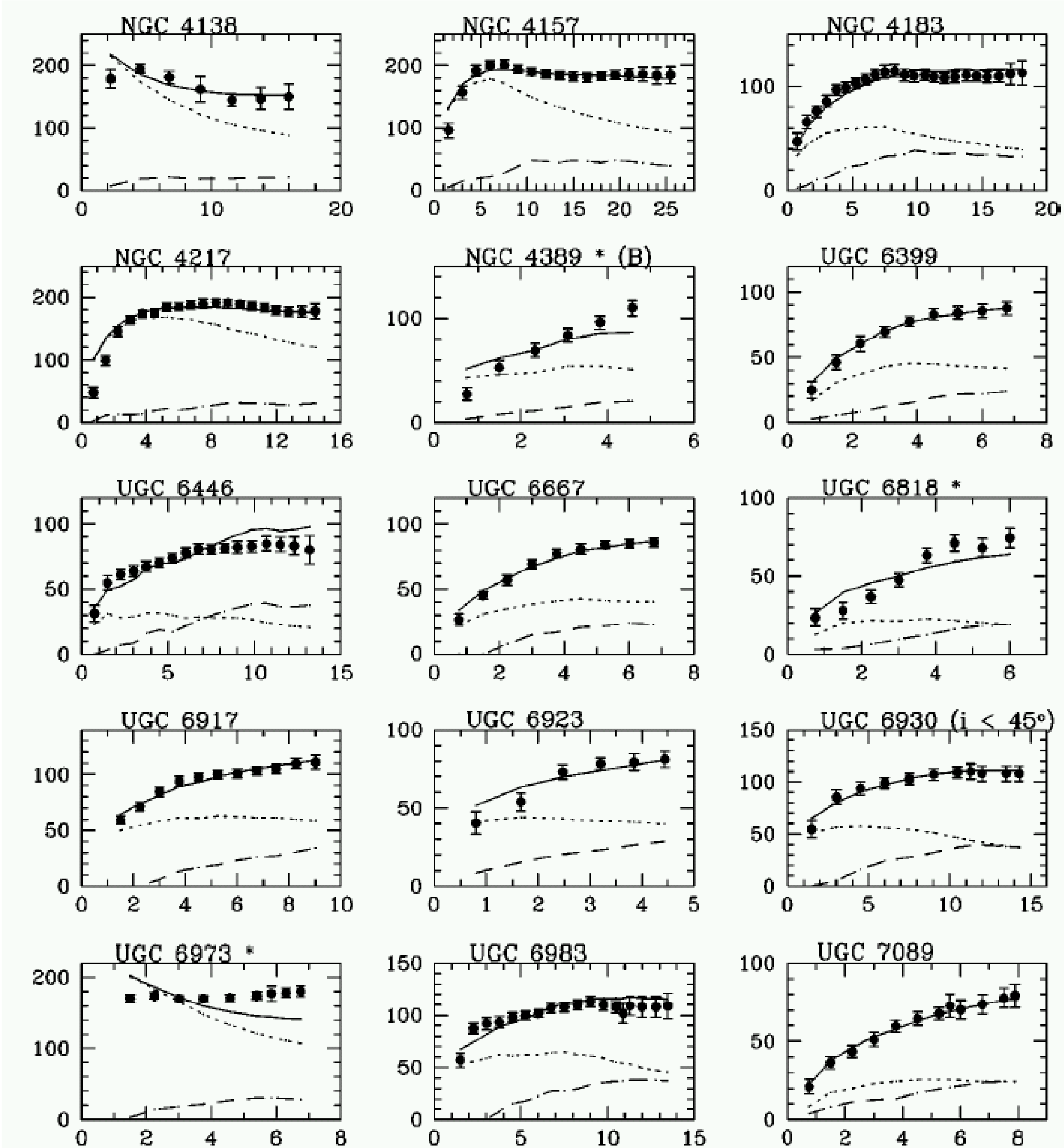
The cluster masses measured by all three of these independent methods agree:

- M/L for most galaxy clusters is greater than 100 $M_{\odot}/ L_{\odot}$
- Galaxy clusters contain far more mass in **dark matter** than in stars

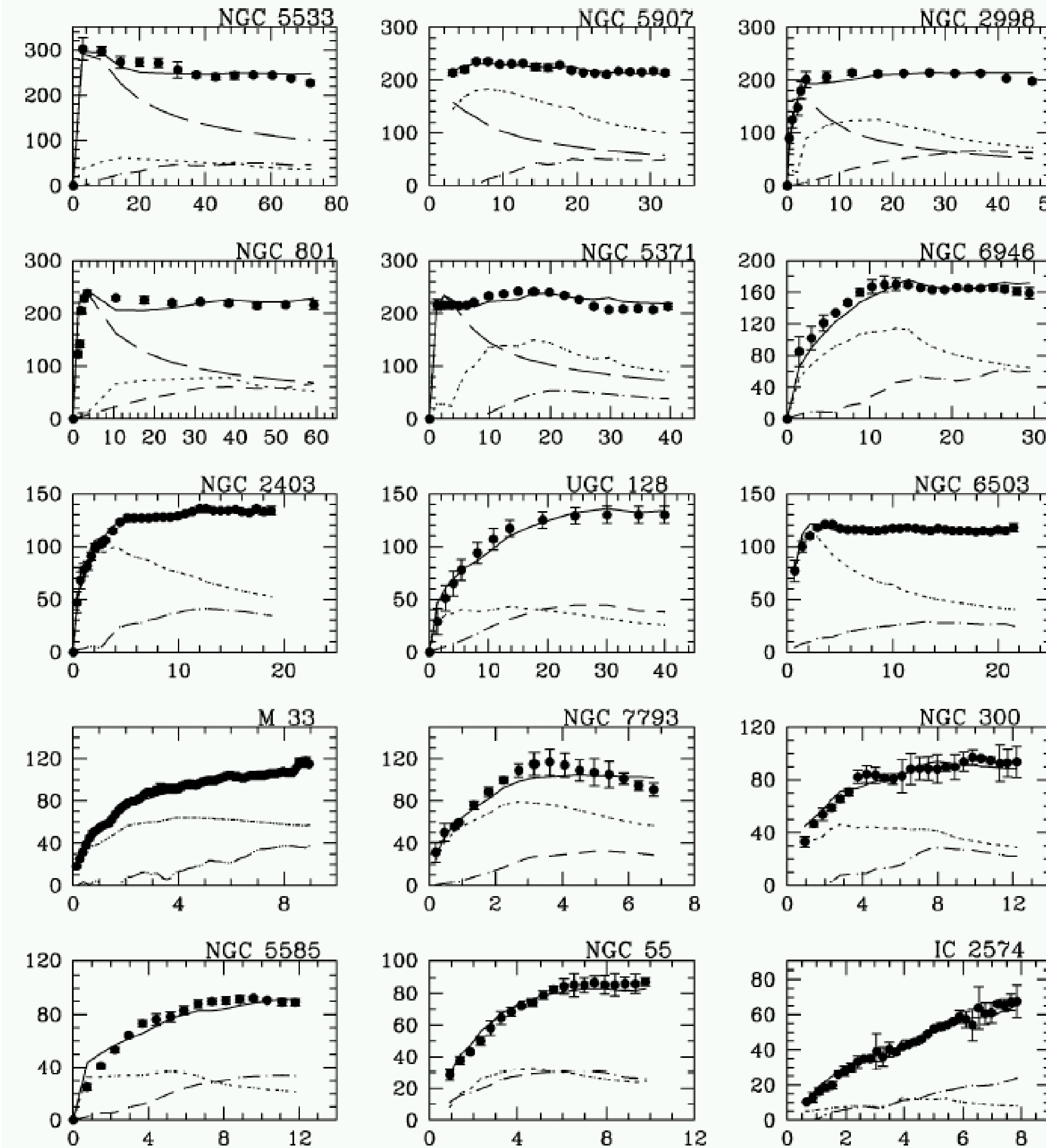
Modifying gravity – "MOND"

- Modify Newtonian theory at large distances?
- or at low accelerations?

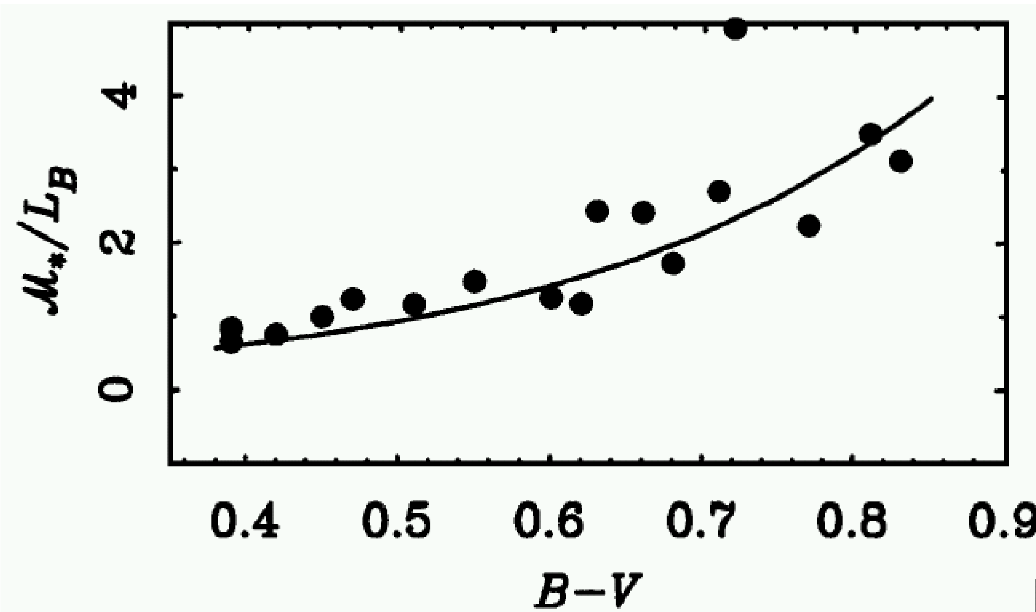


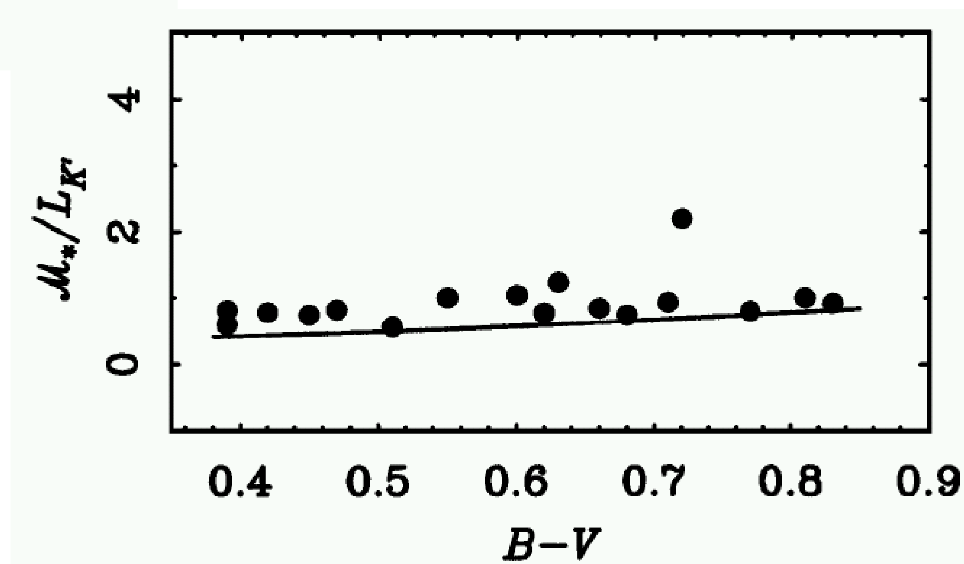


U Maj
Sanders & Verheijen


NGC 5533
NGC 5907
NGC 2998
NGC 801
NGC 5371
NGC 6946
NGC 2403
UGC 128
NGC 6503
M 33
NGC 7793
NGC 300
NGC 5585
NGC 55
IC 2574

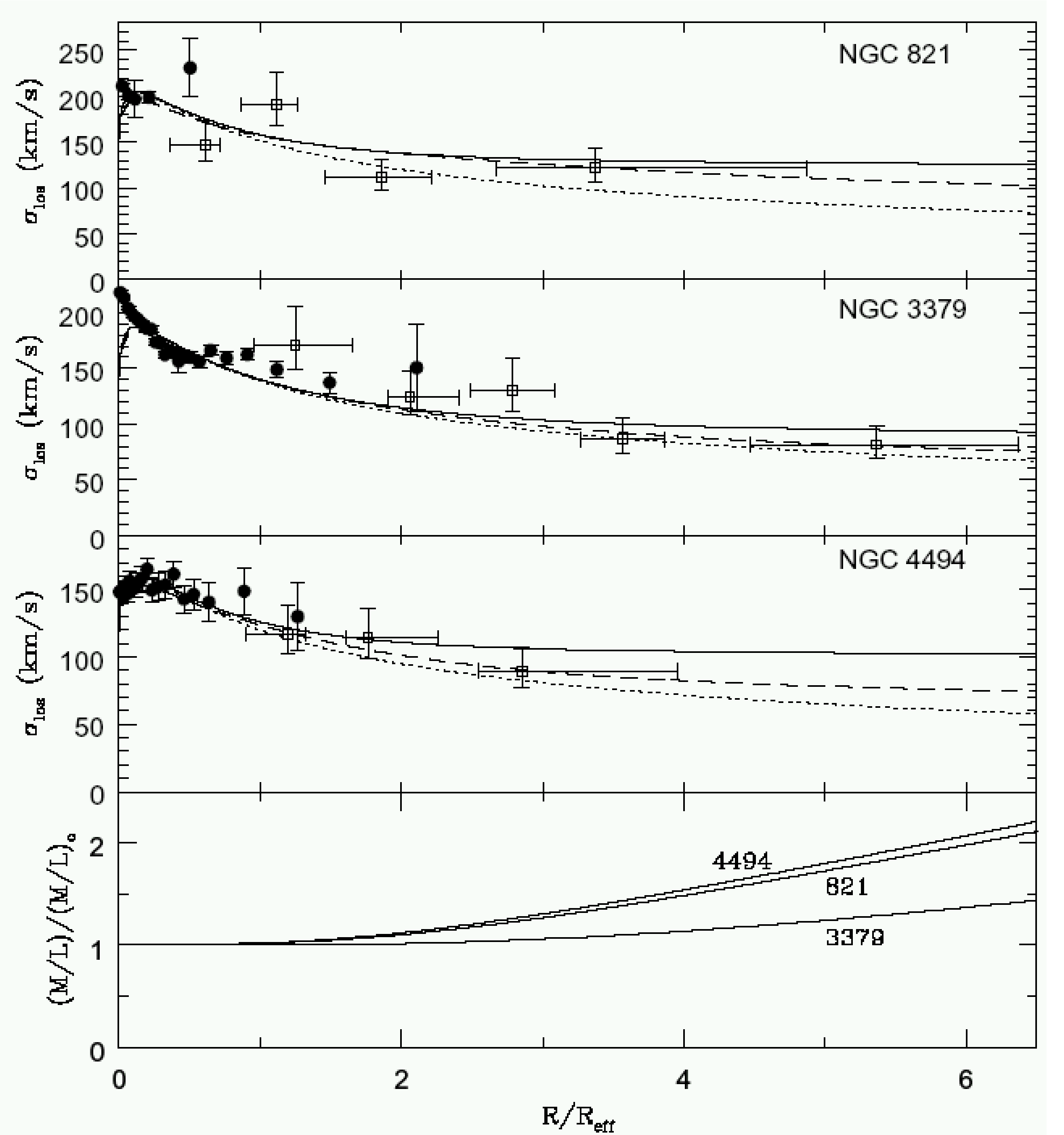
Recover predicted M/L values





Data: Sanders & Verheijen
Models: Bell & de Jong 01

Giant E galaxies



Data:
Romanowsky et al 03
Models:
Milgrom & Sanders 03
Solid: isotropic

Clusters of Galaxies