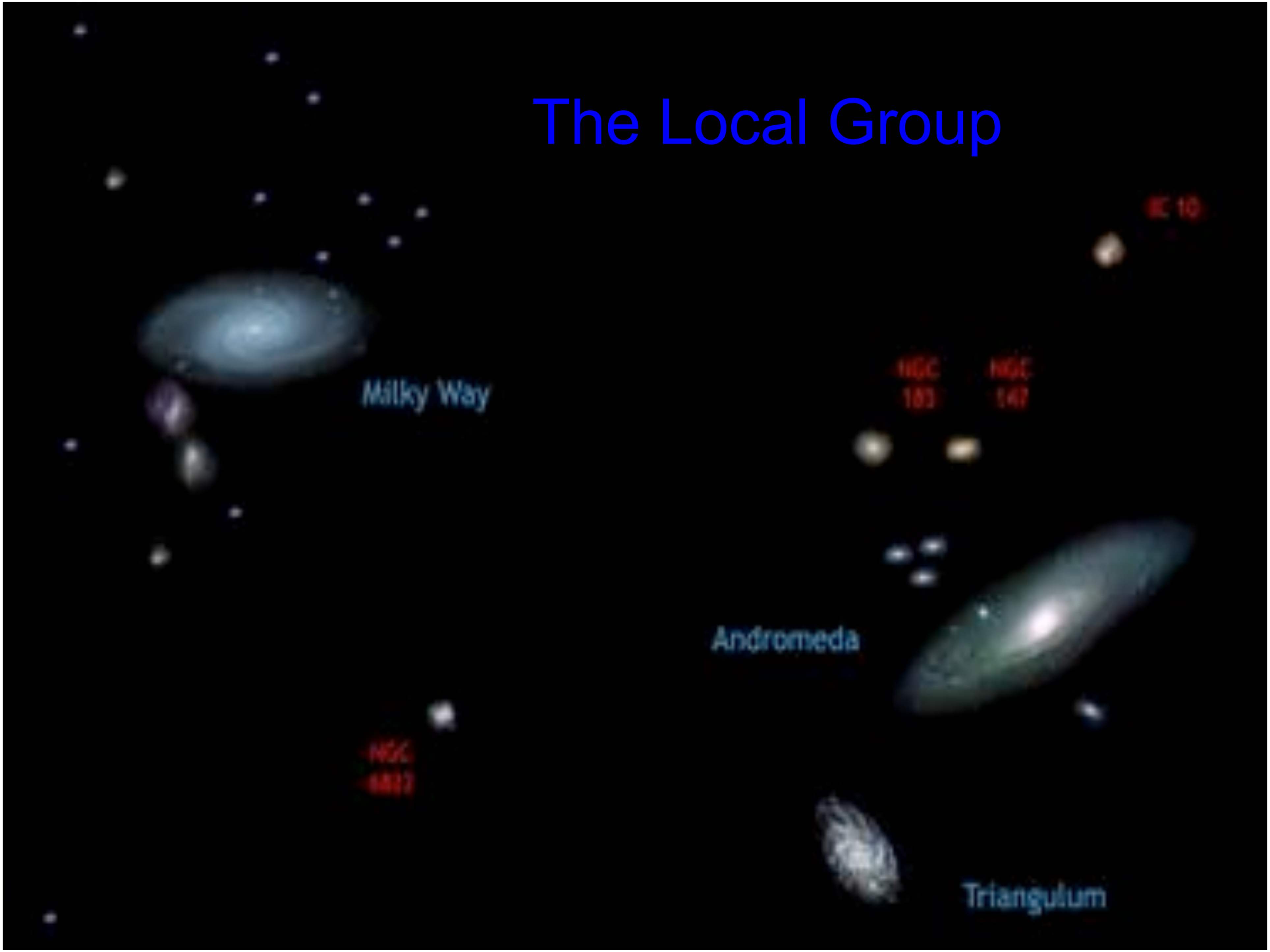
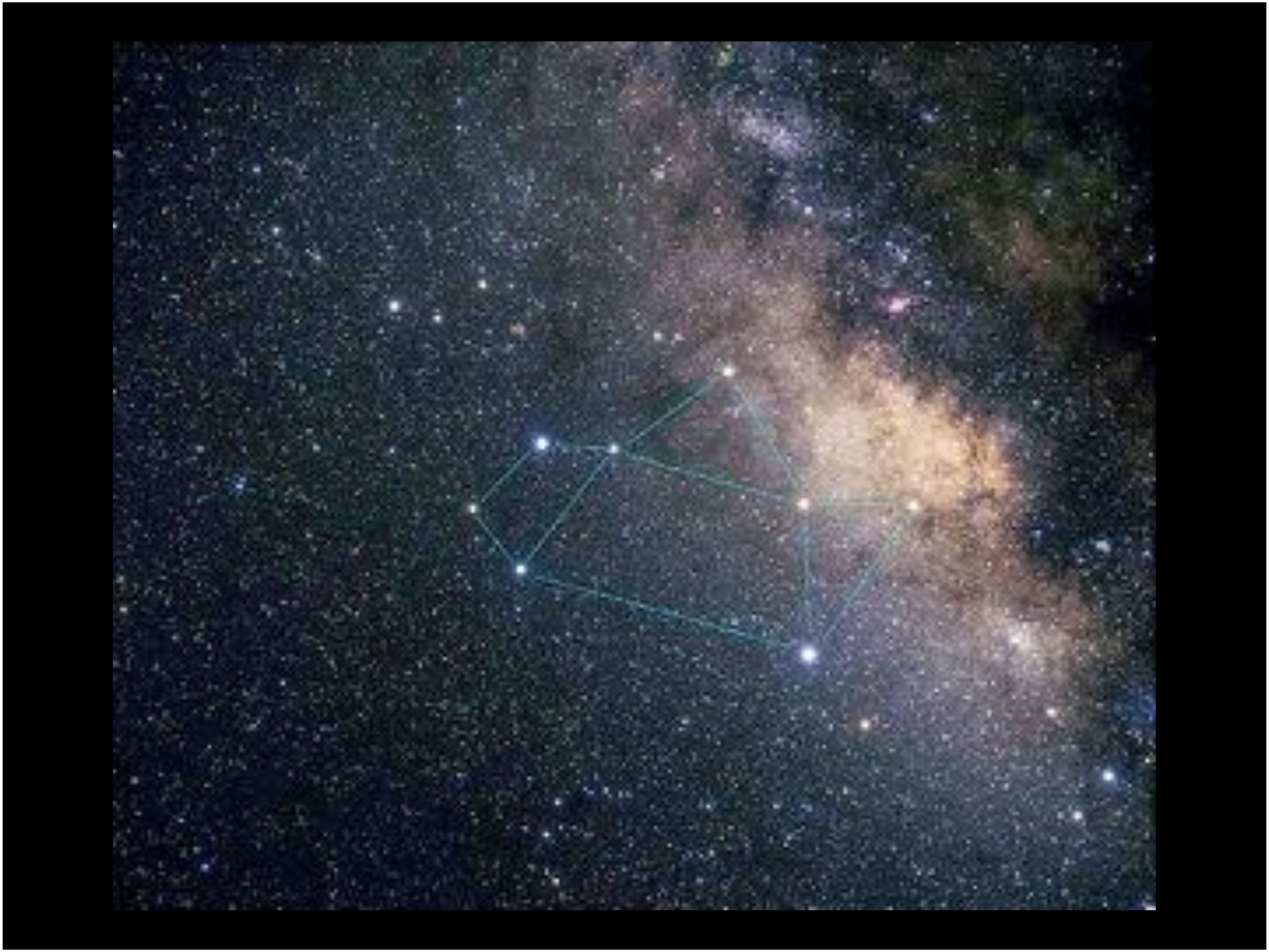
The Local Group



2 large satellite galaxies

Irregular galaxies have a wide variety of shapes. The **Large and Small Magellanic Clouds** are close neighbors to our own Milky Way.



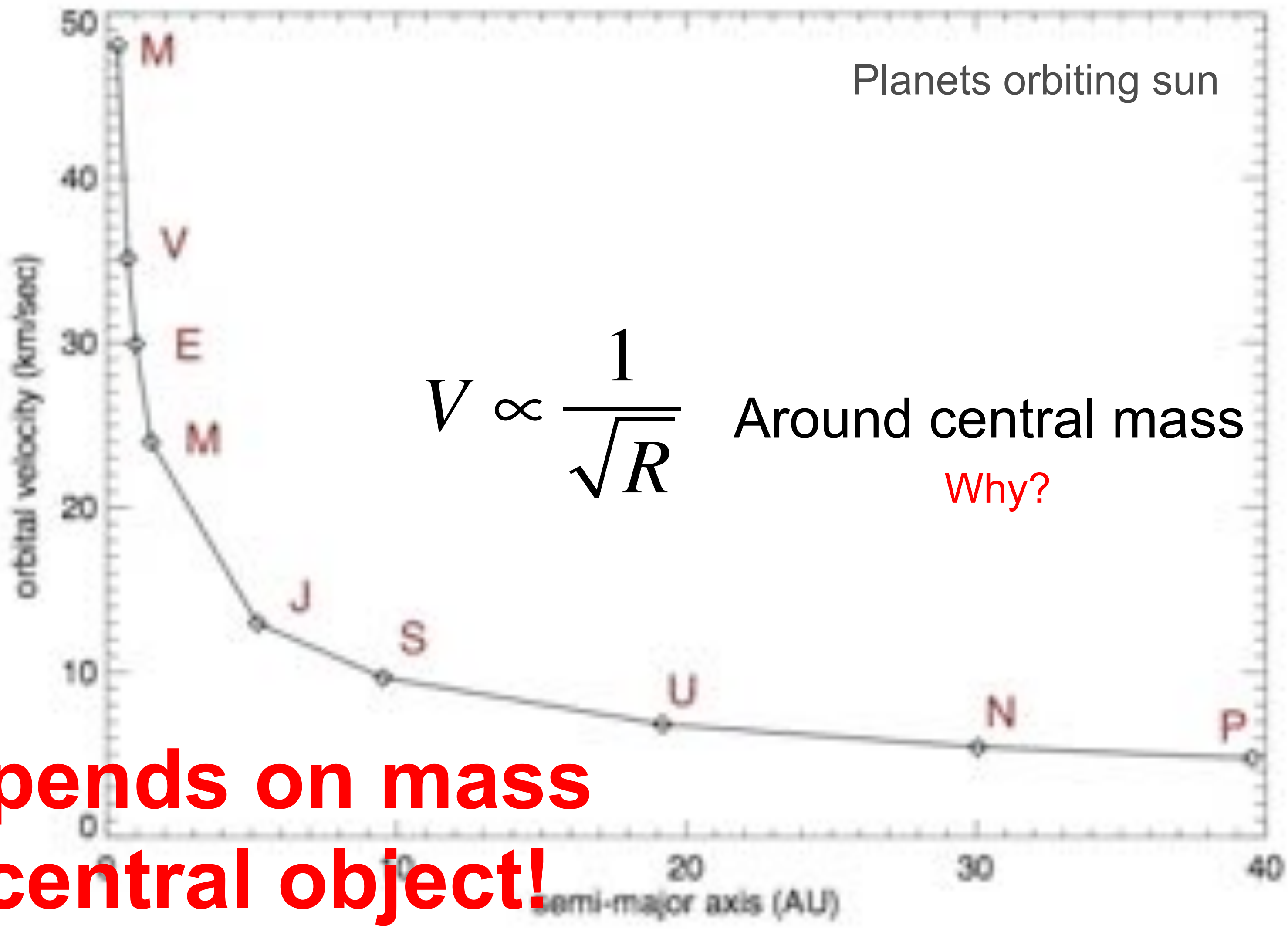

CENTER OF MILKY WAY
DISKS OF MILKY WAY
AREAS OF INITIAL OBSERVATIONS
SAGITTARIUS DWARF GALAXY
LOW SURFACE BRIGHTNESS CONTOURS


The Milky Way Galaxy and Sagittarius Stream

Dark Matter (AT 23.6, 25.1)

The Coma Cluster
d=100 Mpc (300Mly)
About ½ deg across (~1 Mpc)

Kepler – orbital velocity



$$V \propto \frac{1}{\sqrt{R}}$$

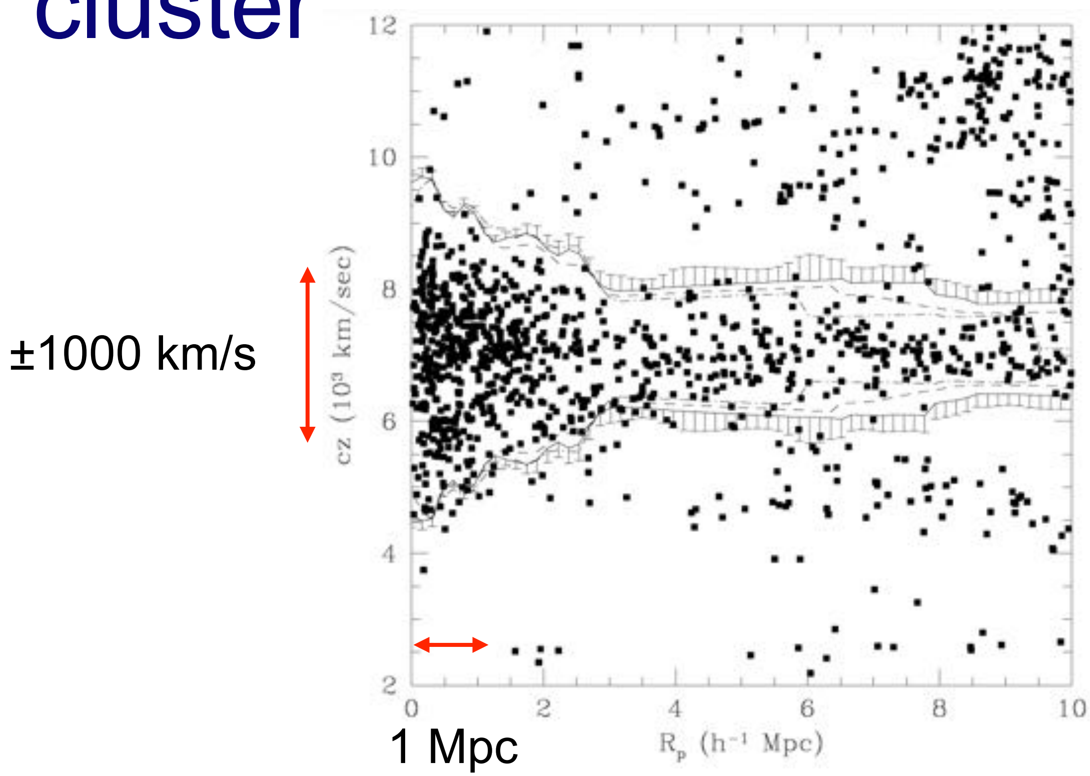
Around central mass

Why?

Depends on mass of central object!

Zwicky 1933

- radial velocities of individual Coma galaxies vs. distance from centre of cluster



Dark Matter - Fritz Zwicky 1933

- Doppler shifts of individual Coma galaxies
- gives mass of Coma - why?
- about 10X that expected from light from galaxies (starlight)!

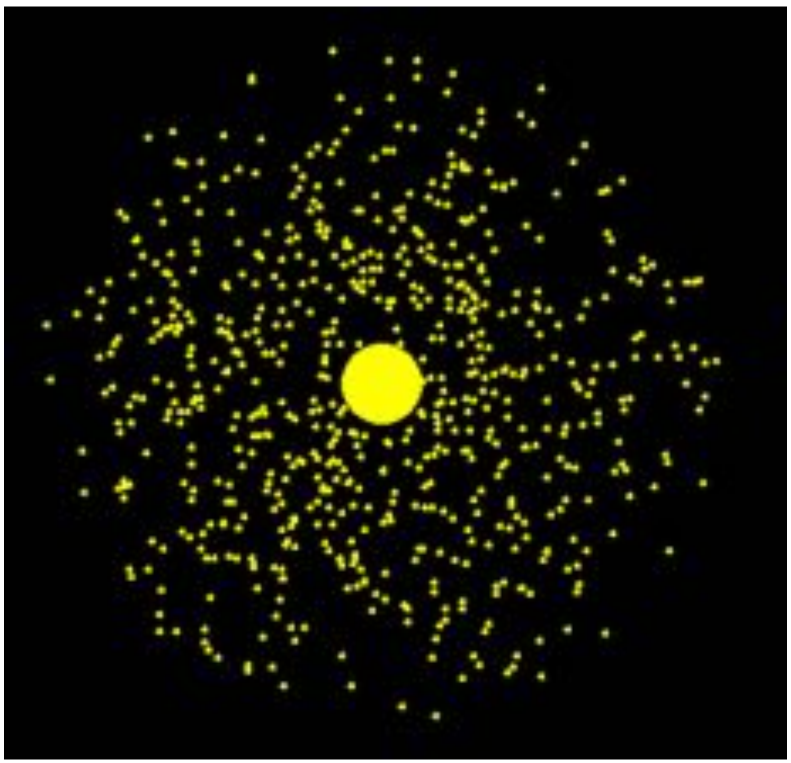
Dark Matter - Ignored for 40 years!

Year	No. of citations
1955-59	2
1960-64	6
1965-69	5
1970-74	2
1975-89	63
1990-99	71

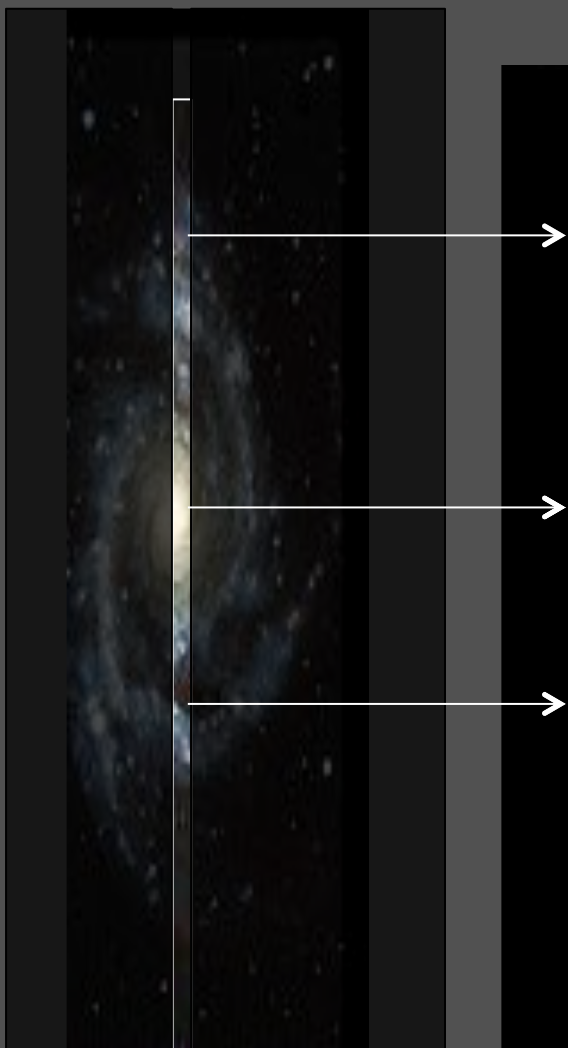
Zwicky 1933 citations

Dark Matter - Galaxy Rotation

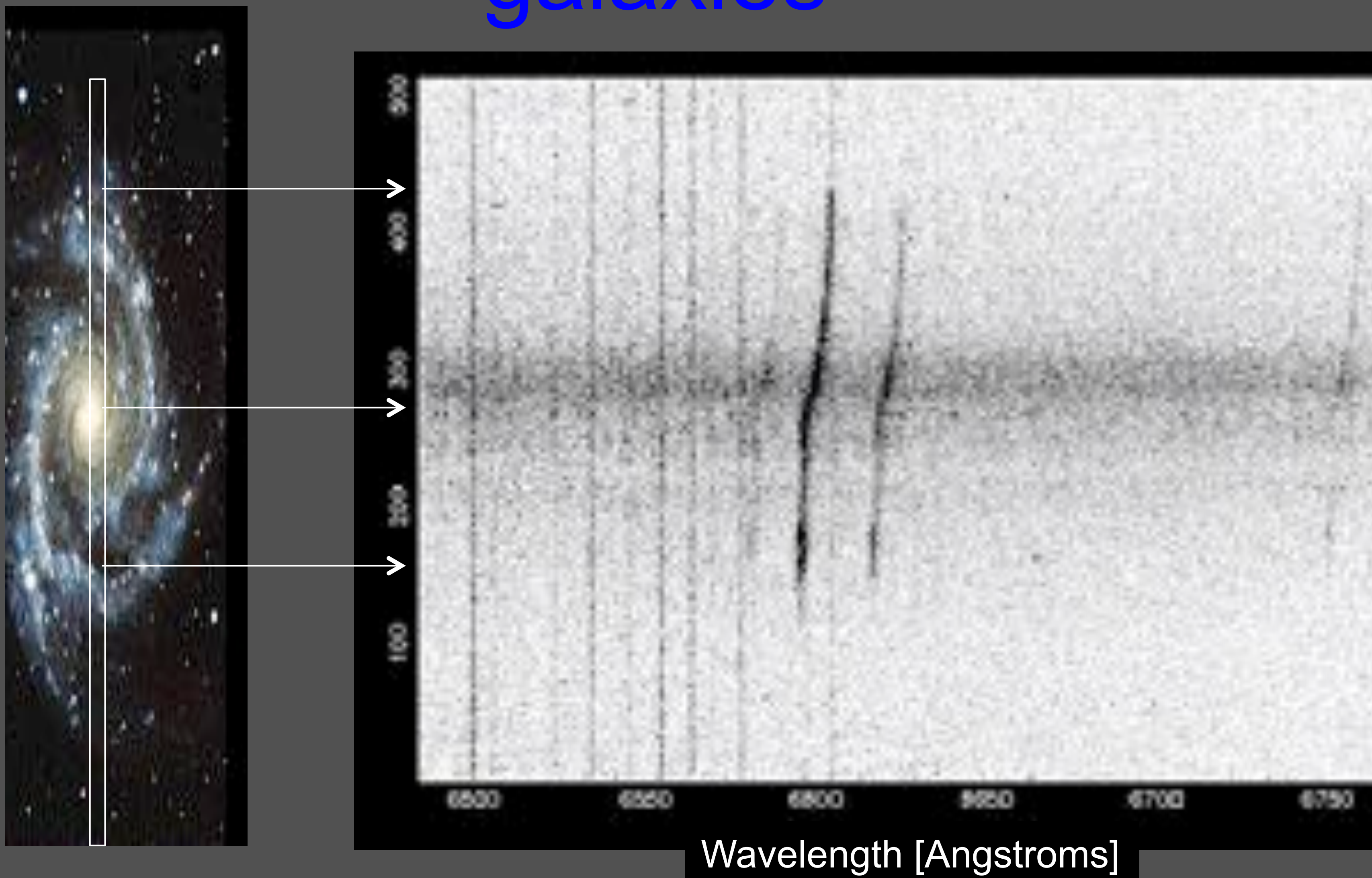
- Known since the 1920's that galaxies like the Milky Way rotate



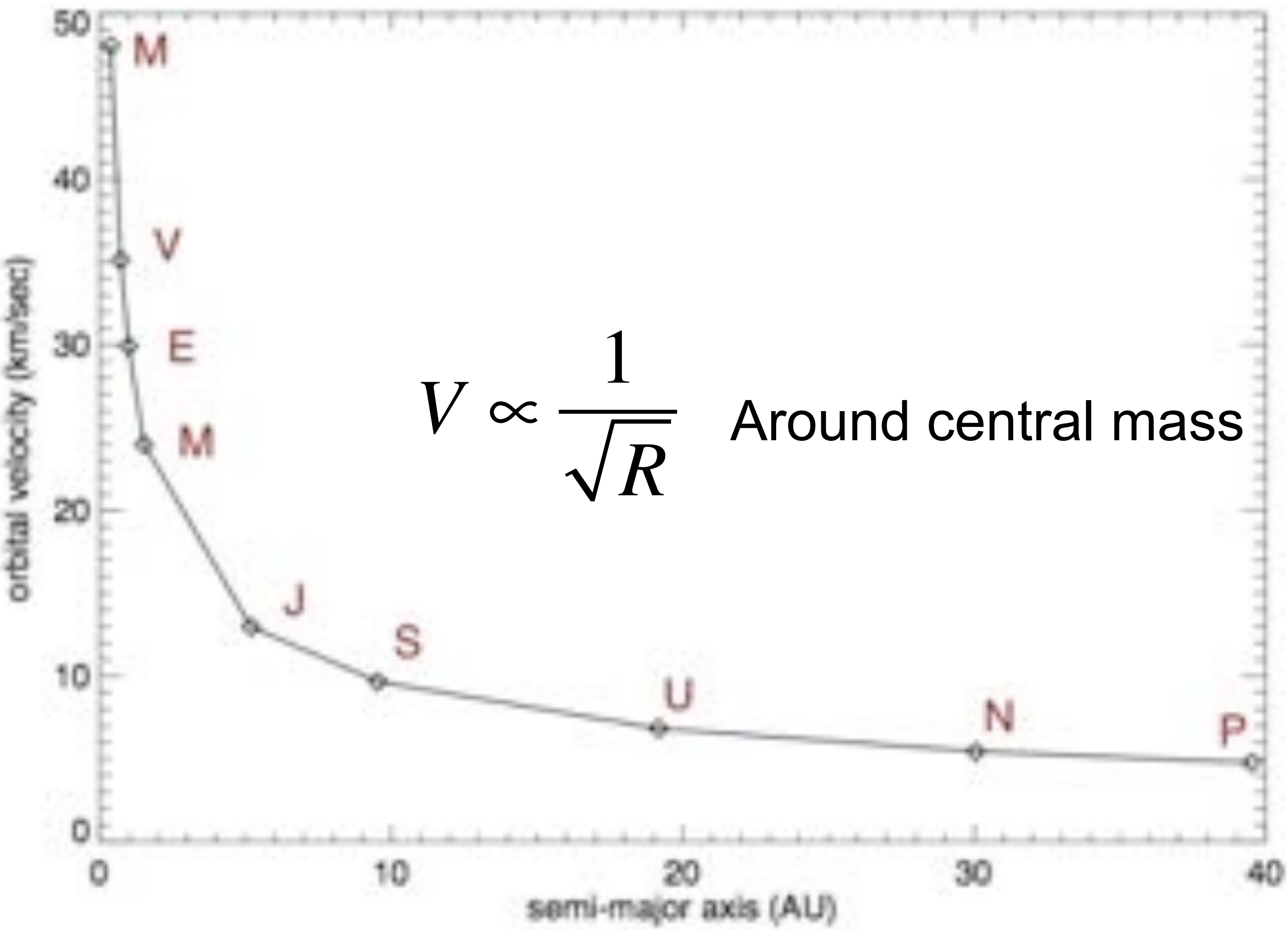
Dark Matter - Rotation curves of galaxies



Dark Matter - Rotation curves of galaxies



Kepler – orbital velocity



$$V \propto \frac{1}{\sqrt{R}}$$ Around central mass

Mass of Milky Way inside sun's orbit

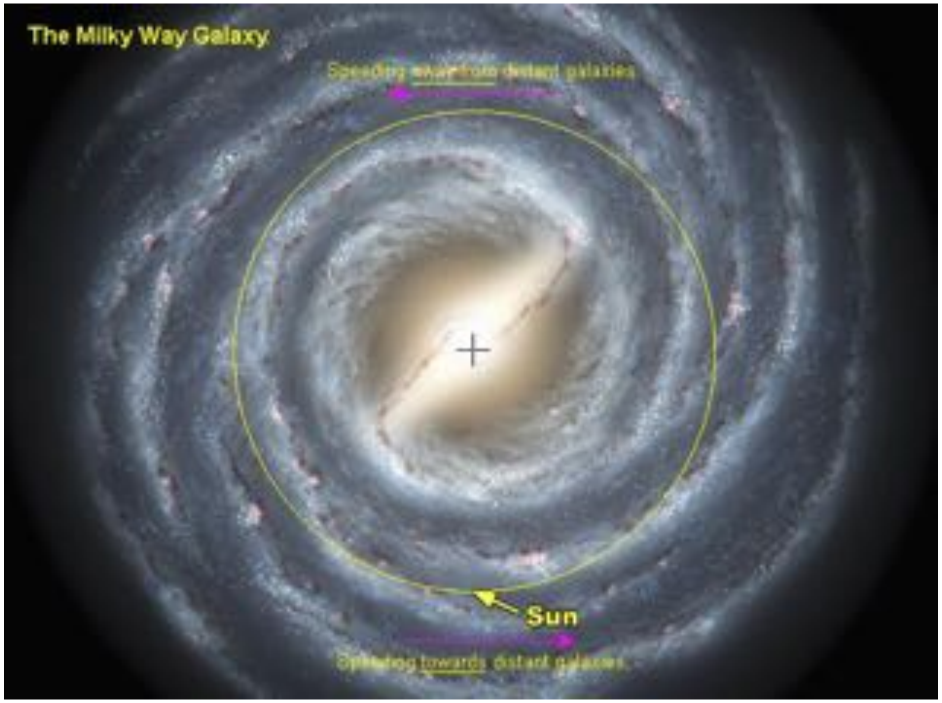
- Mass outside sun's orbit is irrelevant - why?

Box 23-2 p. 618 FK

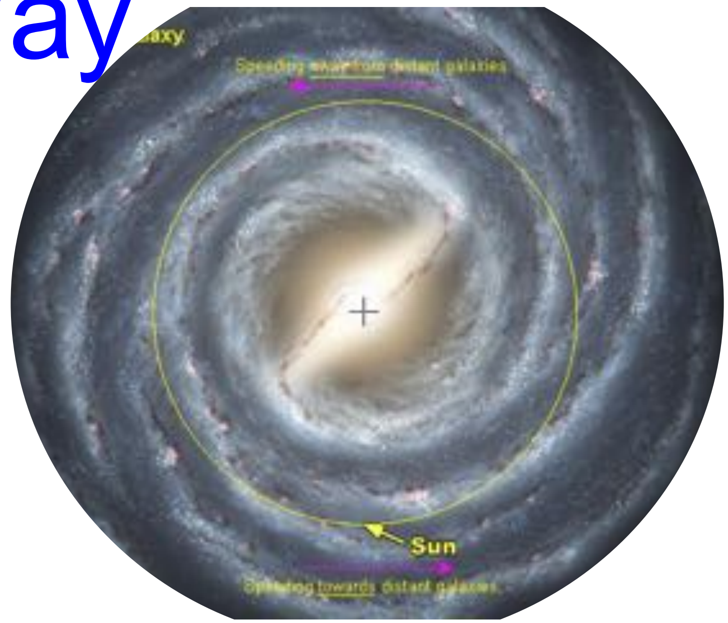
$$M = \frac{v^2 R}{G} \text{ (show)}$$

$$v = 220 \text{ km/s}, R = 8000 \text{ pc}$$

$$\mathrm{M} \simeq 10^{11} \mathrm{M}_{\odot}$$



Rotation velocity *outside* Milky Way



- What happens beyond the "edge" of a galaxy, where there's no more mass?

$$M = \frac{v^2 R}{G} \text{ as before } \rightarrow v^2 = \frac{GM}{R}$$

But M = constant for $R > R_{\odot}$ (orbit) [why?]

So $v \propto \frac{1}{R^{1/2}}$ - "Keplerian fall-off"

Milky Way Rotation Curve

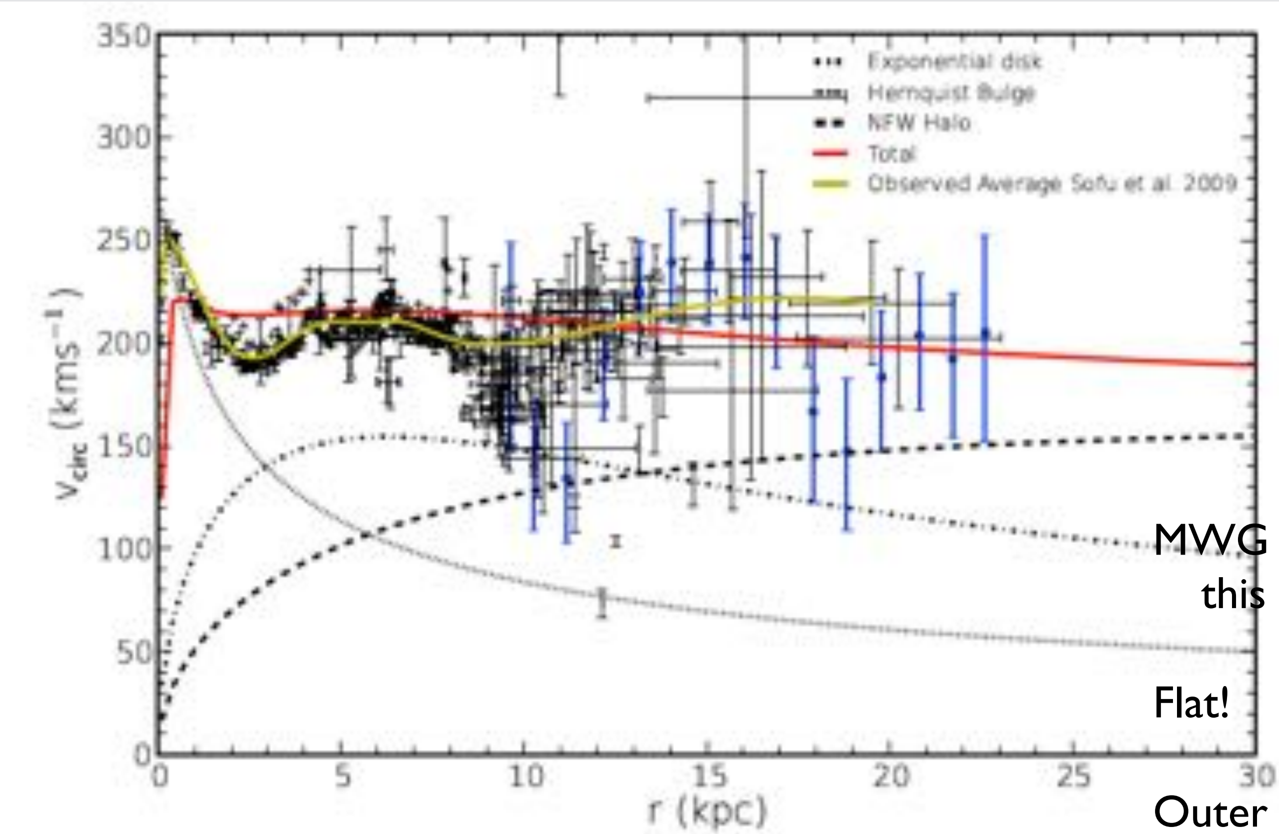


Figure 10. Circular velocity curve of the Galaxy and their individual components along a galactocentric distance (r). The blue marker represents the value of v_{circ} obtained in the CME bins in r. Red solid line is our fit of the total potential. Black dotted and dotted-dashed lines are the fitted disk and the bulge circular velocity profile for set of adopted values of masses and scale radii. Dashed line is the fitted NFW profile. Black dots with error bars are the collated v_{circ} values given by Sofue et al. (2009) whereas yellow solid line is the average of the given observed values.

MWG rotation curve to > 20 kpc
this is ~ 7 disk scale lengths

Flat!

Outer rotation curve is not easy!

Prajwal et al. 2012

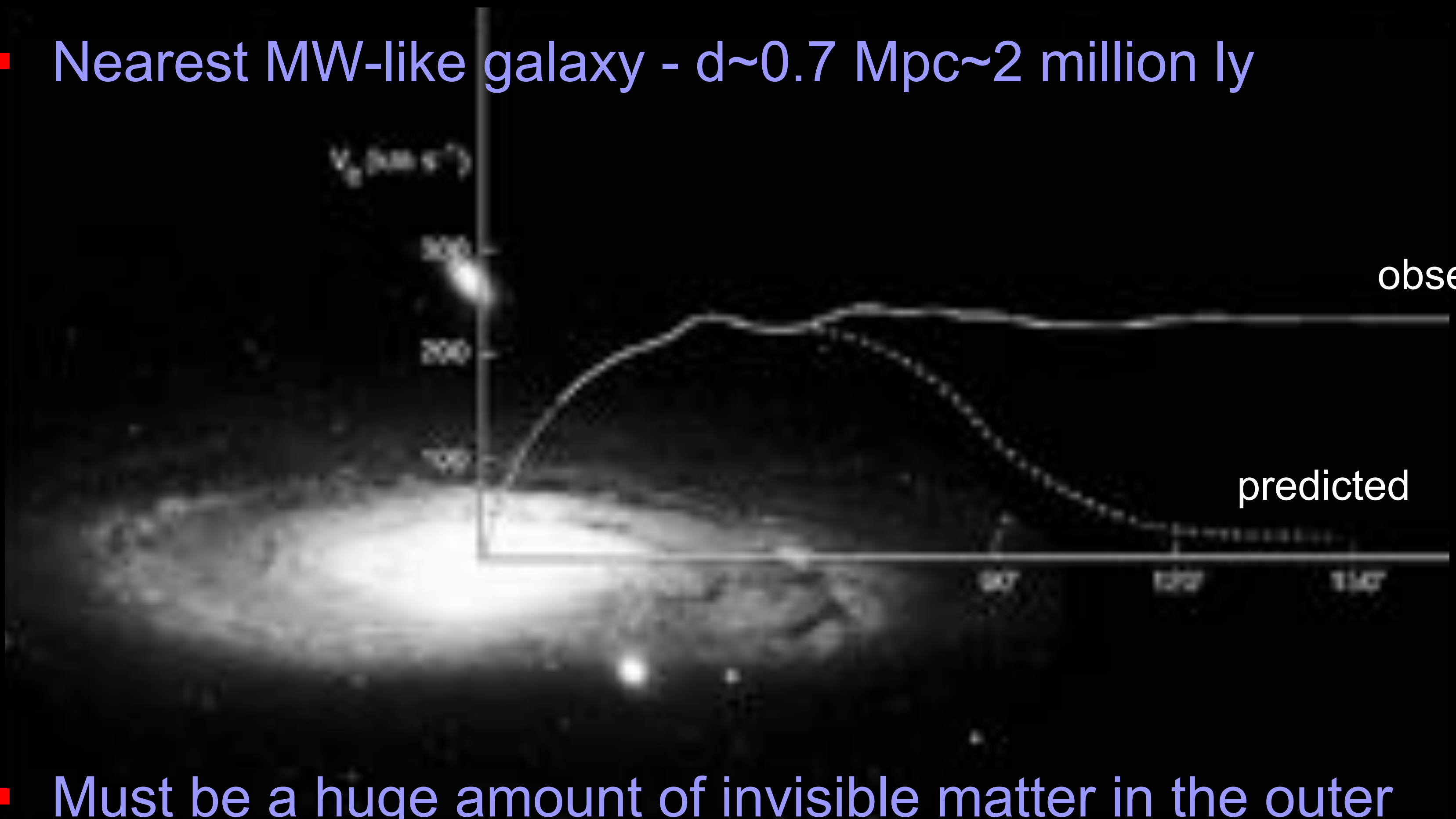
Dark Matter - Andromeda nebula

- Nearest MW-like galaxy - d~0.7 Mpc~2 million ly – easier – radio data

- Must be a huge amount of invisible matter in the outer regions - it is ***DARK!***

Dark Matter - Andromeda nebula

- Nearest MW-like galaxy - d~0.7 Mpc~2 million ly

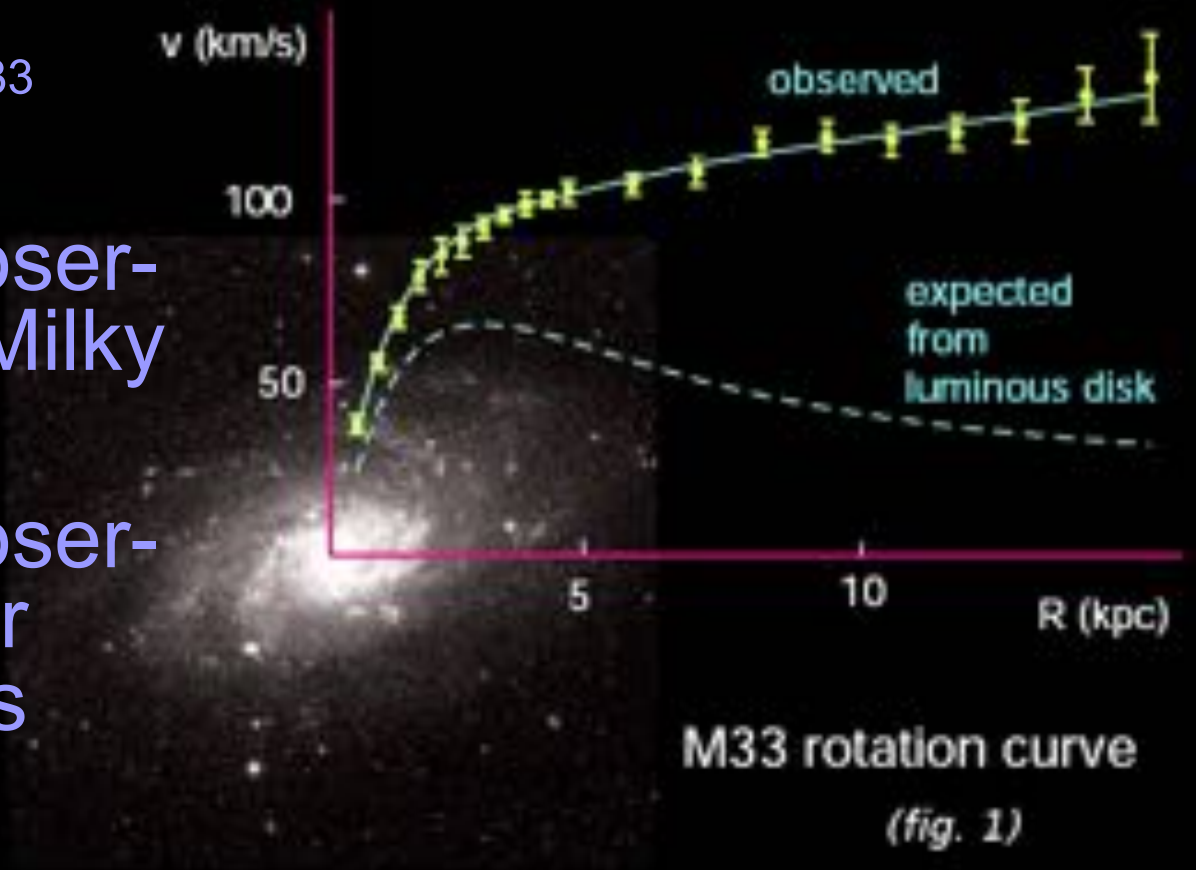


- Must be a huge amount of invisible matter in the outer regions - it is ***DARK!***

Dark matter from rotation curves - 1975

Another example - M33

- Agrees with observations in the Milky Way
- Agrees with observations of other similar galaxies



90% of matter in galaxies and clusters is "dark", only 10% is "luminous" - e.g. stars.

What does v=const mean?

Let M_R = mass enclosed within R,

$\rho(R) =$ density at R

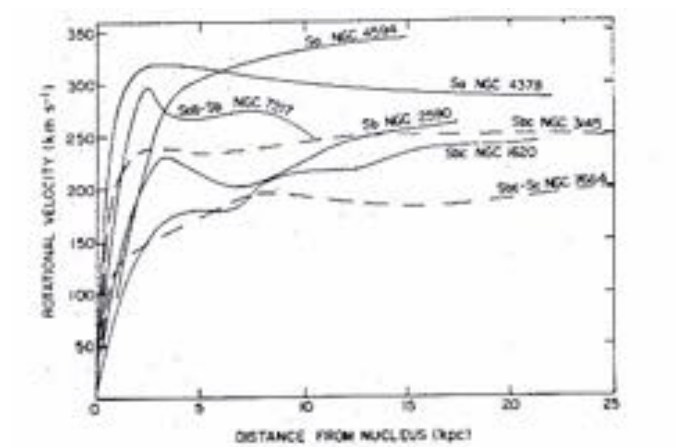
$$v^2 = \frac{GM_R}{R} = \text{constant - what does this mean?}$$

Answer: $M_R \propto R$

What does this mean? Assume a spherical distribution with a power-law density distribution $\rho(R) = c / R^n$

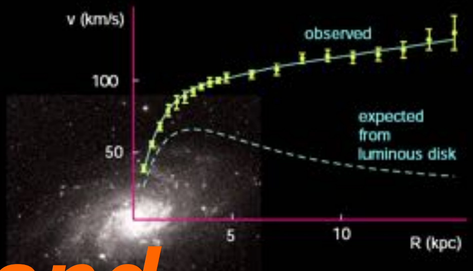
$$M_R = \int_0^R 4\pi r^2 \rho(r)\, dr = 4\pi c \int_0^R r^2 r^{-n}\, dr = \ldots = \frac{4\pi c}{3-n} R^{3-n}$$

Result: $M_R \propto R^{3-n}$



Flat (constant velocity) rotation curves mean n=2 - i.e. galaxies possess enormous halos of material with $\rho \propto 1 / R^2$.

Dark matter



M33 rotation curve
(fig. 1)

- ***90% of matter in galaxies and clusters is "dark", only about 10% is "luminous" - e.g. stars.***
  - ***From motions in clusters of galaxies, and from rotation curves of individual galaxies***

- ***Dark matter is associated with individual objects like galaxies and clusters, and not just spread diffusely through the Universe***

The Dark Matter is **not** …

- **Not**: stars gas rocks baseballs
- **Not**: mini-blackholes
- **Not:** blah blah blah

The Dark Matter is **not** …

- Not: Massive black holes?
  - Would see their effect - tides, X-rays, …

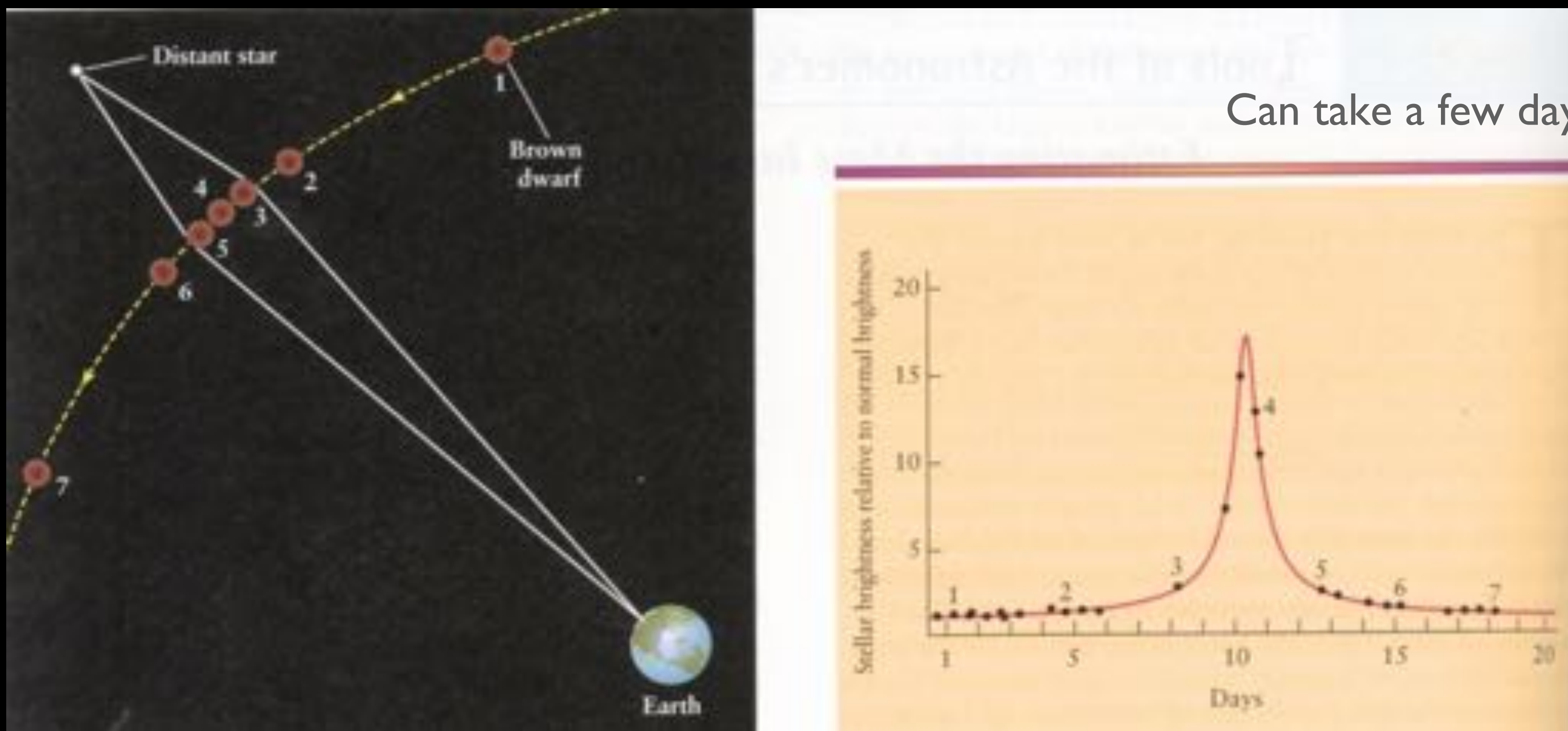
Dark matter – could it be …?

- Dark stars ?
  - E.g. neutron stars, black holes, white dwarfs, black dwarfs, red dwarfs, brown dwarfs …?

https://www.youtube.com/watch?v=gonDj95O_VE

What is the Dark Matter?

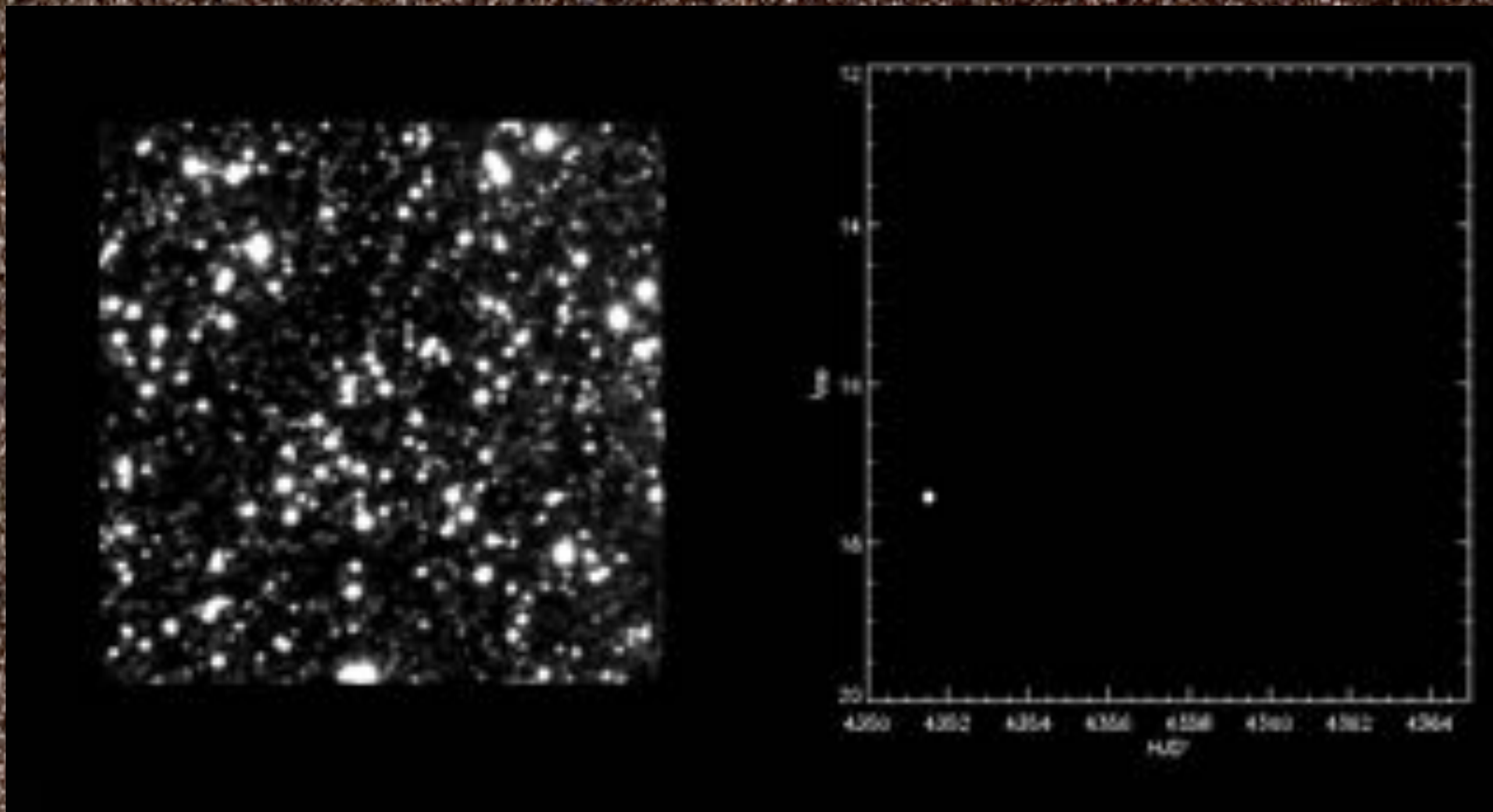
MACHOs
microlensing experiments towards the LMC



Can take a few days

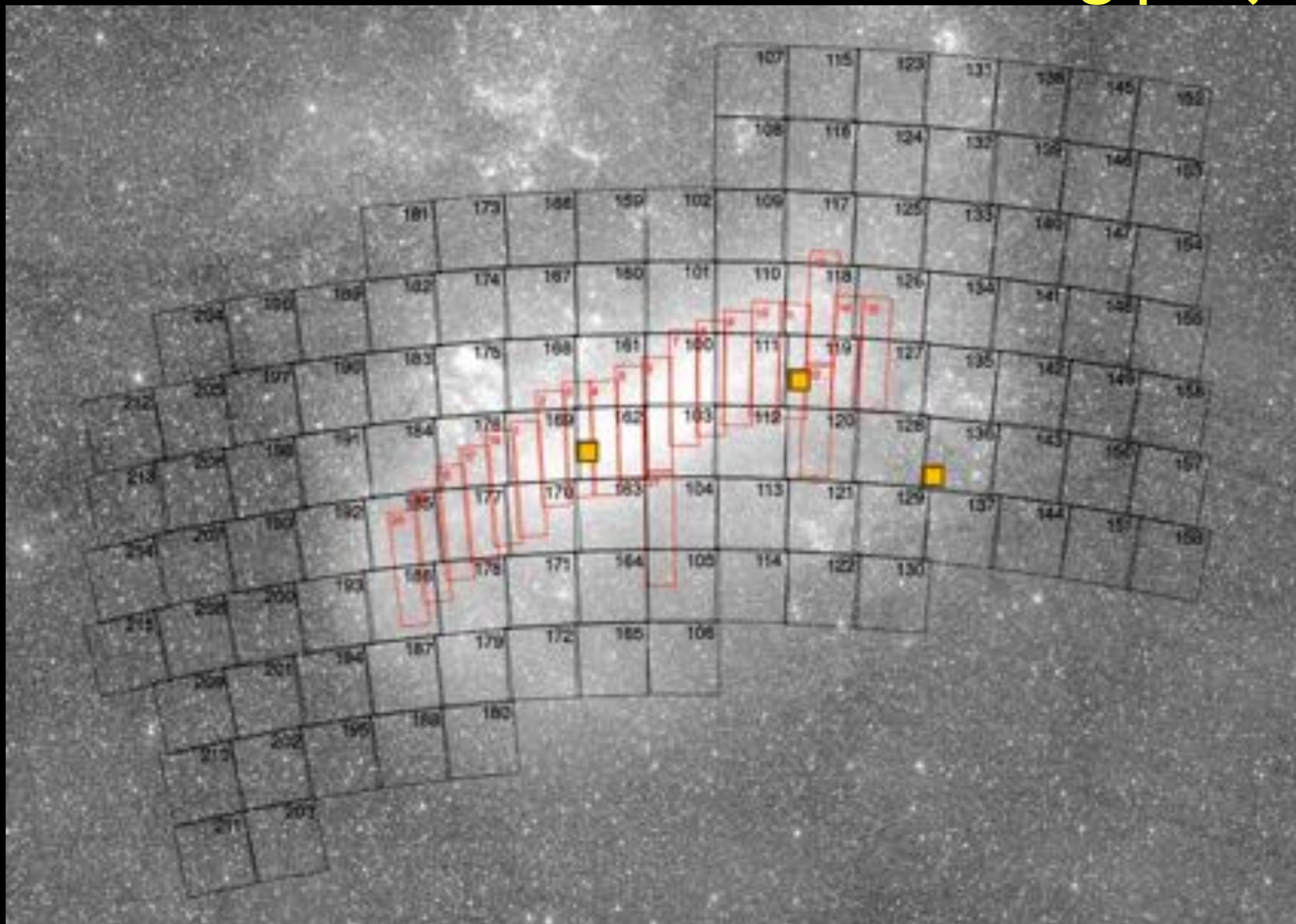
Gravitational lensing

Gravitational lensing



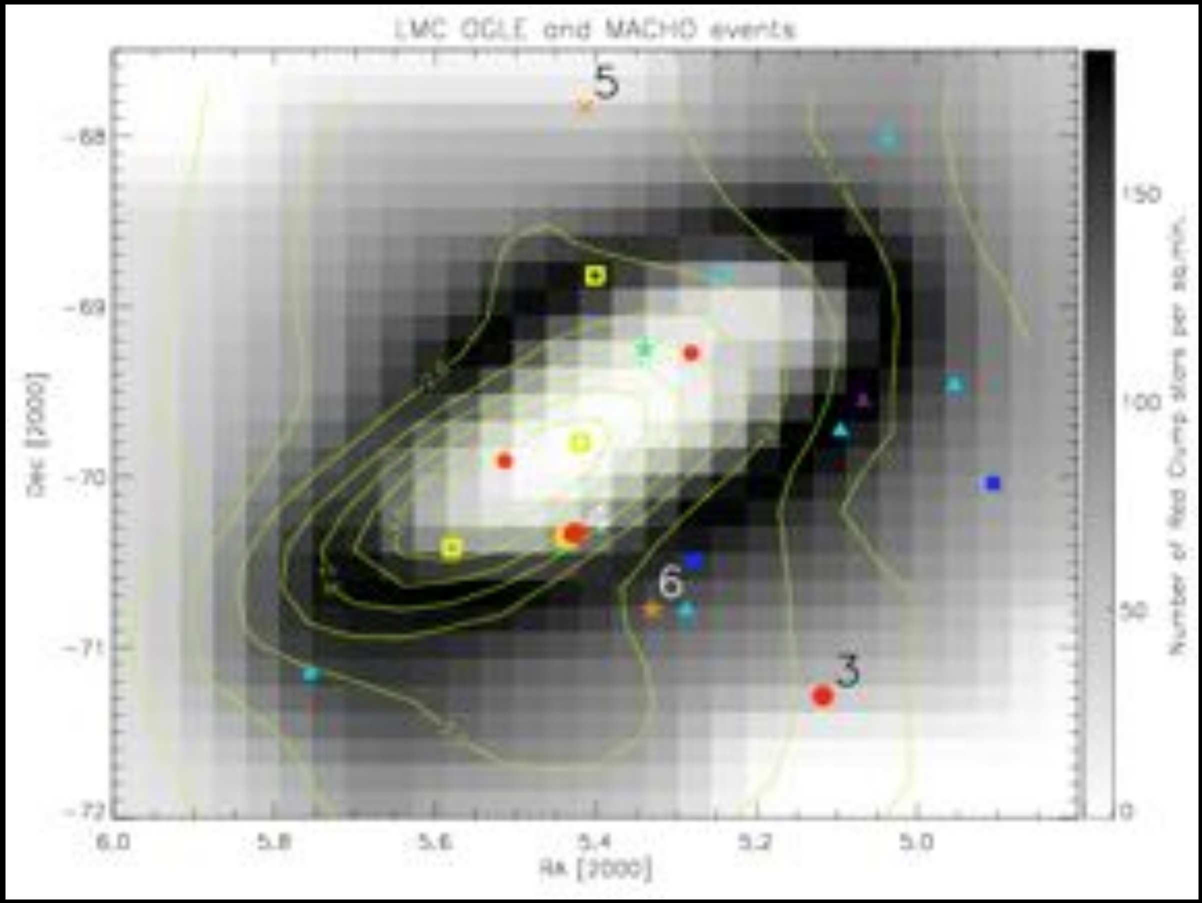
http://www.youtube.com/watch?v=J_w1OJlXTzg

OGLE, MACHO, & HST microlensing projects



Location of Lensing events towards the LMC

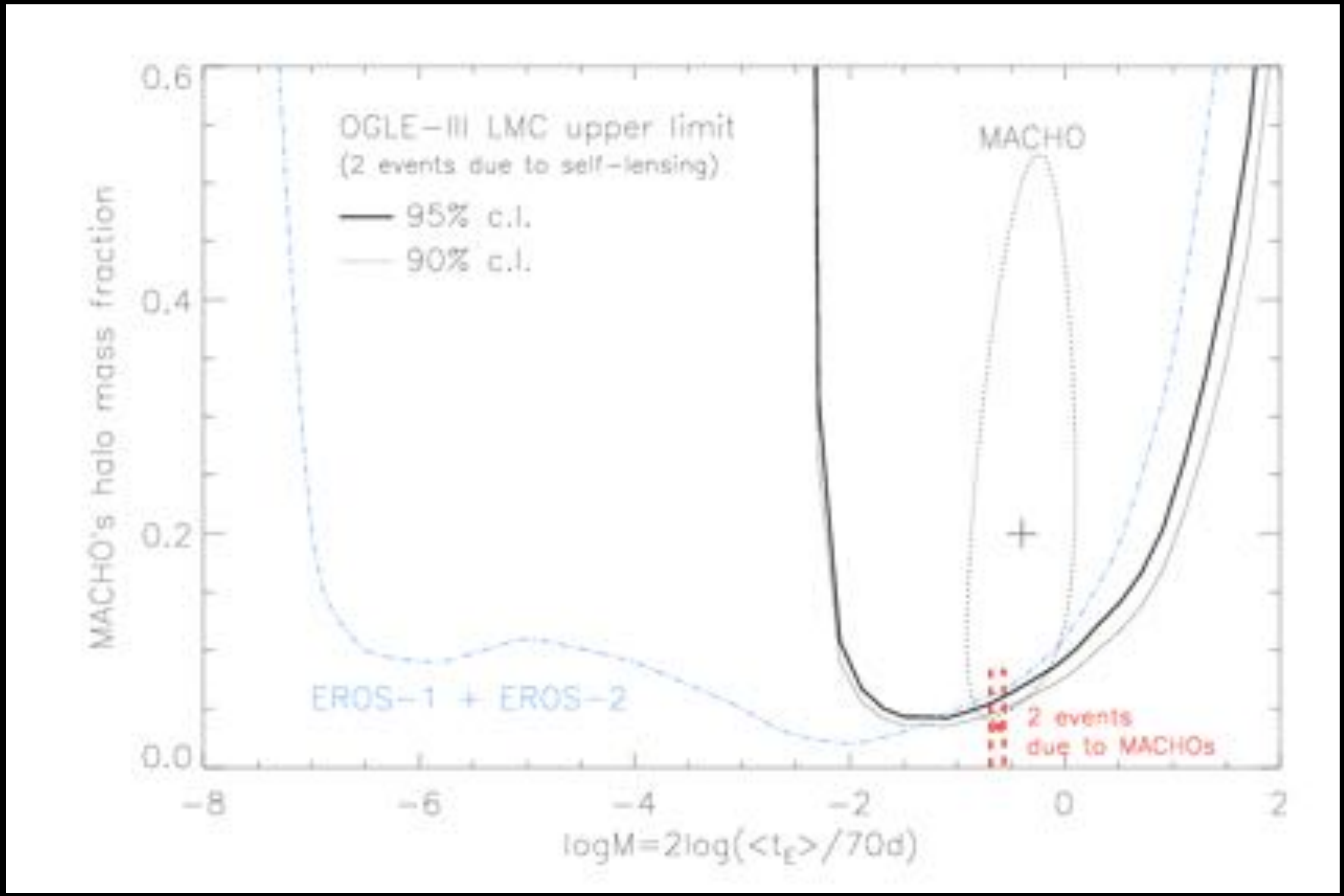
Not that many between 2001 - 2009



OGLE, MACHO, EROS microlensing results

MACHO & OGLE constrains the mass of the lensing objects well, whereas EROS constrains the mass of the halo as lensing objects well. Together suggests less than 10% galactic halo due to 0.01 - 10 M⊙ objects.

Nowhere near the 90% total mass needed to explain rotation curves



The Dark Matter is **not** …

- **Not**: White dwarfs, neutron stars, stellar mass black holes!
  - MACHO, OGLE surveys for lensing events

http://www.youtube.com/watch?v=J_w1OJlXTzg

What is the Dark Matter?

Large Hadron Collider, Geneva

What is the Dark Matter?

- Exotic particles?
  - Probably, though what exactly? a number of candidates that could work …
  - almost certainly "weakly interacting" with ordinary matter (somewhat like neutrinos)

Dark Matter Summary

90% of the matter in the Universe is in a form that doesn't interact with ordinary matter. We don't know what it is, though there are some ideas from particle physics. It is contained in galaxies, and in clusters of galaxies

Evidence:

1. Motions of galaxies in clusters
2. Rotation curves of galaxies

Dark Matter Summary

During the Twentieth Century astronomers have discovered that the Universe contains ~10 times more mass than had previously been suspected; most of it in forms that are very difficult to observe (see Table 2). It is slightly disconcerting that perhaps only 0.001% of humanity is presently aware of the enormous paradigm shift towards a universe in which 99% is in invisible form. One of the reasons for this is, no doubt, that we live on Earth, which has a mean density that is almost 30 orders of magnitude greater than the mean density of the universe. In other words, we live in an atypical environment in which cold baryonic matter dominates over the dark energy of the vacuum by an overwhelming factor. In some ways the revolutionary discovery that ~99% of the mass of the universe is in invisible form was similar to the quantum revolution of the 1920s, of which Sam Treiman wrote: “There was no immediate commotion in the streets. Only a small band of scientists were participating in or paying close attention to these developments.”

van den Bergh 2001