Week 14 Tuesday

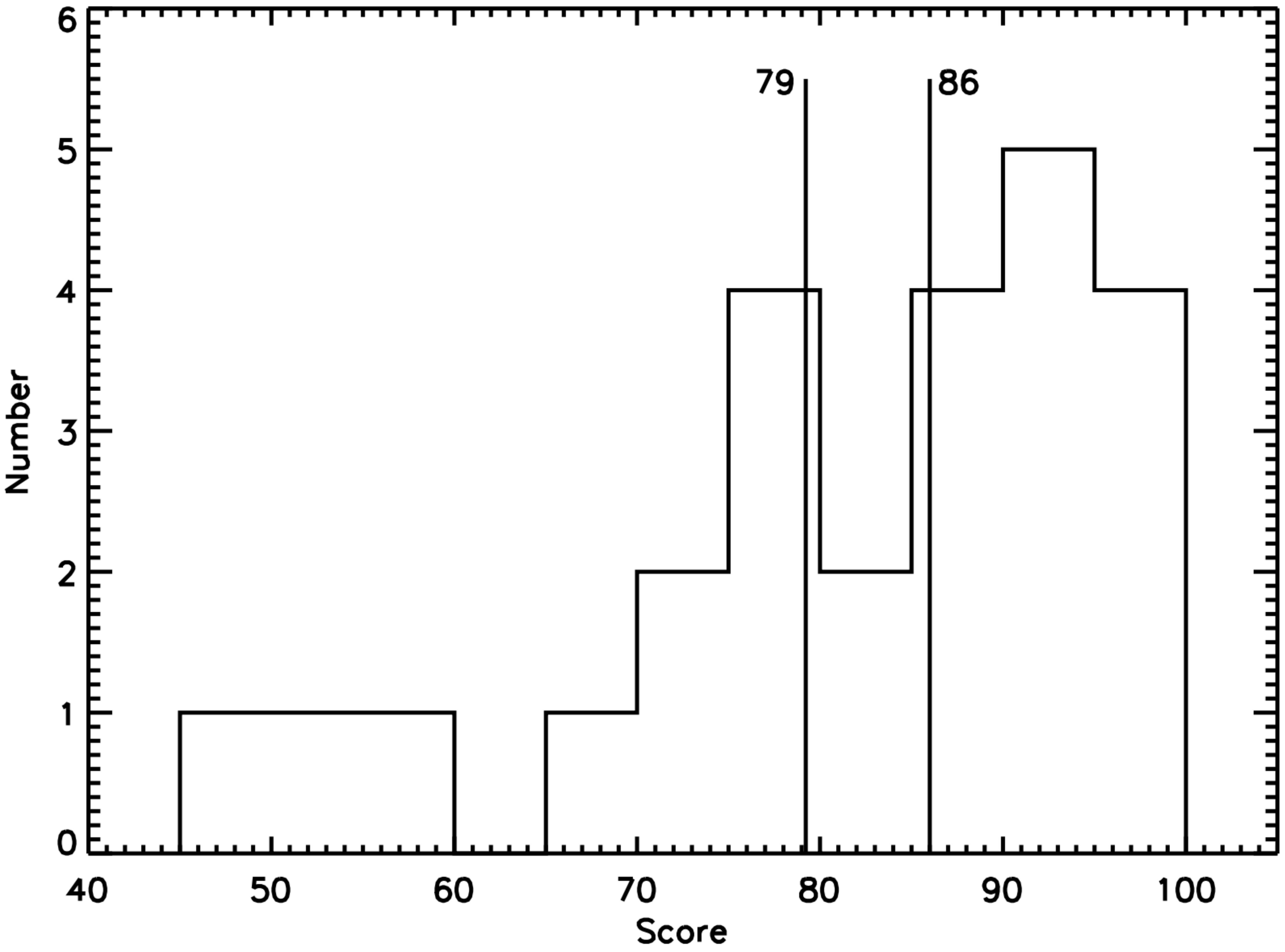
Today's Agenda

- Midterm 2 returned
- Black Holes & XRBs
- Group Discussion
- Milky Way structure
- Evidence for dark matter
- Galaxy types

Announcements / Reminders

- Read Chapter 20 (19 would be good too, but not required
- No HW due this Friday!

Midterm 2 Results



Mean similar to Midterm 1 (81) but the median is better than before (82)

Black Holes

If the Sun suddenly collapsed and formed a black hole, what would happen to the Earth?

For a spherically symmetric object, its gravitational force (outside the object) is identical to that of an object with the same mass all at *r* = 0 —> exactly the case of a black hole!

The escape speed for a BH is the same as usual then, but b/c we can get much closer to them, the escape speed can get really high

$$v_{\rm esc} = \left(\frac{2GM}{r}\right)^{1/2}$$

Set $v_{\rm esc} = c$ (speed of light)

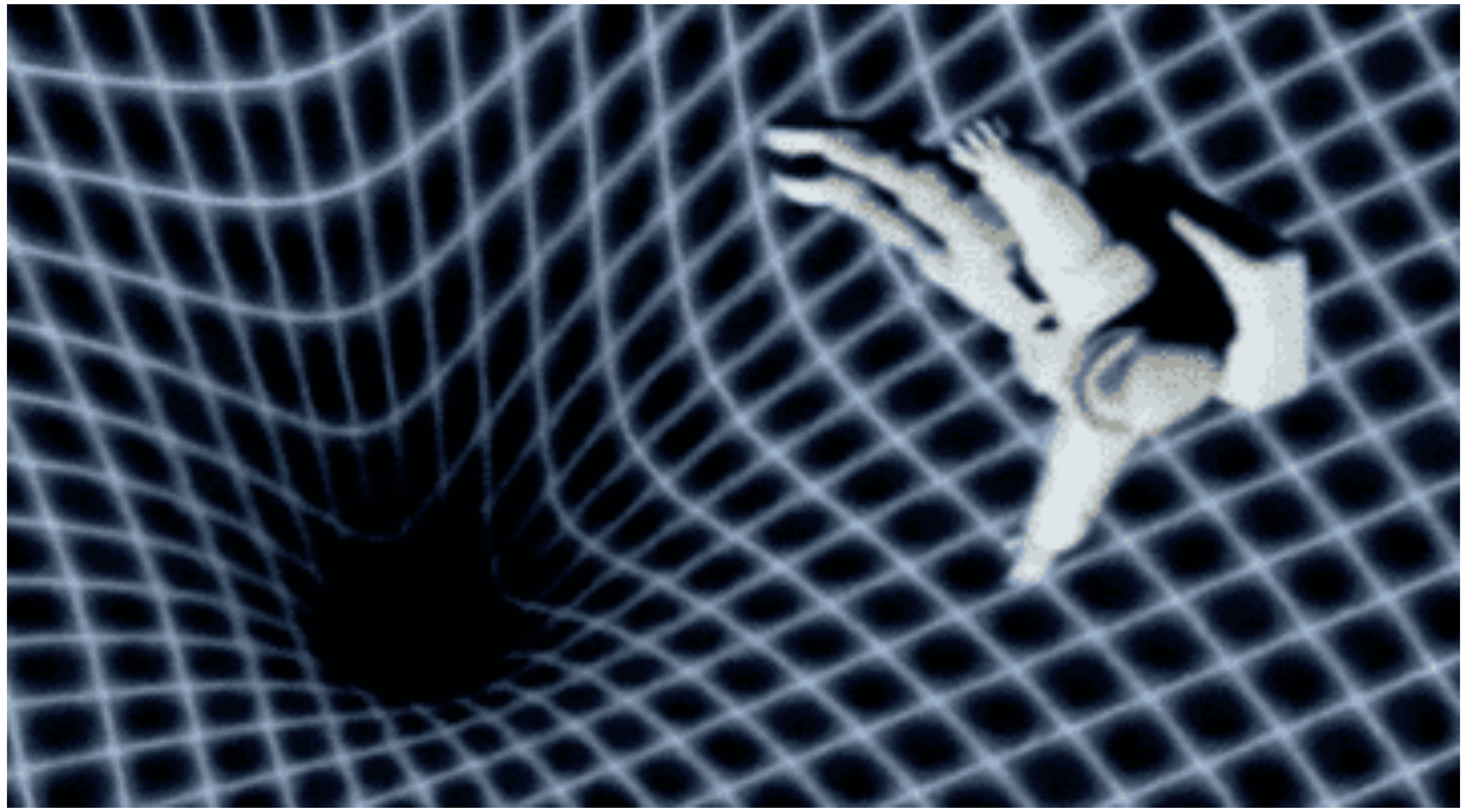
$$r_{\rm Sch} = \frac{2GM}{c^2}$$

<u>Schwarzschild radius</u>

The spherical surface defined by this radius is called the <u>event horizon</u>

Black Holes

Spaghettification



F_g changes so quickly with radius that gravitational tidal forces (the difference in F_g between your head and your feet) become strong enough to rip you apart as you fall towards a BH's singularity

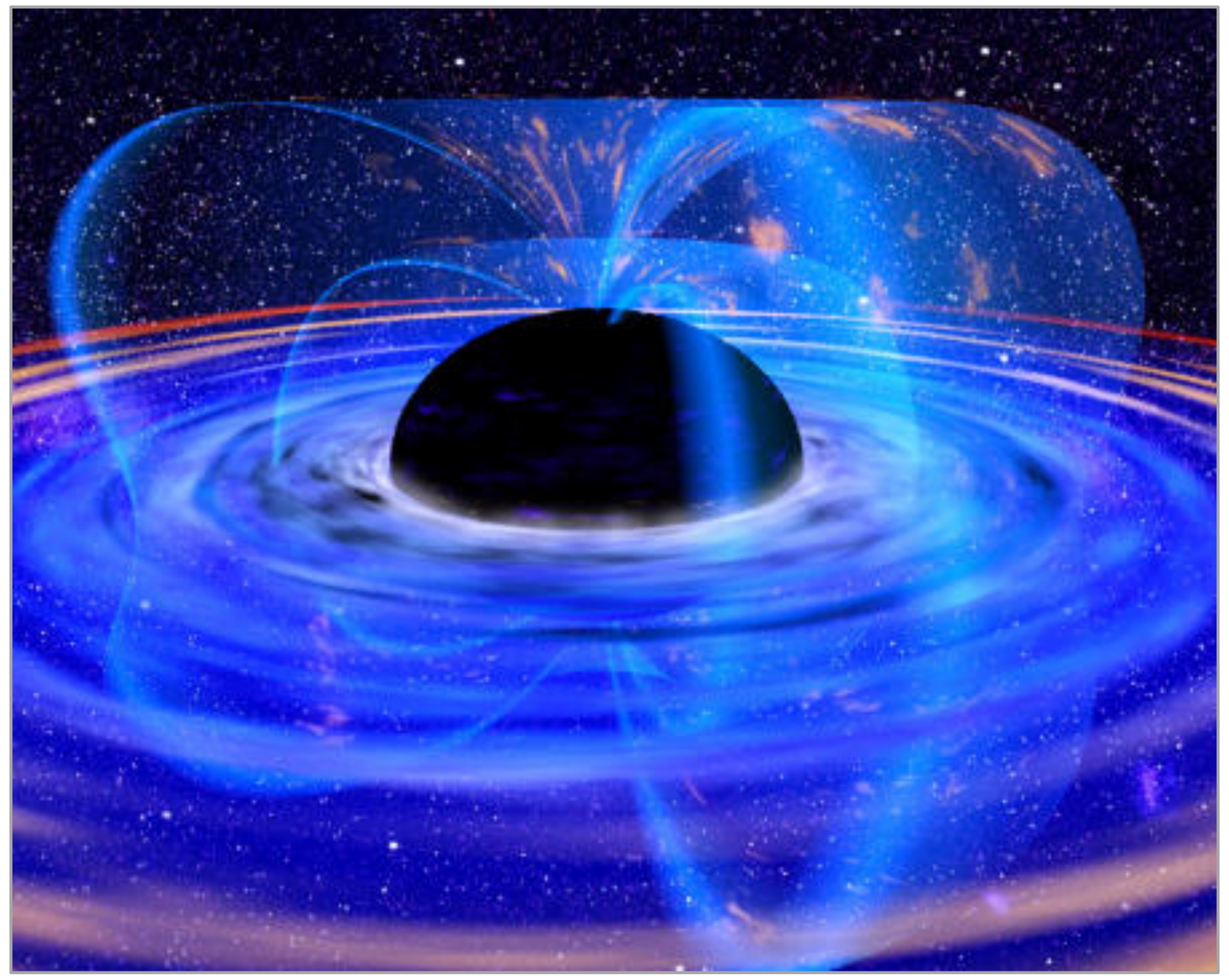
$$\Delta F \approx \frac{GMm}{r^3}\ell$$

m → Your mass

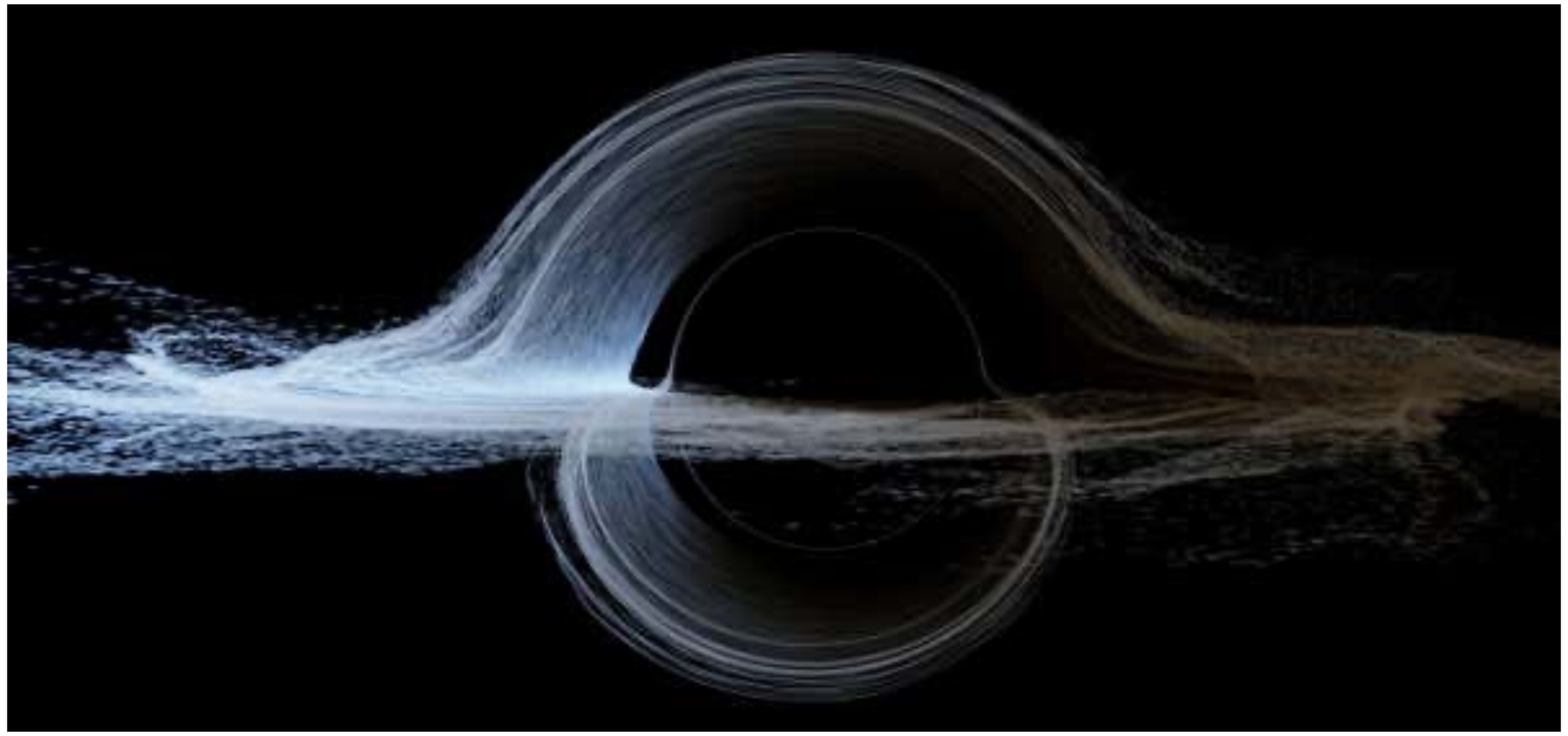
ℓ → Your height

Other effects (e.g., explaining *Interstellar*)

BH with accretion disk (no gravitational lensing)



What it would actually look like



<u>Gravitational Lensing</u>

Light follows shortest path b/t 2 points, but space-time curved, so light rays are curved

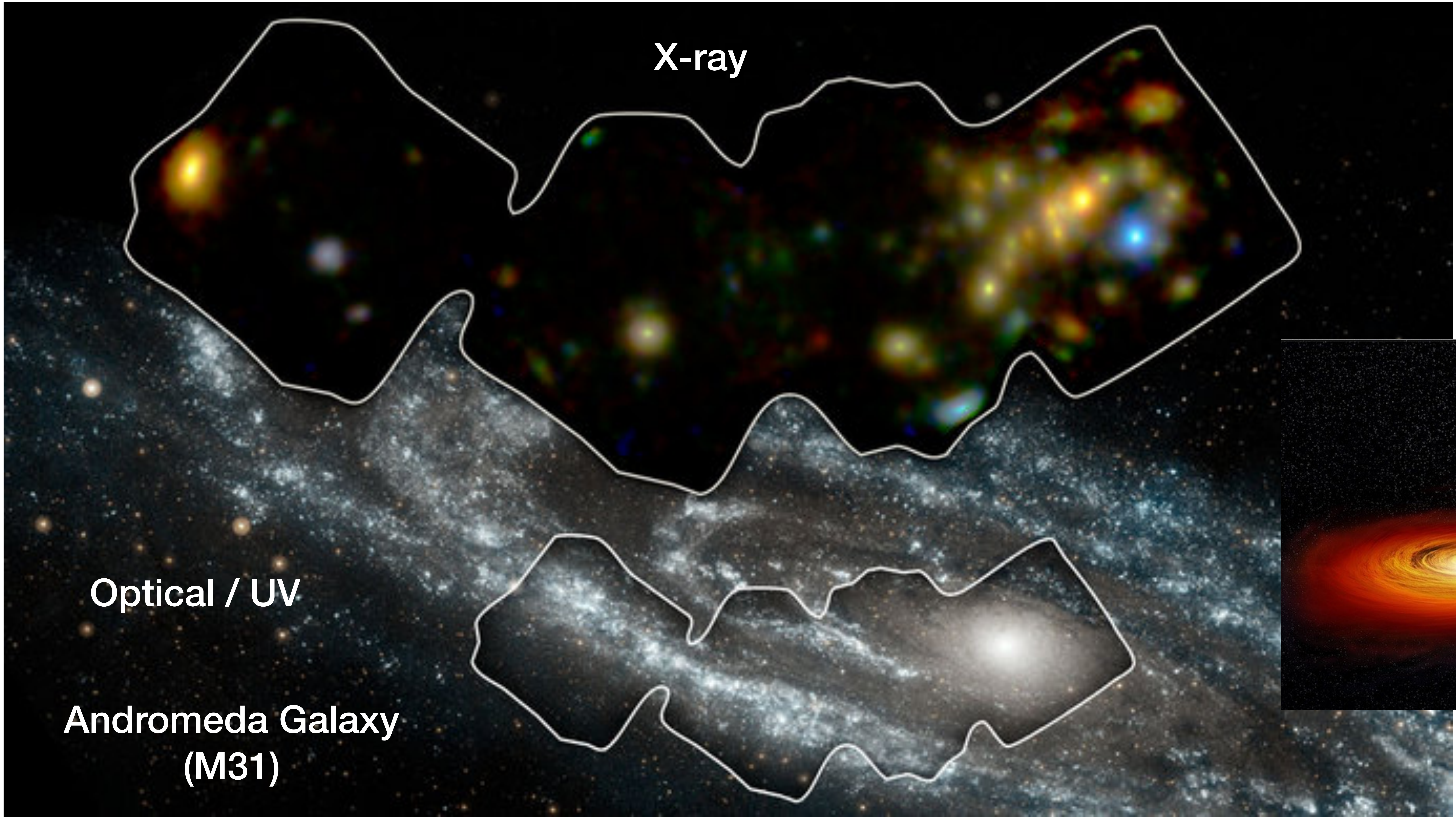
<u>Time Dilation</u>

Time passes slower the closer you are to a massive object (GPS satellite clocks "have more ticks" than our clocks in a given interval of time)

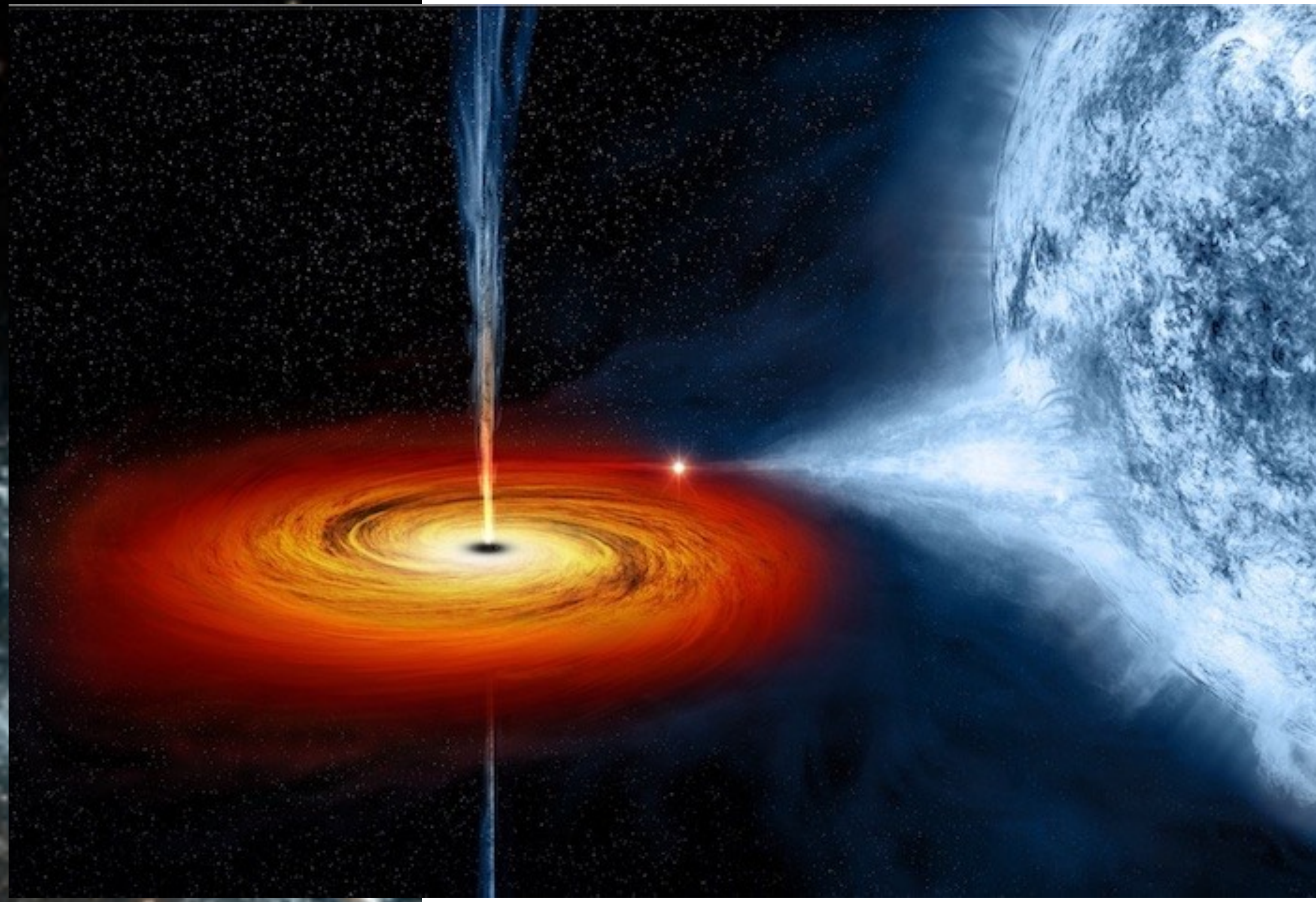
<u>Gravitational Redshift</u>

Light has to "climb out" of a gravitational potential well, losing energy — light with less energy has a longer wavelength (just outside the event horizon, light is nearly infinitely redshifted)

Observing real NSs and BHs



<u>X-ray Binaries</u>
Close binary stars where 1 star has exploded and is now accreting matter from its companion



Group Discussion Problem

The radiation powering pulsars results from high energy processes due to the very strong magnetic field of the star.

As the pulsar radiates, the star must lose energy assuming energy conservation. What is the effect of that lost energy on the star?

If the pulsar was formed with a mass very close to its Chandrasekhar mass, will it eventually become a black hole (assuming it remains isolated, accreting a trivial amount of matter over that time)?

What happens to you (at that moment) when you cross the event horizon of a black hole (defined by the Schwarzschild radius)?

From the terrible Netflix TV show *Another Life*, when they're knocked out of FTL by a flare from a MAGNETAR, which they must be awfully close to…

Star's life determined mostly by its initial mass

White Dwarf:

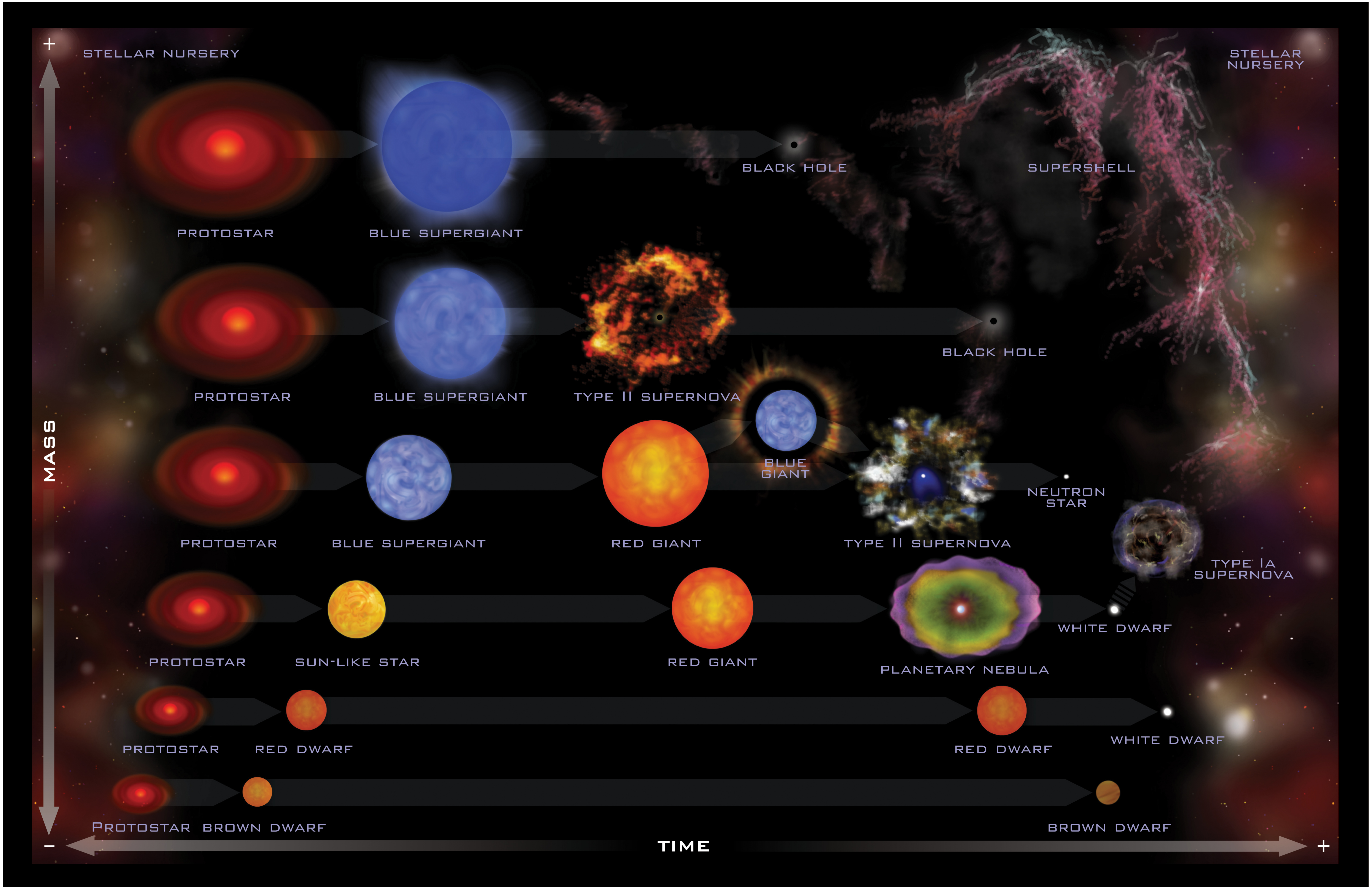
$$M < 7M_\odot$$

Neutron Star:

$$7M_\odot < M < 18M_\odot$$

Black Hole:

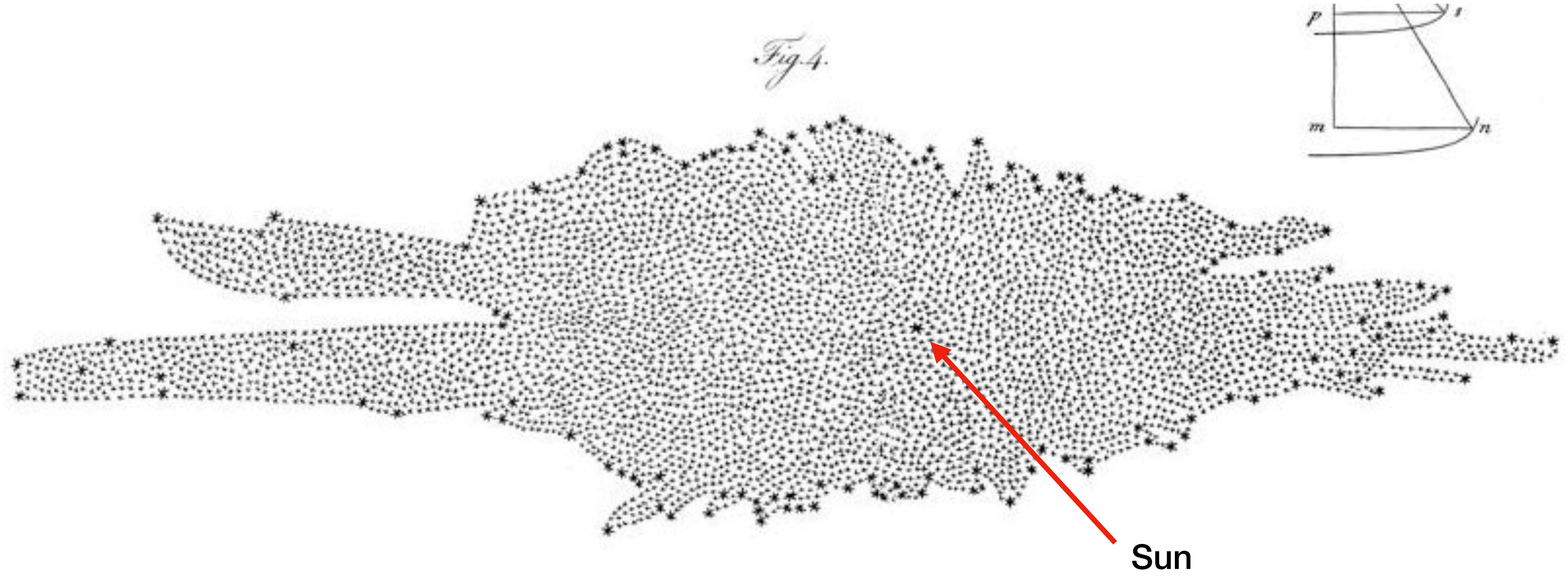
$$M > 18M_\odot$$



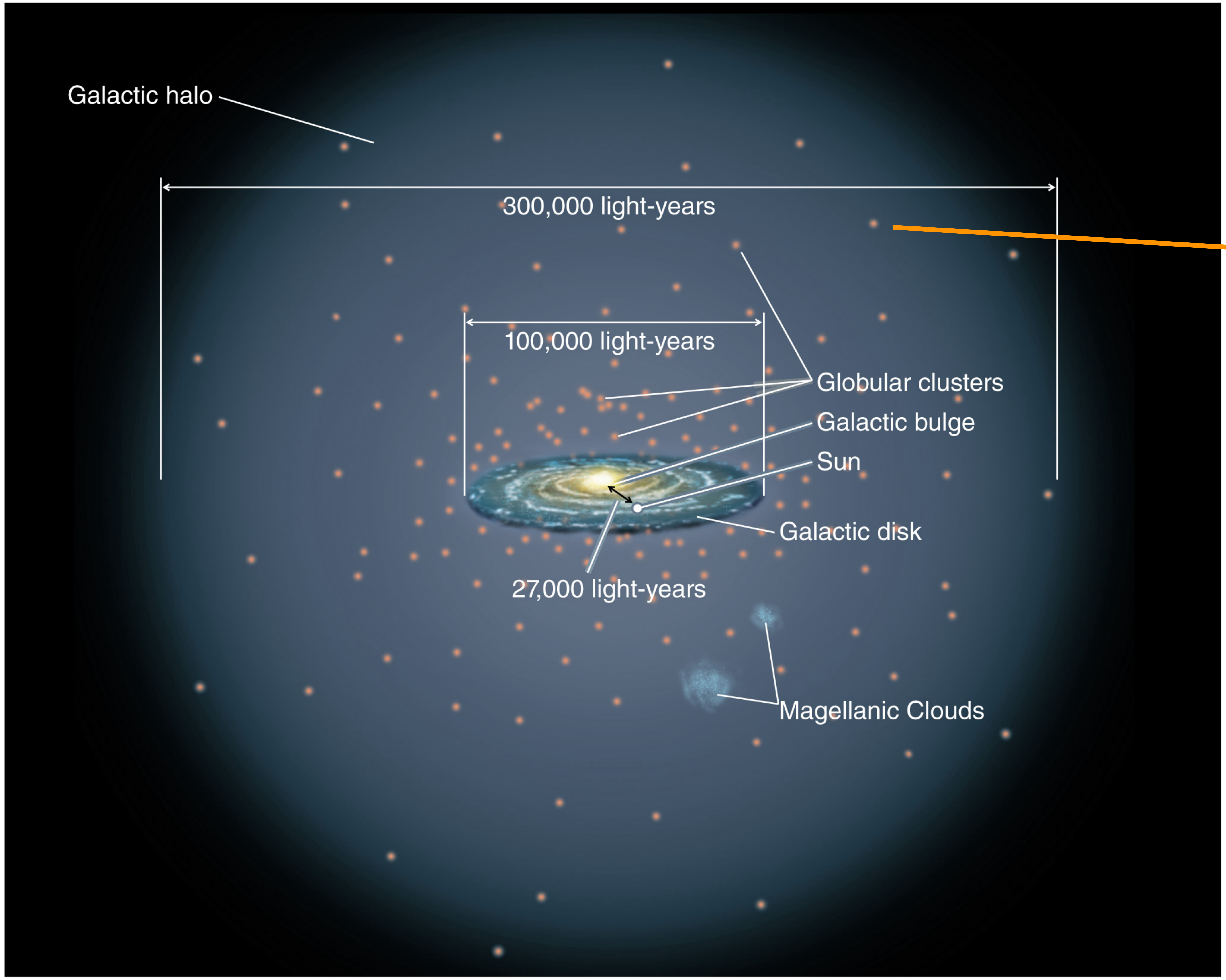
Galaxies

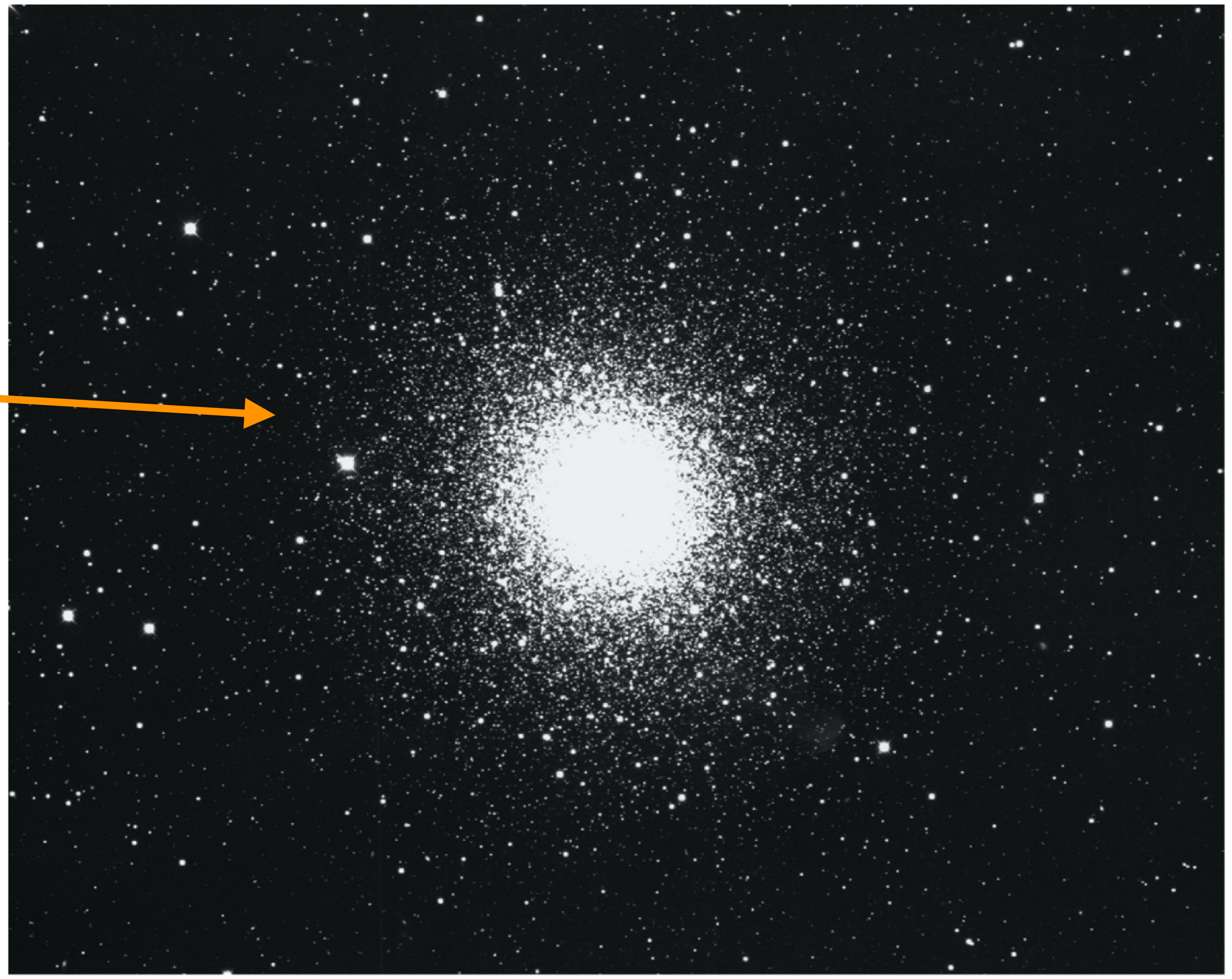
Our Galaxy, the Milky Way

Star counts: William and Caroline Herschel (1785)



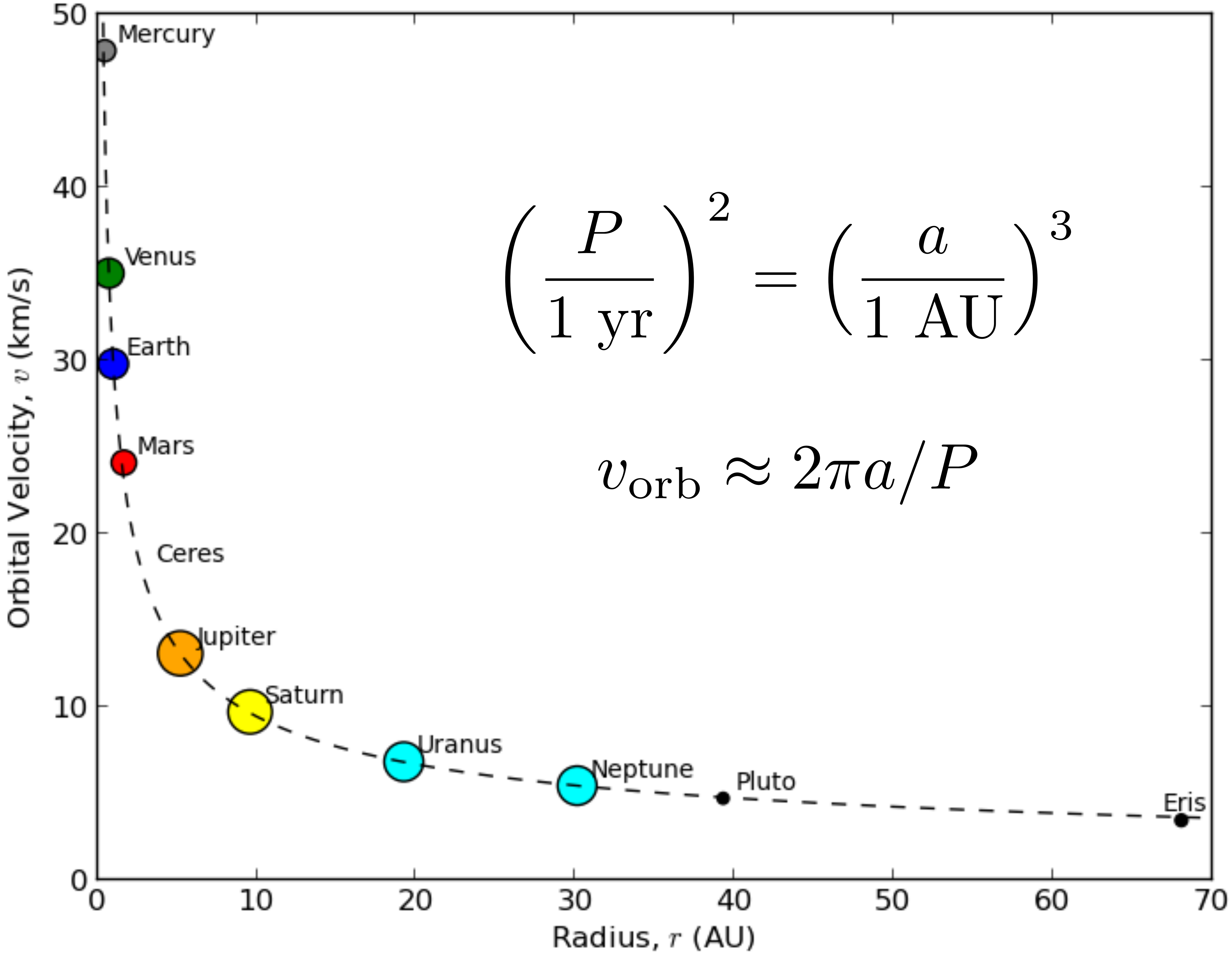
Globular clusters revealed the scale of the MW





Variable stars like Cepheids (called RR Lyrae stars) were used to estimate the distance to globular clusters, which were assumed to be distributed uniformly around the center of the MW

How do stars move in the Galaxy?



$$\left(\frac{P}{1\ \mathrm{yr}}\right)^2 = \left(\frac{a}{1\ \mathrm{AU}}\right)^3$$

$$v_{\mathrm{orb}} \approx 2\pi a/P$$

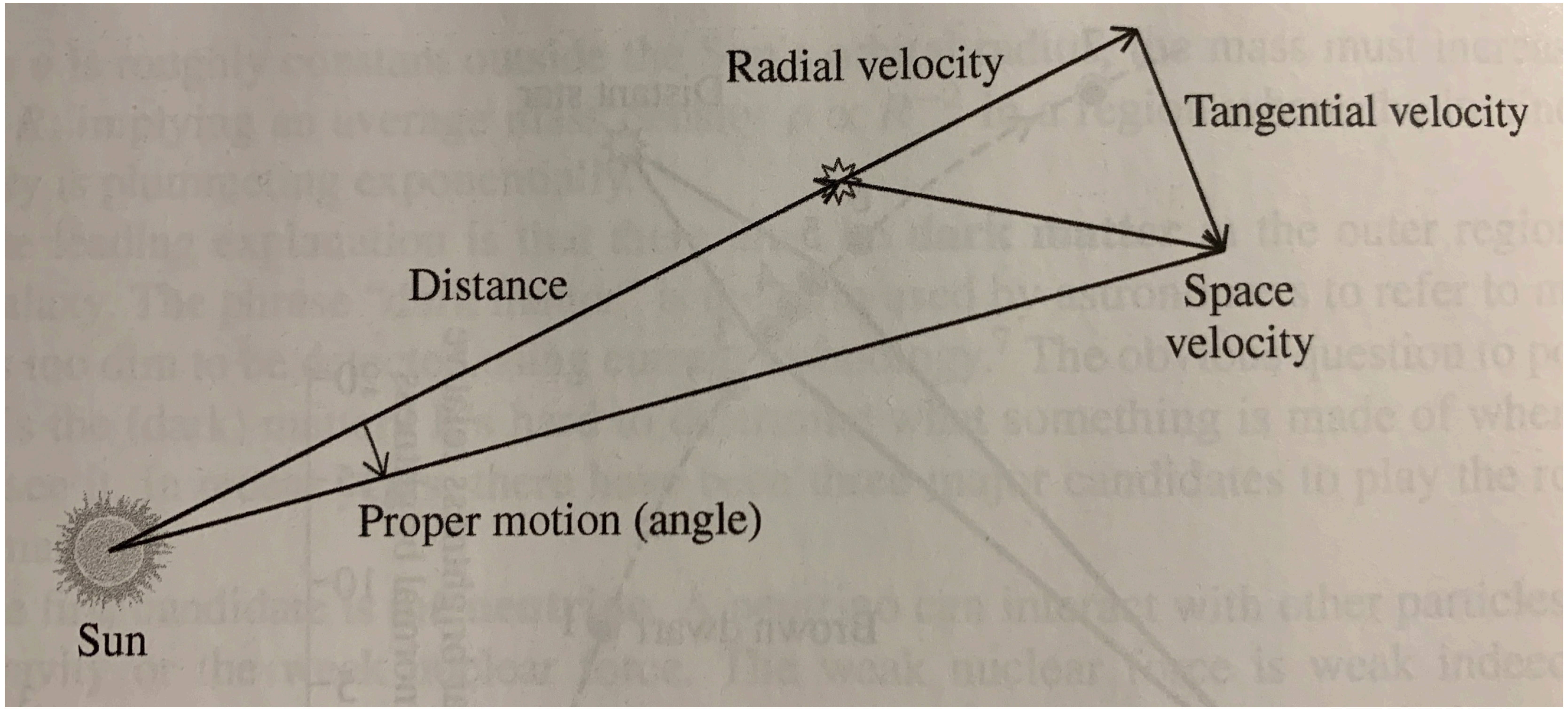
Kepler's 3rd Law in the Galaxy

$$M_\odot + M_G(< r) = \frac{(a/1\ \mathrm{AU})^3}{(P/1\ \mathrm{yr})^2}$$

Mass inside Sun's orbit

How do we get 3D star velocities?

Radial Velocity: $$v_r = \frac{\Delta\lambda}{\lambda} c$$

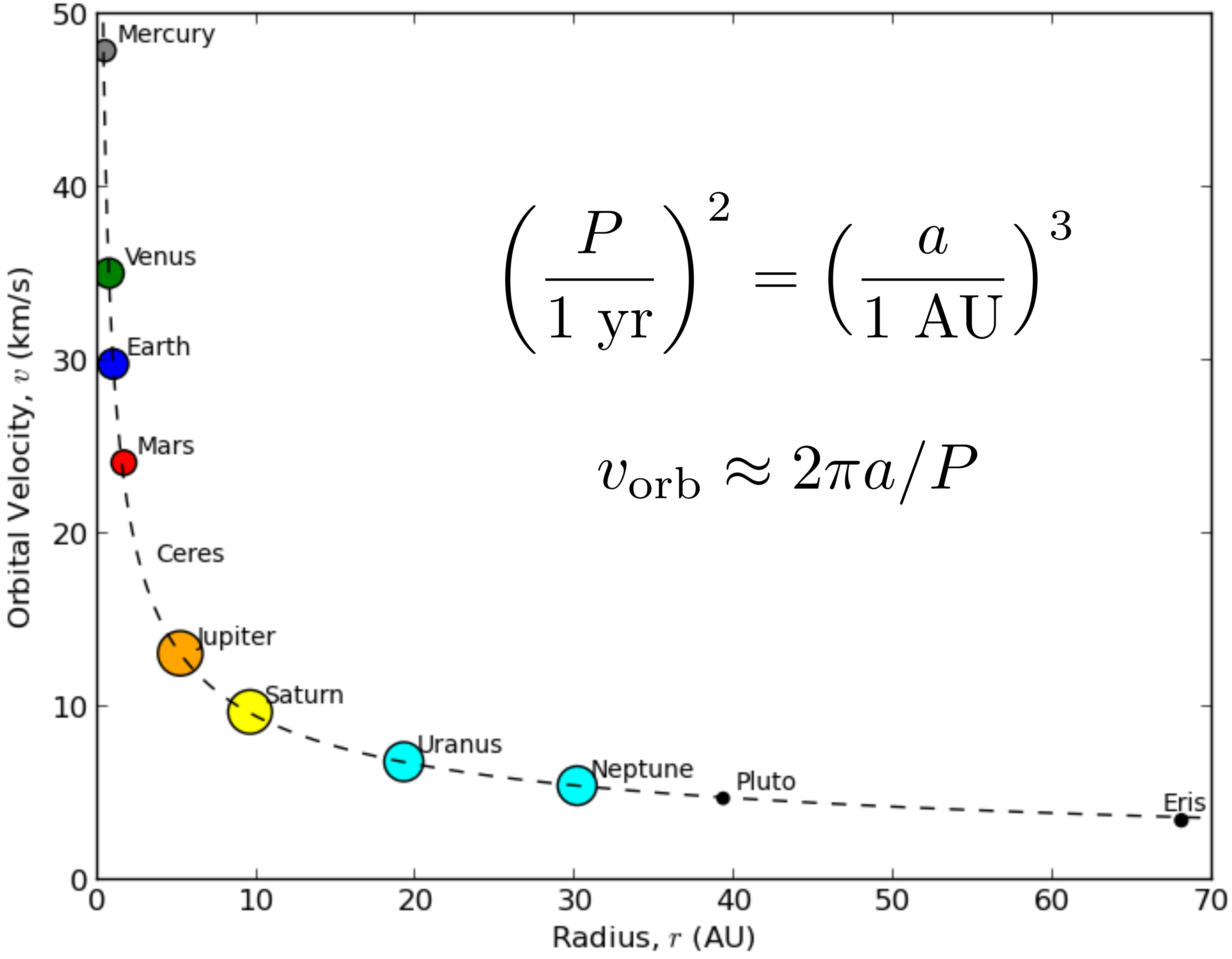


Proper Motion:

$$\mu = \frac{v_t}{d}$$

$$v = \sqrt{v_r^2 + v_t^2}$$

How do stars move in the Galaxy?



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Kepler's 3rd Law in the Galaxy

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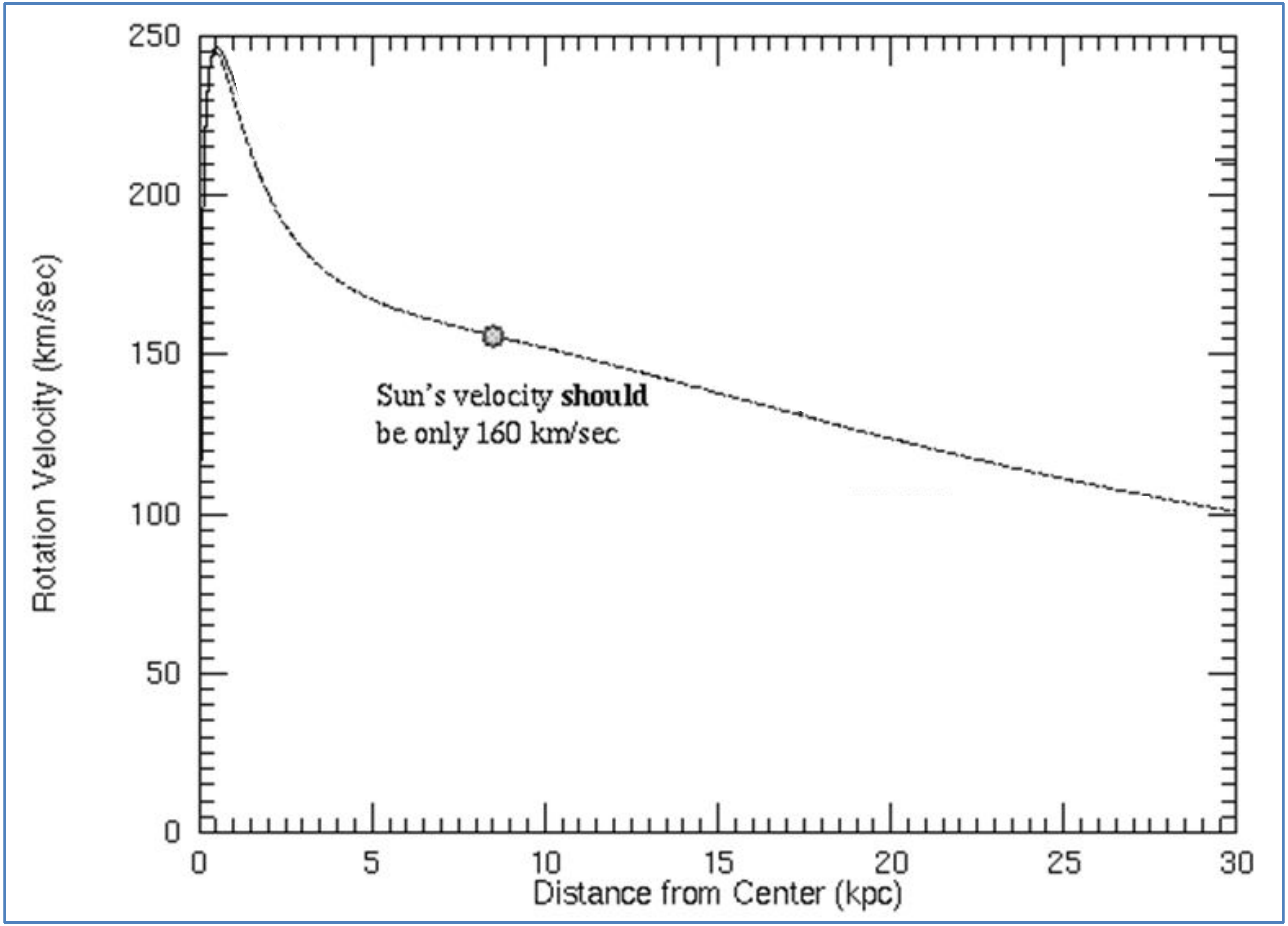
Mass inside Sun's orbit

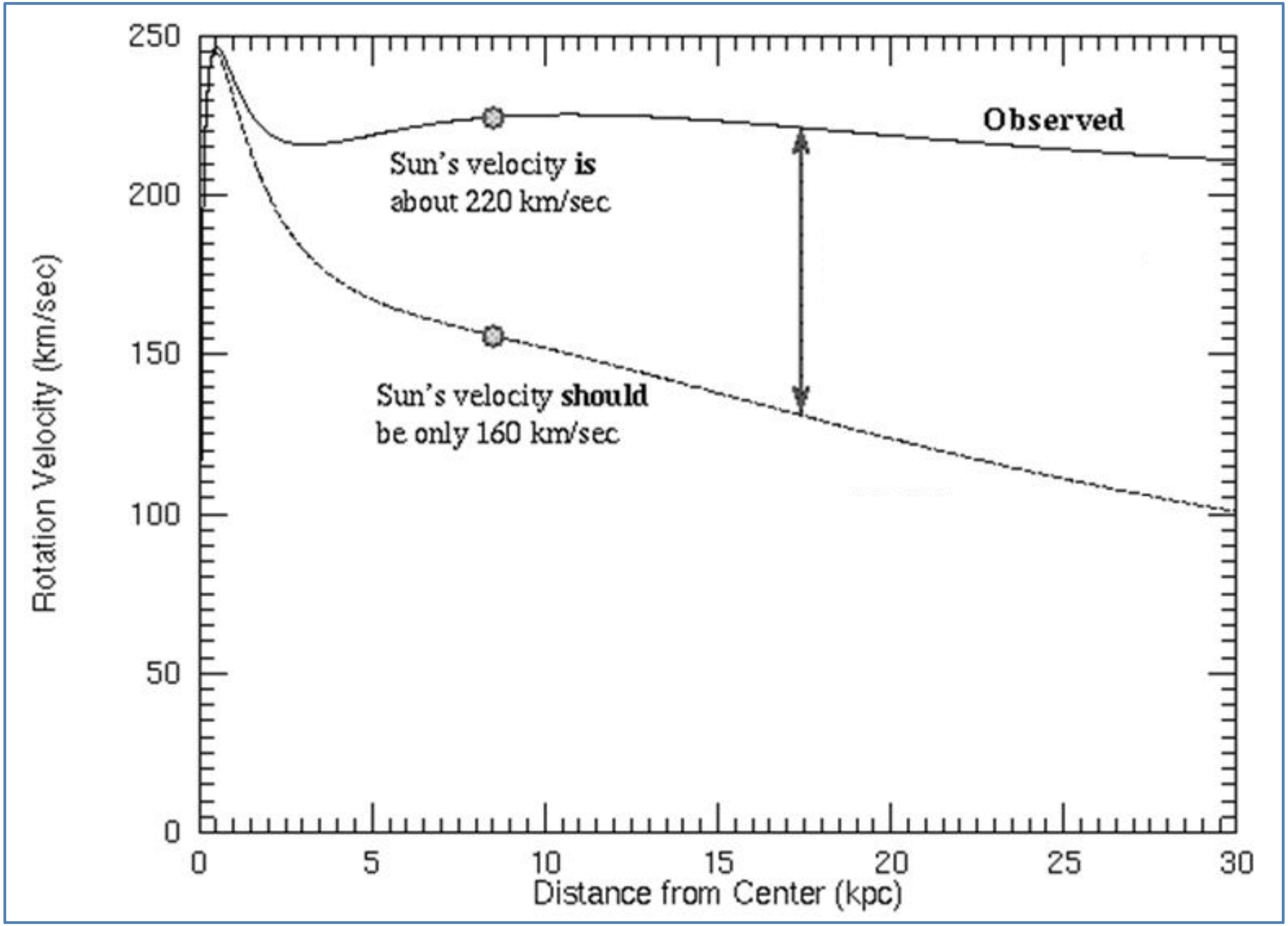
$$a \approx 8\ \mathrm{kpc}$$
$$P \approx 220\ \mathrm{Myr}$$

$$M_G(<r) \approx 9.3 \times 10^{10}\ M_\odot$$

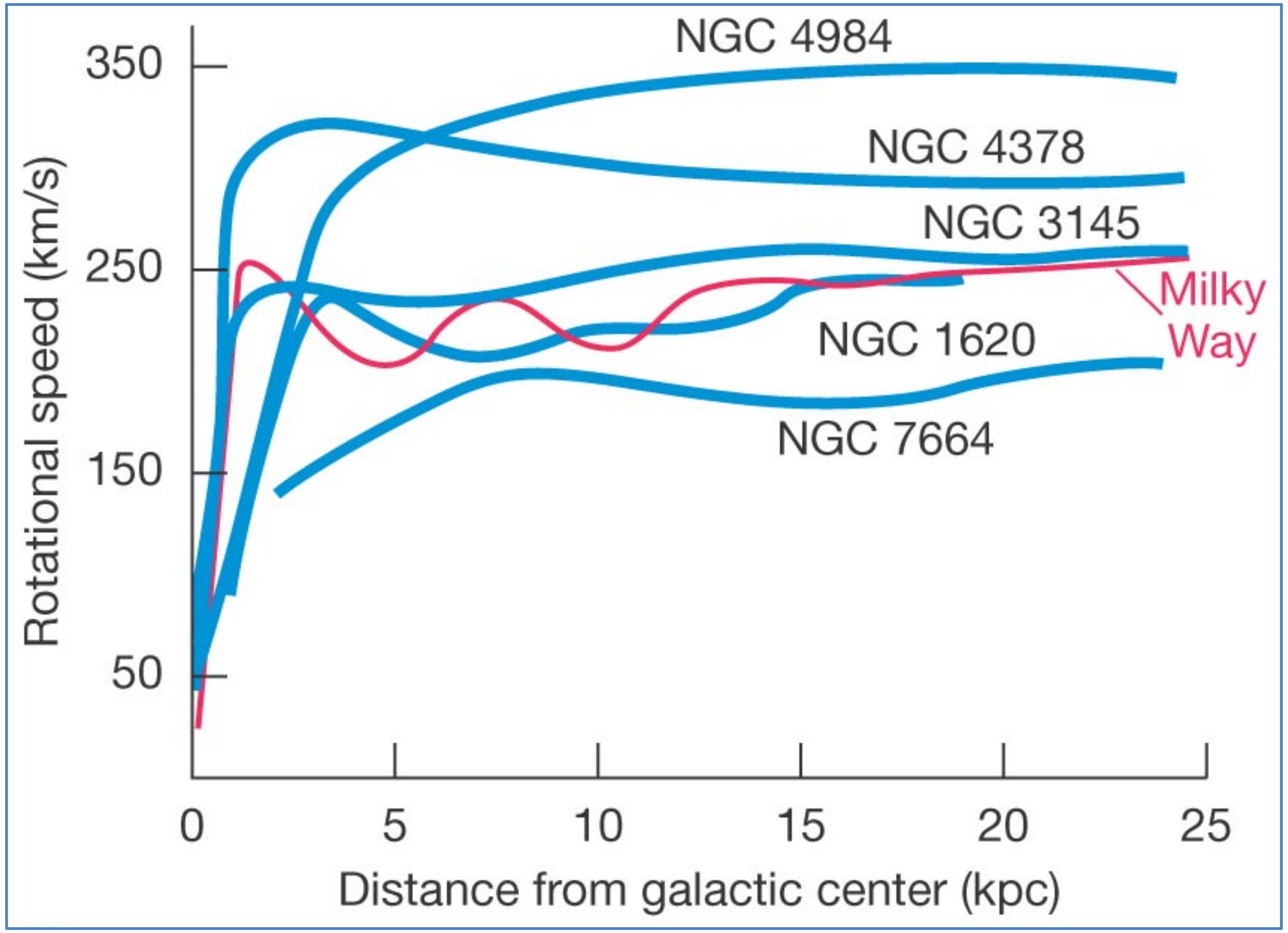
$$\frac{v(R)^2}{R} = \frac{GM_G(<R)}{R^2}$$

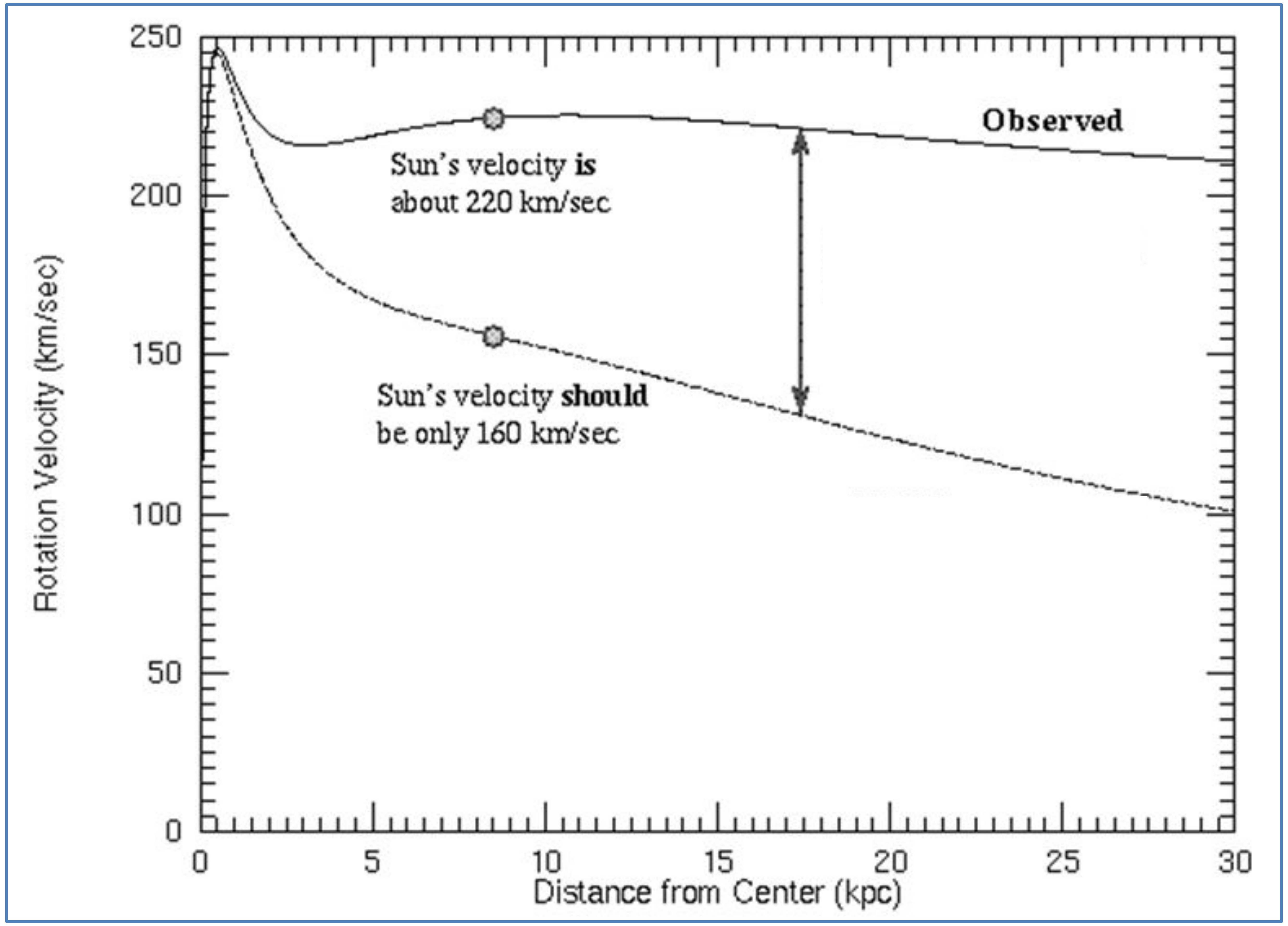
$$v(r) \propto \left(\frac{M_G(<R)}{R}\right)^{1/2} \propto R^{-1/2}$$


Rotation Velocity (km/sec)
250
200
150
100
50
0
Sun's velocity **should**
be only 160 km/sec
0
5
10
15
20
25
30
Distance from Center (kpc)


Observed
Sun's velocity is
about 220 km/sec
Sun's velocity should
be only 160 km/sec
Rotation Velocity (km/sec)
Distance from Center (kpc)
250
200
150
100
50
0
0
5
10
15
20
25
30

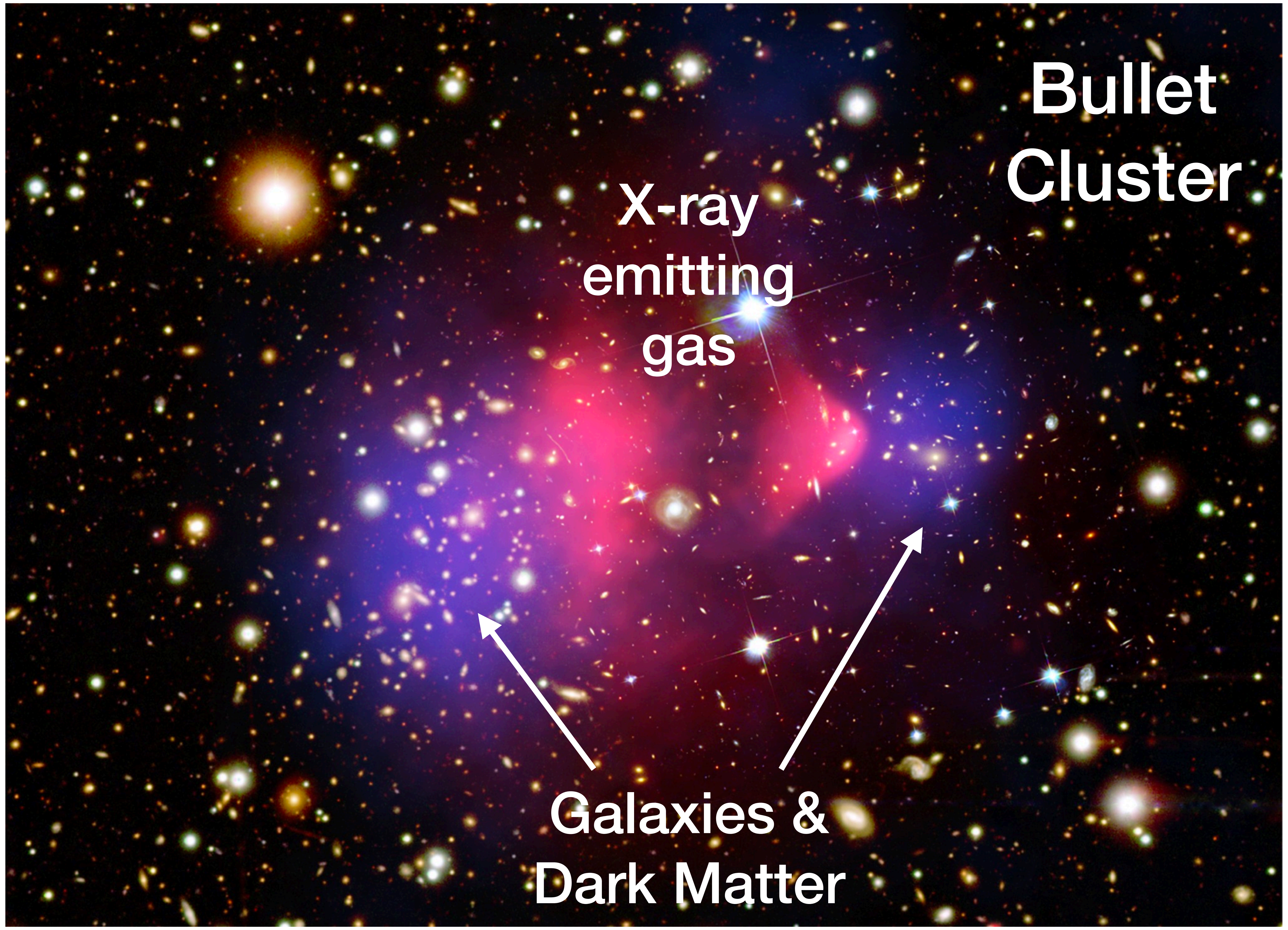
Milky Way is not alone — there is extra, non-luminous matter in galaxies: “dark matter”






Expected rotation
Observed rotation

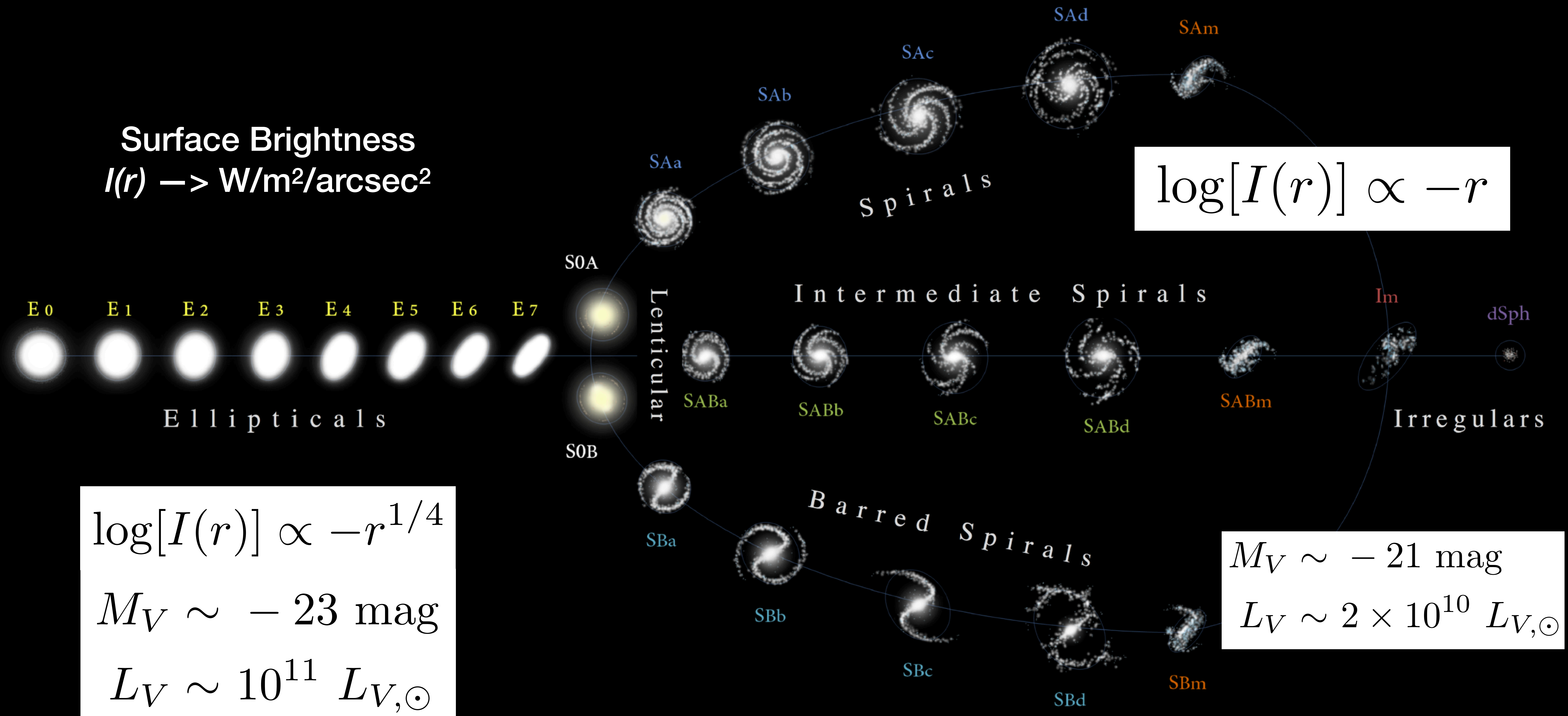
Dark Matter: what is it?



- Neutrinos (like those produced in fusion
  - Have mass, but not enough
  - New kind? Sterile Neutrino
- WIMP (Weakly Interacting Massive Particle)
  - Direct detection searches have failed
  - "WIMP miracle" not miraculous
- MACHO (MAssive Compact Halo Object)
  - WDs, NSs, BHs roaming around
  - Can detect via gravitational lensing - ruled out
- Theorists are clever - can invent other options!
- Modified Gravity (explains galaxy rotation, but…)

HUBBLE-DE VAUCOULEURS DIAGRAM

Surface Brightness
***I(r)* —> W/m²/arcsec²**



$$\log[I(r)] \propto -r$$

$$M_V \sim -21 \text{ mag}$$

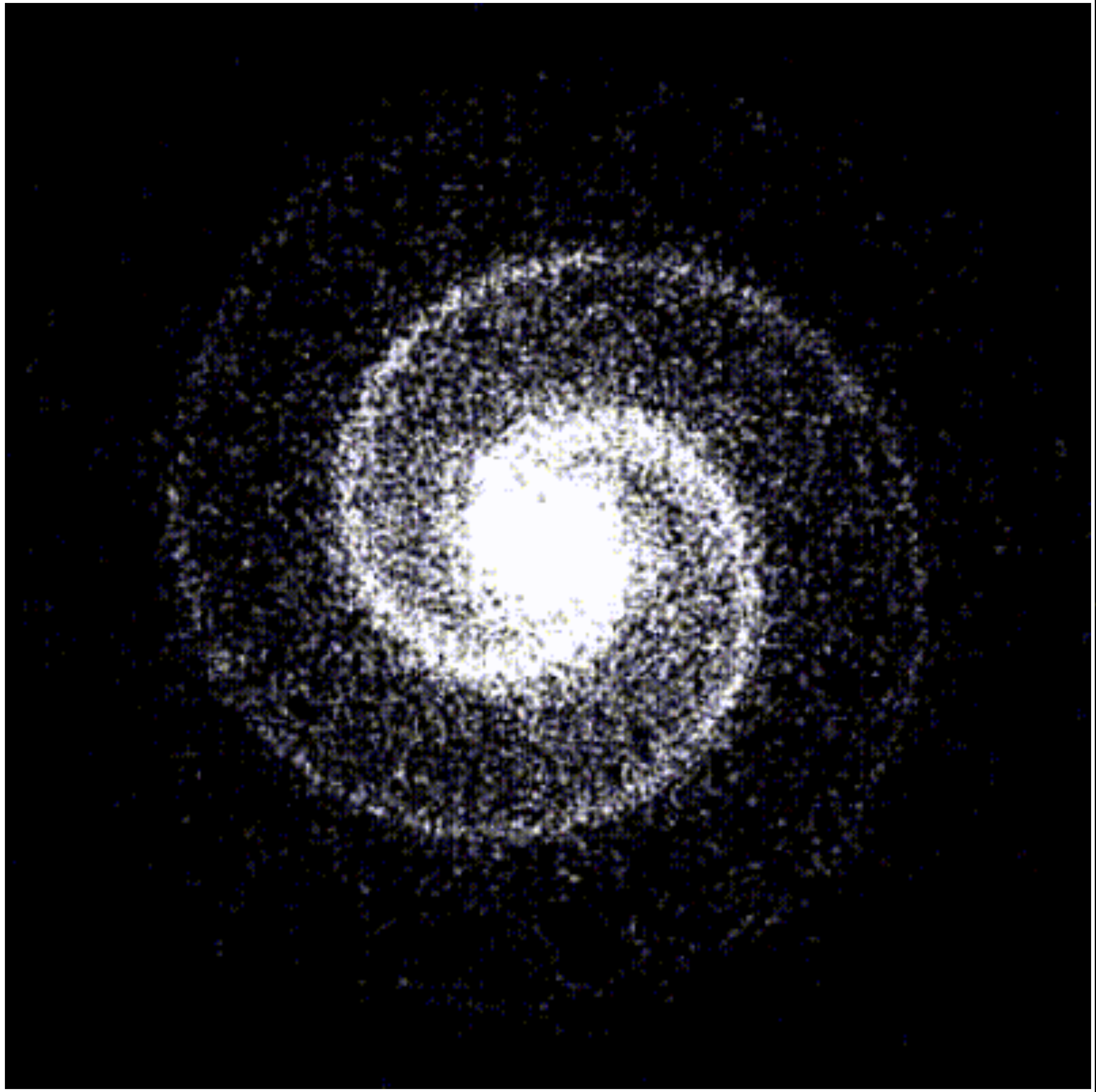
$$L_V \sim 2 \times 10^{10}\ L_{V,\odot}$$

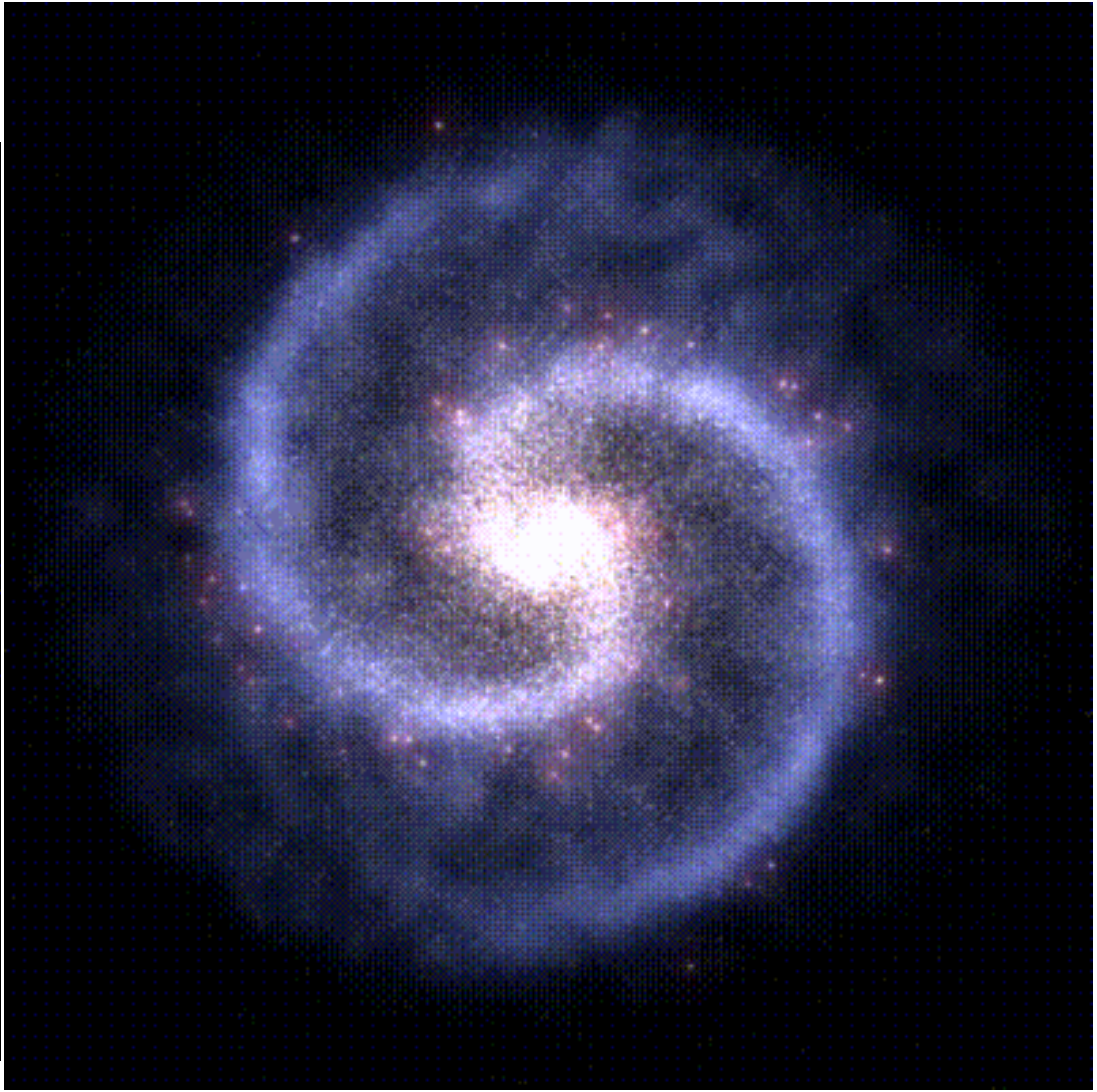
$$\log[I(r)] \propto -r^{1/4}$$

$$M_V \sim -23 \text{ mag}$$

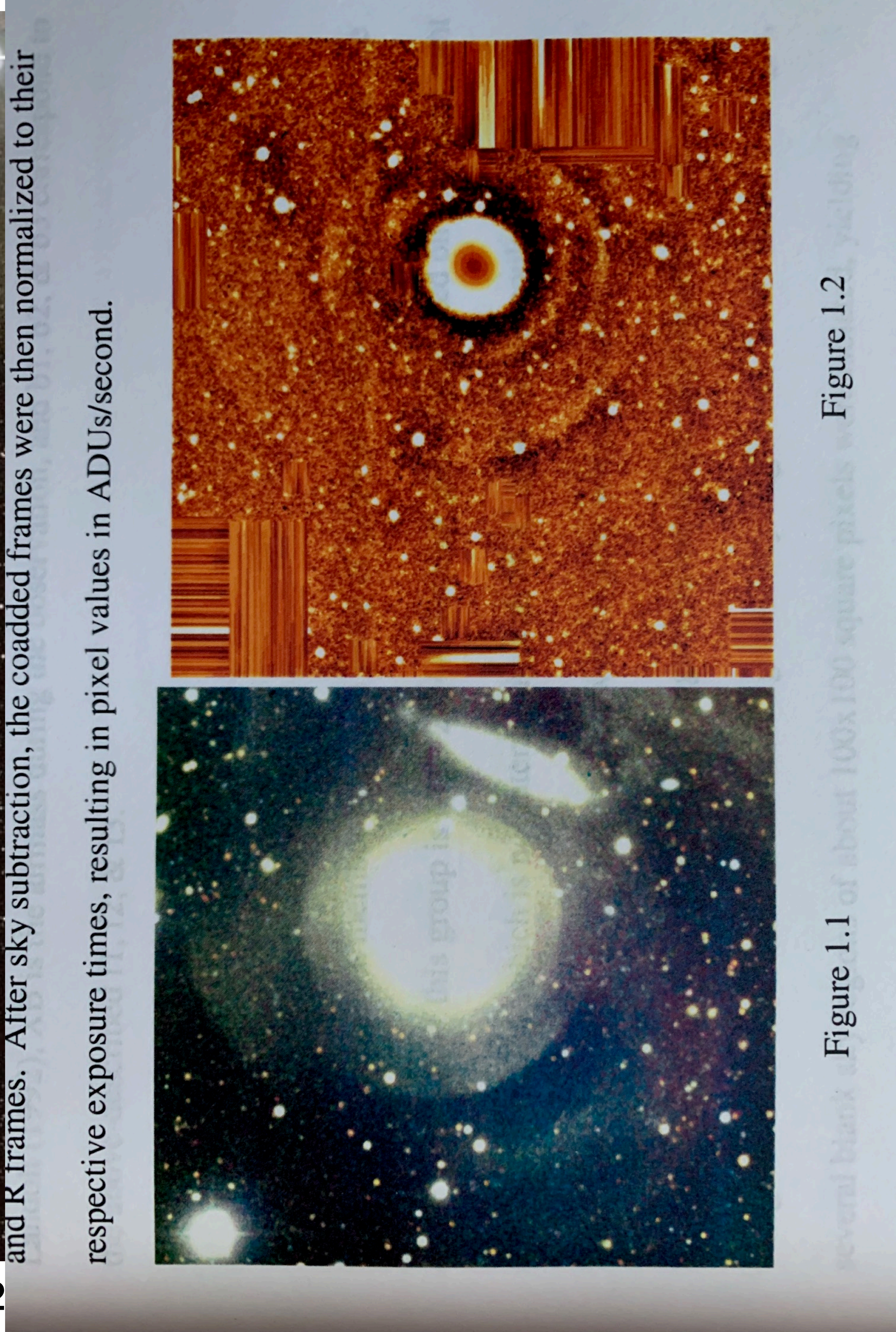
$$L_V \sim 10^{11}\ L_{V,\odot}$$

Spiral Arms





Galaxies are not isolated



and R frames. After sky subtraction, the coadded frames were then normalized to their
respective exposure times, resulting in pixel values in ADUs/second.
Figure 1.2
Figure 1.1