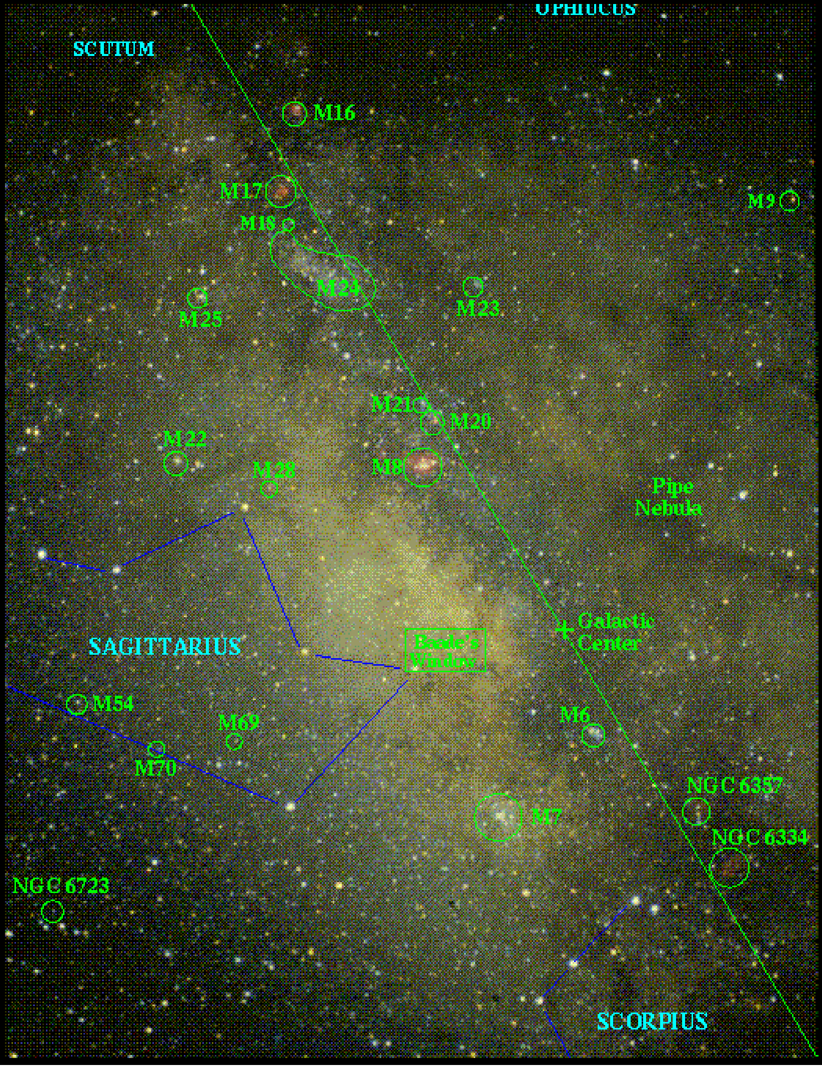
Today in Astronomy 142: the Milky Way

- ❑ The shape of the Galaxy
- ❑ Stellar populations and motions
- ❑ Stars as a gas:
  - Scale height, velocities and the mass per area of the disk
  - Missing mass in the Solar neighborhood



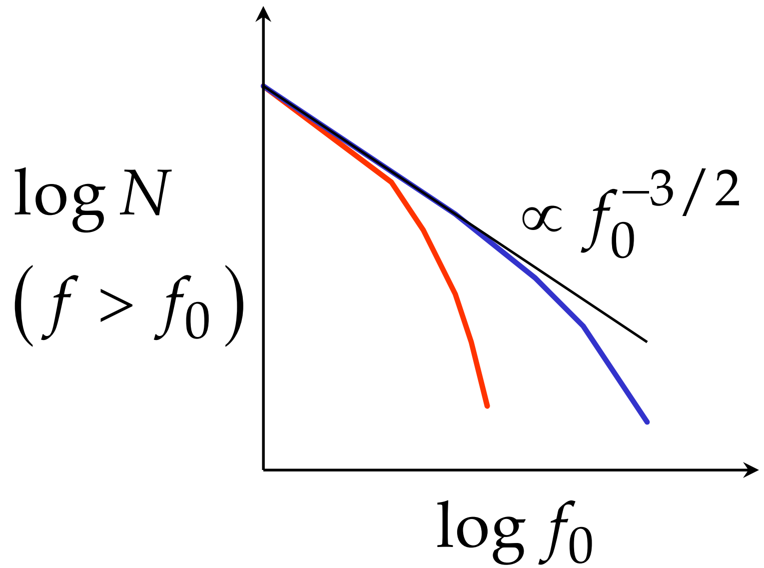
Wide-angle photo and overlay key of the Sagittarius region of the Milky Way. The very center of the Milky Way lies behind particularly heavy dust obscuration. (By [Bill Keel](), U. Alabama.)

What is the shape of the Milky Way?

First answer, due to Kapteyn, came from star counts. If stars were distributed uniformly in the universe, then the number counted in any patch of the sky, with flux larger than f_0, is given by

$$N(f > f_0) = A f_0^{-3/2} \quad .$$

Actual star counts at low fluxes are less than predicted by this relationship and the numbers at larger fluxes.



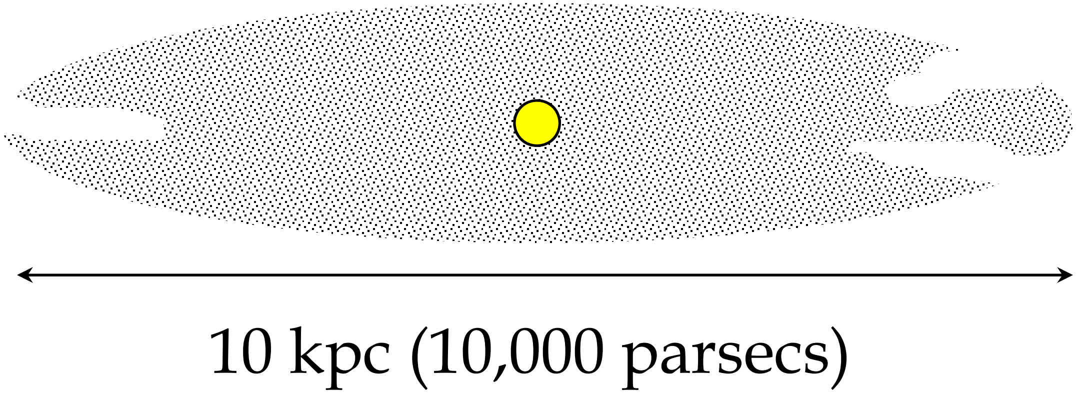
Star counts in directions of the Milky Way disk **(blue)**, and in the perpendicular directions (red).

The “Kapteyn Universe”

Conclusions:

The stellar density is **not** uniform; instead it decreases as distance from the Solar system increases, most slowly in the direction of the Milky Way, quickest in the perpendicular directions.

The Solar system lies near the center of a large, flattened cluster of stars.

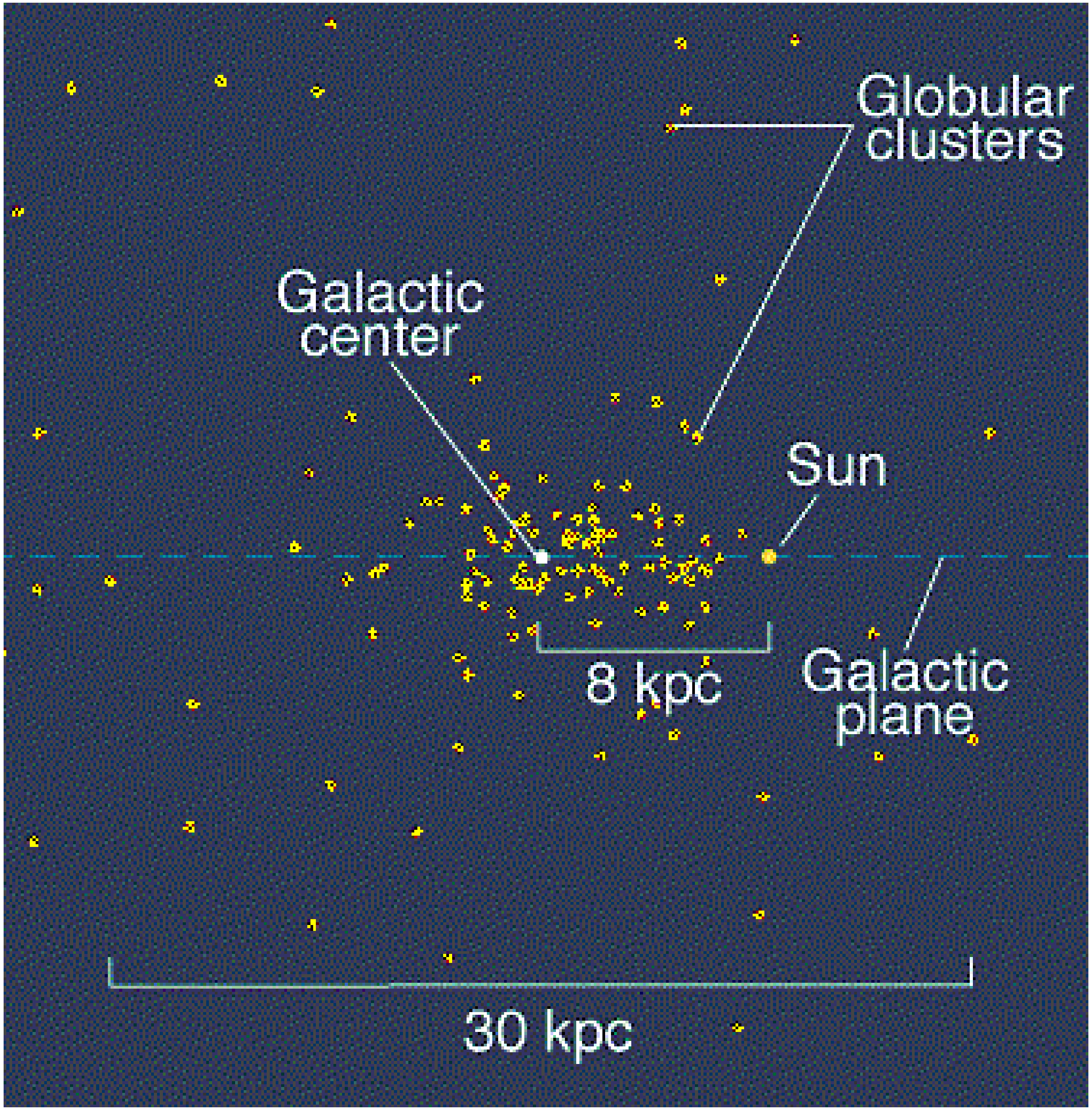


Shapley and the location of the Galactic center

In 1917, Harlow Shapley applied Henrietta Leavitt 's pulsating-star distance-measurement discovery (about which we will learn later) to the RR Lyrae stars in globular clusters. He reasoned that these clusters were so massive that they would accurately trace the Galaxy's gravitational potential.

- He found that globular clusters were arranged spherically symmetrically about a point in the plane of the Milky Way, in the constellation Sagittarius, tens of kpc away.
  - Modern measurements give 8.4 kpc for the distance (Reid et al. 2009).
- Thus the Sun is quite far from the center of the Galaxy, and the star counts are misleading.

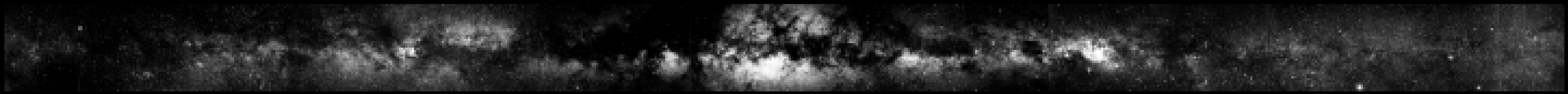
(As we have seen, Trumpler found out later why the star-count method doesn't work: interstellar extinction.)



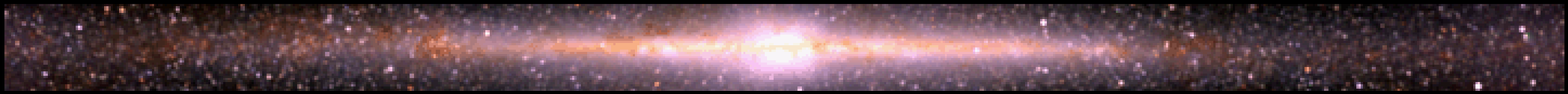
Distribution of the Galaxy's globular clusters

Figure: Chaisson and McMillan, *Astronomy Today*

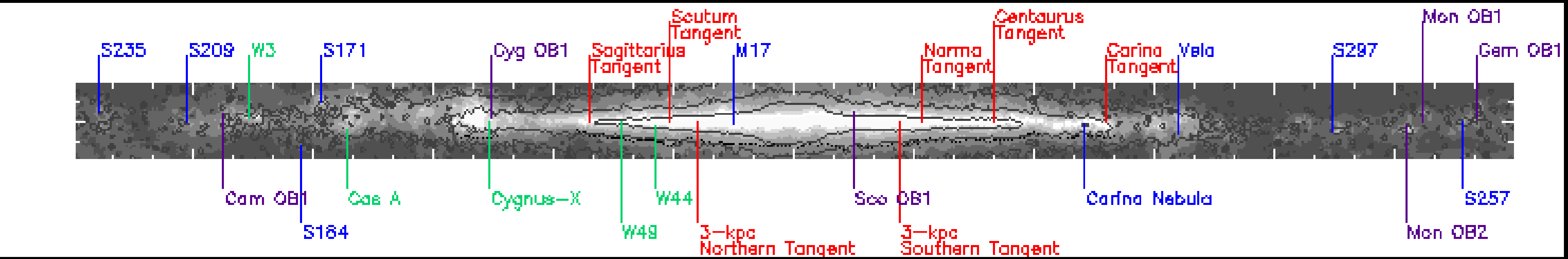
360º views of starlight in the Galaxy



Visible light (and extinction), λ = 0.54 μm

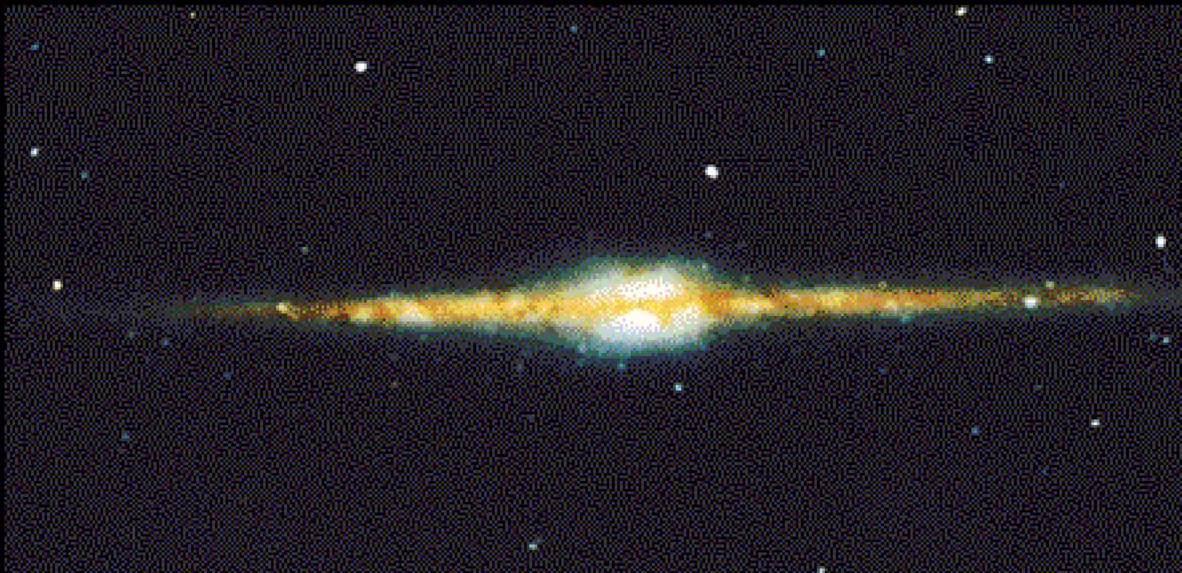


Near-infrared light, λ = 3.5 μm



Key

Figure: NASA



The Milky Way's central regions, in starlight (near-infrared), from the NASA COBE DIRBE experiment.

NGC 891, also in starlight (near-infrared), from the 2MASS survey (U. Mass./NASA).

Schematic structure of the Milky Way

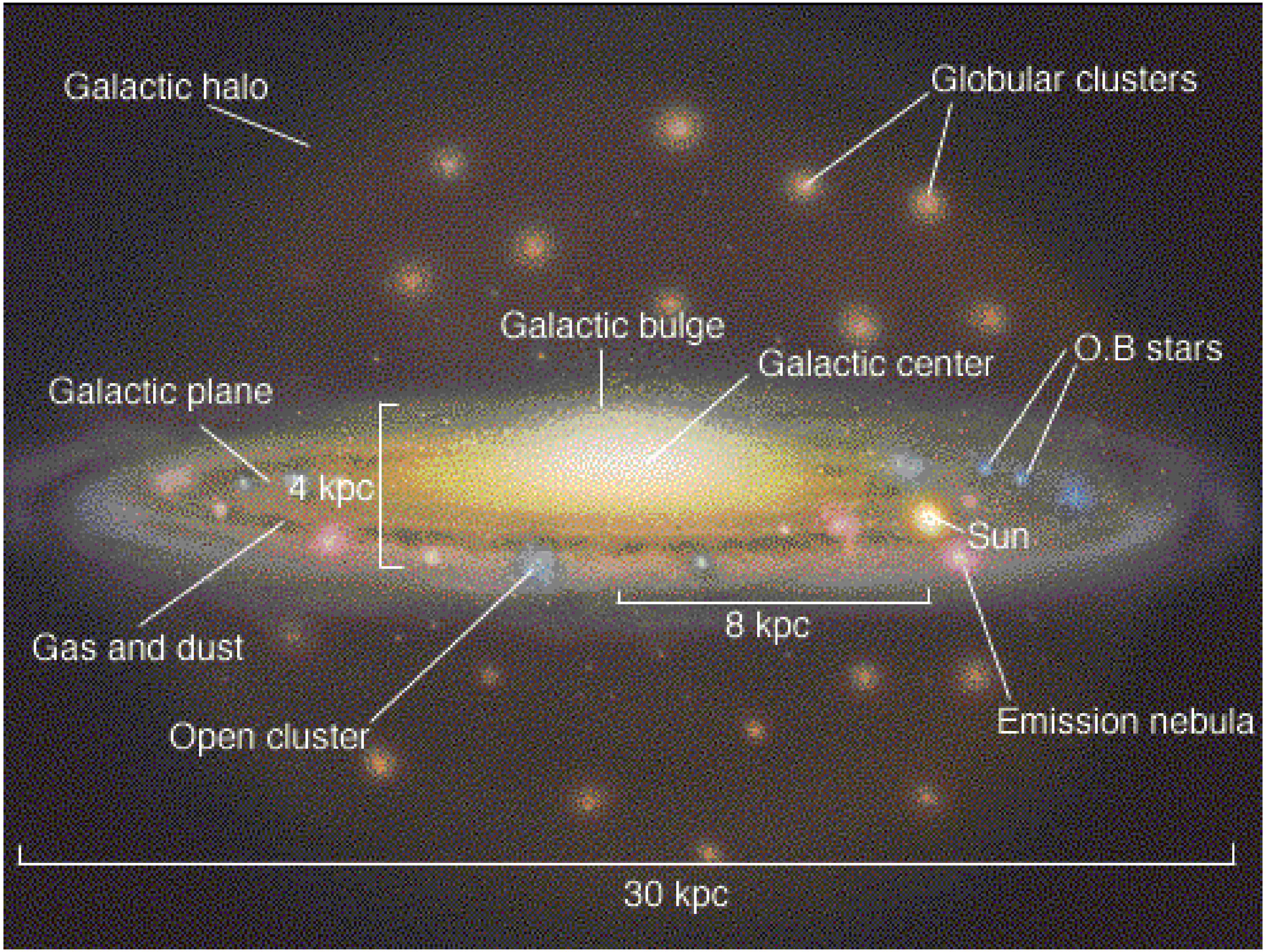


Figure: Chaisson and McMillan, *Astronomy Today*

Stellar populations in the Galaxy

Population I: small dispersion of velocities (i.e. small random velocities), absorption lines of heavy metals, confined to a very thin plane. Relatively young.

Population II: large dispersion of velocities, can lie further from the Galactic plane.

- Population I lies predominantly in the disk, less in the bulge, not in the halo. Population II can be found in all three components.

The visible mass of the galactic halo is small compared to that of the disk and bulge. As we will see, there are reasons to think that the true mass of the halo is comparable to the rest, leading to a hypothetical **Population III** composed of (dim) low-metal-abundance stars.

Motions of stars in the Galaxy, and their use in determining its mass distribution

How much does the Galaxy weigh? Stars move about in response to the gravitational potential of the rest of the stars in the galaxy, so…

- their systematic motions (rotation) can be used with Newton's Laws to measure masses within the Galaxy.
  - This works even better with interstellar gas than with stars.
- Stars collide inelastically very rarely, so their random motions can be used with **thermodynamics** to measure masses within the Galaxy - the stars in this sense can be thought of as particles in a gas.

Let's do some examples of the latter technique.

Mass per unit area of the Galaxy's disk, in the Sun's neighborhood

Recall formula for pressure in terms of particle number density, speed and momentum (lecture, 10 February):

$$P \cong \frac{F}{A} = \frac{1}{A}\frac{dp}{dt} \cong \frac{1}{A}\frac{nA\delta z}{\delta t}p_z$$

$$= nv_z p_z = \rho v_z^2$$

Number of particles that hit wall ($nA\delta z$)

Typical momentum per particle (p_z)

Time interval in which they hit (δt)

Consider a certain class of stars to be gas particles, and consider the component of their motion perpendicular to the Galactic plane.

Suppose the distribution of these stars extends above and below the plane by some **scale height** $H/2$. Consider stars lying on the ends of a cylinder of Galactic matter that extends one scale height above and below the plane.

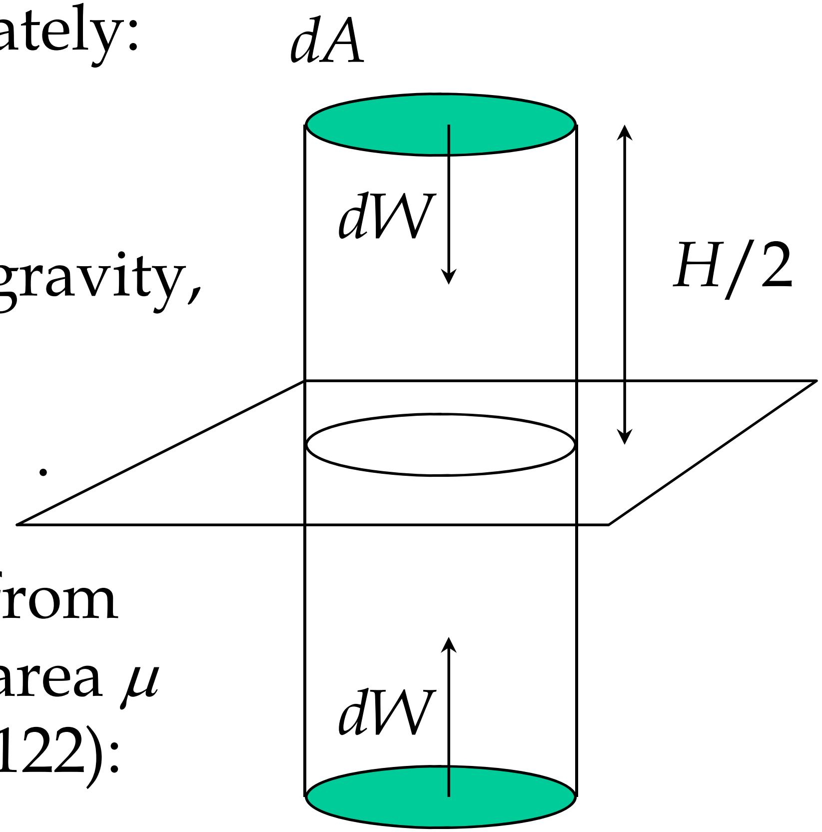
Mass per unit area of the Galaxy's disk, in the Sun's neighborhood (continued)

Weight of the cylinder, approximately:

$$w = \frac{dW}{dA} = \frac{\bar{g}_z dm}{dA} = \bar{g}_z \rho H$$

If stellar "gas pressure" balances gravity, then

$$\rho v_z^2 = \rho \bar{g}_z H \quad , \text{ or } \quad \bar{g}_z = v_z^2 / H \quad .$$

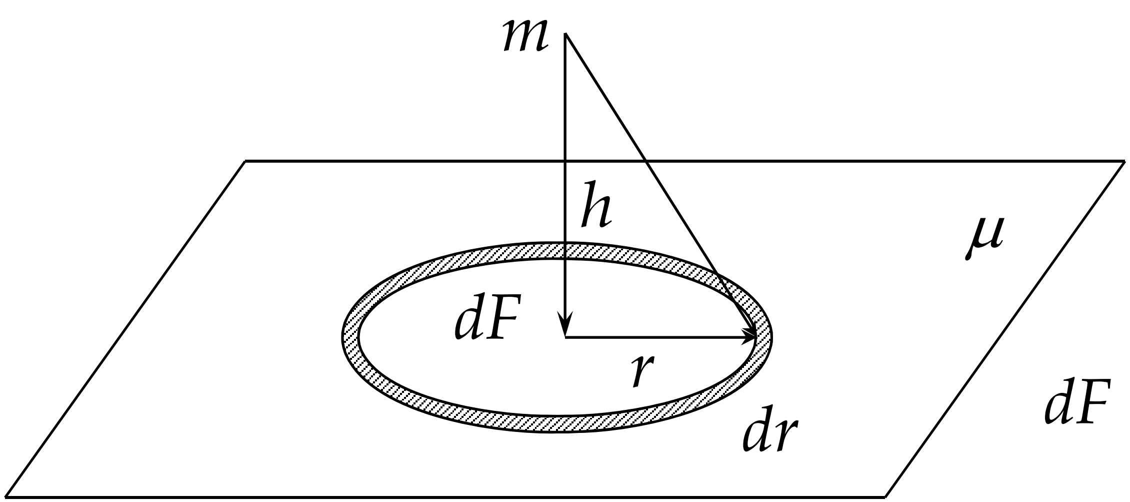


Compare to force on test mass *m* from infinite plane with mass per unit area μ (presumably done in PHY 121 or 122):

$$F = 2\pi G \mu m = m g_z$$

$$\Rightarrow \mu = g_z / 2\pi G = v_z^2 / 2\pi G H \quad .$$ (All on RHS observable.)

Proof of the previous assertion



$$dF = \frac{Gm\left(2\pi r dr\,\mu\right)}{h^2 + r^2}\frac{h}{\sqrt{h^2 + r^2}}$$

$$F = \pi G\mu m h\int_0^\infty \frac{2rdr}{\left(h^2 + r^2\right)^{3/2}} = \pi G\mu m h\int_{h^2}^\infty \frac{du}{u^{3/2}}$$

$$= \pi G\mu m h\,\frac{u^{-1/2}}{-1/2}\Bigg|_{h^2}^{\infty} = 2\pi G\mu m h\,\frac{1}{\sqrt{h^2}} = 2\pi G\mu m$$

Mass per unit area of the Galaxy's disk, in the Sun's neighborhood (concluded)

Putting the numbers in, for the solar neighborhood:

$$\mu_\odot = 1.5 \times 10^{-3} \text{ gm cm}^{-2}$$

Star counts in the solar neighborhood enable us to estimate the luminosity per unit area $\mathcal{L}$ (also called the **surface brightness**) of the disk locally. This leads to the **mass to light ratio**:

$$\left(\frac{\mu}{\mathcal{L}}\right)_\odot = 5\, M_\odot L_\odot^{-1} \quad .$$

Thus the solar neighborhood on average emits light less efficiently than the Sun does – consistent with there being more lower-mass stars than higher-mass stars.

Dark matter I: the Galactic disk in the solar neighborhood

When this procedure was first applied to observations by Oort in the late 1940s, the resulting value of μ was greater than that of visible stars and interstellar gas in the Solar neighborhood by a factor of about 2.

- **Missing mass**, or **dark matter**: mass that emits no light but can be detected by its gravity?

Since then,

- Better (less biased) samples of stars have led to smaller estimates of the total μ.
- The discovery of neutral atomic and molecular gas in the ISM has increased the "luminous" mass a bit.
- Now the luminous and gravitating μ match precisely: **this form of dark matter has vanished** (e.g. Kuijken and Gilmore 1991).