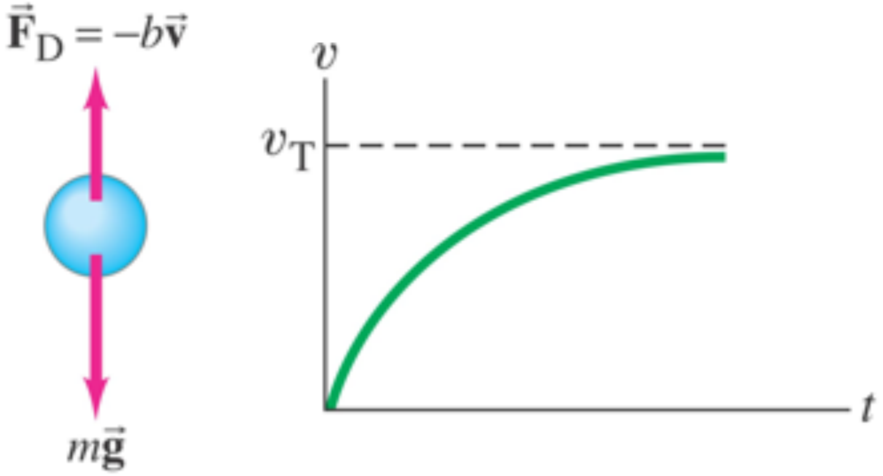
Physics 51 LECTURE 4 October 21, 2011

- Falling with Drag (again)
- Introduction to Special Relativity
- Galaxies and Dark Matter

Drag at Low and High Speeds

$F_{drag} = -bv$ (low speed)

low speed $v_{terminal} = mg/b$



$F_{drag} = -kv^2$ (high speed), $k = \rho A C_d/2$

where ρ=density of air, A=area of object,

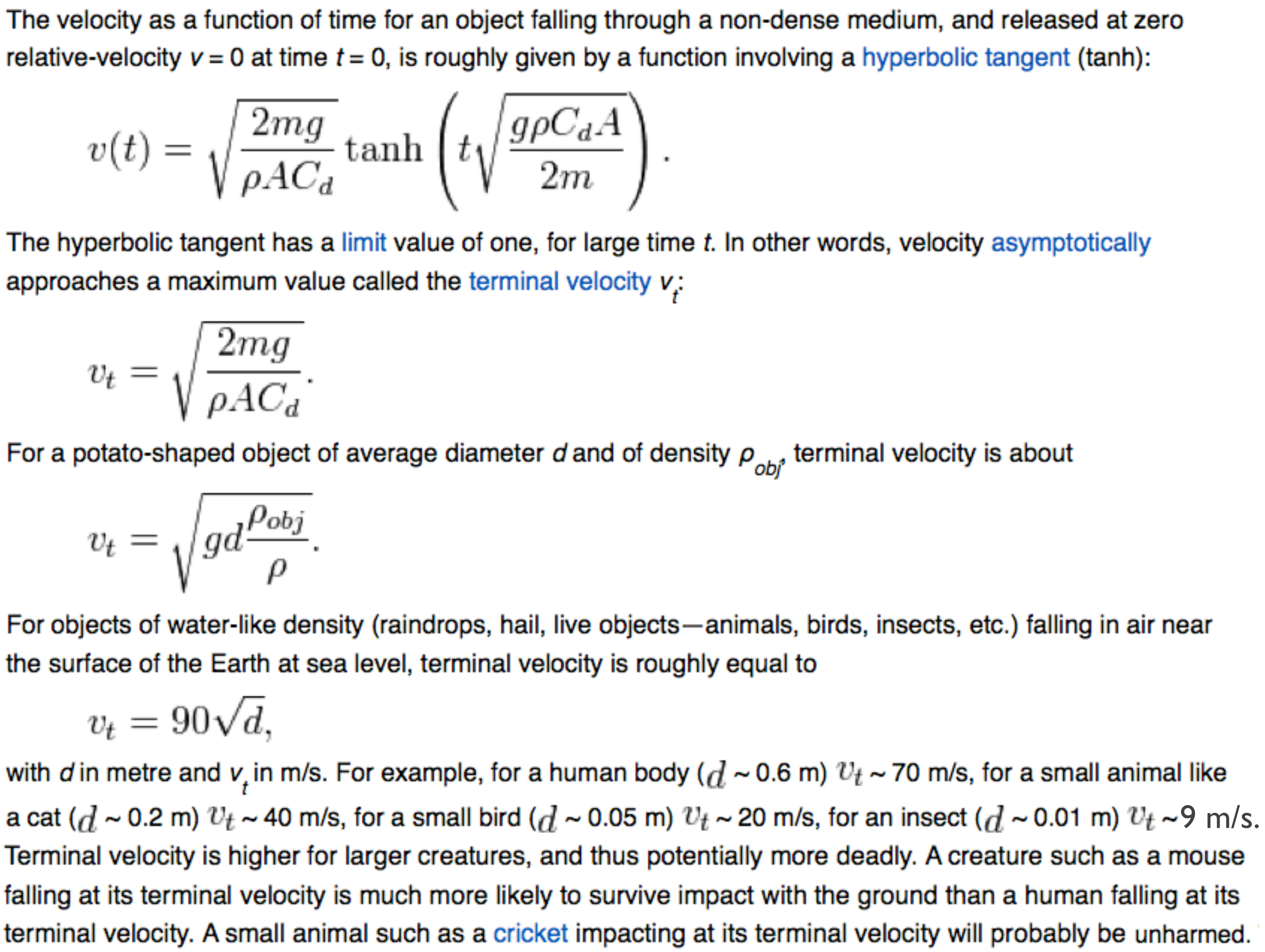
and C_d=drag coefficient ~1, $g = 10\ m/s^2$

high speed $v_{terminal} = [mg/k]^{1/2} = [2mg/\rho A C_d]^{1/2}$

Animals all have density about the same as water, ~1 g/cm^3. Suppose an animal has linear dimension L. Then $m \sim L^3$ while $A \sim L^2$, so $v_{terminal} \sim L^{1/2}$. A mouse has L~5 cm and a human has L~1 m, so the ratio of their $L^{1/2}$ is $\sim 20^{1/2} \sim 4.5$, which is also the ratio of their terminal velocities. For a skydiver, $v_{terminal}$ ~ 70 m/s ~ 250 km/hr. But a parachute (A -->100 A) can slow $v_{terminal}$ to ~ 7 m/s.

Drag at High Speeds

(from Wikipedia: http://en.wikipedia.org/wiki/Drag_%28physics%29)



The velocity as a function of time for an object falling through a non-dense medium, and released at zero relative-velocity $v = 0$ at time $t = 0$, is roughly given by a function involving a hyperbolic tangent (tanh):

$$v(t) = \sqrt{\frac{2mg}{\rho A C_d}} \tanh\left(t\sqrt{\frac{g\rho C_d A}{2m}}\right).$$

The hyperbolic tangent has a limit value of one, for large time t. In other words, velocity asymptotically approaches a maximum value called the terminal velocity v_t:

$$v_t = \sqrt{\frac{2mg}{\rho A C_d}}.$$

For a potato-shaped object of average diameter d and of density ρ_{obj}, terminal velocity is about

$$v_t = \sqrt{gd\frac{\rho_{obj}}{\rho}}.$$

For objects of water-like density (raindrops, hail, live objects—animals, birds, insects, etc.) falling in air near the surface of the Earth at sea level, terminal velocity is roughly equal to

$$v_t = 90\sqrt{d},$$

with d in metre and v_t in m/s. For example, for a human body (d ~ 0.6 m) v_t ~ 70 m/s, for a small animal like a cat (d ~ 0.2 m) v_t ~ 40 m/s, for a small bird (d ~ 0.05 m) v_t ~ 20 m/s, for an insect (d ~ 0.01 m) v_t ~9 m/s. Terminal velocity is higher for larger creatures, and thus potentially more deadly. A creature such as a mouse falling at its terminal velocity is much more likely to survive impact with the ground than a human falling at its terminal velocity. A small animal such as a cricket impacting at its terminal velocity will probably be unharmed.

Einstein's Special Theory of Relativity

Special Relativity is based on two postulates:

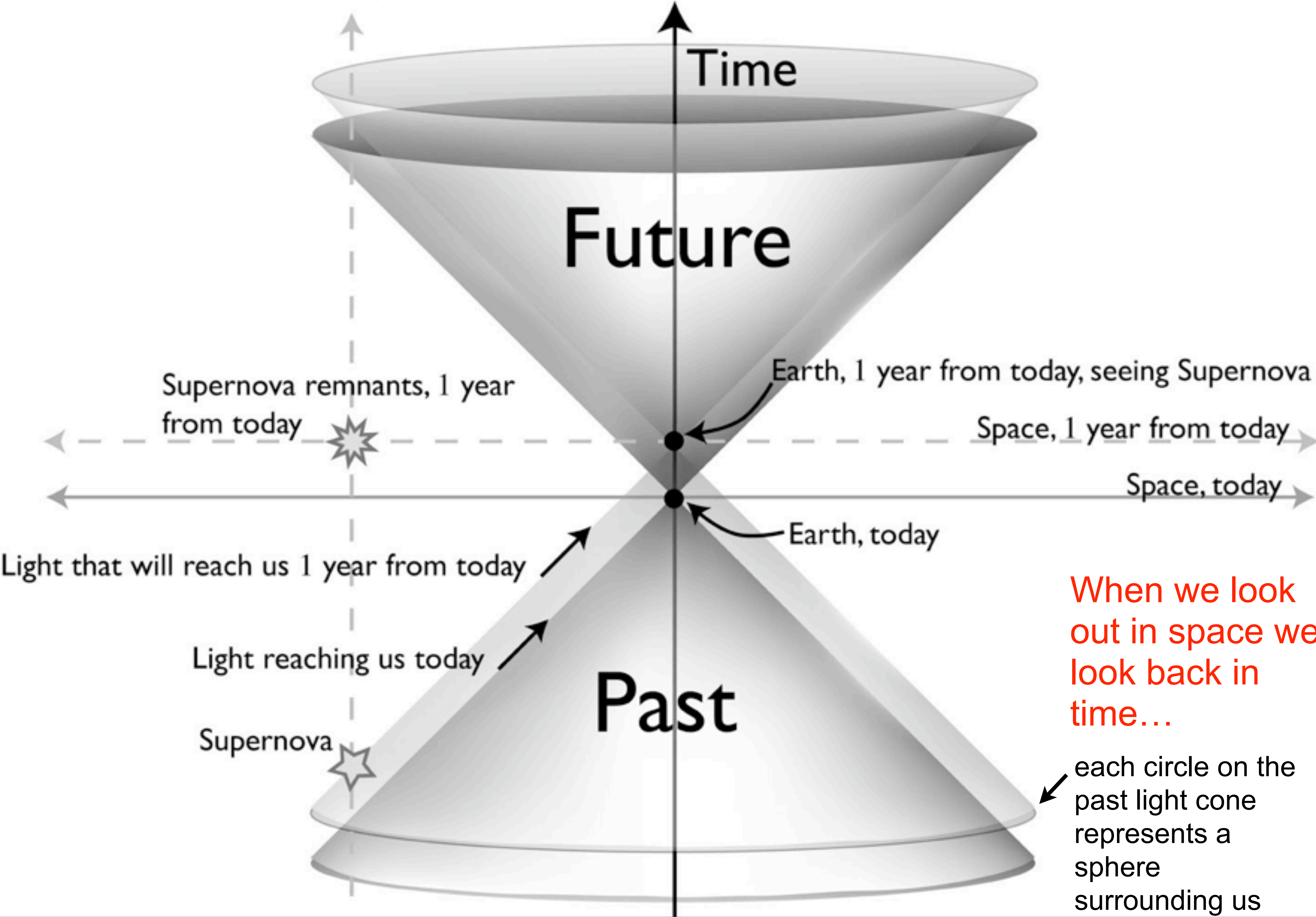
1. The Principle of Relativity: If a system of coordinates K is chosen so that, in relation to it, physical laws hold good in their simplest form [i.e., K is an inertial reference system], the same laws hold good in relation to any other system of coordinates K' moving in uniform translation relatively to K.

2. Invariance of the speed of light: Light in vacuum propagates with the speed *c* in terms of any system of inertial coordinates, regardless of the state of motion of the light source.

Einstein’s Special Theory of Relativity

http://physics.ucsc.edu/~snof/er.html

Lightcone of Past and Future



When we look out in space we look back in time…

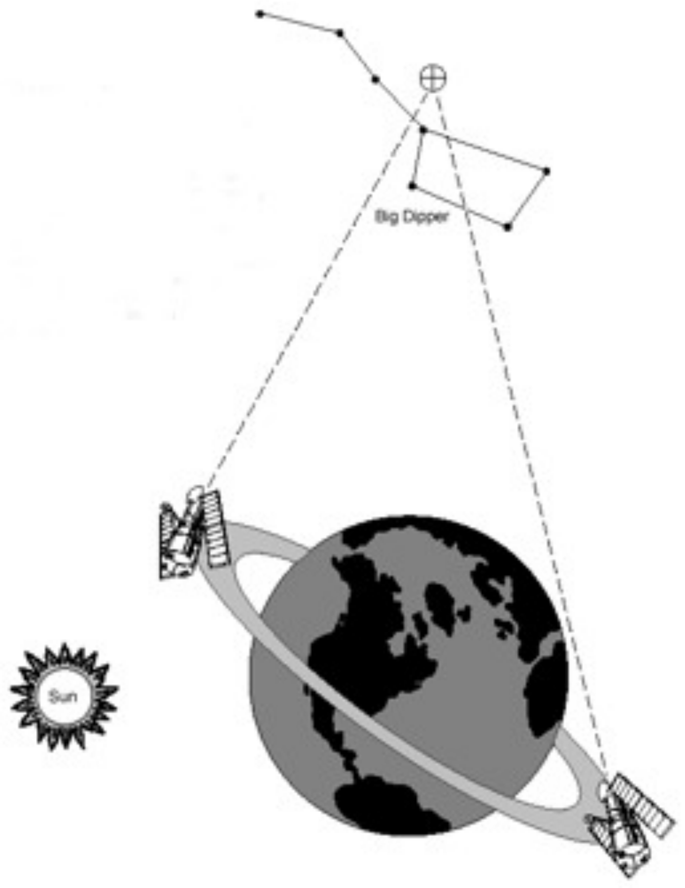
each circle on the past light cone represents a sphere surrounding us

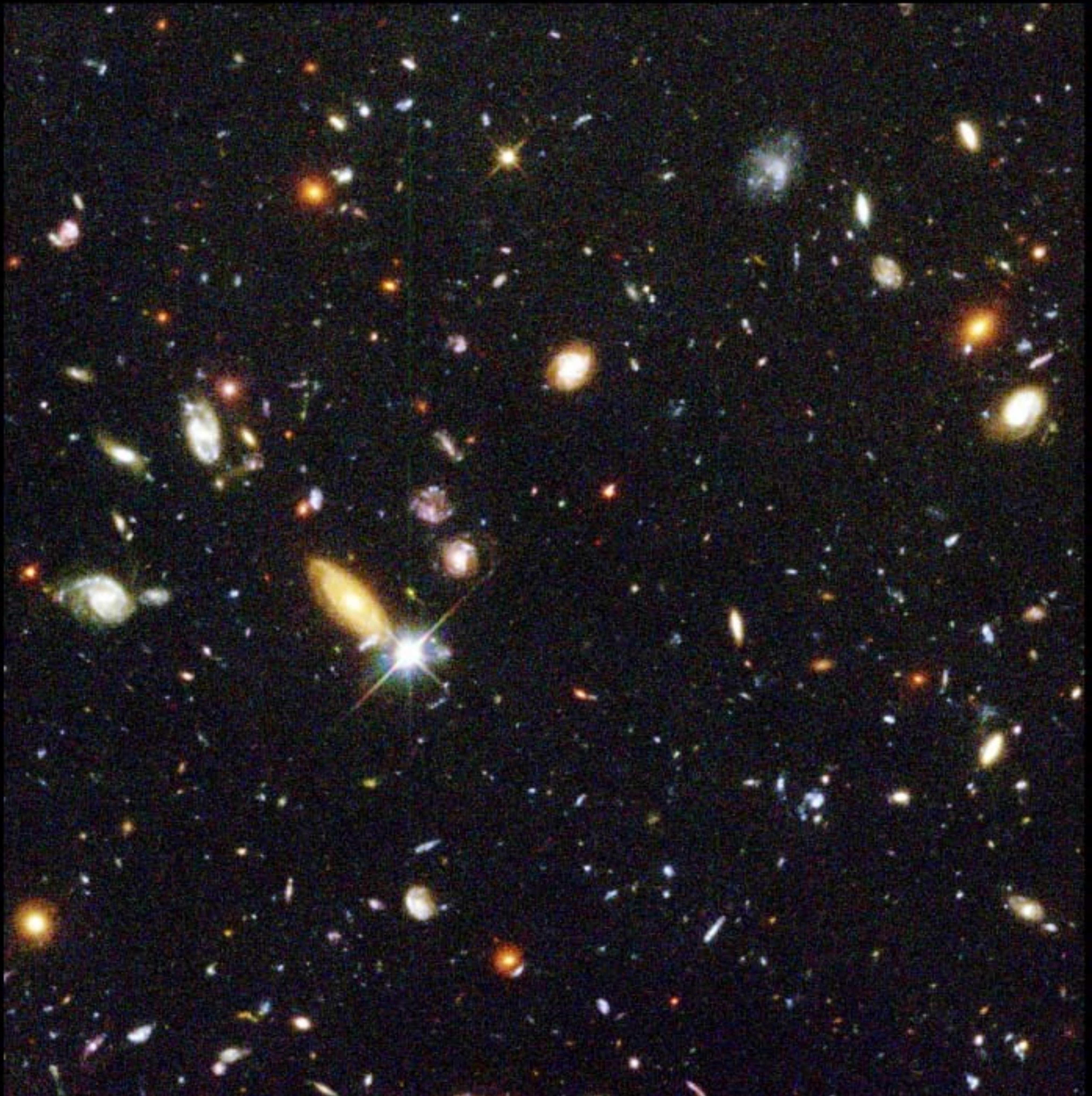
Galaxies & Dark Matter

by Joel R. Primack

- Types of Galaxies Nearby – Ellipticals, Spirals, Irregulars
- Stellar Motions in Elliptical and Spiral Galaxies
- Interpreting Images of Galaxies
- Dark Matter in Galaxies and Galaxy Clusters
- What is the Dark Matter? – Bad and Good Suspects
- How Much Dark Matter – Implications for Fate of Universe

The Hubble Deep Field North



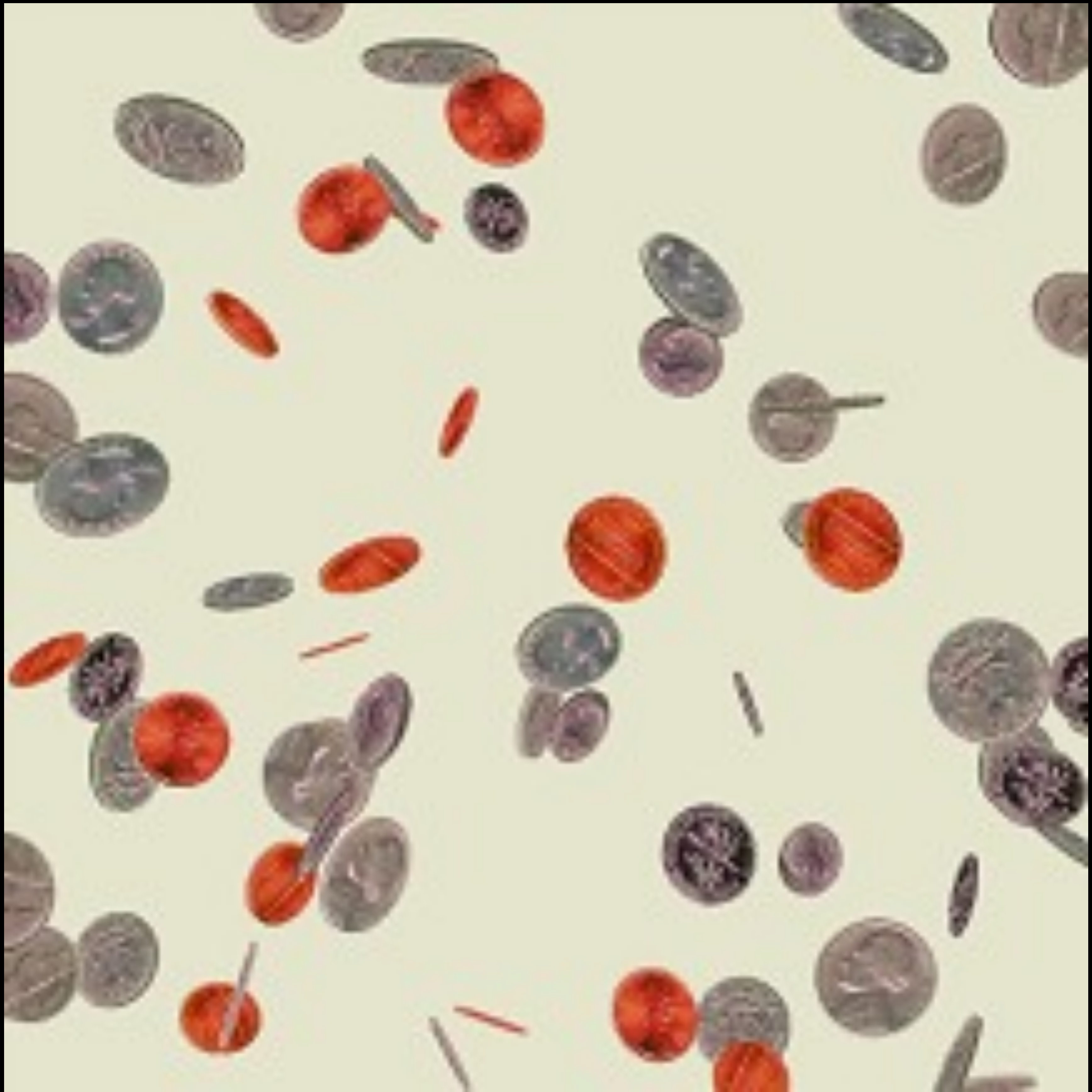


Hubble Ultra Deep Field

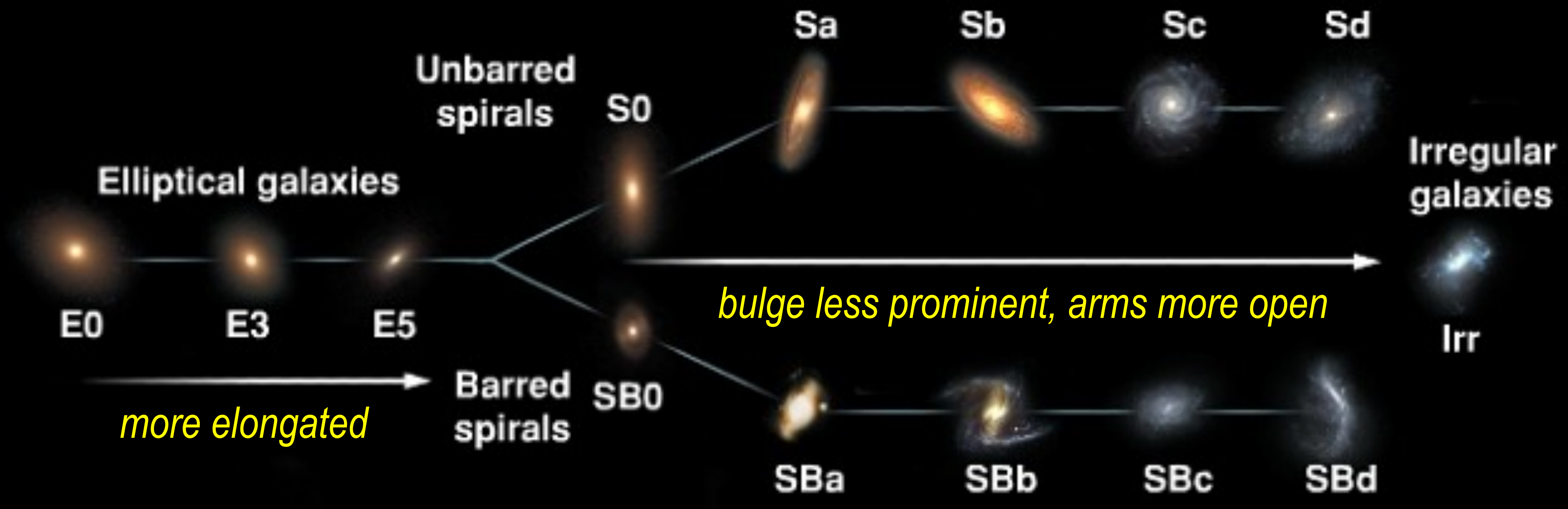
a more recent Hubble Space Telescope Picture

Galaxies are Like Coins Tossed Up in the Air

Some face-on, Some edge-on, Most in-between



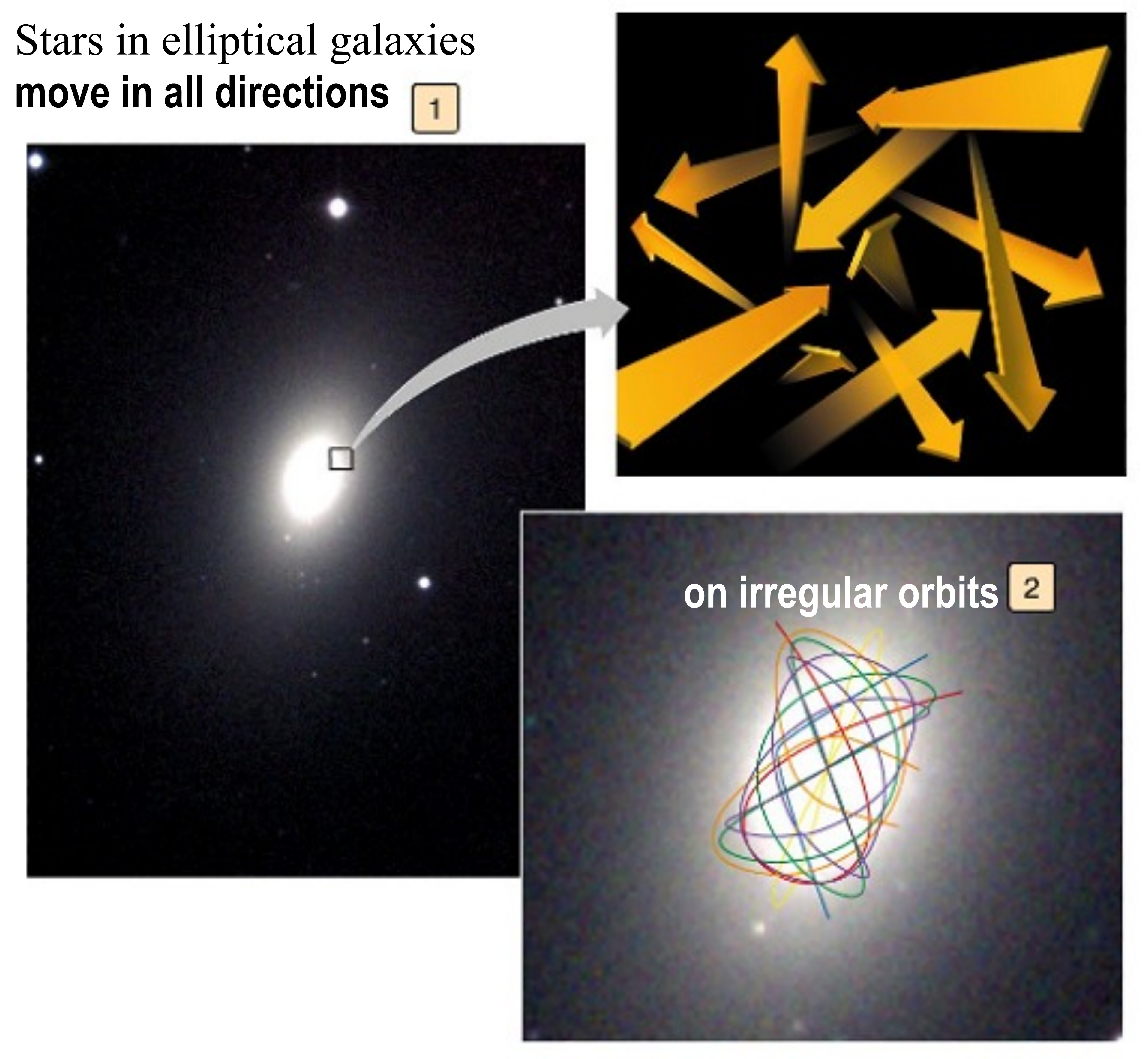
Hubble's Tuning-Fork Diagram of Galaxy Types



bulge less prominent, arms more open

more elongated

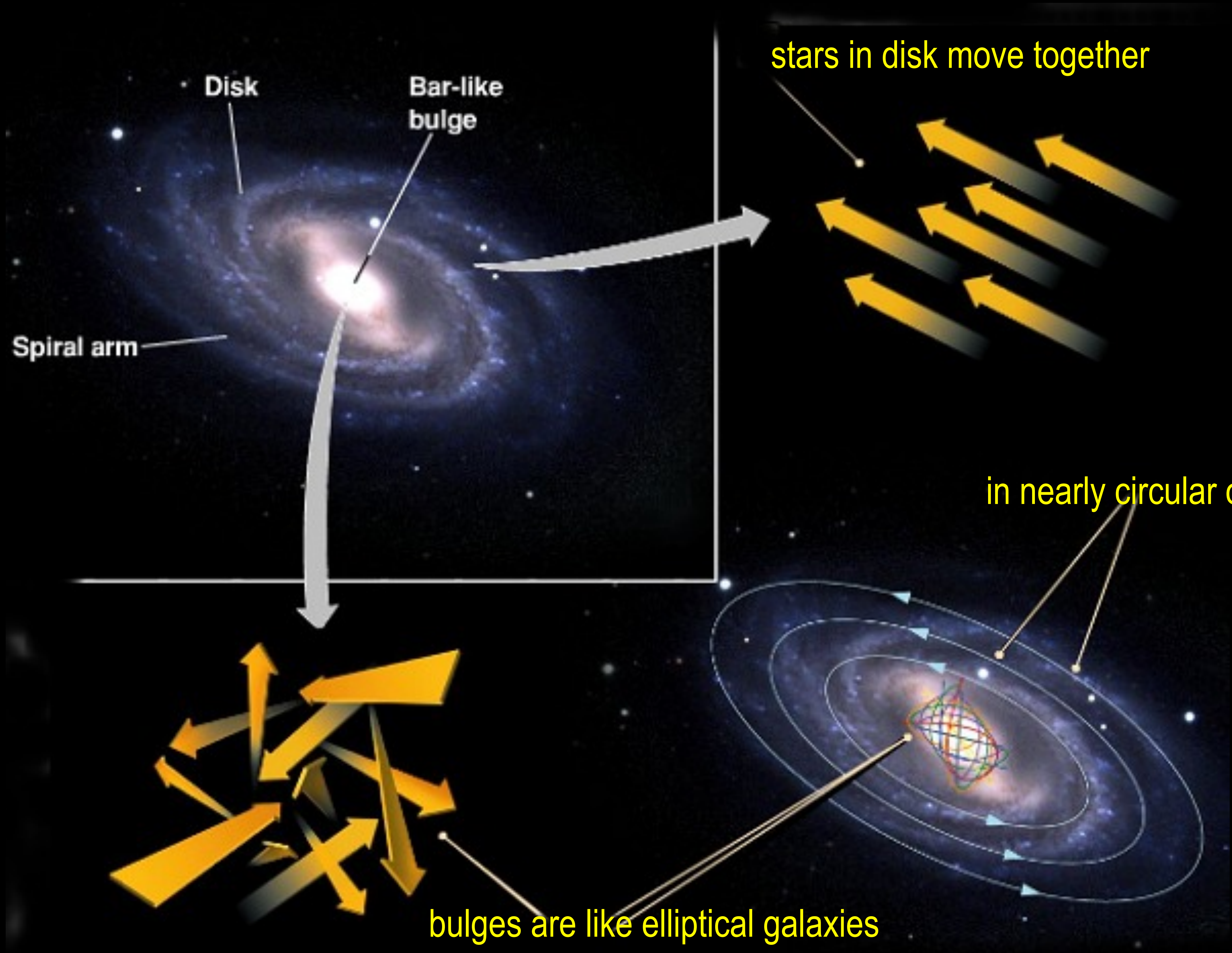
Stellar Motions in Elliptical Galaxies



Stars in elliptical galaxies **move in all directions**

on irregular orbits

Stellar Motions in Spiral Galaxies

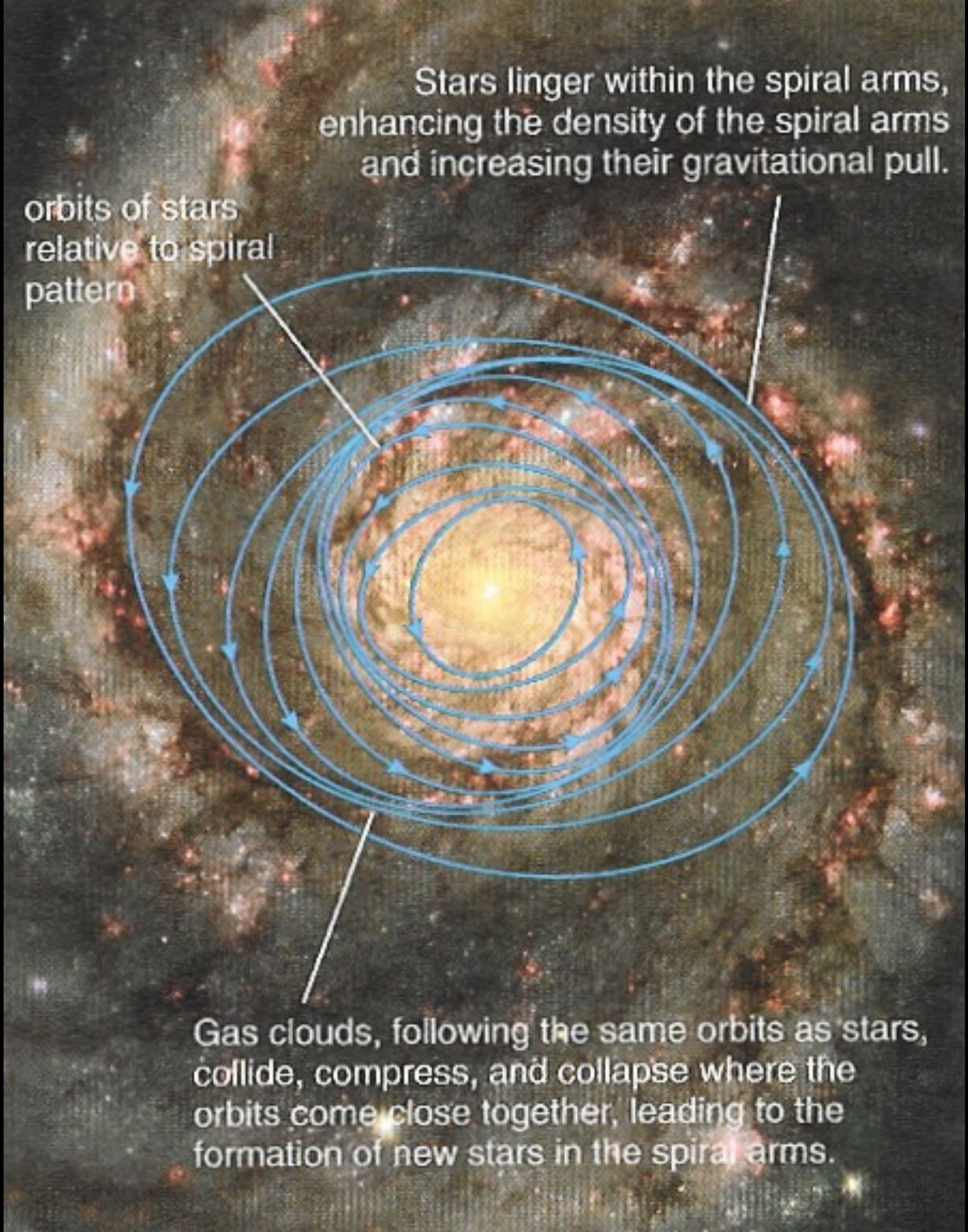


stars in disk move together

in nearly circular orbits

bulges are like elliptical galaxies

Density Waves Make Spiral Arms



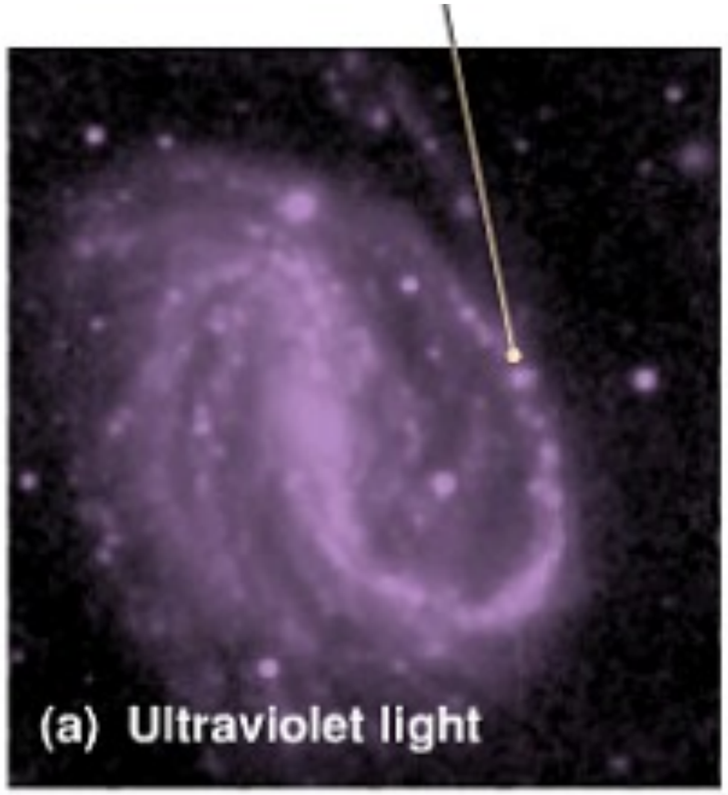
Stars linger within the spiral arms, enhancing the density of the spiral arms and increasing their gravitational pull.

orbits of stars relative to spiral pattern

Gas clouds, following the same orbits as stars, collide, compress, and collapse where the orbits come close together, leading to the formation of new stars in the spiral arms.

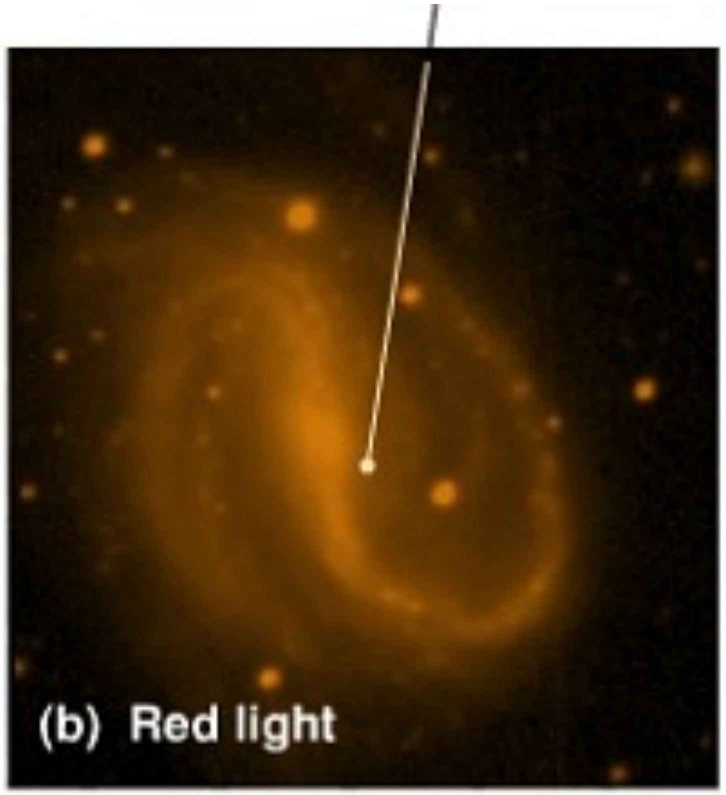
Dust in the plane of edge-on spiral galaxy

Ultraviolet light shows where massive young hot stars are forming



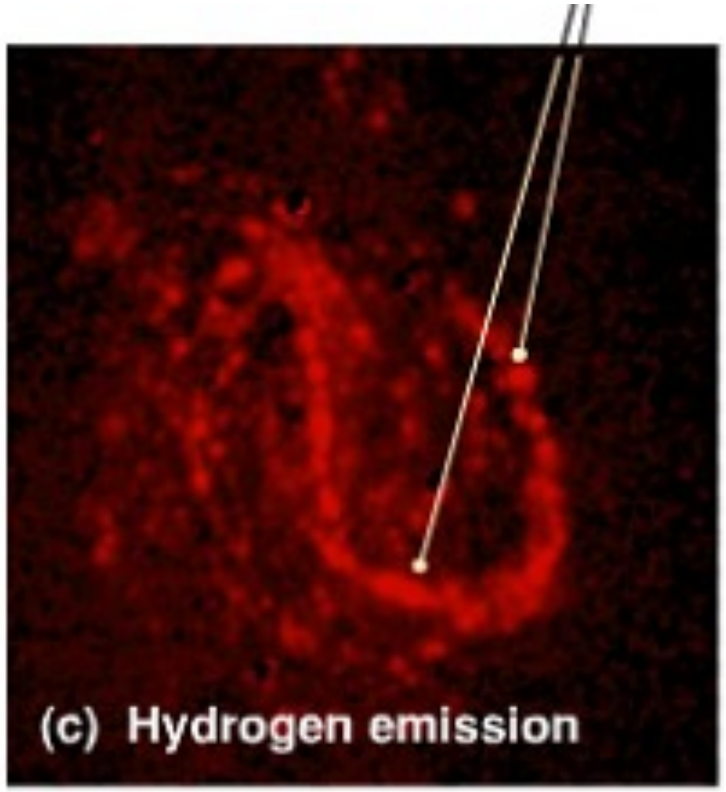
(a) Ultraviolet light

Red giants show where older stars are



(b) Red light

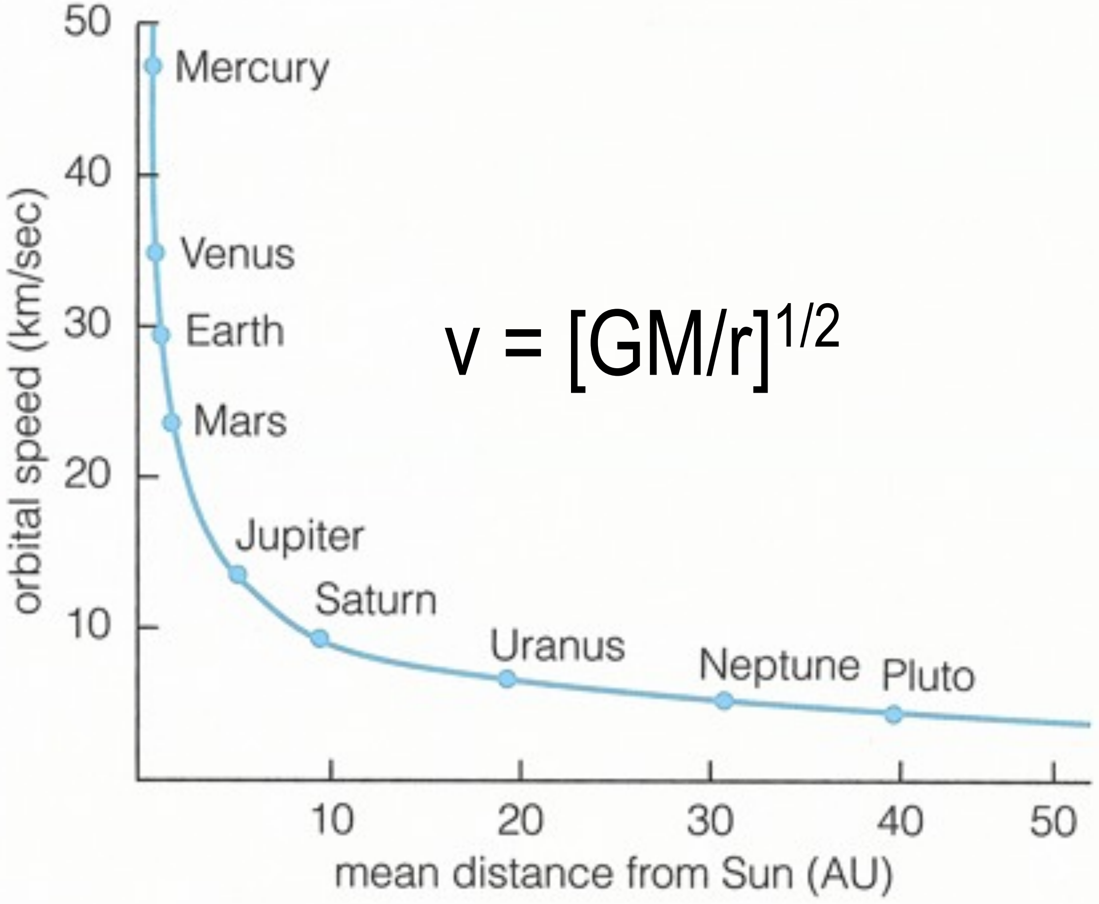
Glowing clouds of hydrogen trace massive star formation



(c) Hydrogen emission

Rotation Curves

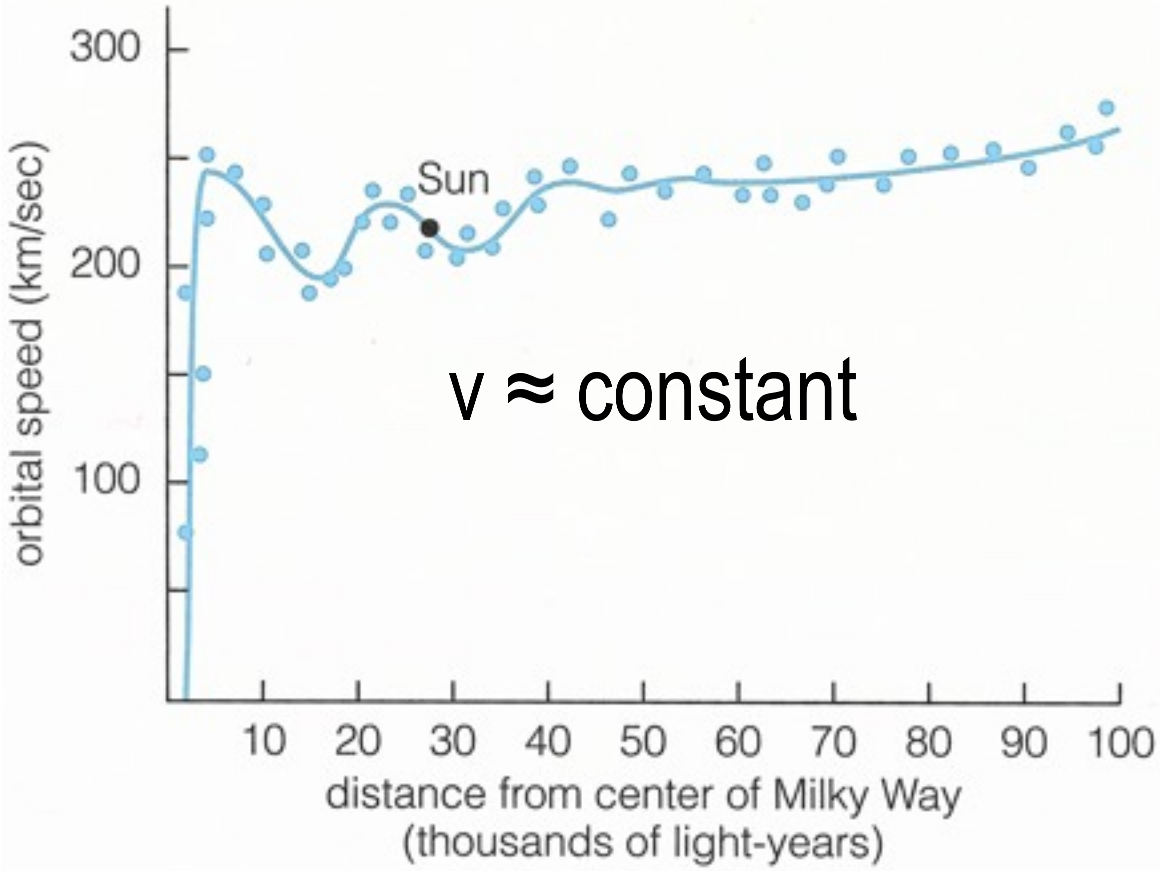
Solar System



$v = [GM/r]^{1/2}$

The rotation curve for the planets in our solar system.

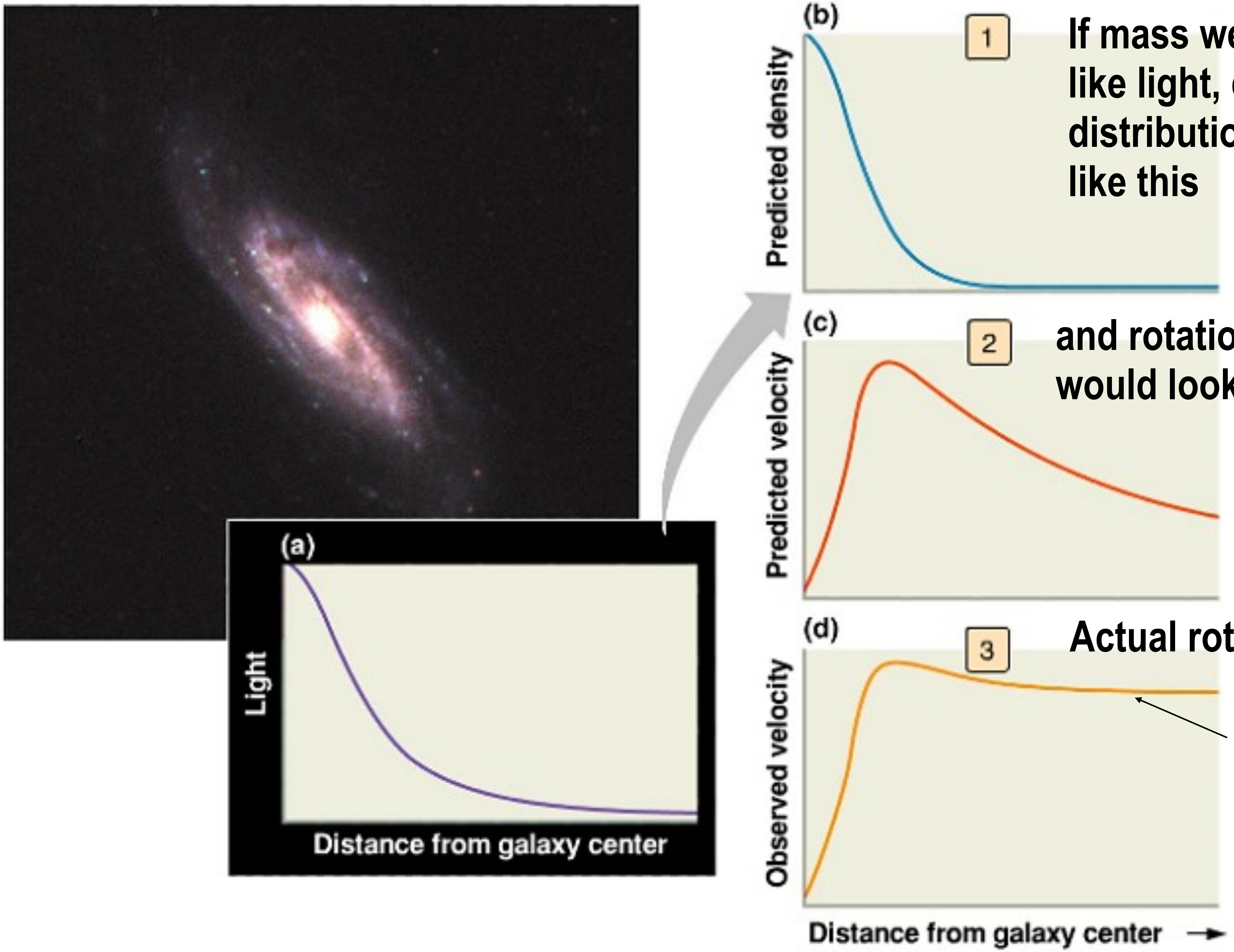
Milky Way



$v \approx \text{constant}$

The rotation curve for the Milky Way Galaxy.

Galaxies are held together by dark matter

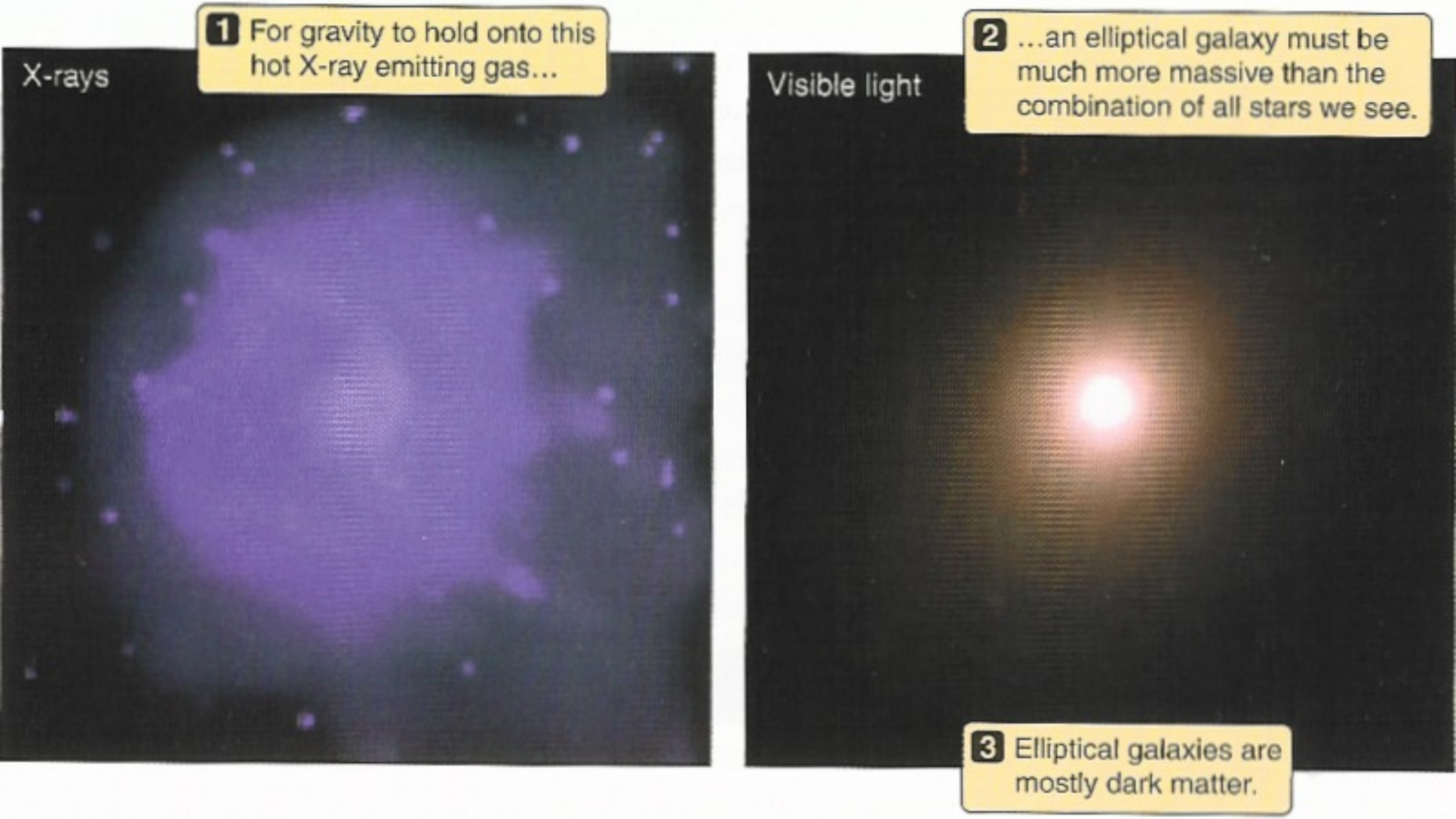


If mass were distributed like light, density distribution would look like this

and rotation curve would look like this

Actual rotation curve

Indicates invisible matter at large radii



1 For gravity to hold onto this hot X-ray emitting gas...

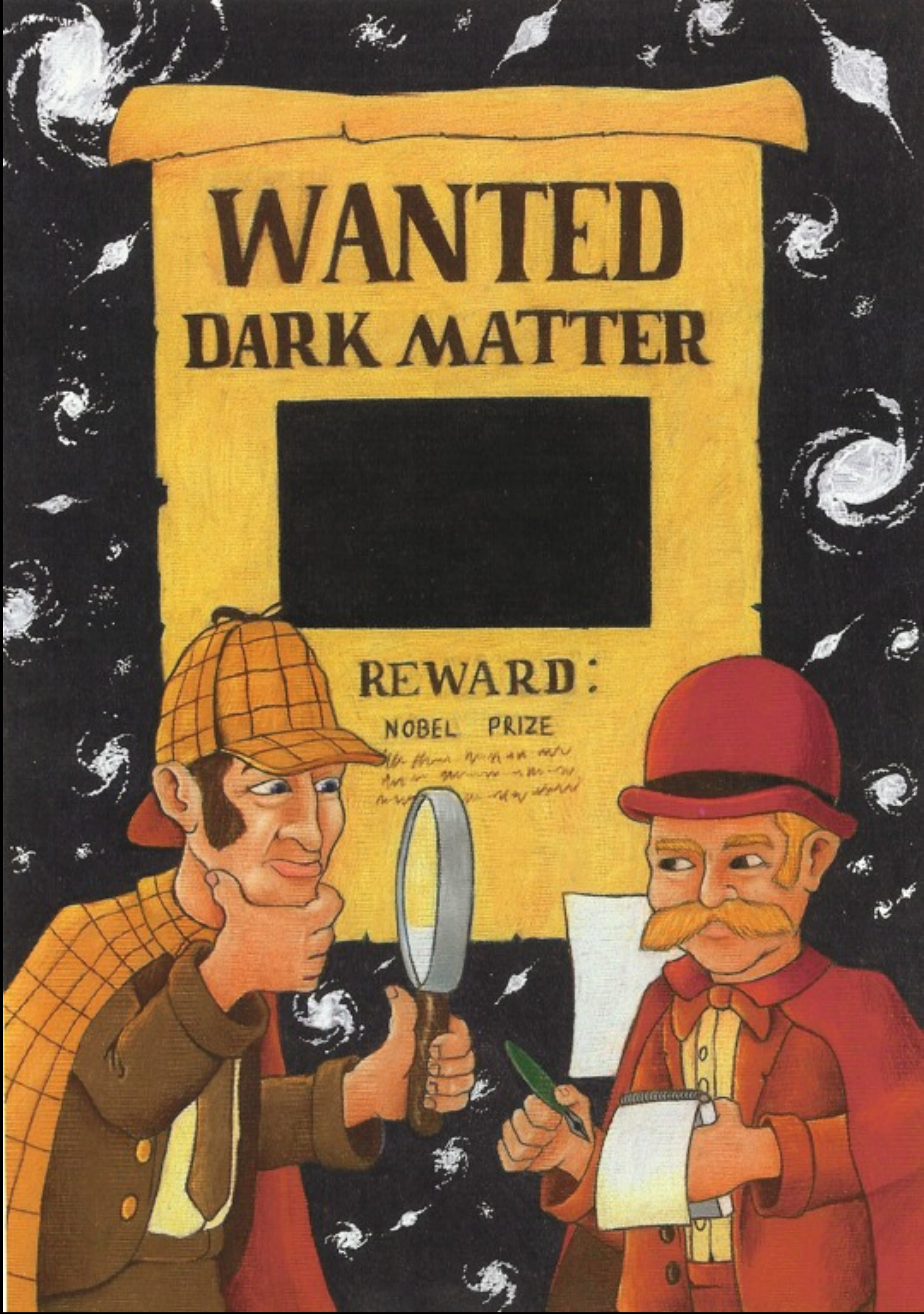
2 ...an elliptical galaxy must be much more massive than the combination of all stars we see.

3 Elliptical galaxies are mostly dark matter.

“The Case of the Dark Matter”

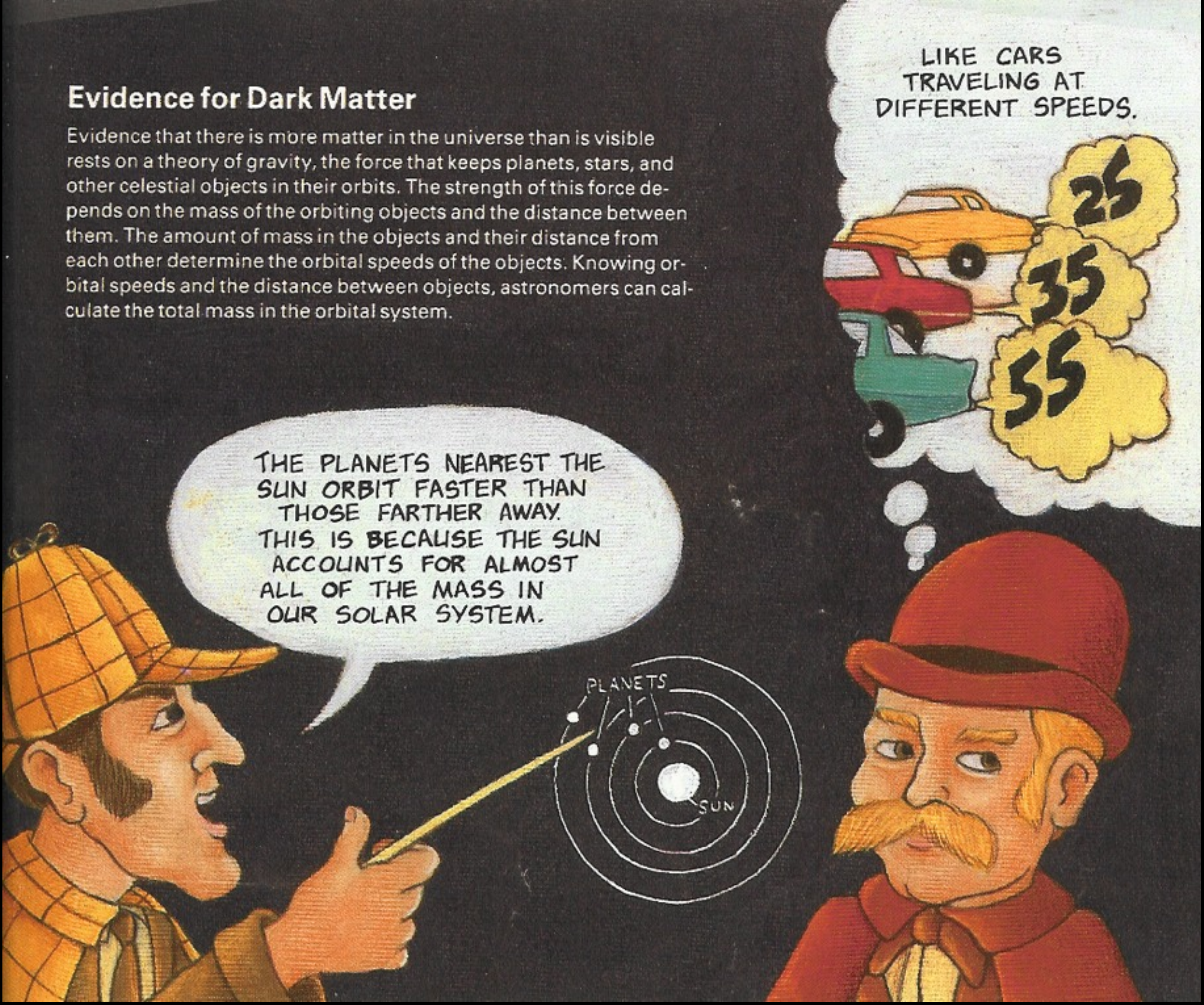
from *World Book Science Year 1990*

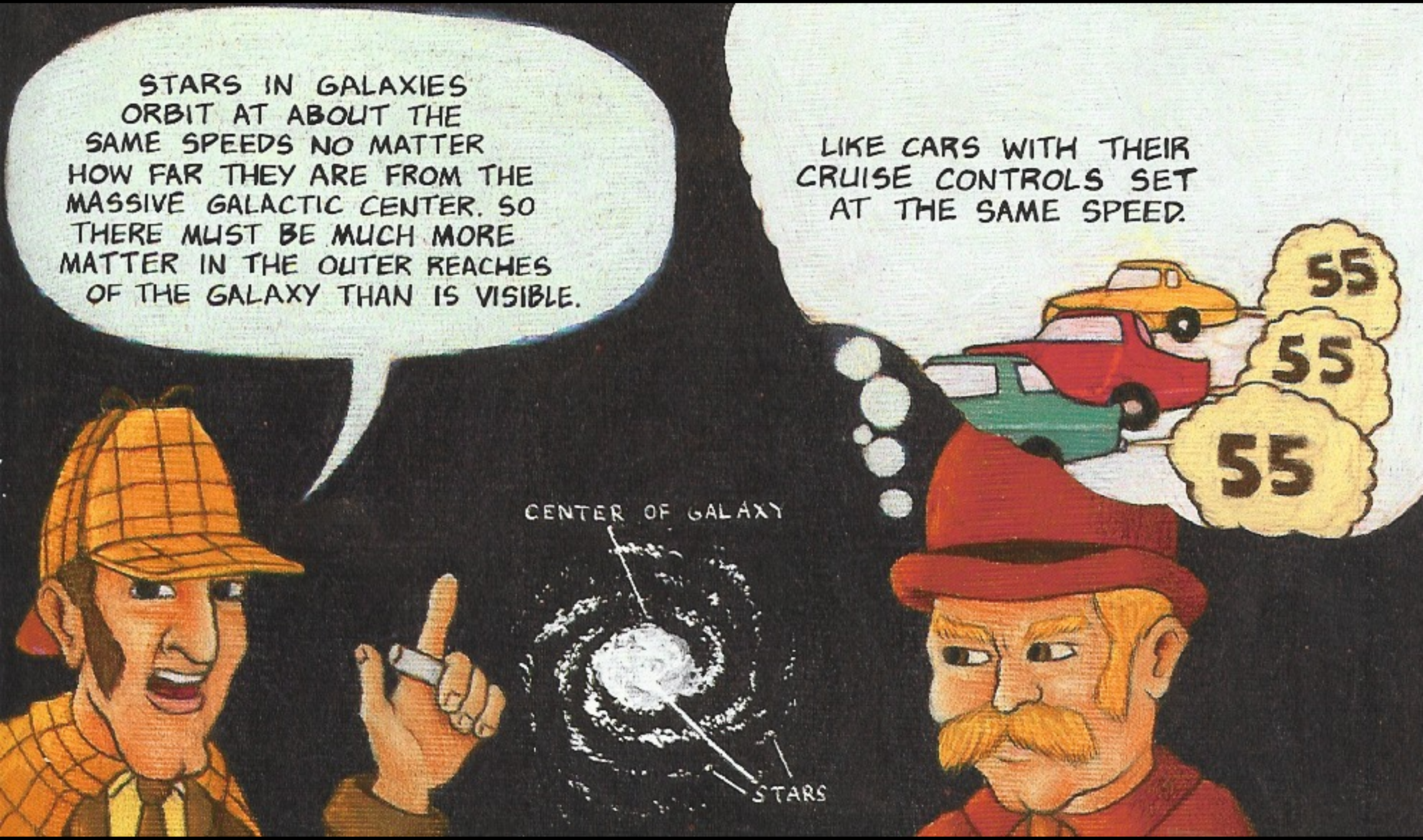
by Joel R. Primack



Evidence for Dark Matter

Evidence that there is more matter in the universe than is visible rests on a theory of gravity, the force that keeps planets, stars, and other celestial objects in their orbits. The strength of this force depends on the mass of the orbiting objects and the distance between them. The amount of mass in the objects and their distance from each other determine the orbital speeds of the objects. Knowing orbital speeds and the distance between objects, astronomers can calculate the total mass in the orbital system.

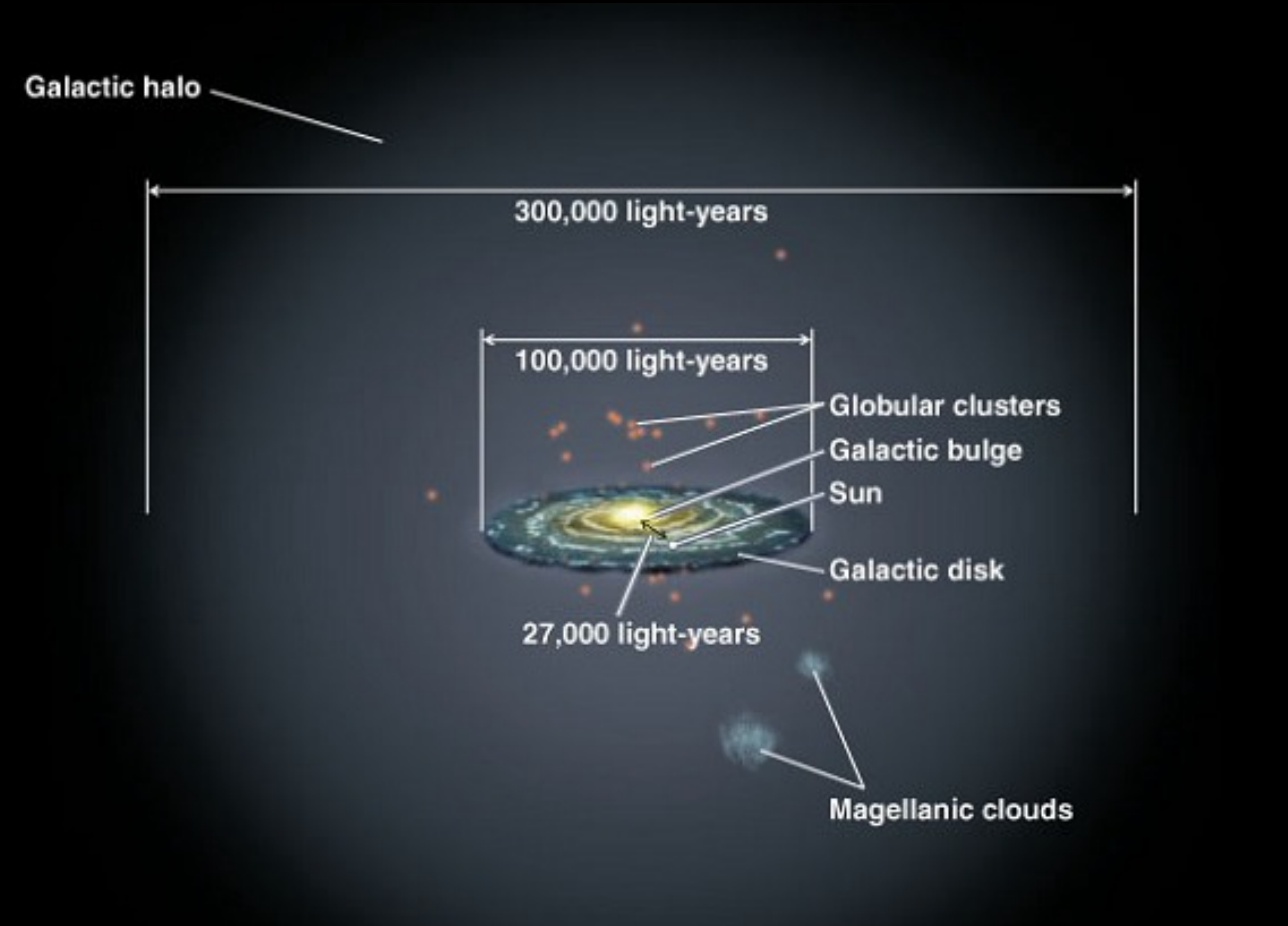



STARS IN GALAXIES ORBIT AT ABOUT THE SAME SPEEDS NO MATTER HOW FAR THEY ARE FROM THE MASSIVE GALACTIC CENTER. SO THERE MUST BE MUCH MORE MATTER IN THE OUTER REACHES OF THE GALAXY THAN IS VISIBLE.
LIKE CARS WITH THEIR CRUISE CONTROLS SET AT THE SAME SPEED.
55
55
55
CENTER OF GALAXY
STARS

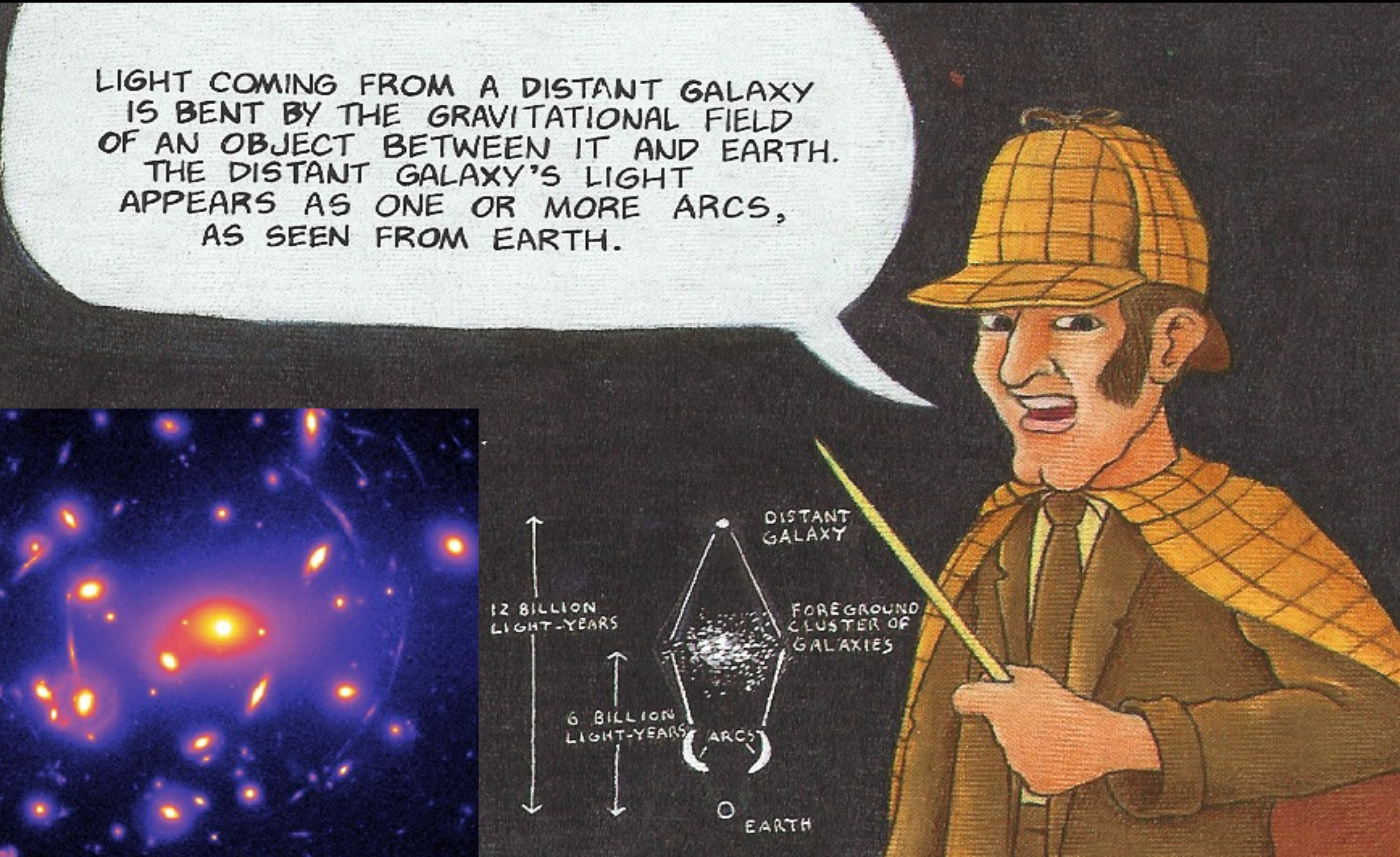
Most of the Mass is in the Dark Matter Halo

(denser in center)

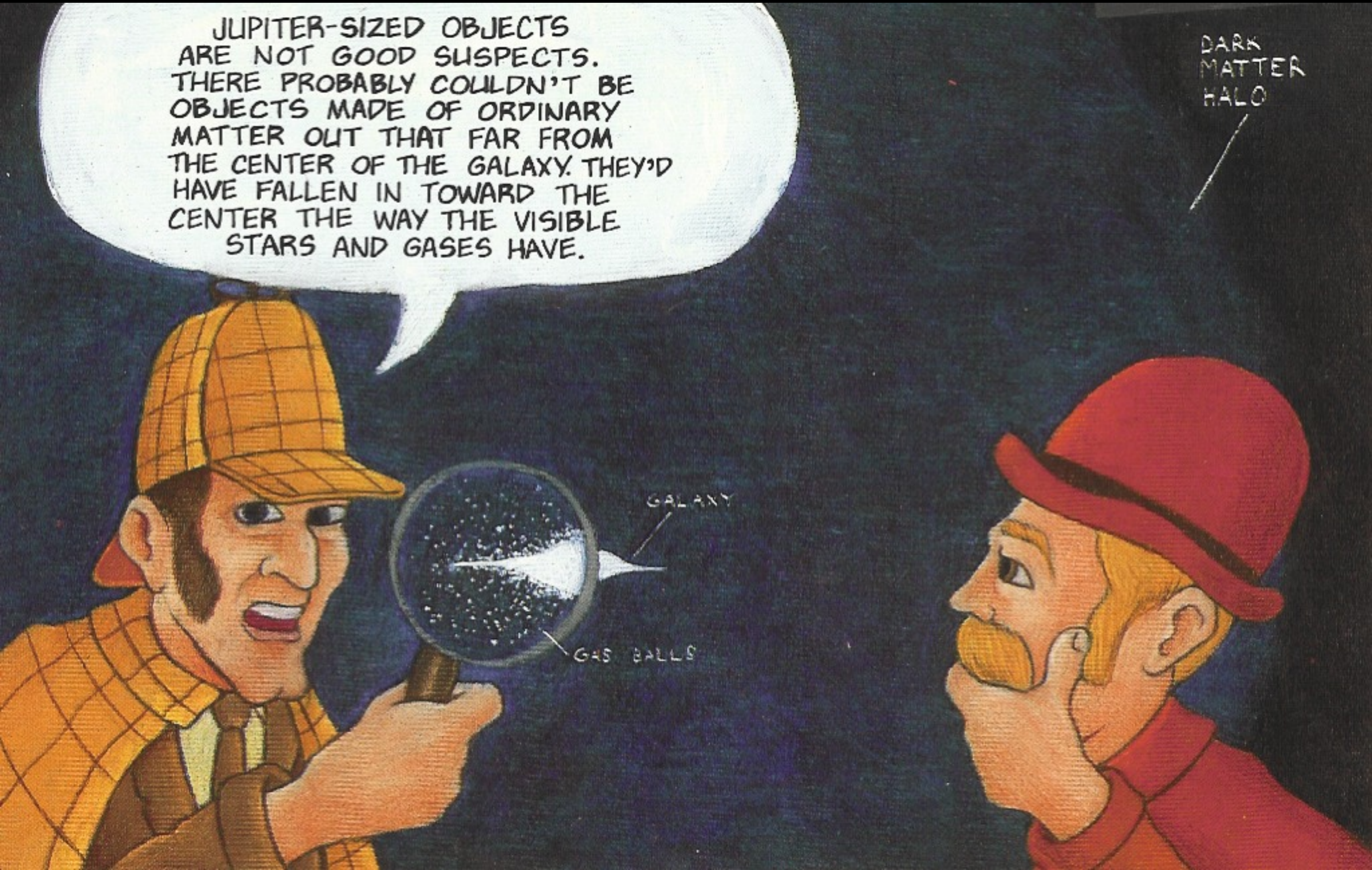
The Milky Way Within Its Dark Matter Halo



Gravitational Lensing Confirms Dark Matter in Galaxy Clusters

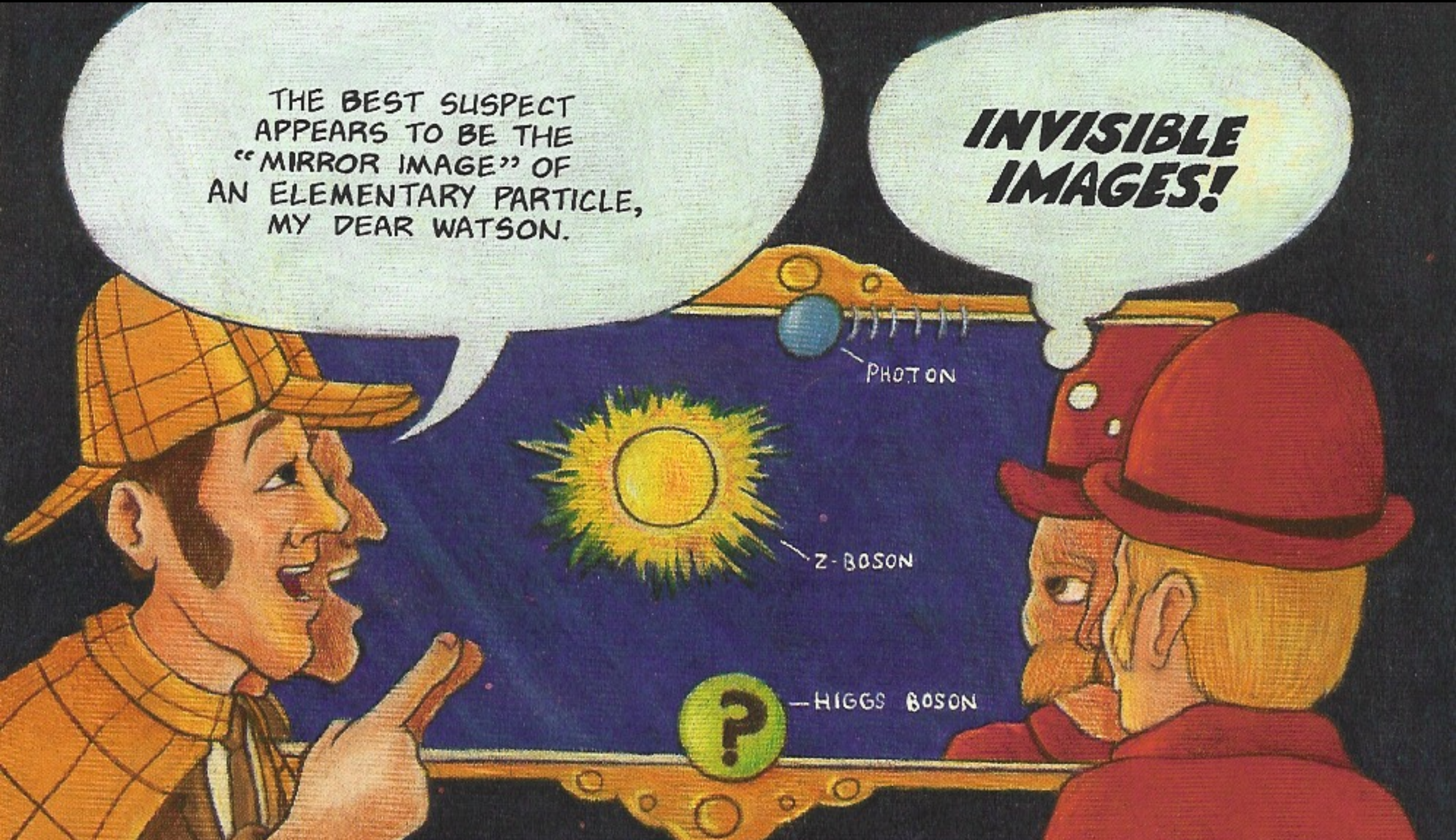


Jupiter-sized objects are not good dark matter suspects



Black Holes are not good suspects either

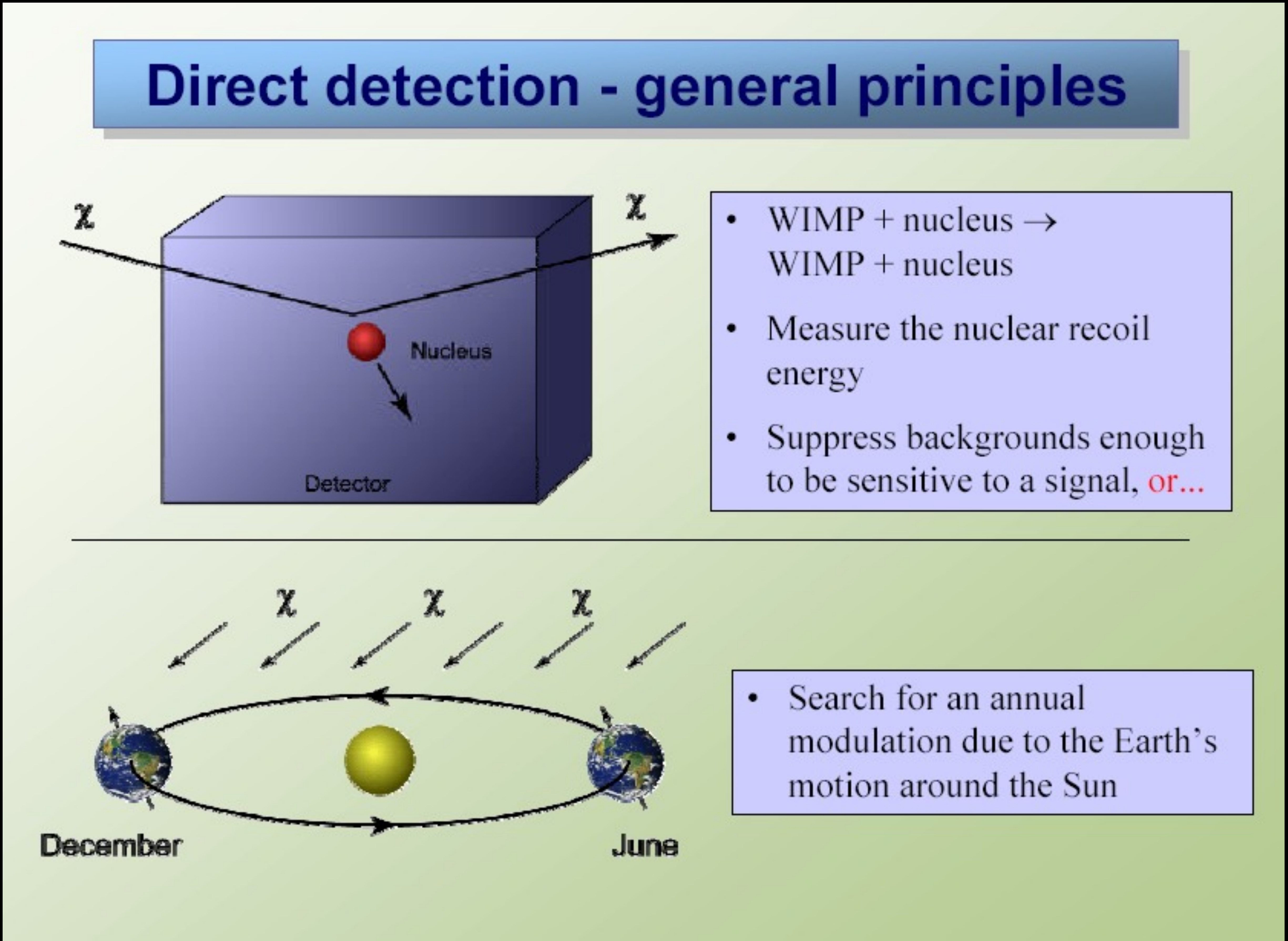
Photon, Z, and Higgs Supersymmetric Partners (*Photino, Zino, Higgsino*) are Prime Suspects



Supersymmetry is the basis of most attempts, such as superstring theory, to go beyond the current “Standard Model” of particle physics. Heinz Pagels and Joel Primack first pointed out in 1982 that the lightest supersymmetric partner particle is a good candidate for the dark matter particles – weakly interacting massive particles (**WIMP**s).

Michael Dine and others pointed out that the **axion**, a particle needed to save the strong interactions from violating CP symmetry, could also be the dark matter particle. Searches for both are underway.

Experiments are Underway for Detection of WIMPs



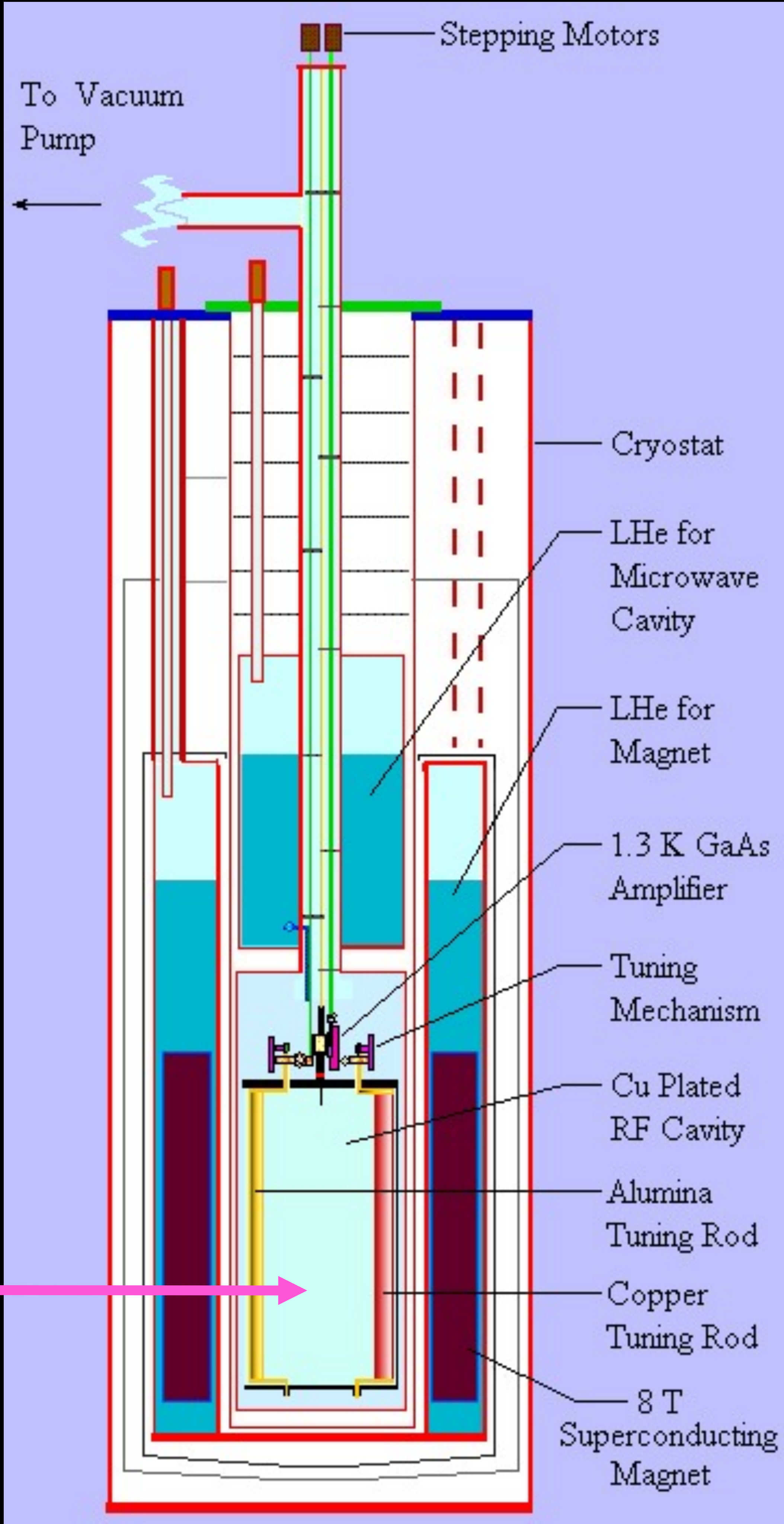
Direct detection - general principles

- WIMP + nucleus → WIMP + nucleus
- Measure the nuclear recoil energy
- Suppress backgrounds enough to be sensitive to a signal, or...

- Search for an annual modulation due to the Earth's motion around the Sun

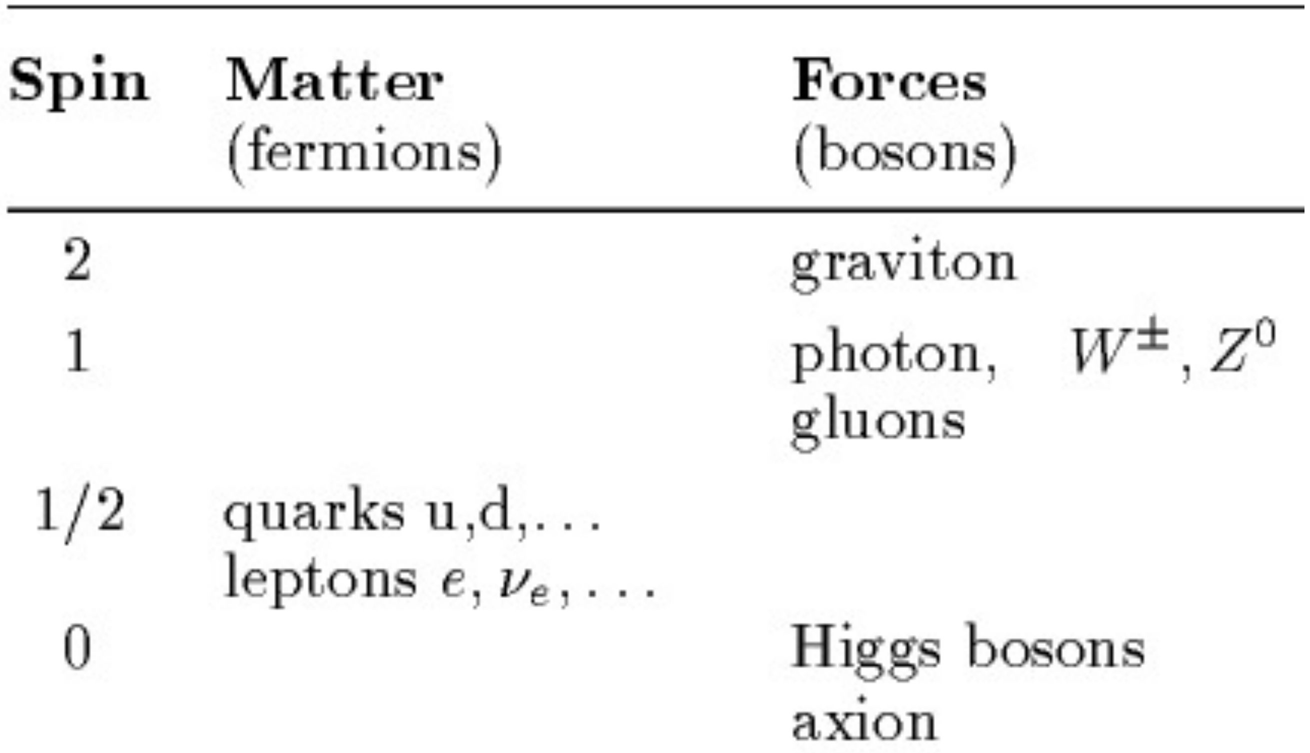
and also AXIONs

The diagram at right shows the layout of the axion search experiment now underway at the University of Washington. Axions would be detected as extra photons in the Microwave Cavity.



Supersymmetric WIMPs

When the British physicist Paul Dirac first combined Special Relativity with quantum mechanics, he found that this predicted that for every ordinary particle like the electron, there must be another particle with the opposite electric charge – the anti-electron (positron). Similarly, corresponding to the proton there must be an anti-proton. Supersymmetry appears to be required to combine General Relativity (our modern theory of space, time, and gravity) with the other forces of nature (the electromagnetic, weak, and strong interactions). The consequence is another doubling of the number of particles, since supersymmetry predicts that for every particle that we now know, including the antiparticles, there must be another, thus far undiscovered particle with the same electric charge but with *spin* differing by half a unit.

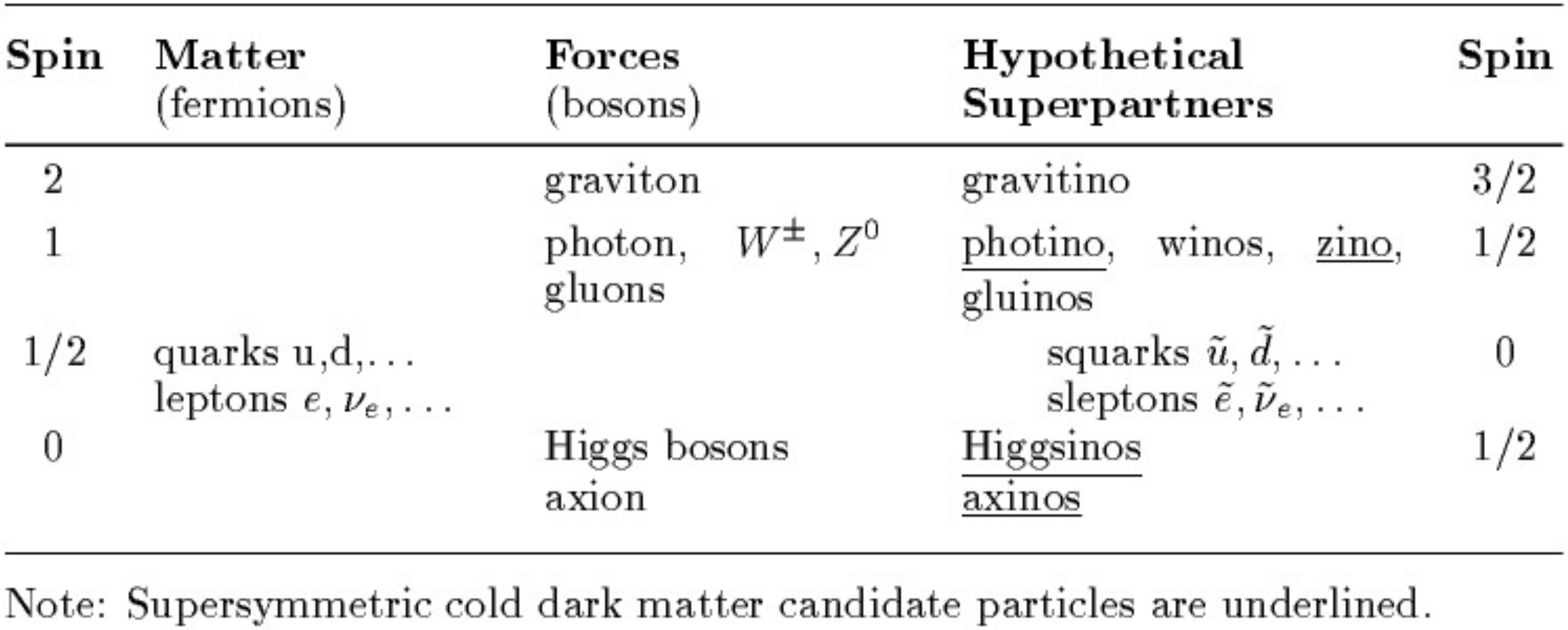


Spin	**Matter** (fermions)	**Forces** (bosons)
2		graviton
1		photon, $W^\pm, Z^0$ gluons
1/2	quarks u,d,. . . leptons $e, \nu_e, \dots$	
0		Higgs bosons axion

Supersymmetric WIMPs

When the British physicist Paul Dirac first combined Special Relativity with quantum mechanics, he found that this predicted that for every ordinary particle like the electron, there must be another particle with the opposite electric charge – the anti-electron (positron). Similarly, corresponding to the proton there must be an anti-proton. Supersymmetry appears to be required to combine General Relativity (our modern theory of space, time, and gravity) with the other forces of nature (the electromagnetic, weak, and strong interactions). The consequence is another doubling of the number of particles, since supersymmetry predicts that for every particle that we now know, including the antiparticles, there must be another, thus far undiscovered particle with the same electric charge but with *spin* differing by half a unit.

after doubling



Spin	**Matter** (fermions)	**Forces** (bosons)	**Hypothetical Superpartners**	**Spin**
2		graviton	gravitino	3/2
1		photon, $W^\pm$, Z^0, gluons	photino, winos, zino, gluinos	1/2
1/2	quarks u,d,... leptons e, ν_e, ...		squarks $\tilde{u}$, $\tilde{d}$, ... sleptons $\tilde{e}$, $\tilde{\nu}_e$, ...	0
0		Higgs bosons axion	Higgsinos axinos	1/2

Note: Supersymmetric cold dark matter candidate particles are underlined.

Supersymmetric WIMPs, continued

Spin is a fundamental property of elementary particles. Matter particles like electrons and quarks (protons and neutrons are each made up of three quarks) have spin ½, while force particles like photons, W,Z, and gluons have spin 1. The supersymmetric partners of electrons and quarks are called selectrons and squarks, and they have spin 0. The supersymmetric partners of the force particles are called the photino, Winos, Zino, and gluinos, and they have spin ½, so they might be matter particles. The lightest of these particles might be the photino. Whichever is lightest should be stable, so it is a natural candidate to be the dark matter WIMP. Supersymmetry does not predict its mass, but it must be more than 50 times as massive as the proton since it has not yet been produced at accelerators. But it will be soon, if it exists!

An Open or Shut Case

Astonomers want to know for sure whether dark matter exists so they can calculate how much matter there is in the universe. The total amount of matter will determine the ultimate fate of the universe, which right now is expanding rapidly in all directions like an enormous balloon.

We now know that there is not nearly enough matter for a big crunch.