Astrophysical Objects

Galaxy Formation

Based on: An introduction to modern Astrophysics chapter 26

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The Euclid satellite

The Perseus Cluster of galaxies

This incredible snapshot from Euclid is a revolution for astronomy. The image shows **1000 galaxies belonging to the Perseus Cluster**, and more than **100 000 additional galaxies further away** in the background.

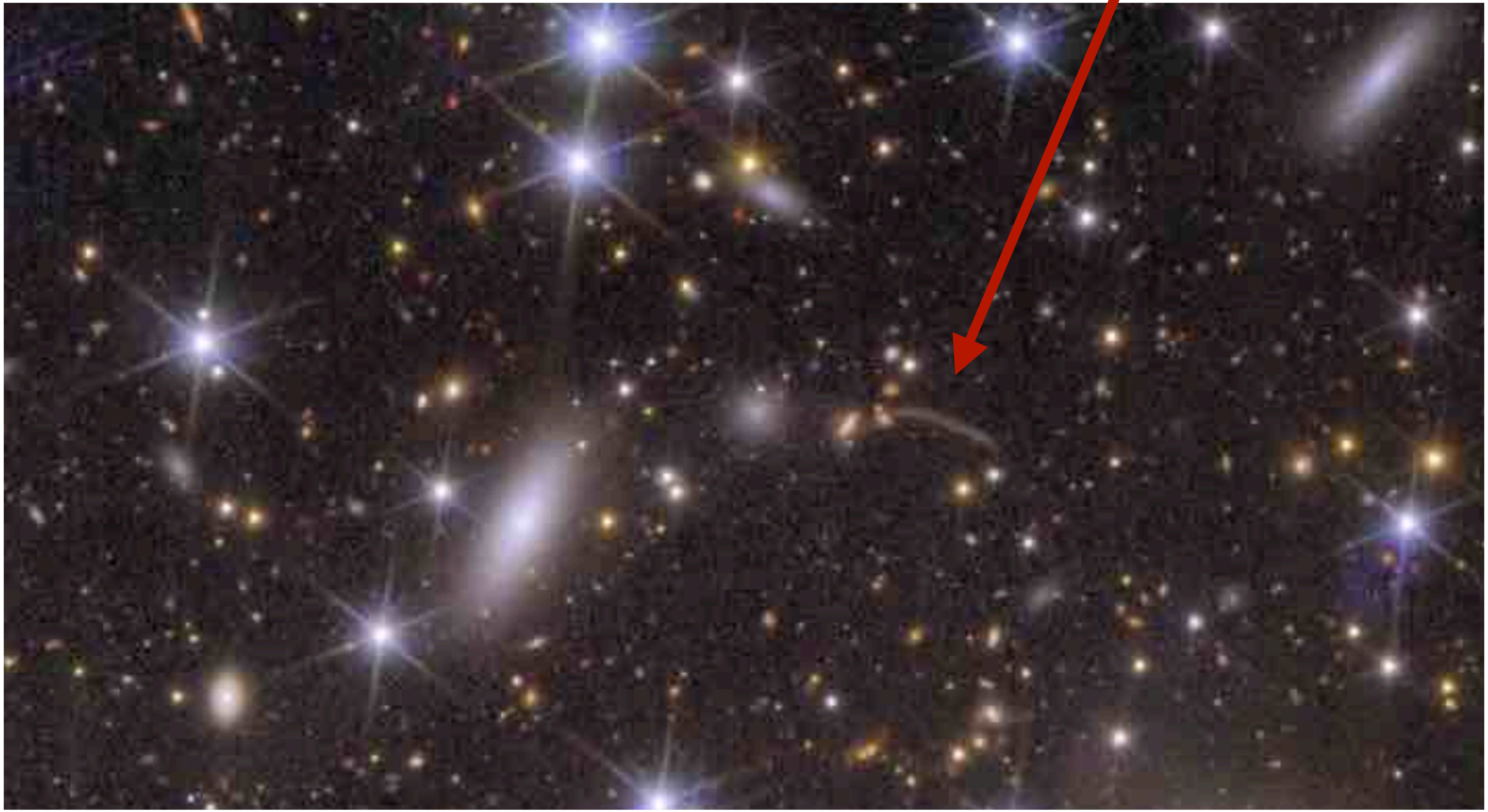
By mapping the distribution and shapes of these galaxies, cosmologists will be able to find out more about **how dark matter shaped the Universe** that we see today.

Perseus is one of the most massive structures known in the Universe, located ‘just’ 240 million light-years away from Earth.

The Euclid satellite

The Euclid satellite

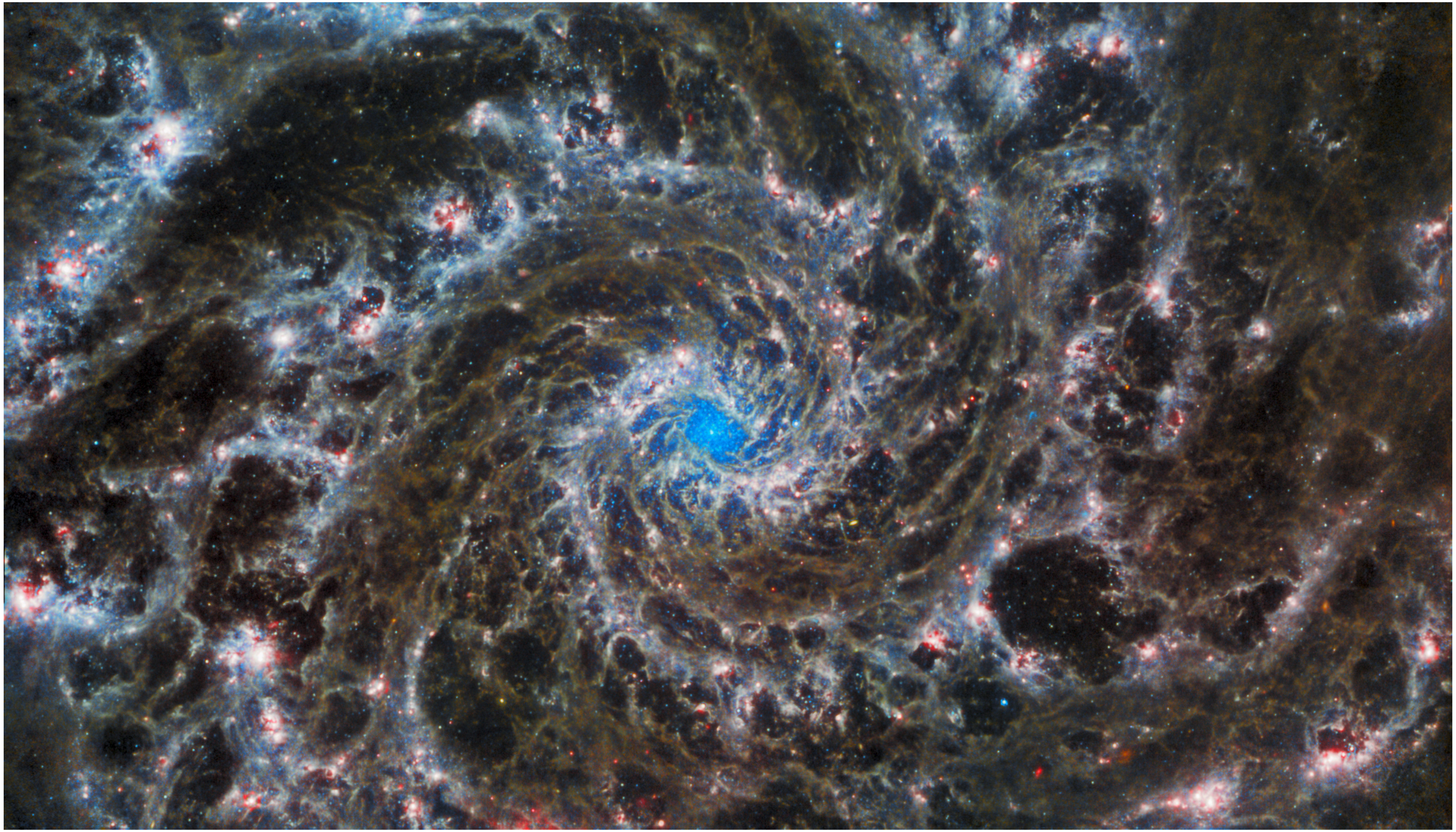
Gravitationally lensed galaxy



The JWST

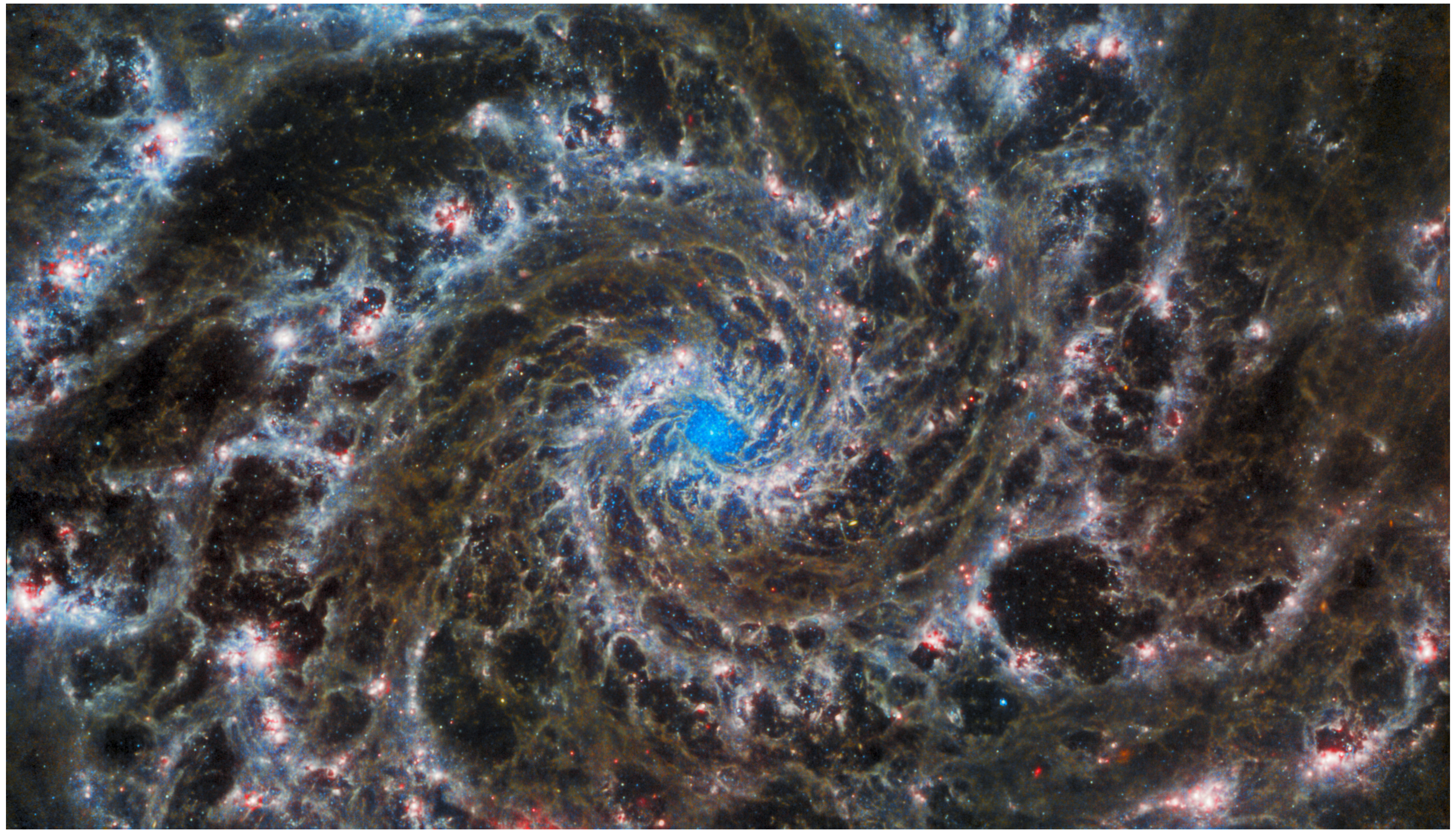
A grand design spiral galaxy M74, JWST image of the dust in this galaxy.

A lot of the stellar feedback is visible as bubbles.



The JWST

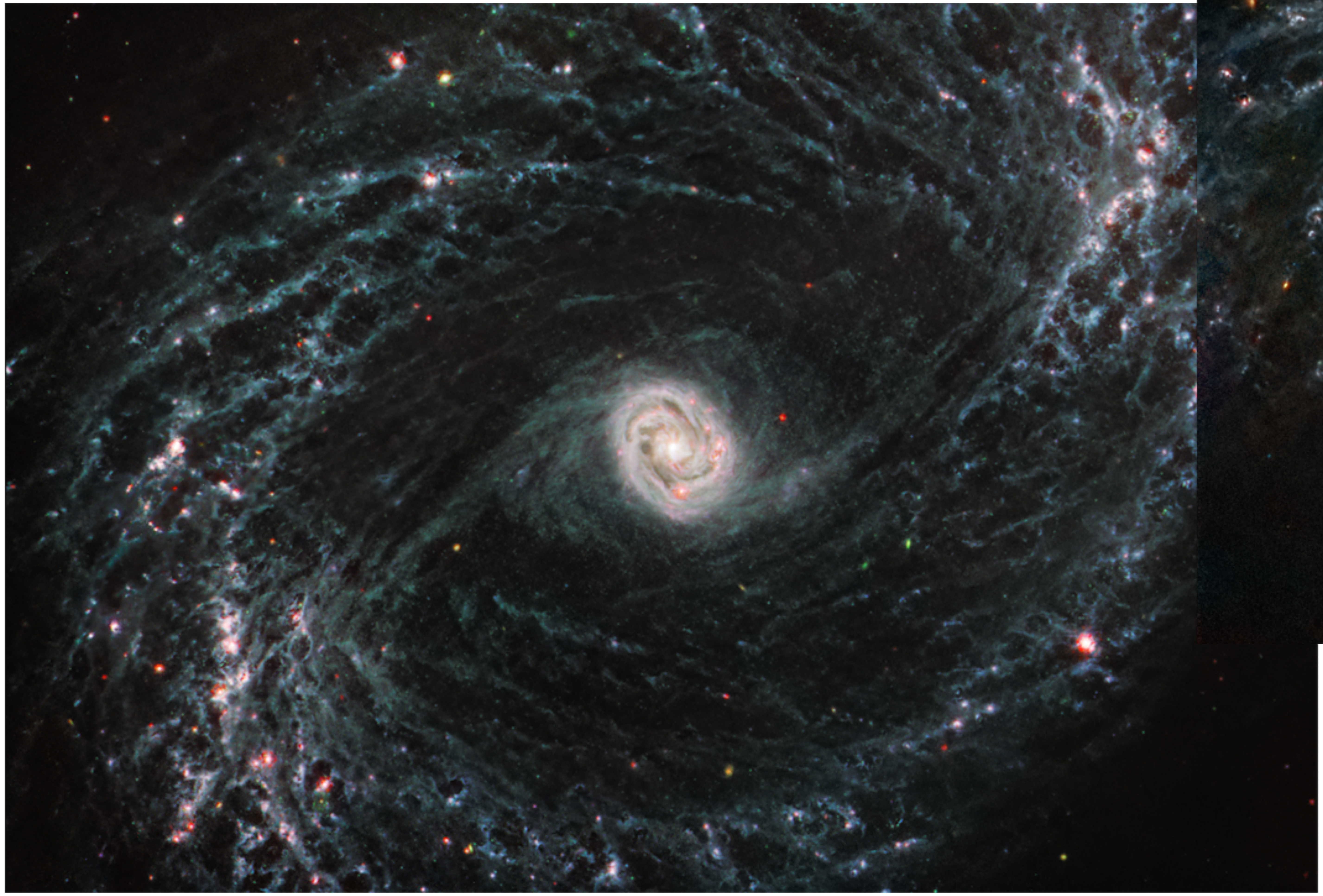
A grand design spiral galaxy M74



The JWST

NGC 7496

NGC 1433



The JWST

https://sites.google.com/view/phangs/home

NGC 7496
HST + JWST

Ram pressure stripping

ALMA (red/orange) data laid over Hubble Space Telescope (optical) images of NGC4921

https://public.nrao.edu/gallery/zooming-in-on-ram-pressure-stripping-in-galaxy-ngc4921/

Galaxy Formation

Galactic structures are complex and varied.

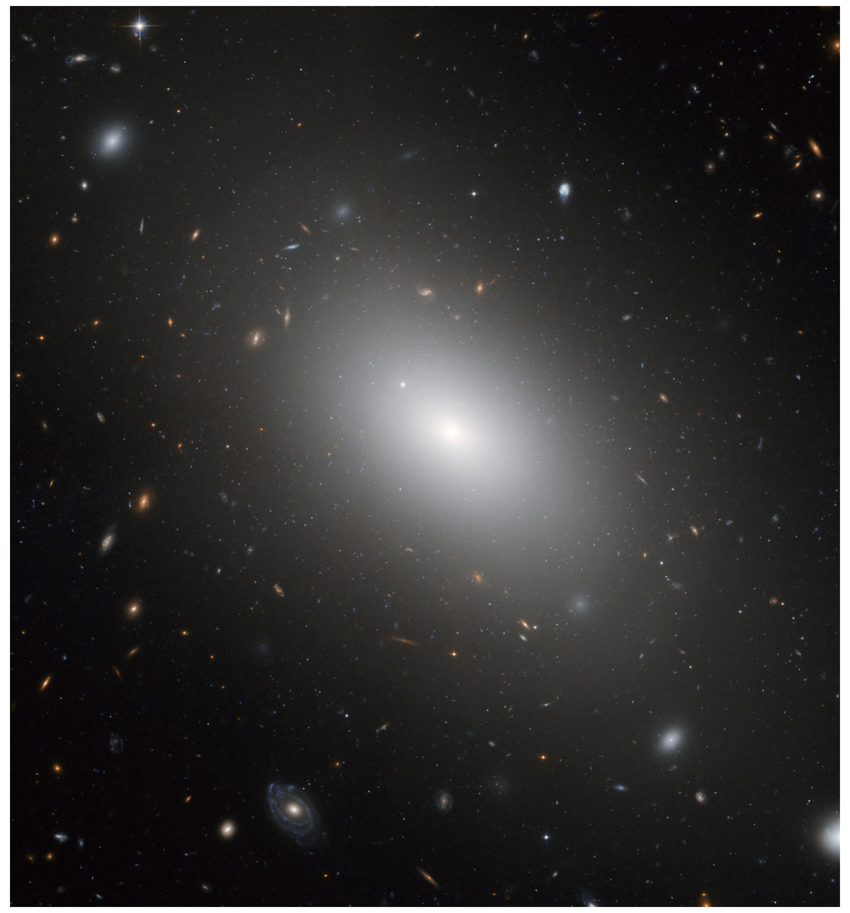
The luminous components of **elliptical galaxies** are dominated by spheroidal mass distributions that are primarily composed of old stars, while **spiral galaxies** contain both relatively old spheroids and appreciable disks of younger generations of stars, dust, and gas.

Important differences even exist within the designations of early- and late-type galaxies, such as the degree of diskiness or boxiness of normal ellipticals, the existence of dwarf spheroidals, and the relative dominance of the bulges and disks of spirals, to name a few.

Furthermore, the presence of **large quantities of dark matter**, accounting for 90% or more of the mass in many galaxies, also plays a critical role in determining their overall structures.

Early-type galaxies => ellipticals (only spheroid shape)

Late-type galaxies => spirals (have a disk)



Collapse model

In 1962 that Olin J. Eggen (1919–1998), Donald Lynden-Bell, and Allan R. Sandage presented an important early attempt at modeling the evolution of our Galaxy, often referred to as the **ELS collapse model**. Their work was based on **observed correlations between the metallicity of stars in the solar neighborhood, and their orbital eccentricities and orbital angular momenta**.

- Eggen, Lynden-Bell, and Sandage noted that the **most metal-poor stars tend to have the highest eccentricities**, the largest w components of their peculiar motions, **and the lowest angular momenta about the rotation axis of the Galaxy**.
- On the other hand, **metal-rich stars** tend to exist in **nearly circular orbits** and are confined to regions **near the plane of the Galaxy.**

To explain the kinematic and chemical properties of stars in the solar neighborhood, ELS suggested that the **Milky Way Galaxy formed from the rapid collapse of a large proto-Galactic nebula. The oldest halo stars formed early in the collapse process** while still on nearly radial trajectories, resulting in their highly elliptical orbits above and below the Galactic plane. As a further consequence of their rapid formation, the model predicts that the **halo stars are naturally very metal-poor (Population II)** since the interstellar medium had not yet had time to become enriched by stellar nucleosynthesis.

Collapse model

As the first generations of massive stars generated heavier elements in their interiors, underwent supernova explosions, and ejected metal-rich material back into the ISM, **the ISM evolved chemically over time.**

As the proto-Galactic cloud continued to fall inward, the model predicts that **the rapid collapse slowed when collisions between gas and dust particles became more frequent** and the **kinetic energy of infall was dissipated** (converted into the thermal energy of random particle motions). Furthermore, the presence of **angular momentum** in the original proto-Galactic nebula meant that the **cloud began to rotate more quickly as the radius decreased**. The combination of the increased dissipation and the increased angular speed led to the **development of a disk of chemically enriched gas** from which **Population I stars continue to form today.**

Collapse model

Example 2.1. The **time required for the free-fall collapse of the proto-Galactic cloud** predicted by the ELS model can be estimated.

Assume that the proto-Galactic cloud contained some **5×10^{11} M⊙, the estimated mass** of the Milky Way Galaxy within a **nearly spherical volume of radius 50 kpc** (which includes the dark matter halo).
If we further assume that the mass was uniformly distributed over the sphere, then the initial density of the cloud was

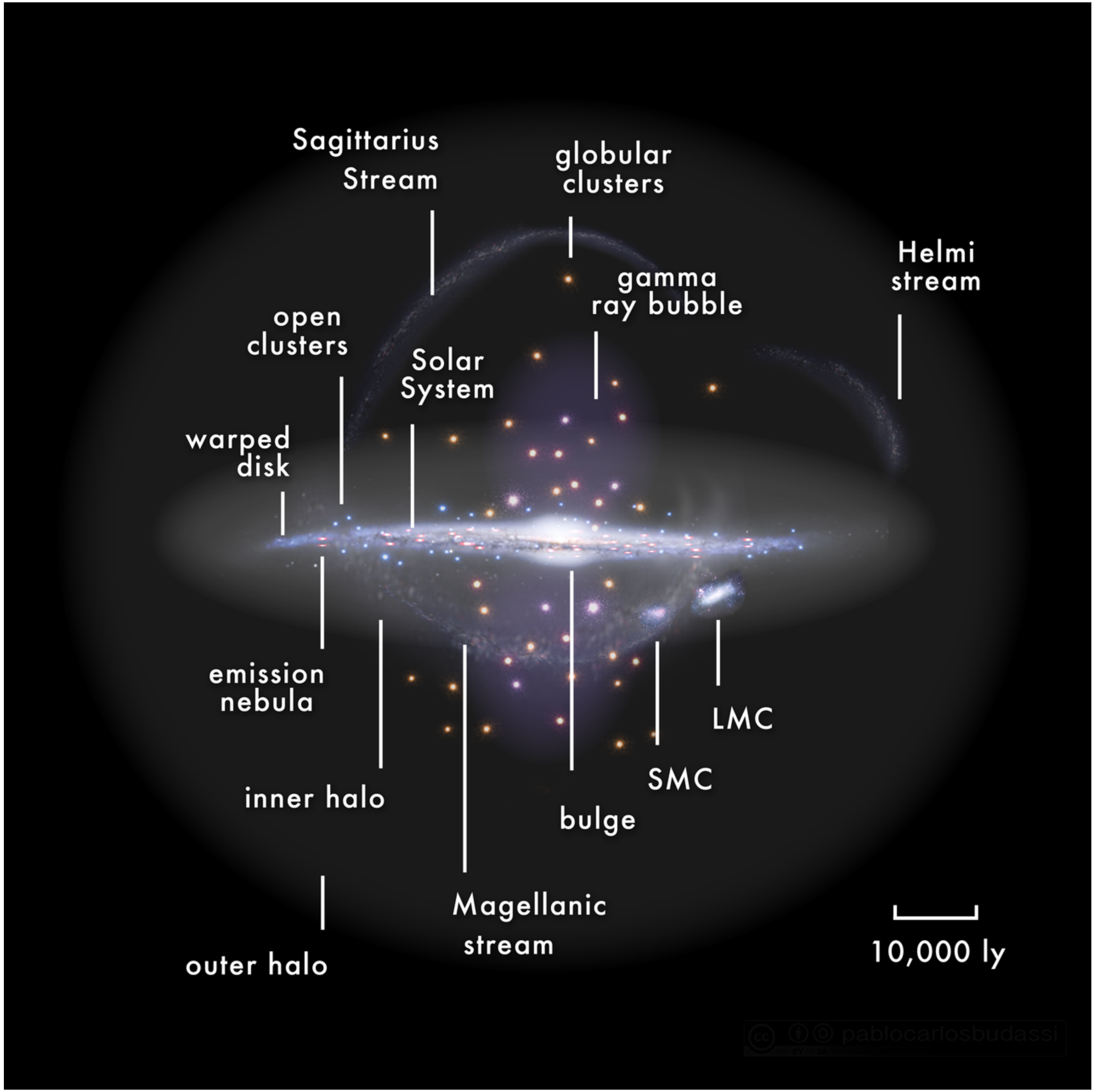
$$\rho_0 = \frac{3M}{4\pi r^3} = 8 \times 10^{-23} \text{ kg m}^{-3}.$$

$$t_{\text{ff}} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2} = 200 \text{ Myr}.$$

Collapse model

Of course, if the nebula were initially **somewhat centrally condensed**, the **inner portions** of the Galaxy would **collapse more rapidly** than the outer, rarefied regions.

This may explain the existence of the **very old stellar population within the bulge**. The **high metal abundance of bulge stars** would arise if the **first, massive, short-lived stars could quickly enrich the relatively dense ISM** in that part of the Galaxy. Recall that the lifetimes of the most massive stars are on the order of one million years, much shorter than the estimated free-fall timescale.



Problems with the ELS Collapse model

Although the model does **account for many of the basic features found in the structure of the Milky Way**, this *top-down* approach involving the **differentiation of a single, immense proto-Galactic** cloud **does not explain several important aspects** of our current understanding of the Galaxy's morphology.

For instance, given an initial rotation of the proto-Galactic cloud, essentially **all halo stars and globular clusters should be moving in the same general direction**, albeit with highly eccentric orbits about the Galactic center. However, astronomers have come to realize that **approximately one-half of all outer-halo stars are in retrograde orbits** and the net **rotational velocity of the outer halo is roughly 0 km s^{-1}**. On the other hand, stars in the **inner halo**, along with the inner globular clusters, appear to have **a small net rotational velocity.** (Our current understanding of the kinematics of halo stars and clusters seems to suggest that the **early environment of the Galaxy was fairly turbulent and clumpy.)**

A second problem is the apparent **age spread among the globular clusters and halo stars**. If the approximately **2-billion-year variation in ages** is real (the age range being perhaps 11 to 13 Gyr), then the **collapse must have taken roughly an order of magnitude longer to complete than proposed** by the ELS model. The model also does not readily explain the existence of a **multicomponent disk having differing ages**. The young disk is probably about 8 Gyr old, whereas the age of the thick disk may be 10 Gyr (both being significantly younger than the halo).

Problems with the ELS Collapse model

Another difficulty lies in the **compositional variation found between globular clusters**. The **clusters located nearest the Galactic center are generally the most metal-rich and oldest,** while the **clusters in the outer halo exhibit a wider variation in metallicity and tend to be younger.** The clusters also seem to form **two spatial distributions**; one set is associated with the **spheroid**, and the other may more properly be affiliated with the **thick disk**.

The problems that have developed with the early ELS view of the formation of the Milky Way suggest that our understanding of its formation and subsequent evolution must be revised or is otherwise incomplete. Furthermore, the rich **variety of galaxies**, along with their **ongoing dynamical evolution via mutual interactions and mergers,** poses interesting challenges to the development of an overall, coherent theory of galactic evolution.

The stellar birthrate function

Any theory of galaxy formation must be able to **explain the rate of formation of stars of various masses, as well as the chemical evolution of the interstellar medium.** Since the ISM is enriched by mass loss via stellar winds and supernovae of various types, the theory must also **incorporate the rates of stellar evolution** and the chemical yields of stars.

One problem immediately arises in this regard: Although astronomers have been able to develop a reasonable description of the evolution of individual stars, **our understanding of stellar birthrates is not yet complete.** It is customary to express the **stellar birthrate function**, $B(M, t)$, in terms of the **star formation rate** (SFR), $\psi(t)$, and the **initial mass function** (IMF), $\xi(M)$, in the form

$$B(M, t)\, dM\, dt = \psi(t)\, \xi(M)\, dM\, dt,$$

where M is the stellar mass and t is time.

$B(M, t)$ represents **the number of stars per unit volume** (or per unit surface area in the case of the Galactic disk) **with masses between M and M + dM that are formed out of the ISM during the time interval between t and t + dt.**

The stellar birthrate function

The **SFR describes the rate per unit volume at which mass in the ISM is being converted into stars**; the present value for the SFR within the Galactic disk is believed to be $5.0 \pm 0.5\ M_\odot\ \mathrm{pc}^{-2}\ \mathrm{Gyr}^{-1}$, integrated over the z direction (this corresponds to the **two to three stars formed per year** that was mentioned previously).

Finally, the **IMF represents the relative numbers of stars that form in each mass interval.**

To understand the birthrates of stars and their ensuing contribution to the chemical evolution of the ISM, different researchers have made **various assumptions about the SFR**.

- For instance, some astronomers have assumed that the SFR is time-independent,
- while others have argued for an exponentially decreasing function with time,
- or perhaps one that is proportional to some power of the surface mass density of the Galactic disk.

The stellar birthrate function

One computer simulation of the evolution of the disk of our Galaxy, performed by Andreas Burkert, James W. Truran, and G. Hensler (1992), produced an **SFR that reached a maximum value and then decreased with time as the available gas and dust in the ISM was consumed** (see Fig. 18). Other studies have considered the possibility that the **SFR may be highly variable in both space and time.** Such a situation could occur because of **short-timescale starburst activity,** for instance.

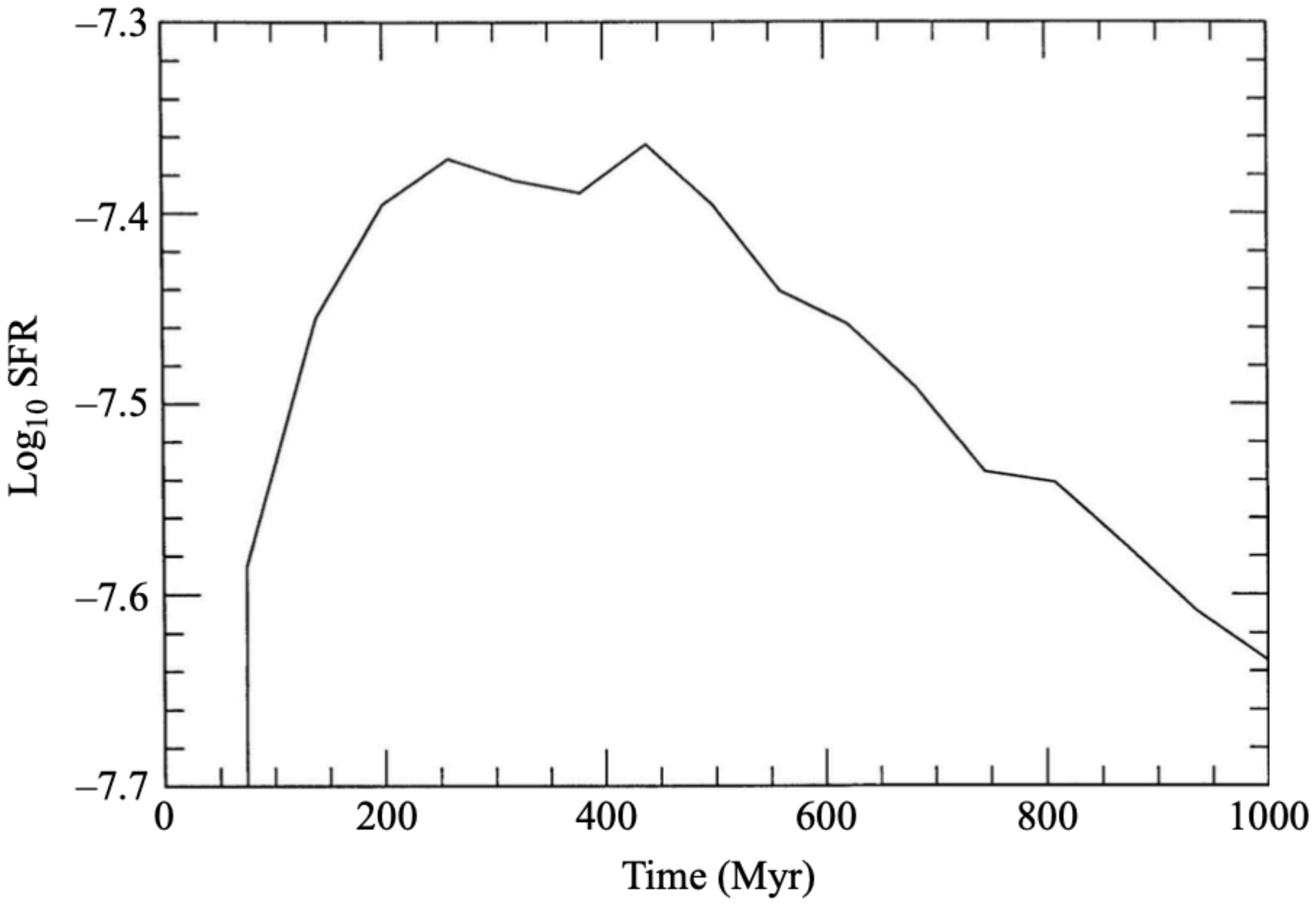


FIGURE 18 A model of the total star formation rate (in units of $M_\odot$ pc^{-2} yr^{-1}) for the disk of the Milky Way Galaxy as a function of time. (Figure adapted from Burkert, Truran, and Hensler, *Ap. J.*, *391*, 651, 1992.)

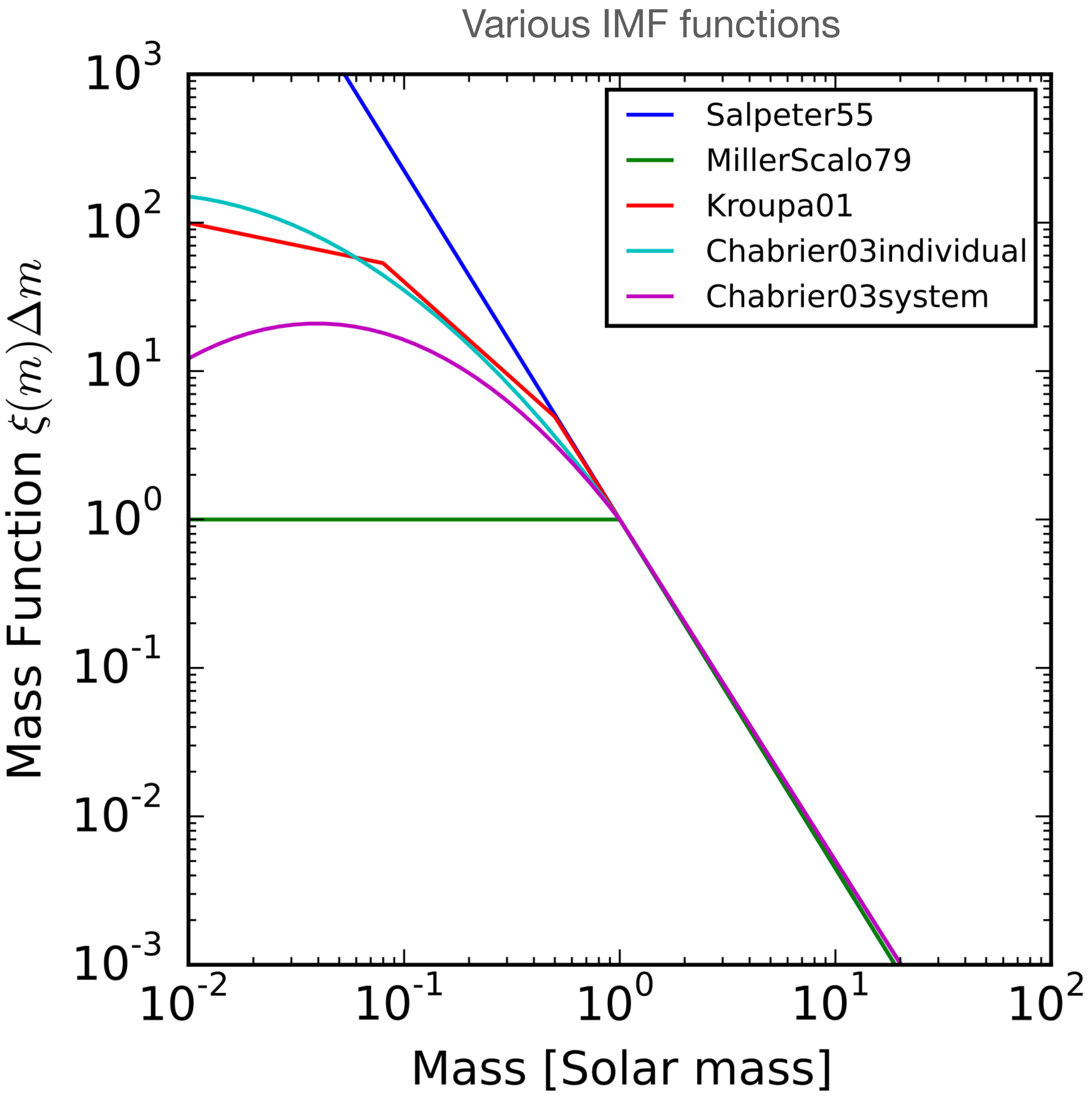
The stellar birthrate function

The **IMF is often modeled as a power-law fit** of the form

$$\xi(M) = \frac{dN}{dM} = CM^{-(1+x)},$$

where x may take on different values for various mass ranges and C is a normalization constant.

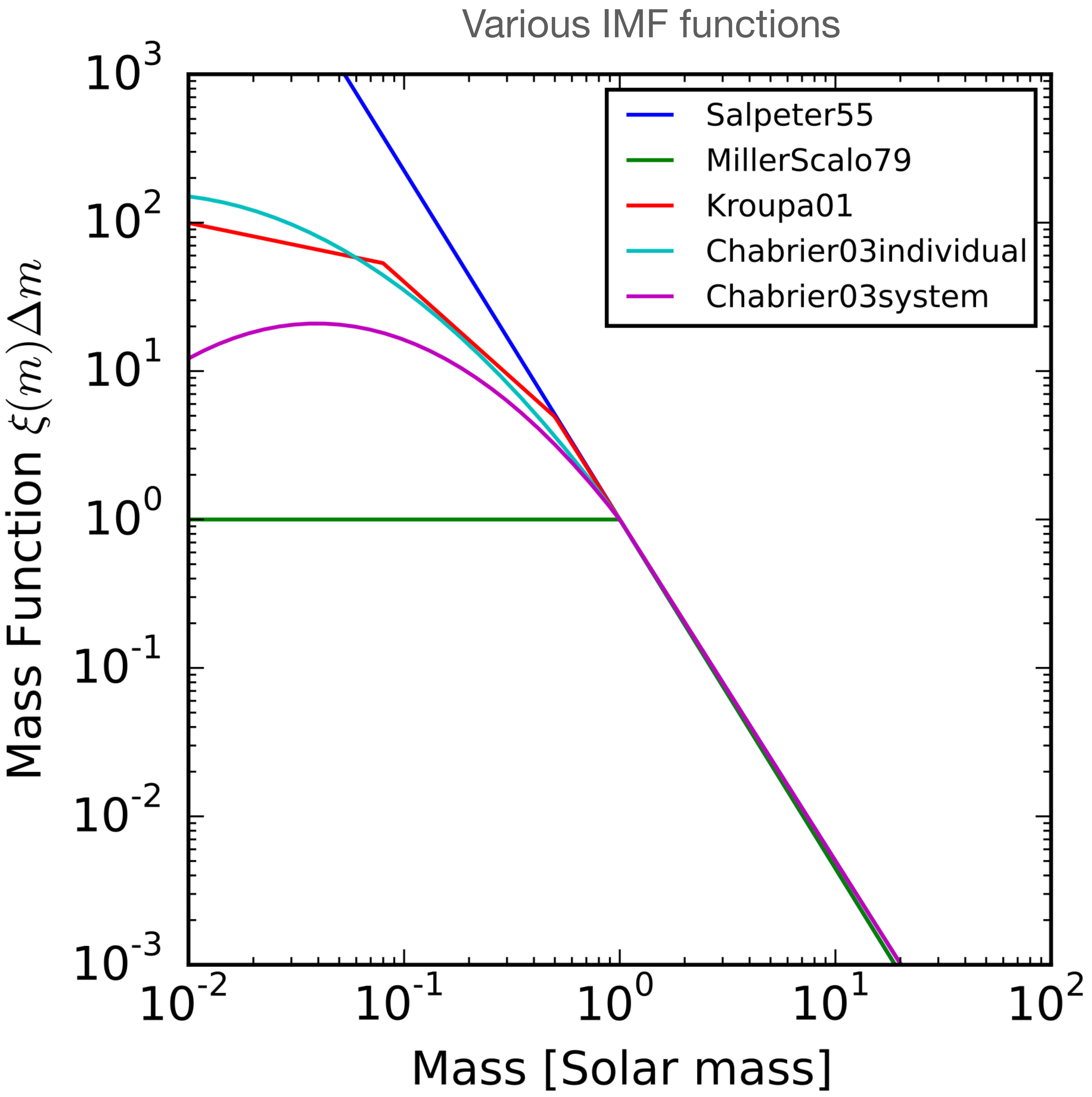
The first attempt to derive an IMF for the solar neighborhood was carried out by Edwin E. Salpeter in 1955, where he argued for a value of $x = 1.35$. According to more recent determinations, it appears that $x = 1.8$ may be a better fit for stars in the approximate mass range 7 $M_\odot$ to 35 $M_\odot$ (and perhaps down as low as 2 $M_\odot$).



The stellar birthrate function

For stars more massive than about 40 M⊙, x = 4 may be required, **implying that the production of massive stars drops off very rapidly with increasing mass**.

For lower-mass stars, x is **very difficult to determine** through observational studies. The complications arise because the IMF must be decoupled from the **present-day mass function** and the SFR, which itself can be quite complicated. It has been suggested that the IMF may flatten considerably at low masses. **Unfortunately, an exact form of the IMF is not yet known**, and it is not even clear whether the IMF varies with time or location.



The G dwarf problem

Attempts to use the SFR and IMF to model the chemical evolution of the Galactic disk in the solar neighborhood have resulted in predictions that do not always agree with observations.

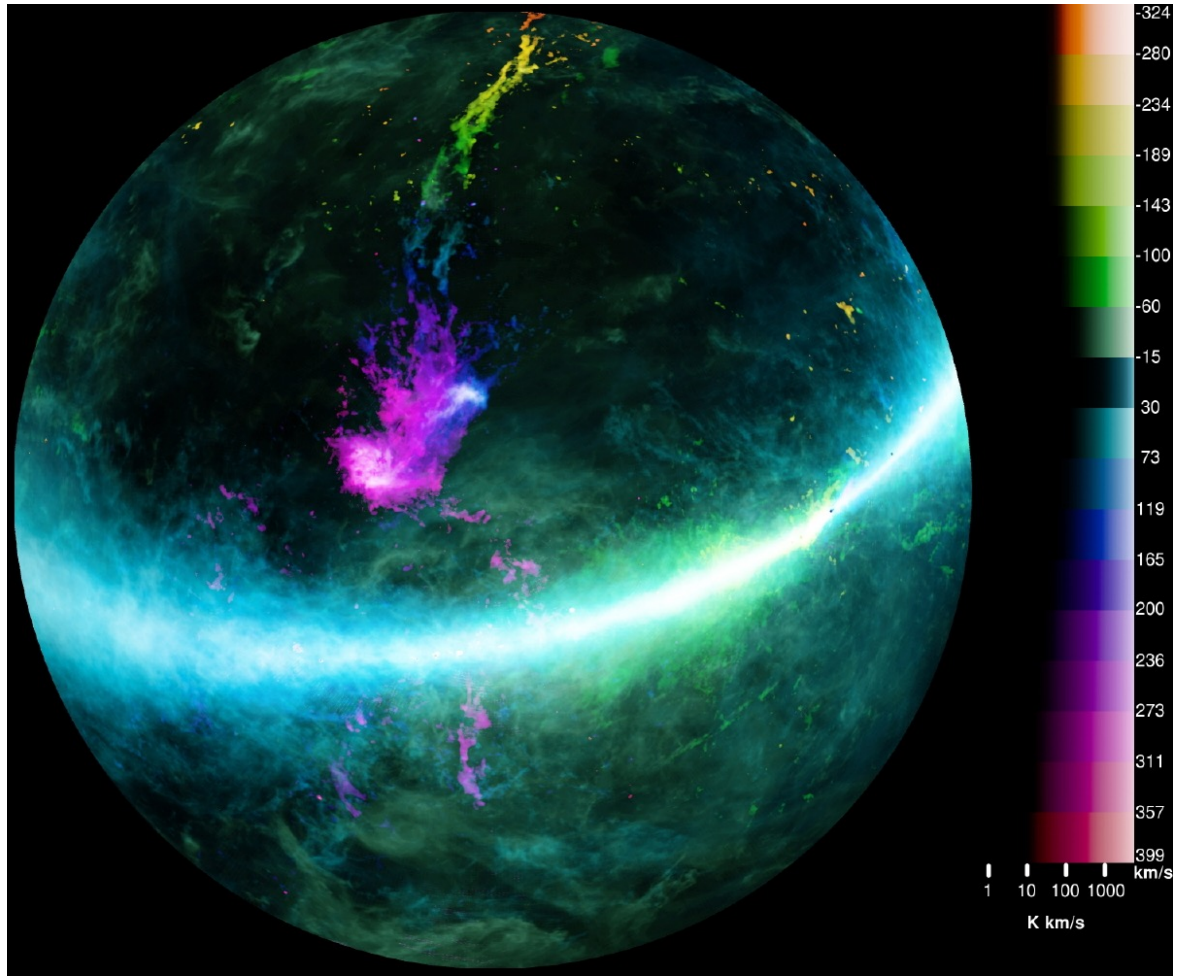
If we assume that the first generation of stars was born without any metals ($Z_0 = 0$; Population III) and the **chemical evolution of the ISM occurs within a *closed box*** (meaning that no gas or dust is allowed to enter or leave the system being modeled), then the **calculations predict too many stars of low metallicity** when compared with observations.

- For instance, this simple model suggests that roughly **one-half of the stars** in the solar neighborhood should have values for **Z** that are **less than one-quarter of the solar value** ($Z_\odot \simeq 0.02$).
- However, **only about 2% of the F and G main-sequence stars have such low Z values.** This is known as the **G-dwarf problem**.

The G dwarf problem

One possible solution to the G-dwarf problem, referred to as **prompt initial enhancement**, is to assume that the disk of our Galaxy formed with $Z_0 \neq 0$, which could occur **if heavy-element enrichment** of the ISM resulted from rapidly evolving massive stars b**efore the gas and dust settled into the disk**.

A second suggestion is that **the disk accumulated mass over a significant period of time,** perhaps even continuing to the present (in other words, the **closed-box assumption is invalid**). In this scenario a **substantial infall of metal-poor material onto the Galactic disk** has occurred since its initial formation; as the gas entered the system, it **mixed with the metal-enriched ISM.** Since a lower initial mass density would imply fewer stars formed during the early history of the disk, **fewer metal-poor stars would be observed today.** -> This is almost certainly the case. There is evidence for galaxies continuously getting gas from somewhere. E.g. the **Milky Way is getting gas from the metal poor Magellanic Clouds.**



The G dwarf problem

Yet another proposal argues that the **IMF was different in the early history of the Galaxy, and a larger fraction of more massive stars were formed with correspondingly fewer low-mass stars**. Since massive stars are short-lived, this hypothesis would result in fewer metal-poor stars today.

A Dissipative collapse model

Another issue that must be addressed by a comprehensive theory of galactic evolution is the question of a **free-fall collapse versus a slow, dissipative one**. A free-fall collapse is governed by the free-fall timescale, sometimes alternatively referred to as the **dynamical timescale**.

On the other hand, a **dissipative collapse** can be described in terms of the **time necessary for the nebula to cool significantly**.

If the **cooling timescale**, t_{cool} **, is much less than the free-fall timescale,** then the cloud will not be pressure-supported and the **collapse will be rapid** (i.e., essentially in free-fall).

However, **if the cooling time exceeds the free-fall timescale**, the gas cannot radiate its energy away fast enough to allow for a rapid collapse, and the gravitational potential energy that is released during the collapse will **heat the nebula adiabatically**. This situation is yet another example of the **virial theorem.**

-> an example for this is the outer halo of galaxies made of hot gas

A Dissipative collapse model

To estimate the cooling timescale, we must first determine the characteristic amount of **thermal kinetic energy** contained within each particle in the gas. According to the virial theorem, if we assume that the gas is in **quasistatic equilibrium**, the average thermal kinetic energy of the gas must be **related to its potential energy** by,

$$\boxed{-2\langle K\rangle = \langle U\rangle .}$$

If we further assume that the gas has a mean molecular weight of μ and contains N particles, then the virial theorem gives

$$-2N\frac{1}{2}\mu m_H \langle v^2\rangle = -\frac{3}{5}\frac{GM^2}{R},$$

where $m = \mu m_H$ is the average mass of a single particle, R is the radius of the nebula, and $M = N\mu m_H$ is the nebula's mass.

A Dissipative collapse model

In the last expression, we used a gravitationally bound, spherical mass distribution of constant density to estimate the potential energy of the system. Solving for the velocity dispersion $\sigma = \langle v^2 \rangle^{1/2}$ gives

$$\sigma = \left(\frac{3}{5} \frac{GM}{R} \right)^{1/2} .$$

Now we may determine a characteristic temperature of the gas, known as the **virial temperature**, by equating the typical kinetic energy of a gas particle to its thermal energy, or

$$\frac{1}{2} \mu m_H \sigma^2 = \frac{3}{2} k T_{\mathrm{virial}},$$

$$T_{\mathrm{virial}} = \frac{\mu m_H \sigma^2}{3k}.$$

A Dissipative collapse model

Finally, to estimate the cooling time we must determine the rate at which energy can be radiated away from the gas. This is done by expressing the cooling rate per unit volume as

$$\boxed{r_{\rm cool} = n^2 \Lambda(T),}$$

where r_{cool} has units of energy per unit time per unit volume, n is the number density of particles in the gas, and $\Lambda(T)$ is a quantum mechanical **cooling function**.

A Dissipative collapse model

$\Lambda(T)$, shown in Fig. 19, includes the same physical processes of bound–bound, bound–free, free–free, and electron scattering.

The two **"bumps"** in the curve just above 10^4 K and near 10^5 K correspond to the **ionization/ recombination temperatures** of **hydrogen and helium**, respectively. Above about **10^6 K,** the cooling is due to **thermal bremsstrahlung and Compton scattering**.

The n^2 dependence in the expression for r_{cool} can be understood in terms of the **interactions between pairs of particles in the gas**; collisions excite ions, atoms, or molecules, which then radiate the energy away in the form of photons, cooling the gas.

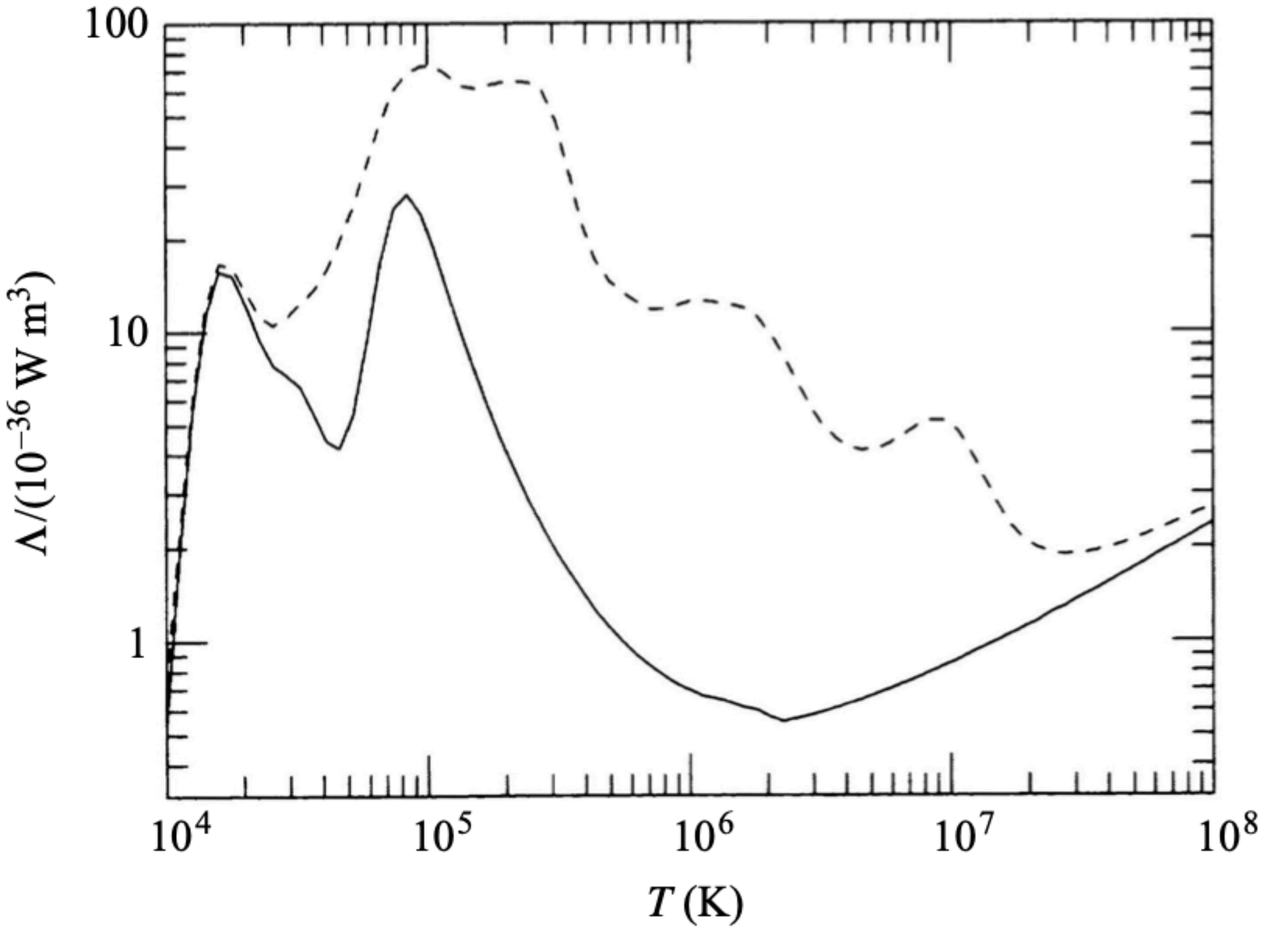


FIGURE 19 The cooling function $\Lambda(T)$. The solid line corresponds to a gas mixture of 90% hydrogen and 10% helium, by number. The dashed line is for solar abundances. (Figure adapted from Binney and Tremaine, *Galactic Dynamics*, Princeton University Press, Princeton, NJ, 1987.)

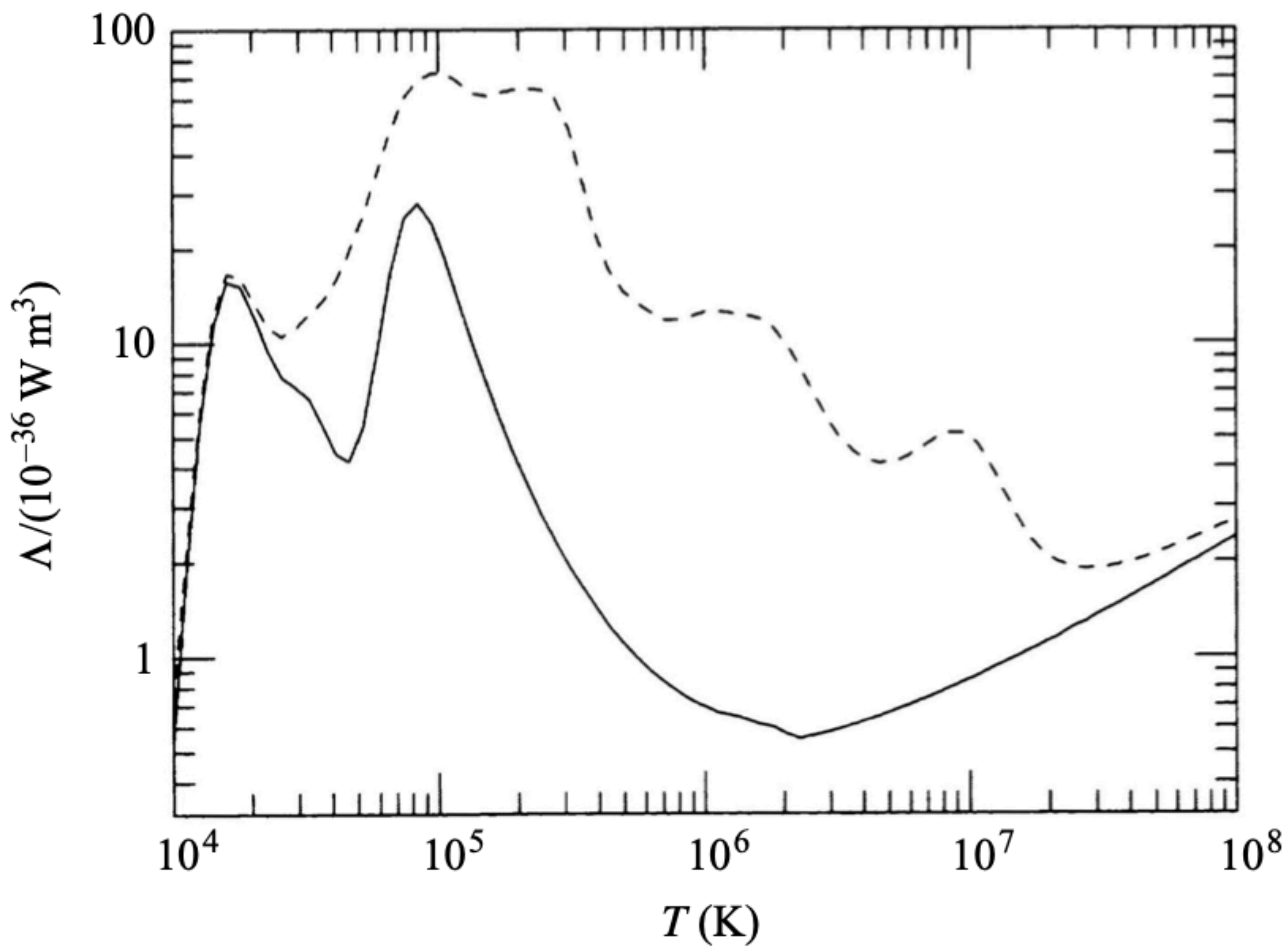
A Dissipative collapse model

If all of the energy in the cloud is radiated away in a time t_{cool}, then

$$r_{\mathrm{cool}} V t_{\mathrm{cool}} = \frac{3}{2} N k T_{\mathrm{virial}},$$

where V is the volume of the cloud. Solving for the cooling time, we have

$$\boxed{t_{\mathrm{cool}} = \frac{3}{2} \frac{k T_{\mathrm{virial}}}{n \Lambda}.}$$



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A Dissipative collapse model

Example 2.2. Assume for simplicity that the **proto-Galactic nebula** discussed in Example 2.1 was initially composed of **90% hydrogen and 10% helium**, by number (this corresponds to $X \simeq 0.7$ and $Y \simeq 0.3$).

If we assume **complete ionization**, then the mean molecular weight is given by $\mu \simeq 0.6$. Also, the **initial velocity dispersion** of the particles in the gas was approximately $\sigma = 160$ km s^{-1}. Then, the virial temperature of the gas at the time of collapse was roughly

$$T_{\text{virial}} = \frac{\mu m_H \sigma^2}{3k}. \qquad T_{\text{virial}} \simeq 6 \times 10^5 \text{ K}.$$

(At this temperature our assumption that the gas was completely ionized is certainly valid.)

Note that we are assuming here that *all* of the mass is in the form of baryonic matter. This means that we are neglecting the influence of dark matter in this example.

A Dissipative collapse model

The **number density of particles** in the gas is given by

$$n = \frac{\rho}{\mu m_H} = \frac{3M}{4\pi R^3 \mu m_H} \sim 5 \times 10^4 \text{ m}^{-3}.$$

This value should be compared to the typical number densities found in Galactic molecular clouds today, which are on the order of $n \sim 10^8$ to 10^9 m^{-3}.

Now, from Fig. 19, $\Lambda \sim 10^{-36}$ W m^3 and the cooling time for the cloud is found to be

$$t_{\text{cool}} = 8 \text{ Myr}.$$

Clearly, in this case $t_{\text{cool}} \ll t_{\text{ff}}$. Apparently the proto-Galactic nebula was capable of radiating energy away at a rate sufficient to **allow for a free-fall collapse.**

A Dissipative collapse model

It is instructive to consider the situation where $\mathbf{t_{cool} > t_{ff}}$. In this case the nebula is **unable to efficiently radiate away the gravitational potential energy** that is released by the collapse. As a result, the **cloud's temperature would rise adiabatically** as the cloud shrinks, resulting in an **increasing internal pressure and a halt to the collapse**.

After the collapse has halted, the **virial theorem governs the equilibrium conditions** of the cloud. For the approximate values of $T \sim 10^6$ K and $n \sim 5 \times 10^4$ m^{-3} characteristic of a protogalactic cloud at the time of formation of the first galaxies, the **upper limit on the mass** that can cool and collapse is on the order of $\mathbf{10^{12}}$ $\mathbf{M_\odot}$, with a corresponding radius of about 60 kpc.

In regions of the cloud where the gas **temperature had decreased** to the level of hydrogen recombination, $\mathbf{T \sim 10^4}$ **K, the mass limit becomes** $\mathbf{\sim 10^8}$ $M_\odot$.

Thus the **galaxies that are observed today would be expected to have masses in the range from** $\mathbf{10^8}$ $M_\odot$ **to** $\mathbf{10^{12}}$ $M_\odot$**.**

A Dissipative collapse model

The **lower limit** corresponds fairly well with the values of the **smallest dwarf elliptical** galaxies, and the **upper limit** agrees with the values measured for the **most massive giant spiral galaxies** (Sa–Sc). Although some **giant ellipticals and cD galaxies exceed 10^{12} M⊙**, they have certainly been affected significantly by **mergers** throughout their histories and are not in virial equilibrium near their outer edges.

Although the proto-Galactic cloud was able to radiate away the initial release of gravitational energy content from the system, shortly after the collapse began a **new source of energy** became available. The deaths of the first generations of very massive stars meant that **supernova shock waves** moved through the ISM at speeds on the order of 0.1c. As the expanding shells struck the gas, the **gas was reheated to temperatures of a few million kelvins, slowing the rate of collapse** somewhat. However, calculations of the supernova production rate that are based on estimates of the IMF seem to indicate that even this new source of energy was unable to slow the collapse appreciably.

The hierarchical merger model

How then can we explain the apparent age and metallicity differences among the globular clusters, as well as the existence of distinct components of varying ages within the disk of our Galaxy (i.e., the thick disk and the younger thin disk)? The answer appears to be that not only did galaxy-building involve the top-down process but it also incorporated a *bottom-up* **hierarchical process of mergers**.

With the realization in the 1970s and 1980s that **mergers play an important role in galactic evolution**, and because of observational and theoretical developments regarding the nature of the early universe, the hierarchical merger scenario has received a great deal of attention.

Scientists now believe that **shortly after the** birth of the universe via the **Big Bang, density fluctuations existed in the overall distribution of matter.** Our current understanding of those fluctuations suggests that **the most common density perturbations occurred on the smallest mass scales**. Consequently, density fluctuations involving 10^6 to 10^8 $M_\odot$ were much more common than those for 10^{12} $M_\odot$ or more.

The hierarchical merger model

Formation of the Milky Way as an example: As these **10^6 to 10^8 $M_\odot$ proto-Galactic fragments** were gravitationally attracted to one another, they **began to merge into a growing spheroidal mass** distribution.

Initially, many of the **fragments evolved in virtual isolation, forming stars and, in some cases, globular clusters in their centers.** As a result, they developed their **own chemical histories** and unique abundance signatures. In the **inner regions of the growing spheroid**, where the **density of matter was greater,** its rate of collapse and subsequent **evolution** would have been **more rapid.** This resulted in the **production of the oldest stars** that are observed today, together with a **greater degree of chemical enrichment** (hence the old, metal-rich central bulge). In the **rarefied outer regions** of the Galaxy, chemical **evolution and star formation** would have been **much slower.**

According to the hierarchical model, **collisions and tidal interactions between merging fragments disrupted the majority of the fragments** and left exposed the globular cluster cores of others. Furthermore, in this model the disrupted systems would have led to the **present distribution of the field halo stars, while leaving the remaining globular clusters scattered throughout the spheroid**. Those proto-Galactic fragments that were initially moving in a retrograde direction relative to the eventual orbital motion of the Galactic disk and inner halo produced the net zero rotation of the outer halo that is observed today.

The hierarchical merger model

Certainly the **rate of collisions** would have been **greater near the center** of the Galaxy, **building the bulge more rapidly than the halo**. Consequently, according to this picture, the spheroidal component of the Galaxy can be considered as **forming from the inside out.**

The globular clusters still present in the Galaxy today probably total only some 10% of the number that originally formed from proto-Galactic fragments. The other 90% were disrupted by collisions and tidal interactions during the early merger process and by the subsequent ongoing effects of dynamical friction. This may help to explain the relative uniformity in the masses of globular clusters observed today (approximately 10^5 to 10^6 $M_\odot$).

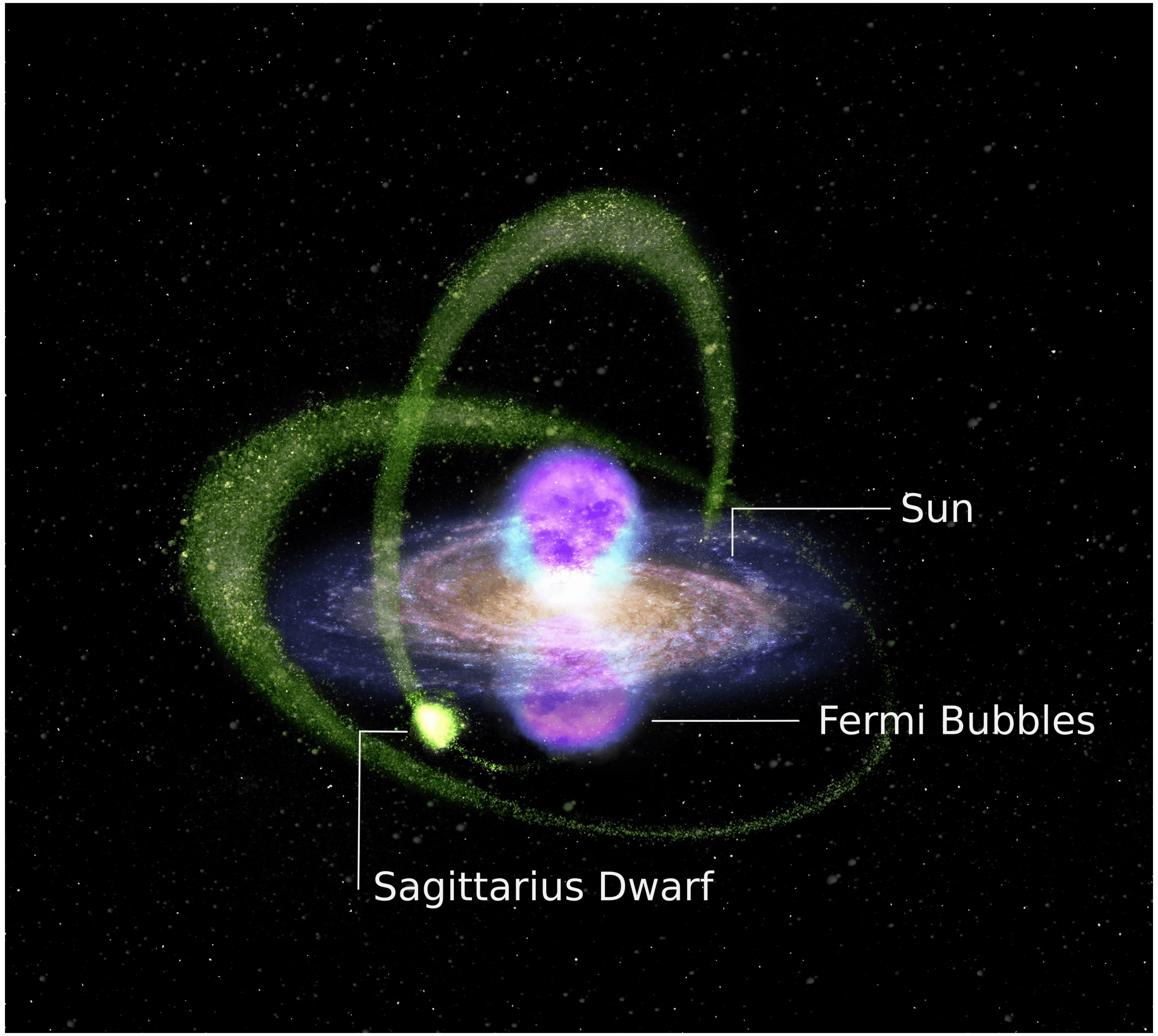
Low-mass globular clusters would have had small gravitational binding energies, allowing them to be **disrupted comparatively easily** and rapidly when the Galaxy was young. On the other hand, dynamical friction is strongly dependent on the mass of the cluster ($f_d \propto M^2$) so that **massive clusters would have spiraled rapidly into the inner regions** of the Galaxy where stronger and more frequent interactions ultimately disrupted them as well.

The hierarchical merger model

It is important to note that because of their **isolation in the outer reaches of the Galaxy** and the slower rate of evolution there, the proto-Galactic **fragments in that region would have evolved almost like individual dwarf galaxies** for a time.

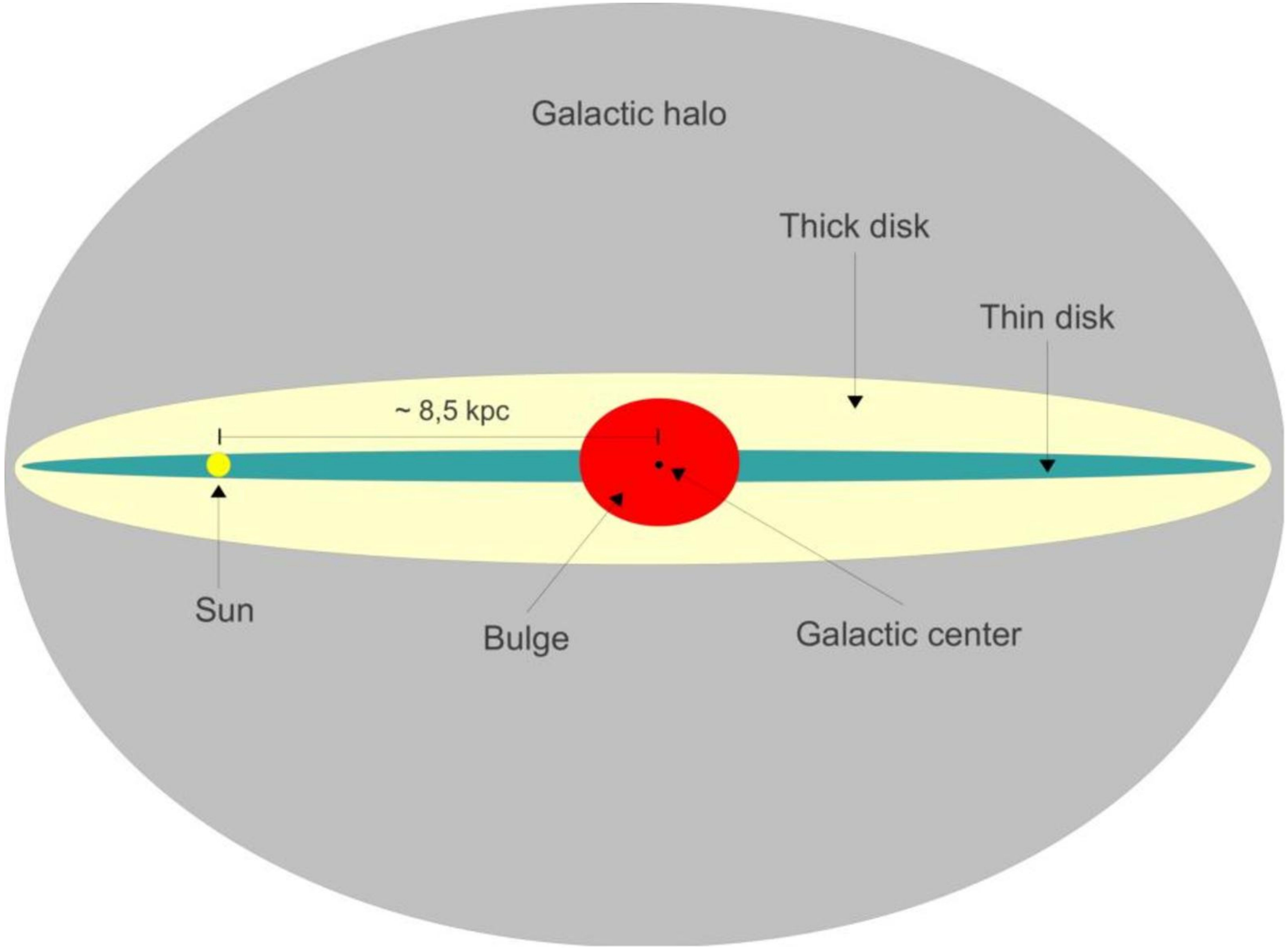
In fact, the **significant number of dSph galaxies still present in the Local Group are assumed to be surviving** proto-Galactic **fragments.**

In addition, there is **clear evidence of ongoing mergers today,** such as the dwarf spheroidal Sagittarius galaxy and the Magellanic Stream, indicating that the construction of the Milky Way's halo is still a work in progress.



Formation of the thick disk

Edge on view of the Milky Way with several structures indicated (not to scale). The thick disk is shown in light yellow.



Formation of the thick disk

As the gas clouds of disrupted proto-Galactic fragments collided, the collapse became largely **dissipative**. This means that the **gas began to settle slowly toward the central regions of the Galaxy.** However, because of the presence of some **initial angular momentum** in the system, possibly introduced through torques from other neighboring protogalactic clouds, the **collapsing material** eventually **became rotationally supported and settled into a disk** about the Galactic center. Of course, the already-formed halo stars did not participate in the collapse to the disk, except through gravitational forces.

One model of thick-disk formation suggests that the thick disk may have formed around the Galactic midplane with a characteristic temperature of **$T \sim 10^6$ K**.

By equating the kinetic energy of a typical particle in the gas to its gravitational potential energy above the midplane of the disk, the approximate **scale height, h, of the disk** of gas can be estimated.

To determine the local acceleration of gravity, g, at a height, h, above the midplane, imagine that the disk has a mass density, ϱ, given by

$$\rho(h) = \rho_0 e^{-z/h},$$

where ϱ_0 is the mass density in the Galactic midplane.

Formation of the thick disk

Now, according to the gravitational version of "Gauss's law",

$$\oint \mathbf{g} \cdot d\mathbf{A} = -4\pi G M_{\text{in}},$$

where the integral is over a closed surface that bounds the mass M_{in}, and **g** is the local acceleration of gravity at the position of d**A**. If h is much smaller than the diameter of the disk, then for a Gaussian cylinder of height 2h and cross-sectional area A, centered on the midplane (see Fig. 20),

$$2Ag = 4\pi G M_{\text{in}},$$

where $\mathbf{M_{in}}$ **is the amount of disk mass contained within the cylinder.**

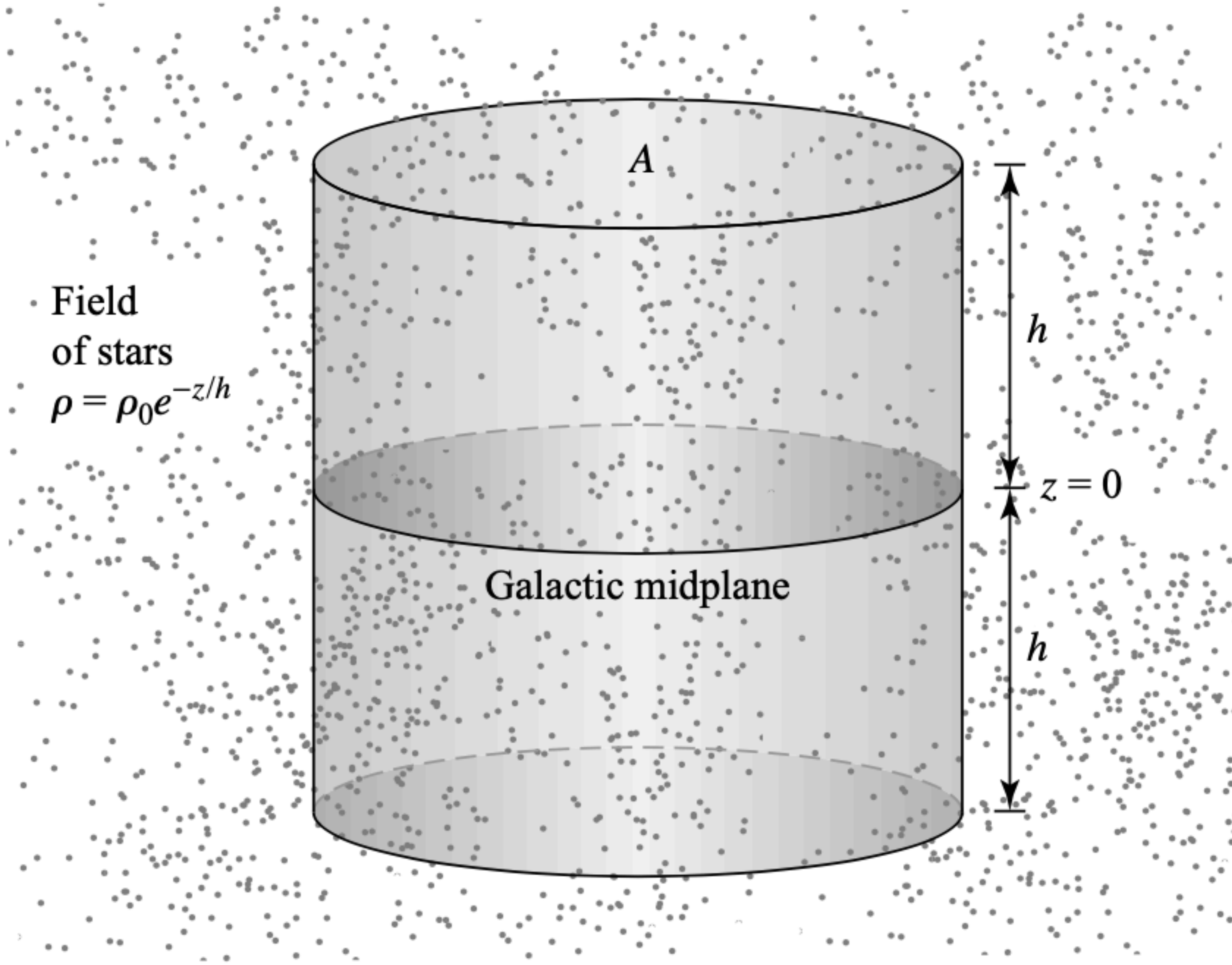


FIGURE 20 A Gaussian cylinder located entirely within the field of stars of the Galactic disk.

Formation of the thick disk

M_{in} can be estimated by integrating the mass density throughout the volume of the cylinder, or

$$M_{\text{in}} = 2\int_0^h \rho_0 e^{-z/h}\, A\, dz = 1.26\rho_0 A h.$$

Substituting into our previous expression, we have that the **local acceleration** of gravity at a height, h, is given by

$$g(h) = 2.53\pi G\rho_0\, h.$$

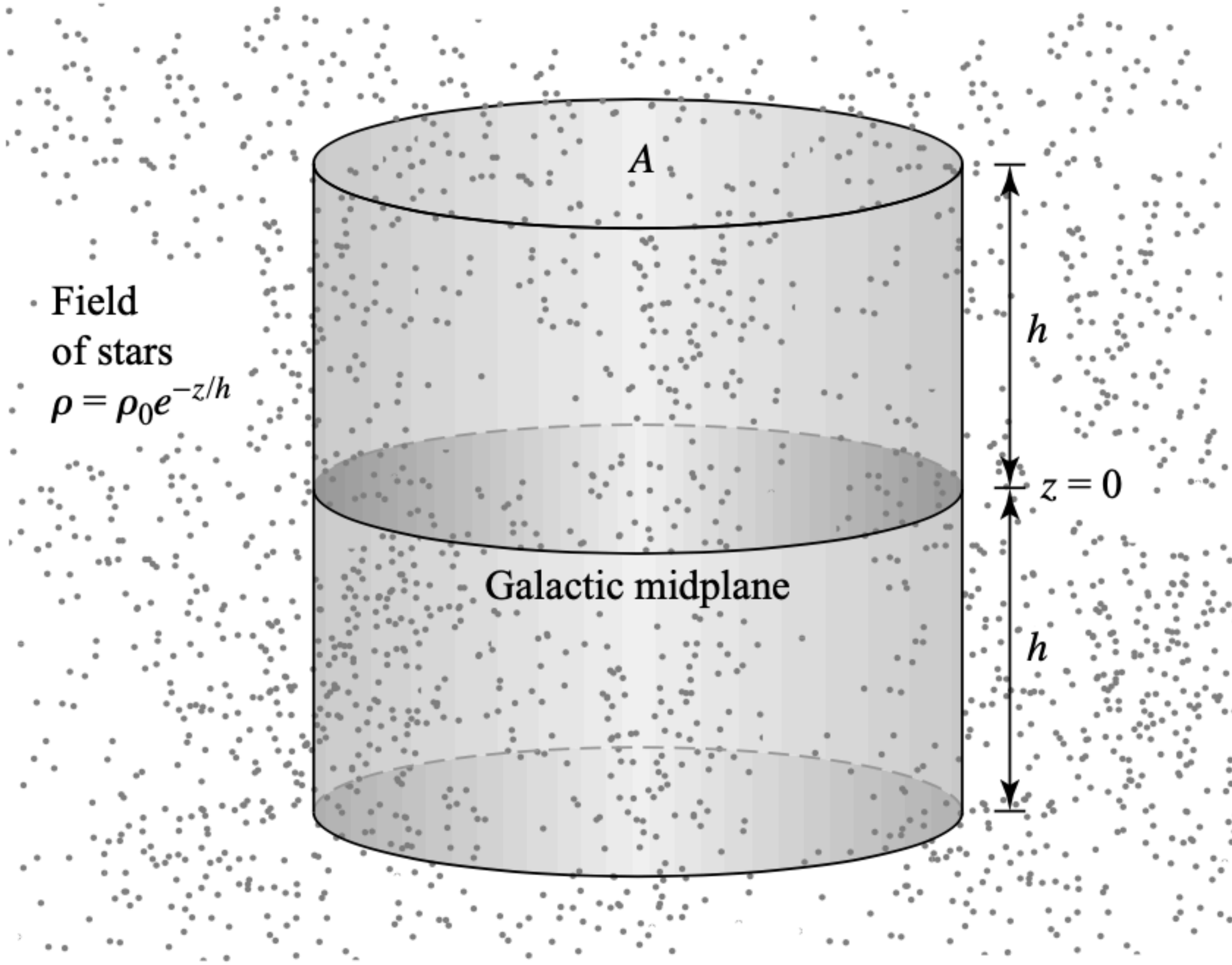


FIGURE 20 A Gaussian cylinder located entirely within the field of stars of the Galactic disk.

Formation of the thick disk

Next, the **gravitational potential energy** of a particle of mass, m, at a height, h, above the midplane is given by

$$U(h) = \int_0^h mg(z)\,dz = 1.26\pi G m \rho_0 h^2.$$

Equating the potential energy to the average thermal kinetic energy of a particle, K = 3kT /2, we find that

$$\boxed{h(T) = \left(\frac{3kT}{2.53\pi G m \rho_0}\right)^{1/2}.}$$

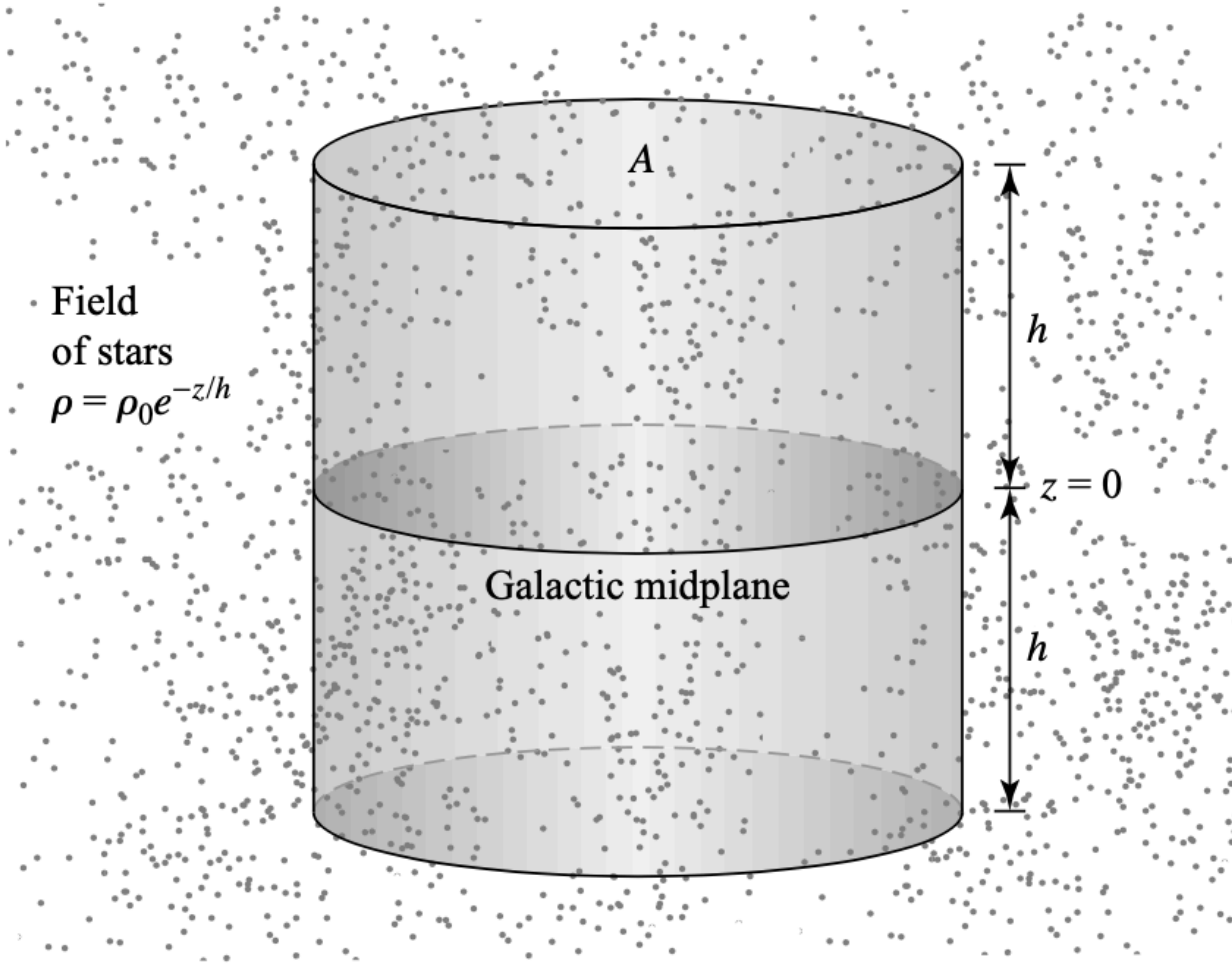


FIGURE 20 A Gaussian cylinder located entirely within the field of stars of the Galactic disk.

Formation of the thick disk

Example 2.3. If the gas in the proto-Galactic thick disk had a characteristic temperature of $T \sim 10^6$ K, and if we assume that the central mass density was comparable to the value that is estimated today for the solar neighborhood,

$$\rho_0 \simeq 0.15\ \mathrm{M_\odot\ pc^{-3}} = 1.0 \times 10^{-20}\ \mathrm{kg\ m^{-3}},$$

Then

$$h\left(10^6\ \mathrm{K}\right) \simeq 2.2\ \mathrm{kpc},$$

where we have used the mass of a hydrogen atom for m. **The measured value for the scale height of the thick disk is approximately 1 kpc.**

Formation of the thick disk

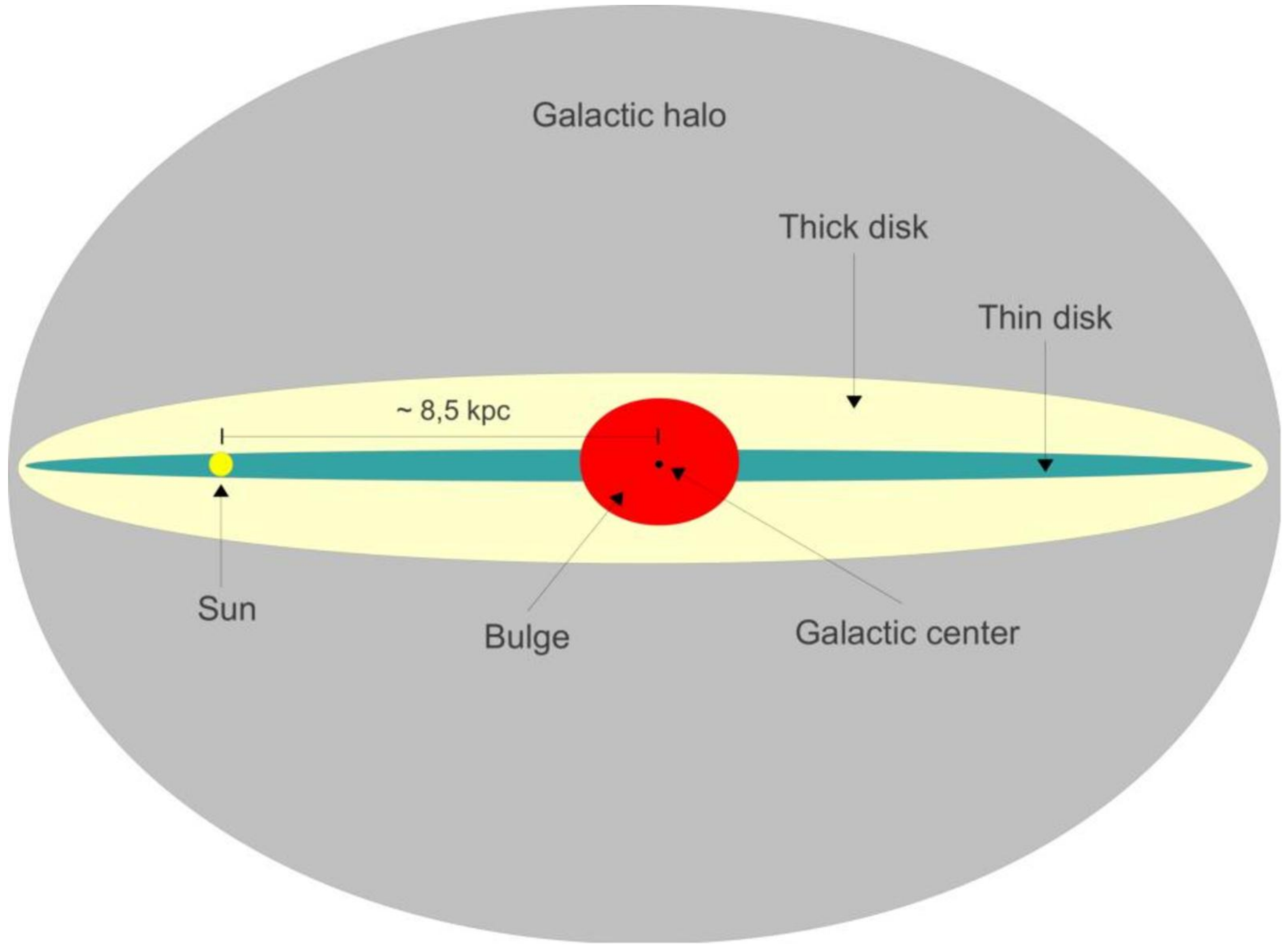
In regions where the **gas was locally more dense,** it **cooled more rapidly,** since $t_{cool} \propto n^{-1}$. This was accomplished first through thermal **bremsstrahlung and Compton scattering**, and then, when the temperature reached ~ **10^4 K**, via the **radiation emitted by hydrogen atoms**. This meant that once the hydrogen recombination temperature was reached, **H I clouds could form and begin producing stars**.

Within a **few million years**, the most massive stars underwent core-collapse **supernova** detonations and their shocks began to **reheat the gas between the molecular clouds, maintaining the temperature of the intercloud gas at roughly 10^6K**.

At the same time, the **production of iron** in the supernovae raised the metallicity from an initial value of [Fe/H] < –5.4 to [Fe/H] = –0.5. About **400 million years after the first stars** were created in the thick disk, **star formation nearly ceased**. In total, a **few percent of the mass** of the gas was **converted into stars** during this thick-disk-producing period of the Galaxy's evolution.

Formation of the thick disk

A modified version of the thick-disk **formation model** described above suggests that the **infalling gas was initially much cooler.** This meant that the **gas (and dust) was able to settle onto the midplane with a much smaller scale height, similar to today's thin disk**. **Star formation was then able to proceed** due to the greater local density of gas and dust. However, as a direct result of **a significant merger event with a proto-Galactic fragment some 10 Gyr ago**, the **disk was reheated** by the energy of the interaction, causing it to **puff up to its present 1-kpc scale height.**



Formation of the thin disk

After the formation of the thick disk, **cool molecular gas continued to settle onto the midplane with a scale height of approximately 600 pc**. During the next **several billion years**, **star formation occurred** in the **thin disk**.

The process of **maintaining the scale height was essentially a self-regulating one**. If the disk became thinner, its mass density would increase. This in turn would cause the SFR to increase, producing more supernovae and reheating the disk's intercloud gas component. The ensuing expansion of the disk would again decrease the SFR, yielding fewer supernovae, and the disk would cool and shrink. However, despite the self-regulating process, **as the gas was depleted in the ISM the SFR decreased** from about 0.04 $M_\odot$ pc^{-3} Myr^{-1} to 0.004 $M_\odot$ pc^{-3} Myr^{-1}. At the same time, the **metallicity continued to rise**, reaching a value of approximately [Fe/H] = 0.3. Because of the **decrease in the SFR, the thickness of the disk decreased to about 350 pc**, the scale height of **today's thin disk**. During the development of the thin disk, some **80% of the available gas was consumed in the form of stars.**

Finally, as the **remaining gas continued to cool**, it **settled into an inner, metal-rich and gas-rich component of the thin disk with a scale height of less than 100 pc**. Today most **ongoing star formation** occurs in this young, inner portion of the thin disk, the component in which the Sun resides.

Young stars in the bulge

The existence of young stars in the central bulge of our Galaxy can be understood in the context of the evolution just described by arguing for **recent mergers with gas-rich satellite galaxies.** When those galaxies were disrupted by tidal interactions with the Milky Way, their **gas settled into the disk and the center of the Galaxy, ultimately forming new stars.** It also appears that the **Milky Way's central bar** plays a role in the migration of dust and gas into the inner portion of the Galaxy by generating dynamical instabilities as it rotates.

Metallicity gradients

The **hierarchical merger** scenario just outlined **predicts that metallicity gradients** ought to exist in galaxies that have undergone a dissipative collapse. If a galaxy is **more metal-rich in its center than it is near the outskirts of the system, then a color gradient should also exist**. Because of the enhancement of opacity with metallicity, the galaxy would be **redder in its center** than it is farther out.

Of course, the strength of the metallicity and color gradients **can be diminished or even destroyed by sufficiently frequent and energetic mergers with other galaxies.** For instance, many **starburst galaxies actually have inverted color gradients and appear bluer in their centers.** This is because of the large **SFR that resulted from the sudden influx of gas-rich material in the galactic center** when another galaxy was disrupted, or from the effects of **tidal torques** that acted on the starburst galaxy itself, causing its **own gas to spiral into the center**.

Simulations

This cosmological simulation follows the development of a single disk galaxy over about 13.5 billion years, from shortly after the Big Bang to the present time. Colors indicate old stars (red), young stars (white and bright blue) and the distribution of gas density (pale blue); the view is 300,000 light-years across. The simulation ran on the Pleiades supercomputer at NASA's Ames Research Center in Moffett Field, Calif., and required about 1 million CPU hours. It assumes a universe dominated by dark energy and dark matter. Credit: F. Governato and T. Quinn (Univ. of Washington), A. Brooks (Univ. of Wisconsin, Madison), and J. Wadsley (McMaster Univ.).

https://www.youtube.com/watch?v=_Ssc1GsqHds&ab_channel=NASAGoddard

The formation of elliptical galaxies

Although we do not fully understand all of the complex details of galactic evolution.

It appears that **many ellipticals may have formed the majority of their stars early in the galaxy-building process, before the gas had a chance to settle into a disk,** whereas late-type galaxies took a more leisurely pace. Current observations indicate that later Hubble types have a higher relative abundance of gas and dust in their disks than galaxies of earlier Hubble type.

However, **other E's probably formed from the collisions of already-existing spirals**. The energy involved in the collision would destroy the disks of both galaxies and cause the merged system to relax to the characteristic $r^{1/4}$ distribution of an elliptical.

Although N-body simulations have been able to produce such a result (see Fig. 21), some questions remain.

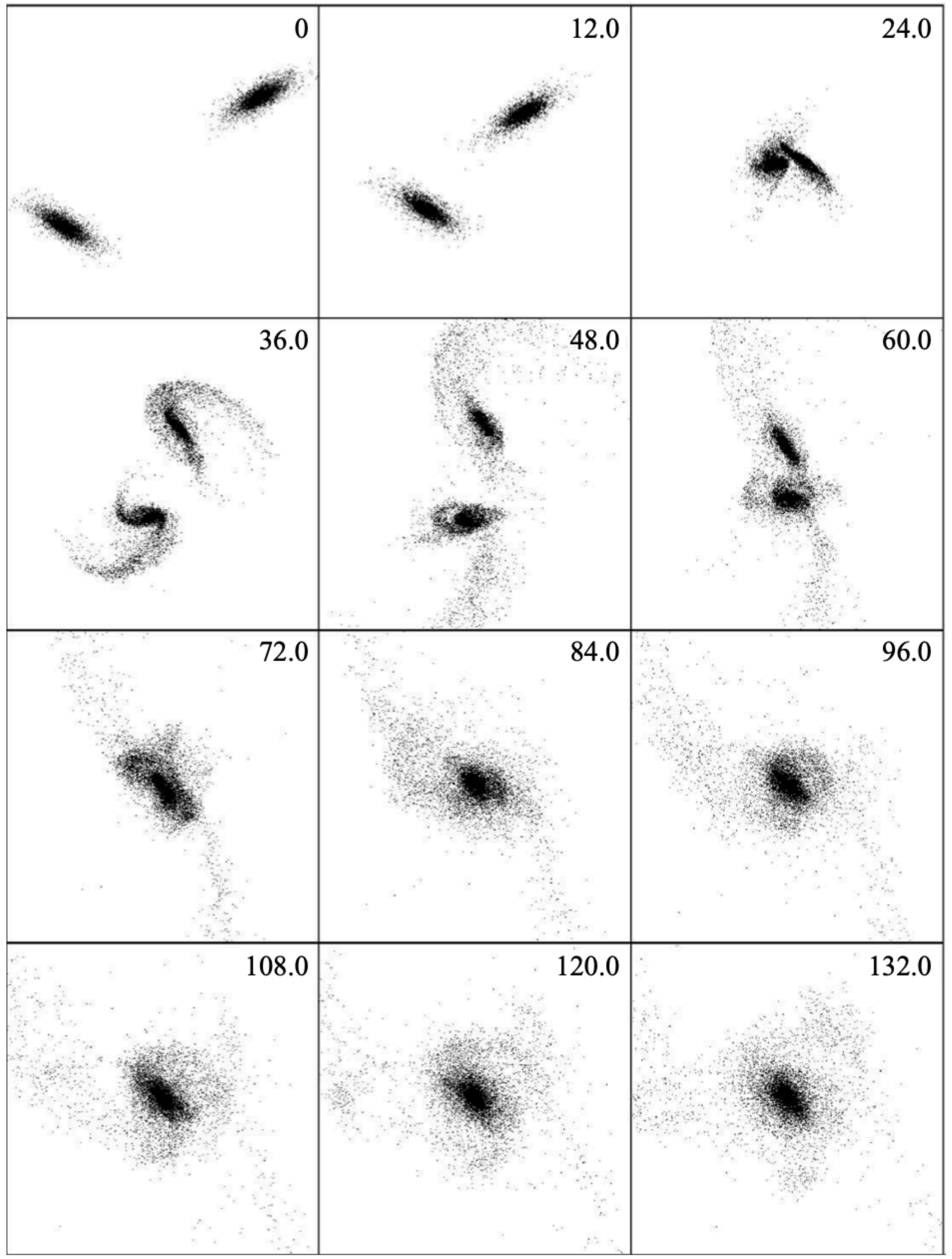
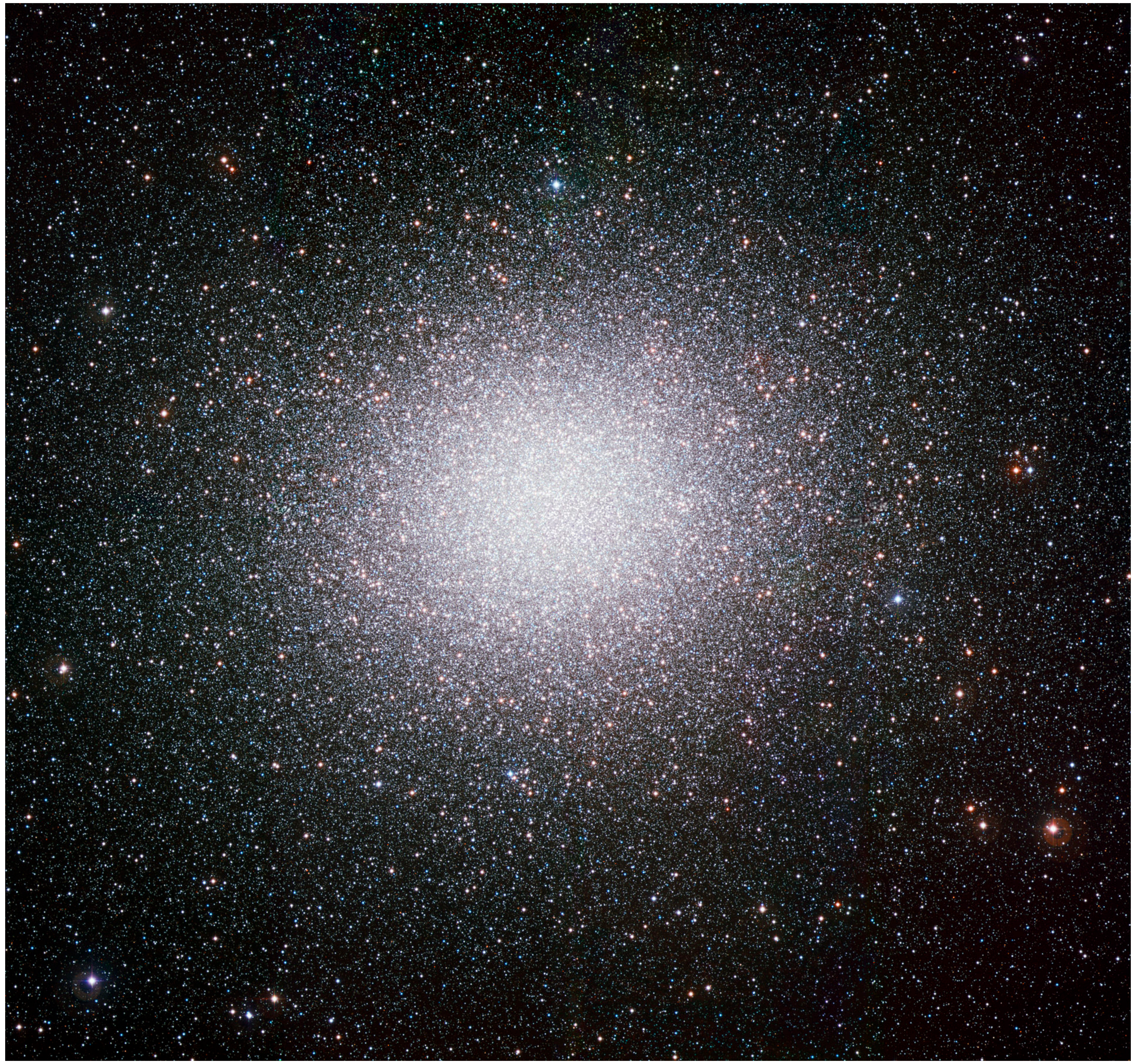


FIGURE 21 An N-body simulation of the merger of two spiral galaxies. Each disk is represented by 16,384 particles, and each bulge contains 4096 particles. The result is an elliptical galaxy with an $r^{1/4}$ profile. (Figure adapted from Hernquist, *Ap. J.*, *409*, 548, 1993.)

The formation of elliptical galaxies

For instance, the **large number of globular clusters in E's relative to spirals** present a serious difficulty in arguing that cataclysmic collisions are the cause of all large elliptical galaxies. On the other hand, **perhaps mergers can actually produce globular clusters** by triggering star formation in clouds, in which case the larger specific frequency of globular clusters may not be a problem. It is also **possible that many of the observed globular clusters are captured dwarf spheroidal galaxies**, just as ω Cen appears to be in the Milky Way.

Omega Centauri



The formation of elliptical galaxies

Elliptical galaxies are much more abundant relative to spirals in the centers of dense, rich clusters of galaxies, whereas spirals dominate in less dense clusters and near the periphery of rich clusters. (This **morphology–density relation** was first reported by Alan Dressler in 1980.) This effect may be partly **explained by the increased likelihood of interactions in regions where galaxies are more tightly packed, destroying spirals and forming ellipticals.**

However, a competing hypothesis has also been suggested—namely, that **ellipticals tend to develop preferentially near the bottoms of deep gravitational potential wells**, even in the absence of interactions. Lower mass-density fluctuations in the early universe may have resulted in spiral galaxies, and the smallest fluctuations led to the formation of dwarf systems. If this is the case, then the large number of dSph's and dE's that exist has a natural explanation in the much larger number of smaller fluctuations that formed in the early universe. This mechanism could help explain galactic morphology if the initial density fluctuations in the early universe were largest in what later became the centers of rich clusters. Because the gravitational potential well in those regions would have been deeper, the probability of collisions between protogalactic clouds should have been correspondingly greater as well.

Galaxy formation in the early Universe

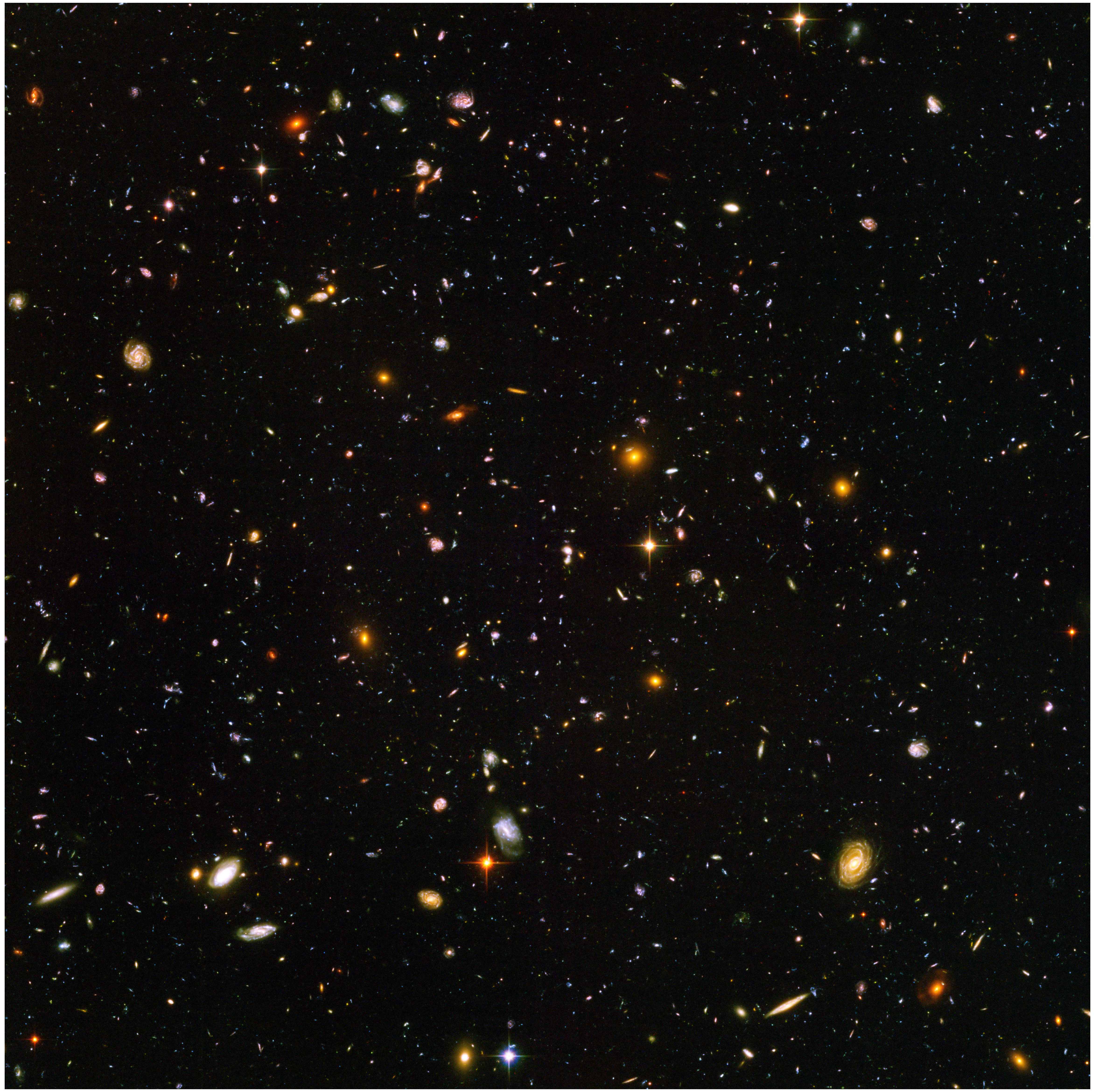
Given the large number of fundamental problems that still remain in our development of a coherent theory of galaxy formation, it is fortunate that a means exists for testing our ideas by observing galactic evolution through time. Because of the finite speed of light, **when astronomers look farther and farther out into space, we are literally looking farther and farther back in time.** For instance, galaxies that are 1 Mpc away emitted their light more than 3 million years ago.

In 1978, Harvey Butcher and Augustus Oemler, Jr., noted that there appeared to be an **overabundance of blue galaxies in two distant clusters**. They speculated that there may have been a significant evolution in galaxies over time, leading to the types of objects we see closer to us today. The **Butcher–Oemler effect**, as it is now called, **suggests that galaxies in the early universe were bluer on average than they are today, indicating an increased level of star formation.** The effect has been confirmed in numerous studies.

The morphology–density relation has also been shown to be time-dependent. **As observations probe earlier times (more distant galaxy clusters), elliptical, and lenticular galaxies become less abundant relative to spiral galaxies, suggesting an evolution from later Hubble types to earlier types over time.** This is just what would be expected if some earlier Hubble-type galaxies form from the mergers of spirals. This is also consistent with the overall picture of hierarchical galaxy building.

Galaxy formation in the early Universe

In 2004, the Space Telescope Science Institute released the **Hubble Ultra Deep Field** (HUDF) image shown in Fig. 22. The HUDF image is actually a composite of two images, one taken by the Advanced Camera for Surveys (ACS) and the other from the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS). The region of the sky contained in the HUDF image is only 3 arcmin on a side (about 1/10 the size of the full moon), centered on ($\alpha = 3^{h}32^{m}40.0^{s}$, $\delta = -27^{\circ}48'00''$) in the constellation of **Fornax**. The image required a **total exposure time of 11.3 days** for ACS (obtained between September 24, 2003, and January 16, 2004) **and 4.5 days** for NICMOS (over the period between September 3, 2003, and November 27, 2003).



Galaxy formation in the early Universe

The HUDF reveals **some very distant galaxies** as they existed just 400 Myr to 800 Myr after the Big Bang. As is evident in the close-up of a portion of the HUDF shown in Fig. 23, the very distant galaxies appear quite different from the relatively nearby spirals and ellipticals that are seen in the present-day universe.

Observations like these suggest that the abundance of **strange-looking, remote, blue galaxies seen in the early universe** may be the building blocks of today's Hubble sequence of galaxies. They probably represent the proto-galactic fragments responsible for the hierarchical mergers that are still occuring today at a much diminished rate.