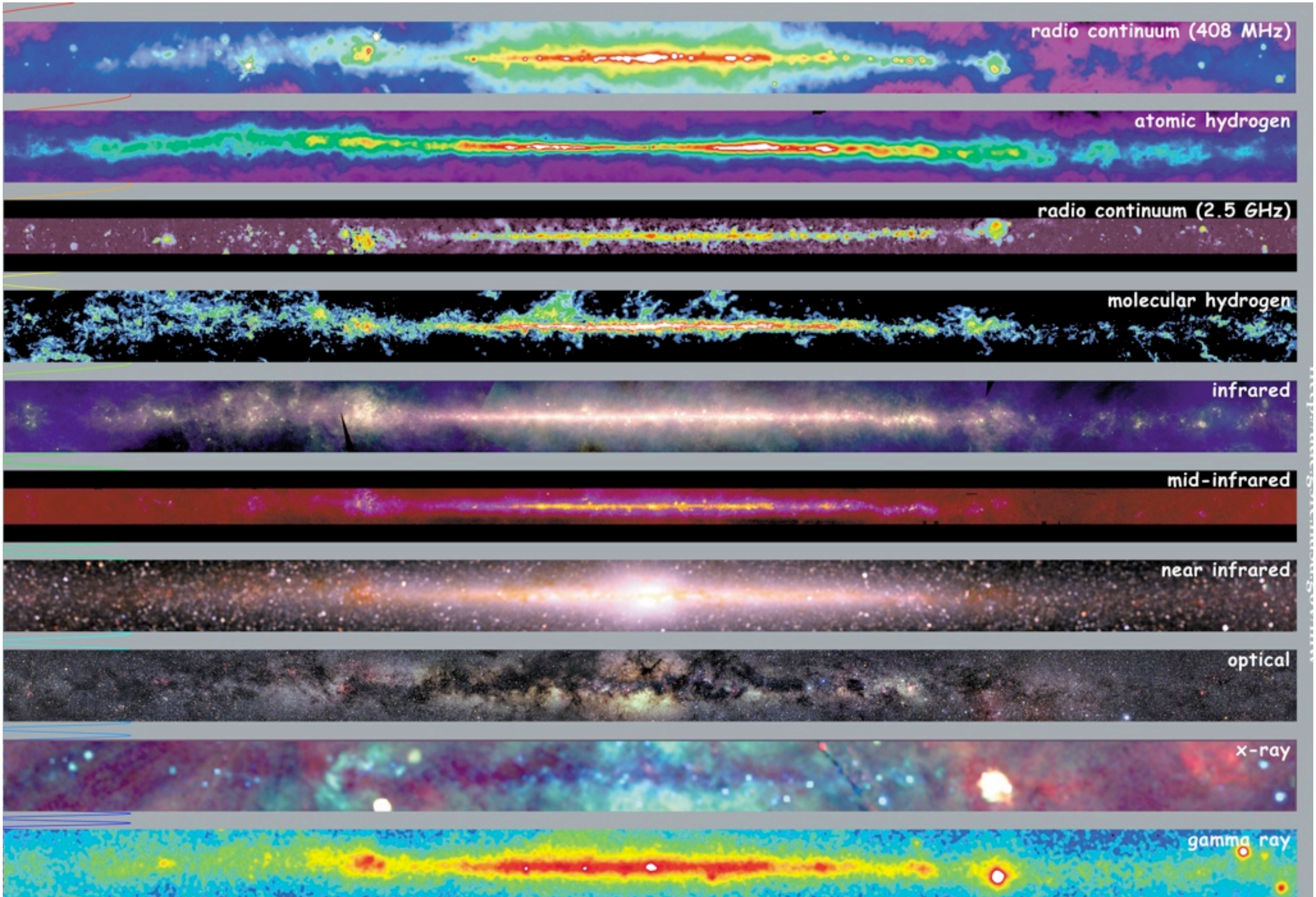
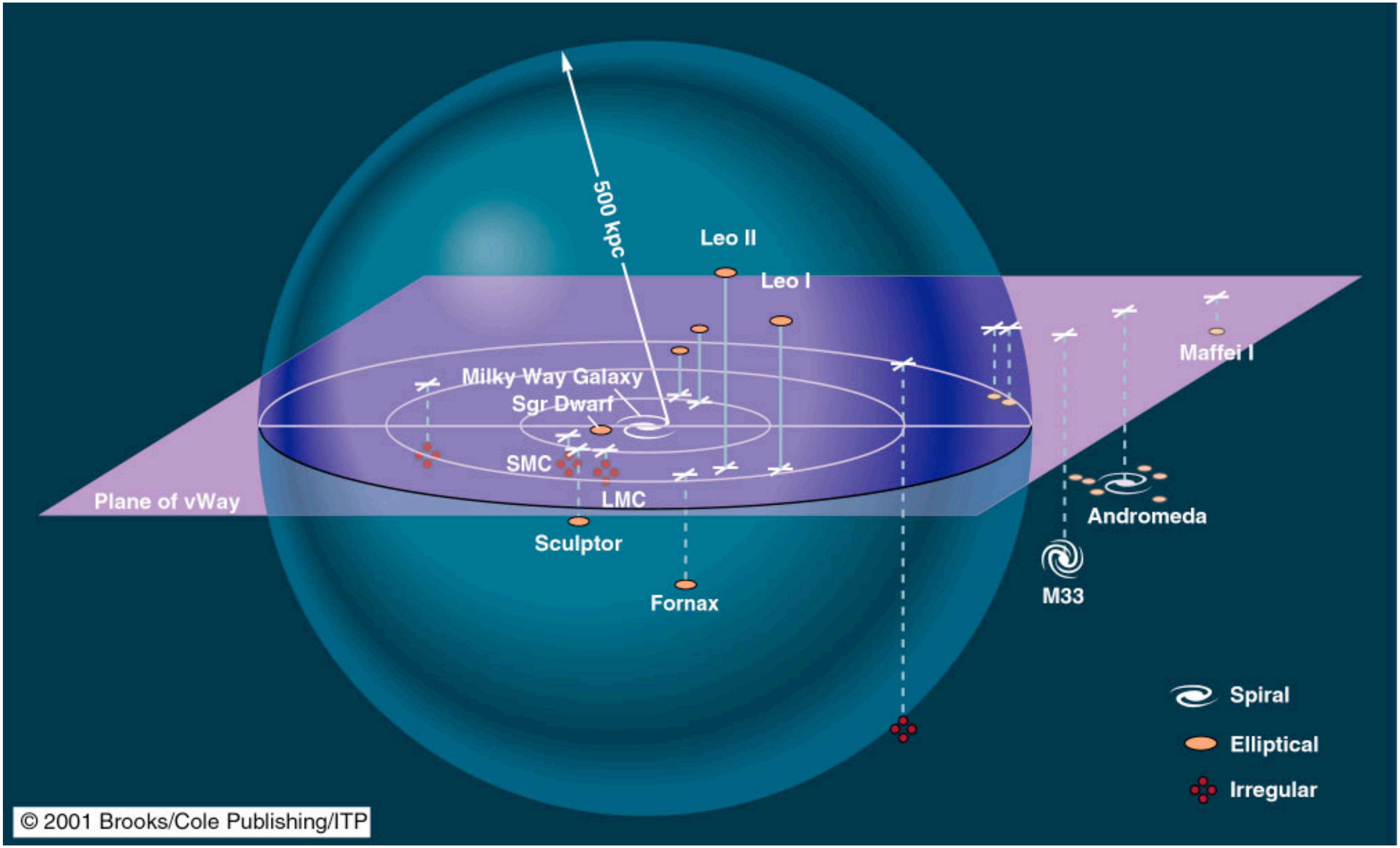
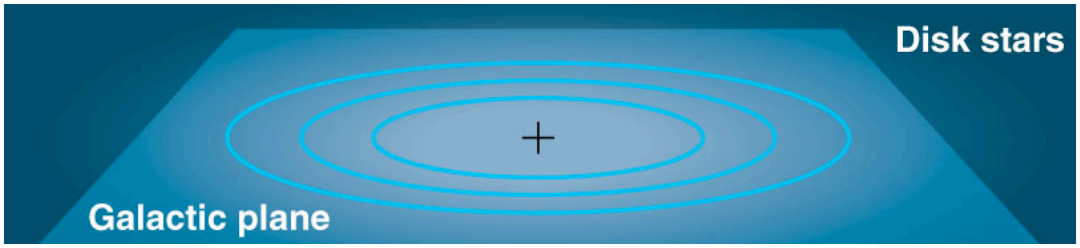


Multiwavelength Milky Way

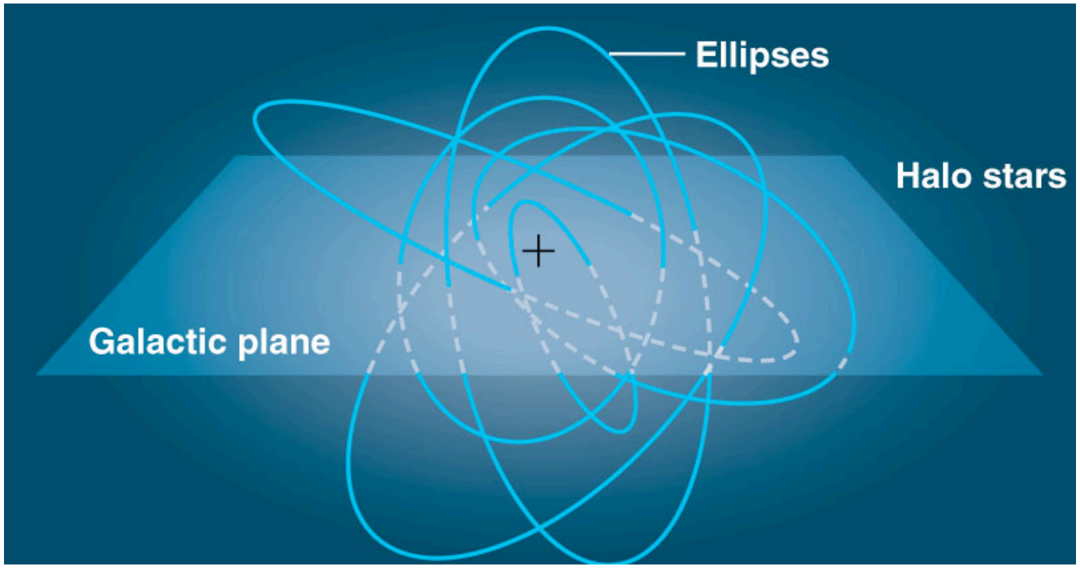
The Milky Way is in a poor cluster – the Local Group



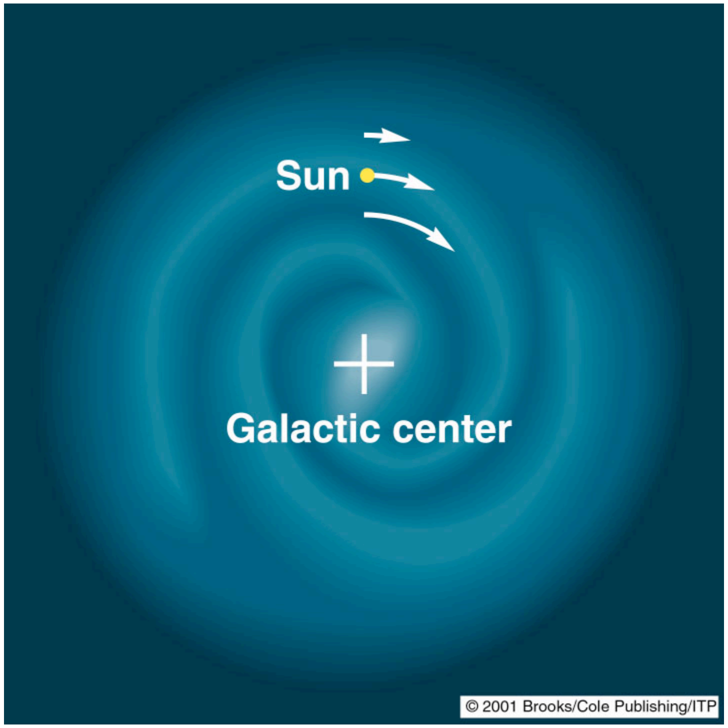
Orbital motions in a spiral galaxy



1. *Disk:* Nearly circular rotation



2. *Halo:* Random, elliptical



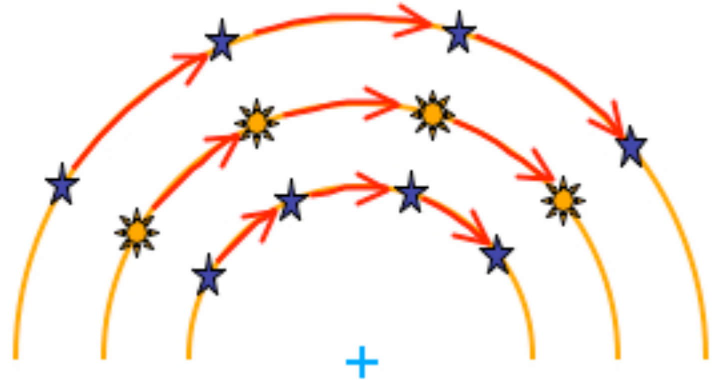
- Differential rotation
- Sun's orbital period

  250 million years

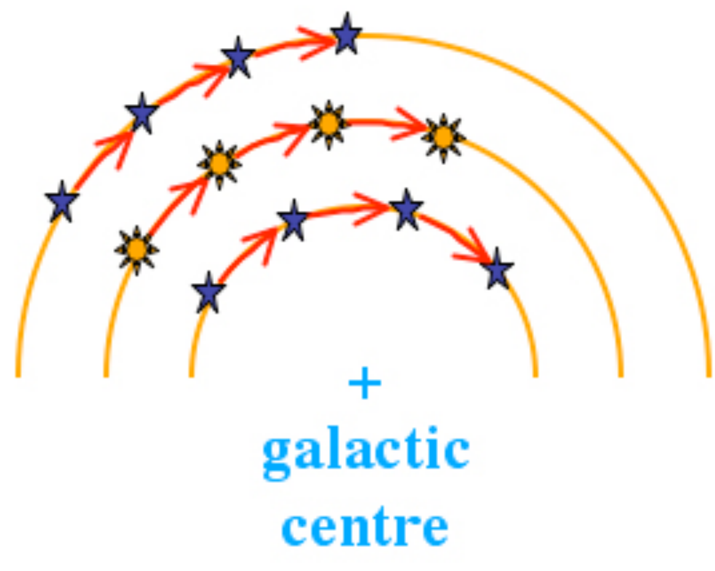
  v_{rot}=220 km/s

Orbital motions in a spiral galaxy

•**Uniform rotation**: material at all radii rotate with constant angular velocity



• **Differential rotation**: material rotates with constant velocity, so angular velocity decreases at larger radii, longer period of rotation

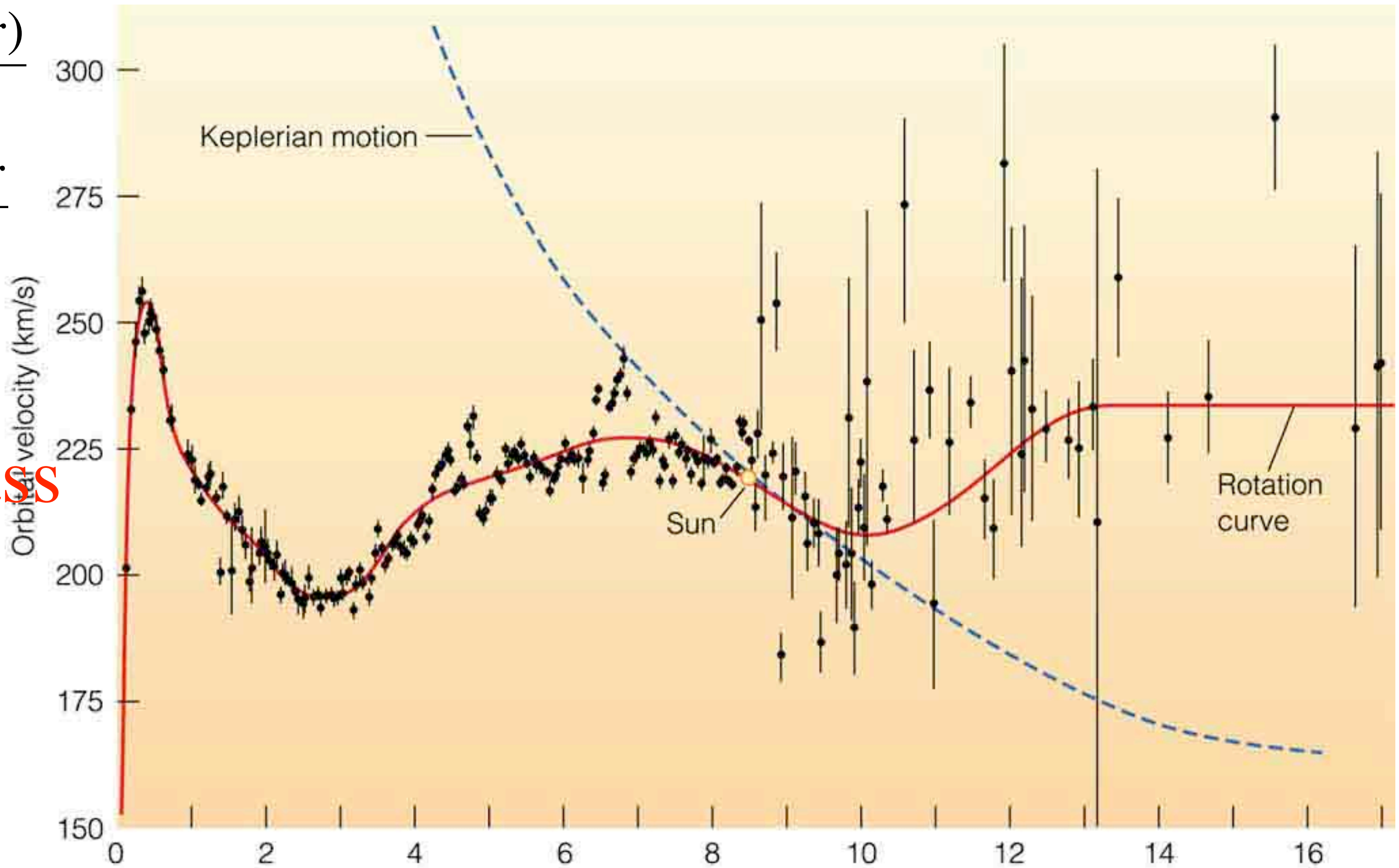


Deriving Mass of a Galaxy from its (non-Keplerian) Rotation

$$\frac{V(r)^2}{r} = \frac{GM(r)}{r^2}$$

$$M(r) = \frac{V(r)^2 r}{G}$$

Only interior mass affects rotation.



Mass of Milky Way Galaxy

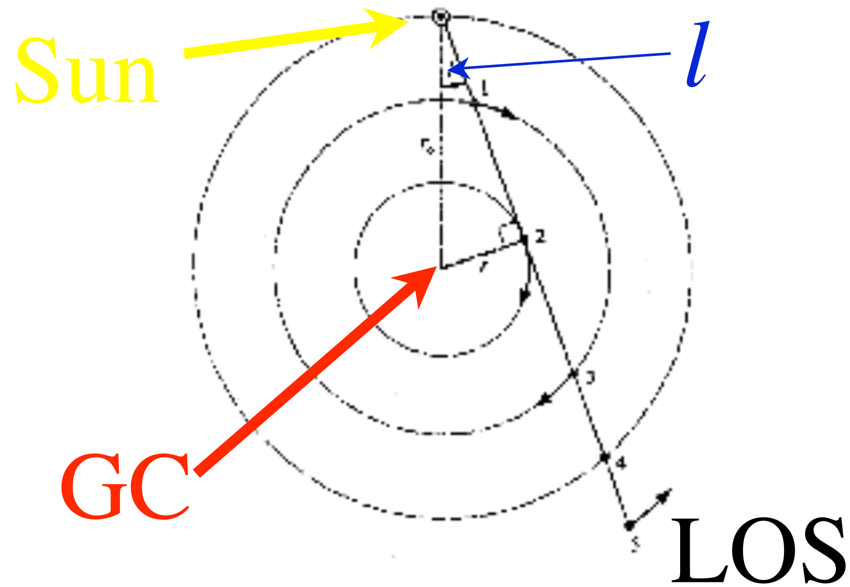
- Within orbit of Sun (8kpc radius):
  - ✶ $M = v_{rot}^2 \times r / G$ = 90 billion M_{sun}
- Within orbit of the most distant star known (30kpc):
  - ✶ >500 billion M_{sun}
    - Yet only ~100 billion M_{sun} can be attributed to known (i.e. luminous) matter (in stars and gas clouds)
    - At these large radii, material is rotating more quickly than expected based on distribution of ordinary matter (stars+gas)

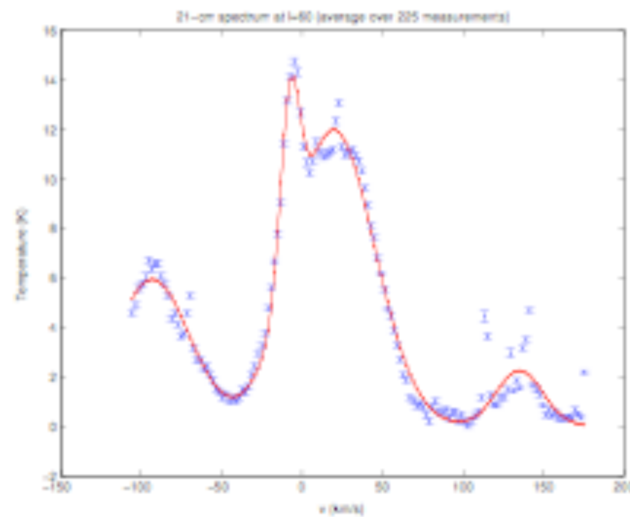
Dark Matter

- Most of the mass in the Milky Way galaxy:
  - ✶Does not radiate
  - ✶Is not ordinary “baryonic” matter, such as protons, neutrons, electrons
- On bigger scales (clusters of galaxies) dark matter fraction even higher.
  - ✶Over 80% of matter is dark

Measuring Rotation Curves

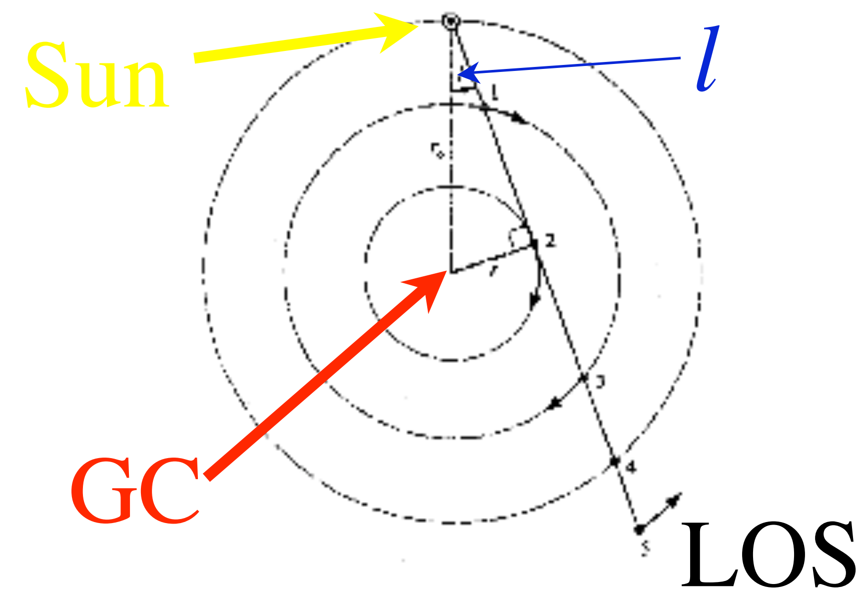
- To measure rotation speed at radii other than the sun (and construct rotation curve), we need to probe velocities at significant distances from sun (not just solar neighborhood)
- For such studies, radio observations of gas in the Milky Way are valuable, because they are not affected by dust extinction (unlike measuring optical spectra of stars)

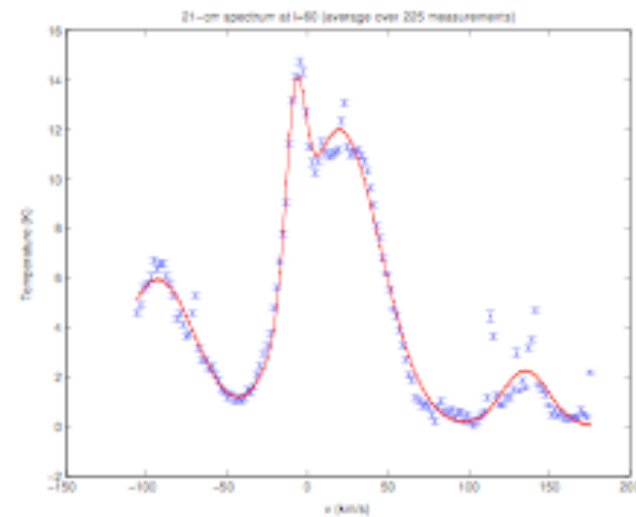




Measuring Rotation Curves

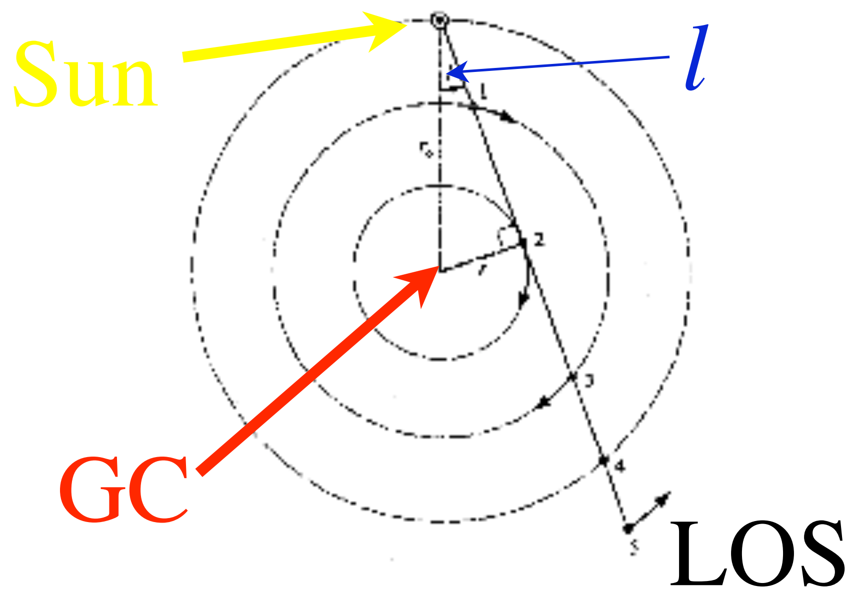
- **Radio**: Use 21 cm emission line from atomic Hydrogen
- **Millimeter**: Use 1.3 mm emission line from CO molecular gas as tracer or H_2 gas





Measuring Rotation Curves

- Observe 21 cm line (or CO) at different galactic longitudes, l
- Because of differential rotation, maximum redshift (radial velocity) occurs at tangent point where you see full orbital velocity.
- Since $r = r_{\odot} \sin l$, you get $V(r)$ inside solar circle ($r < r_{\odot}$)
- Outside solar circle more difficult.

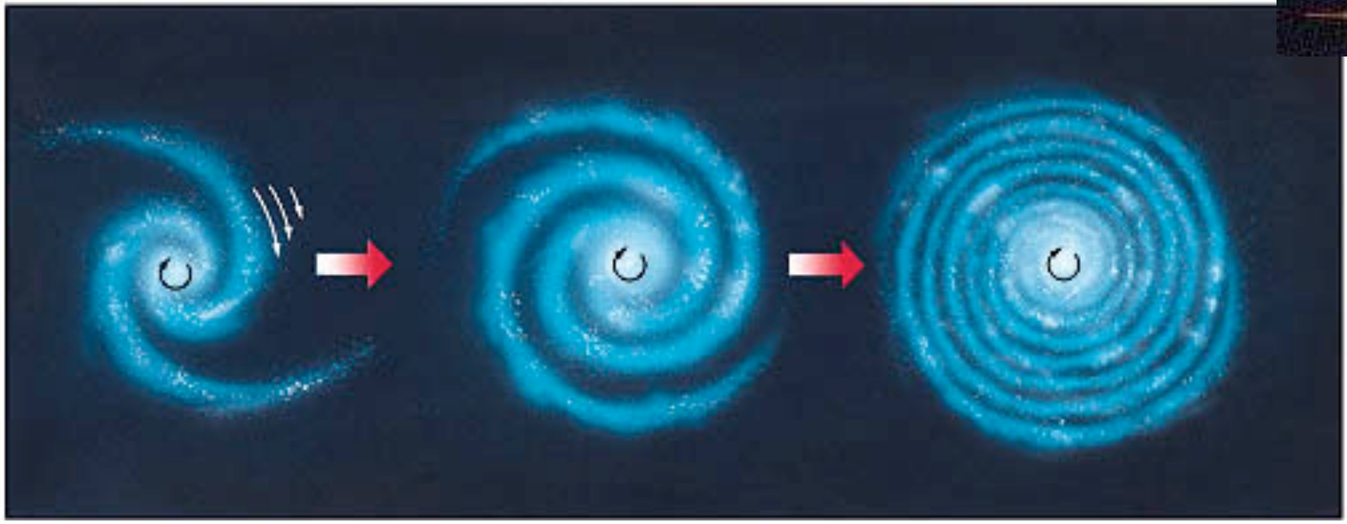


Spiral Structure

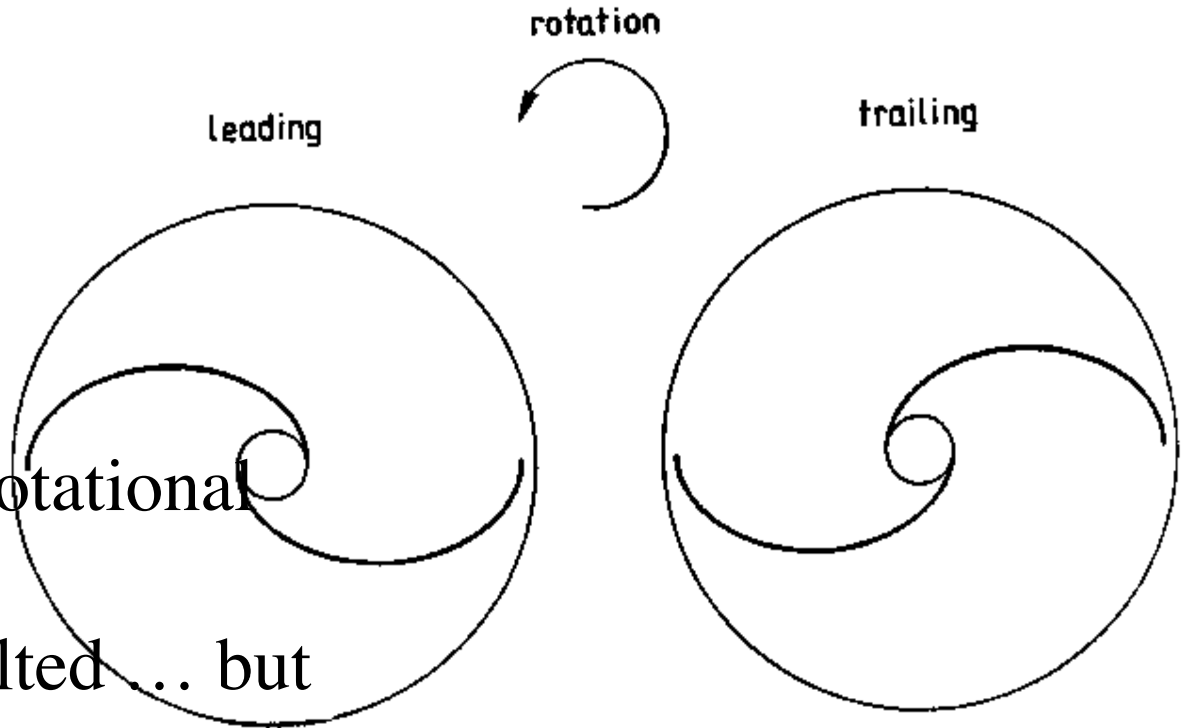
- Significant structure exists within Galaxy disk, especially when using young stars as tracers, (e.g., HII regions, open clusters, neutral gas)
- Observed in external disk galaxies: pinwheel appearance, more pronounced at shorter wavelengths (blue as opposed to red, dominated by young stars)

Understanding Spiral Structure

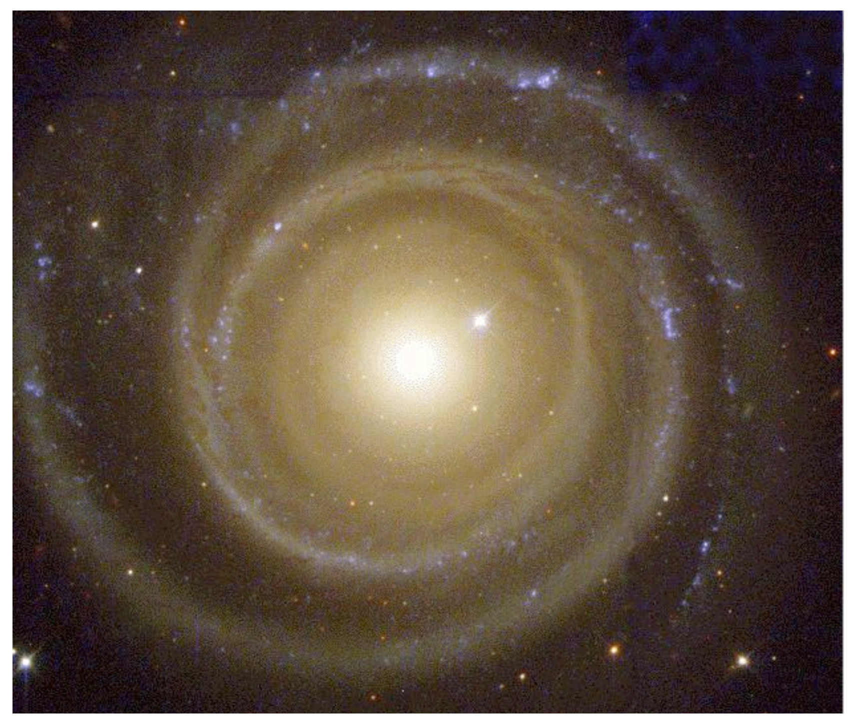
- The winding problem
  - ✶ Galactic rotation period ~0.2 Gyr
  - ✶ Arms short-lived or …
- Density wave theory of Lin-Shu
  - ✶ Material passes through them
  - ✶ Arms are self-gravitating sites of star formation

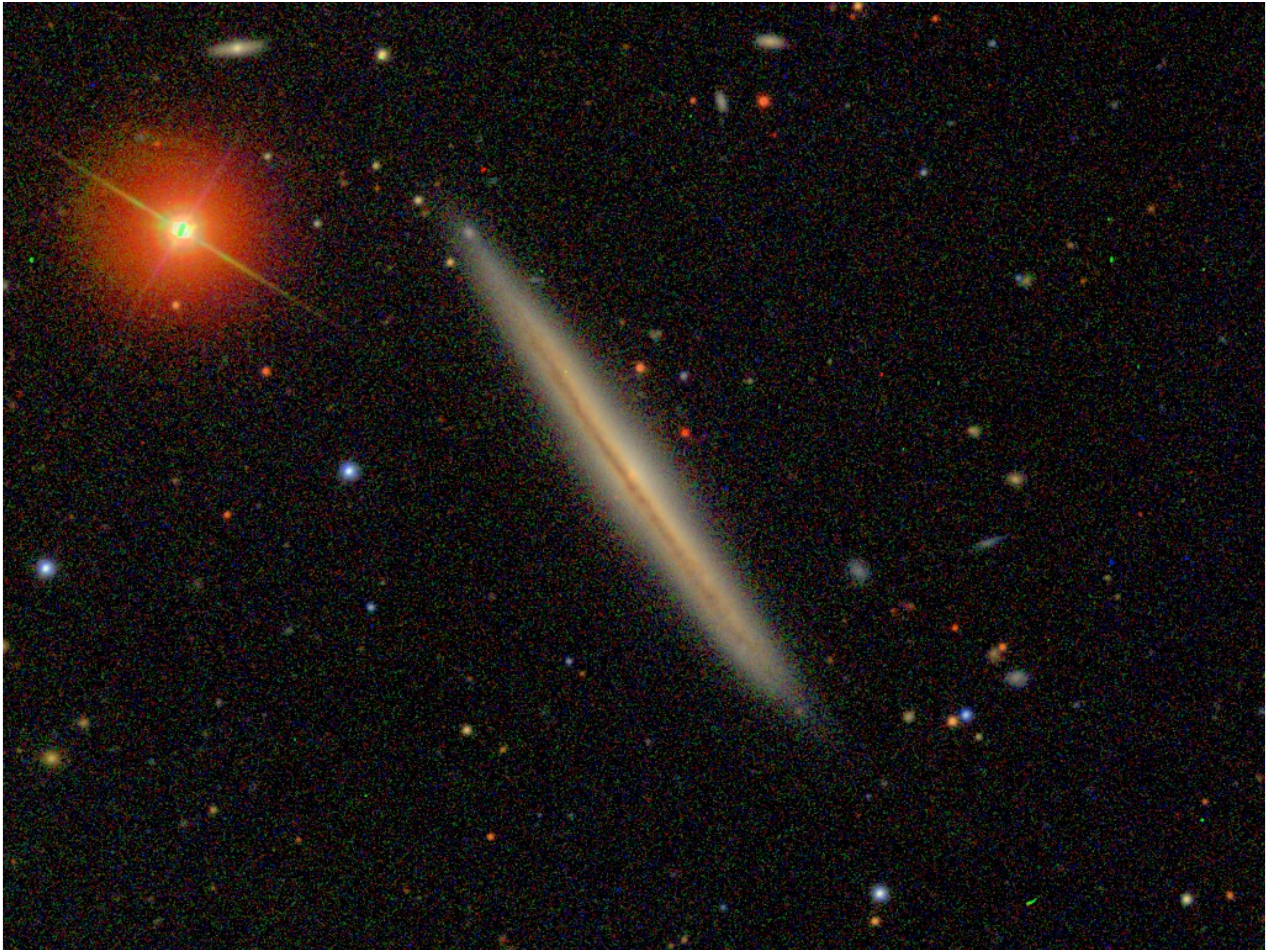


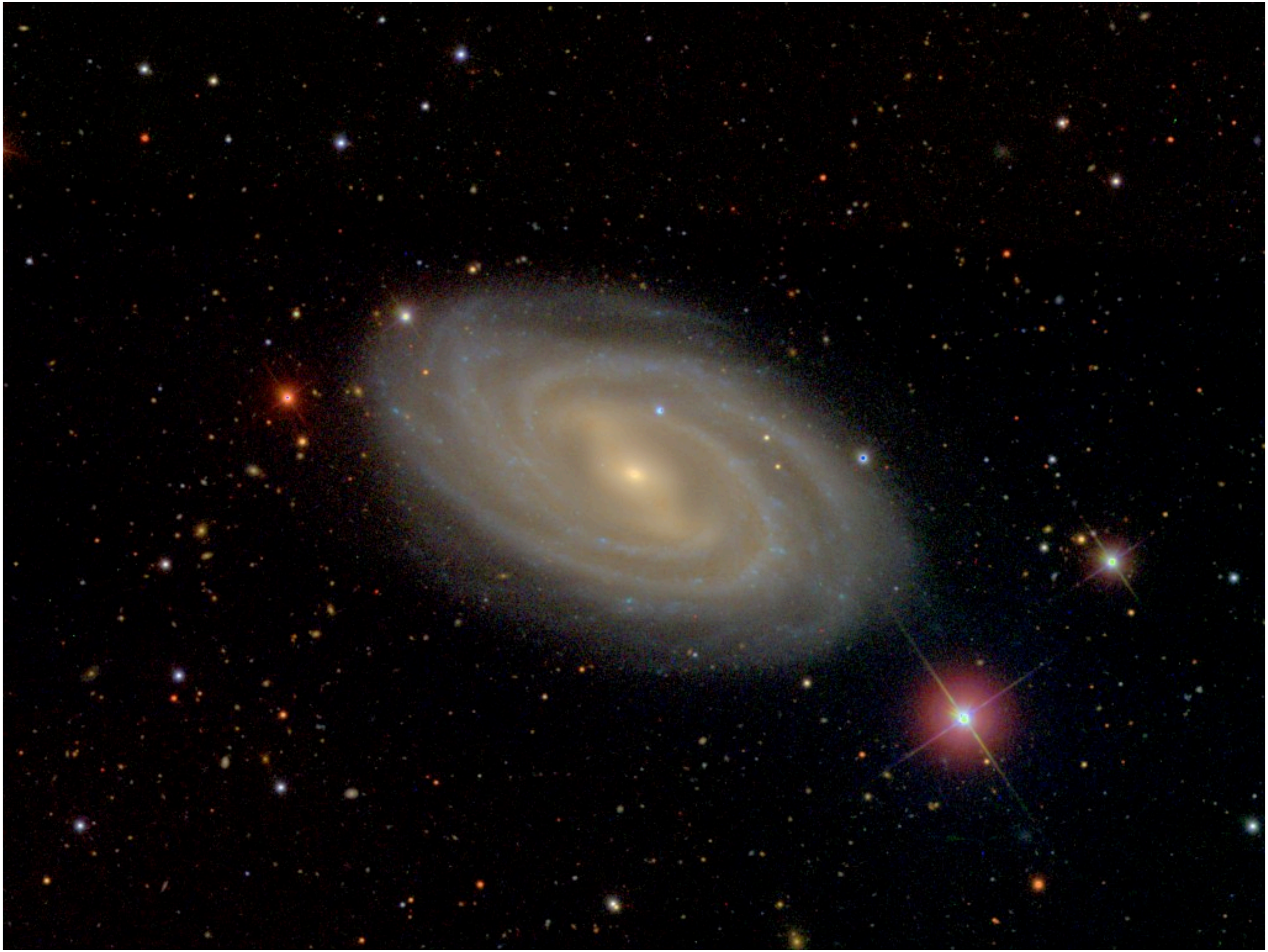
Leading vs. Trailing?

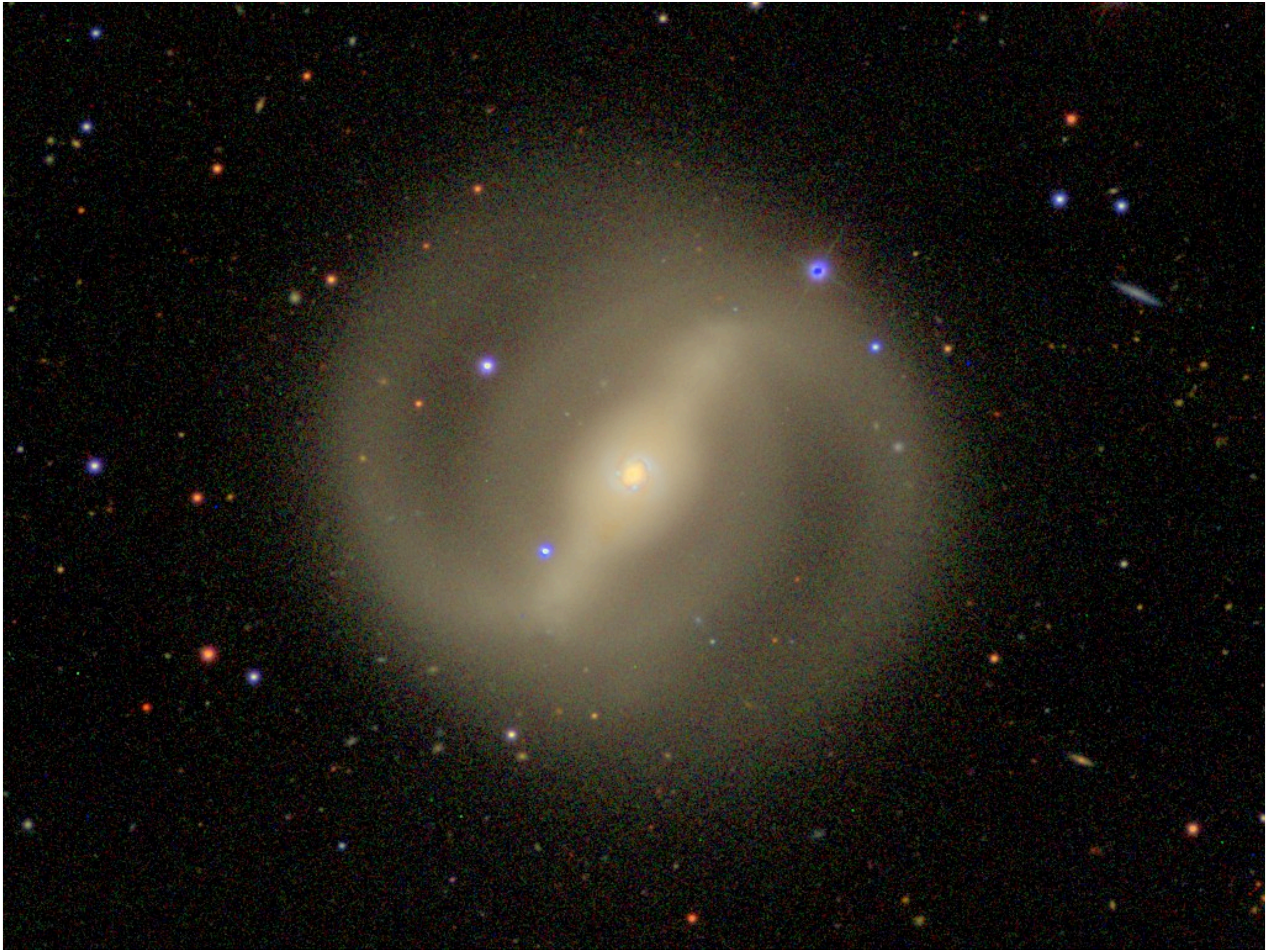


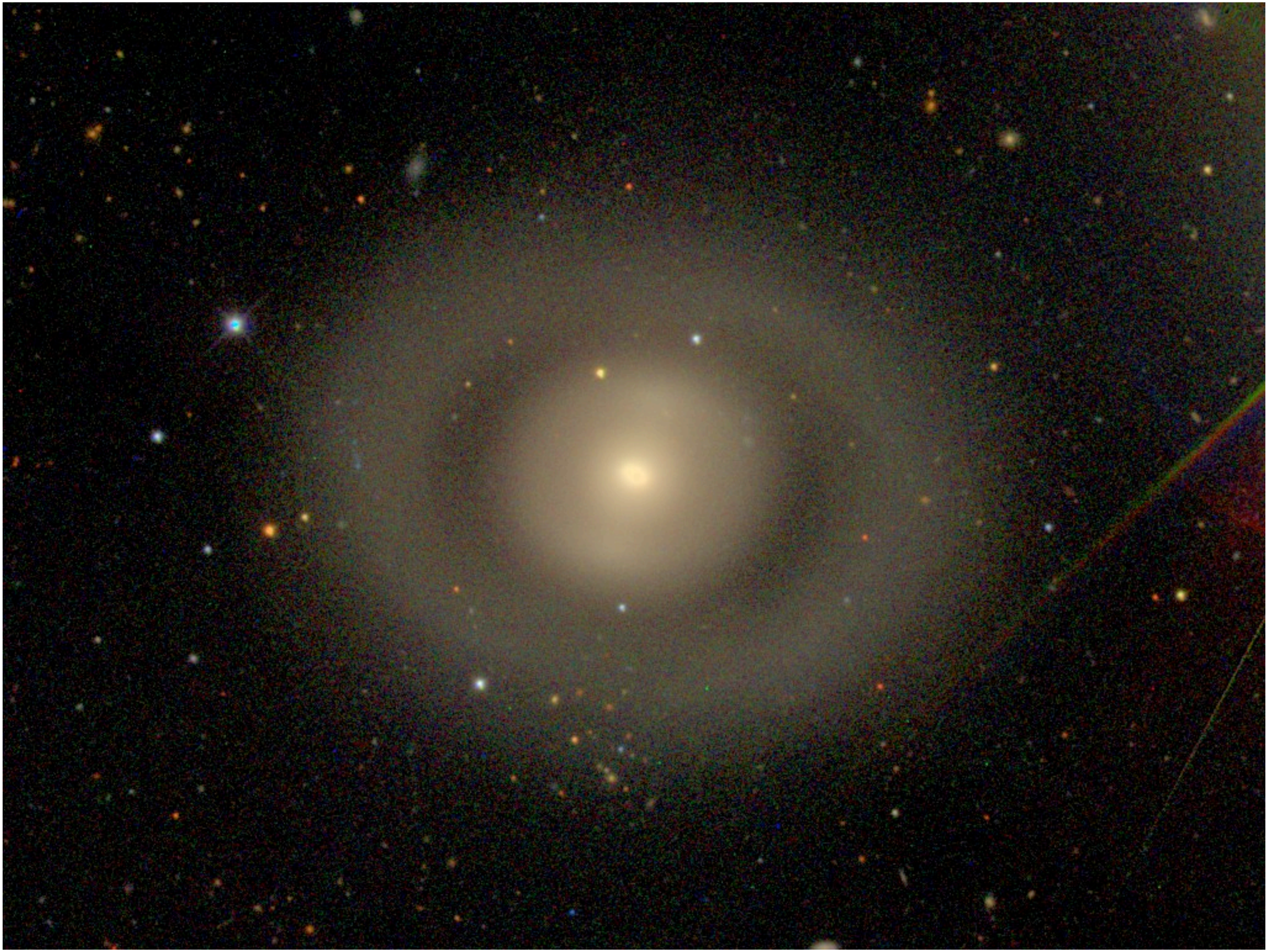
- Use radial velocity to get rotational direction.
- Galaxy must be tilted … but which way?!
- This changes signs of RV.
- Need to look at extinction pattern.
- Most arms are trailing!

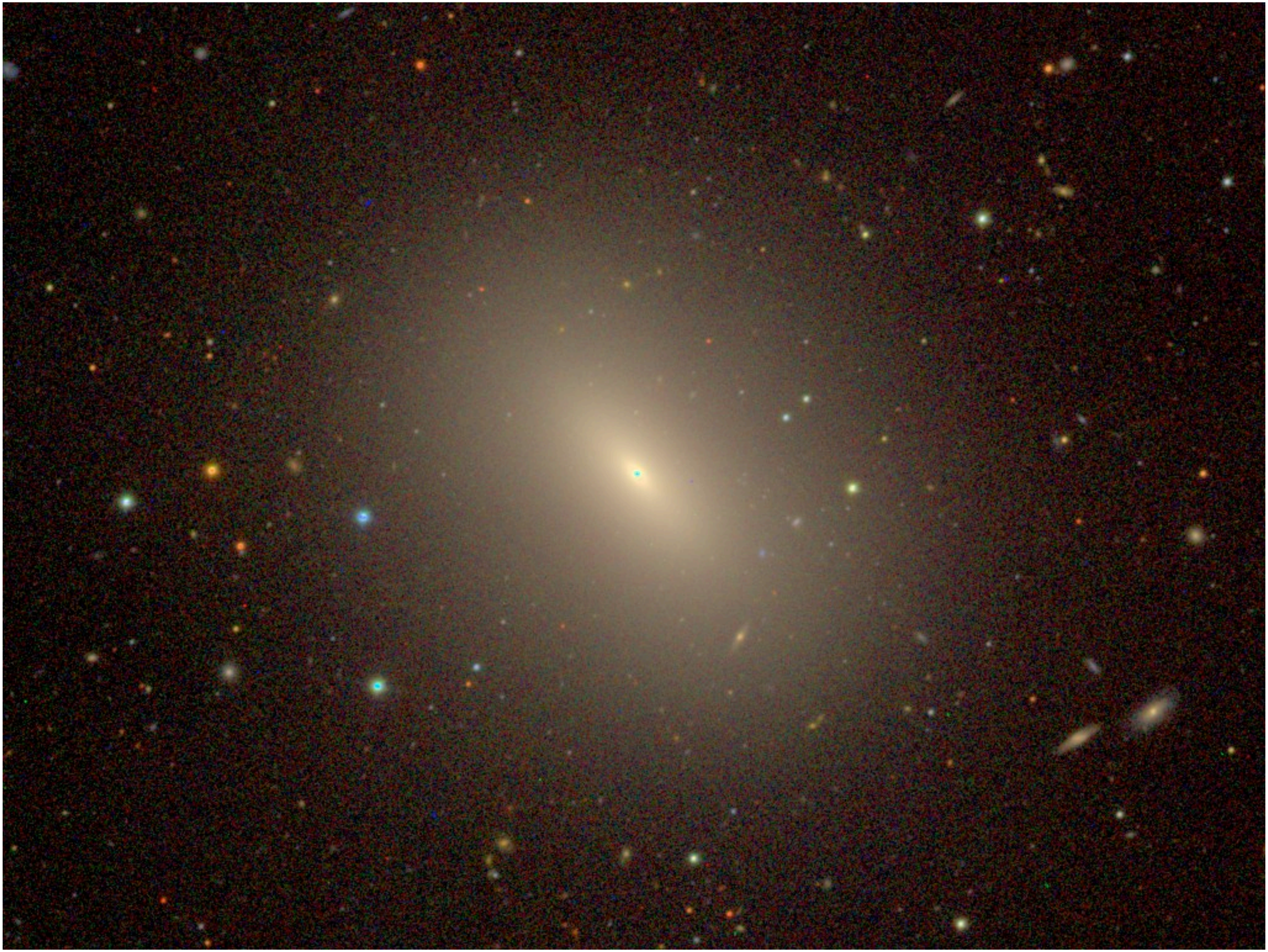


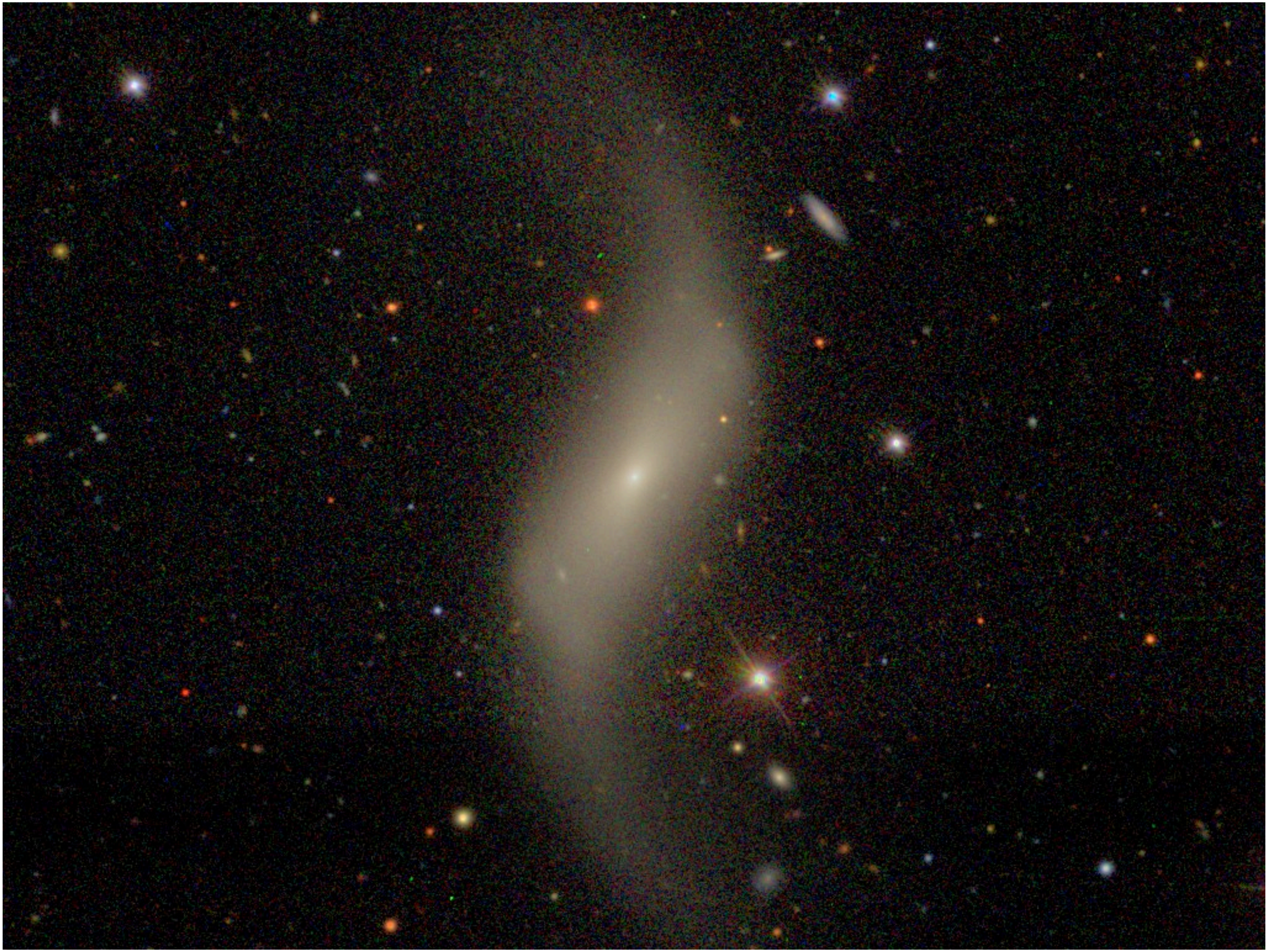


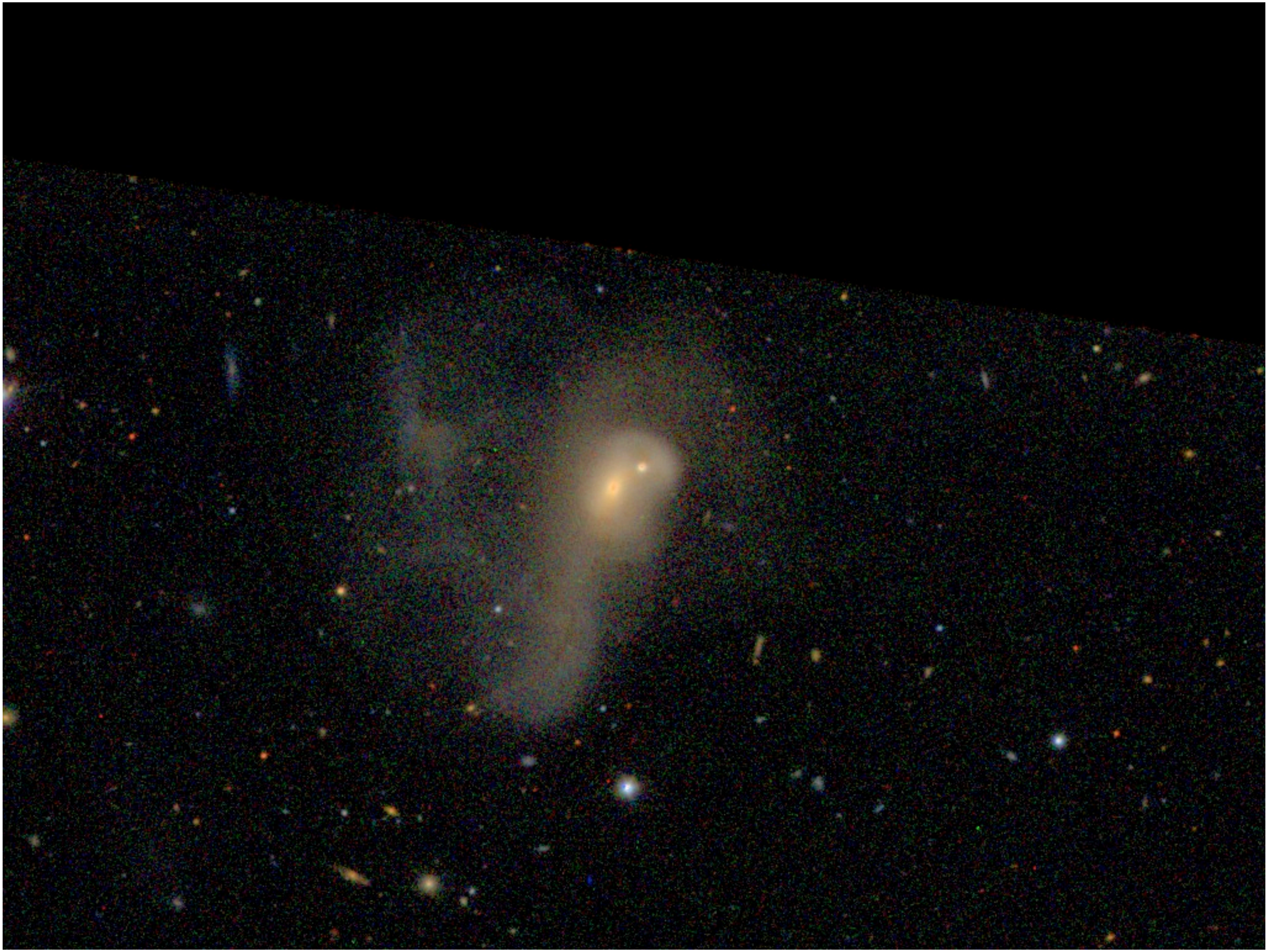


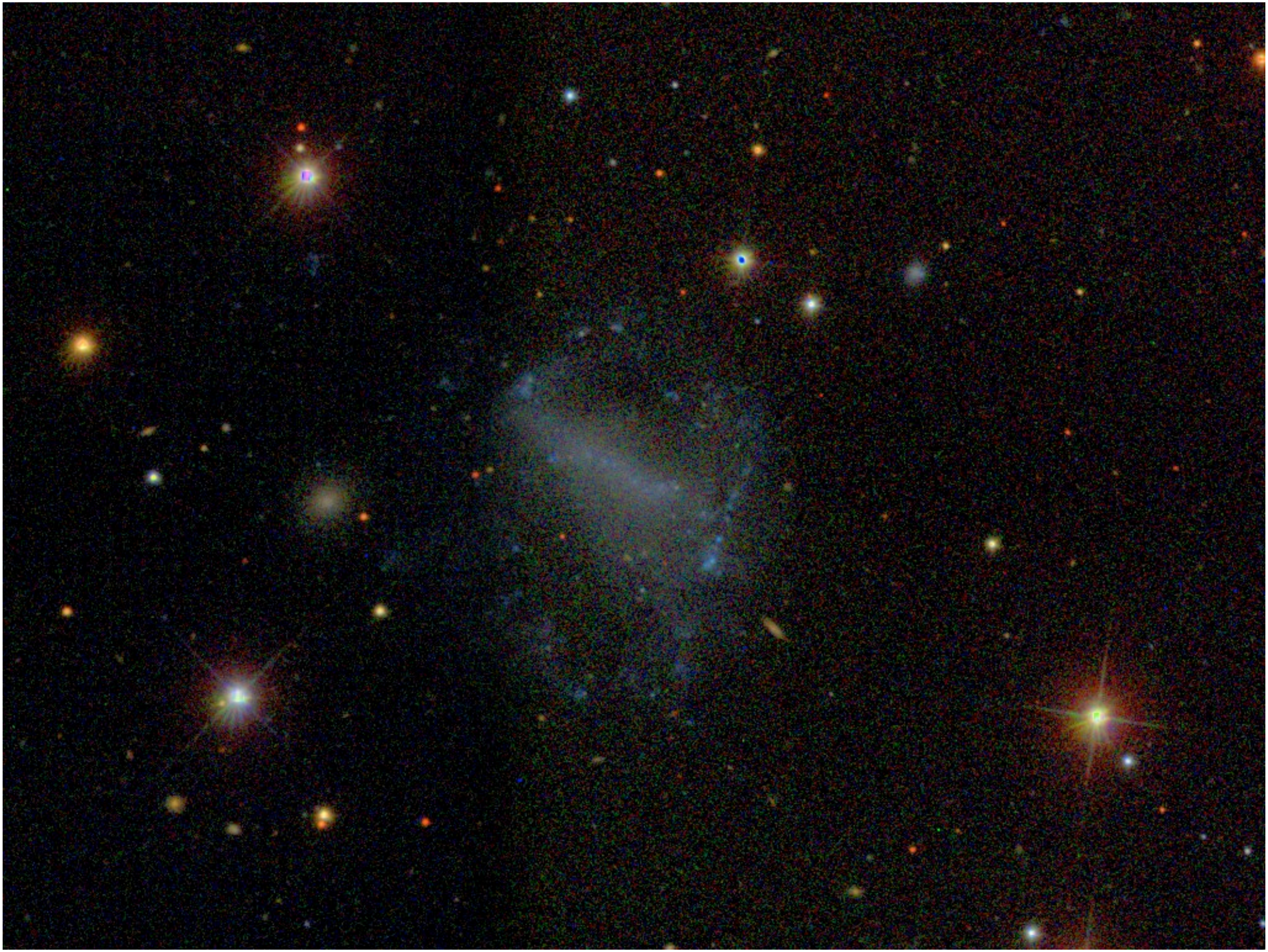




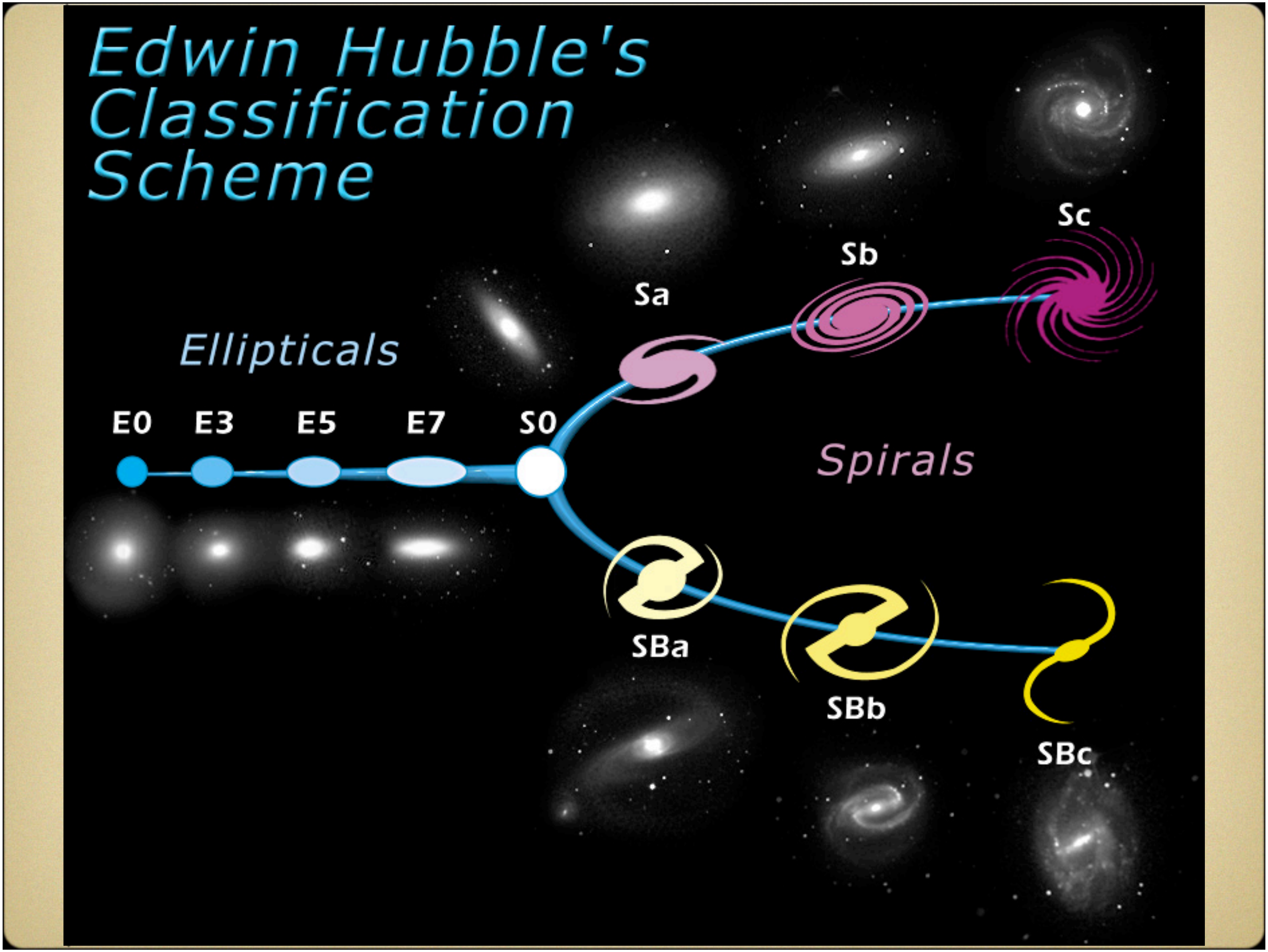




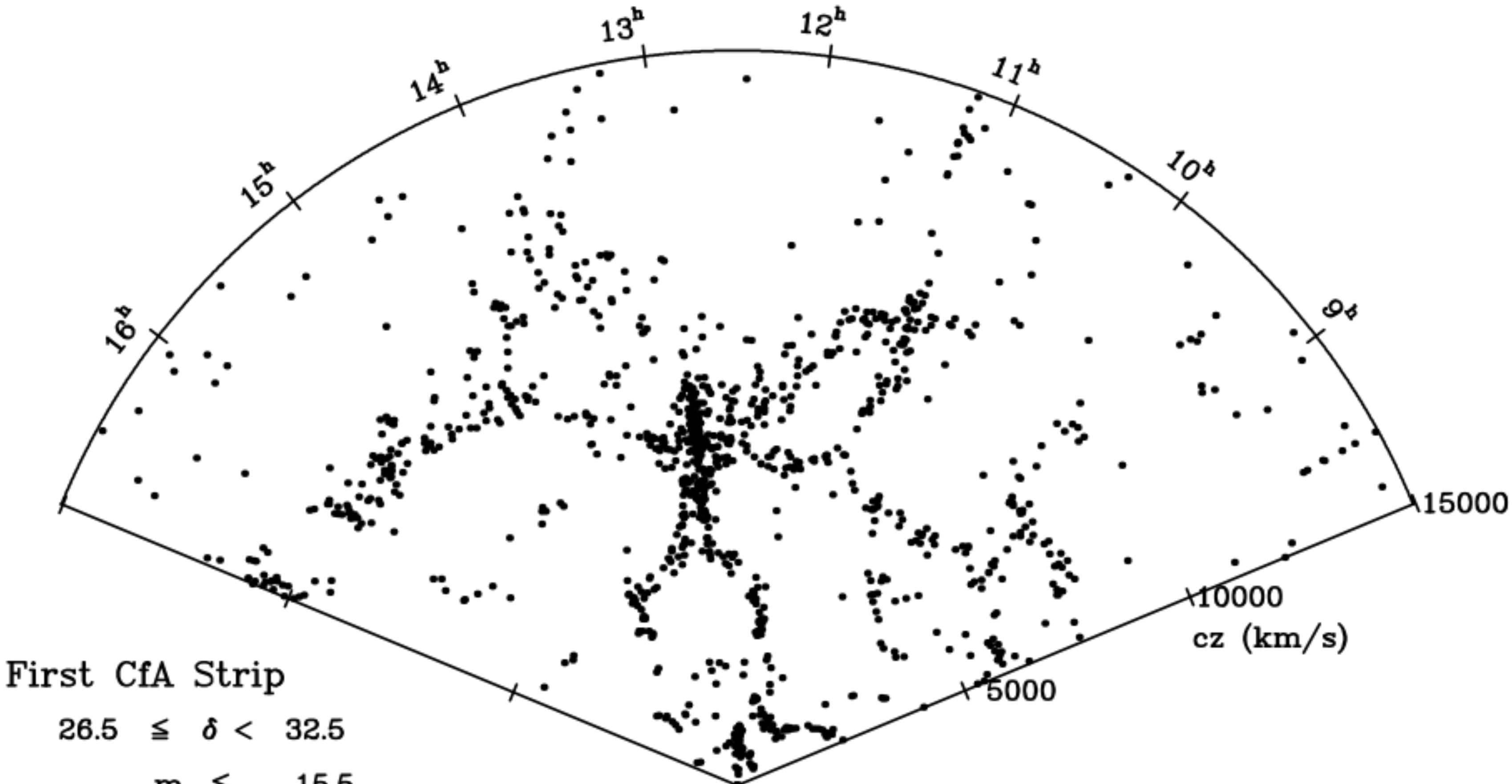




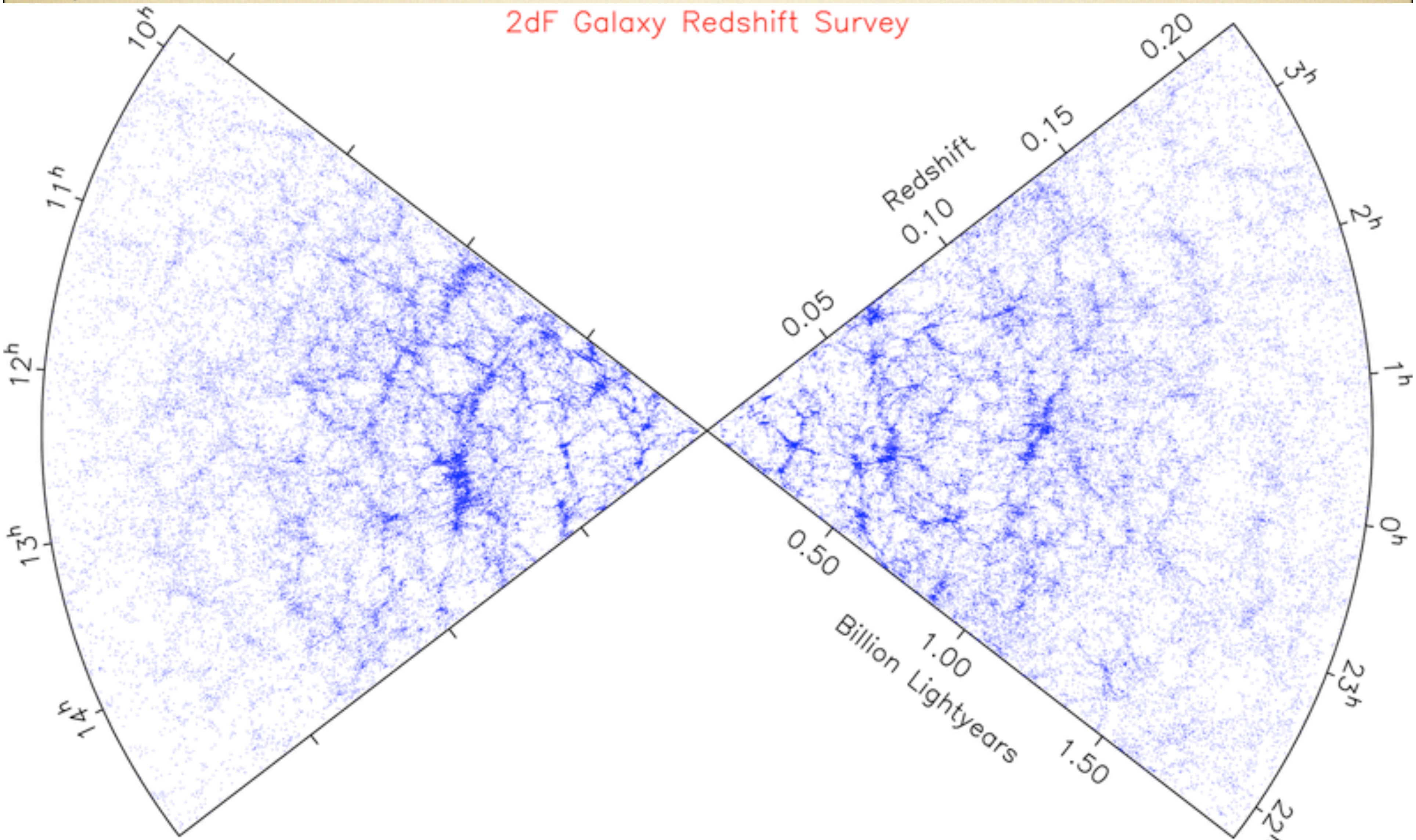

NASA


Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

CfA Redshift Survey

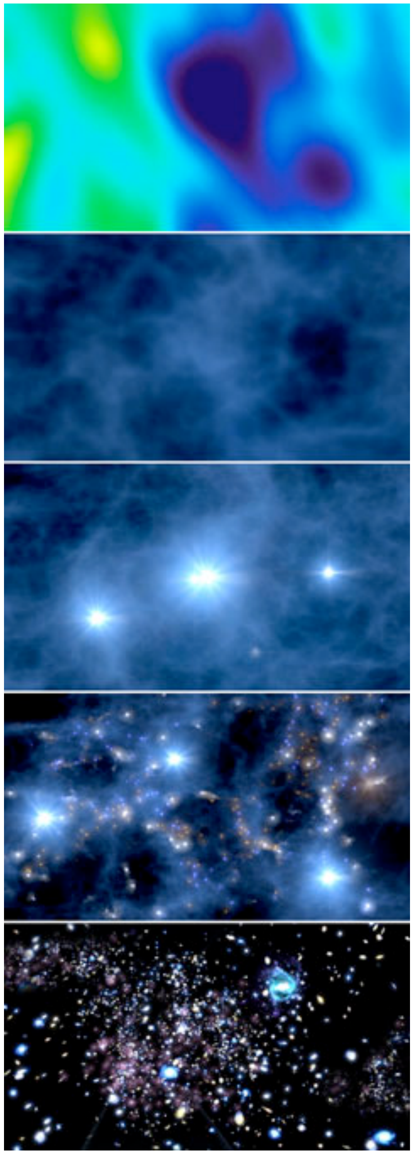


1985

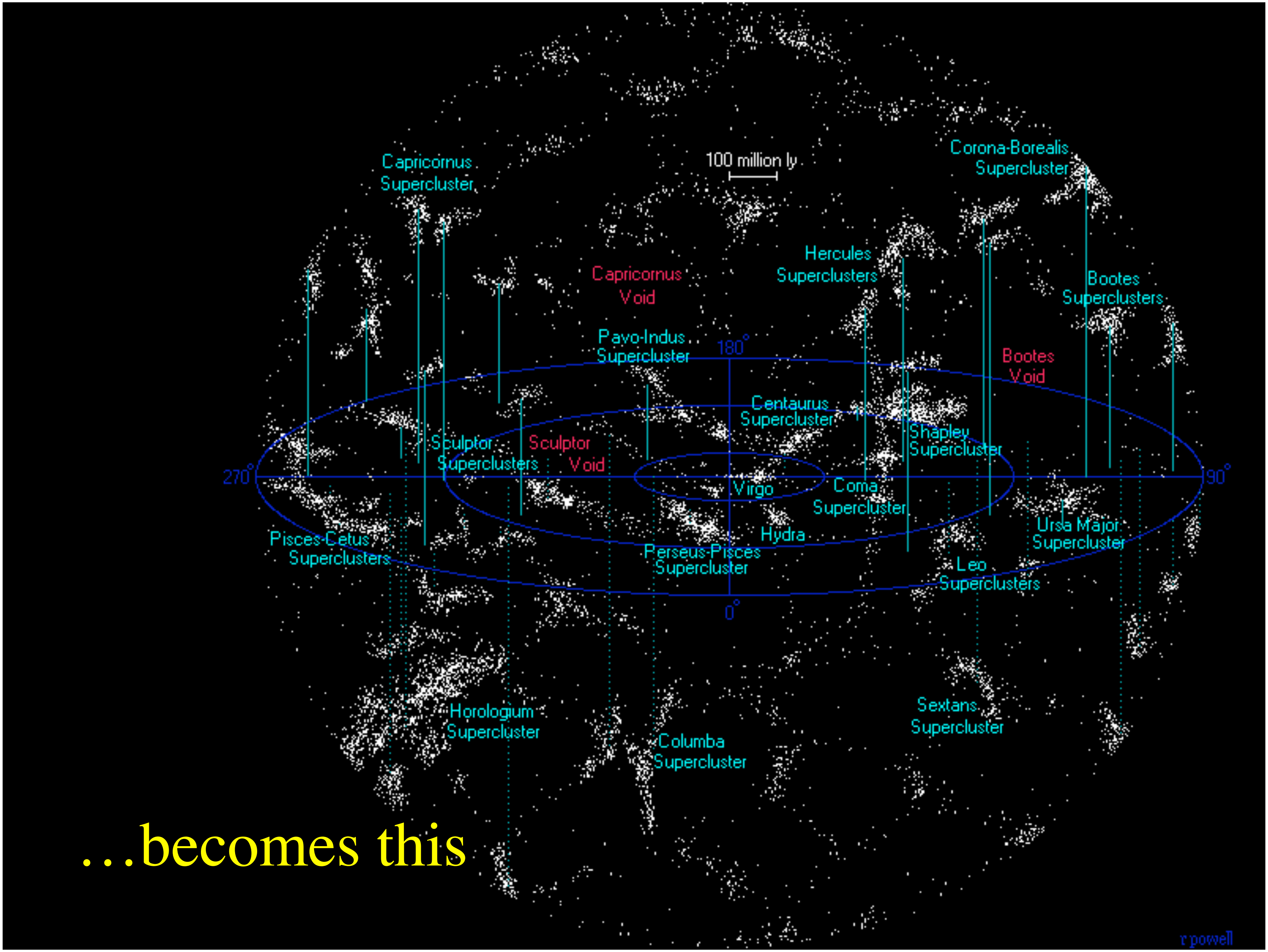


2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50

Growth of Structure



1. Temperature fluctuations in the early universe, from the slight clumping of matter (map on surface of last scattering)
2. Structure growing as denser regions attract more matter, seeded from the early fluctuations
3. The first stars form in the regions of highest density
4. More stars turning on, galaxies forming
5. The modern era



…becomes this

Ways to measure distance

1. *Parallax* – only works for nearby stars (d < 1kpc)
2. *Spectroscopic parallax* - not very accurate
3. *Main sequence fitting* - must be able to resolve dim stars
4. *Cepheid variable stars* – works for d < 10 Mpc
5. *Standard candles* – any object with known luminosity
   - Supergiant stars – works out to 10 Mpc
   - Type Ia supernovae – always reach same peak luminosity – works out to 100Mpc
   - Brightest galaxy in a cluster – works out to 1000 Mpc

The distance *ladder*

1. *Parallax* - most accurate, for nearest stars
2. *Main sequence fitting*
3. *Cepheid variable stars*
4. *Standard candles*
5. *Red-shift* - for most distant objects

Use each method to calibrate the next; like climbing the rungs of a ladder.

Hubble's Law

Astronomers had discovered that the spiral nebulae seemed to be receding

- spectra were *redshifted*

Once Hubble could determine distances, he discovered the *velocity of recession* was proportional to *distance*

$$\boxed{V_r = H\,d}$$

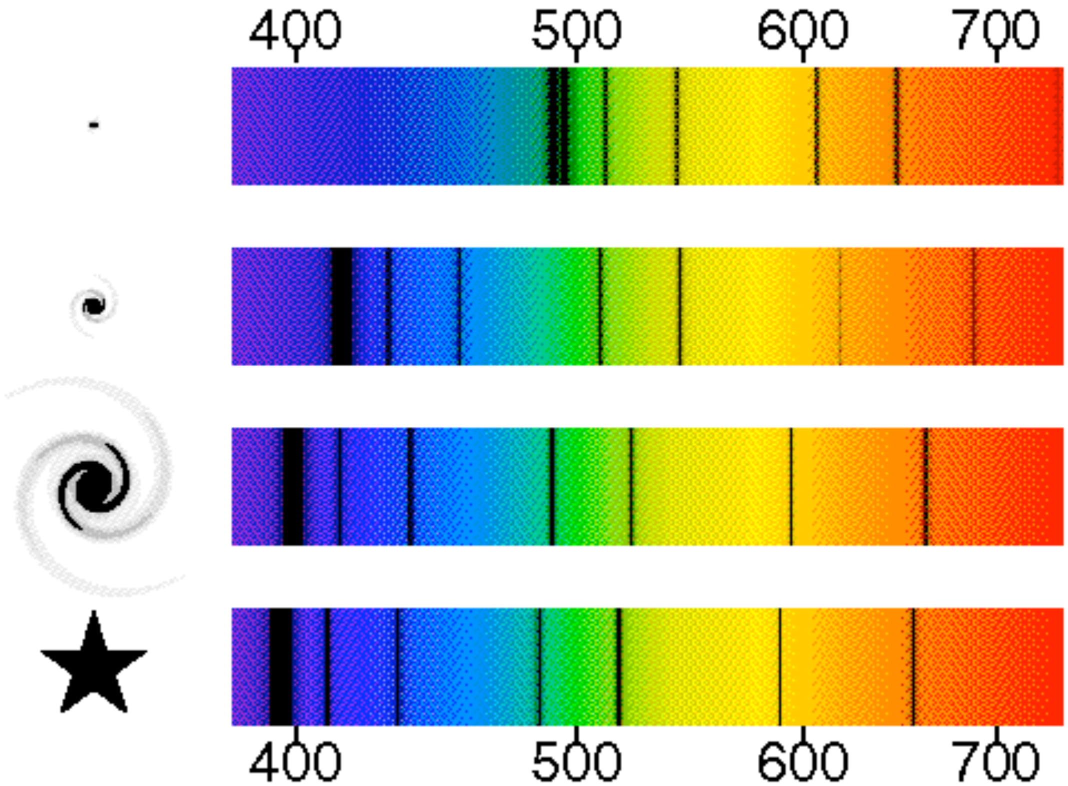
V_r = velocity of recession, d = distance
H = Hubble's constant

Hubble's Law can be used to measure distances

- Measure velocity of recession from spectra
- From Hubble's Law $d = V_r / H$
- Need to know the value of Hubble's constant
  - Currently accepted value H=70 km/s/Mpc

Hubble's Law

Example of spectra showing redshifts

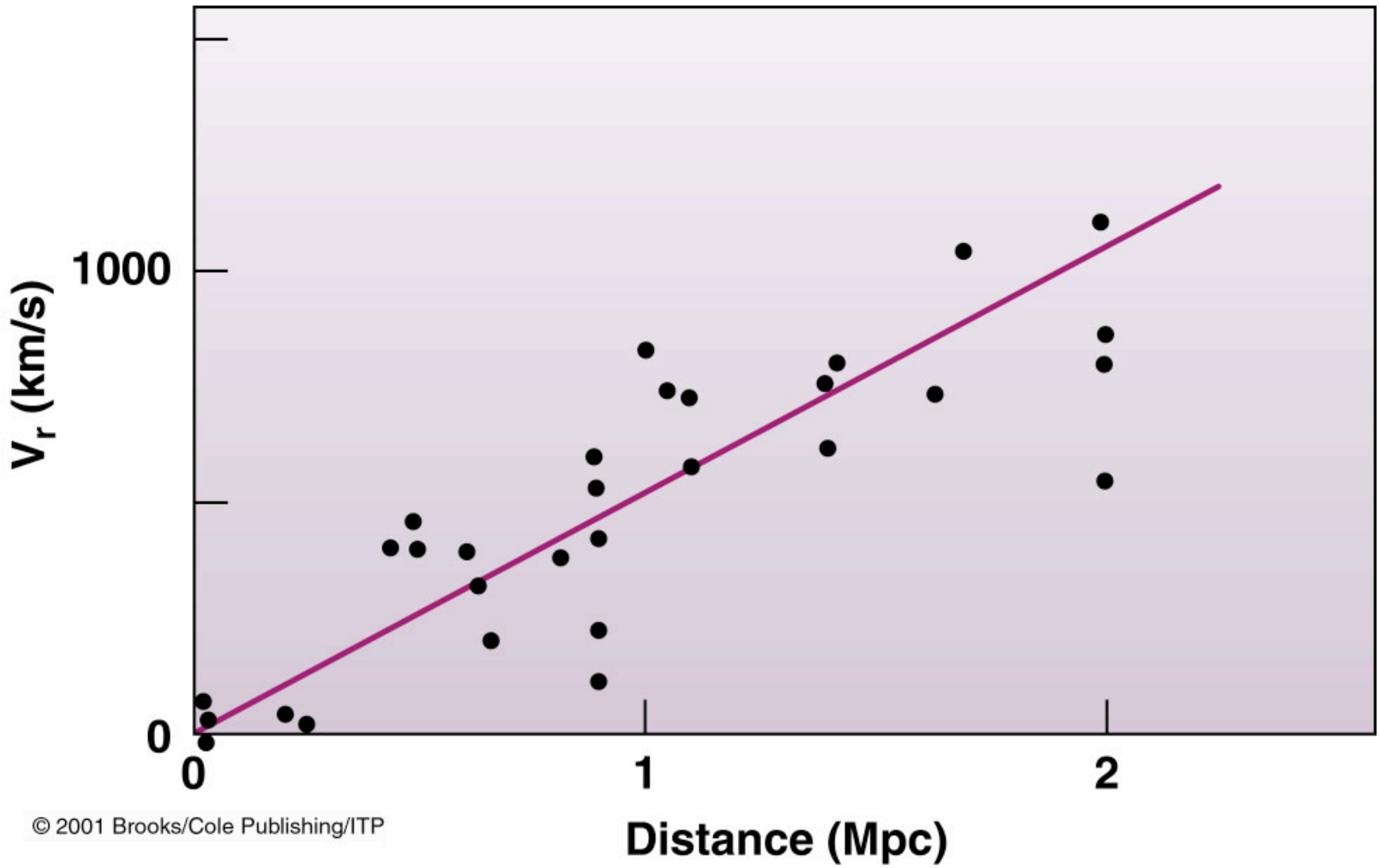


Distant galaxy – high redshift

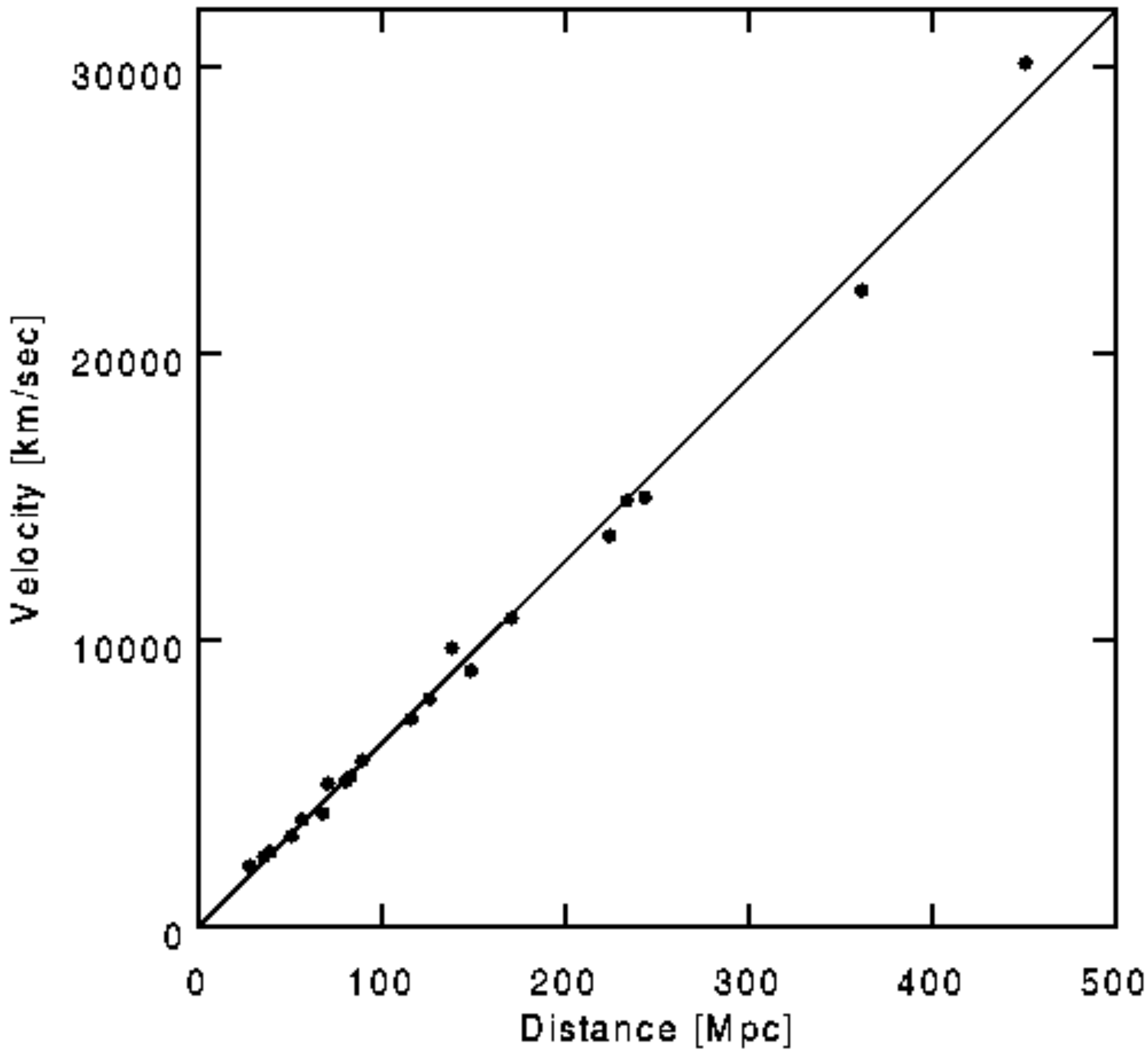
Nearby galaxy – small redshift

Star in MW – no redshift

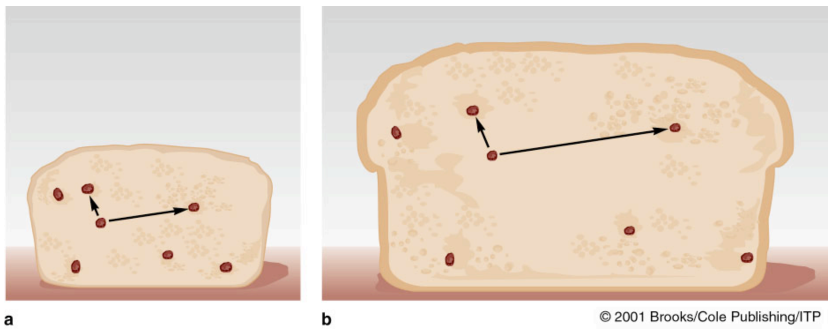
Hubble's Law – original plot

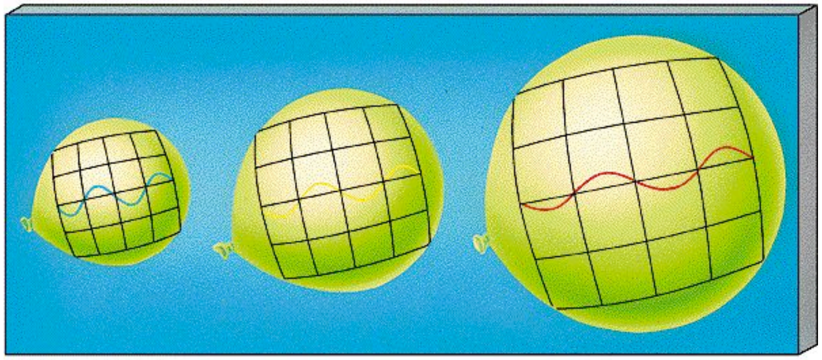


Hubble's Law – modern plot



Hubble's Law results from expansion of Universe





Useful to use *redshift z* to measure changes in size and density of Universe

$z = (\lambda_{obs} - \lambda_{emit})/\lambda_{emit}$

$1+z = R_{obs}/R_{emit}$ R(t) = scale factor, relative linear size of Universe

$(1+z)^3=\rho(z)/\rho_0$

Expansion History

•We have a si… $=H_0xd$.

•This holds in…

•However, it t… of the expansion rate… e per unit time divided b… e). At earlier times, the exp… ling on the matter and en… earlier times, t, $H=H(t)\neq H_0$.

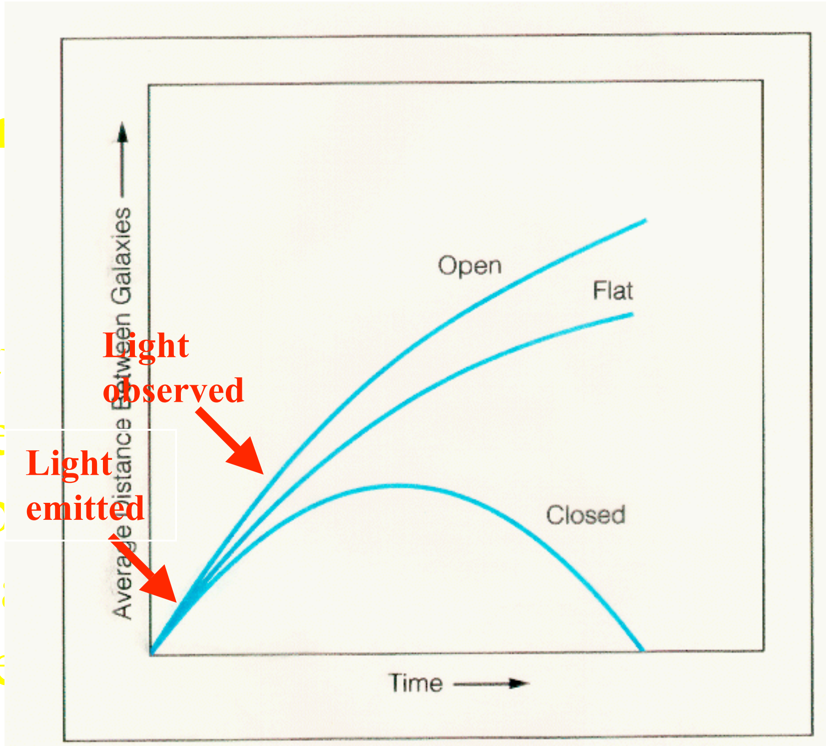


Figure 21.6 The three possible fates of the universe.

•If we interpret redshifts as the expansion factor of the Universe since the light was emitted some distance from us (rather than as recession velocities), we can use redshifts and distances to probe how H(t) evolves.

The critical density

- Useful to think of the case where Kinetic Energy (expansion) just balances Gravitational Potential Energy (matter contained within a given volume).
- Define critical density, $\rho_c = 3H^2/8\pi G$ is the density at which gravity exactly balances the expansion of the Universe.
- Ω_m is defined as the the ratio between the matter density in the Universe and the critical matter density

$$\Omega_m = \rho_m/\rho_c$$

Escape velocity and the critical density

A few important cases (with no Dark Energy):

1. $\Omega_m < 1$, $\rho<\rho_{crit}$, and the Universe will expand forever, and have an "open" infinite geometry
2. $\Omega_m=1$, $\rho=\rho_{crit}$, and the Universal expansion assymptotes to zero at infinity (with no other energy sources), and the Universe has a "flat" infinite geometry (called Einstein-de Sitter Universe)
3. $\Omega_m > 1$, $\rho>\rho_{crit}$, and the Universal expansion stops, turns around, and the Universe collapses back on itself, with a "closed" finite geometry (sometimes called the "Big Crunch")

Matter and the Geometry of Space

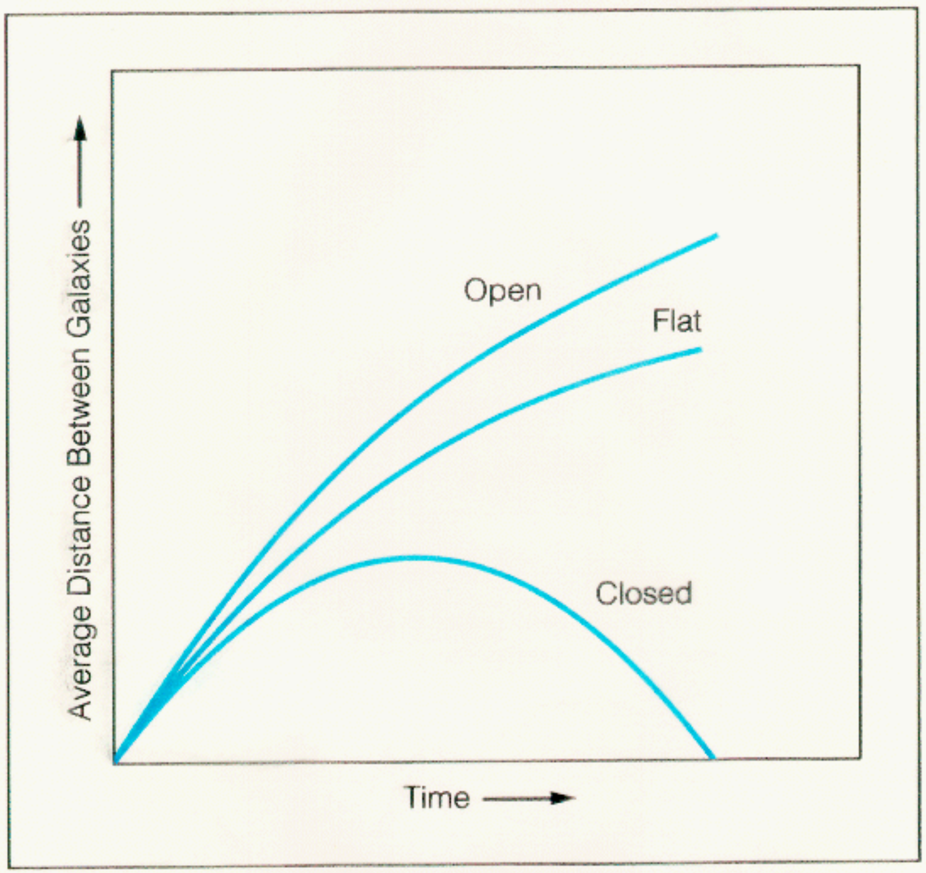


Figure 21.6 The three possible fates of the universe.

Closed Universe recollapses

Flat universe (no dark energy) is just balanced

Open universe expands forever

The geometry and expansion history are both determined by the overall density.

Matter and the Geometry of Space

- Einstein's theory of gravitation states that space is distorted by gravity.
- Gravity curves space, and curvature of space causes matter to move under the influence of gravity.
- Curvature of space causes light not to travel in straight lines (this has been demonstrated, and is called gravitational lensing).
- The global matter and energy density in the Universe determine the overall curvature of space.
- Euclidean geometry doesn't hold when space is curved.

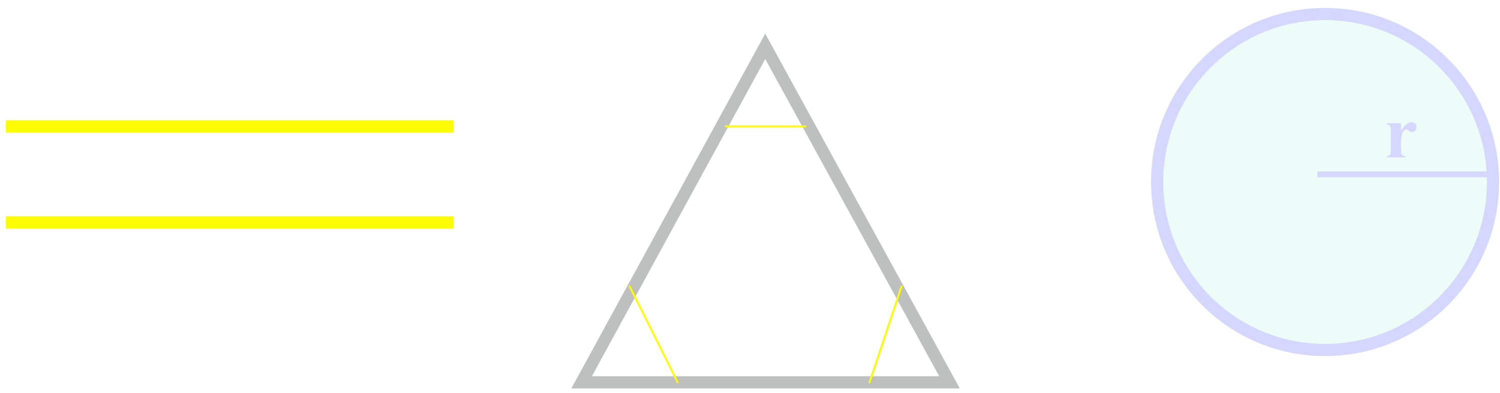
Matter and the Geometry of Space

- What are some examples of Euclidean geometry?

  Parallel lines never meet

  the angles of any triangle add up to 180º

  the circumference of a circle with radius=r is 2πr



- This isn't true in a curved non-Euclidean spacetime

Matter and the Geometry of Space

- What is meant by “curved” and “closed” and “open”
- Curved with respect to an artificial 4th spatial dimension which we cannot perceive, because we are 3D beings
- However, we can make an analogy with 2D curved surfaces embedded in three dimensions

Matter and the Geometry of Space

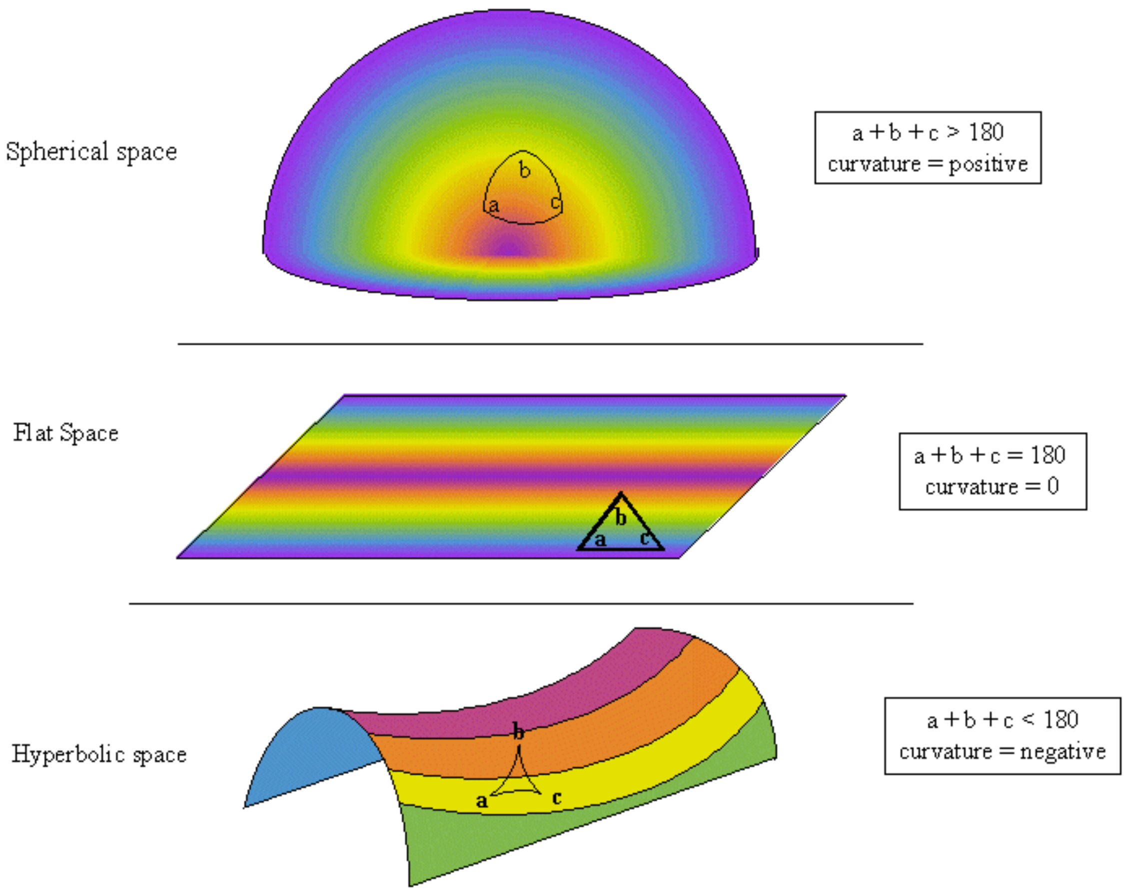
- One example is the surface of the Earth

Think of great-circle routes between e.g. LA and London

The sum of the angles drawn on the surface of the sphere is 270°. The circumference of a circle with radius r is $< 2\pi r$

- We live on the surface of a sphere. While it locally appears flat, over large distances, that assumption breaks down. This is a closed spherical geometry
- 2D surface in 3D; analogy for 3D closed, curved space, with $\Omega_m > 1$

Matter and the Geometry of Space



$\Omega>1$, "closed"

$\rho>\rho_{crit}$

$\Omega=1$, "flat"

$\rho=\rho_{crit}$

$\Omega<1$, "open"

$\rho<\rho_{crit}$

Matter and the Geometry of Space

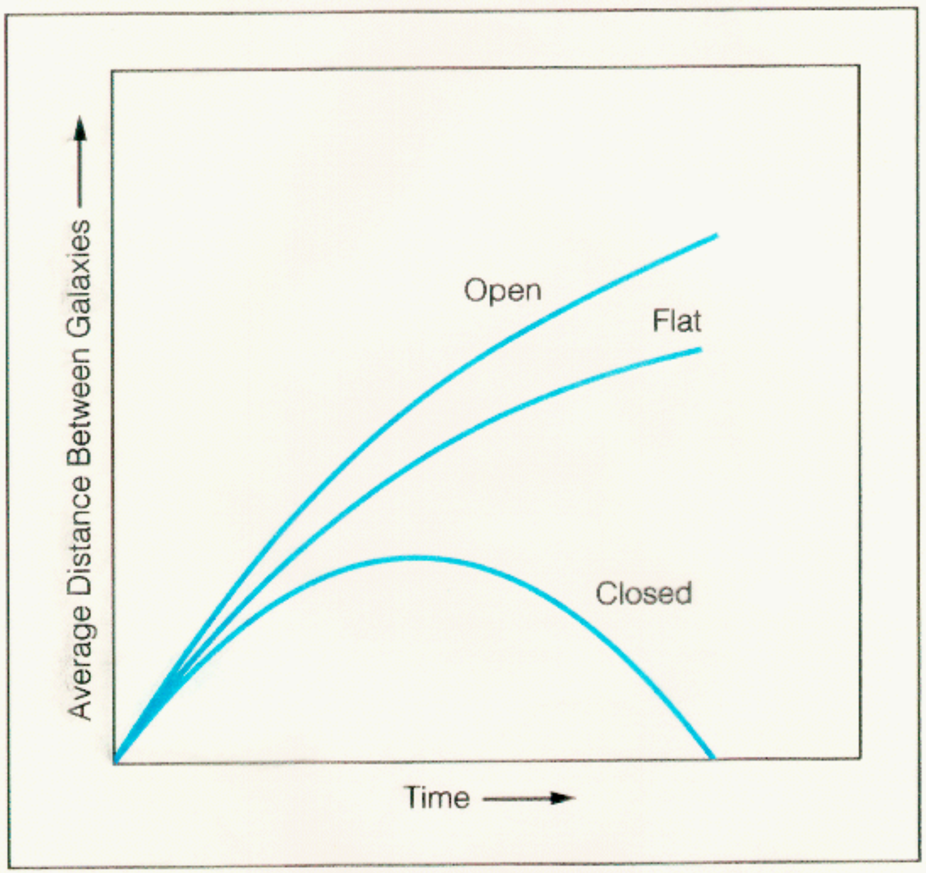


Figure 21.6 The three possible fates of the universe.

Reminder:

Closed Universe recollapses

Flat universe (no dark energy) is just balanced

Open universe expands forever

The geometry and expansion history are both determined by the overall density.

Matter and the Geometry of Space

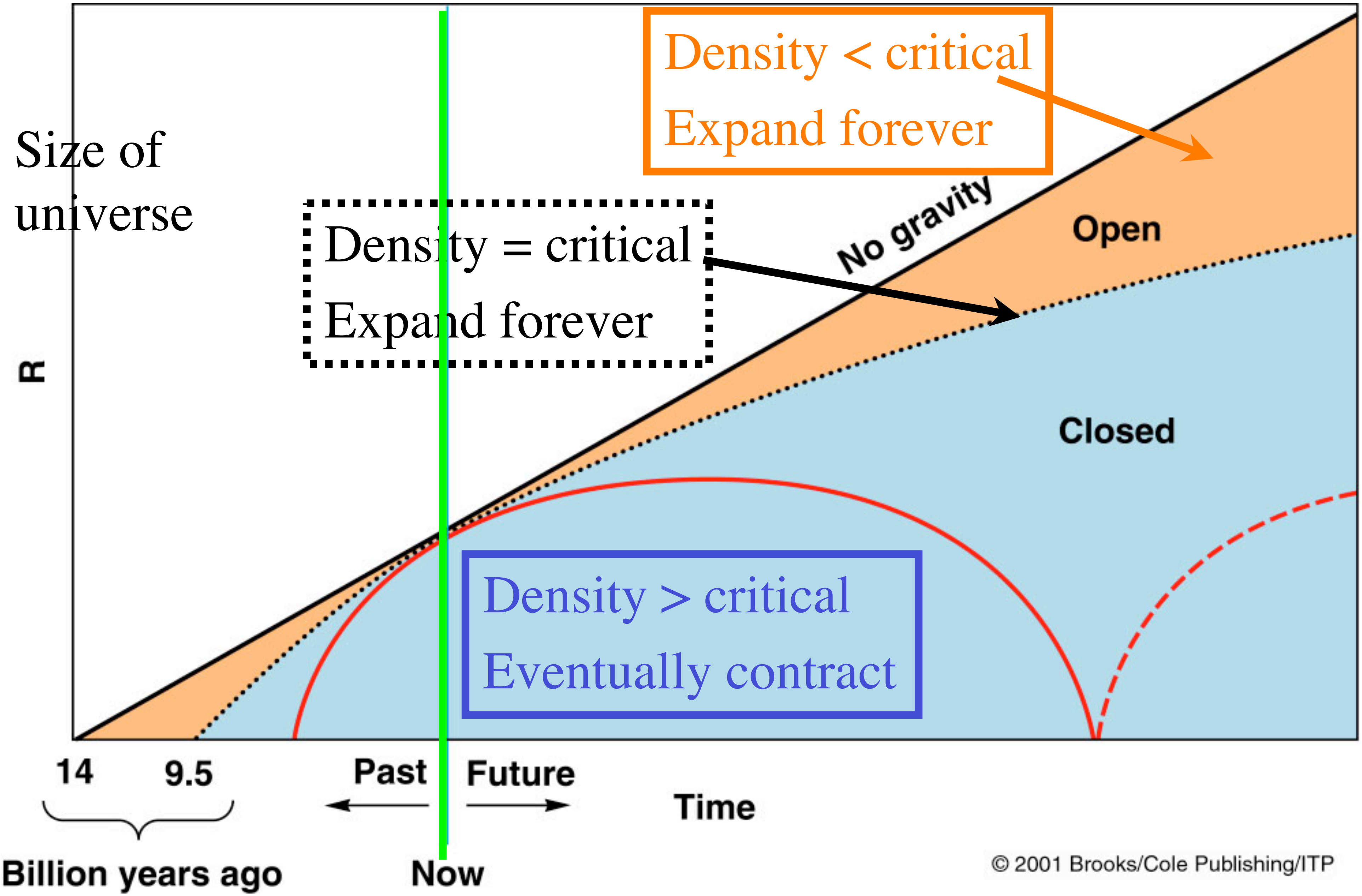
•Locally, most of the time, we can't tell the difference between Euclidean and non-Euclidean space.

• When we start looking out over distances of z> few tenths, then we can start to see the effects of the global geometry

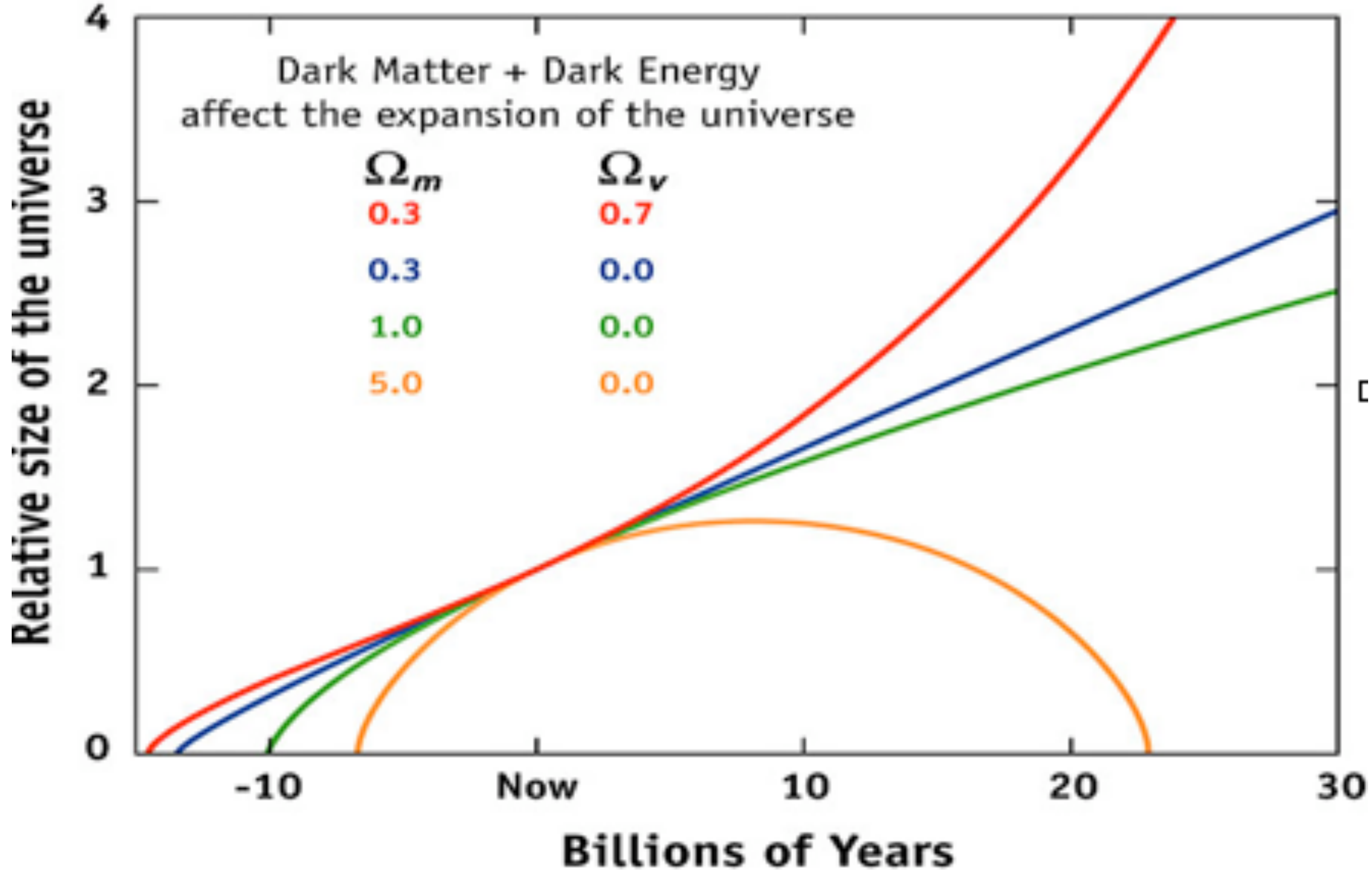
• We see that the Hubble "Constant" is not constant; it was different in the past; we see that the angular size and apparent brightness of objects of known physical size and luminosity change with redshift, and not in a Euclidean fashion. The rate at which they get smaller and fainter also tells us about the geometry of the universe.

•In fact: $\theta=R/d$ and $f=L/(4\pi d^2)$ are very important to measure as a function of redshift. Measuring these for objects of known "R" and "L" make up so-called "Cosmological Tests" and tell us about the global geometry of space.

Fate of Universe: *Density Matters*



Fate of Universe: *Density Matters*



•Non-zero Λ: accelerating Universe

•Different cosmological parameters: different ages for the Universe

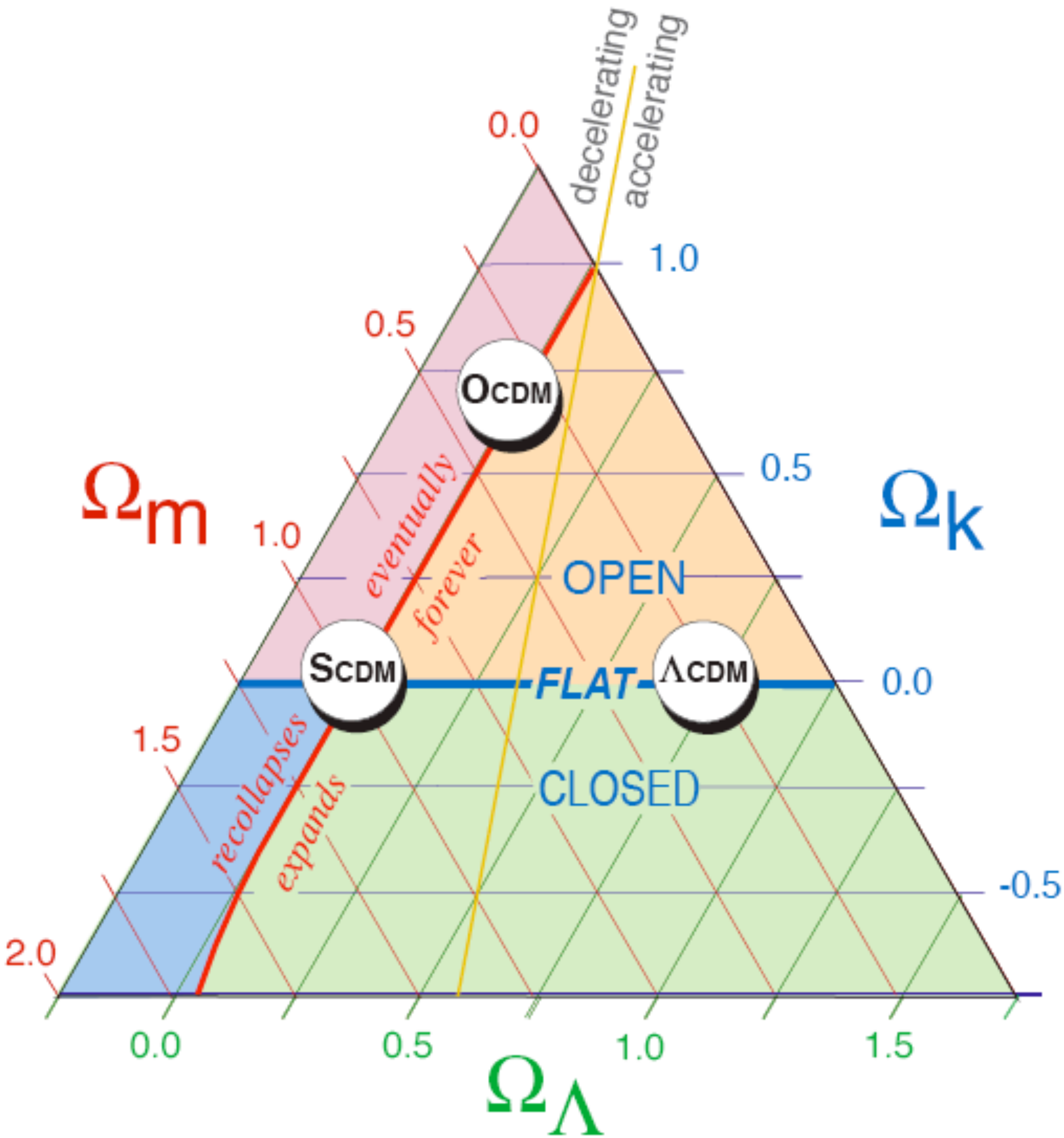
The Accelerating Universe: Return of the Cosmological Constant

- Recent observations suggest that distant supernova have larger redshifts than expected
  - ✶If observations are correct, expansion rate is now ***faster*** than it was in the past.
    - Some force must now be pushing the universe apart

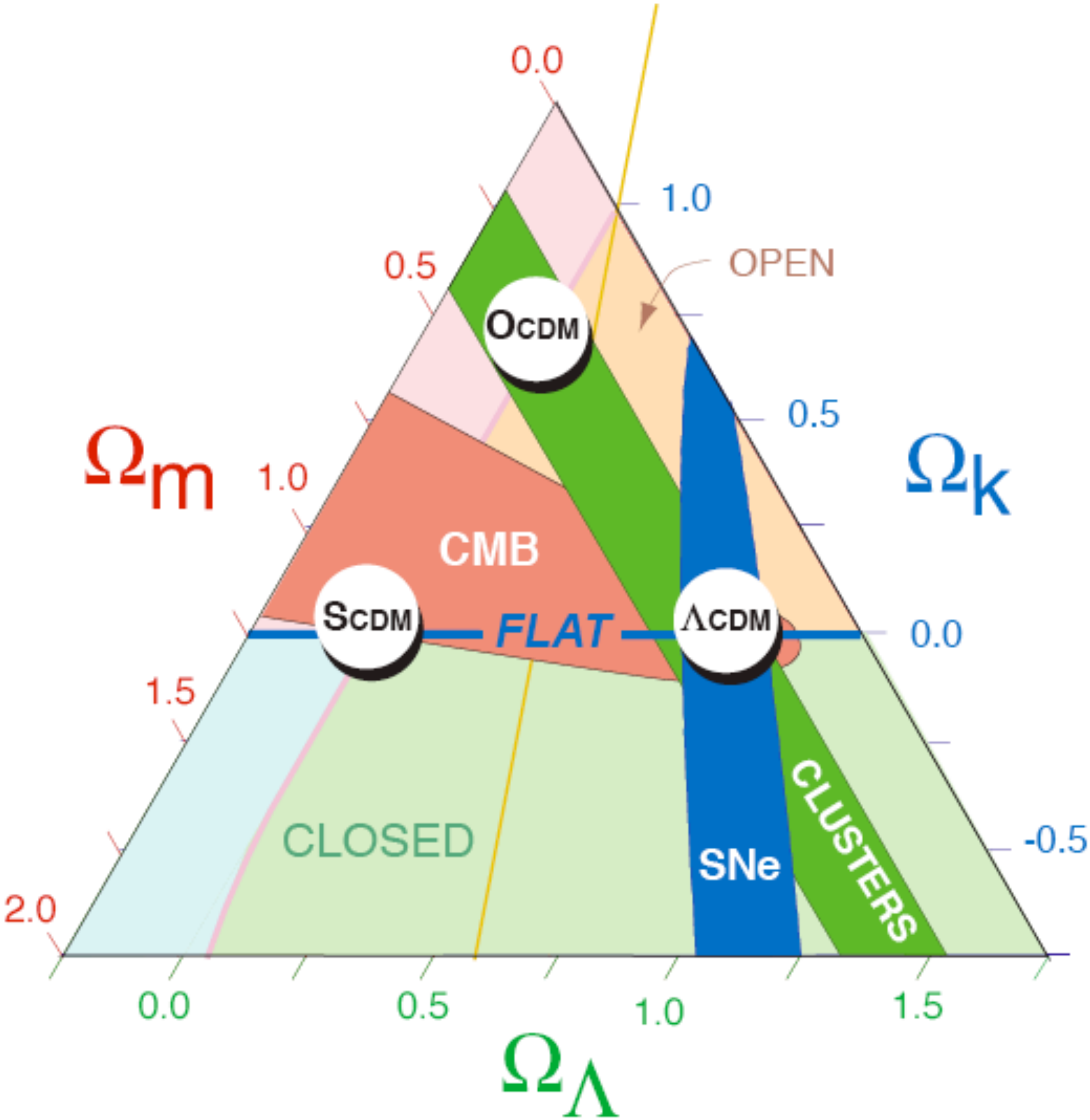
Cosmological constant (Λ)

- Einstein called it his "biggest blunder"
- In order to get a static Universe, space must have a *negative* pressure ("negative vacuum energy density") - parameterized by Λ
- Once Hubble discovered expansion of Universe, Einstein abandoned this idea.
- But more recent observations give evidence that there *is* a non-zero Λ; sometimes called dark energy
- We define Ω_Λ to be the ratio of the "density" in the vacuum energy, relative to the critical density:

$$\Omega_\Lambda = \rho_\Lambda / \rho_{c,} \text{ where } \rho_\Lambda = \Lambda c^2/(3H^2)$$



decelerating
accelerating
0.0
1.0
0.5
0.5
OCDM
Ωm
1.0
eventually
forever
OPEN
Ωk
SCDM
FLAT
ΛCDM
0.0
1.5
recollapses
expands
CLOSED
-0.5
2.0
0.0
0.5
1.0
1.5
ΩΛ


0.0
0.5
1.0
1.5
2.0
Ω_m
1.0
0.5
0.0
-0.5
Ω_k
OPEN
OCDM
CMB
SCDM
FLAT
ΛCDM
CLOSED
SNe
CLUSTERS
0.0
0.5
1.0
1.5
Ω_Λ

The Big Bang

- As universe expands, it gets
  - ✶Less dense
  - ✶Less hot
- Conversely, in the past, the universe was much smaller and so it was
  - ✶Denser
  - ✶Hotter
- We call this hot, dense beginning the ***Big Bang*** (George LeMaitre first proposed this)

The Big Bang

Since it was hot and dense, should have created intense, short-wavelength blackbody radiation

- ✶ But expansion of universe redshifts this creation fireball to radio wavelengths, as Universe cools
- ✶ $T(z) = T_0\ (1+z)$, $\lambda_{max}(z)=\lambda_{max,0}/(1+z)$
- ✶ T_0 is effective temperature of this radiation now, T_0=2.7 degrees K

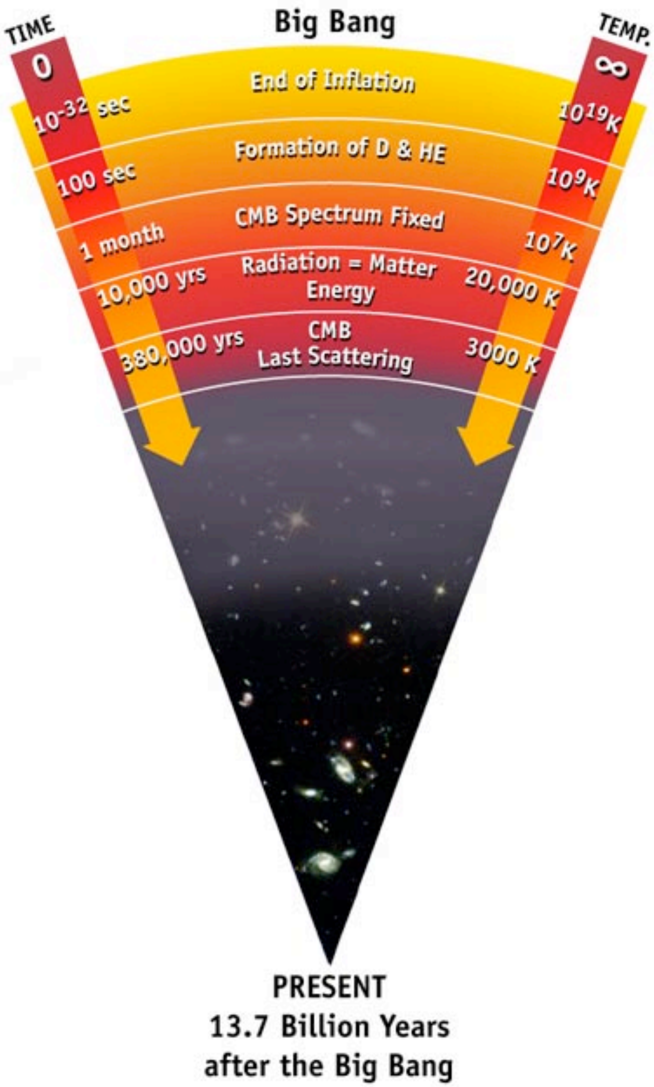
• Th… Universe
coo… Big
Ba…

• P… ons no
lon… to the
poi…

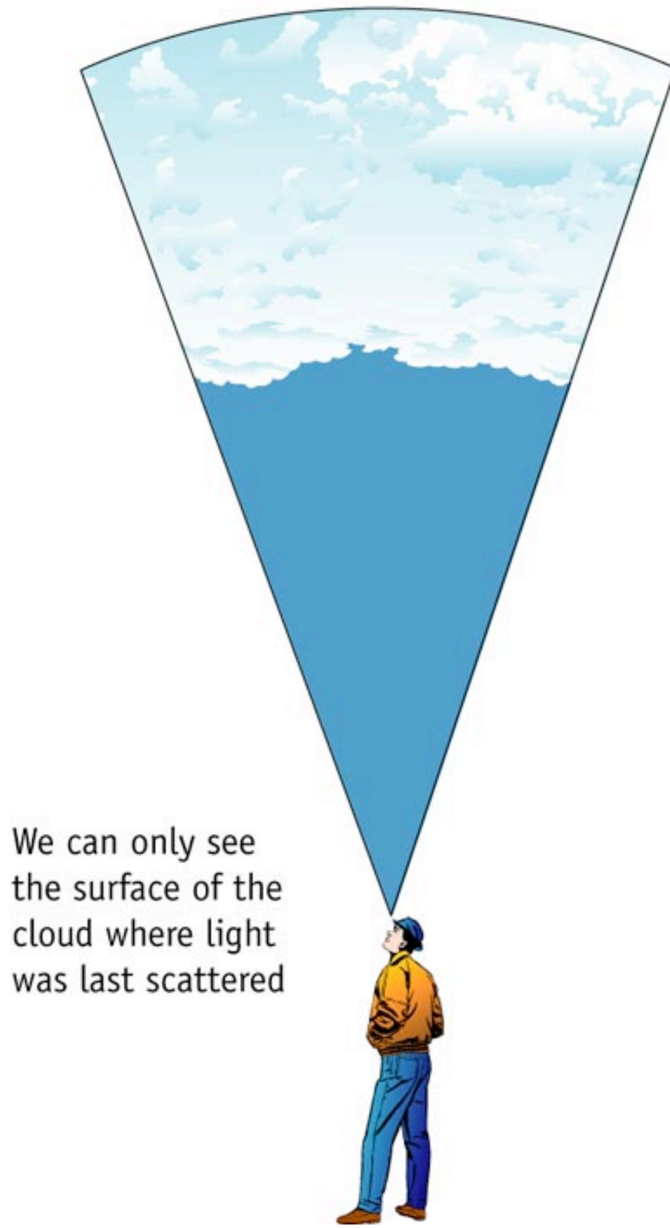
• P… way they
red… the
uni…

• T… ation.

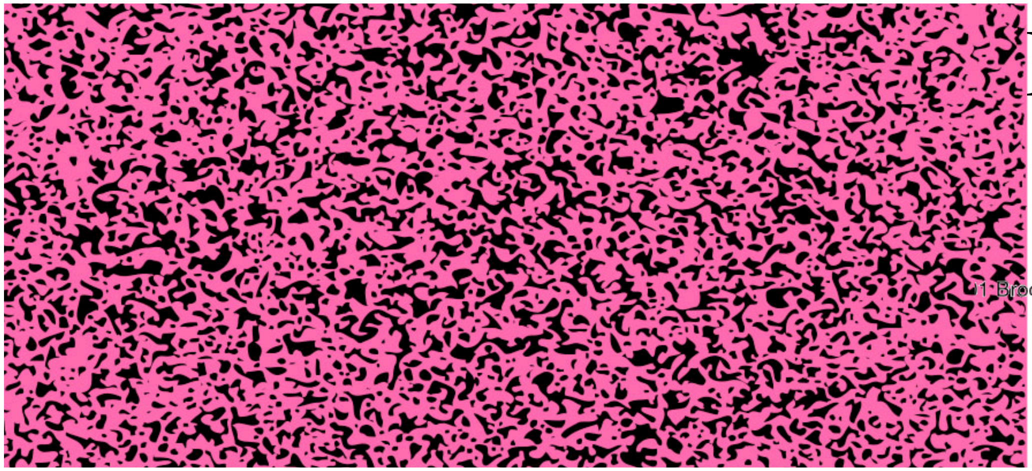
• W… verse
wa…



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

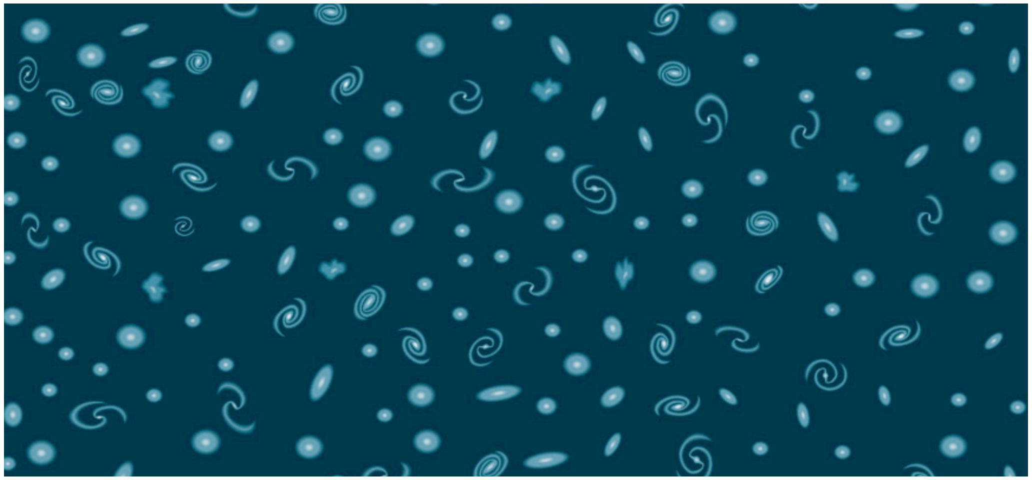


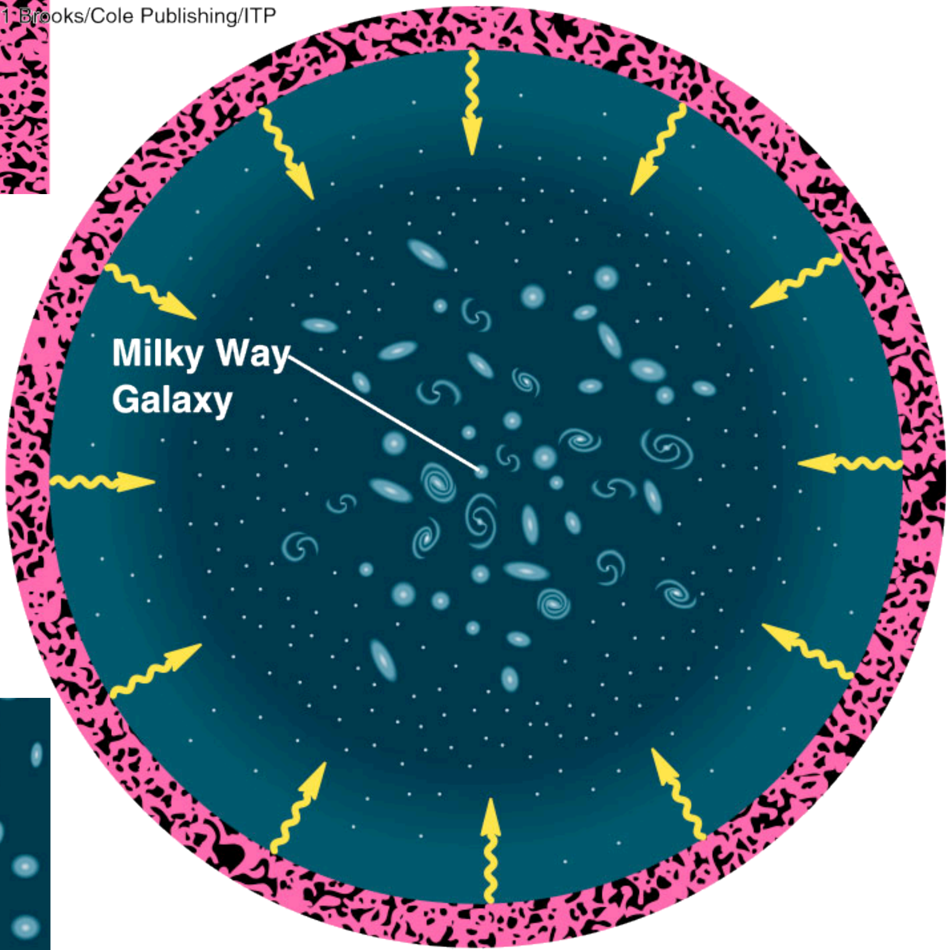
Photons from far-away come from long ago



A region of universe a few 100,000 years after Big Bang

A region of universe now





Present universe as it appears from our galaxy

Discovery of CMB

"Molecular Lines from the Lowest States of Diatomic Molecules Composed of Atoms Probably Present in Interstellar Space"

Andrew McKellar, Publications of the Dominion Astrophysical Observatory (Victoria, BC) 7:251-272

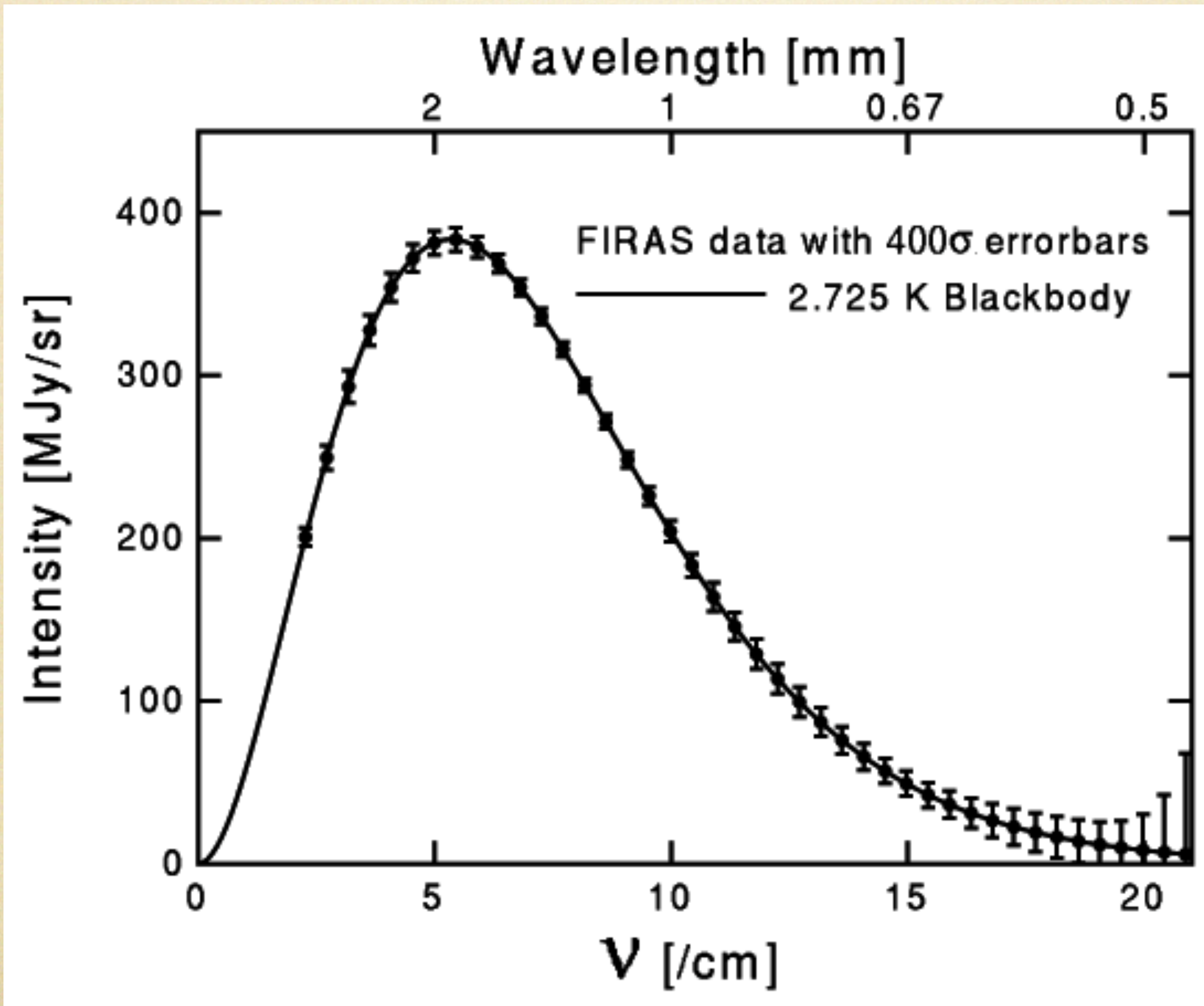
1941!

Another discovery of the CMB

A Measurement of excess antenna temperature at 4080 mc/s

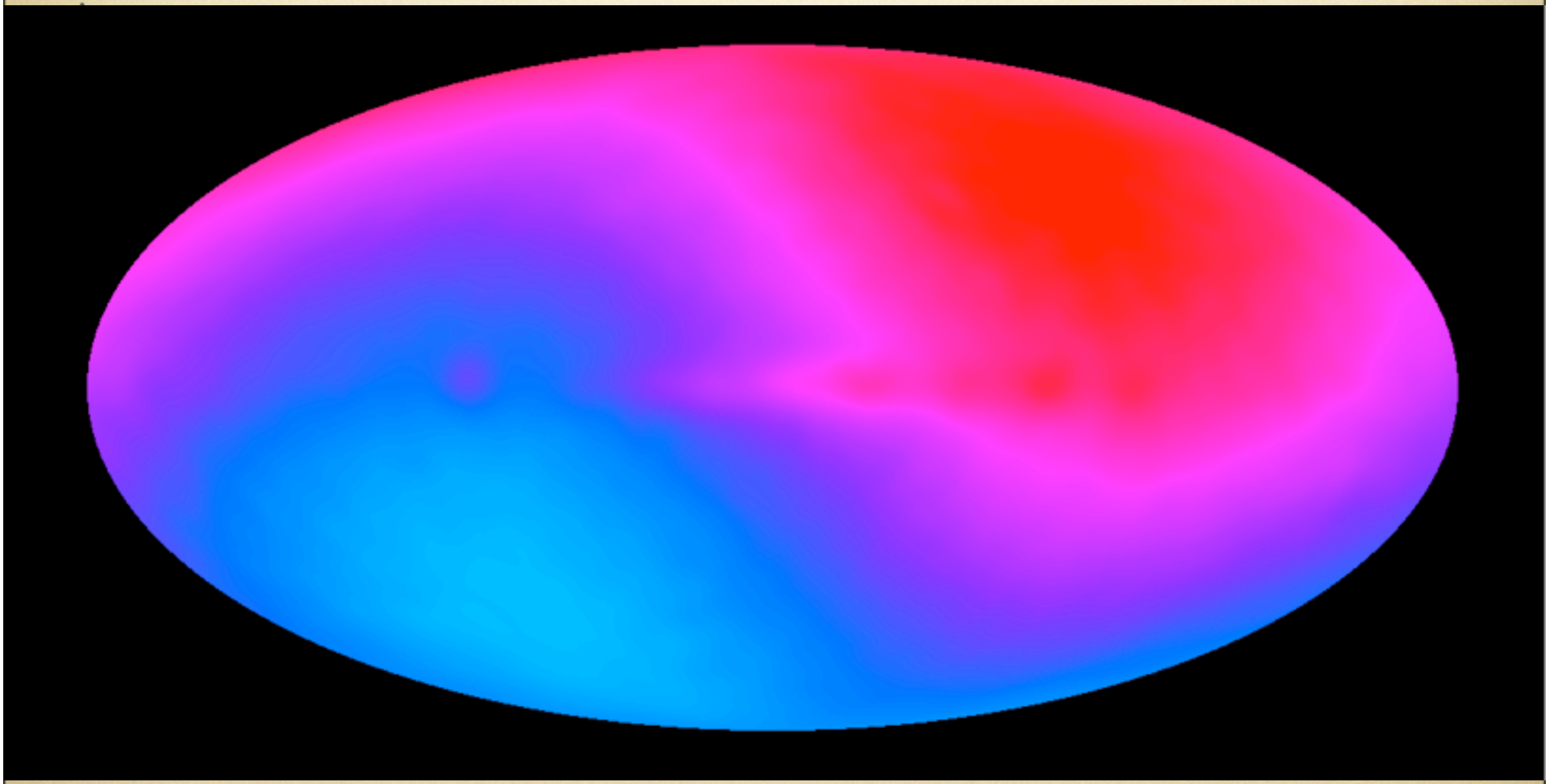
Penzias and Wilson, Astrophysical Journal 142:419-421 (1965)

CMB



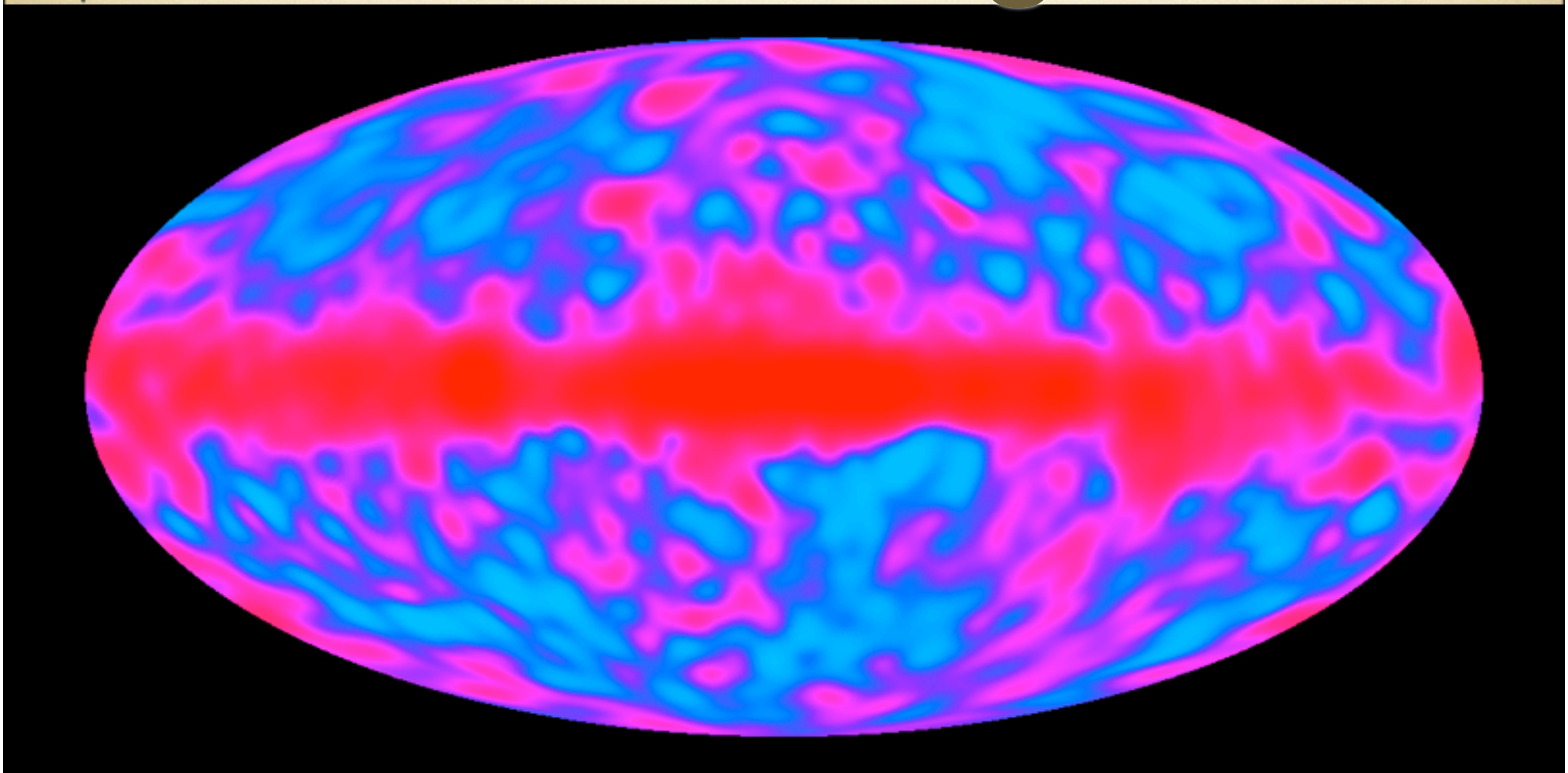
Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
0
5
10
15
20
ν [/cm]

Raw COBE Data



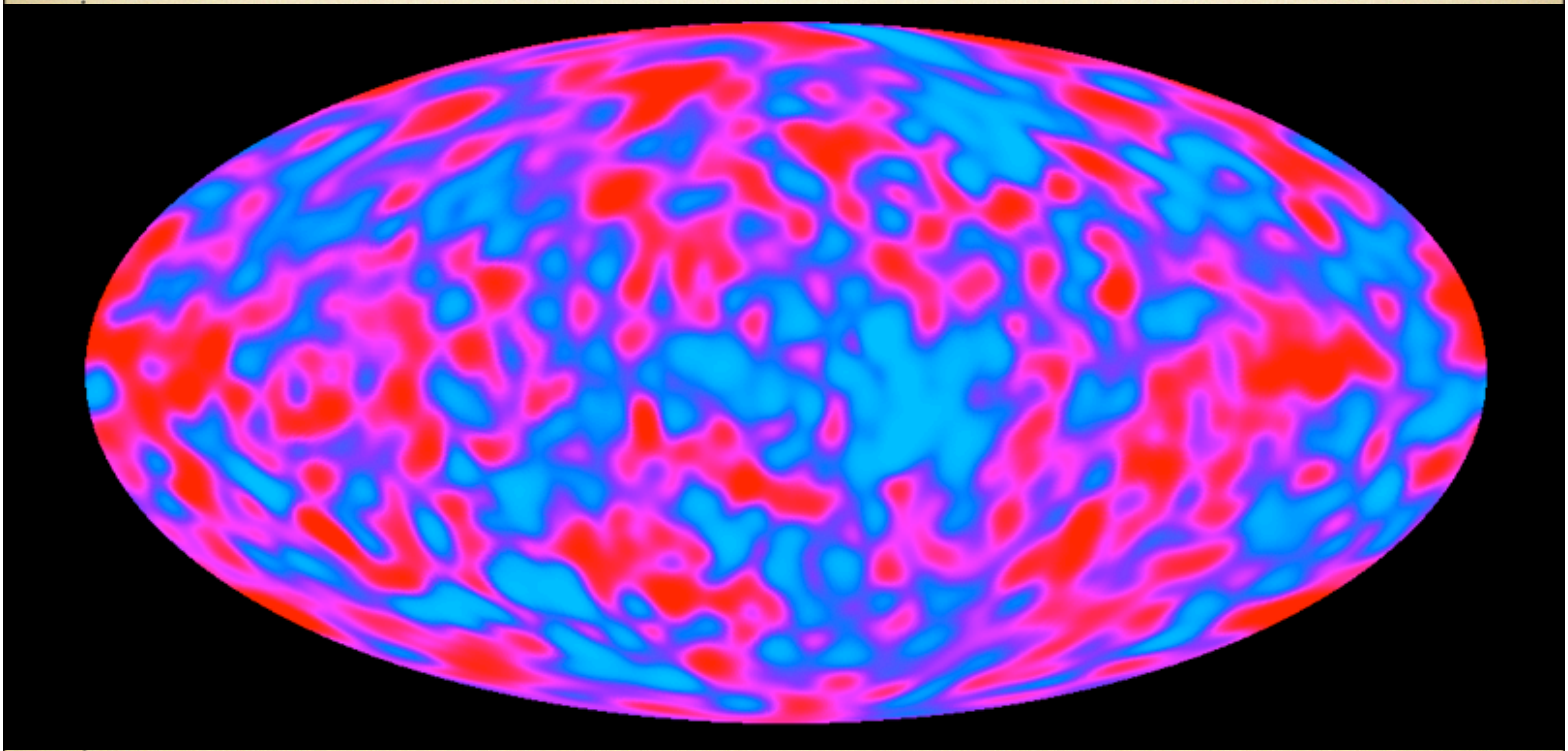
1992

COBE Data with Galactic Foreground



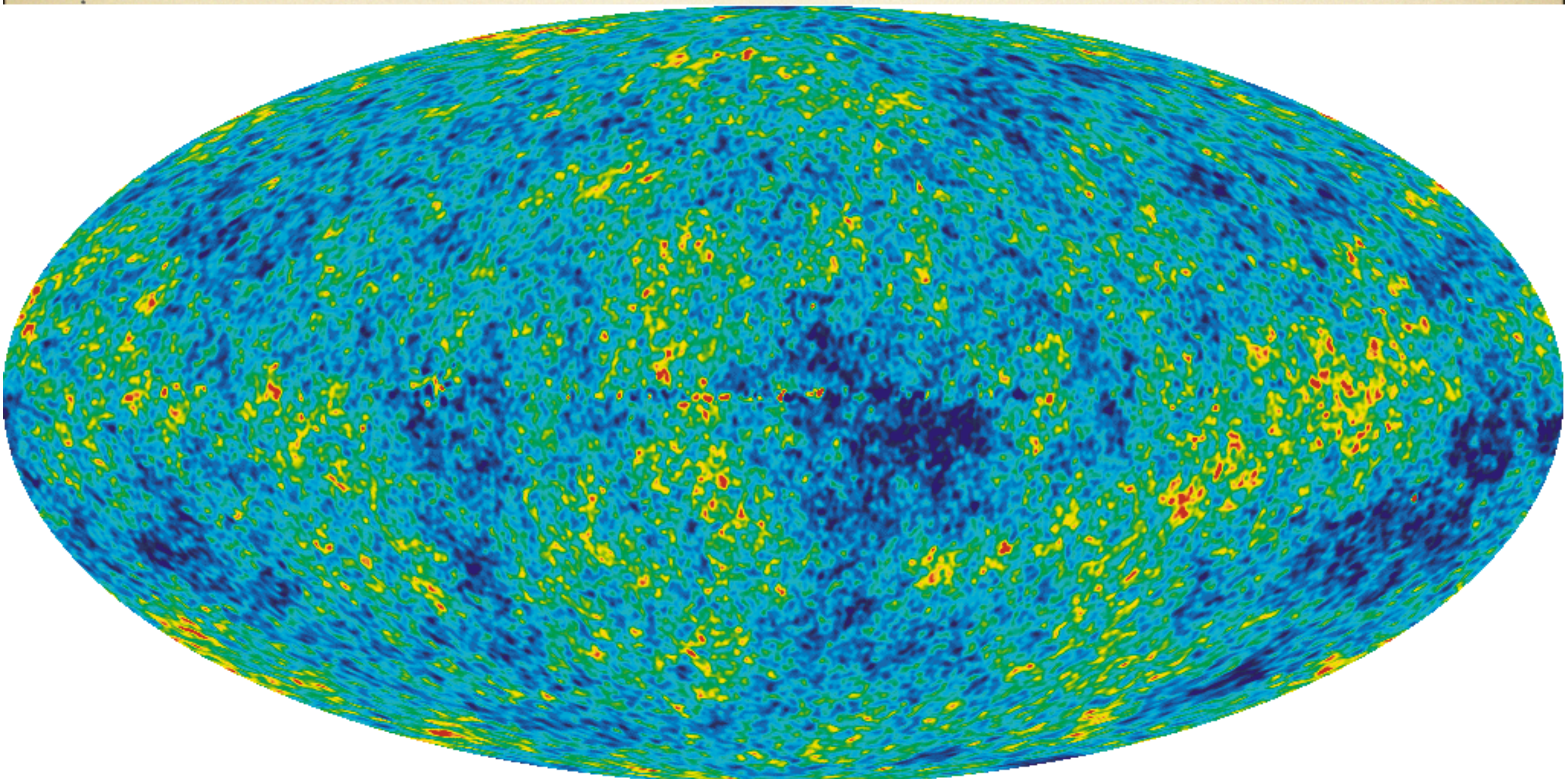
1992

Final COBE Data



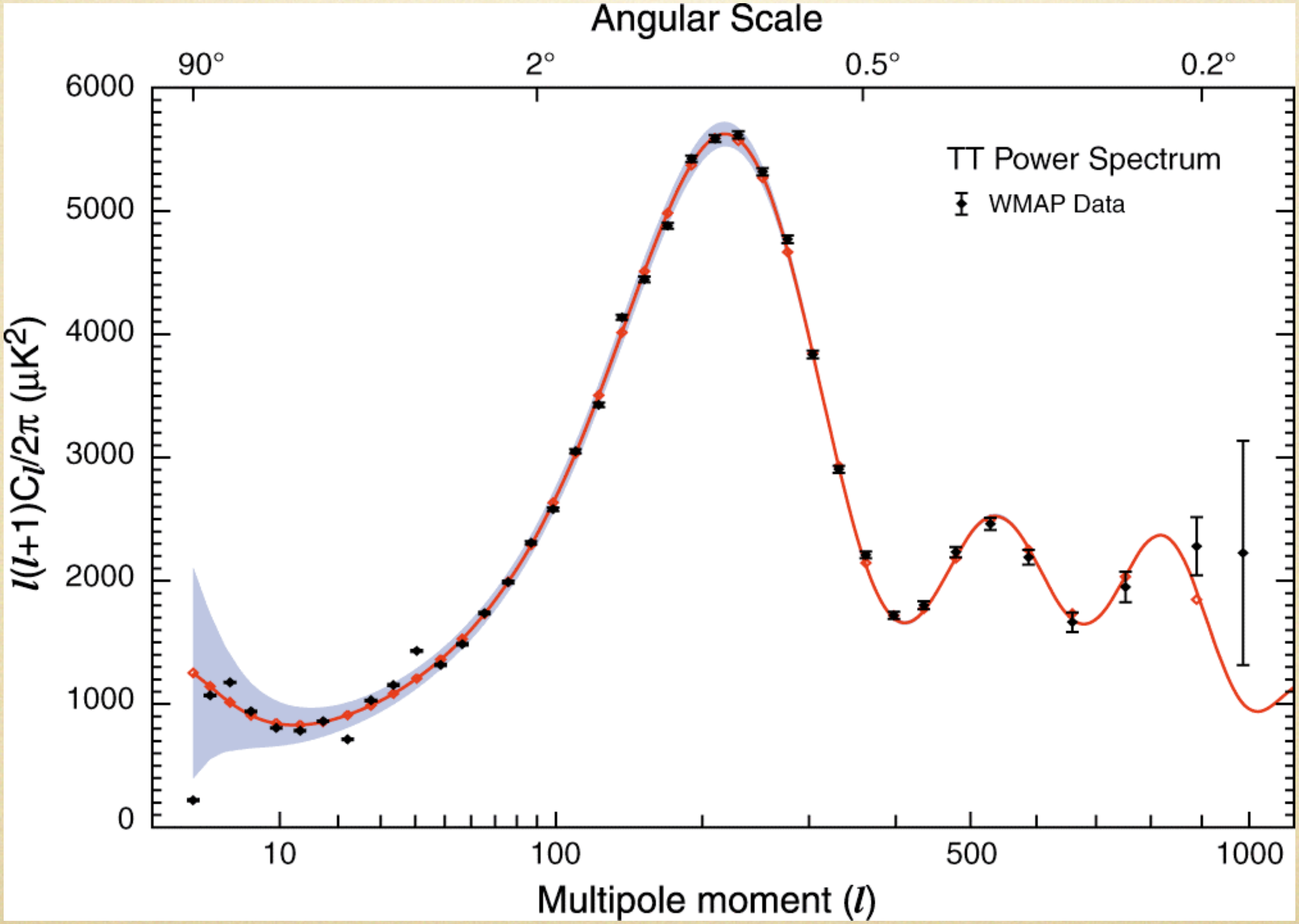
1992

WMAP Data

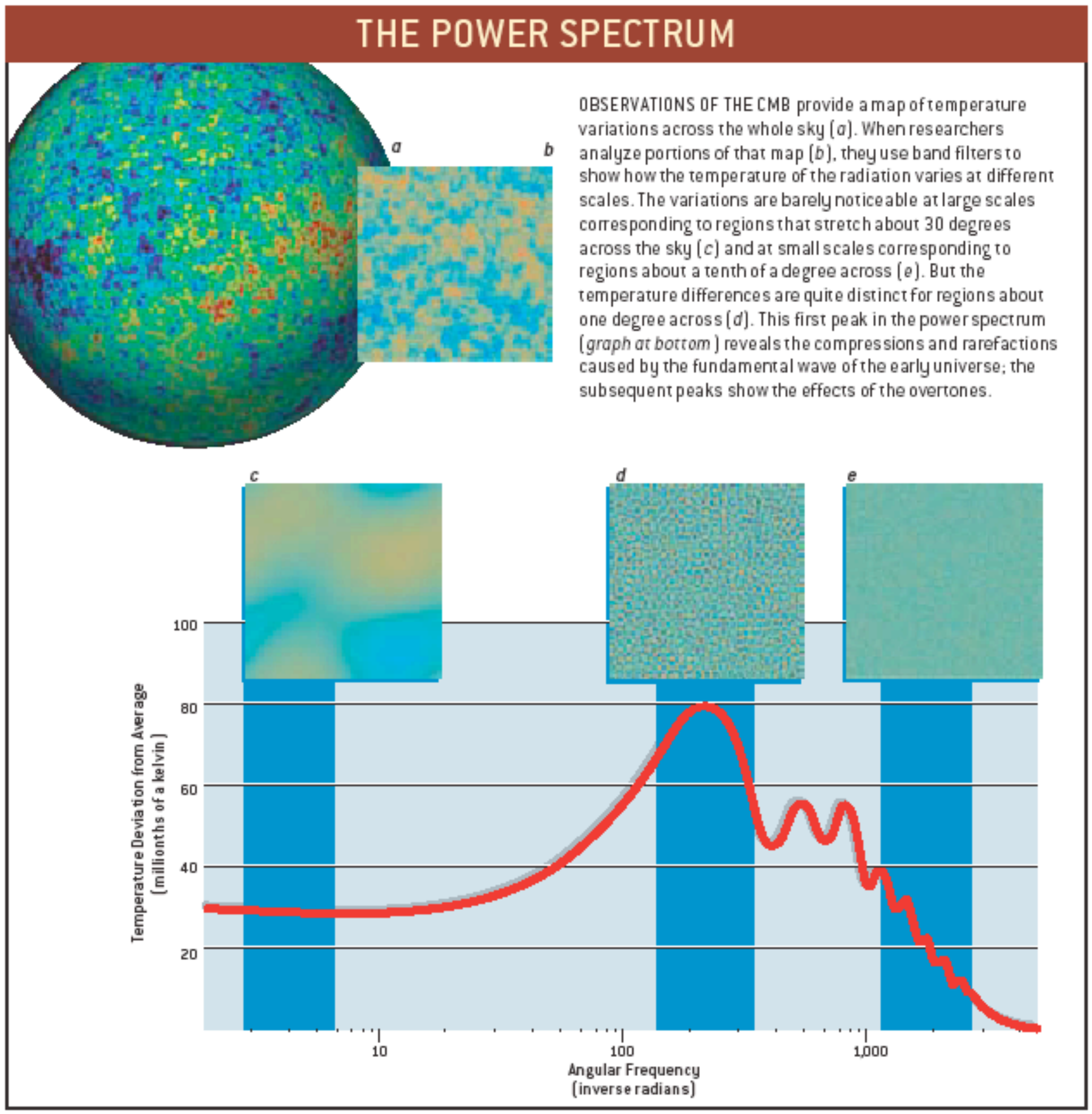


2000

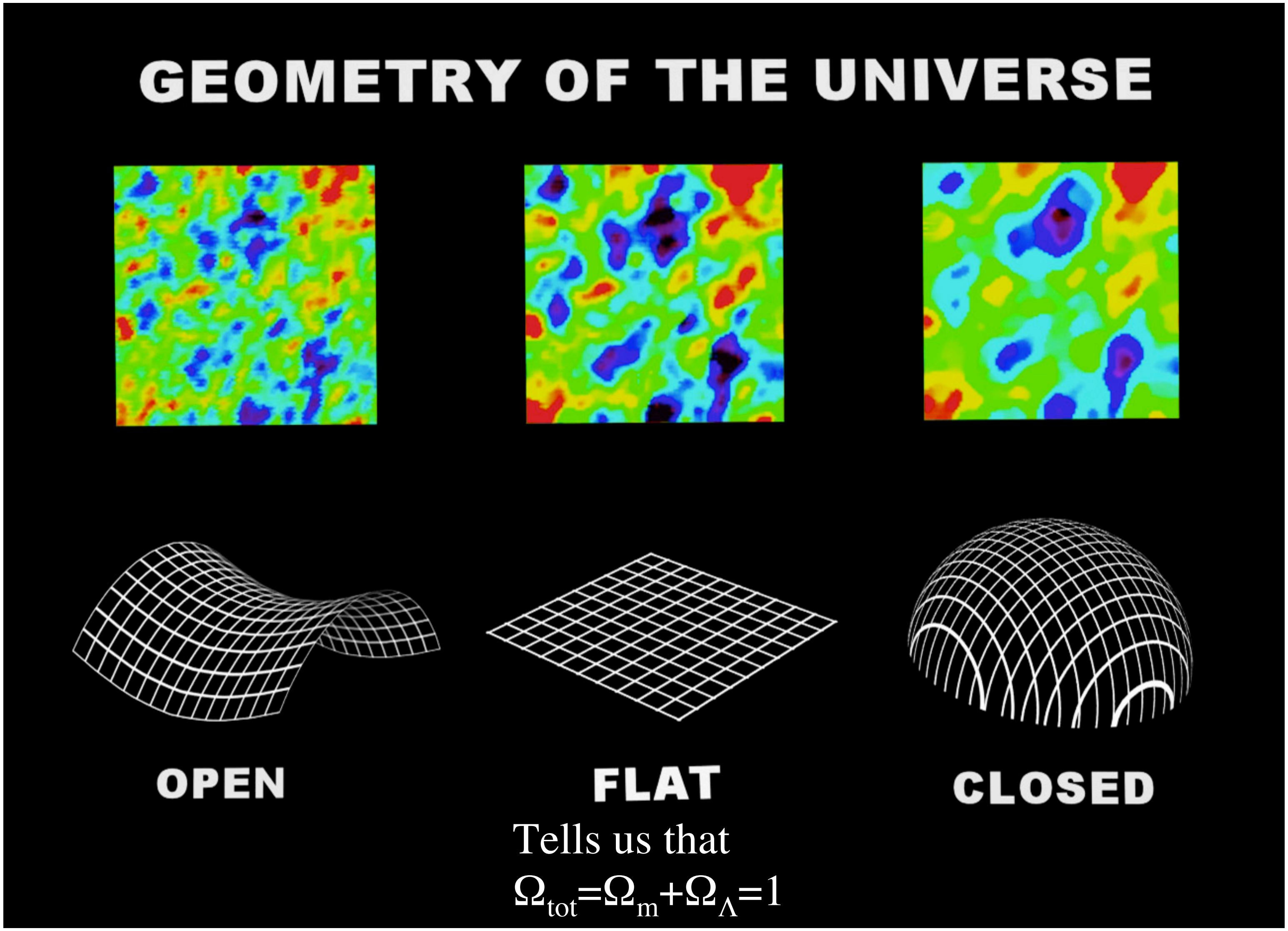
Power Spectrum



A Characteristic Scale in the CMB



A Characteristic Scale in the CMB



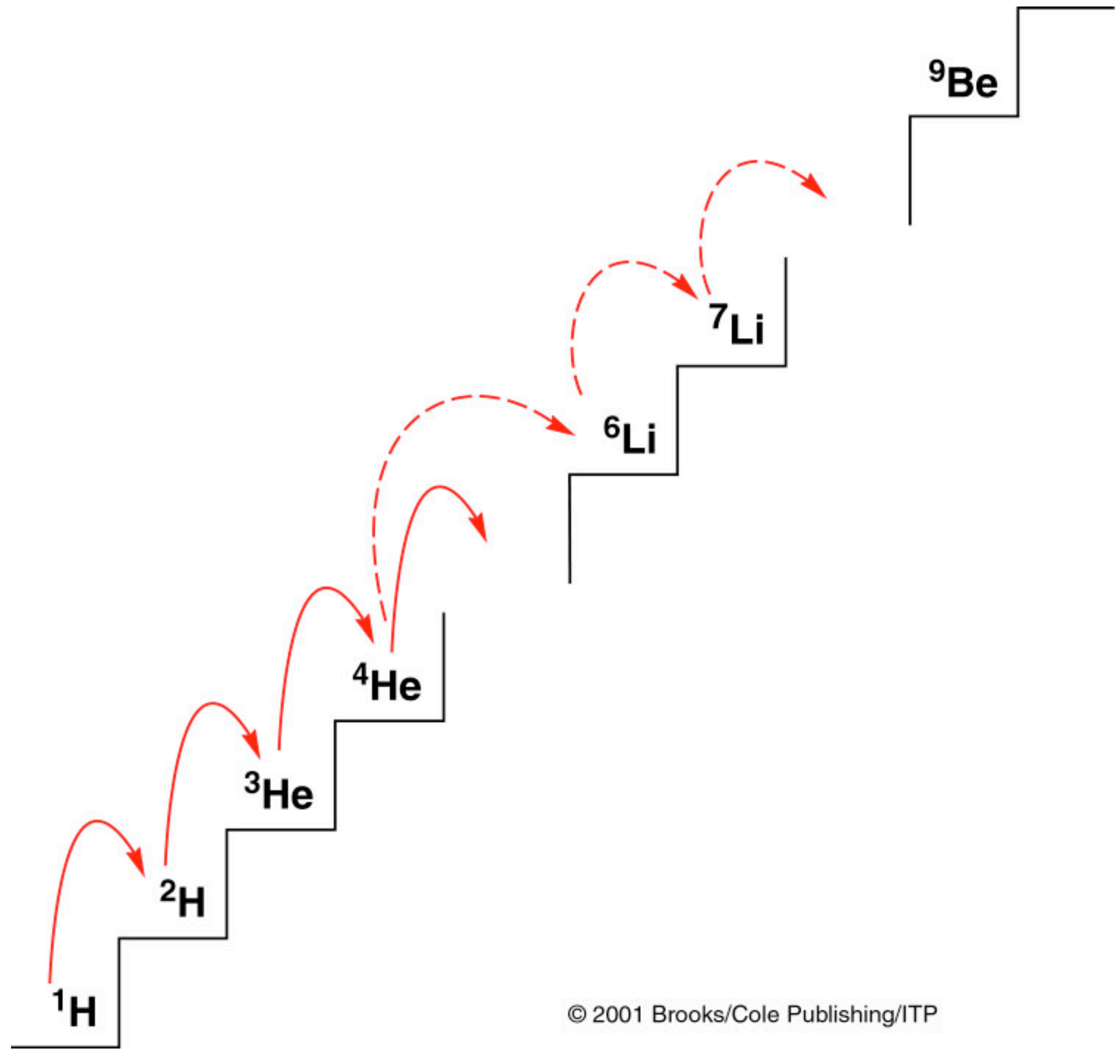
Important Epochs:
Synthesis of deuterium & helium

III. Age = 2 minutes

- Temperature = 10^9 K
  - Now cool enough for deuterium to survive
    - p + p → ^2H (deuterium)
    - ^2H + p → ^3He
  - Universe gets cooler & less dense, so no heavier elements formed

Synthesis of the Elements

- No stable nuclei with atomic weights of 5 or 8
  - ★Barrier to formation of heavier elements in Big Bang



- The Universe is expanding
- Therefore, it had a beginning in the *Big Bang*

Evidence for the Big Bang:

- Darkness of night sky
- Hubble's Law
- Structure of Universe
- 2.7 K blackbody CMB
- Quasars, galaxies, etc. different in past (lookback)
- Light element abundances (^{2}H, ^{3}He, ^{4}He, ^{7}Li)

Some things not explained by *standard* Big Bang Model

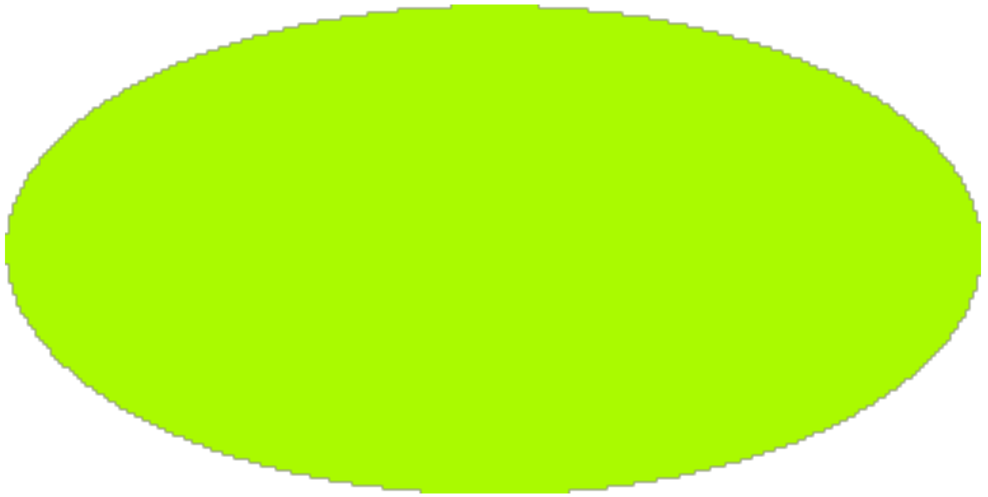
- What happened in earliest 10^{-30} second?
  - ✶How and why did expansion start?

Some things not explained by *standard* Big Bang Model

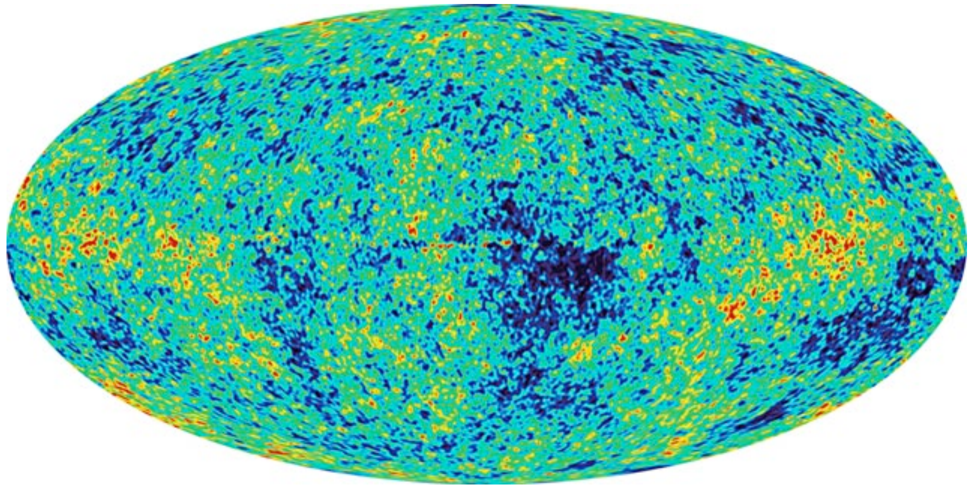
- Why does the universe look nearly the same in all directions? **Horizon Problem**

Horizon problem: smoothness of CMB

CMB is very smooth, smooth to better than a part in 1000



High-contrast view of CMB – fluctuations at level of one part in 30 million

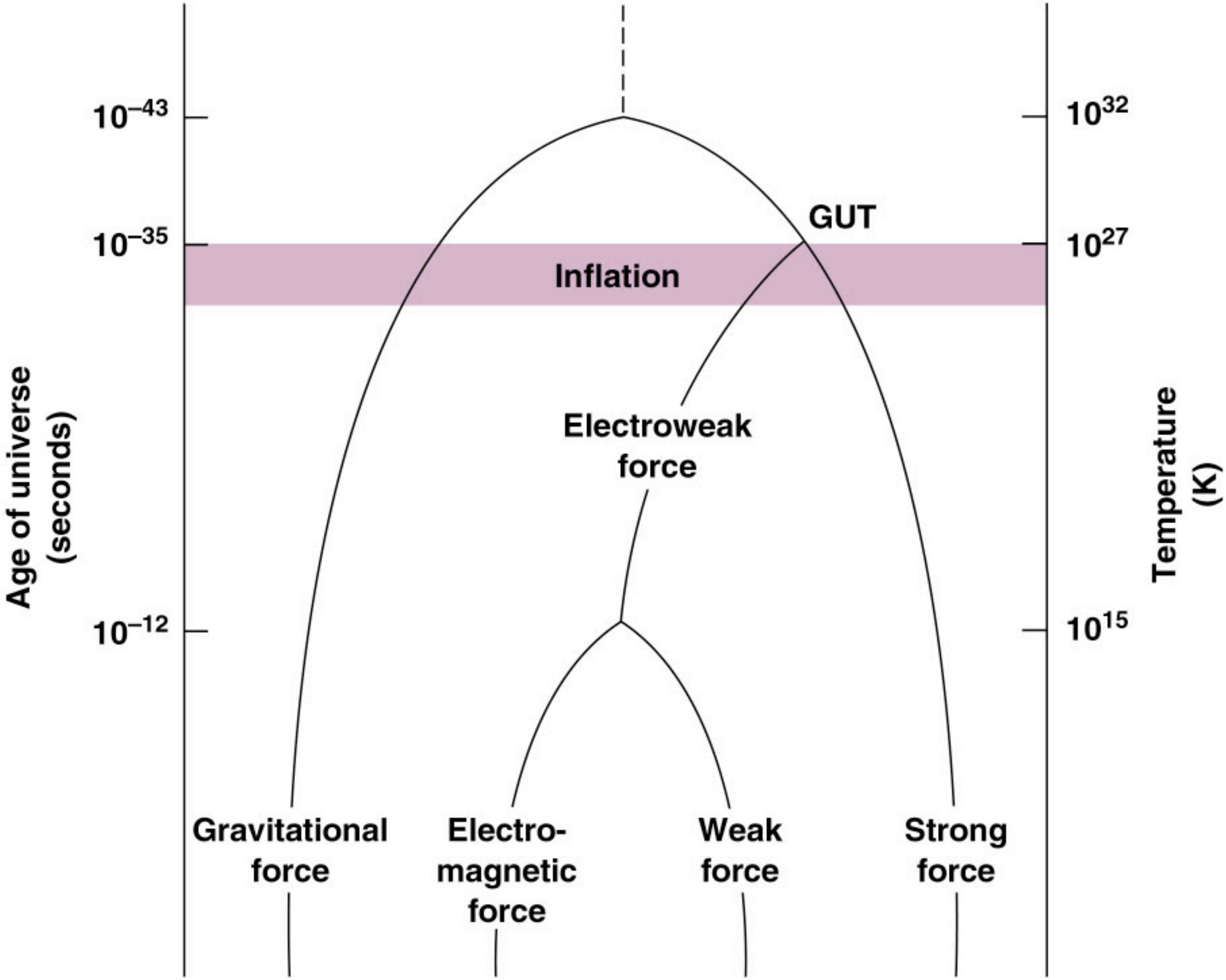


Some things not explained by *standard* Big Bang Model

- Why is the universe so nearly flat? (Why is density so close to critical?) **Flatness Problem**
  - ✶Even a very slight (as small as a part in 10^{49}) deviation from flatness in initial stages of Big Bang would have been magnified by expansion into a very open or very closed universe
  - ✶Yet today's curvature is so small it's hard to measure
  - ✶$\Omega_m = 0.3$ is very close to one

Rescue? Inflationary Universe

- In early Universe (at high temperatures), the 4 forces of nature were indistinguishable
  - ✶Strong, Weak, Gravitational, Electromagnetic
- As Universe cooled, forces split, releasing energy
  - ✶This *might* drive tremendous expansion
- This is still *very speculative*



Age of universe (seconds)
10−43
10−35
10−12
Temperature (K)
10^32
10^27
10^15
GUT
Inflation
Electroweak force
Gravitational force
Electro-magnetic force
Weak force
Strong force

Inflationary Universe

- Electro-weak & strong forces split 10^{-35} seconds after Big Bang)
  - ✶Universe then expanded by > 10^{20} in 10^{-32} sec

    BIG

    - Prior to inflation, all the *observable* universe fit in a volume the size of an atom
    - After inflation, *observable* universe expanded to the size of a cherry pit

Problems Solved by Inflation

- Flatness Problem
  - ✶ Because curvature becomes insignificant when anything is inflated by factor of 10^{20}
- Horizon Problem
  - ✶ Because prior to inflation, the entire observable universe was causally connected (i.e. light could cross it in the age of the universe)
    - So pressure forces would make it smooth
- Inflation is an *extension* of the standard Big Bang model

Can we understand unification of forces of nature?

- perhaps the answer lies in string theory