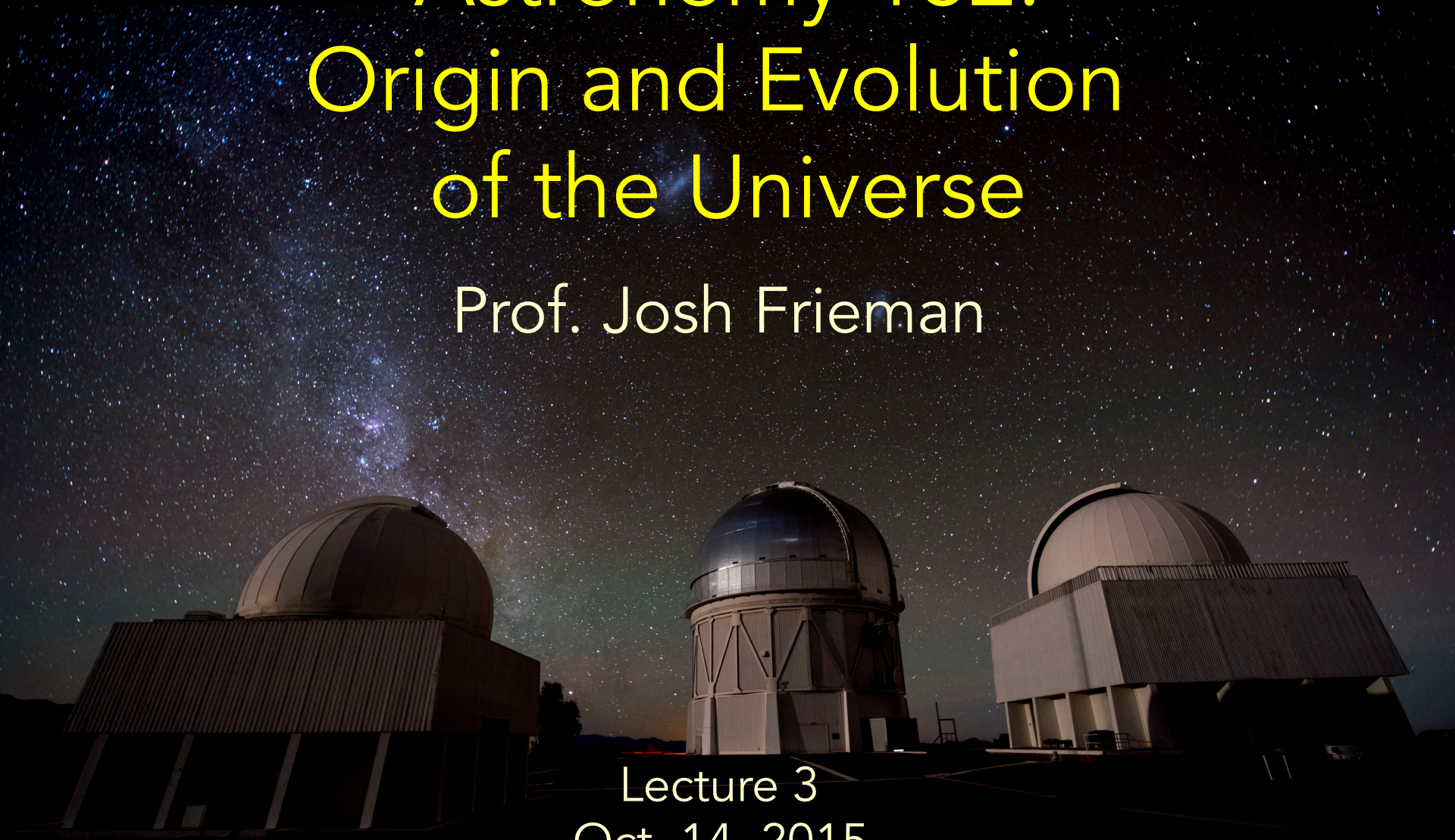
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 3
Oct. 14, 2015

Today

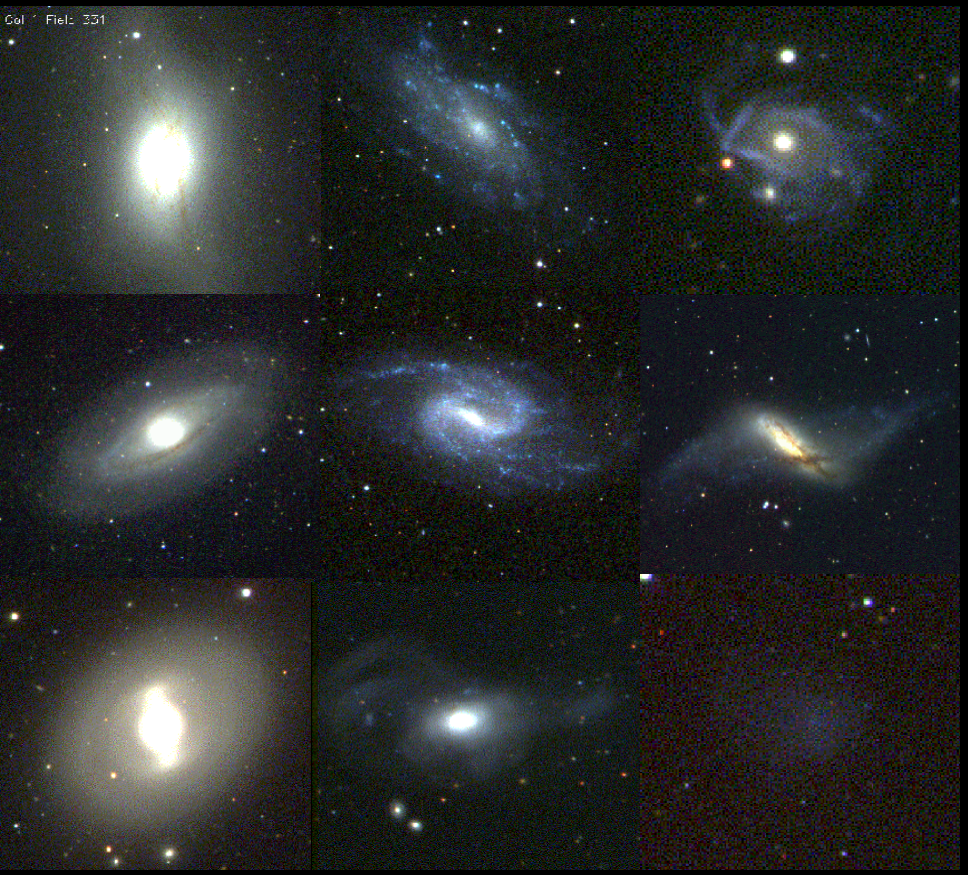
- Expanding Universe and the Cosmological Principle
- Olbers' Paradox and its Resolution
- The Big Bang
- Alternative Cosmologies?

Assignment

- This week: read Hawley and Holcomb, Chapters 3 and 10. A small part of Chap. 10 will seem opaque, since it assumes Relativity, which we have yet to cover—don't worry about that.

- Assignment for next Wed., Oct. 21: Hawley and Holcomb Chapter 10: write ~3 page essay plus ~1 page of questions

Galaxies



- Hubble demonstrated that many diffuse nebulae are extragalactic—far outside our Milky Way galaxy. These are external galaxies.
- He classified the morphologies (shapes/ appearances) of galaxies: spirals, ellipticals, lenticulars.

Hubble's Law

Based on their spectra, the light from almost all galaxies is shifted to the red. Light from those further away is more redshifted. Galaxies are receding from us, with:

speed (redshift) $\propto$ distance

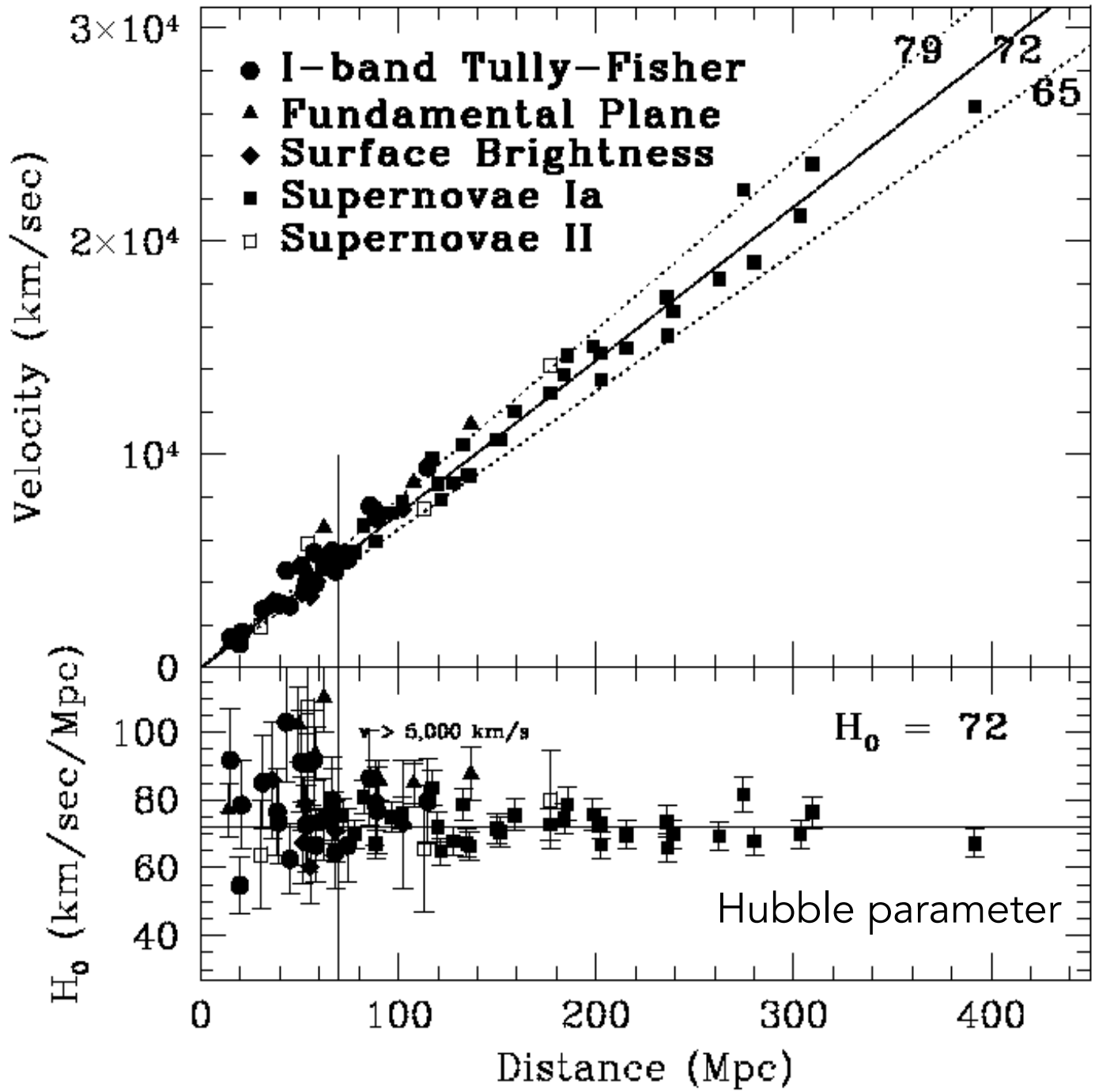
$$v=H_0 d$$

A galaxy 100 Million light years away is receding from us at 2000 miles per second. Hubble parameter: H_0=70 km/sec/Mpc

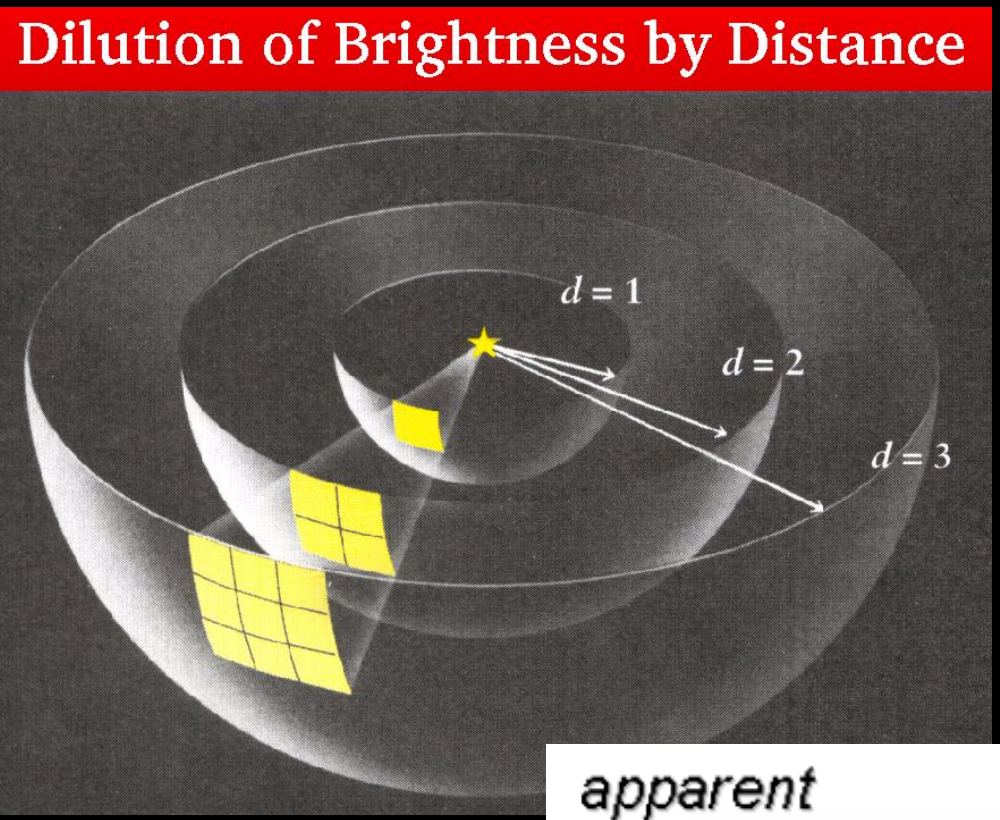
Modern Hubble Diagram

Hubble Space Telescope Key Project

Freedman etal



Measure Distances with Standard Candles



- Astronomical sources of either known intrinsic luminosity L or else known to have all the same intrinsic luminosity.
- Typically calibrate L with nearby sources that overlap: distance ladder.

apparent brightness

luminosity

distance

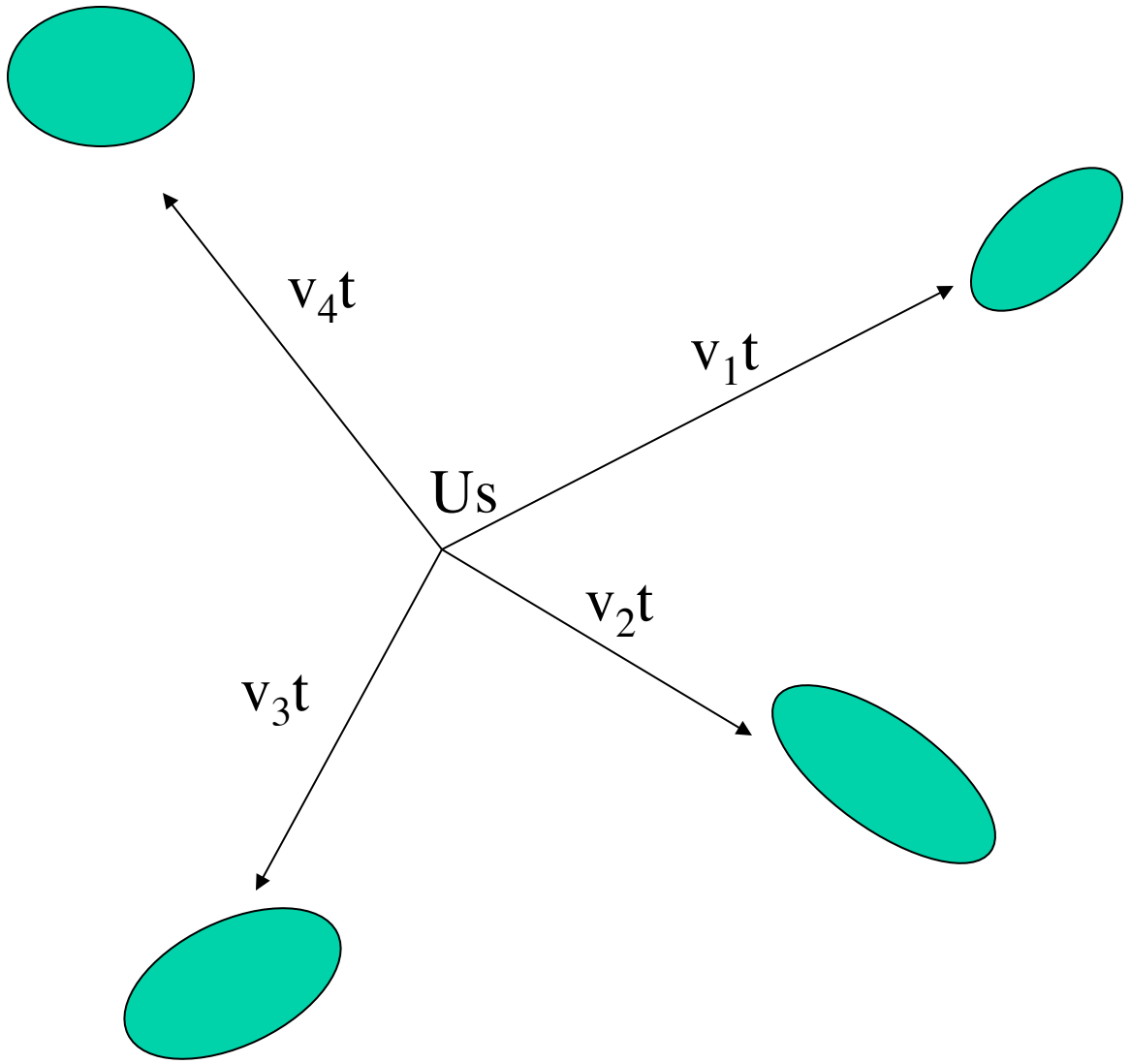
$$B = \frac{L}{4\pi d^2} \Rightarrow d_L = \sqrt{\frac{L}{4\pi B}}$$

Interpretations of Hubble's Law

- Naïve (pre-Copernican) interpretation:
  - We see galaxies distributed around us and receding from us with speeds $v=H_0 d$ in all directions. Hence, we live at the Center of the Universe. Tracing their motions backward, we infer an explosion occurred at our location a time t_H ago:

  - A galaxy moving at (assumed) constant velocity v has travelled a distance $d=vt$ in time t, i.e., $v=d/t$. This agrees with Hubble's law $v=H_0 d$, if the age of the Universe (since explosion) is

$$t_H = 1/H_0$$ (known as the Hubble time)


v_4t
v_1t
Us
v_2t
v_3t

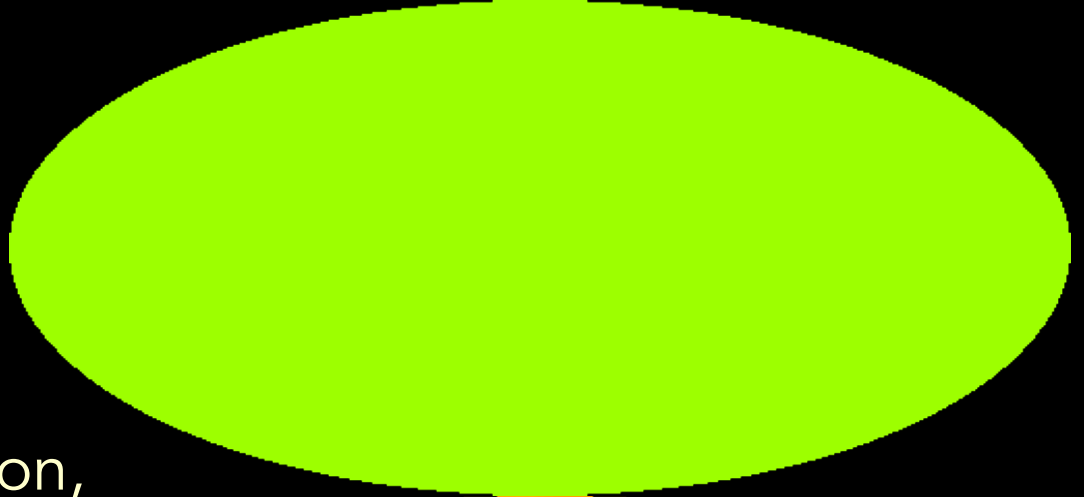
The Cosmological Principle

- On large scales, the Universe appears *isotropic* around us: looks *on average* the same in every direction on the sky.
  - Temperature of the Universe (as measured from the Cosmic Microwave Background) is about 2.7 degrees, within +/- 10^{-5} deg, in all directions
- Let's assume we are not privileged observers: our Galaxy looks much like the others.
- Then the Universe should appear isotropic to *all* observers. In that case, one can show it must be *homogeneous:* has the same properties *on average* at every location. In particular, it has no center.

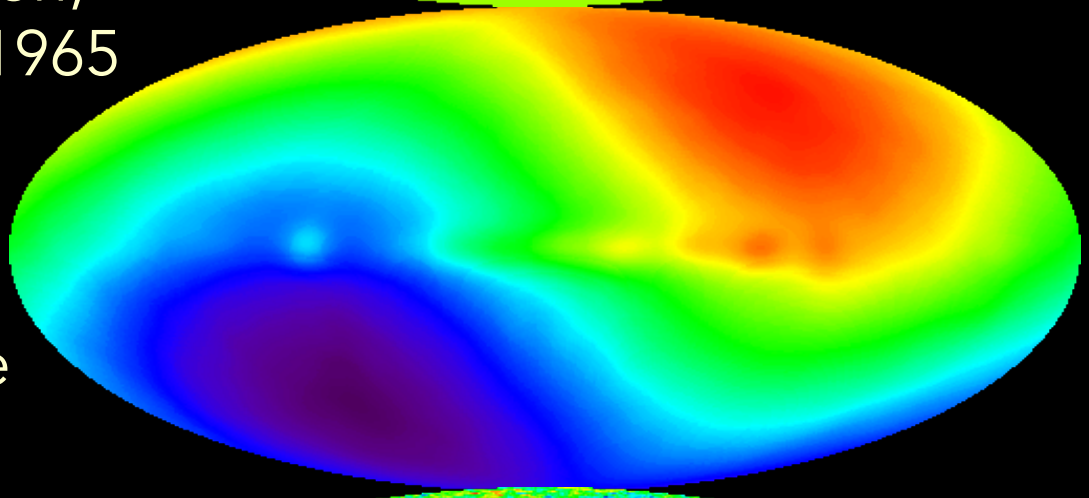
The Cosmic Microwave Background: the Universe is filled with thermal radiation, discovered in 1965

Map of the Temperature of the Universe

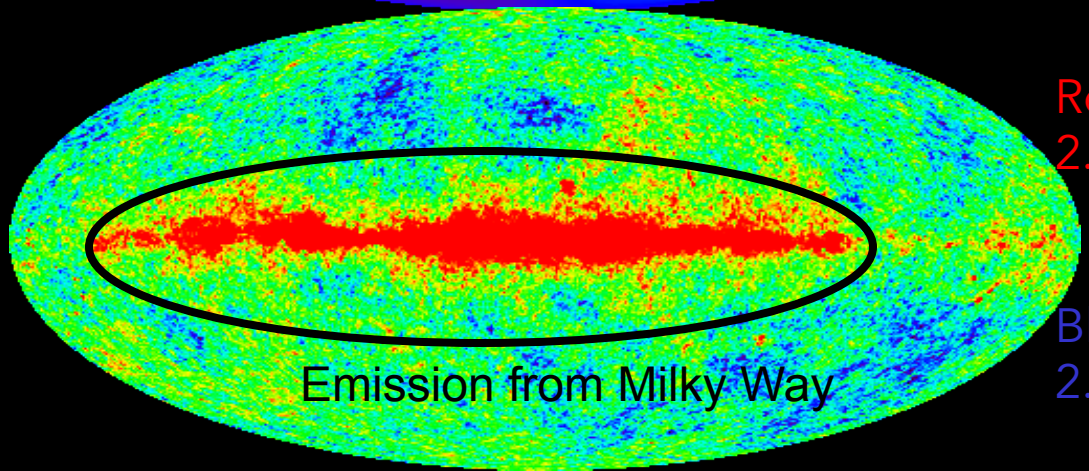
The Universe is (nearly) isotropic around us (the same in all directions)



T = 2.7 degrees above absolute zero



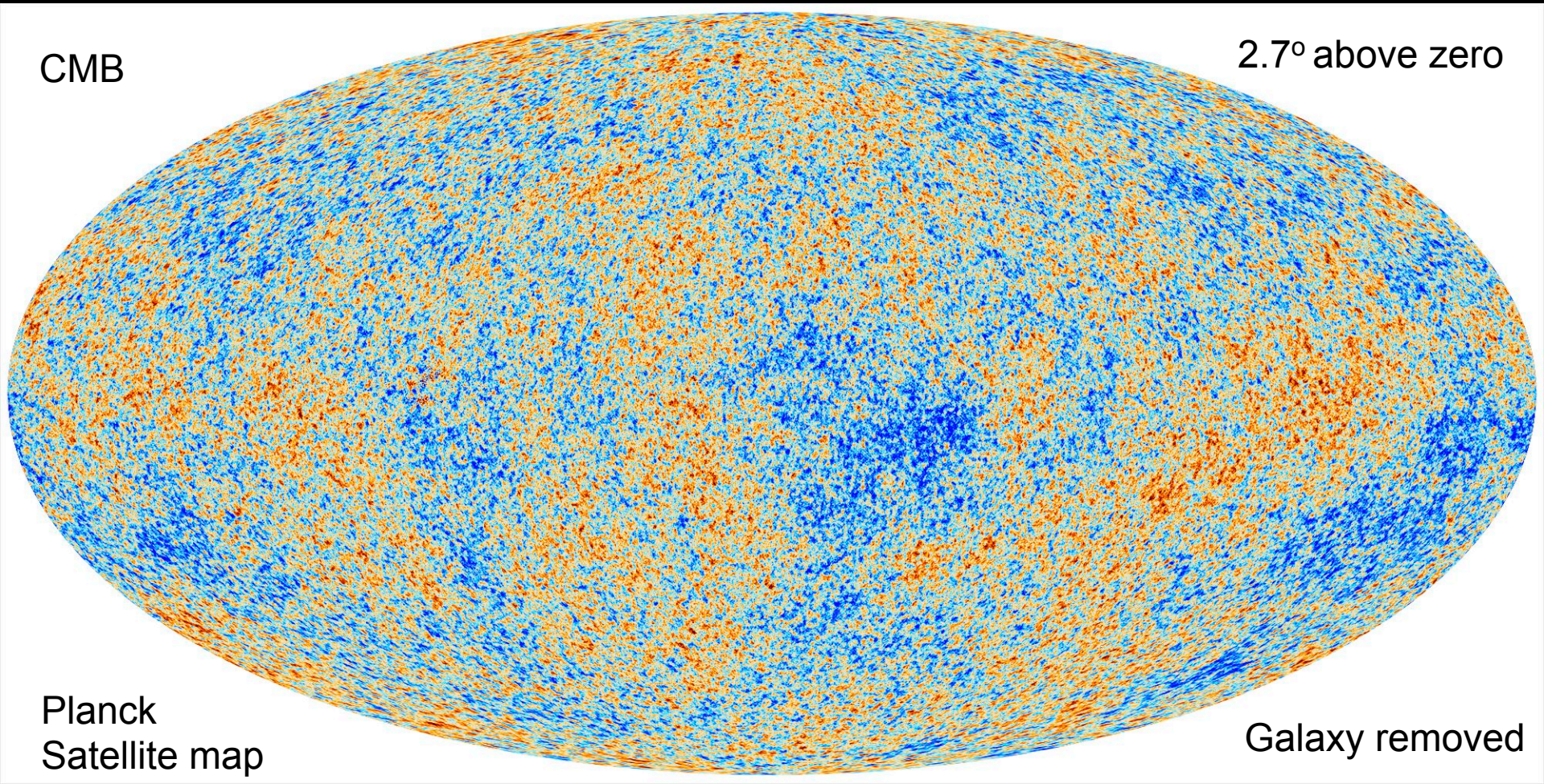
Red: 2.7+0.001
Blue:2.7-0.001



Red:
2.7+0.00001 deg

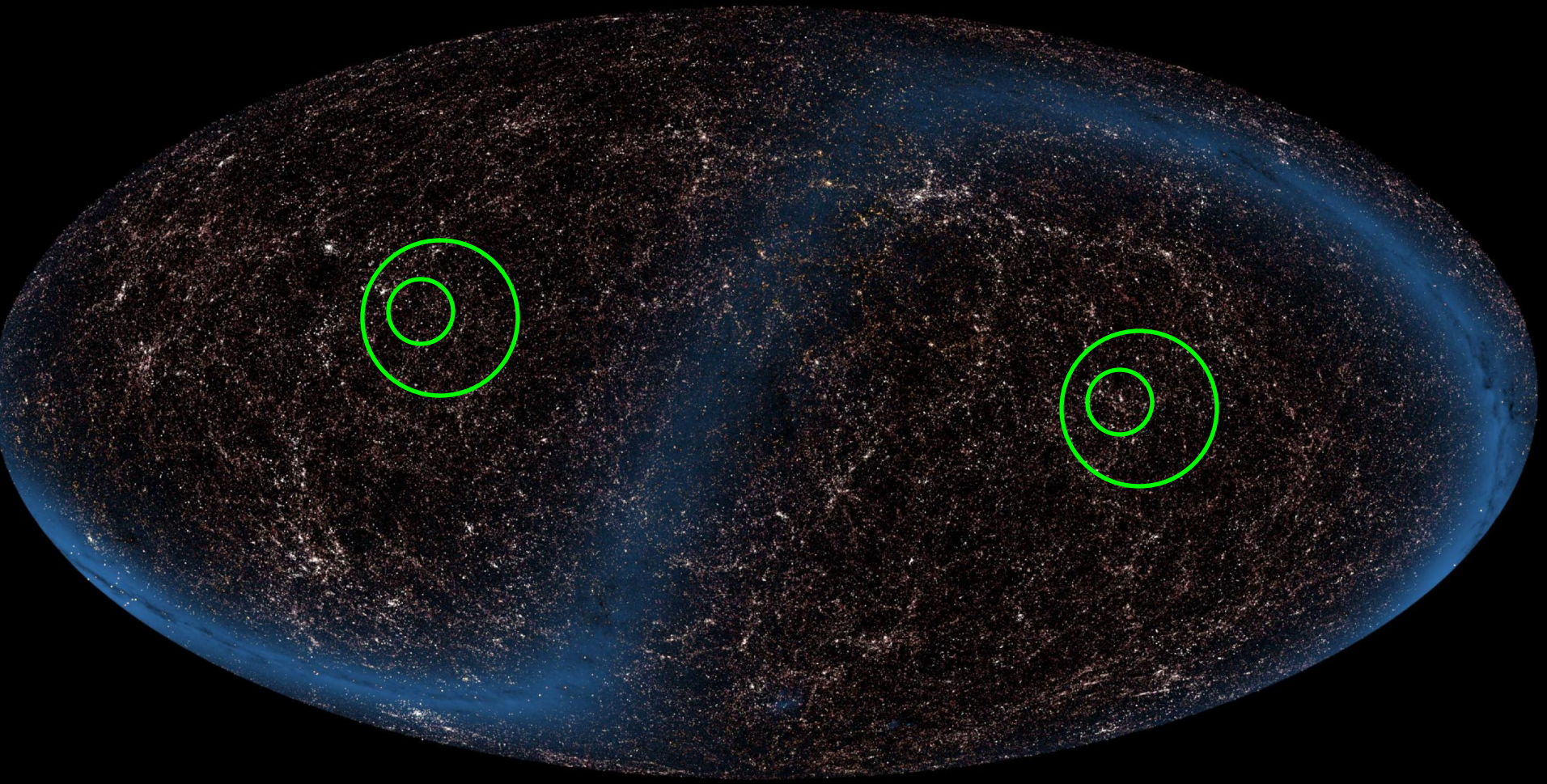
Blue:
2.7-0.00001 deg

Cosmic Microwave Background Radiation



Snapshot of the Universe when it was only 400,000 years old
Temperature varies by only 0.00001 deg across the sky.

Large-scale Map of Galaxies Today

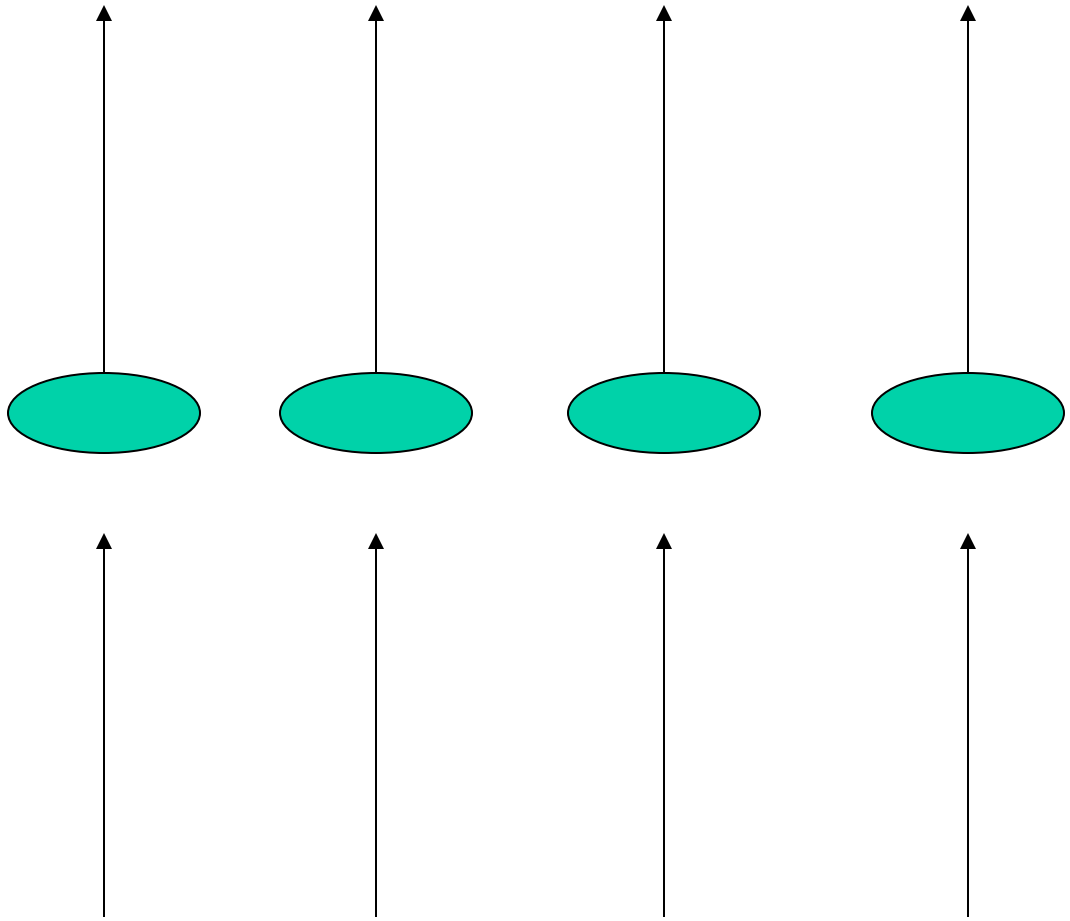


2MASS Infrared Sky Survey: Universe much lumpier now, but it looks homogenous (≠identical) on large scales.

Homogeneity & Isotropy

- Isotropy: on large scales, the Universe appears statistically nearly the same in every direction on the sky.
  - Anisotropies in the Temperature of the Universe are very small: $\Delta T/T \sim 10^{-5}$.

- Homogeneity: on large scales, the spatial variations in the properties of the Universe are small.
  - The density of the Universe ρ, as inferred from the number of galaxies per unit volume, varies by only a small amount from location to location as the volume grows. For spheres of radius >>40M light-years, $\Delta\rho/\rho << 1$.



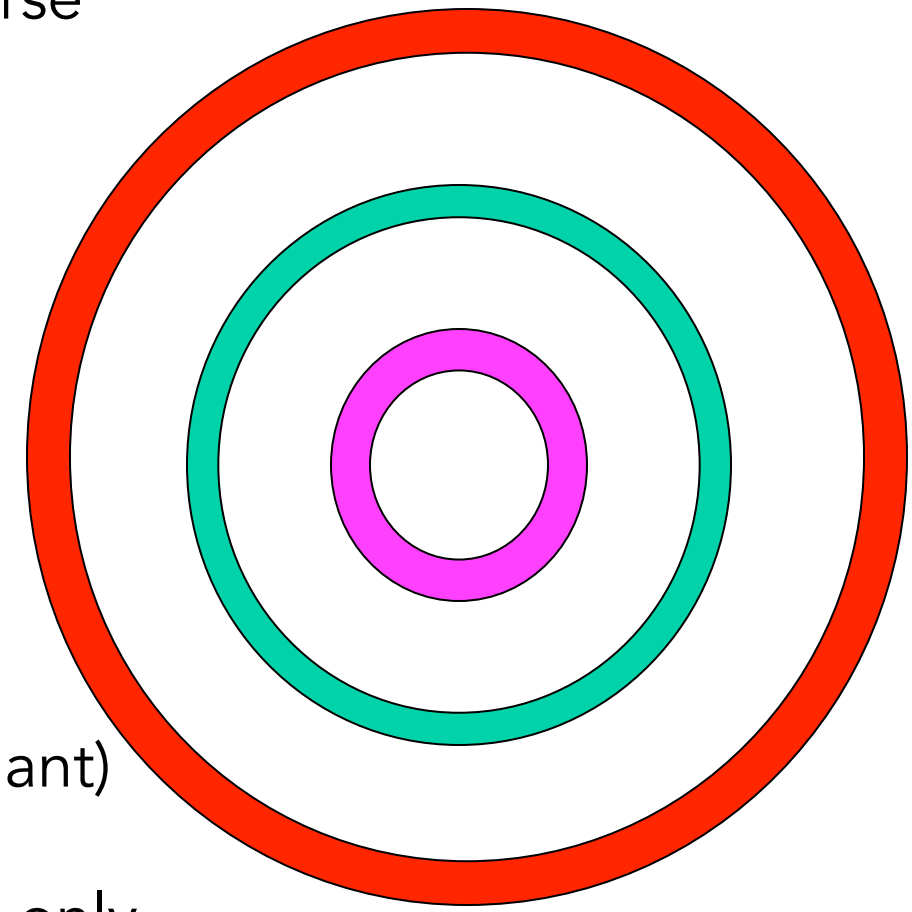
Homogeneous
but Anisotropic:

A `River' Universe

The system is translation-invariant (homogeneous, i.e.,
same density at each point)
but there exists a Preferred Direction (anisotropic: not invariant under rotations)

The `Ring' Universe

Isotropic
(rotation-
invariant)
but
Inhomogeneous
(density varies
with distance
from center: not
translation-invariant)



Isotropic around only
one observer: does not
obey Cosmological Principle

New Interpretation of Hubble Law

- Instead of us being at the Center, there is no Center: all (comoving) observers will measure the Hubble law, i.e., will see galaxies receding from them with speed proportional to distance.

- The Universe is Expanding.

Hubble Parameter and Expansion

- The Universe is Expanding.

- Distance between any 2 galaxies: $d(t)=d_0 a(t)$
- Cosmic scale factor $a(t)$ describes 'size' of the Universe at time t compared to its present size.
- Recession speed: $v=\Delta d/\Delta t=d_0(\Delta a/\Delta t)=(d/a)\ (\Delta a/\Delta t)$
- Agrees with Hubble law $v=Hd$ if $H=(1/a)\ (\Delta a/\Delta t)$
- Hubble parameter H is thus the expansion rate of the Universe: the fractional rate of change of the size of the Universe. H_0 is its current value.

Hubble Parameter and Expansion

- Hubble parameter: H_0=70 km/sec/Mpc
- Hubble time: t_H=1/H_0=14 billion years

- Hubble time reinterpreted not as time since explosion (though it happens to be very close to the age of the Universe) but as the time it currently takes for the Universe to about double in size (or for the distance between a pair of galaxies to double).

Expanding Universe

- How can every galaxy appear to be moving away from everyone else, instead of moving away from some galaxies and toward others?

- It only works if recession speed is linearly proportional to distance: $v \sim d$ (not, e.g., $v \sim d^2$)

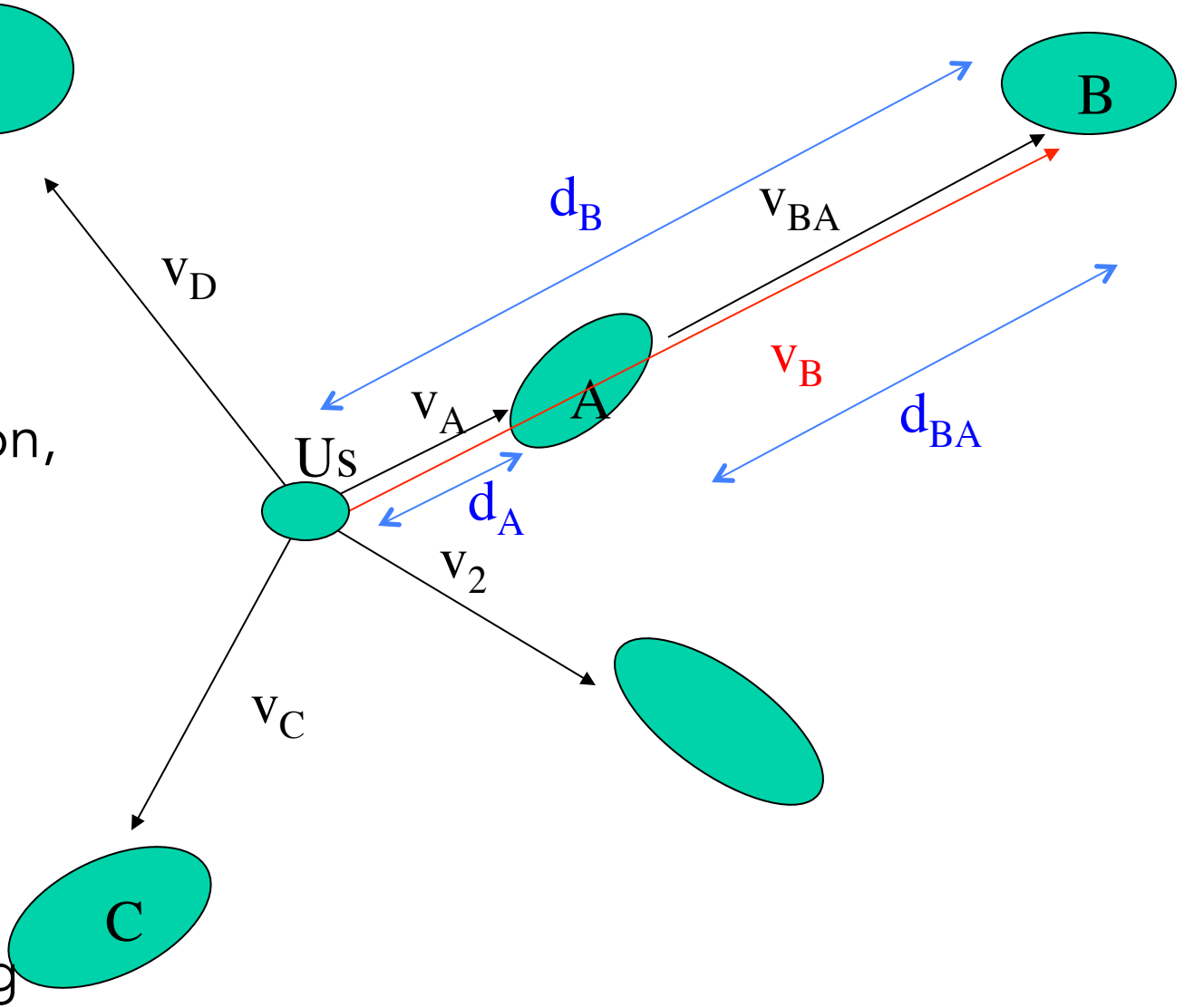
- The Expansion of the Universe preserves homogeneity and isotropy.

We observe Hubble law:

$v_B = Hd_B$
$v_A = Hd_A$

By vector addition,

$v_{BA} = v_B - v_A$
$= H(d_B - d_A)$
$= Hd_{BA}$



Observer A sees Galaxy B recede according to the Hubble Law as well: Hubble's Law is Universal

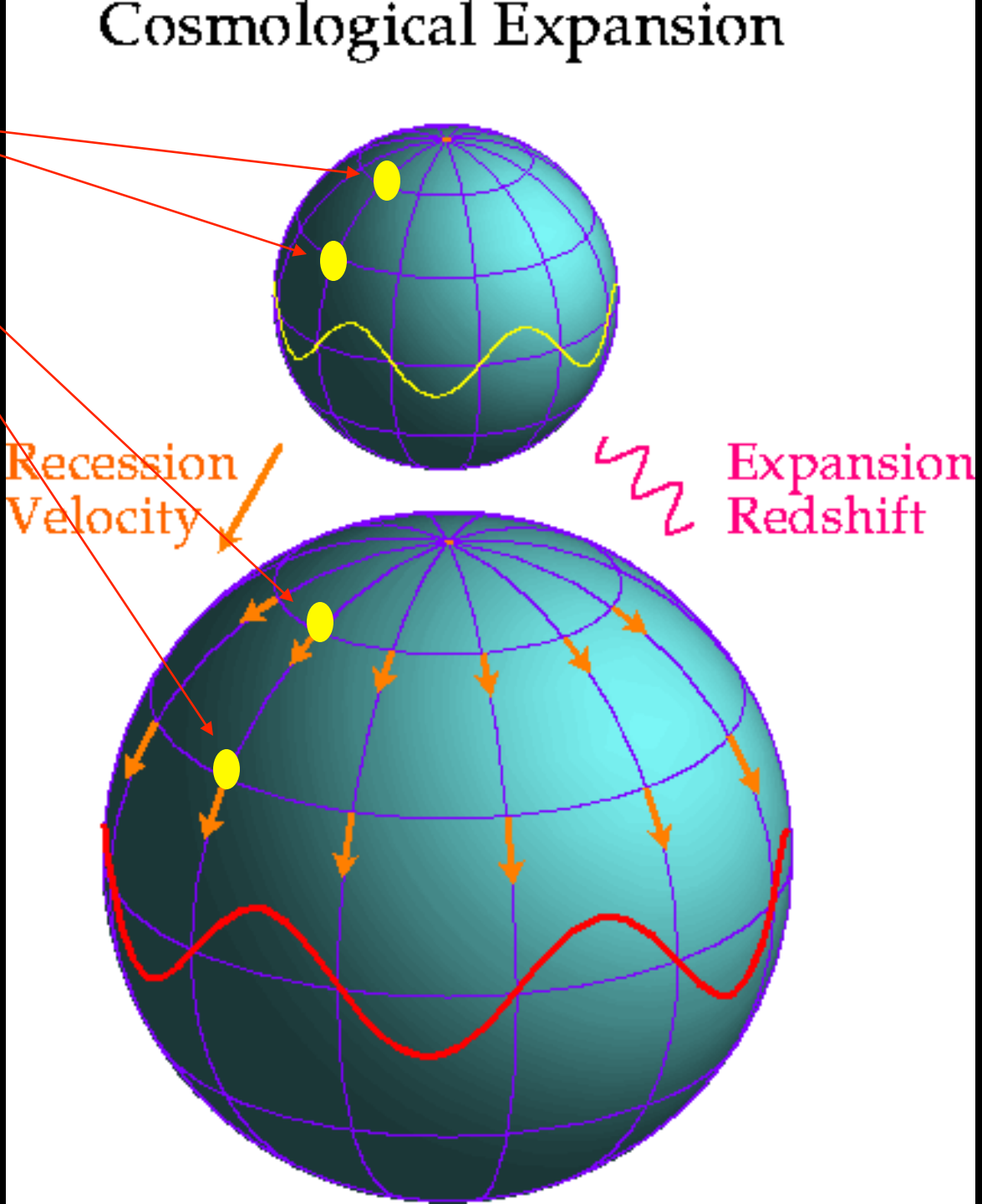
The Expanding Universe

No reason to assume we are at the Center: observers in all galaxies can see Hubble law

The distance *between* galaxies increases with time

A galaxy 100 Million light years away is moving away from us at 2000 miles per second.

Galaxies are not expanding: they are bound together by the gravity of dark matter.



On average, galaxies are at rest in these expanding (comoving) coordinates.

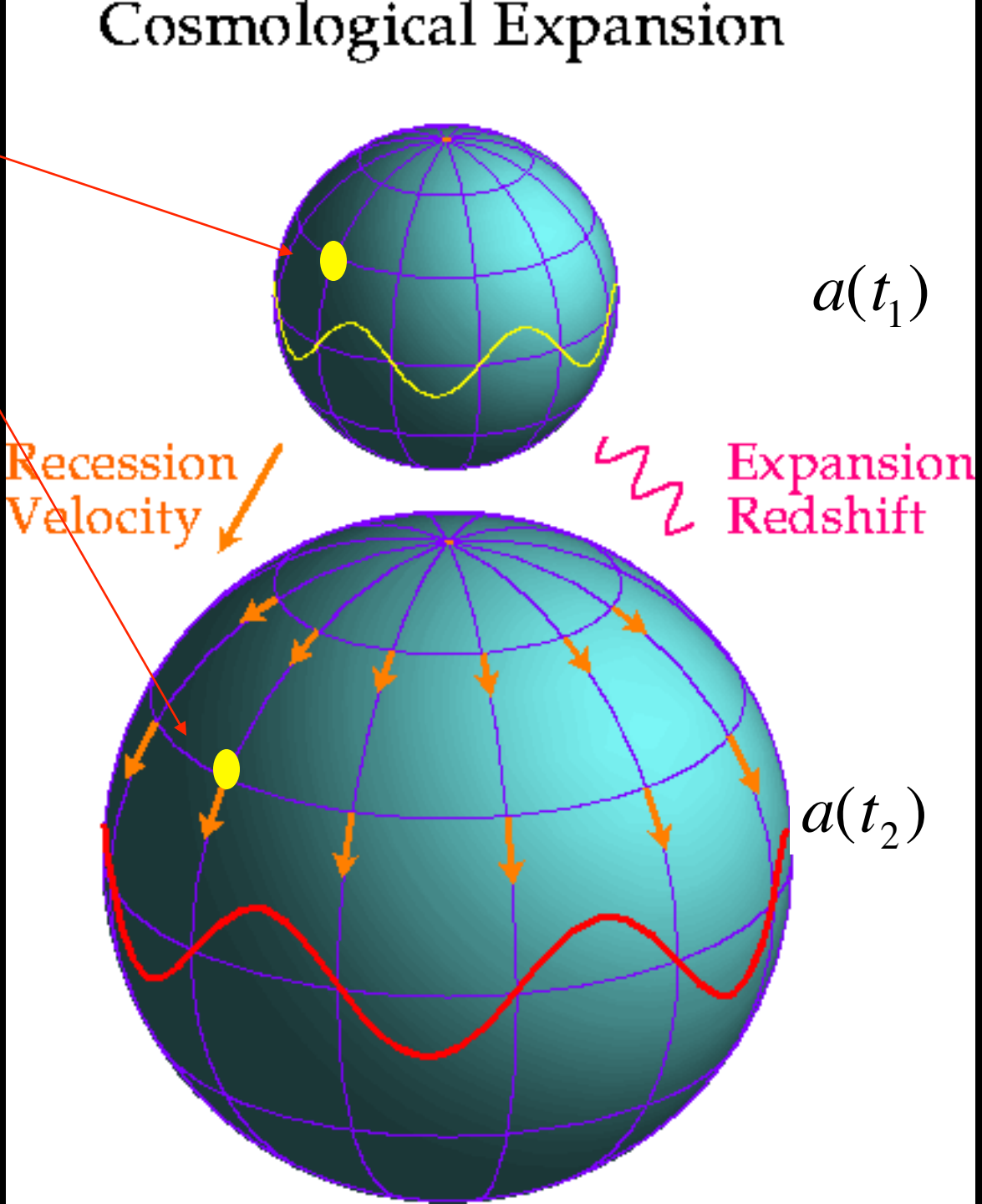
Wavelength of radiation scales with scale factor:

$$\lambda \sim a(t)$$

Redshift of light:

$$1 + z = \frac{\lambda(t_2)}{\lambda(t_1)} = \frac{a(t_2)}{a(t_1)}$$

emitted at t_1, observed at t_2



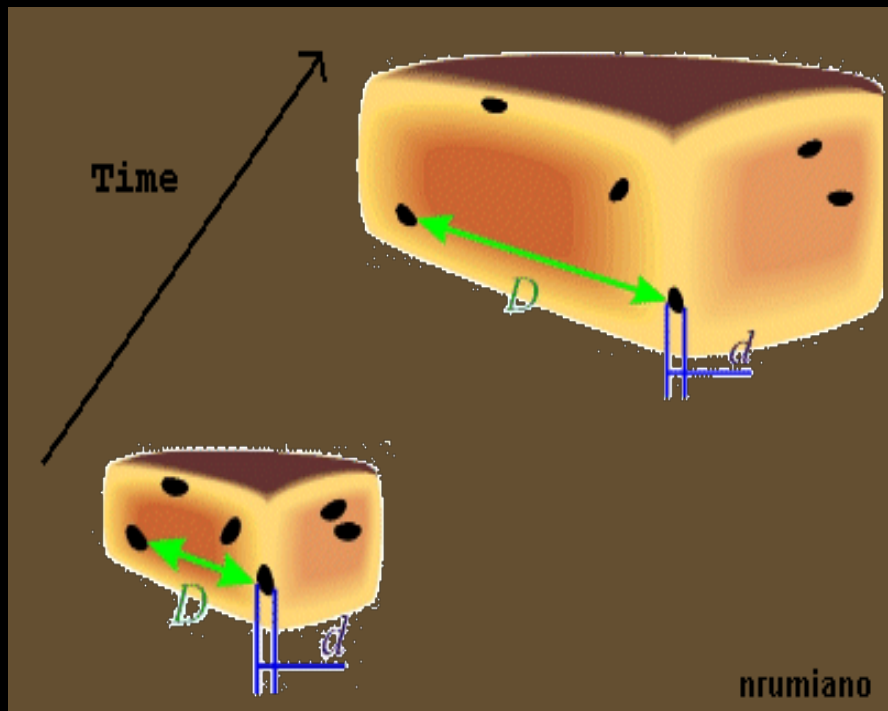
Expansion of the Universe

- The Universe has no center and no edge (that we can see): it looks the same everywhere.
- The expansion is happening everywhere: the Universe is not exploding into empty space.
- Expanding raisin bread offers a better analogy.

3D Model

- Think of the Universe as an infinite, yeast-filled raisin cake with some heat source. Each raisin represents a galaxy. As the cake expands due to the heat, the raisins recede away from each other, with a relative speed proportional to their distance from each other.

- Since the cake is infinite, it is not expanding into empty space: the raisin cake IS the Universe.



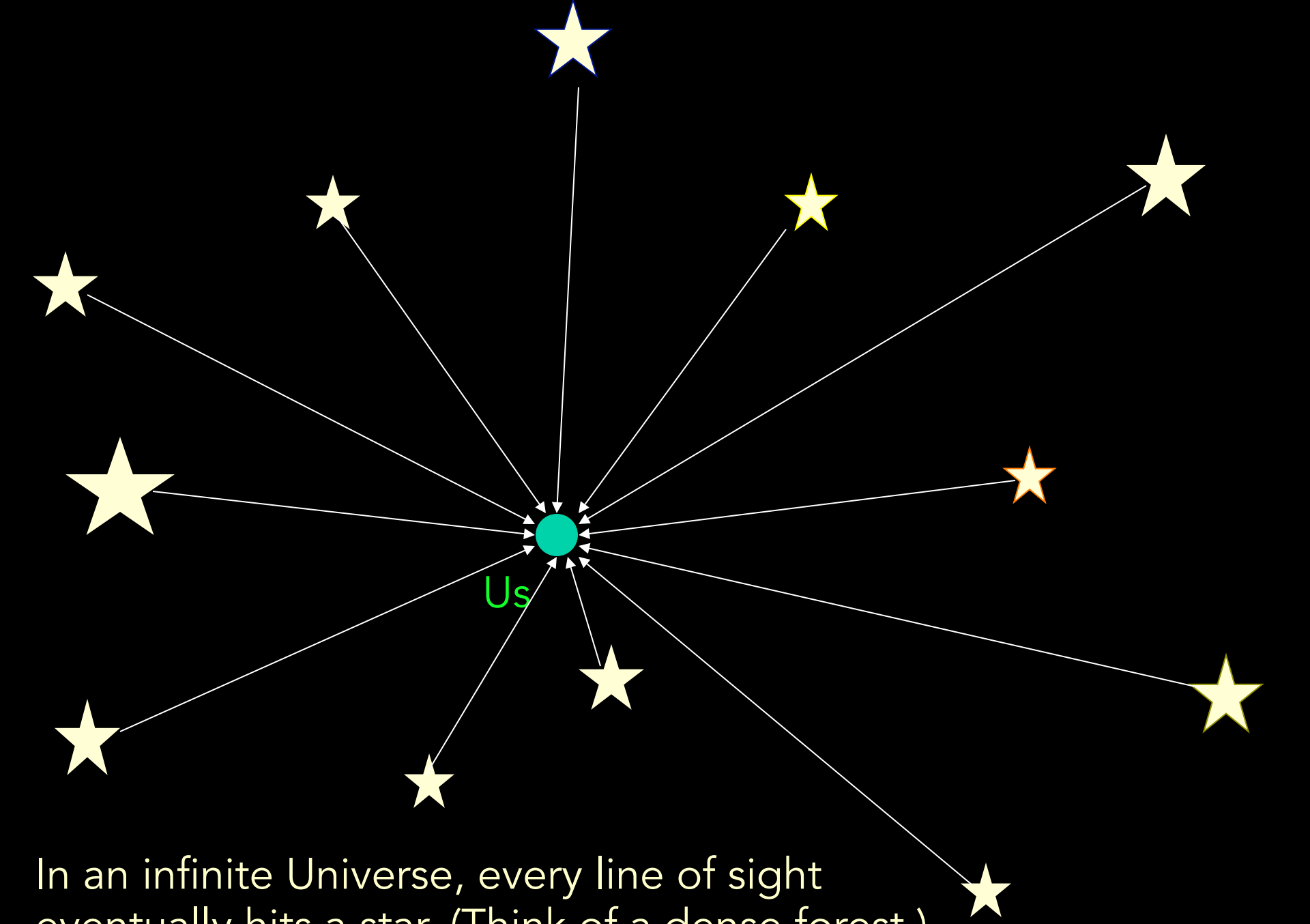
Olbers' Paradox

- Why is the night sky dark?

- Edgar Allan Poe (1848), following Kepler, Halley, Olbers (1823):

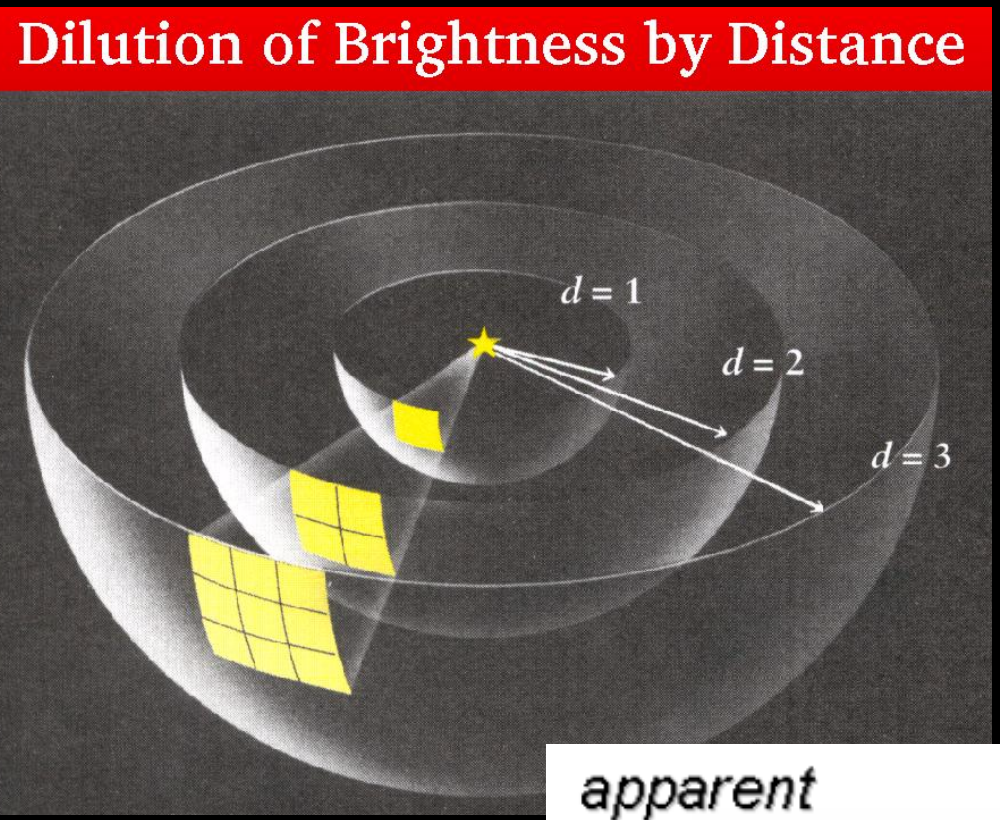
  "Were the succession of stars endless, then the background of the sky would present us a uniform luminosity."

- In an *infinite* universe, every line of sight should eventually intersect a star. Therefore, the night sky should appear in all directions as bright as a star, rather than mostly dark with isolated stars.



In an infinite Universe, every line of sight eventually hits a star. (Think of a dense forest.)

Brightness and Distance



Brightness falls off with distance, but number of stars increases with distance: $N_\star(<d) \sim n_\star d^3$ if density of stars $n_\star$ is uniform.

$B_{tot} \sim N_\star B_\star \sim n_\star (L_\star/d^2) d^3 \sim n_\star L_\star d$

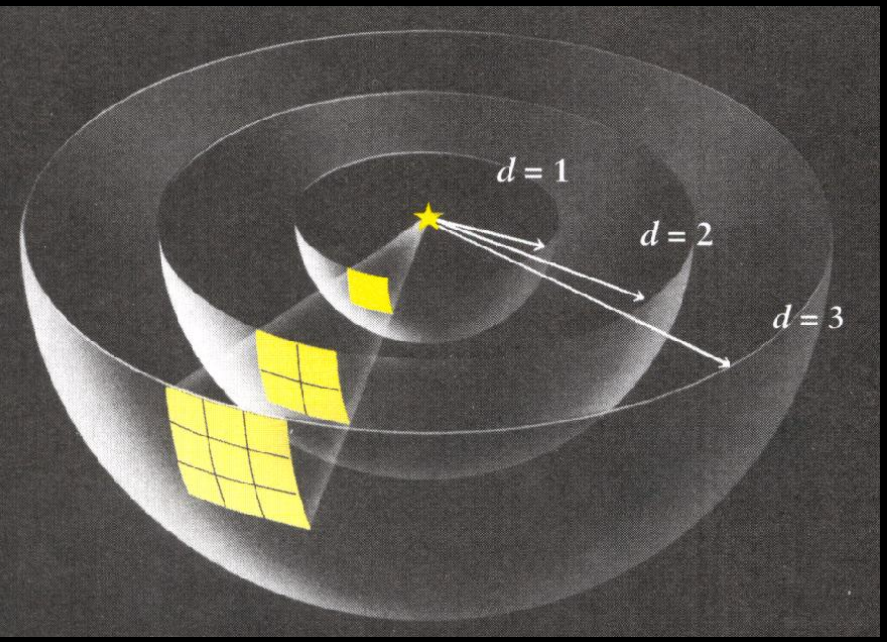
apparent brightness

luminosity

distance

$$B = \frac{L}{4\pi d^2} \Rightarrow d_L = \sqrt{\frac{L}{4\pi B}}$$

Another Approach



Imagine observer sending out a photon in a given direction on the sky. What is the chance that it hits a star? Consider stars of size $R_\star$ in a spherical shell of radius d and thickness Δd around us. Probability that our photon hits a star in that shell is

$P \sim n_\star d^2 \Delta d (R_\star/d)^2 \sim n_\star R_\star^2 \Delta d$

Add up contributions from all shells out to distance d:

$P \sim n_\star R_\star^2 d$

approaches 1 (100%) for large d

Scattering of Starlight

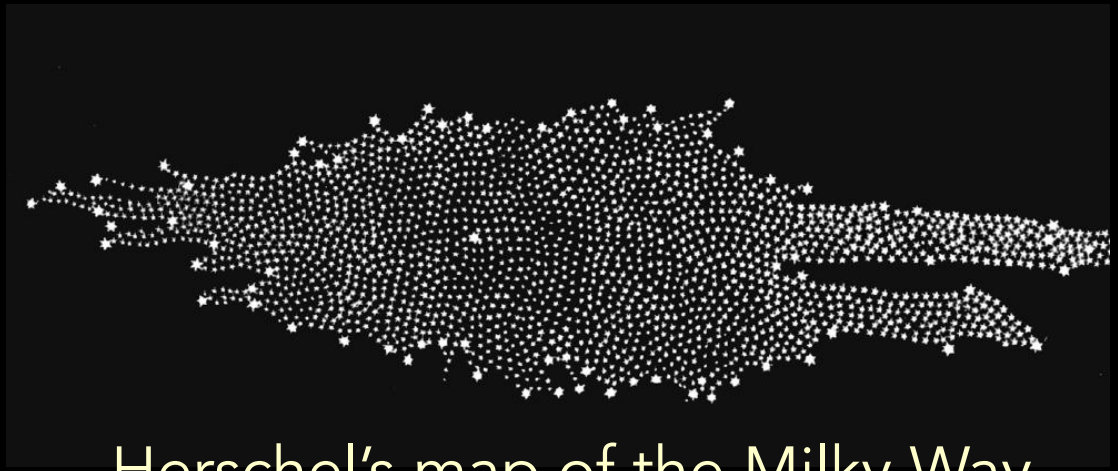
Perhaps light from distant stars gets blocked on its way to us?

Earth's atmosphere and dust in our galaxy and solar system do scatter light from stars.

But this only diffuses the star light out on the sky, doesn't stop it from reaching us.

A Resolution of the Paradox

- Poe (1848): Universe must be finite: d does not extend to infinity.
- Concorded with view of the Milky Way as a finite system of stars with nothing outside it.



Herschel's map of the Milky Way


© A. Gregersen 2010

Modern Resolution

- Universe—and stars within it—has finite age of $t_0 \sim 14$ billion years.
- Light travels at speed c=300,000 km/sec. Looking out in space = looking back in time.
- Tracing light paths back to the Big Bang, almost none of them intersect stars:

$$P \sim n_\star R_\star^2 c t_0 << 1$$

- Brightness:

$$B_{tot} \sim N_\star B_\star \sim n_\star (L_\star / d^2) d^3 \sim n_\star L_\star d \sim n_\star L_\star c t_0$$

is much less than brightness of sun

- Secondary effect: expansion of the Universe reduces energy and arrival frequency of photons.

Physical Implications of Expansion

- An expanding gas cools and becomes more dilute (less dense) over time.
- Consider the Universe as an expanding 'gas' of atoms, dark matter, radiation, etc.
- Density of the gas $\rho \sim mn \sim m(N_{particles}/V)$, where volume $V \sim a^3(t)$. If particles are not created or destroyed, then $\rho \sim 1/a^3$.
- Microwave Background: frequency $\nu \sim 1/\lambda \sim 1/a$
- Quantum mechanics: photon energy $E \sim \nu$.
- Thus, temperature of CMB $T \sim 1/a$.

The Hot Big Bang

- Universe is currently cool and dilute.
- During expansion, a(t) increases with time.
- Run expansion backward: a(t) decreasing as go back in time.
- Since $\rho \sim 1/a^3$ and $T \sim 1/a$, the Universe becomes hotter and denser as go back in time.
- Going back 14 billion years, $a(t) \rightarrow 0$, density and temperature of the Universe approach infinity: the Big Bang.

The Big Bang Singularity

- Just 'before' that singular point of infinite temperature and density is reached, the known laws of physics, and our current conceptions of space and time, break down.
- Space and time described by Einstein's Theory of General Relativity (as we will see), which breaks down at the Planck time, $t_{Pl} \sim 10^{-43}$ seconds after the Big Bang.
- At that point, quantum fluctuations of spacetime become large: requires a theory of Quantum Gravity, perhaps Superstring Theory, which isn't yet well understood.

The Big Bang Theory

- The Universe is expanding isotropically from a hot, dense beginning—the Big Bang---about 14 billion years ago.
- The Big Bang model provides a well-tested framework that explains key cosmological observations:
  - Hubble Law: cosmic expansion
  - Thermal spectrum of Cosmic Microwave Background
  - Cosmic abundances of the light elements
    - Hydrogen, Helium, Deuterium, Lithium, formed in nuclear reactions in first 3 minutes
  - Formation and evolution of galaxies and large-scale structure

Alternative Cosmologies?

- Degrees of departure from the 'standard' Big Bang model:

- Socialism: models that incorporate cosmic expansion, but not the Big Bang.
  - Example: Steady State Model

- Radical anarcho-syndicalist fringe: models that reject both expansion and Big Bang.
  - Example: Tired Light Model

Steady State Model

- Bondi, Gold, and Hoyle (1948)
- Theoretical motivation: "Perfect" Cosmological Principle: Universe homogeneous (unchanging) in time as well as space
- For density to remain constant as Universe expands, they had to postulate continuous creation of matter to fill in the space between galaxies.
- Universe expands but does not evolve: infinite in time and space, no Big Bang.

Problems for Steady State Model

- Matter creation requires new laws of physics that violate conservation of energy, with no other motivation (and no evidence for).
- Galaxy properties have since been observed to evolve over cosmic time.
- Cannot explain isotropic, thermal Cosmic Microwave Background
- No explanation for abundances of light elements
- No explanation for origin and evolution of galaxies and large-scale structure
- Of purely historical interest only

Radical Alternatives

- Start from the premise that redshifts are not due to recession velocities, so cannot infer expansion from Hubble law.

- No alternative explanation for redshift has been put forward that is physically plausible and also consistent with the very large body of redshift data: redshifts for ~1 million galaxies have been measured

Tired Light Model

- Postulates that light loses energy as it travels, so redshift is not due to expansion.
- Problems:
  - Requires unobserved interaction to cause light to lose energy
  - Doesn't predict observed linear redshift-distance relation found by Hubble
  - Doesn't automatically imply redshift independent of light wavelength, as observed.
  - Required scattering of light would smear out appearance of distant sources, not observed.
- Of not even historical interest.

Expansion and the Big Bang

- Evidence for interpretation of redshift in terms of expansion is now overwhelming.
- Multiple lines of evidence that the early Universe was hotter and denser: Big Bang very well established.
- Expanding Big Bang Model is one of the most firmly established paradigms in science.
- At the same time, most of the constituents of the Universe (dark matter, dark energy) are not understood.

Padres Use Big-Bang Theory to Beat Mets

Mets	5
Padres	12

By BUSTER OLNEY

SAN DIEGO, April 1 — Even before the Mets began the 1997 season today, Manager Bobby Valentine would not endorse his bullpen. "It is what it is," he said.

What it is, on opening day, is embarrassing. Mets relievers inherited a 4-3 lead from starter Pete Harnisch in the bottom of the sixth inning, and before achieving three outs, the bullpen etched for itself a place in club history — the Padres scored 11 runs in the sixth, tying a single-inning record for Mets opponents. It was the most runs ever allowed by a National League team in one inning on opening day.

It is what it is: Padres 12, Mets 5. Only 161 more games to go, and there's no telling how many relievers the Mets will employ before the end of this season.

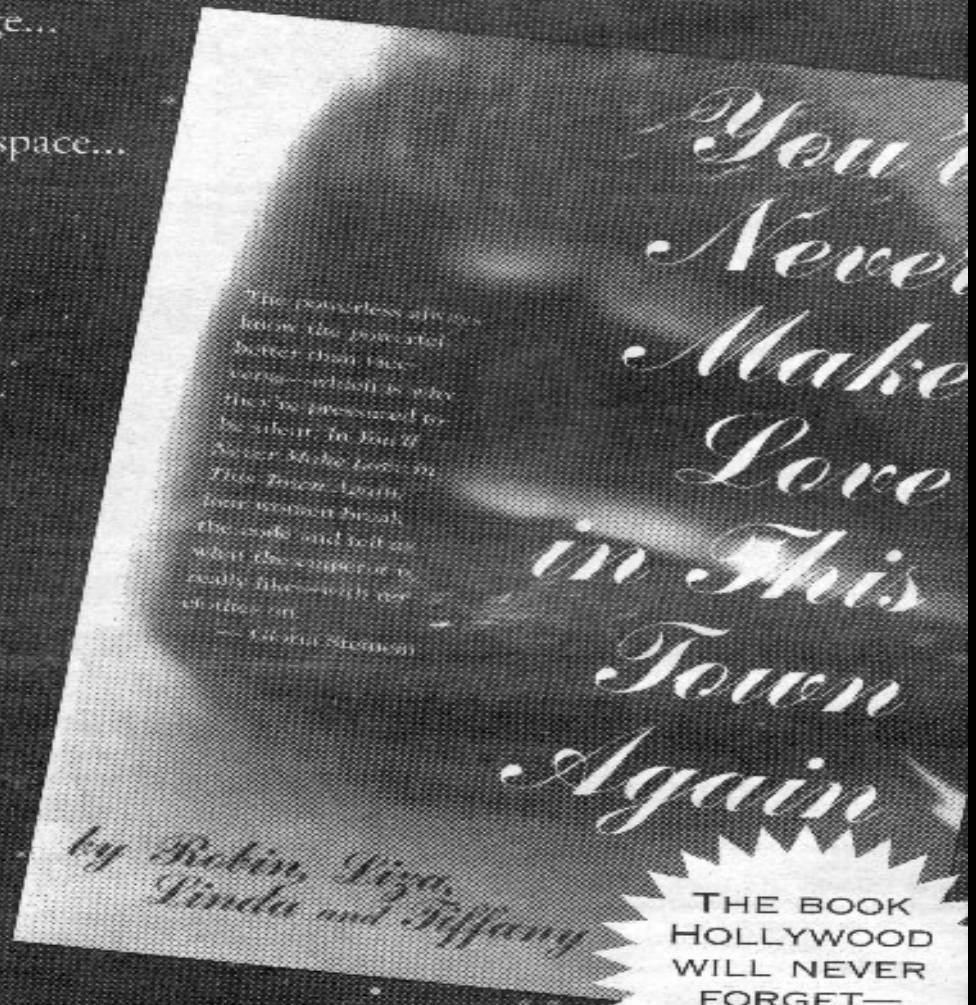
After watching Mets relievers blow many leads last season, General Manager Joe McIlvaine traded for relievers Toby Borland, Ricardo Jordan and Greg McMichael and intended to promote Derek Wallace into a more prominent role in the bullpen hierarchy.

But Wallace began losing feeling in his fingers, and following surgery for an aneurysm, he will miss most of the season. His injury seemed to create fissures in the fragile Mets bullpen, and three weeks into spring training, Valentine began to speak of his bullpen with strain in his voice. In the last five days, McIlvaine bought Barry

Start Your New Year off with a Big Bang

In the ultimate quest for knowledge...
in the ongoing search for the
secrets of the heart in time and in space...
every once in a while a
new theory comes along...
about the intricacies of mankind...
the beginning of the universe...
and space, time and matter...
that is so utterly shocking...
it changes our view of the world!

Find out Robin, Liza, Linda, and Tiffany's version of the big bang theory in *You'll Never Make Love in This Town Again*, the uncensored Hollywood tell-all that exposes the flip-side of the *Pretty Woman* story.



THE BOOK HOLLYWOOD WILL NEVER FORGET— OR FORGIVE

The book that reveals the truth about the biggest stars in Hollywood.

The Big Bang Theory

The Big Bang Theory