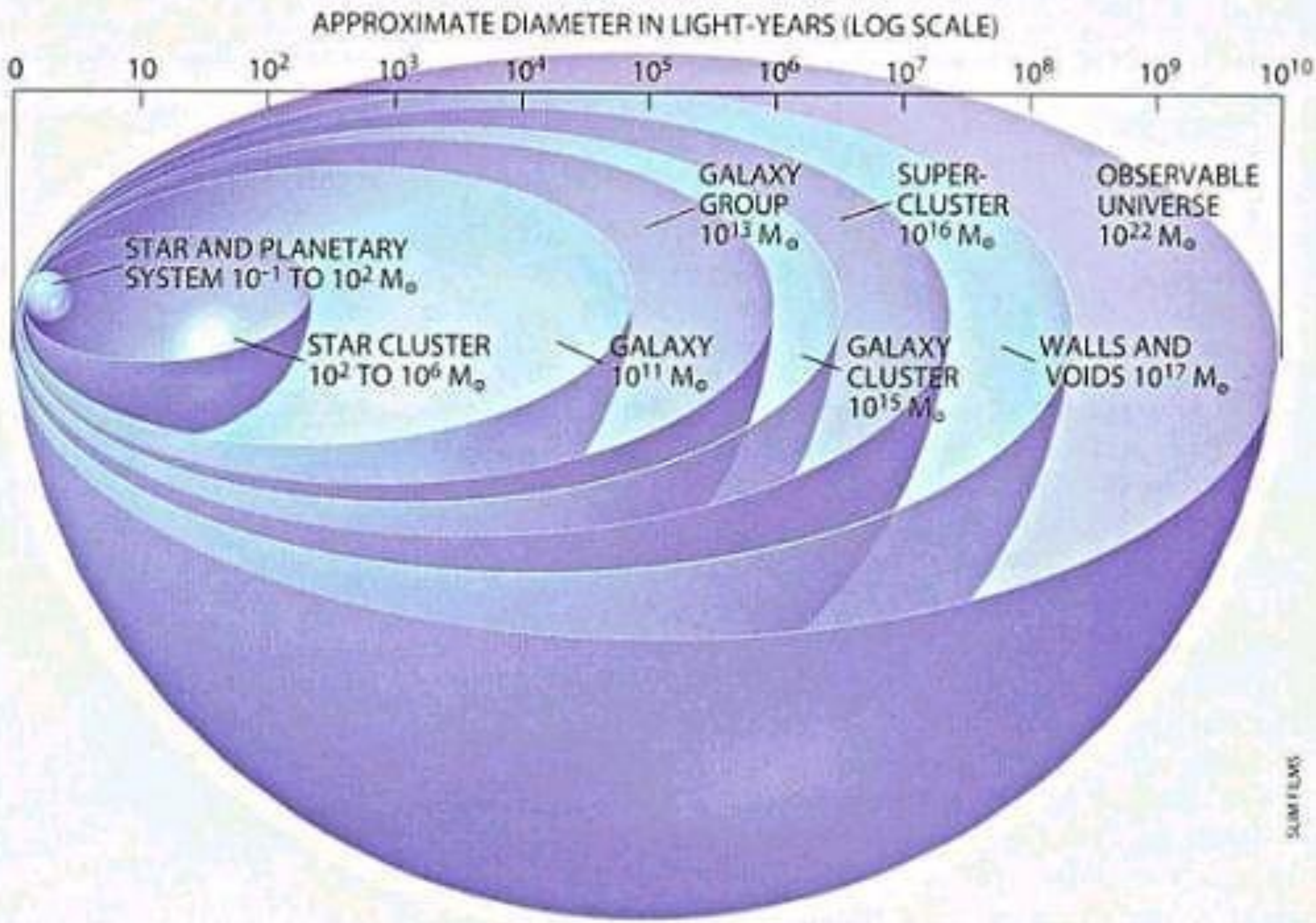
Large Scale Structure in the Universe

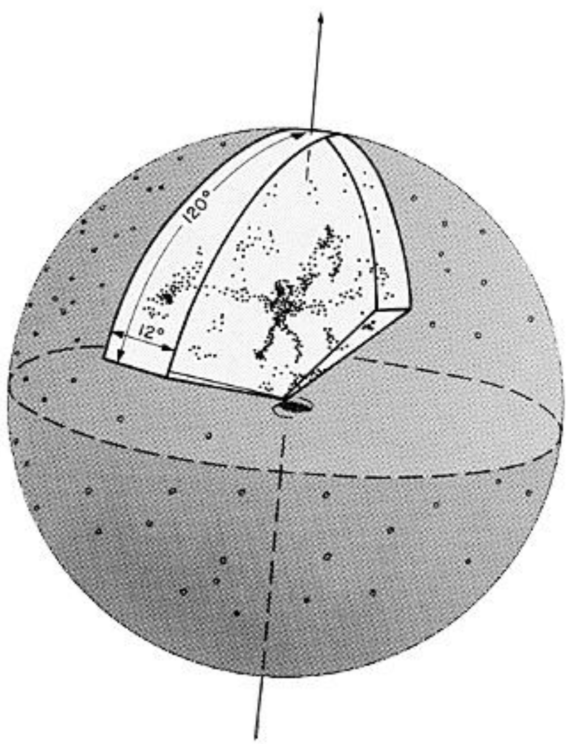
- We seem to be located at the edge of a Local Supercluster, which contains dozens of clusters and groups over a 40 Mpc region.
- Galaxies and clusters seem to congregate in "sheets", with extensive intervening "voids"
- Must reflect on how clusters of galaxies form
- Are the voids *real* voids, or could they be filled with dark matter?

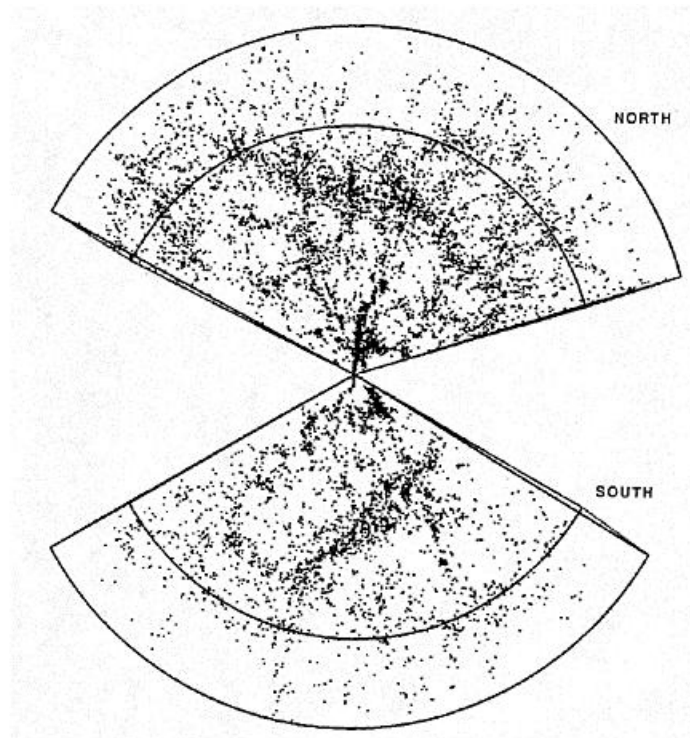


HIERARCHY OF COSMIC STRUCTURES ranges from stars and planets to the universe itself. The largest objects held together by gravity are galaxy clusters with masses up to 10^{15} times that of the sun (denoted as $M_\odot$). Although there is a higher level of organization consisting of superclusters and great walls, these patterns are not bound gravitationally. On even larger scales, the universe is featureless. Astronomers think most of these structures form from the progressive agglomeration of smaller units.

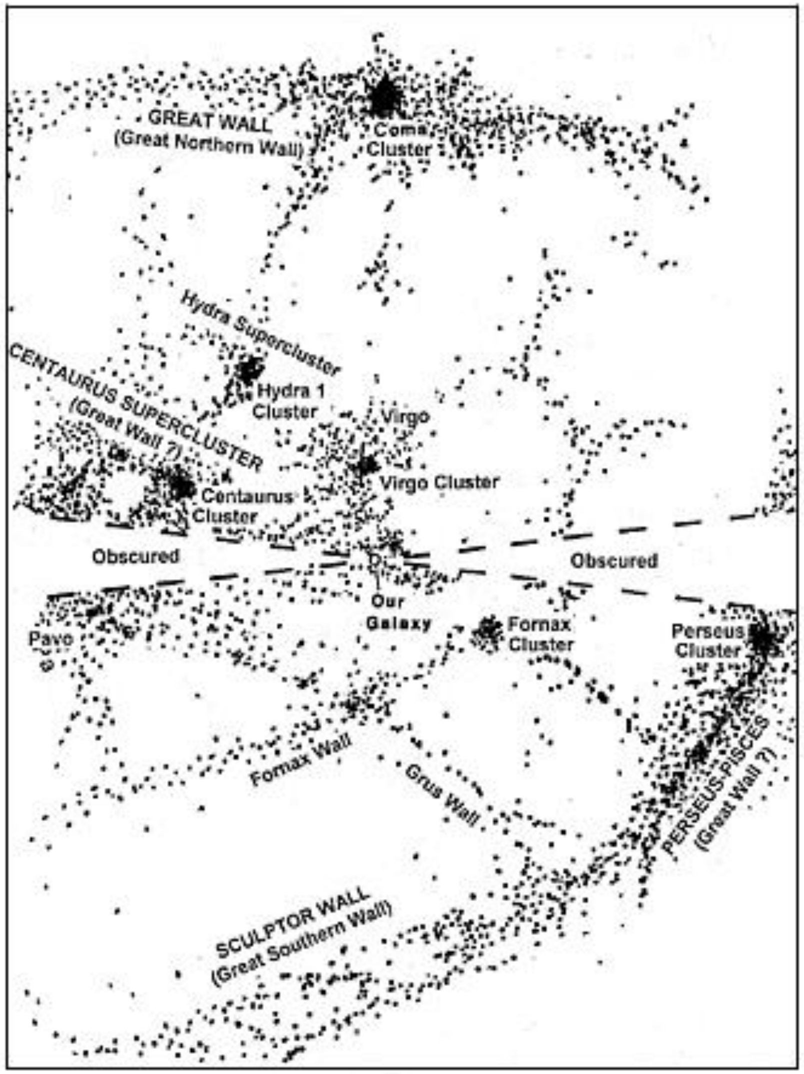
1 light year ~ 10^{18} cm.

Galaxy Counting

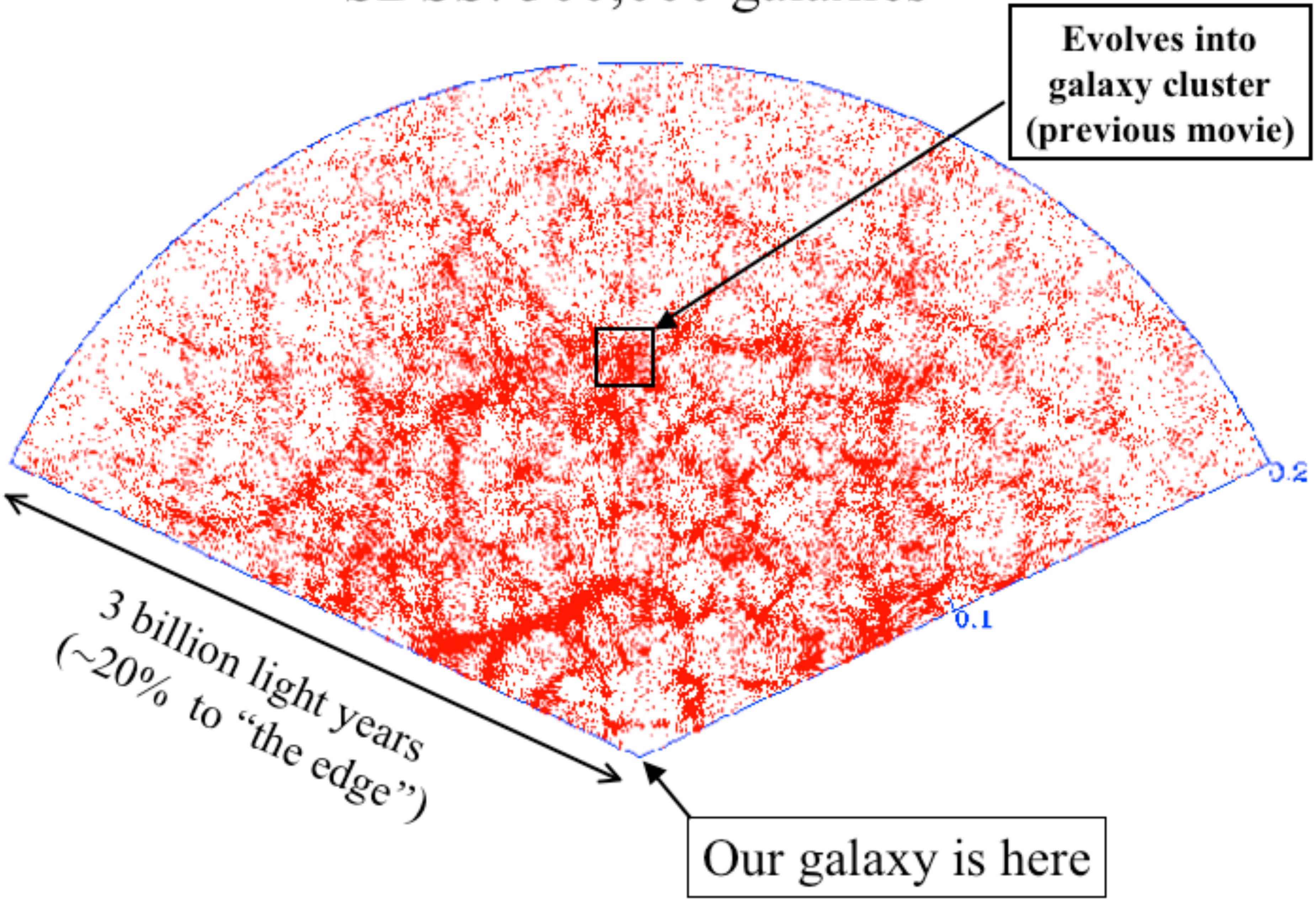




Mapping How Galaxies Are Distributed

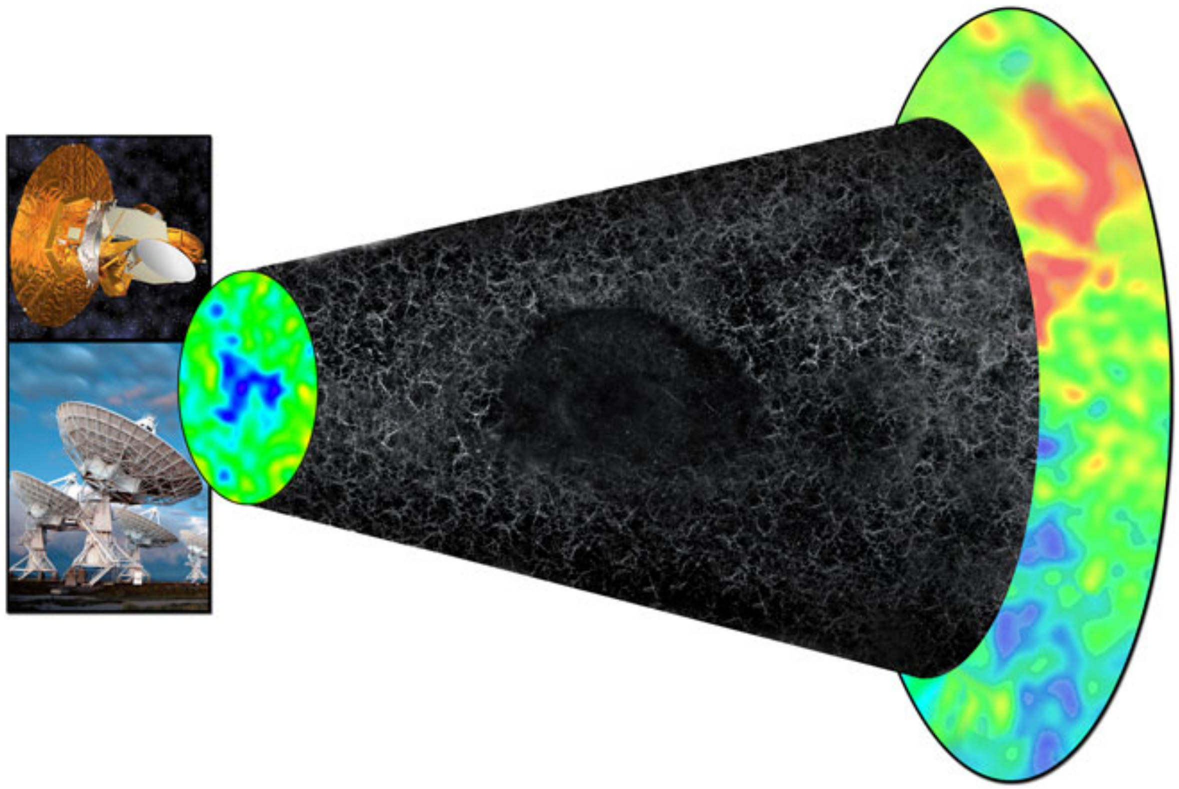


SDSS: 300,000 galaxies



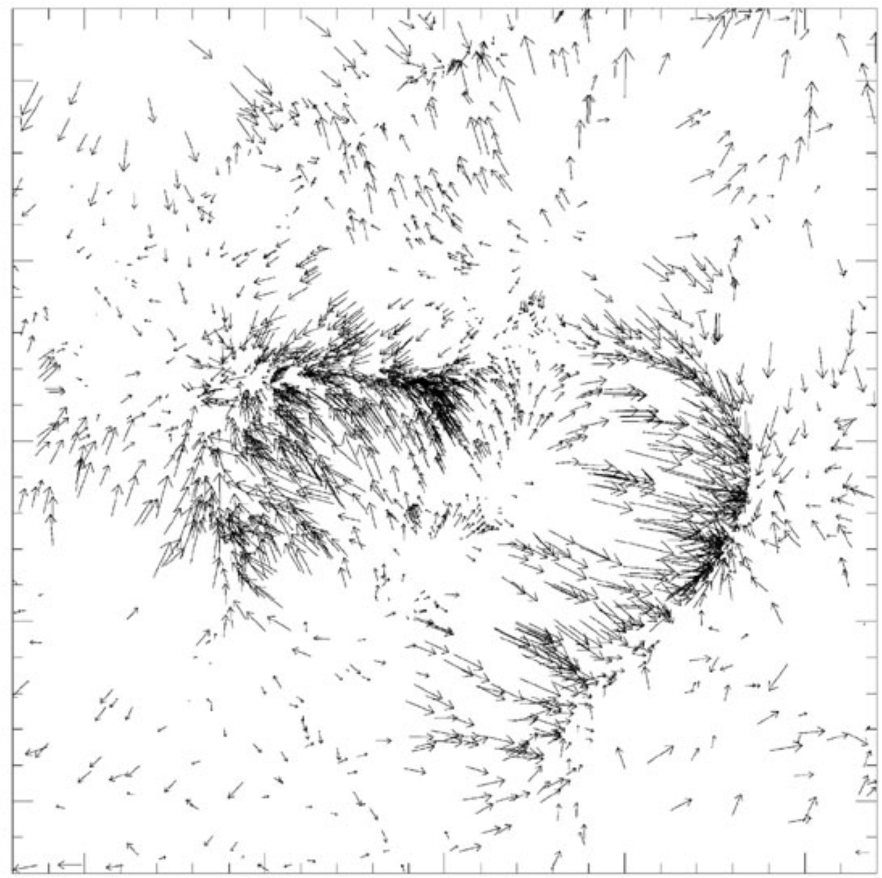
Biggest Void in Town

NRAO radio mapping has revealed a sizable region of space about 1 billion LY across that is devoid of galaxies, gas, and dark matter. It is About 6-10 billion LYs from Earth.

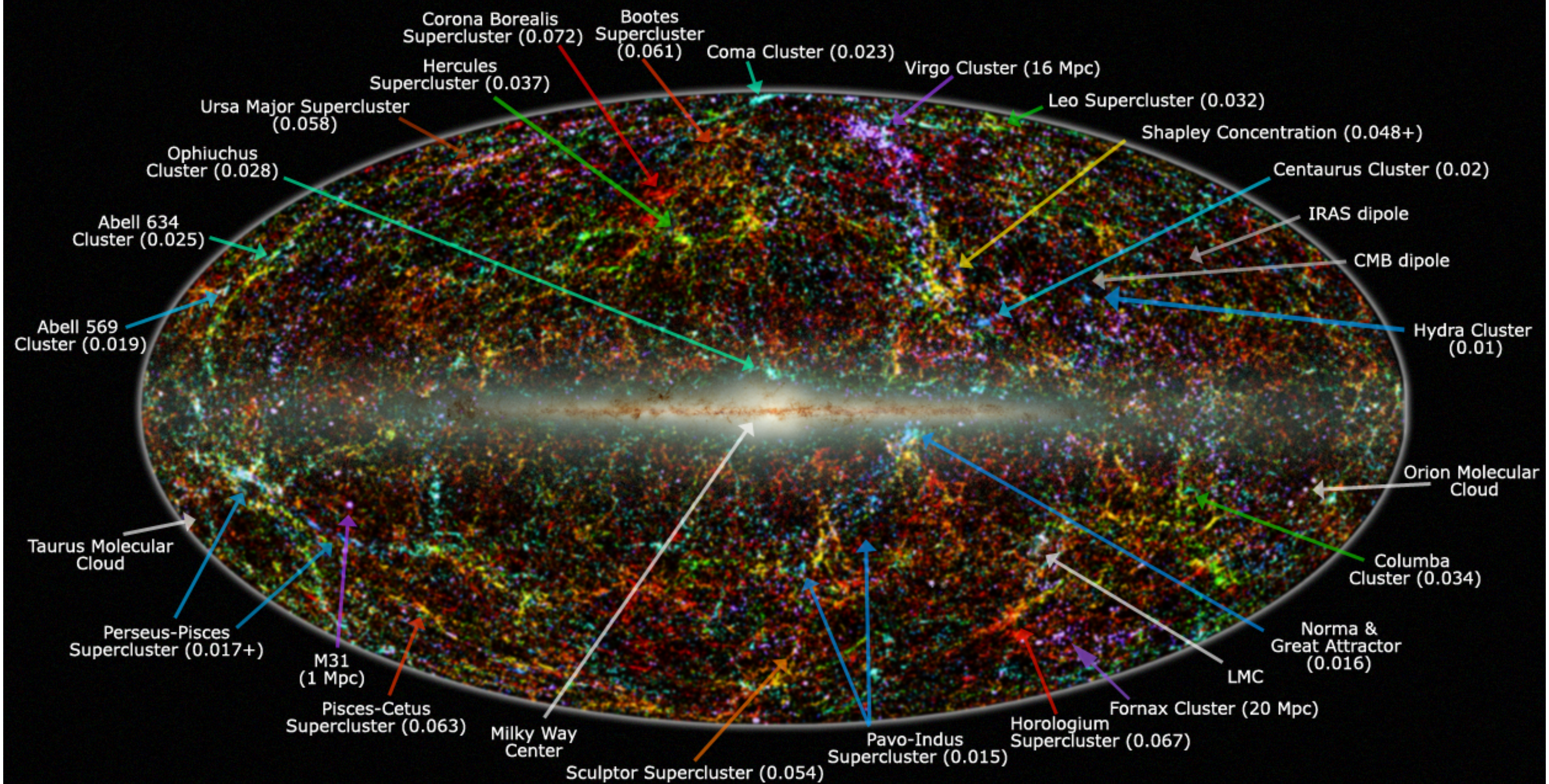


Comment on "Peculiar" Velocities

In clusters of galaxies bound by mutual gravity, the cluster participates in the Hubble flow, but the individual galaxies move in bound orbits

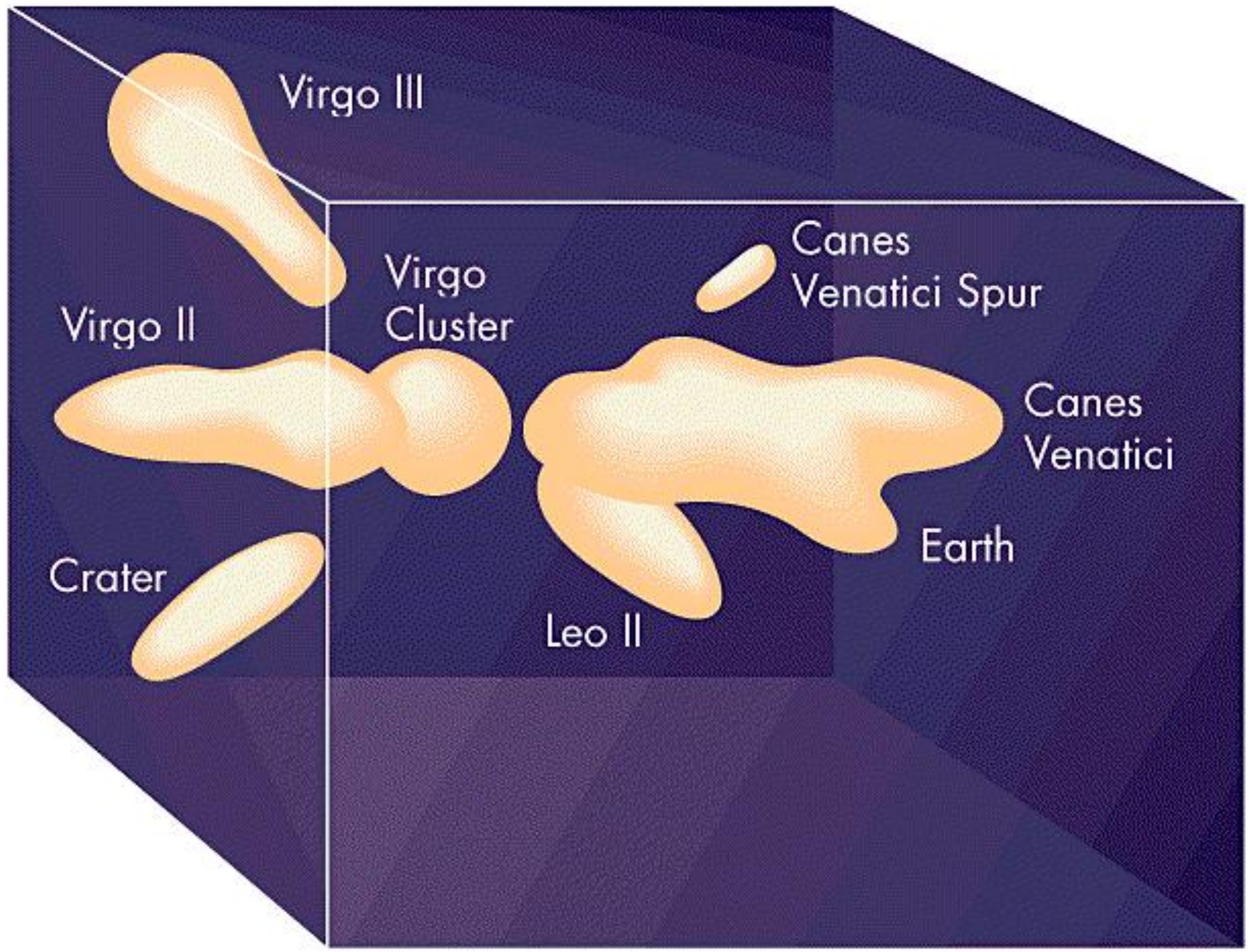


Large Scale Structure in the Local Universe

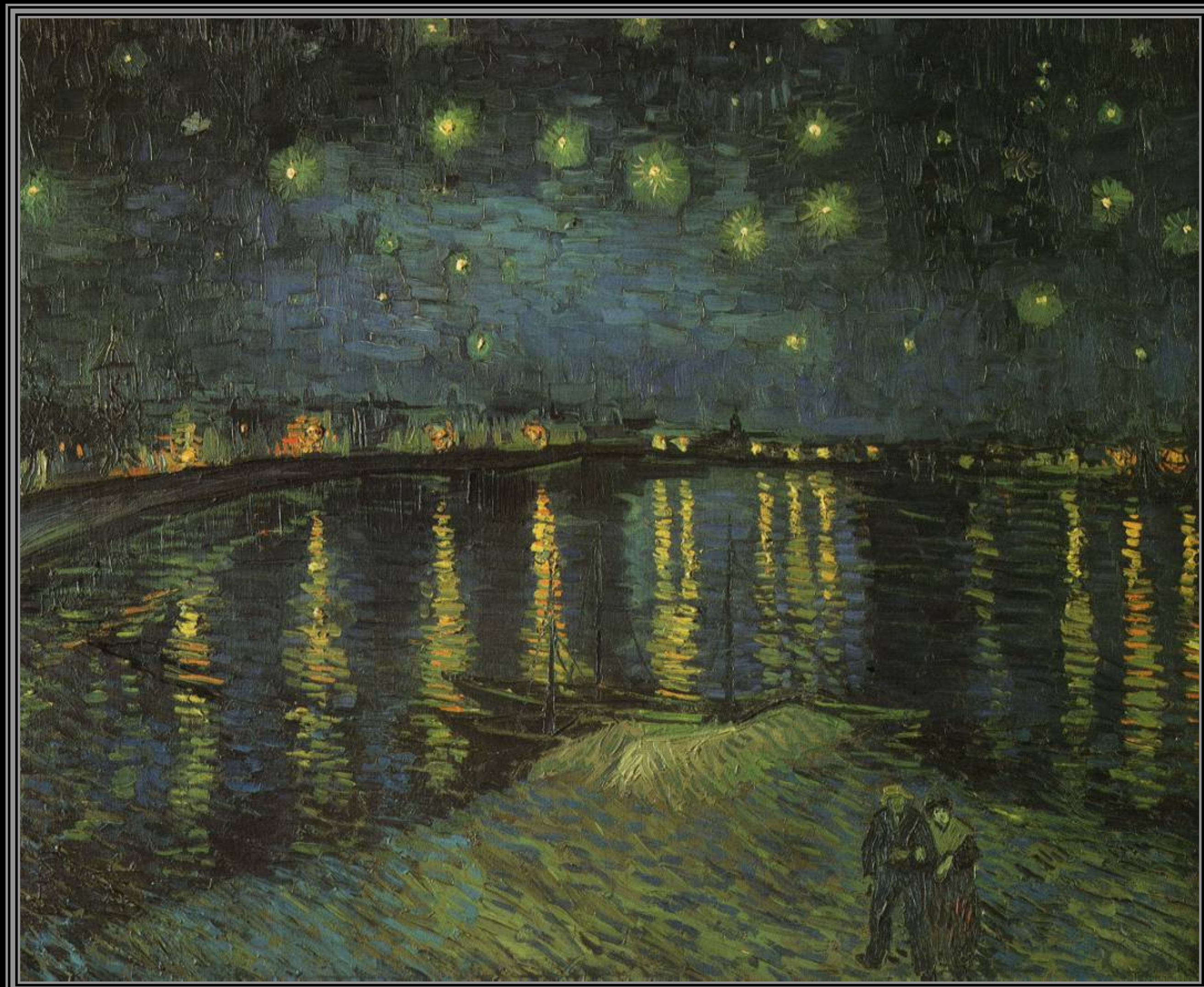


Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004);
familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).
Graphic created by T. Jarrett (IPAC/Caltech)

The Local Supercluster



The Sky Is … Dark?

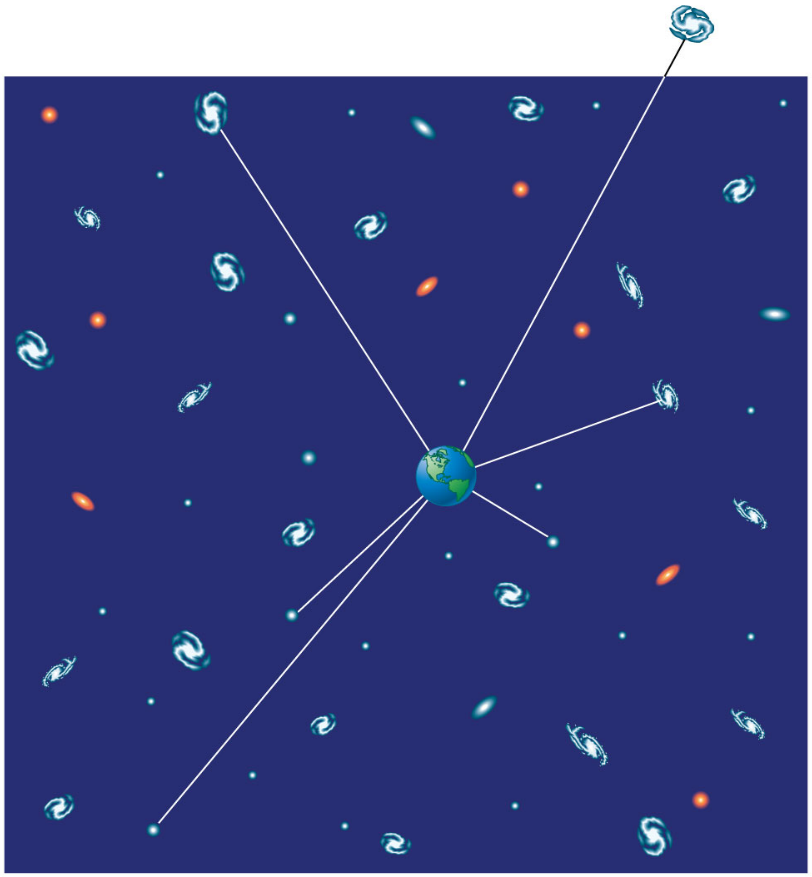


Olber's Paradox

Why is the night sky dark?

Imagine a universe:

1. Universe is finite in time
2. Universe is finite in space
3. Universe is changing with time (and/or, either, or neither of the above)

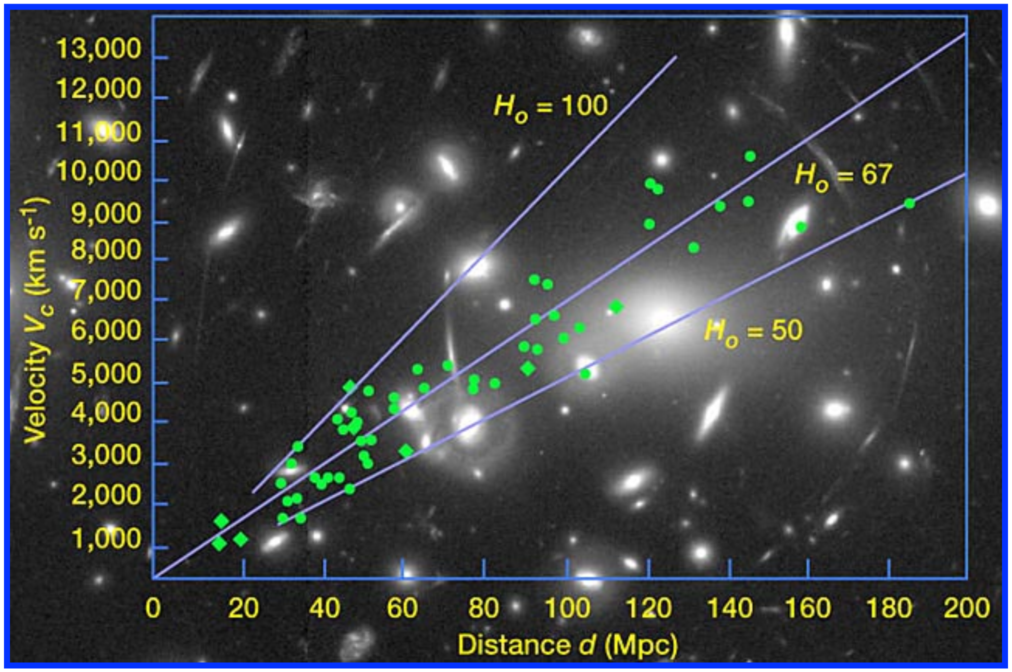


Beginnings in Cosmology

- Hubble's Law can be used to estimate the age of the universe

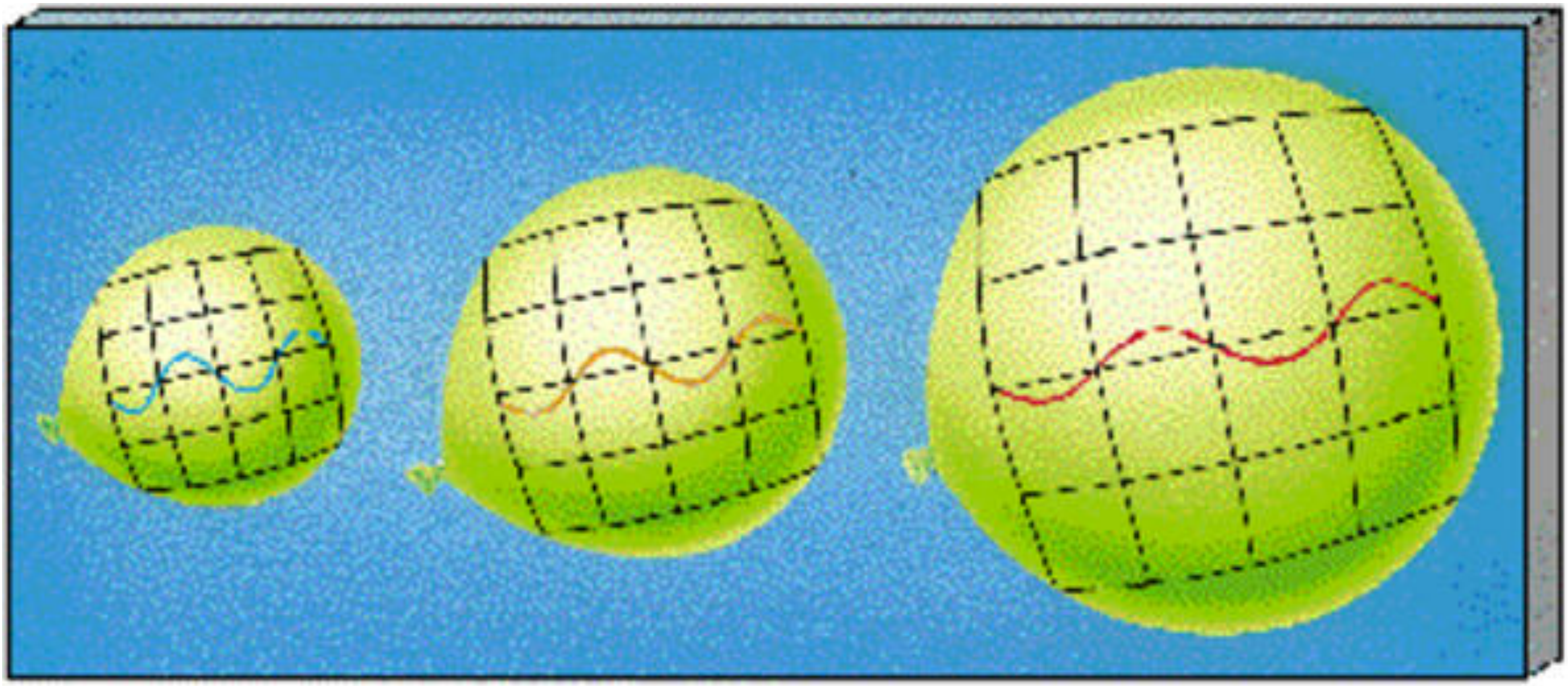
$$v_r = \frac{d}{t} = Hd$$

$$t = {}^{1}\!/_{H} \approx 1.5 \times 10^{10} \text{ years}$$



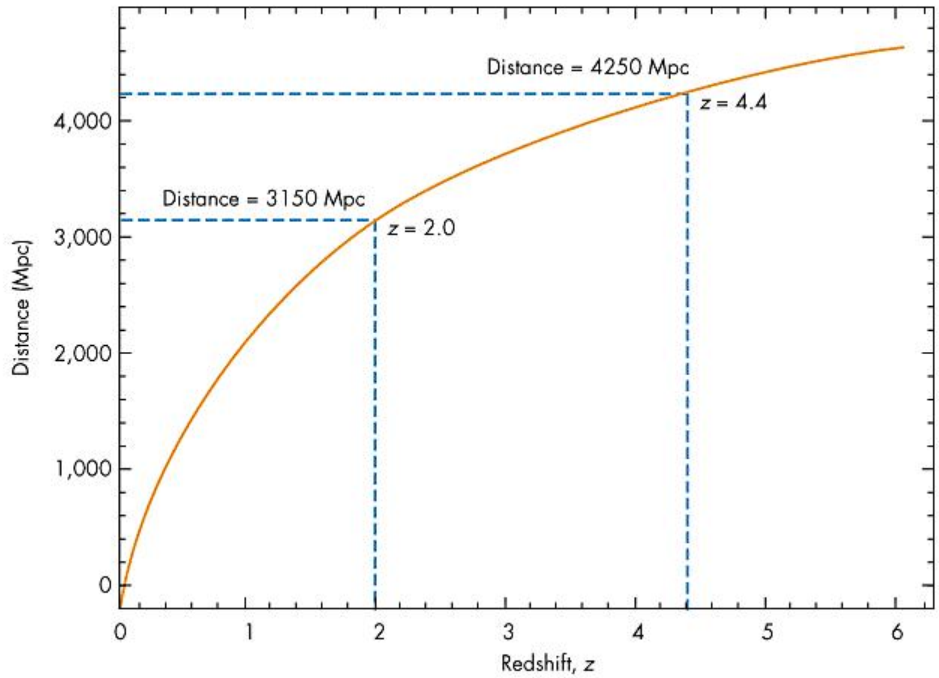
- The universe had a beginning in time, and its age is around 15 billion years.

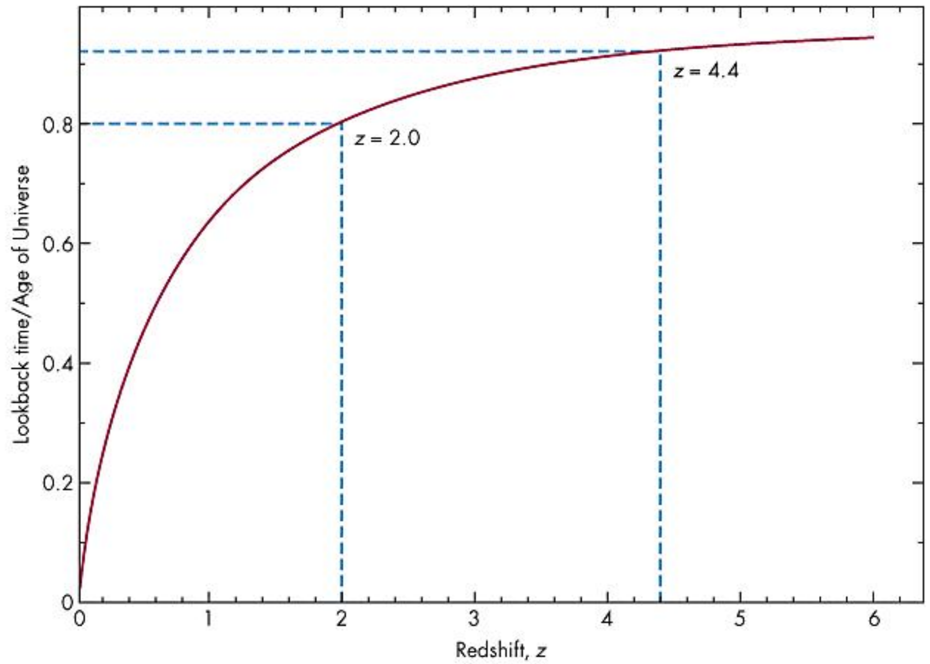
Expansion and a New Look at Cosmological Redshift



Observed redshifts of galaxies is not due to their motion but instead due to the literal expansion of space itself.

Redshift as a Ruler





The linear Hubble law only works for relatively nearby galaxies. At very high redshifts (z), the Hubble law becomes a curve. Above left: Distance with redshift. Above right: Look-back time with redshift.

The Cosmological Principle

The universe is

1. *Homogeneous* – observers everywhere and anywhere see the "same" thing

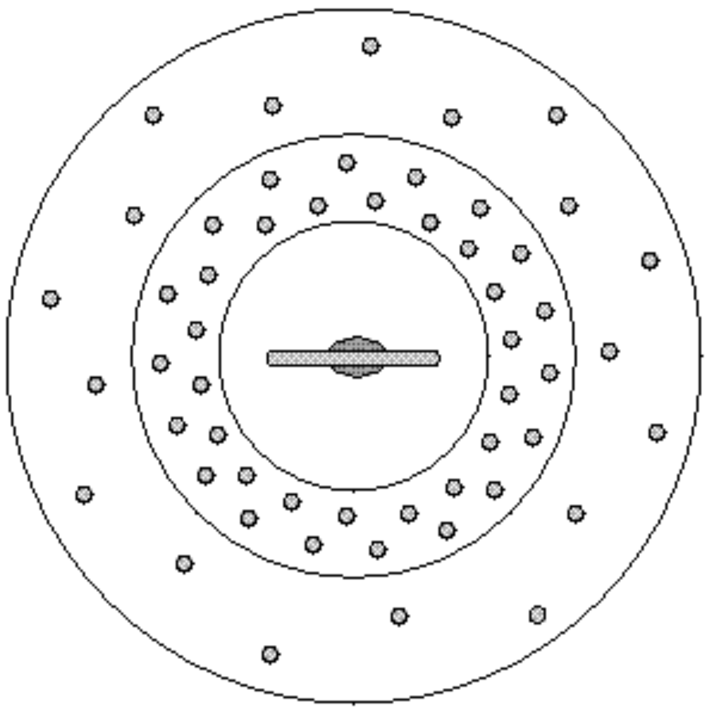
AND

2. *Isotropic* – every direction presents the same view

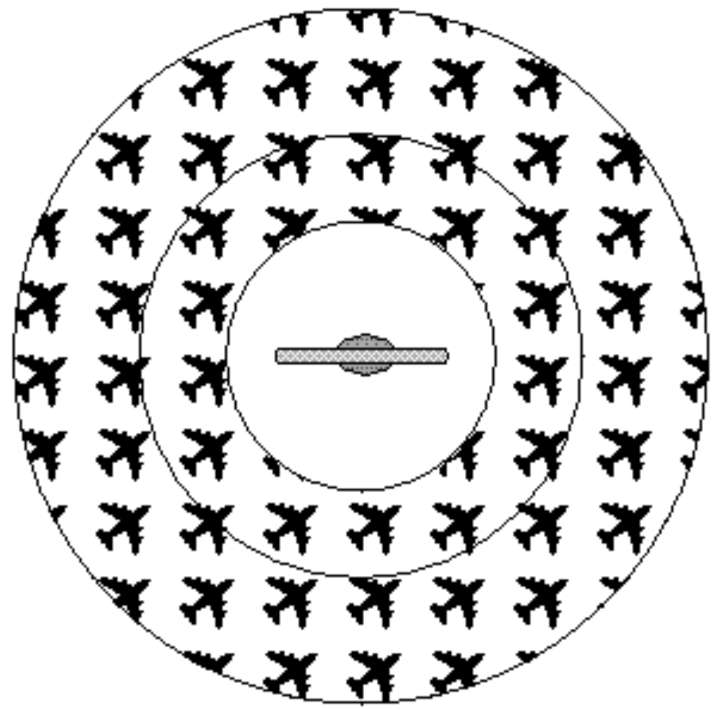
These two assumptions form the basis for our interpretations of how the universe works.

[perfect cosmological principle includes "static"]

Contrasting Homogeneity and Isotropy



Is this *homogeneous* and *isotropic*? Which aspect is it not?

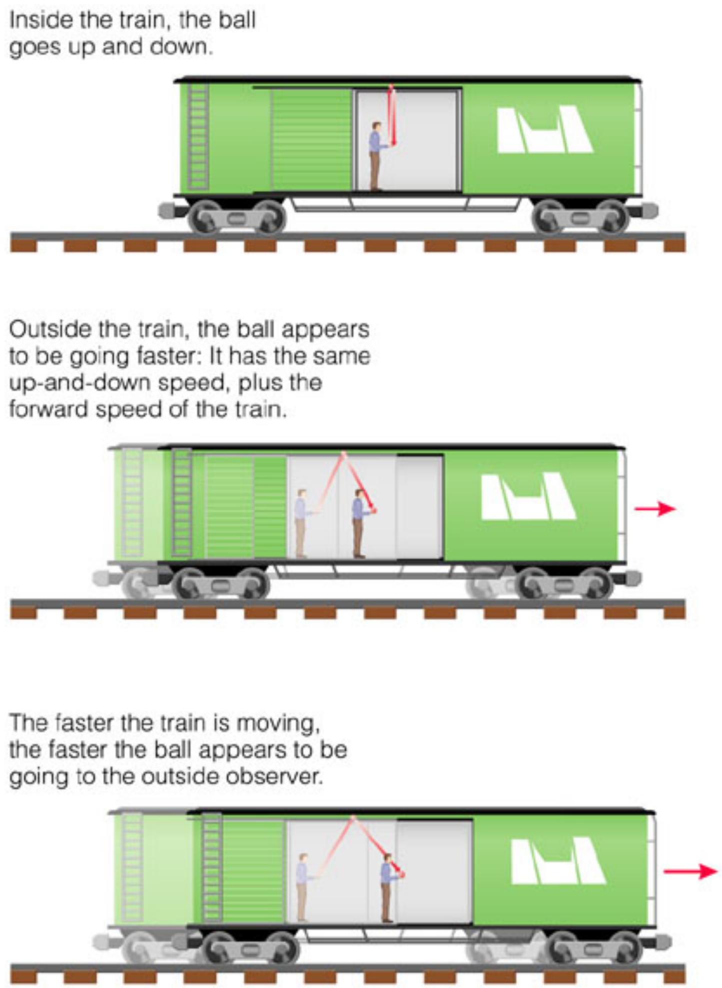


Outside the central sphere, is this universe *homogeneous* and *isotropic*? Which aspect is it not?

Special Relativity

- Einstein (1905): Two fundamental postulates
  - The laws of physics are the same for everyone and everywhere
  - The speed of light (300,000 km/s) is the same for everyone, even when things are in motion
- Relativity is a *misnomer*; the theory is one of *absolutism*, but an odd one in terms of the idea that the light speed is the same for all
- The counterintuitive aspect is that observers no longer agree on things being **simultaneous**

The Train Car Experiment



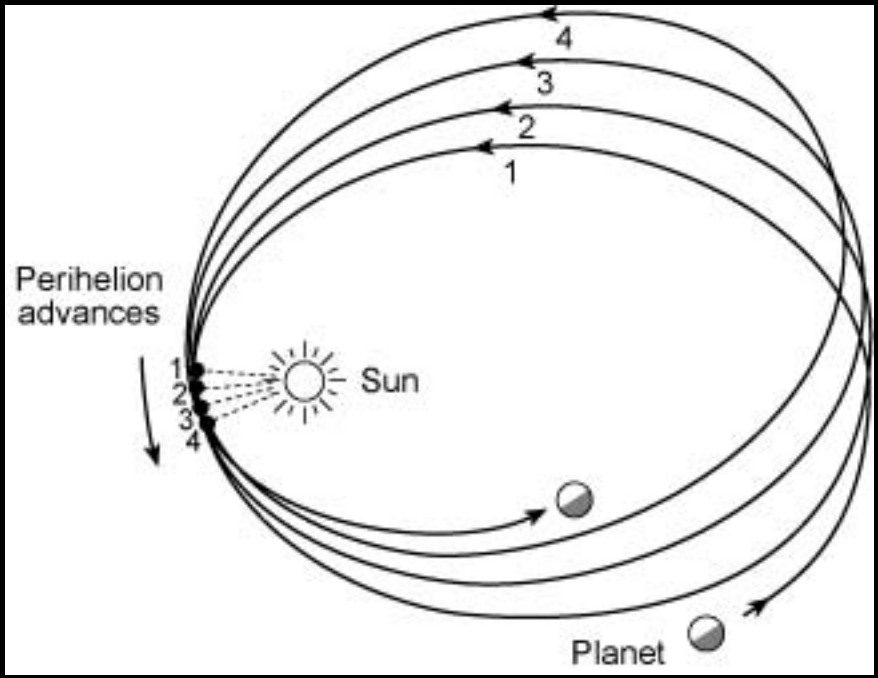
General Relativity

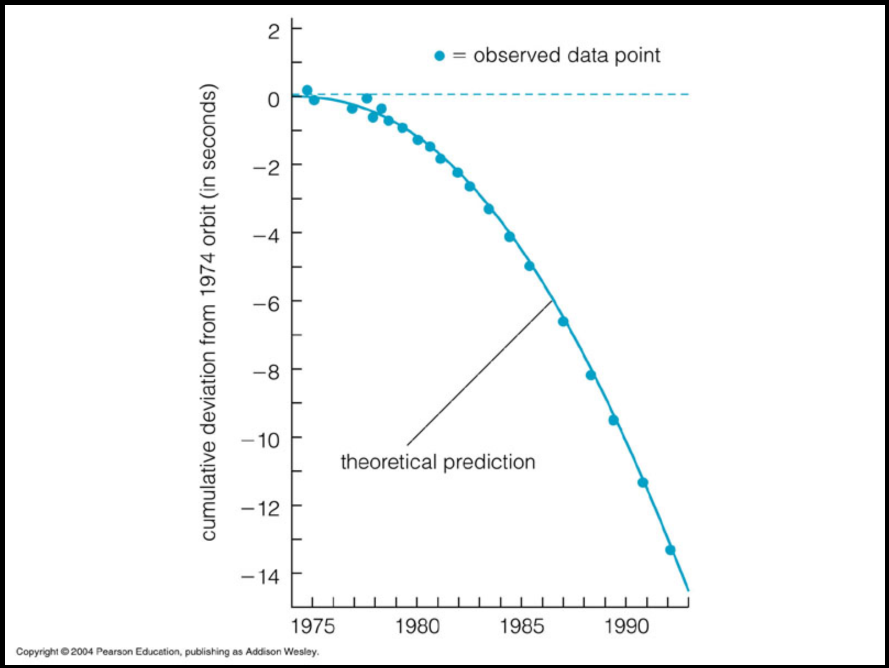
- Einstein (1915): A description of gravity relating matter and spacetime
- Spacetime – 4D "space": location in time and regular 3D space (e.g., time, N/S, E/W, alt)

- ***Principle of Equivalence:***

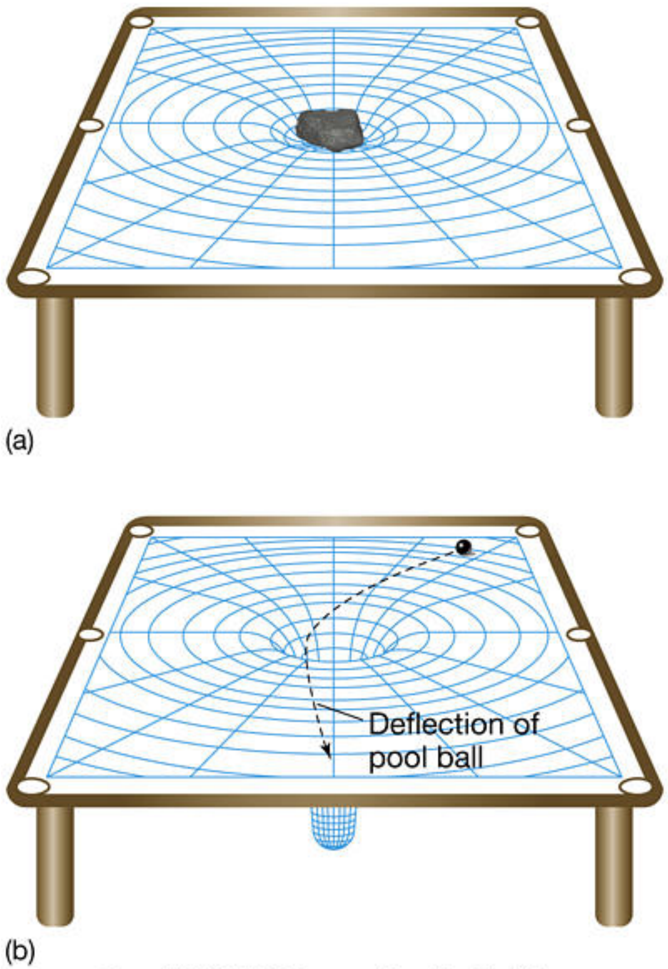
  Cannot distinguish between a uniform gravitational field versus a frame of reference undergoing uniform acceleration.

Test of G.R.: Precession of Mercury

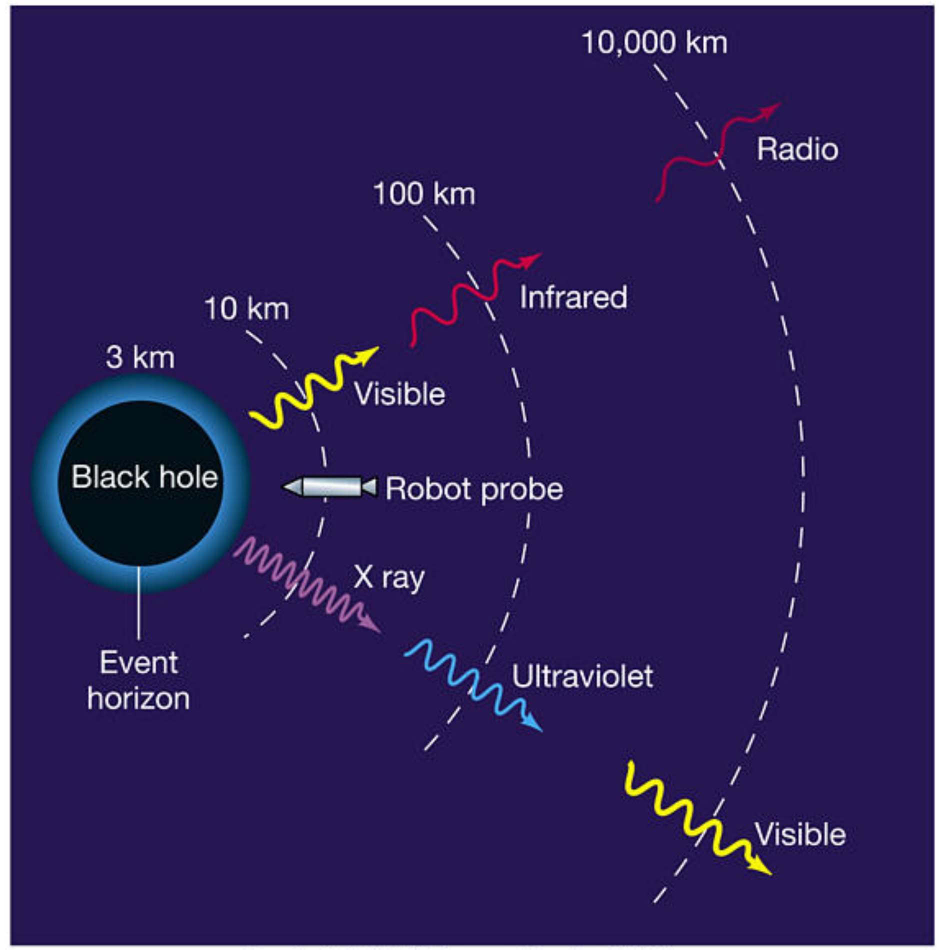




The Bizarre of G.R.

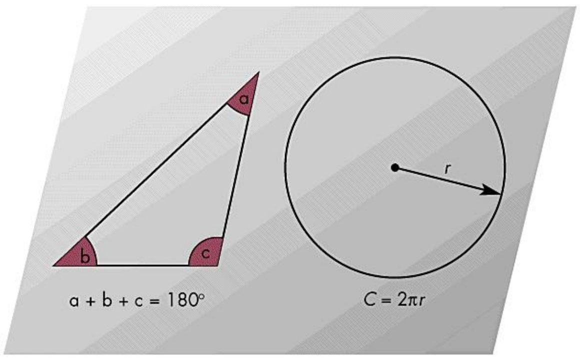


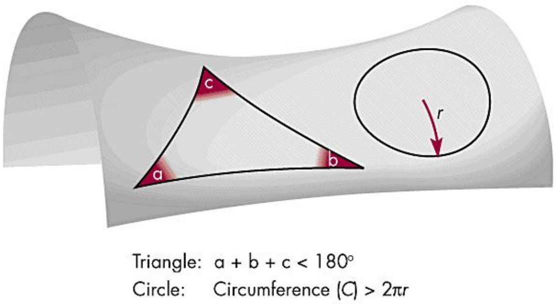
Mass distorts space



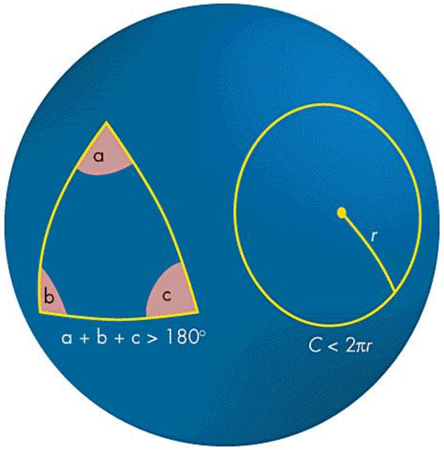
Gravitational redshift

Curved Spacetime - Consequences

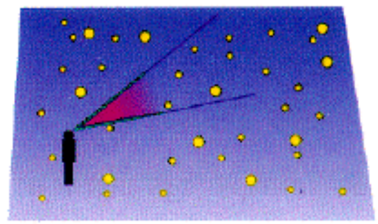




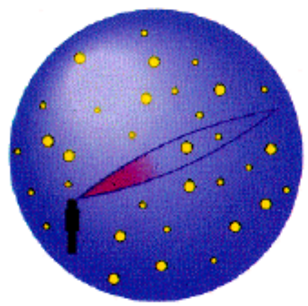
Examples for how the shape of a surface modifies familiar rules of geometry.



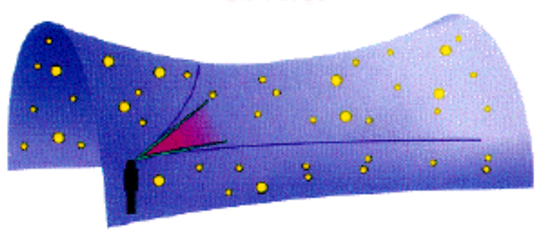
Measuring Curvature



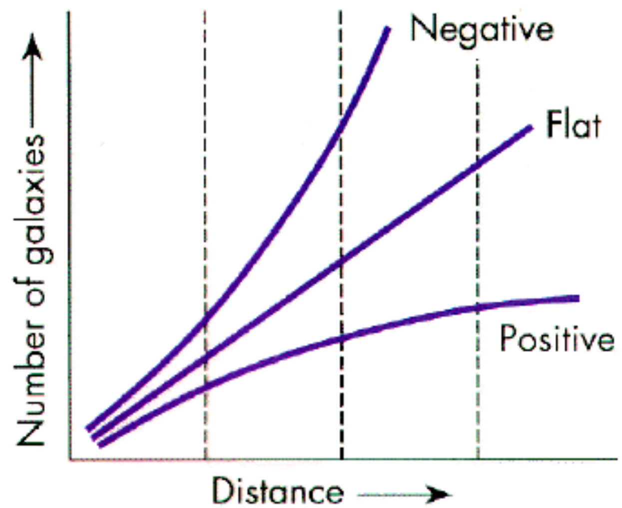
Flat universe



Positively curved universe

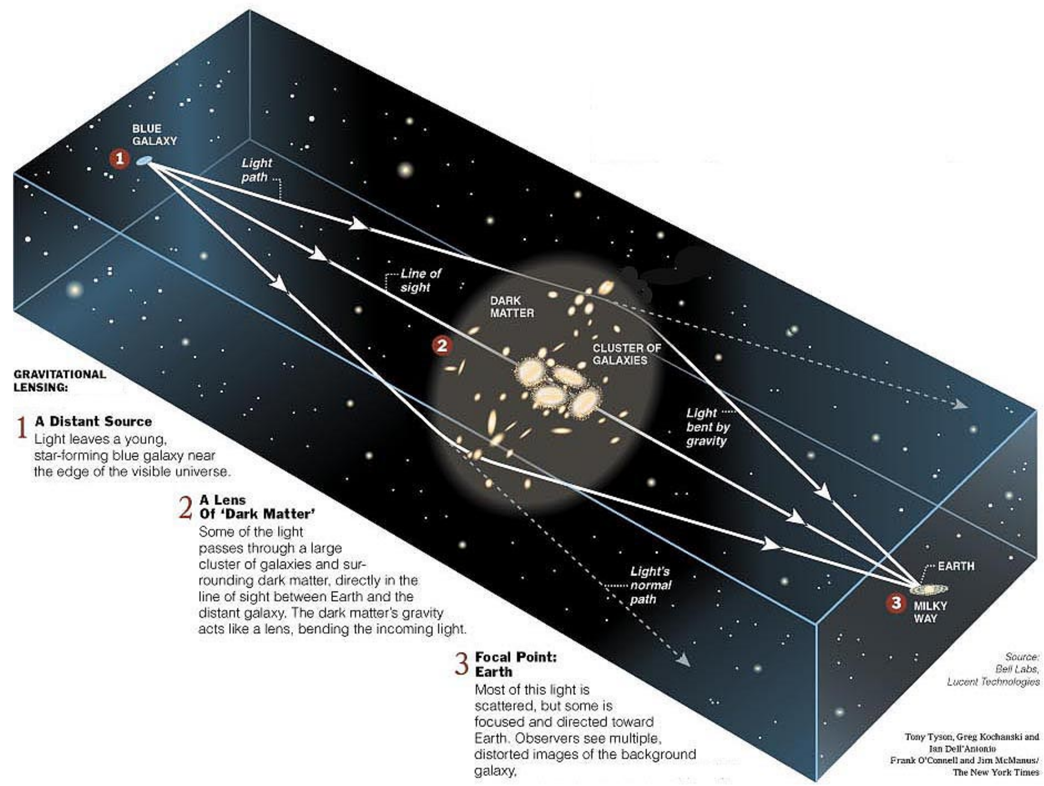


Negatively curved universe



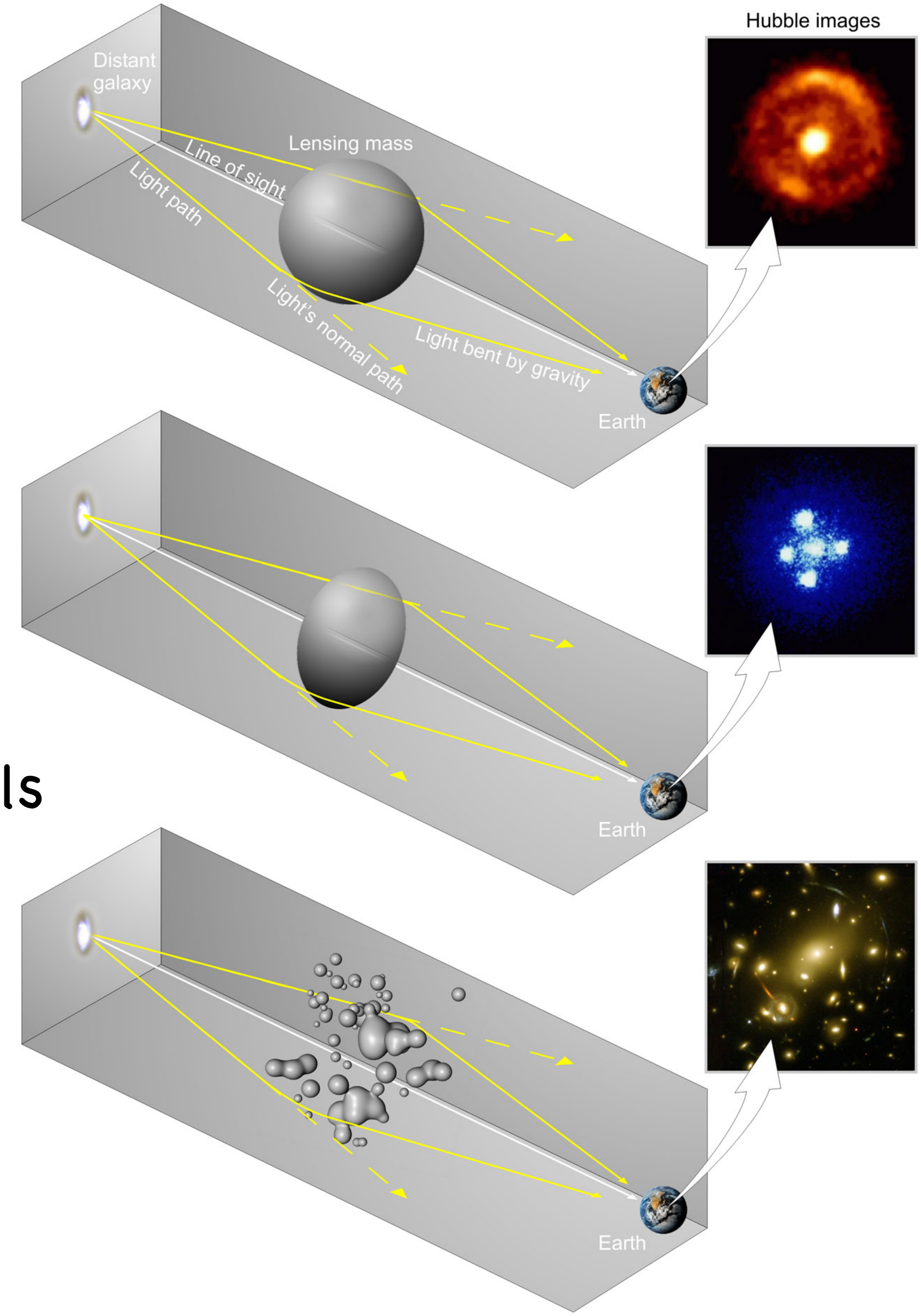
Curvature of Spacetime

Einstein's theory predicts that matter "curves" spacetime. Consequently, light "bends" when passing near a mass. Phenomenon is "lensing" and is actually observed!

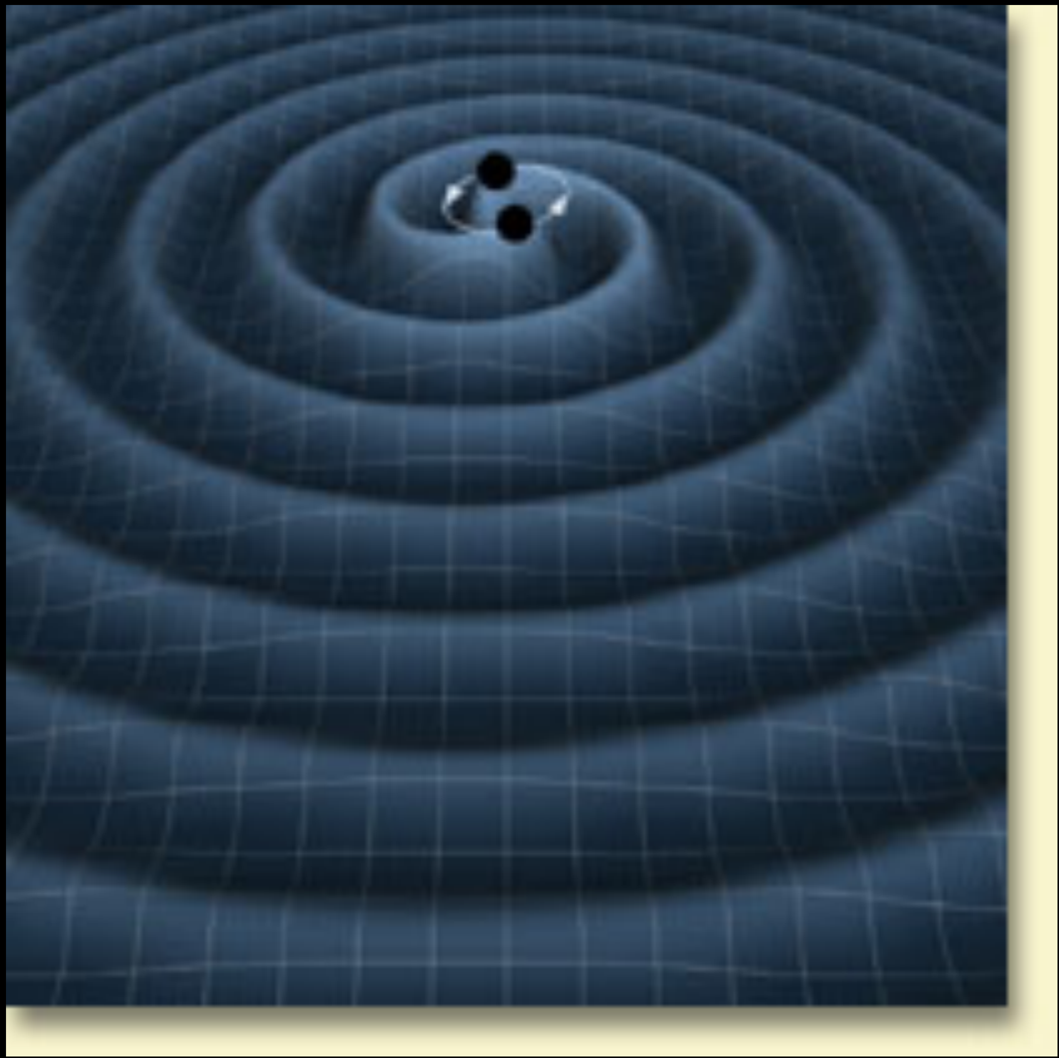


"Gravy" Lensing as a Tool

What you can see reveals what you cannot see: lensing can reveal mass distribution, especially dark matter



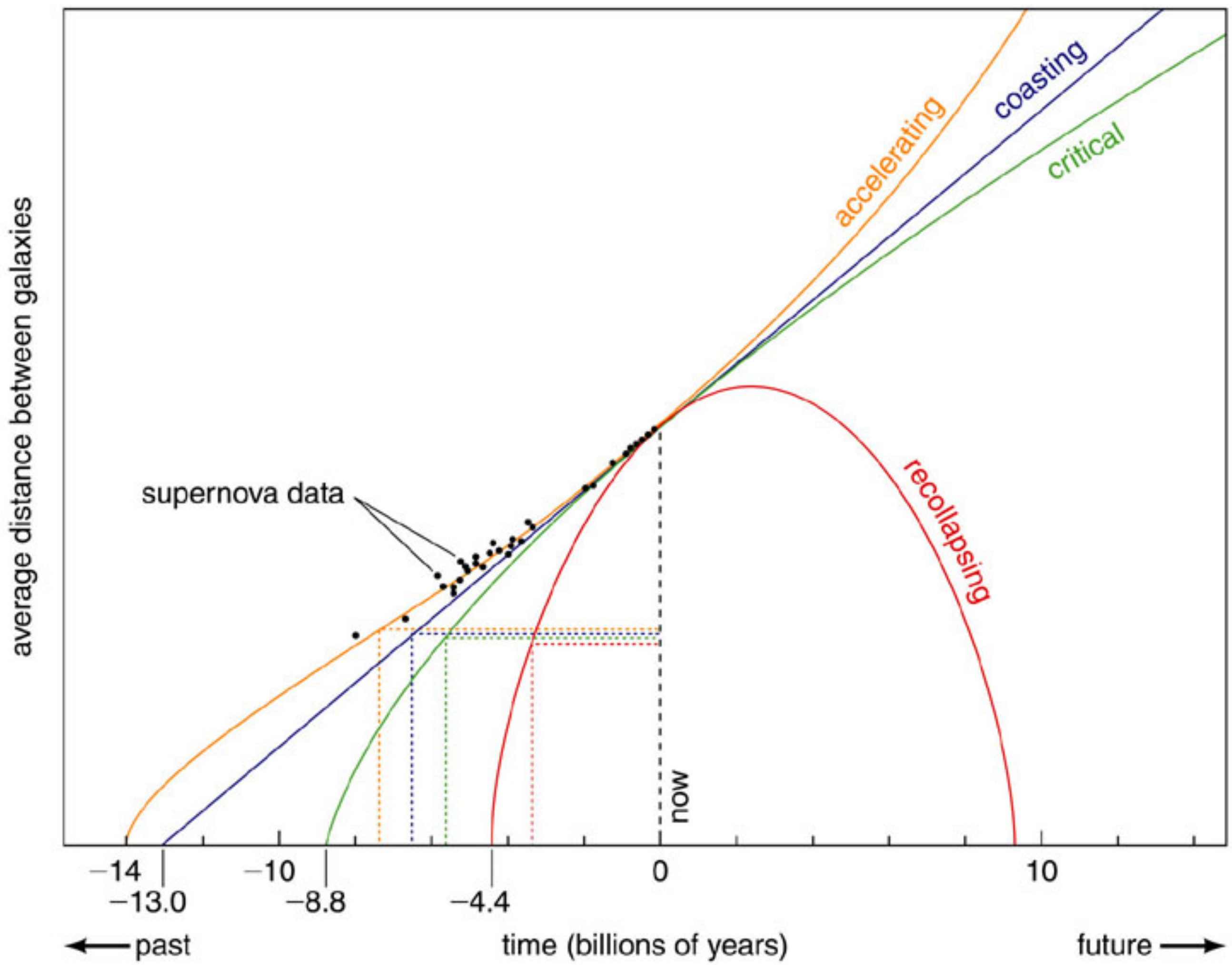
The Cutting Edge in G.R.: Gravitational Waves



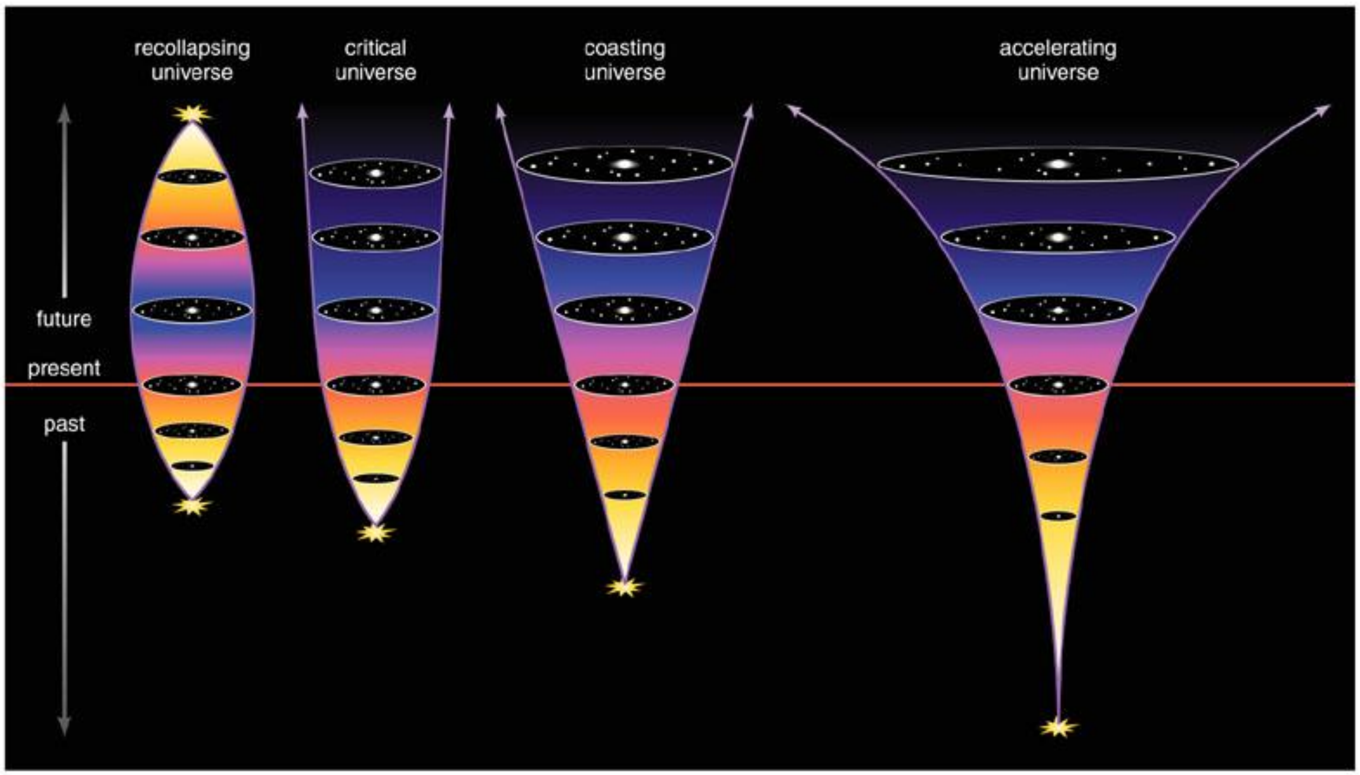
Standard Big Bang Model

- Expansion suggests
  a) A beginning
  b) An "explosion"
- Big Bang highlights:
  1) Universe was hot, dense, and expanding (at an age of 10^{-6} sec, temperature about 10^{13} K)
  2) A universe dominated by light. High energy photons are so energetic that they can combine to make basic matter: protons, neutrons, electrons.
  3) At t=100 sec, T ~ 10^{11} K, and nuclear fusion leads to the formation of He (and some other stuff)

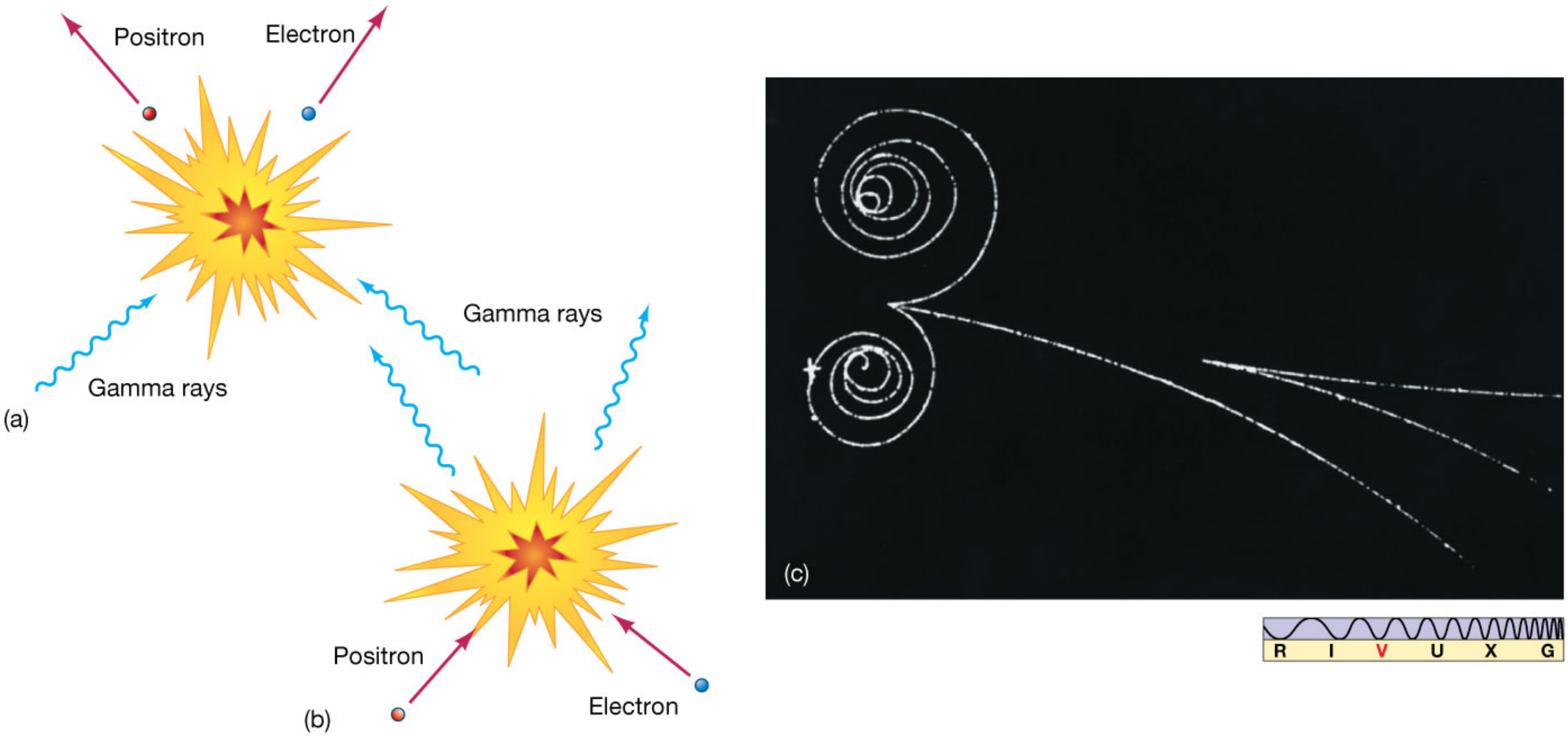
Cosmological Models



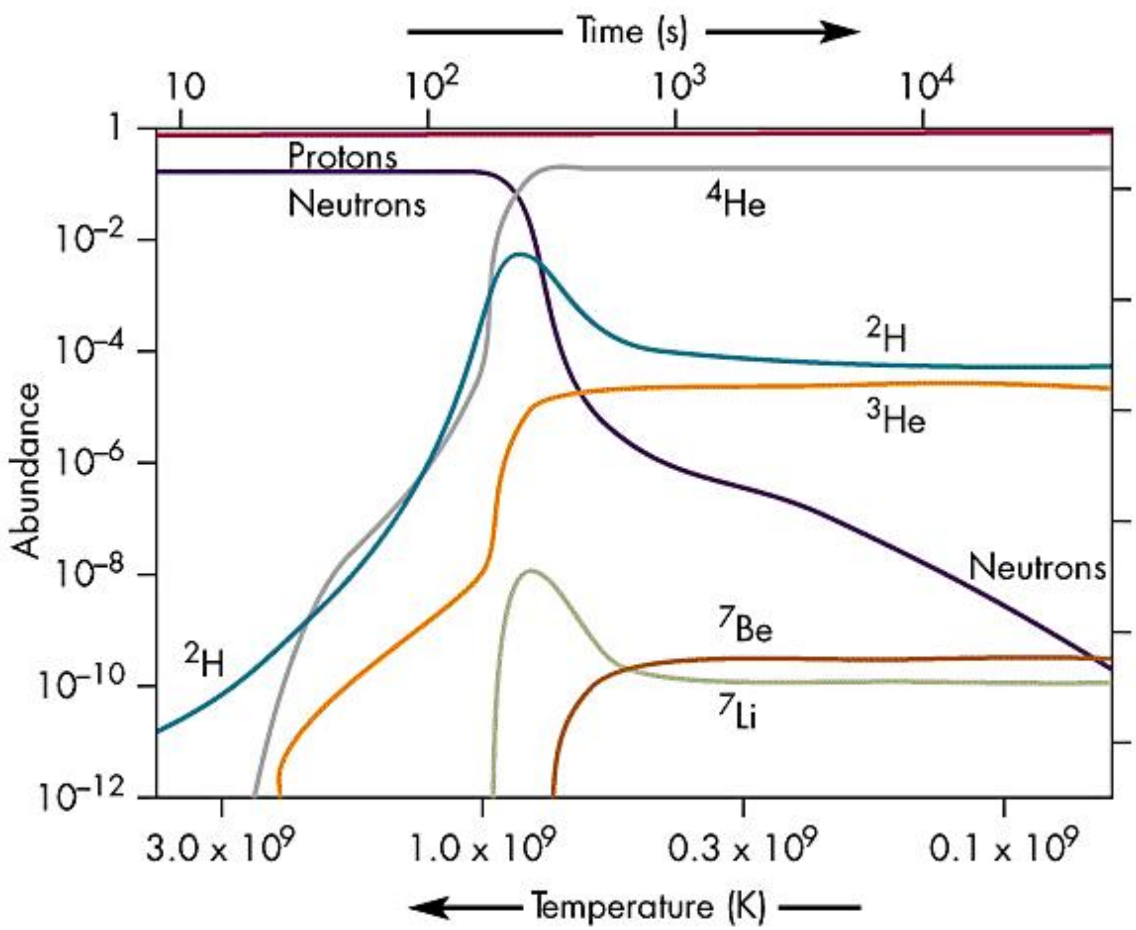
Expansion/Contraction of the Universe with Time for Different Models



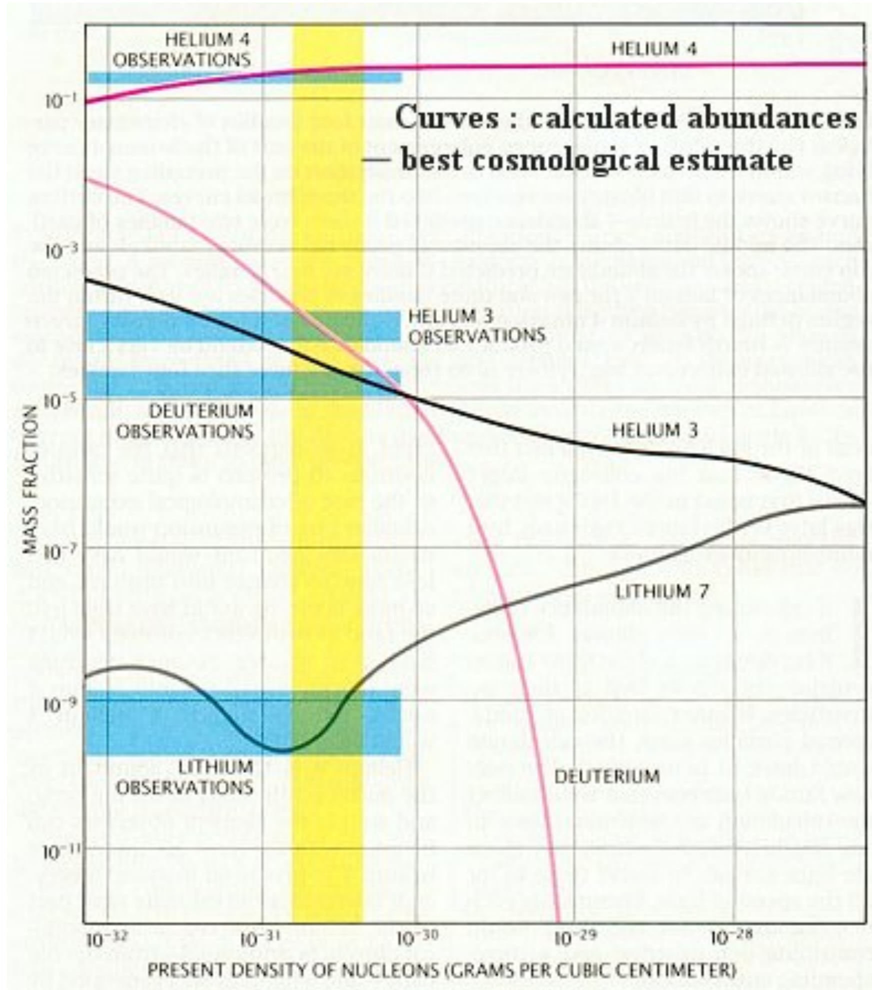
The High Energy Early Universe: Pair Production and Annihilation

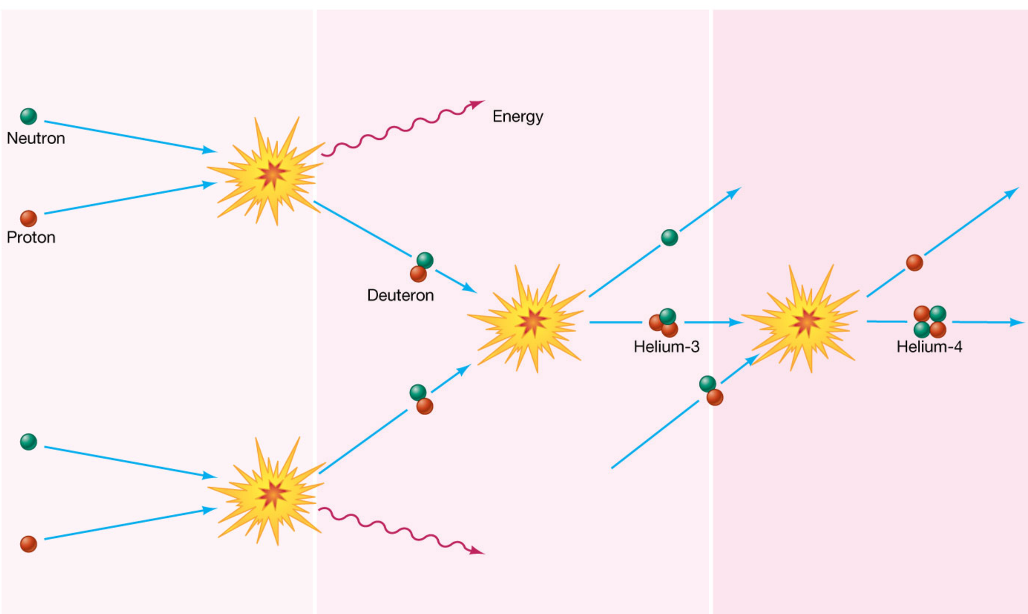


Nucleosynthesis in the Early Universe: Predictions of the Big Bang Model



Big Bang Nucleosynthesis Constraints

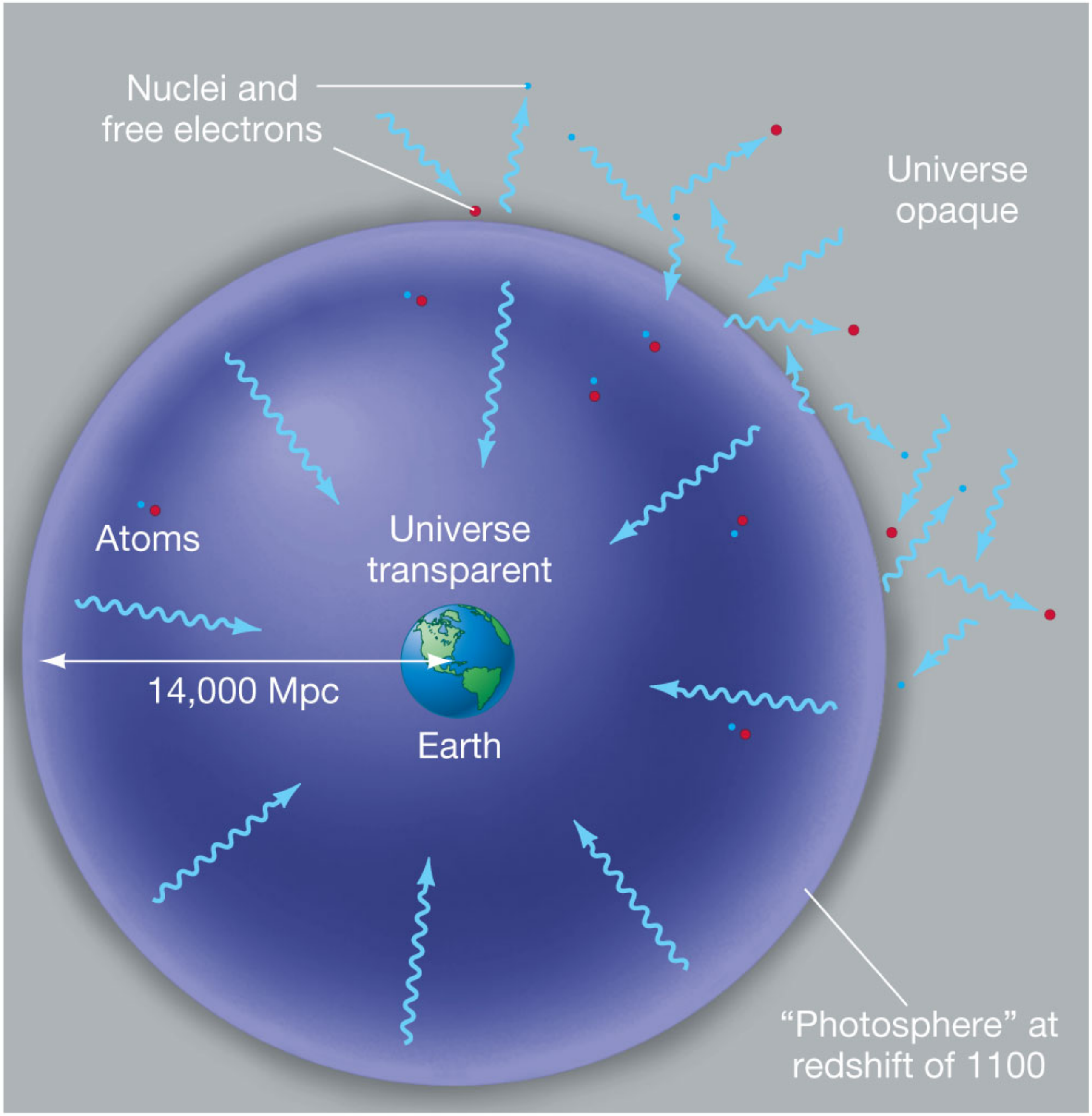




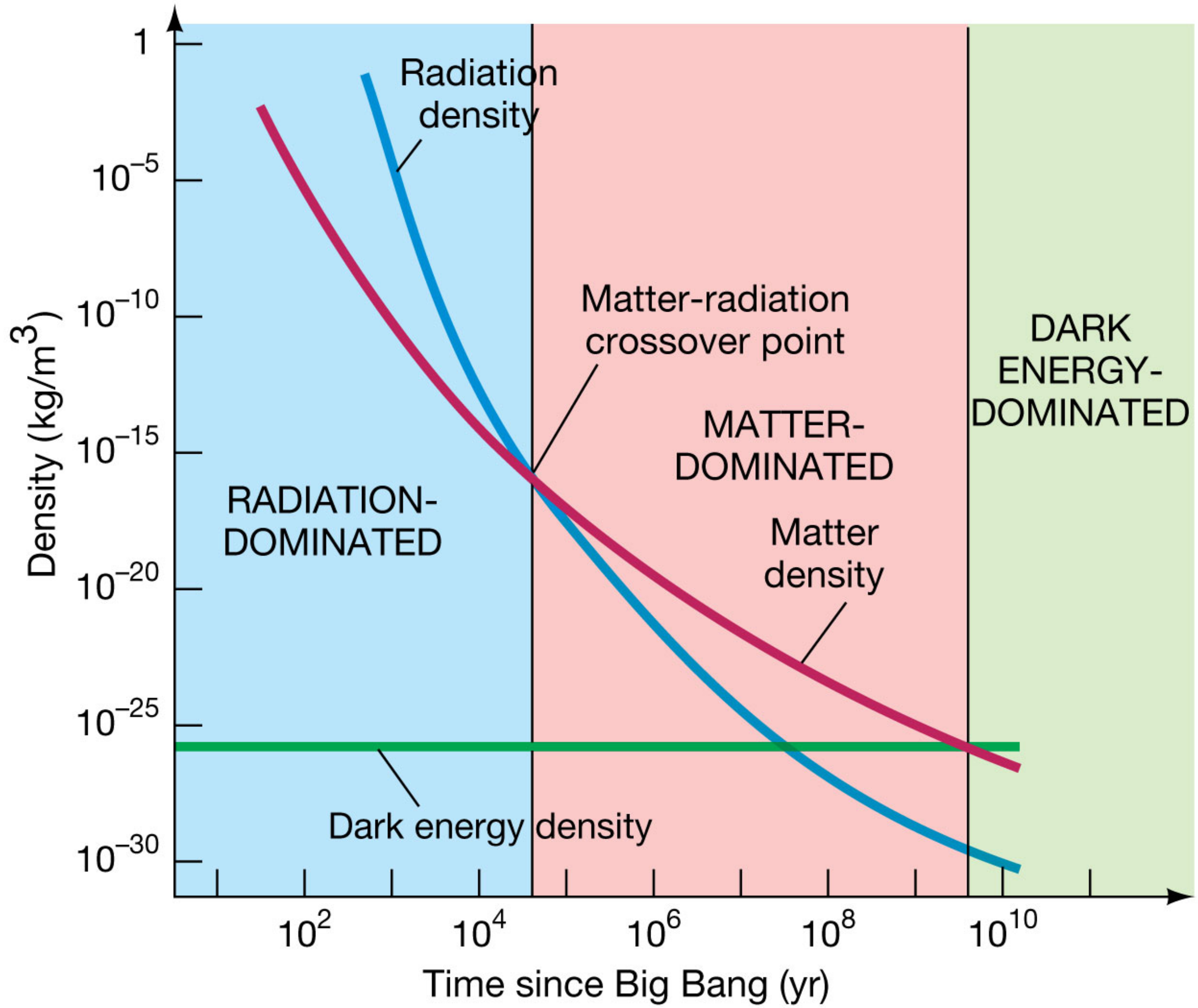
Big Bang Highlights (cont.)

4) At t ~ 700,000 yrs, T ~ 3000K, photons too weak to ionize H-atoms. Matter and light "decouple" (no longer interact)
5) At t ~ 1 billion yrs, galaxies begin to form (?)

Decoupling Era

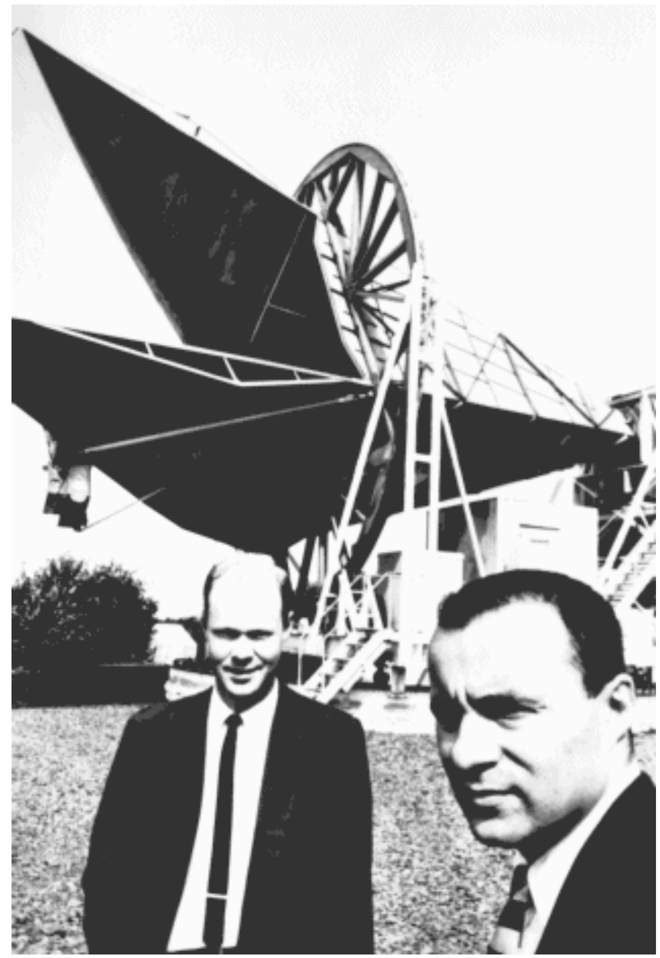


Universe Eras



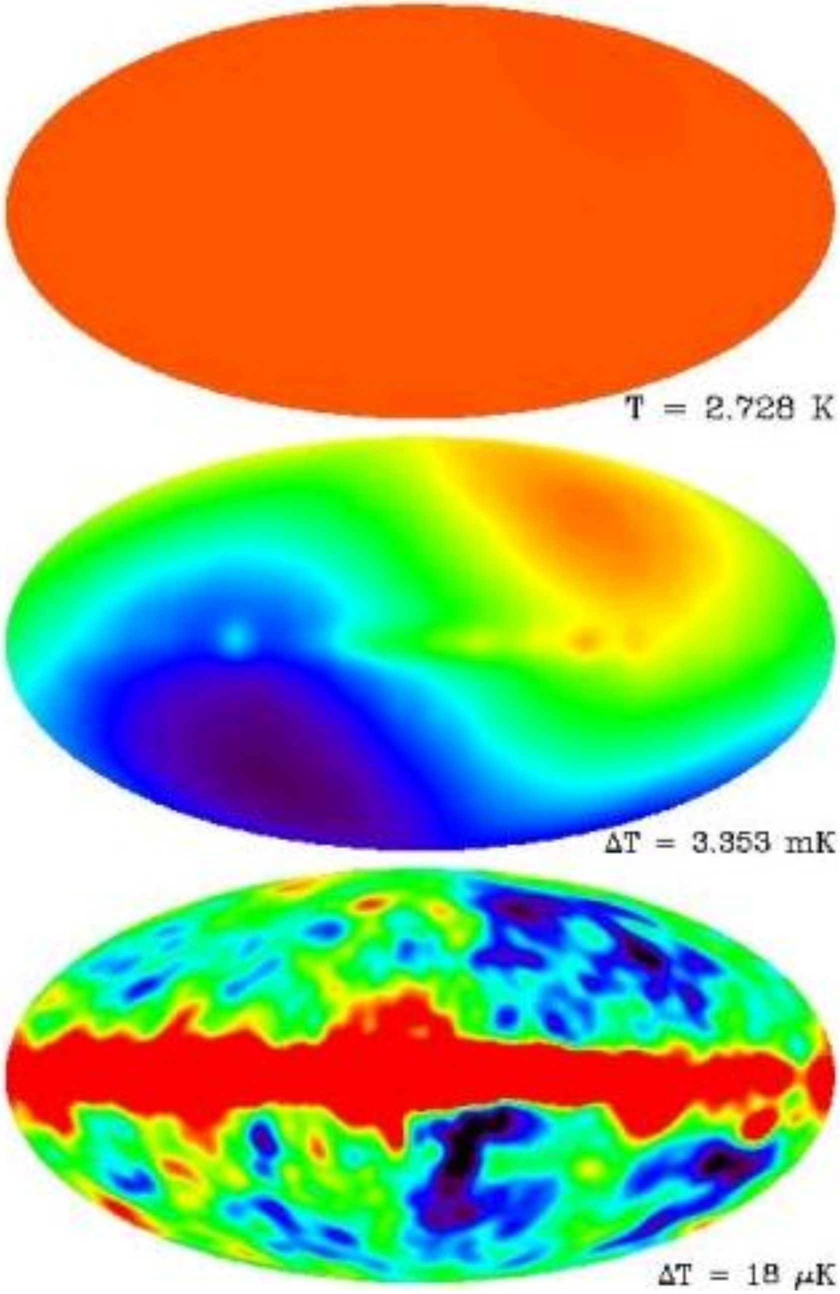
Prediction and Discovery of the Cosmic Background Radiation (CBR)

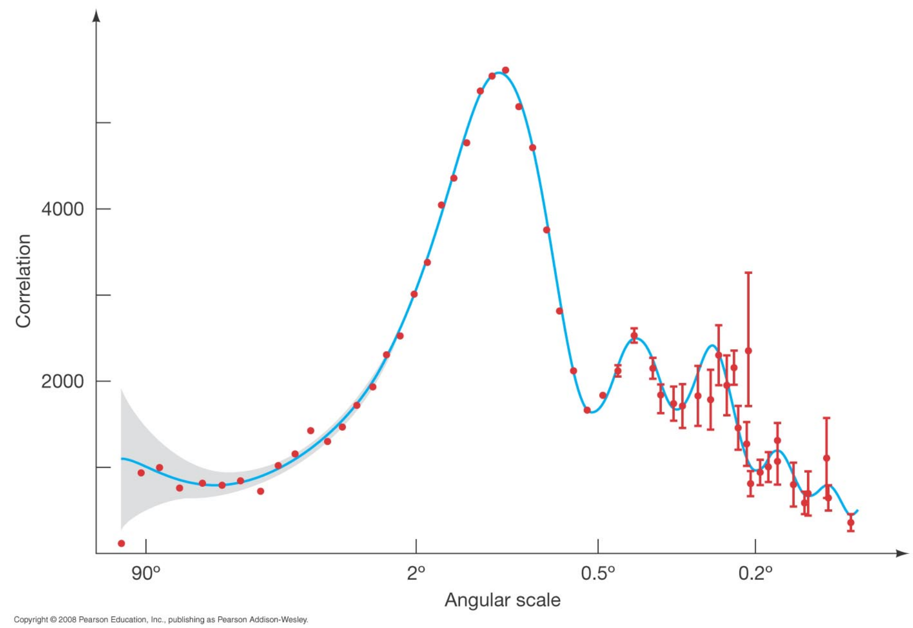
- **1940's, Gamow:** predicts
  - a remnant glow from the early, hot universe should "pervade" space and be highly redshifted
  - BB glow of T ~ 5-50K
- **1964, Penzias and Wilson:** stumbled upon CBR while looking for sources of radio interference

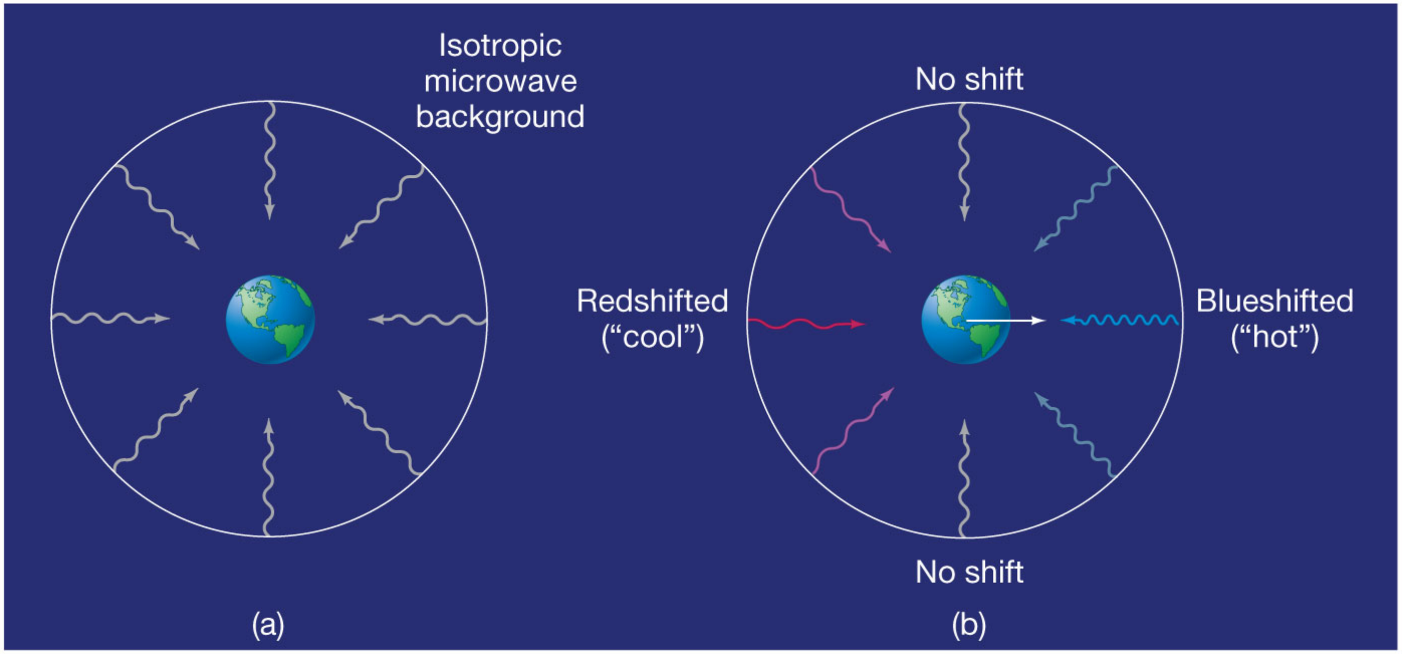


Found T=2.7K !

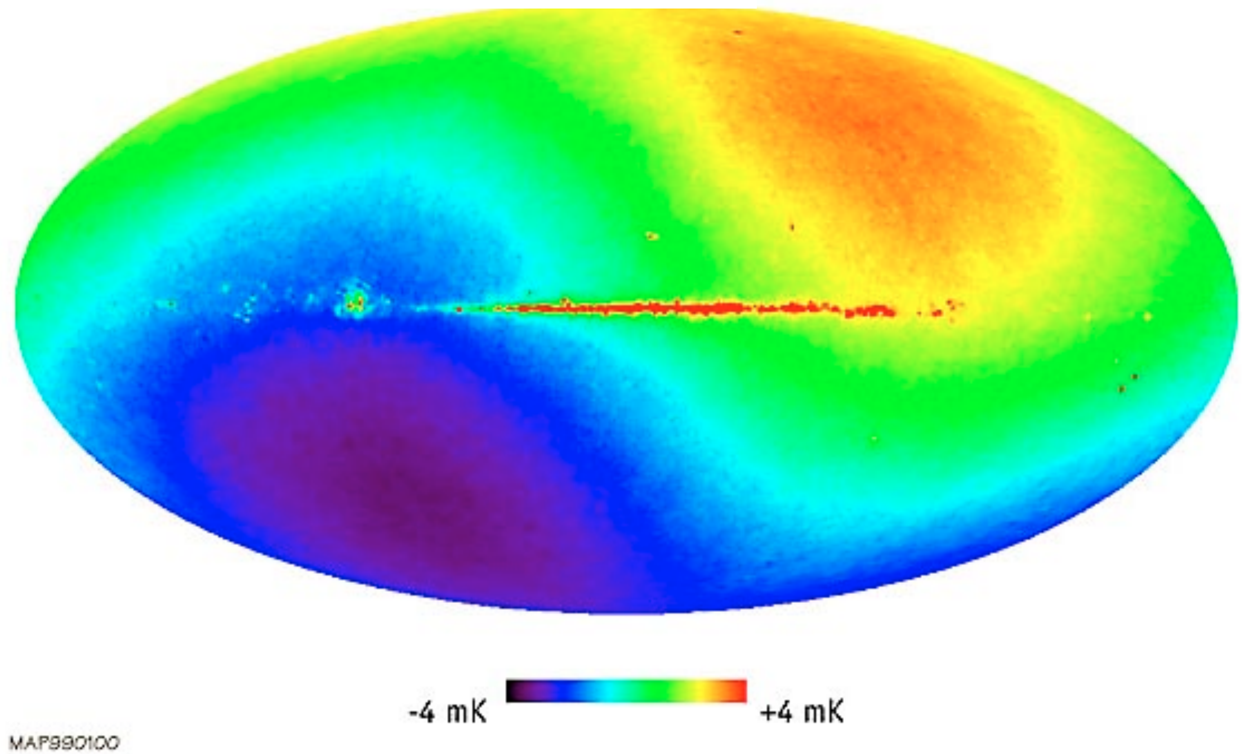
CBR Analysis

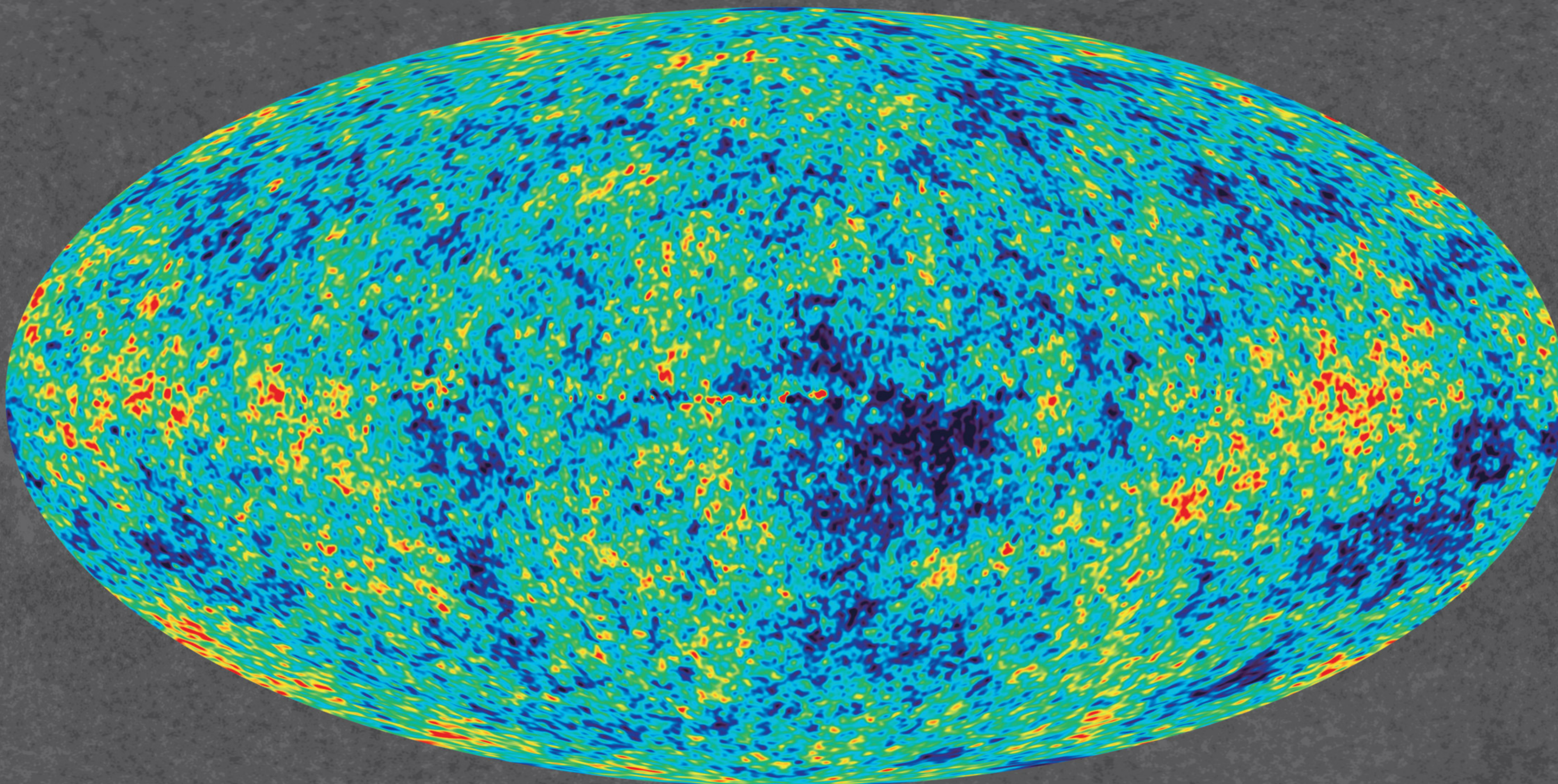





Isotropic
microwave
background
No shift
Redshifted
("cool")
Blueshifted
("hot")
No shift
(a)
(b)

CBR: Dipole


-4 mK
+4 mK
MAP990100

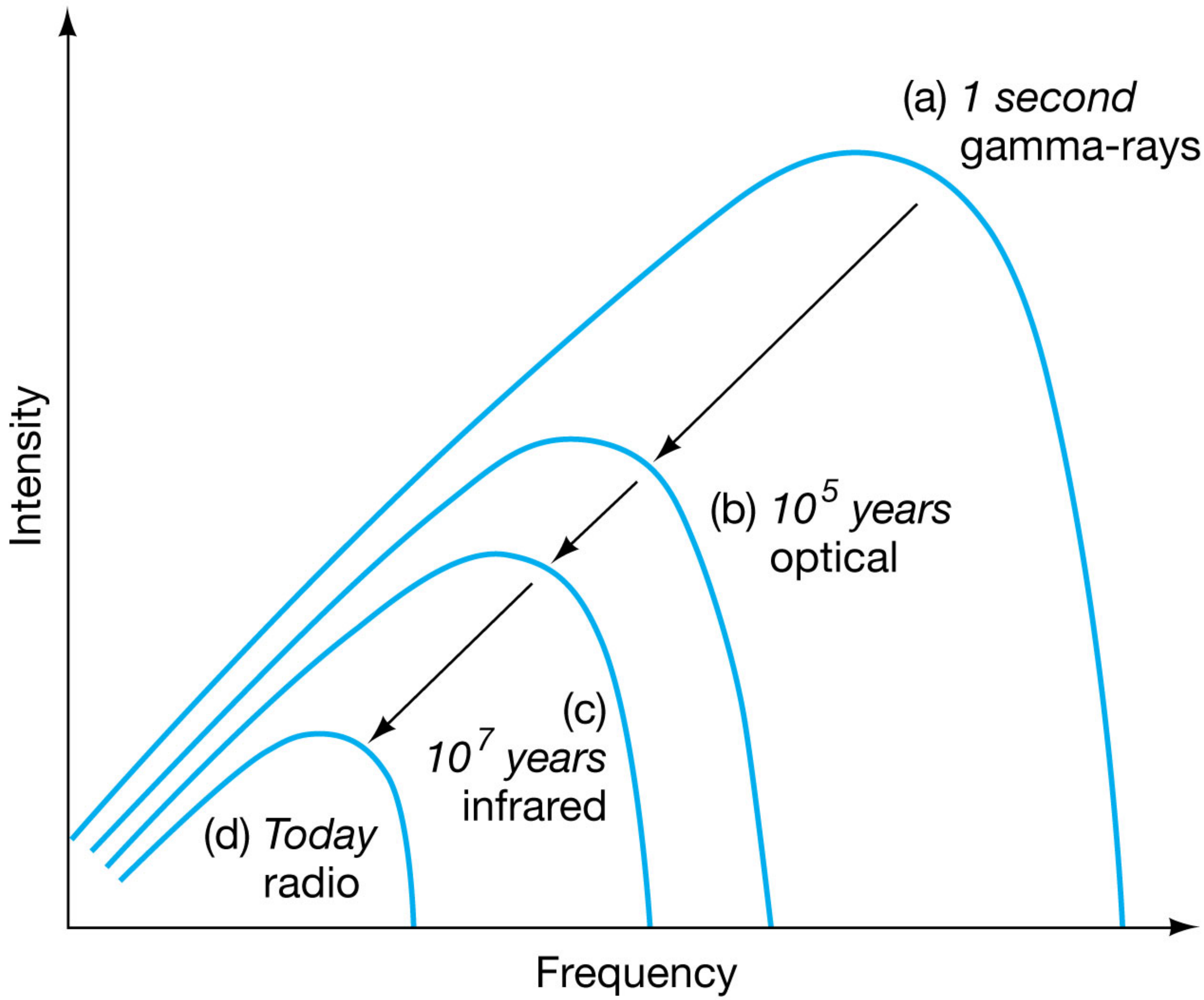


Wilkinson Microwave Anisotropy Probe

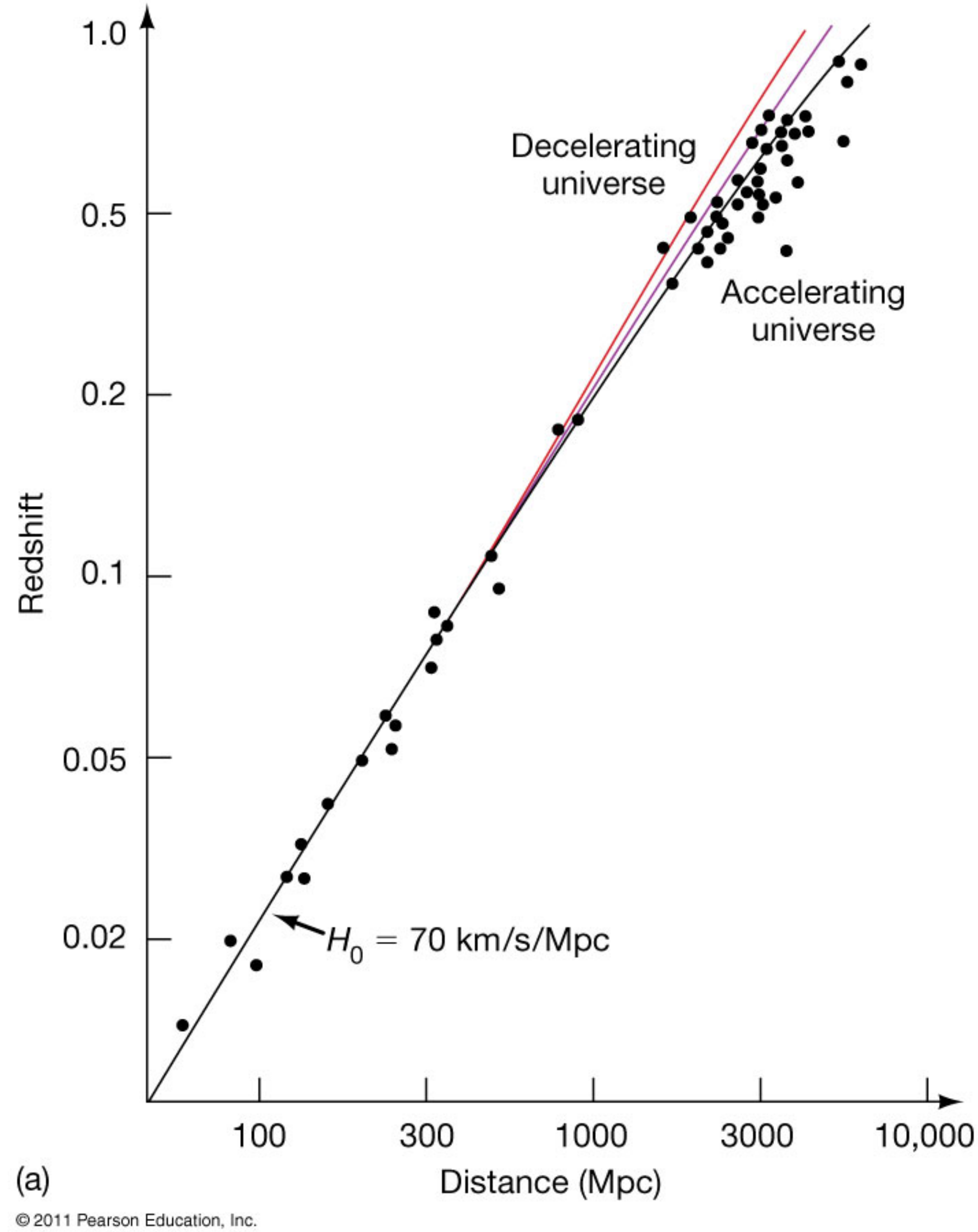
Goddard Space Flight Center • Princeton University • University of Chicago • UCLA • University of British Columbia • Brown University

http://map.gsfc.nasa.gov http://lambda.gsfc.nasa.gov

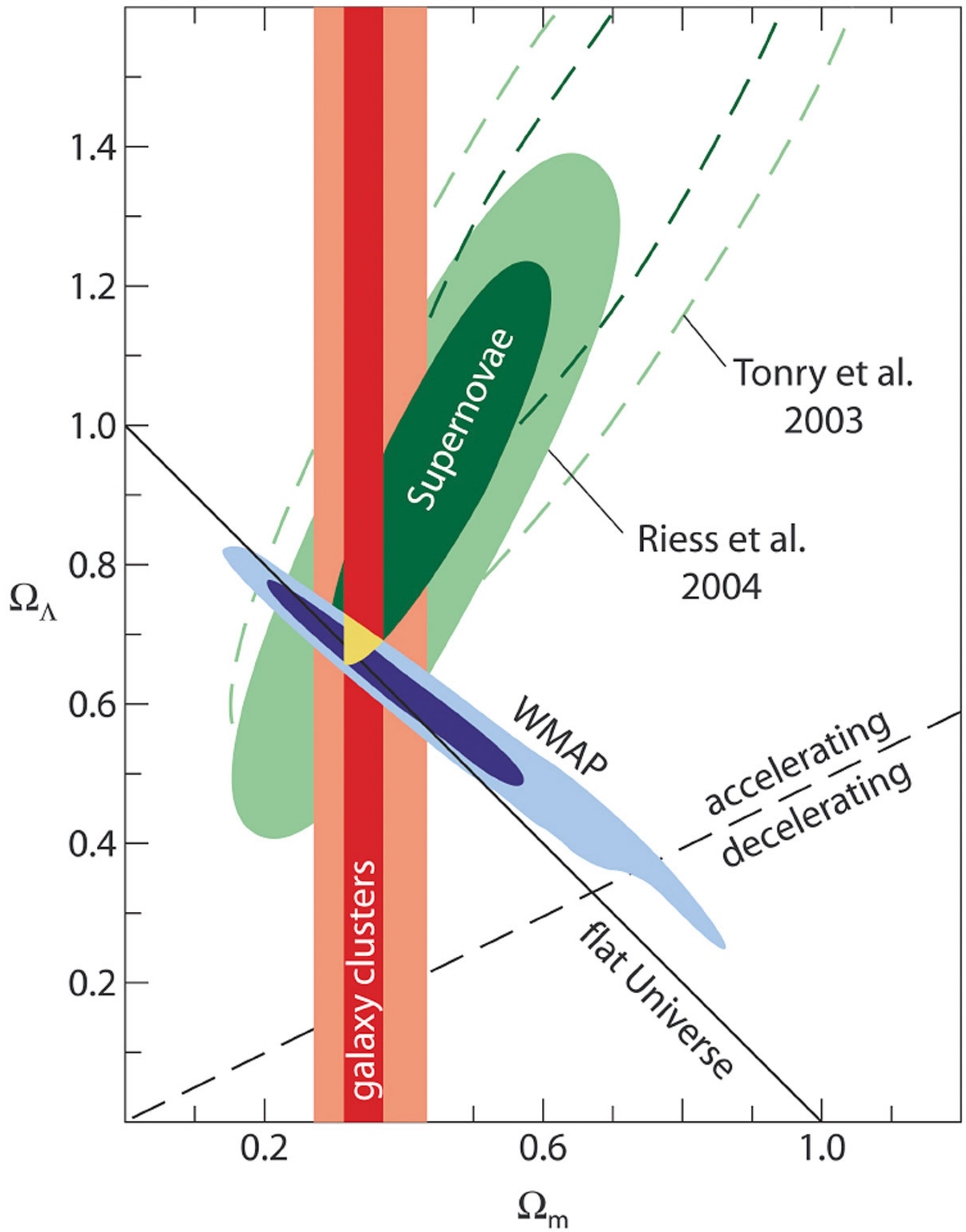
The CBR in Time

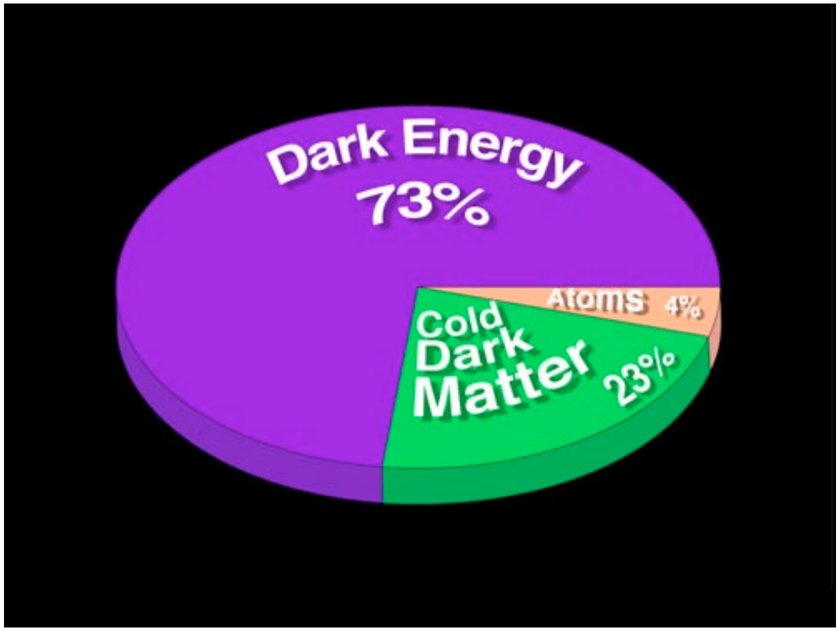


Evidence from Sne for an Accelerating Expansion of the Universe

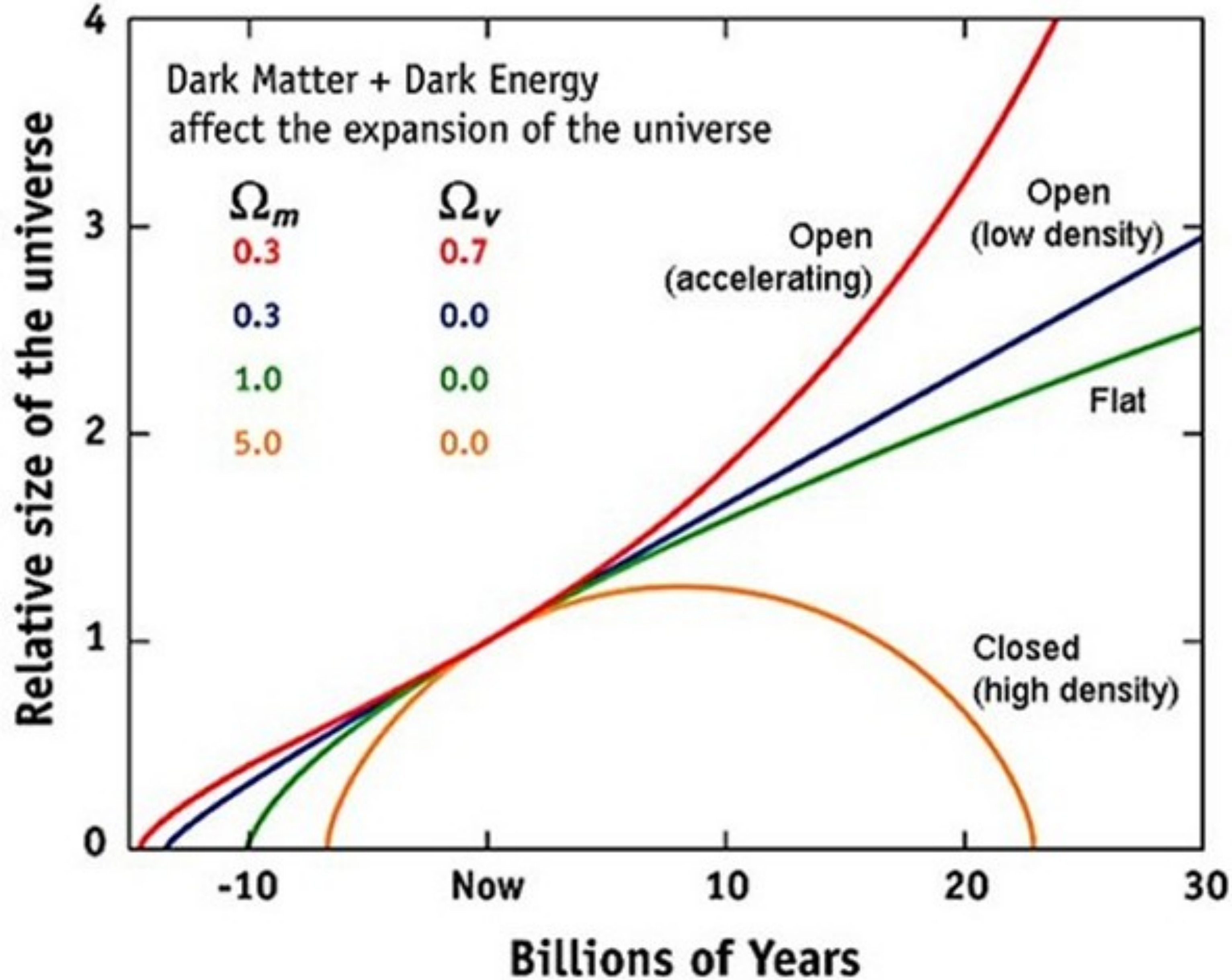


Narrowing the Scope of Cosmological Models

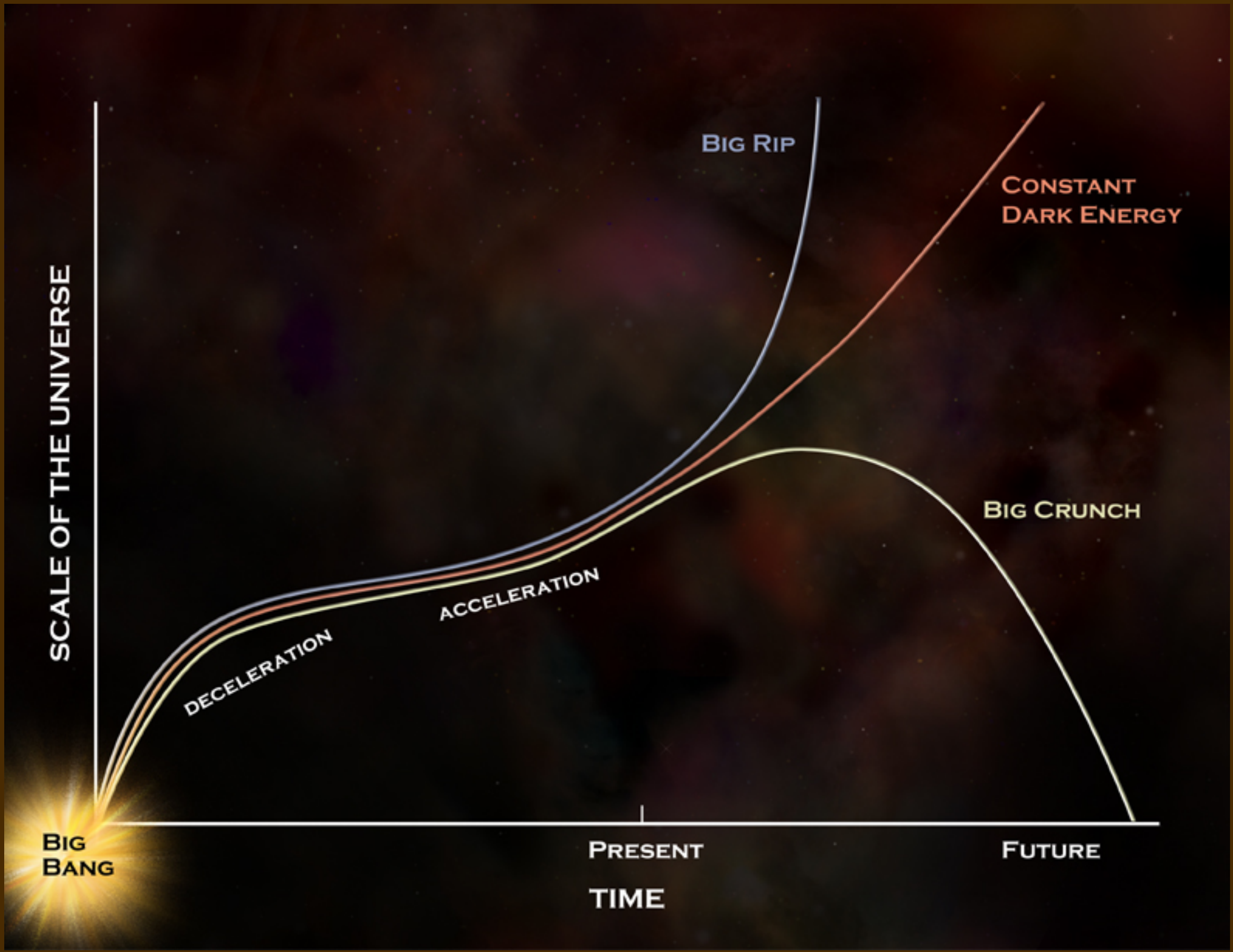




Models with Dark Energy



Cosmological Models with D.E.



Oddities of the Universe

The universe shows oddities that the Big Bang model would not predict:

- *Flatness problem* - the curvature of space could be positive or negative to any degree, or just exactly zero ("flat"); it appears to be very near zero; why that special value?!

- *Horizon problem* - the cosmic background temperature is extremely uniform, but how can one side of the universe "know" about the temperature at the other side?!

Inflationary Theory

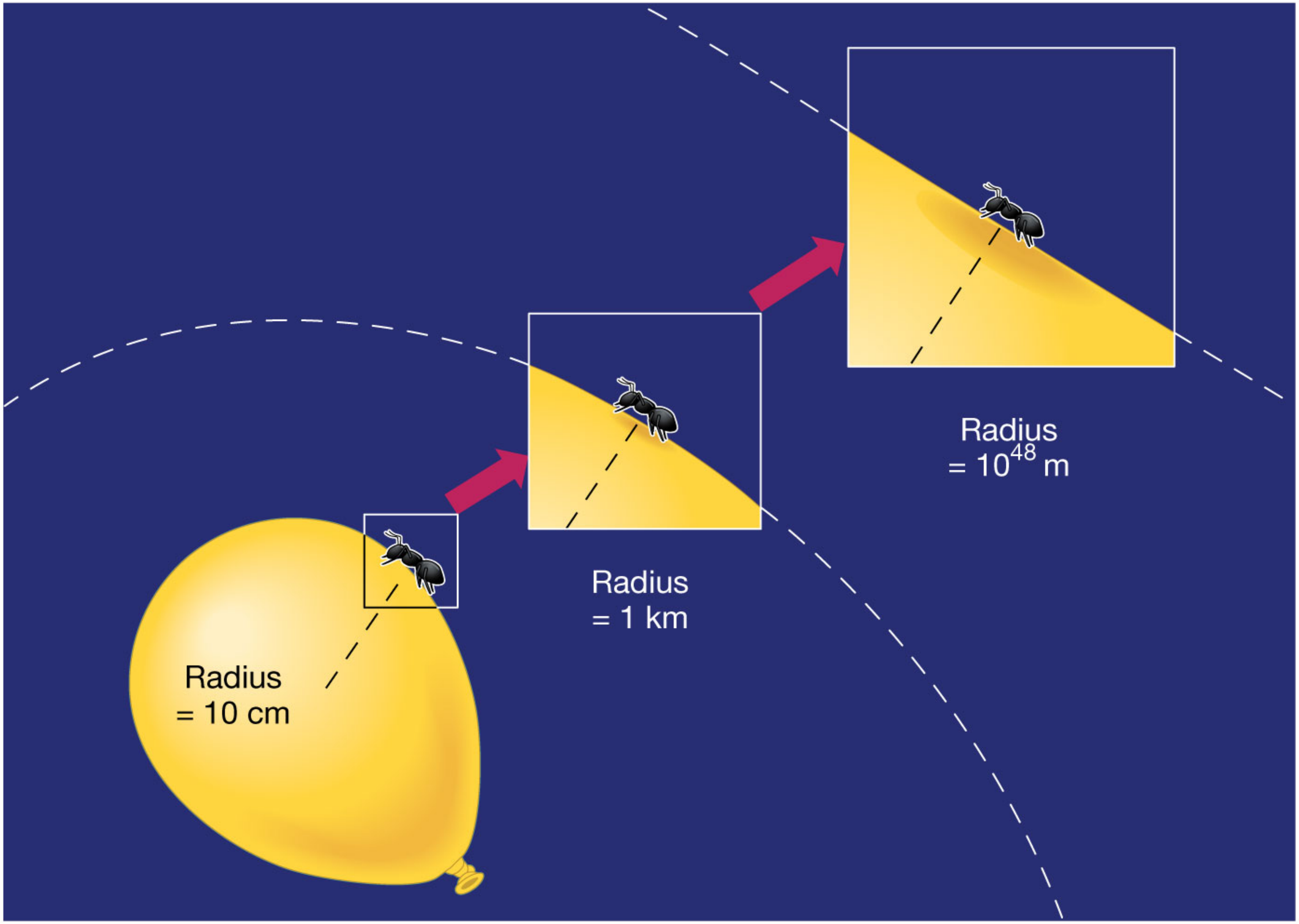
- This is a fairly recent theory that attempts to explain the oddities. It suggests an early, short period of **exponential** expansion of space.

- How does this help?
  - If you take a ballon and manage to expand it to the size of the Earth, then its surface will appear to be flat like the ground, even though you know that the surface is curved and closed. Rapid expansion makes any kind of initial curvature appear flat.
  - Also, rapid expansion suggests that regions vastly separated today were far more intimately connected in the past.
  - YES, we are talking about faster-than-light-speed expansion of space.

- Physical Motivation: Production of the major forces of nature. As if the universe experienced a paradigm shift and went ballistic. :)

- Evidence: It explains some oddities, plus details about the CBR fluctuations are consistent with predictions of inflationary theory.

Inflation and the Flatness Problem



Graphic for Inflation