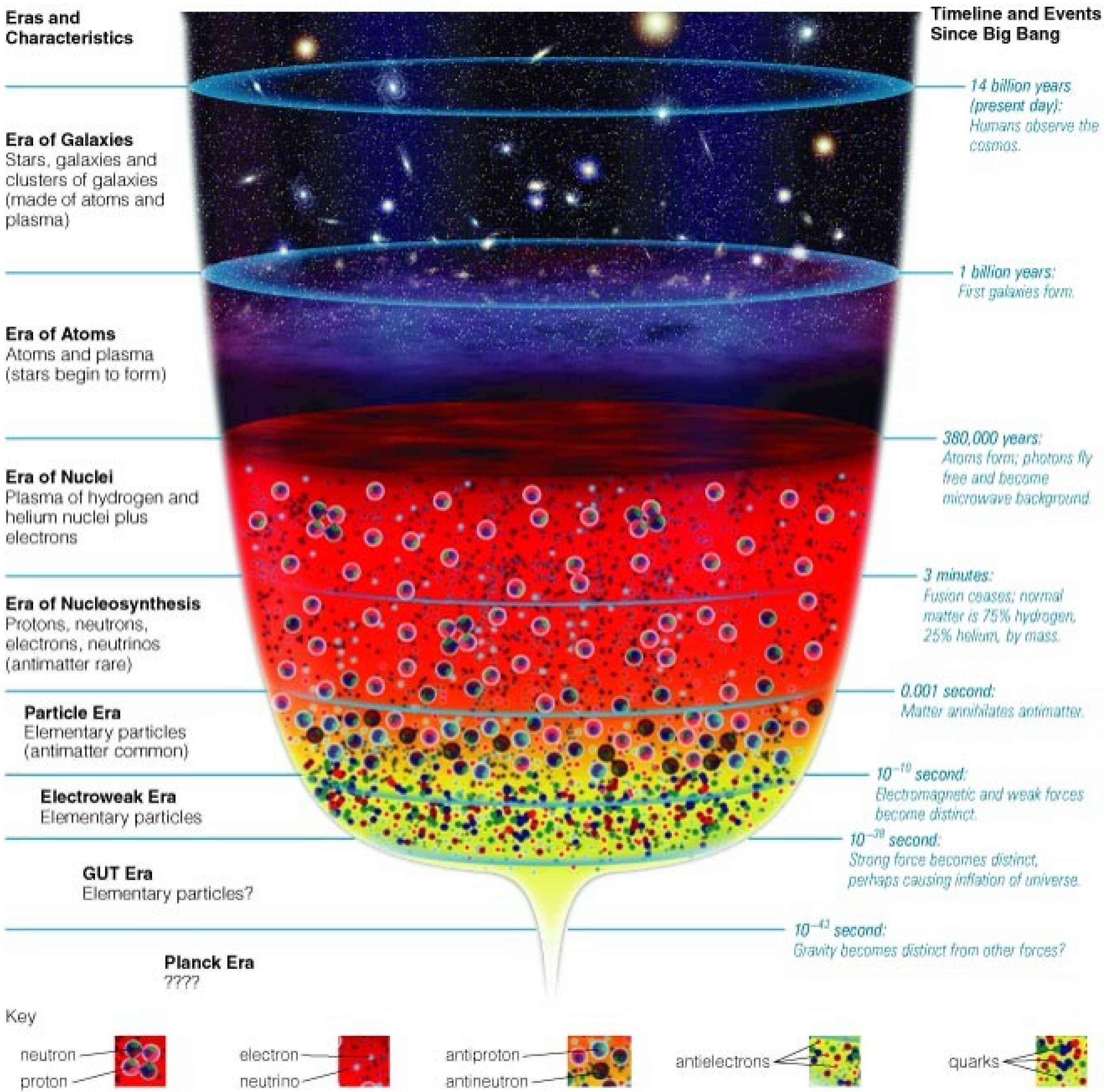
PHY126 Overview



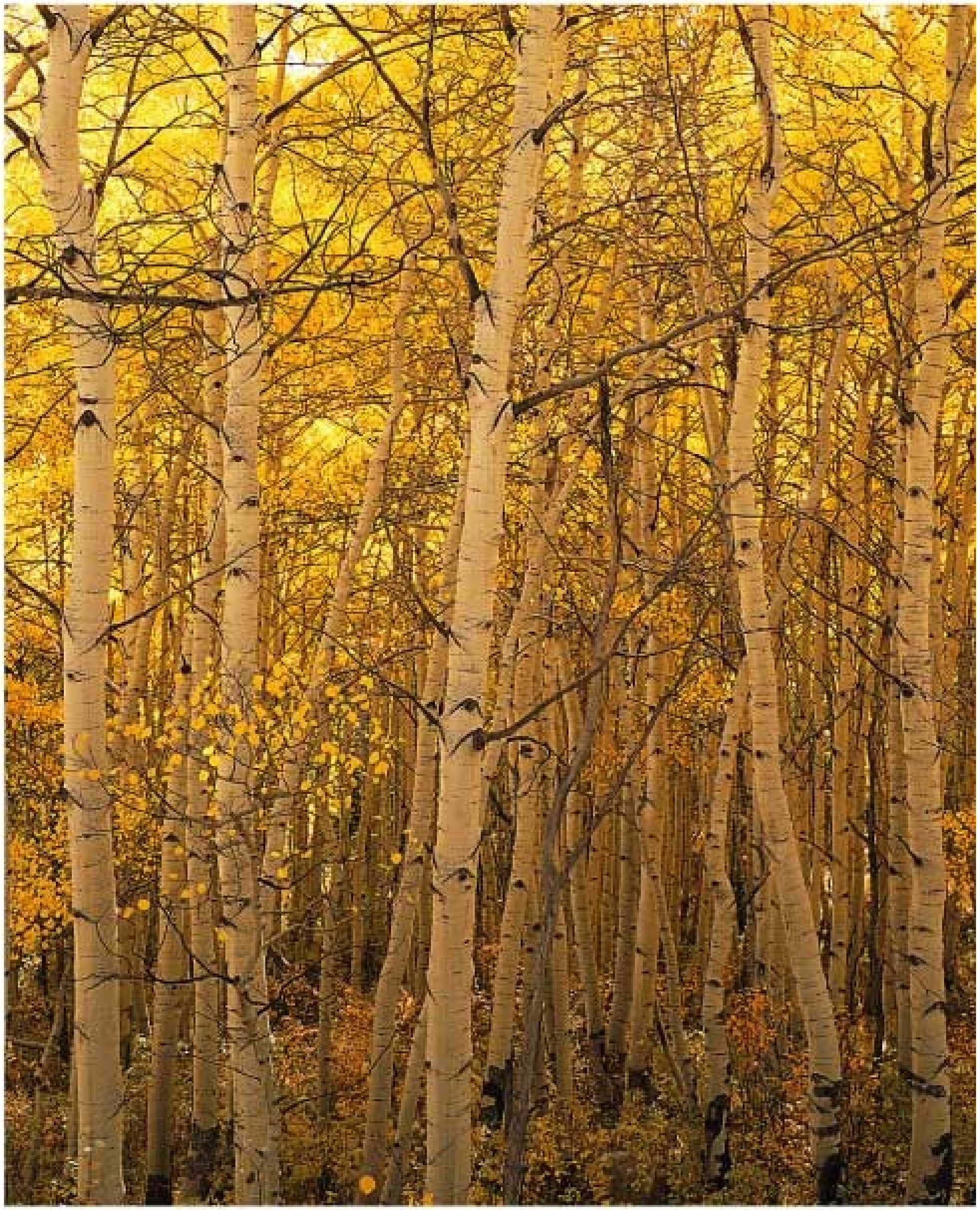
Disclaimer

- These slides are at a basic level, but contain a *lot* of material. (An overview of the whole course!)
- Don't feel overwhelmed when we cover this in a single lecture. The point is to stimulate your curiosity, rather than for you to master all the details.
- We will revisit each subject in much more depth later.
- You may also find the PDF file useful for review later.

Basic Observations

- Olbers' “paradox”: night sky is dark
- isotropy
- Hubble's Law: $v=Hd$
- mass fraction of He is ~25%
- age of oldest stars ~12 Gyr
- Cosmic Microwave Background (CMB): T=2.73 K (with order 10^{-5} fluctuations)

Olbers' Paradox



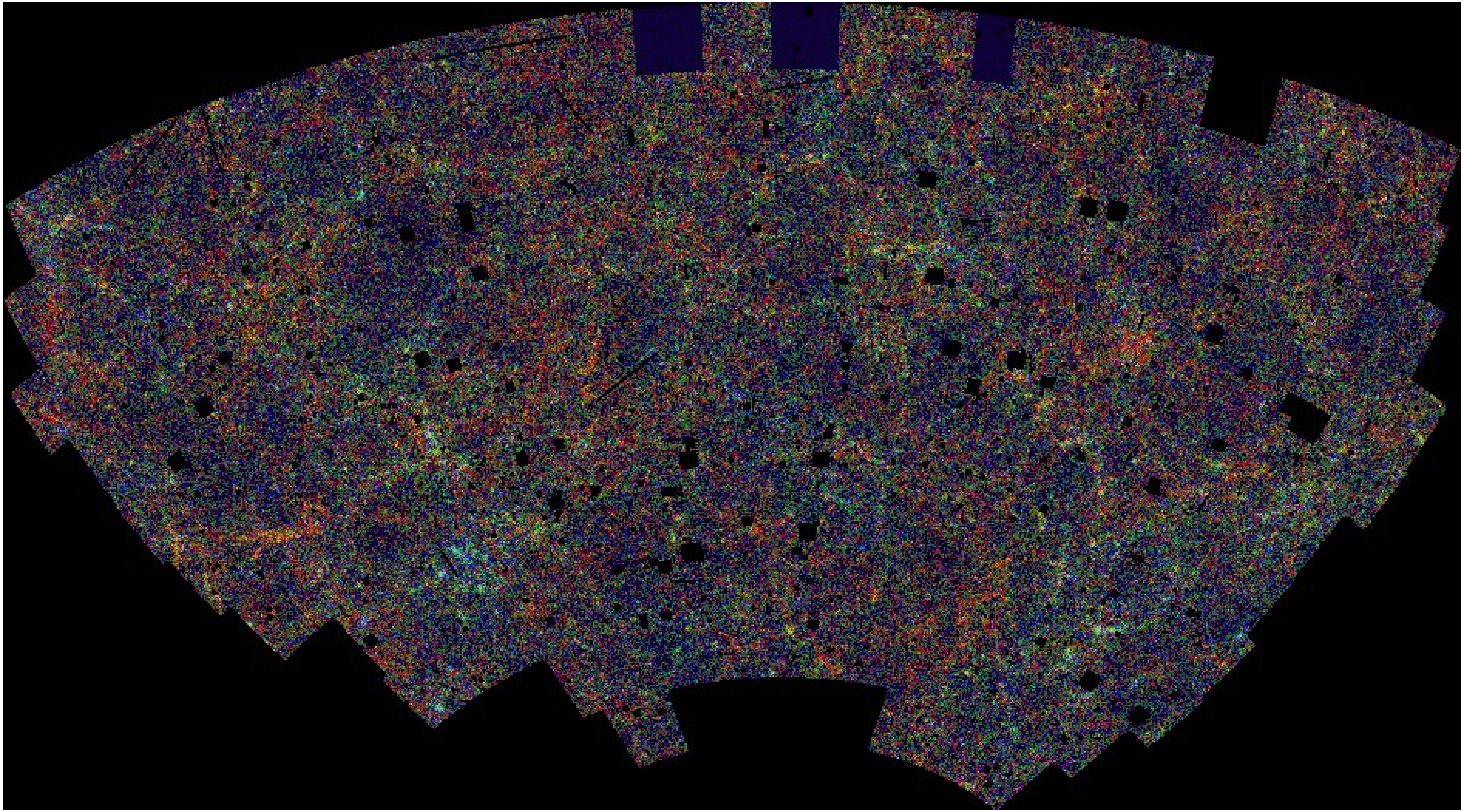
Olbers' Paradox: Answer

"Were the succession of stars endless, then the background of the sky would present us an uniform luminosity, like that displayed by the Galaxy -since there could be absolutely no point, in all that background, at which would not exist a star. The only mode, therefore, in which, under such a state of affairs, we could comprehend the voids which our telescopes find in innumerable directions, would be by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all."

Edgar Allen Poe, *Eureka*, 1848

Note: redshift helps also, but we'll cover that later.

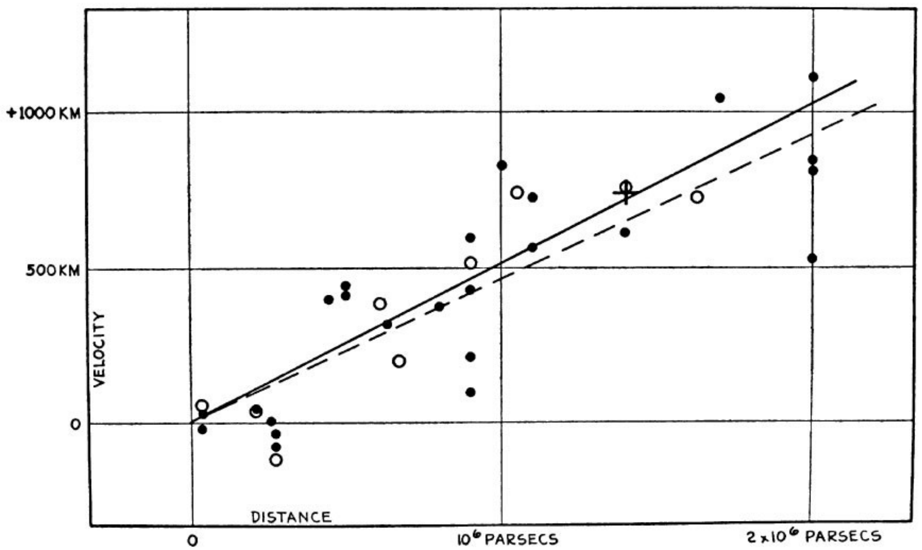
Isotropy



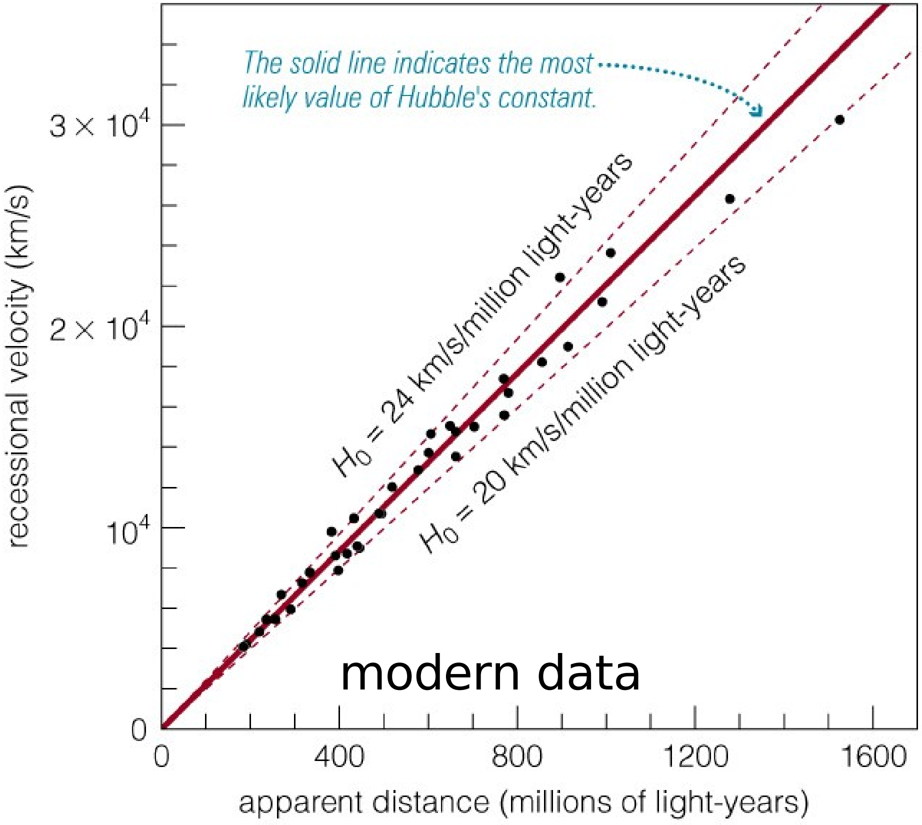
APM galaxy survey: ~100x50 deg area. Color encodes number of galaxies in each pixel.

Hubble Diagram

- galaxies are moving away from us
- more distant ones are moving away faster: $v=H_0 d$ where H_0 is Hubble constant, ~70 km/s/Mpc
- does this mean we are at the center?



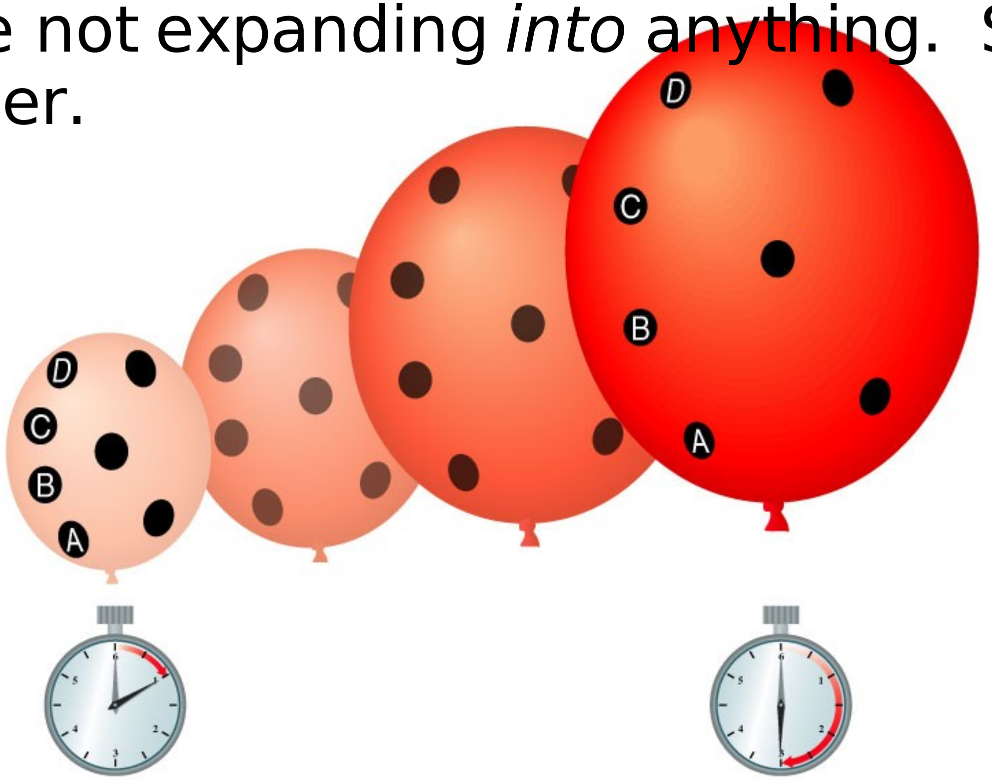
Hubble's original data



modern data

Cosmological Principle

- Assume we do not occupy a special position or time. In fact, assume there *is no* special position.
- All galaxies are rushing away from all other galaxies!
- Requires no center and no edge, fits all data.
- Galaxies are not expanding *into* anything. Space itself is getting bigger.



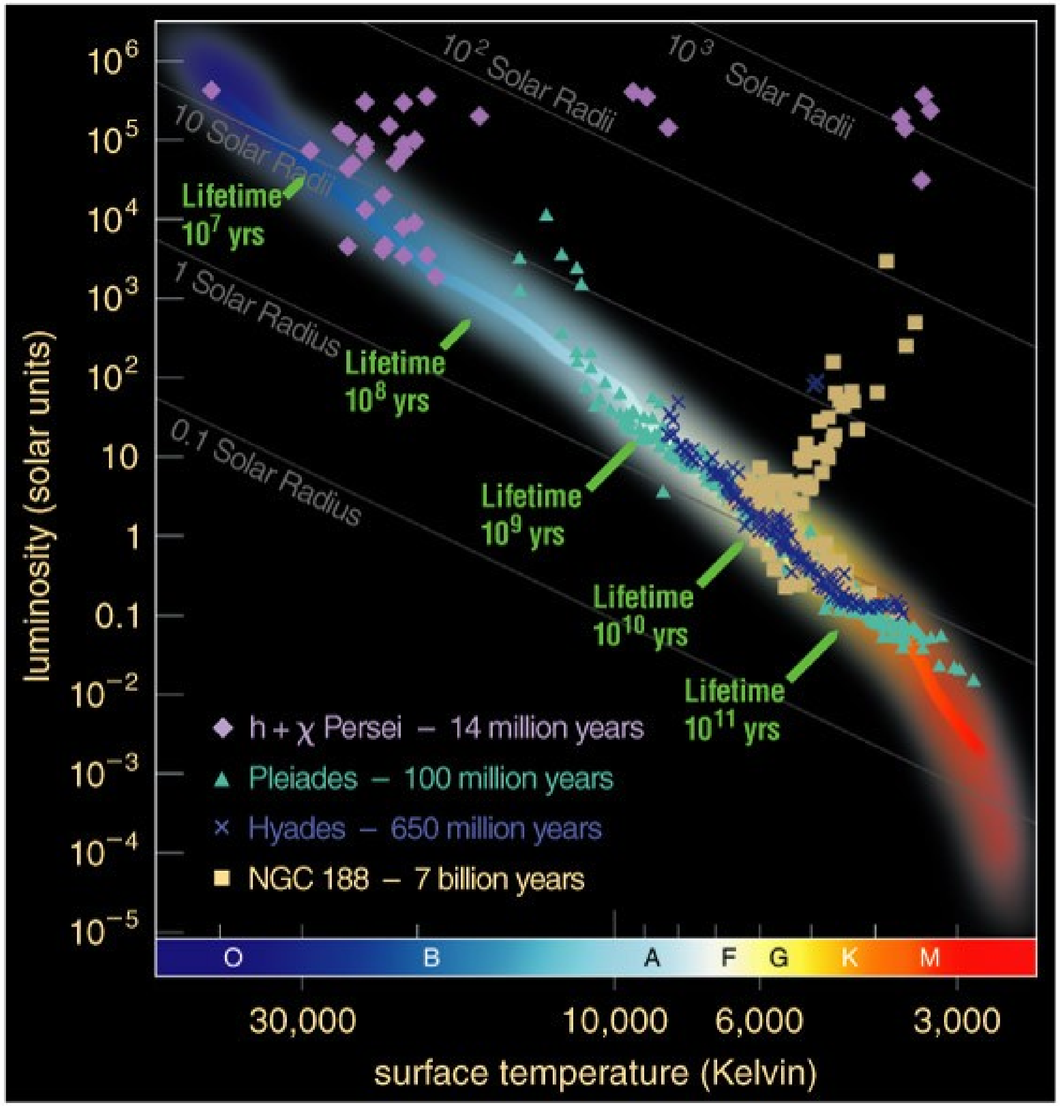
Big Bang: Age Example

A galaxy 1 billion light-years away is receding at 24,000 km/s (Hubble's constant is 24 km/s per million ly). When was its distance zero?

- 10^9 light-years = 10^{22} km
- 10^{22} km / 2.4×10^4 km/s = 4.2×10^{17} s or 13.2 billion years
- Just greater than age of oldest stars!

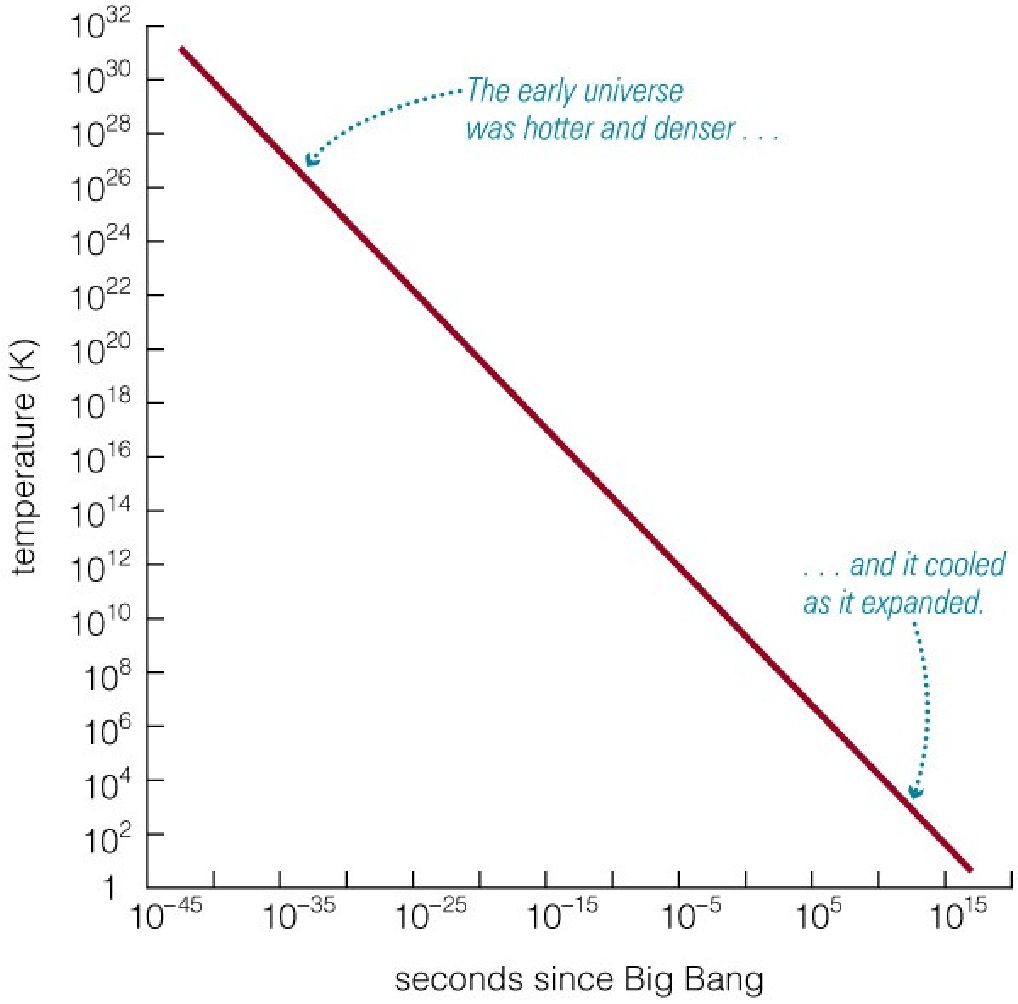
Stellar Ages

- oldest star clusters (not shown here) are 13 billion years old
- how does that compare to Big Bang estimate?



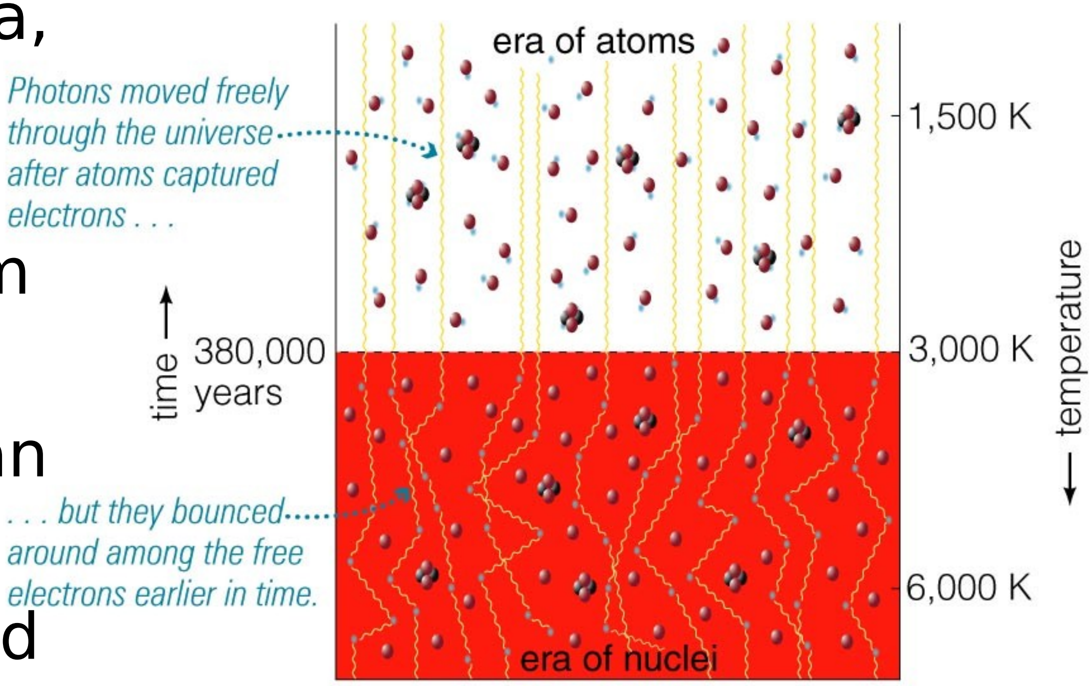
Hot Big Bang Cosmology

- if universe is expanding, it must have been denser and hotter in the past
- what would be the observable consequences of this?

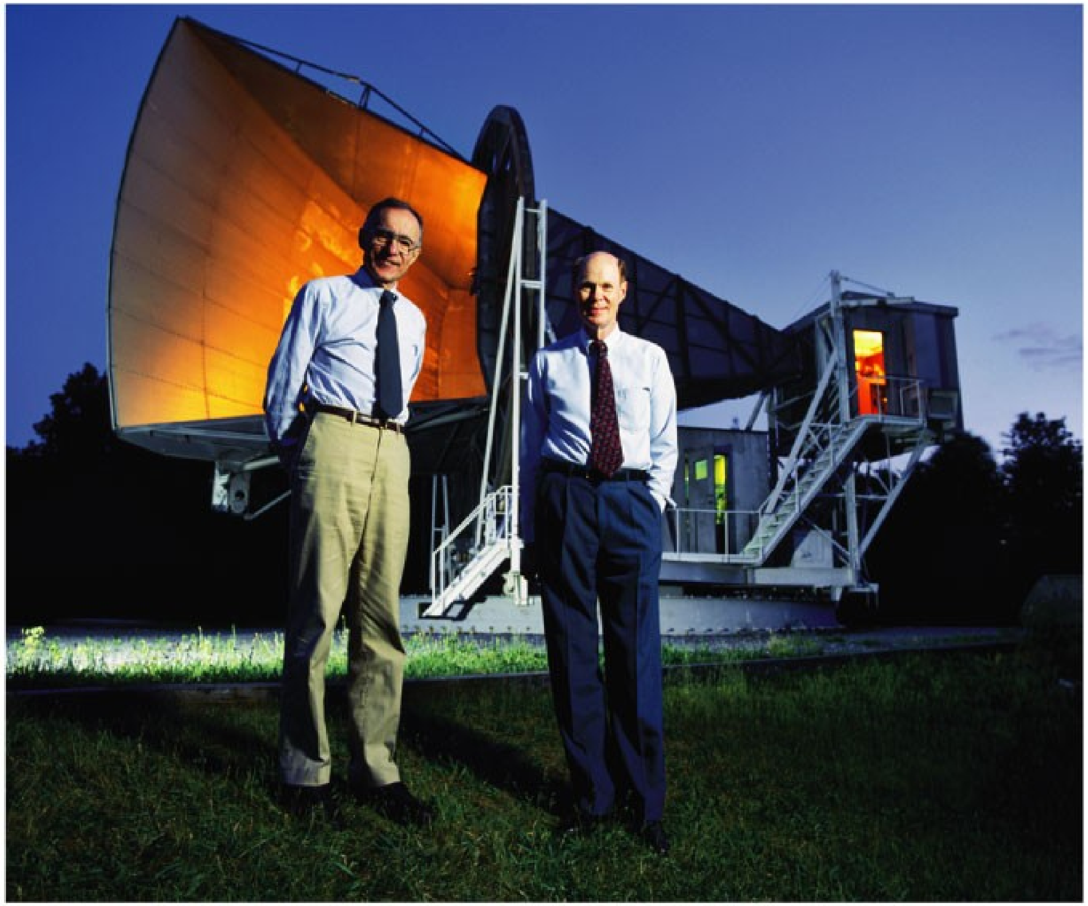


Cosmic Microwave Background

- thermal radiation left over from era of plasma, predicted 1948
- 1950's: temperature predictions ranged from 5-50 K
- 1960's: observers began to look for it
- what wavelength should it be?



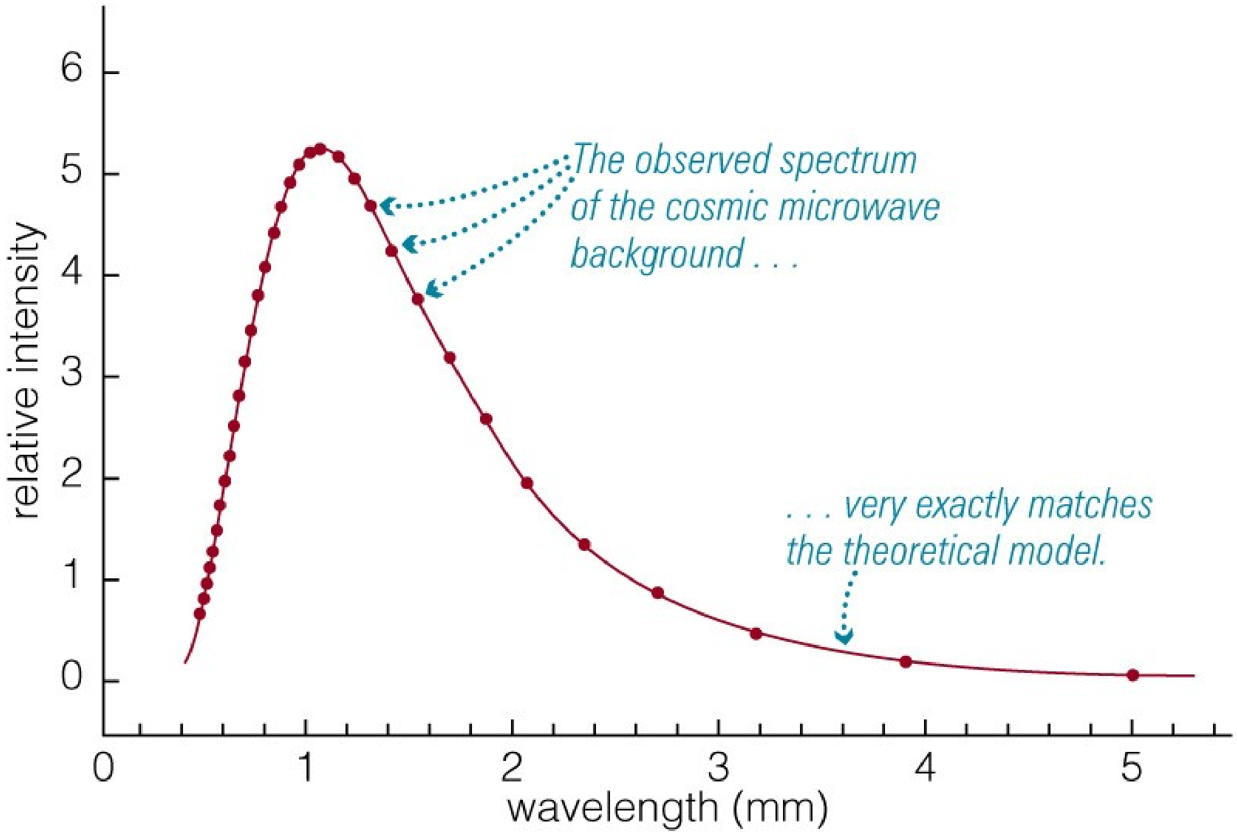
Penzias & Wilson

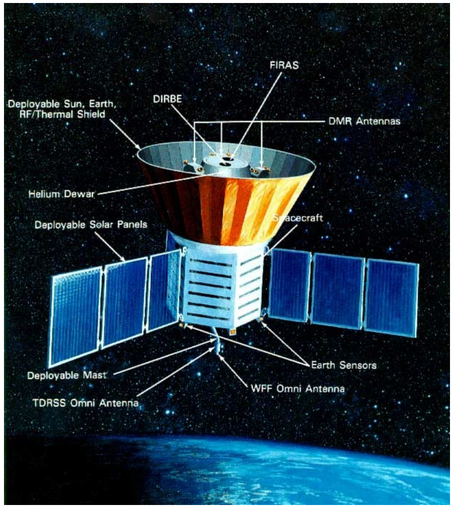


- stumbled into CMB in 1965 while studying galaxy
- found excess ~3 K thermal radiation in all directions (~1 mm wavelength)
- only later realized what it was
- Nobel Prize 1978

CMB Spectrum

Most Perfect Thermal Emitter Ever Measured!





COBE, early 1990's

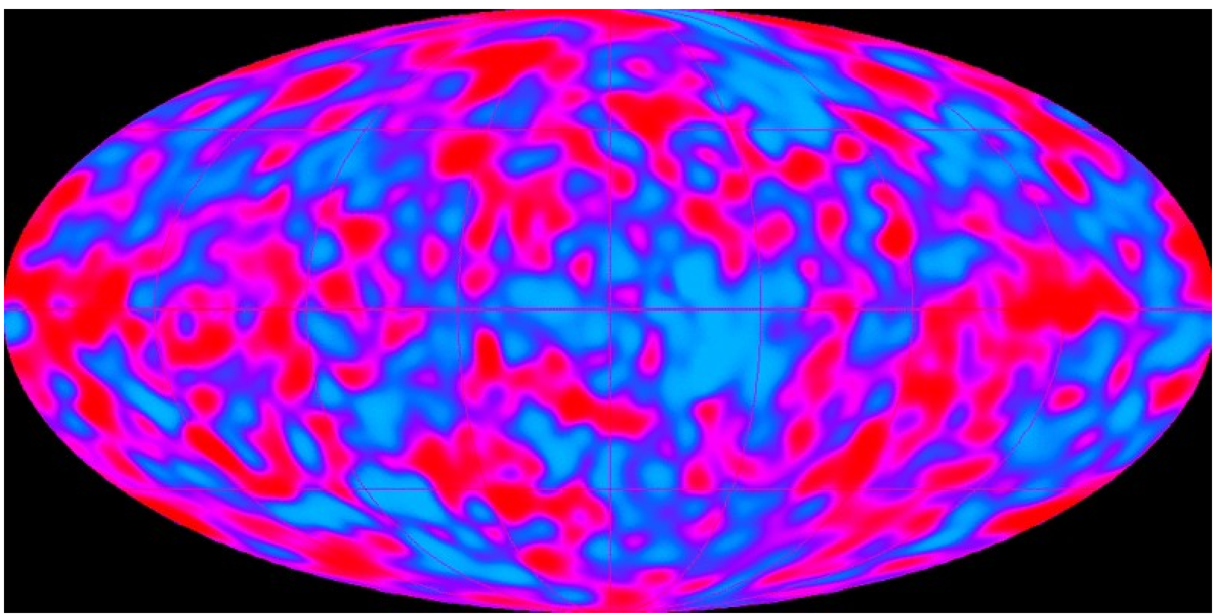
John Mather
2006 Nobel Prize

CMB Fun Facts

- ~400 photons per cm^3
- speed of light is large! 10^{13} photons per cm^2 per second!
- accounts for a few percent of the TV “snow” you see between stations (for those of you without cable…..)

Initial Conditions

- full description of a system includes physical laws *and* initial conditions (more generally, *boundary conditions*)
- the initial conditions for these simulations come from bright and dark spots in the CMB



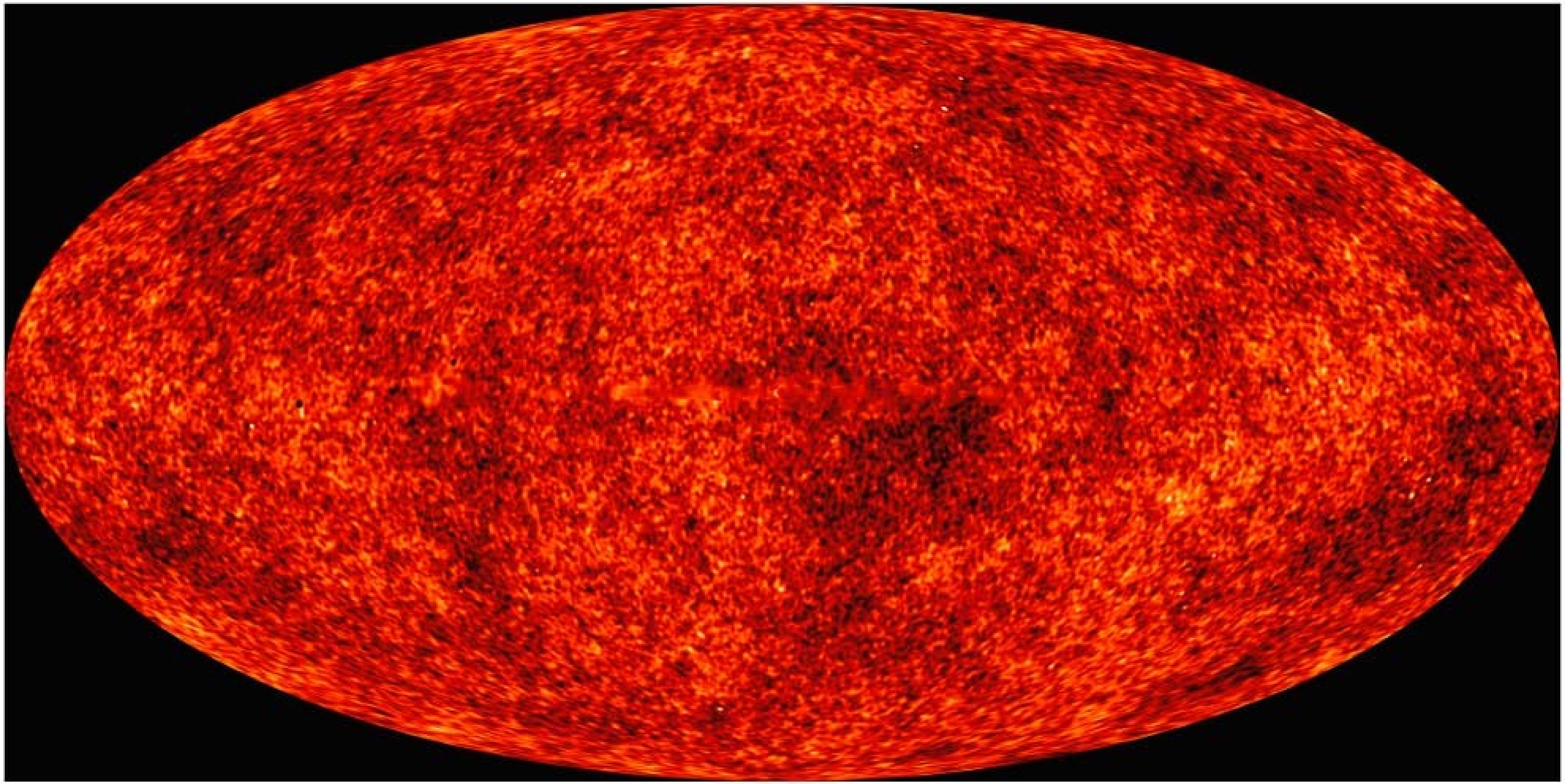
first map of CMB fluctuations, early 1990's, COBE mission

George Smoot
2006 Nobelist

Universe's Baby Pictures

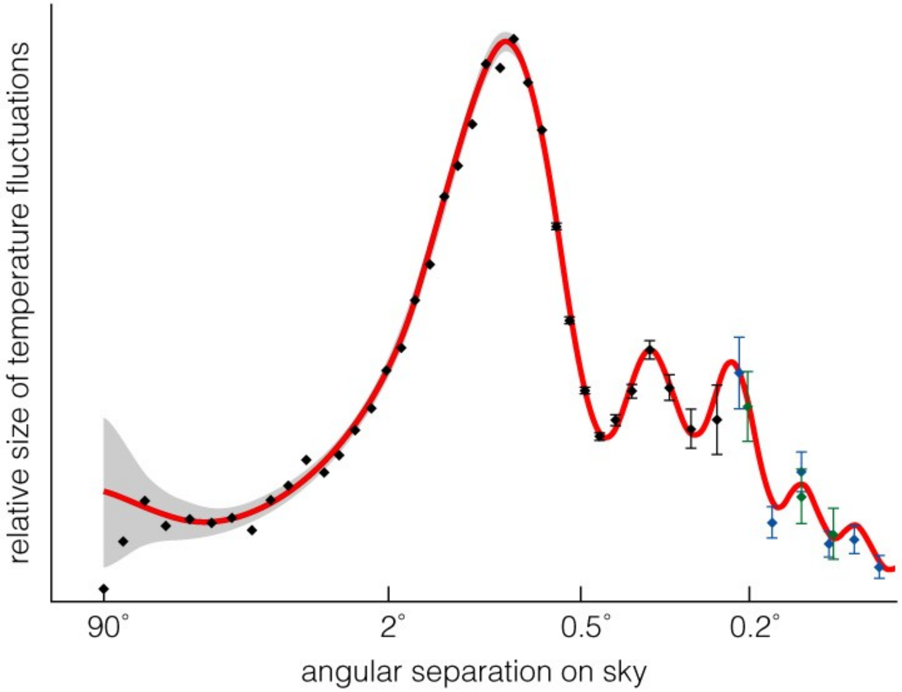
Cosmic Microwave Background, Imaged by WMAP Satellite

Emitted at ~380,000 years old. Bright spots are only ~10^{-5} brighter than dark spots!



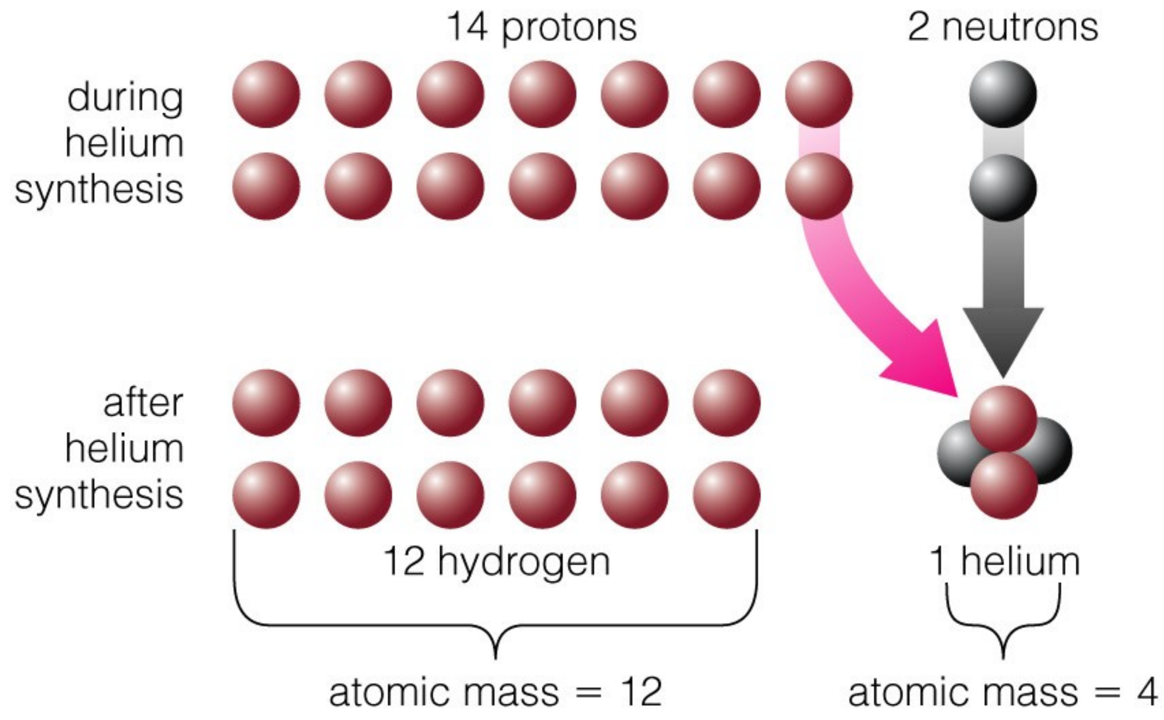
CMB Anisotropies

- Reminder: CMB is 2.7 K thermal radiation, emitted at t~300,000 years
- Anisotropy: some areas are ~10^{-5} K brighter, indicating denser plasma
- typical size ~1 degree (but come in a spectrum of sizes)
- after 13 billion years of gravitational contraction, these dense spots match the structure we see today!



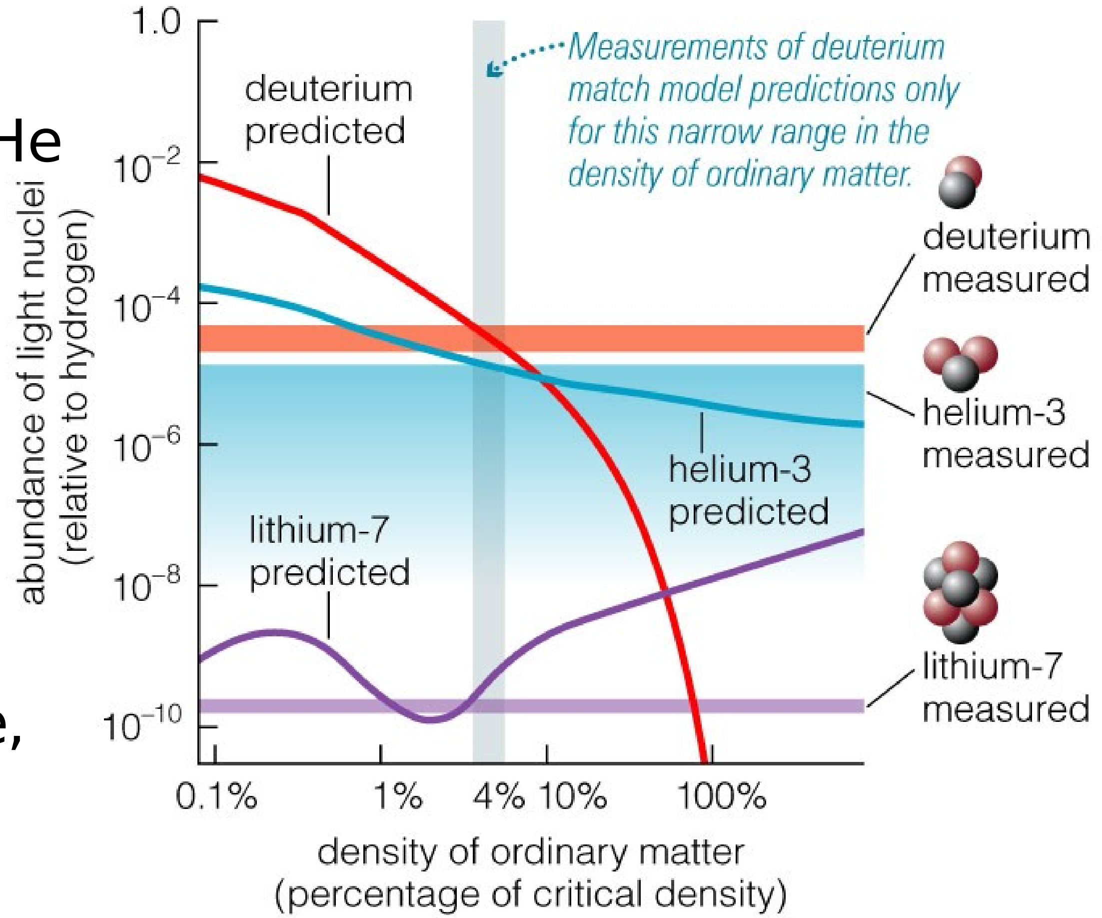
Further back in time…

- universe must have been hot enough for nuclear reactions (everywhere). "The First Three Minutes"
- starting with a proton/neutron soup in a 7:1 ratio (explain why later), can form 12 H nuclei for each He nucleus
- predict 3:1 ratio by mass
- how does it change with time/vary by galaxy?
- agrees well with observations!

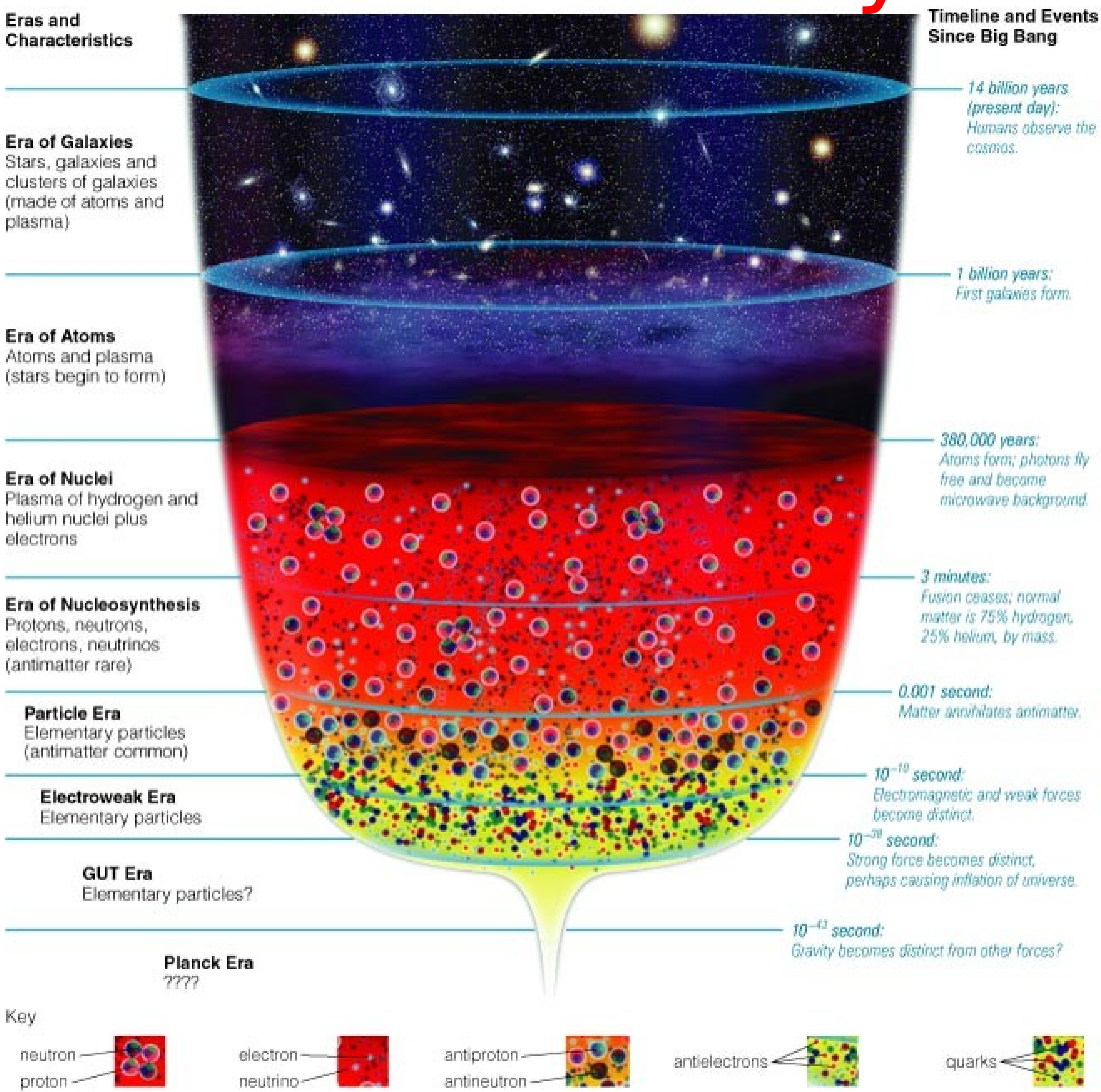


Big Bang Nucleosynthesis: Details

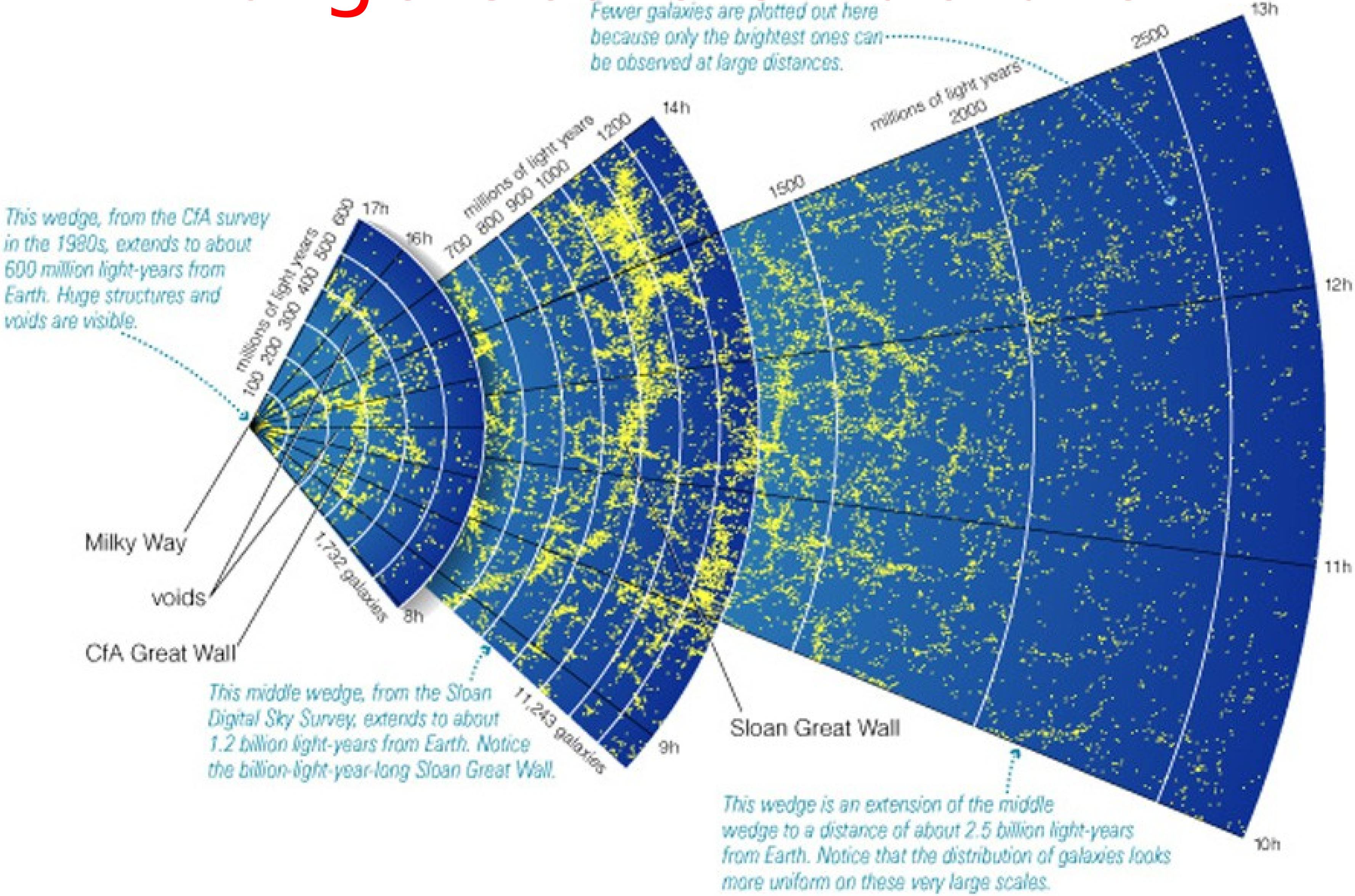
- after He formation, universe had expanded, cooled too much to fuse He
- trace amounts of intermediate stage ^2H (deuterium) left over
- more ^2H is used up if neutron+proton (baryon) density is higher
- similar arguments for ^3He, Li
- inferred baryon density matches census of stars+gas!



Cosmic History

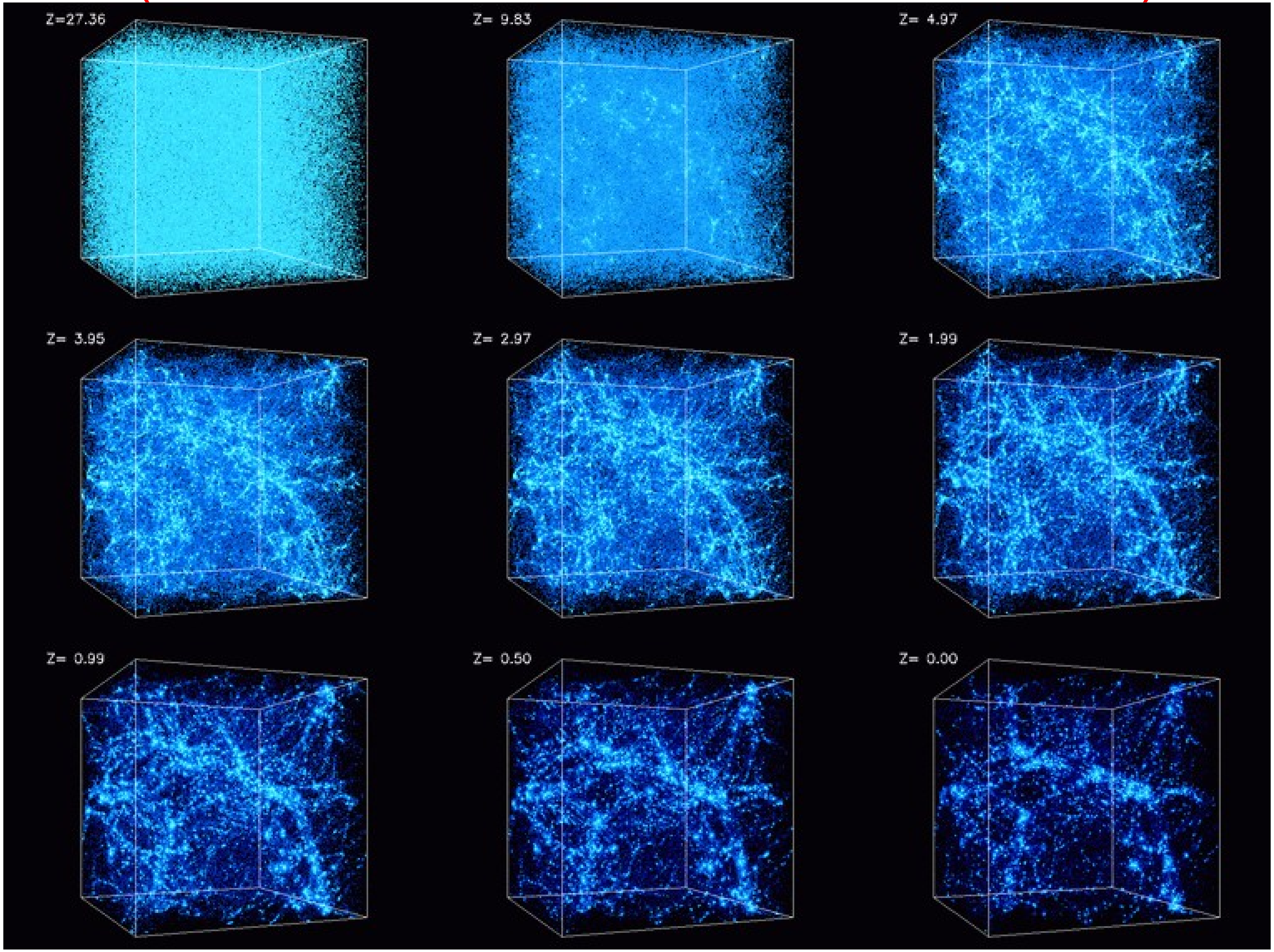


Large-Scale Structure



Structure Formation Simulation

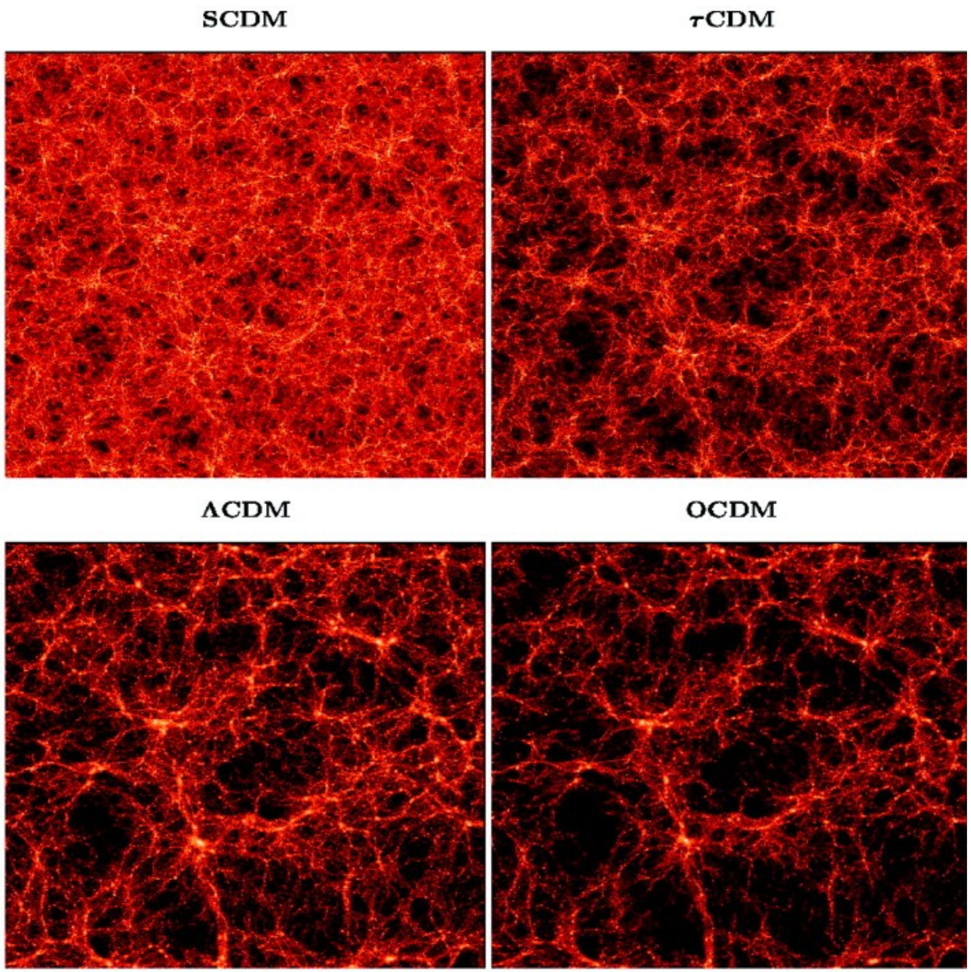
(stills from the movie, cosmicweb.uchicago.edu/filament.html)
(screensavers available on same website!)



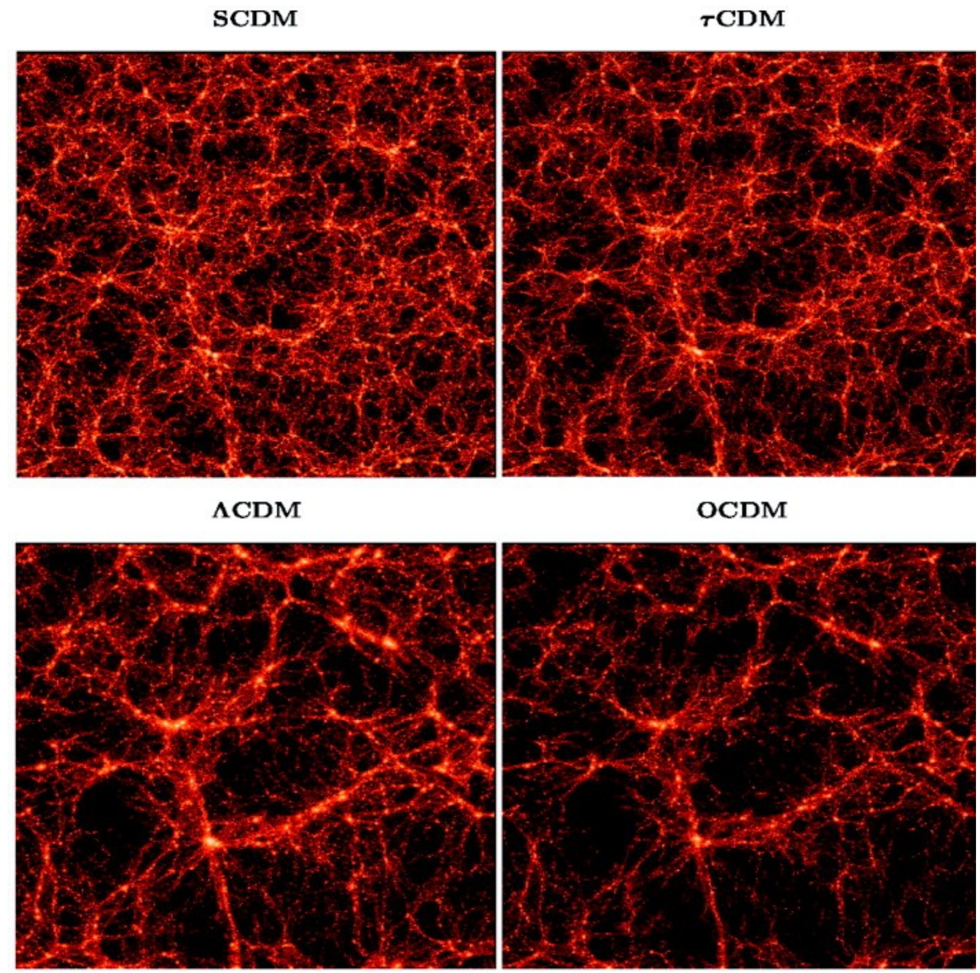
box is 140 million light-years across

Structure Formation: Different Models

redshift = 1

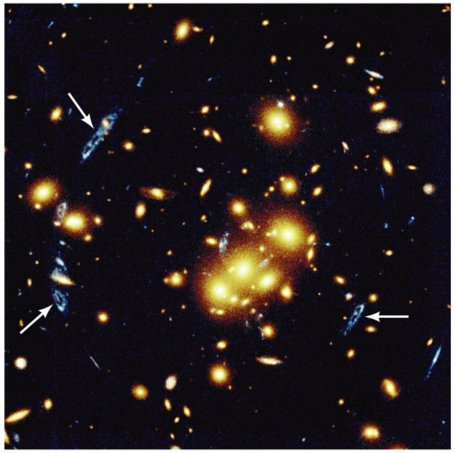


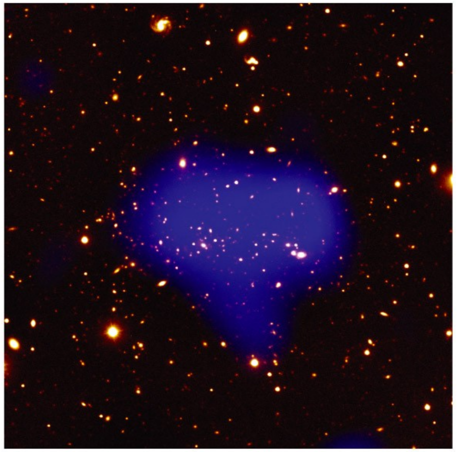
redshift = 0

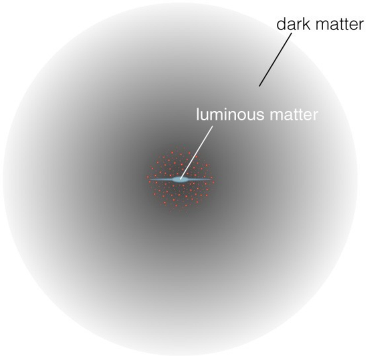


Dark Matter: Review the Evidence

- Stellar orbits in spiral galaxies (rotation curves) and elliptical galaxies (velocity dispersion)
- Velocity dispersion of galaxies in clusters
- Thermal pressure of hot (X-ray emitting) gas in galaxy clusters
- Gravitational lensing by galaxy clusters (and galaxies)
- Galaxy infall to large clusters
- Formation of structure since “Universe's baby pictures” (cosmic microwave background)







Structure: Summary

- Evolution of structure from tiny ripples in CMB is well understood.
- Simulations produce structures much like what we see today (clusters, voids, filaments, in the right amounts and sizes.
- Amount of dark matter inferred from CMB matches the amount inferred from cluster X-rays, lensing, etc!
- Baryon density inferred from CMB matches that inferred from Big Bang nucleosynthesis!
- But still haven't explained where ripples in the CMB came from...

Flatness Problem

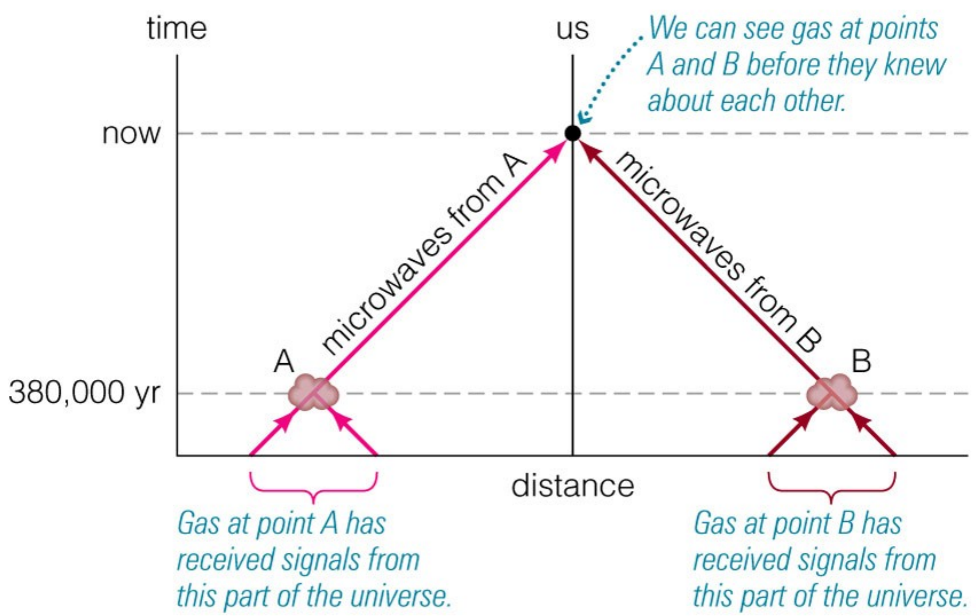
- If the universe has enough mass, it will halt the expansion. "Critical density" is 4.5×10^{-27} kg m^{-3} or ~3 protons m^{-3}!!
- A universe at critical density is called "flat". Less dense is "open", more dense is "closed."
- Our universe is suspiciously close to flat, even if only 27% of critical density.*
- Could have been 0.0000001% of critical density or 10^{40} times larger than critical density
- Worse: nonflat universes get more nonflat with time. Our universe must have been extremely close to flat in its early stages. Why??

*we will learn later that it is even closer than that!

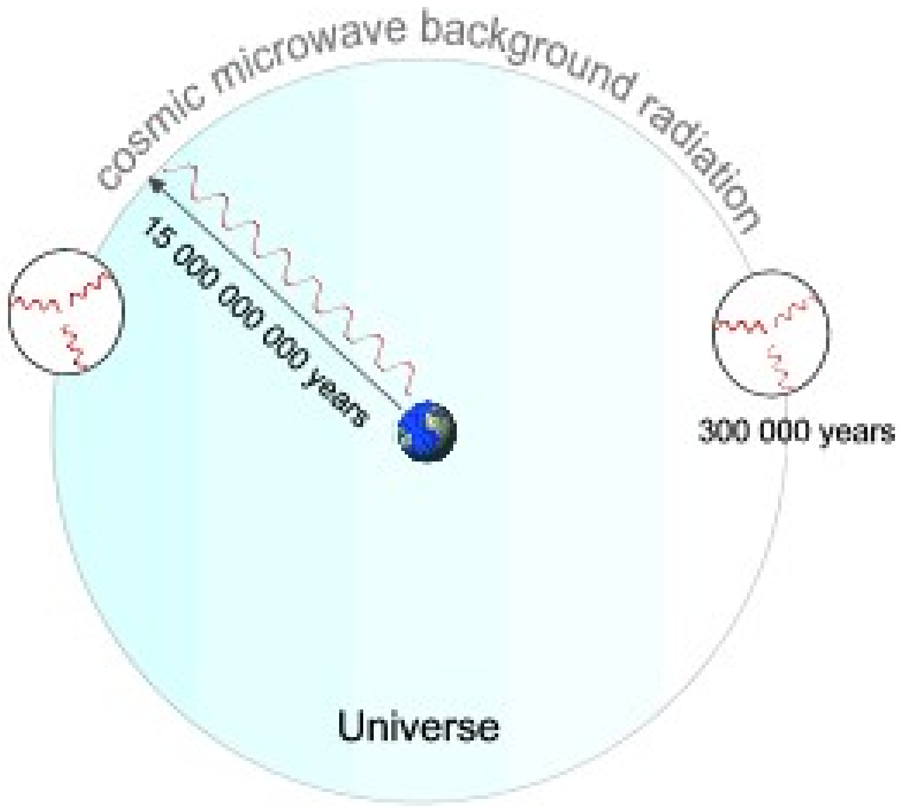
Horizon Problem

- widely separated patches of horizon have not had "causal contact" with each other
- so why should their physical conditions be the same?!

(Bennett Fig. 23.13)



(Wikipedia)



Magnetic Monopole Problem

- very early universe ($t \sim 10^{-36}$ s, well before neutron/proton era) should have created lots of bizarre particles called magnetic monopoles (and others)
- none have ever been found

Big Bang vs. Observations

- ✓ Hubble's law
- ✓ prediction of CMB: temperature *and* isotropy
- ✓ “postdiction” of He abundance
- ✓ matching 2H, 3He, Li abundances and census of stars/dust/gas
- ✓ postdiction of 7:1 proton:neutron ratio
- ✓ age of universe slightly greater than age of oldest stars
- structure: understood from CMB to present, but where does it originally come from?
- ✗ flatness problem
- ✗ horizon problem
- ✗ magnetic monopole problem

Inflation

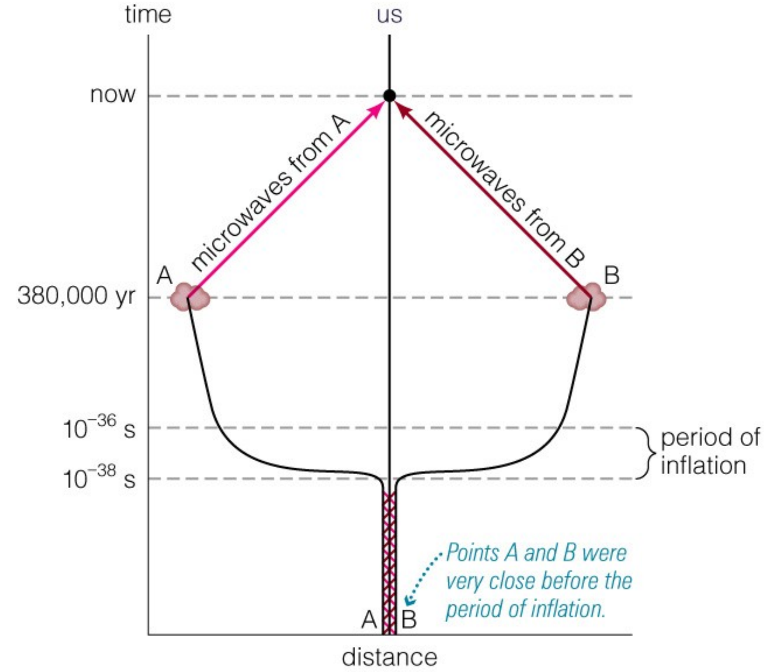
If the very early universe expanded very rapidly:

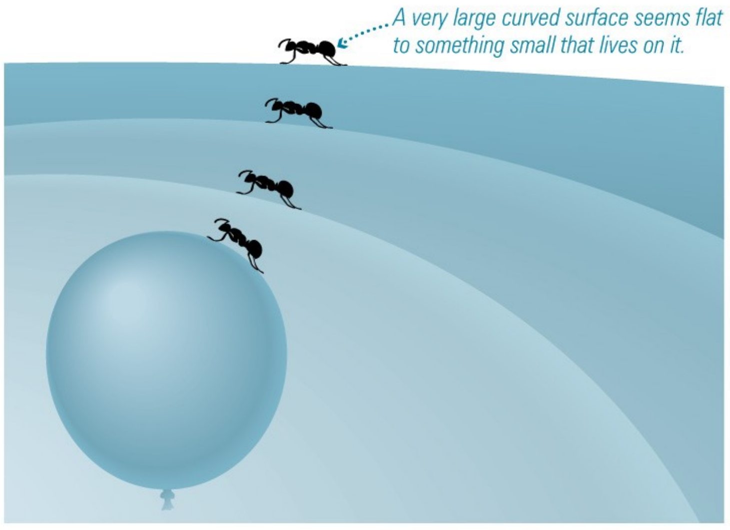
– quantum fluctuations would have expanded to become the peaks in the CMB

– areas in causal contact would have expanded to larger than the current observable universe

– expansion would make any curvature appear less pronounced

– magnetic monopoles would be diluted over a much larger volume

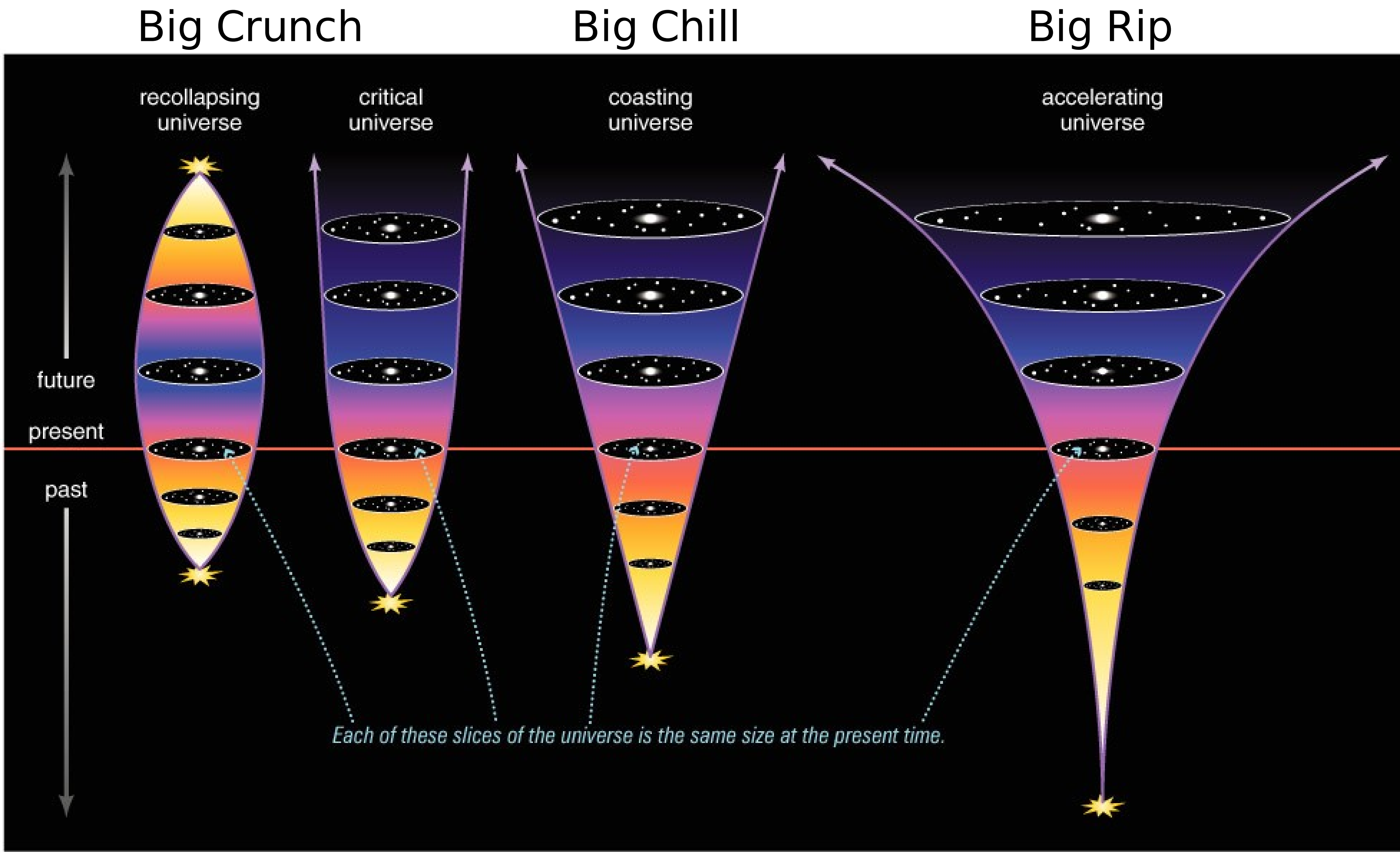




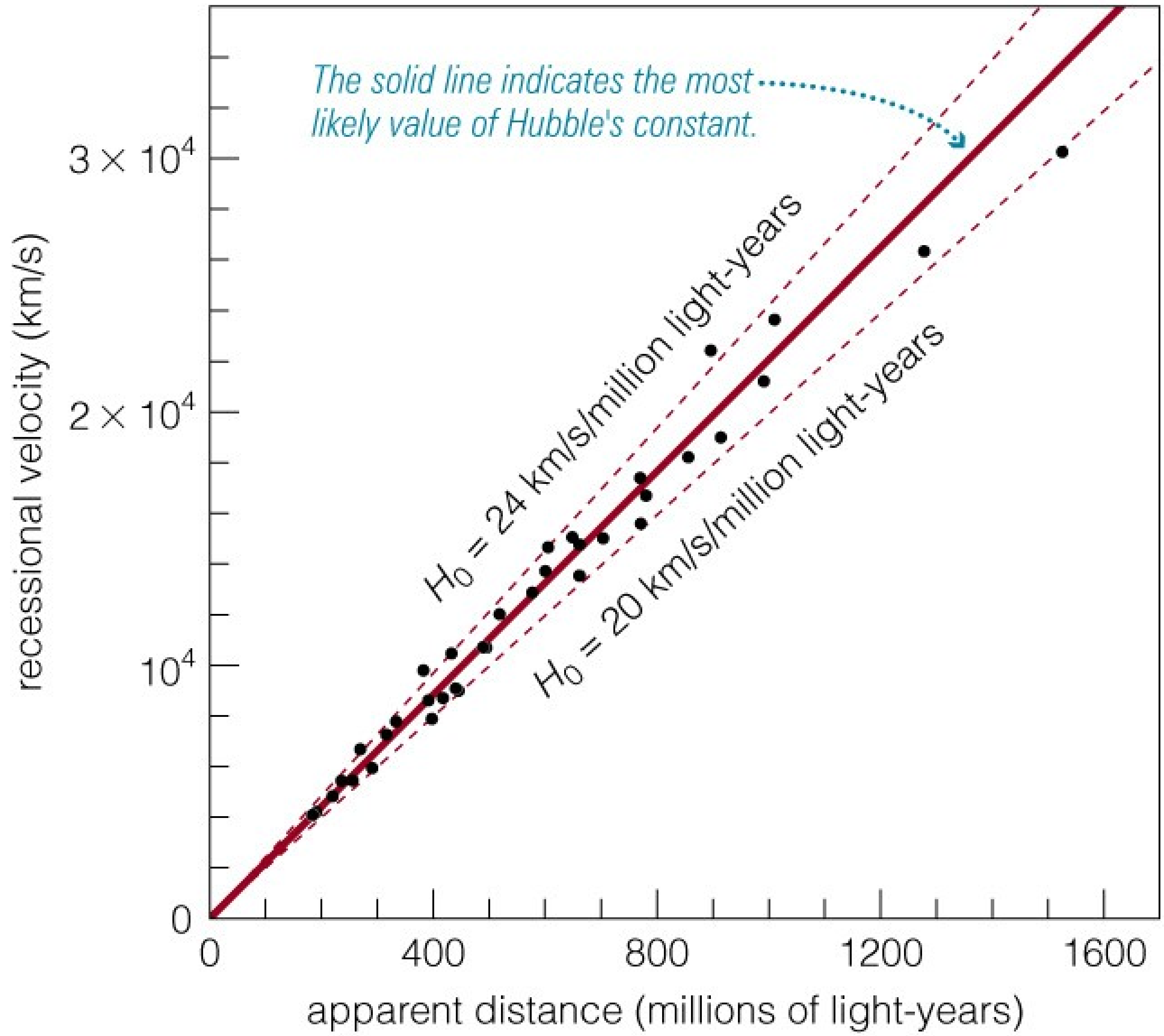
Inflation

- require that universe expanded by a factor of $\sim 10^{30}$ in $\sim 10^{-36}$ seconds!!
- a bold hypothesis that “explains” four major problems of original Big Bang cosmology
- makes predictions about CMB anisotropies and polarization that are borne out by WMAP
- WMAP and Planck (a future CMB mission) will continue to test inflation
- weight of evidence is not as massive as for other aspects of Big Bang, but looking good

Possible Expansion Histories



Distance-Redshift Relation



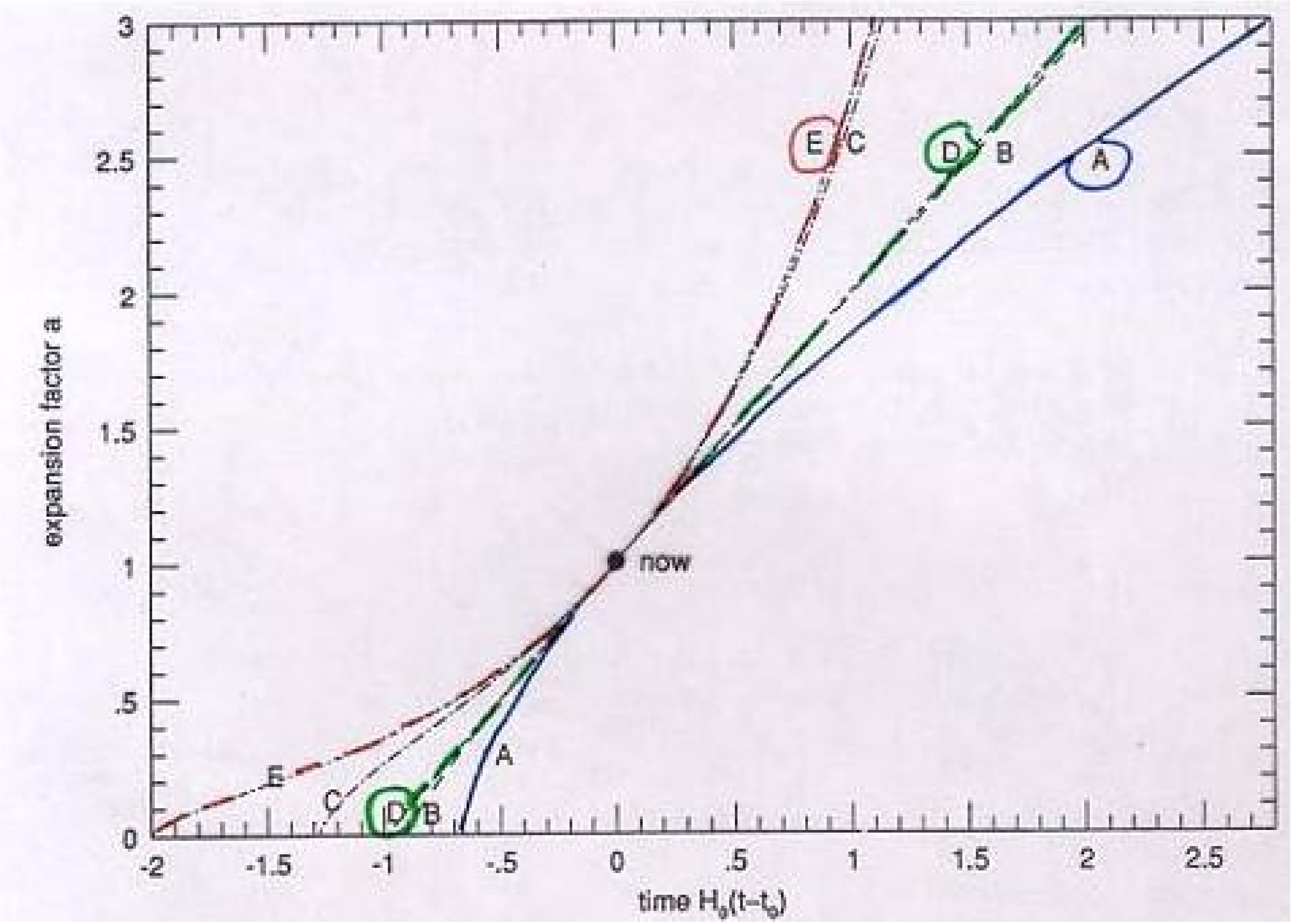
Hubble's constant is the slope of this line.

If the slope was steeper in the past (at higher redshift), that indicates deceleration.

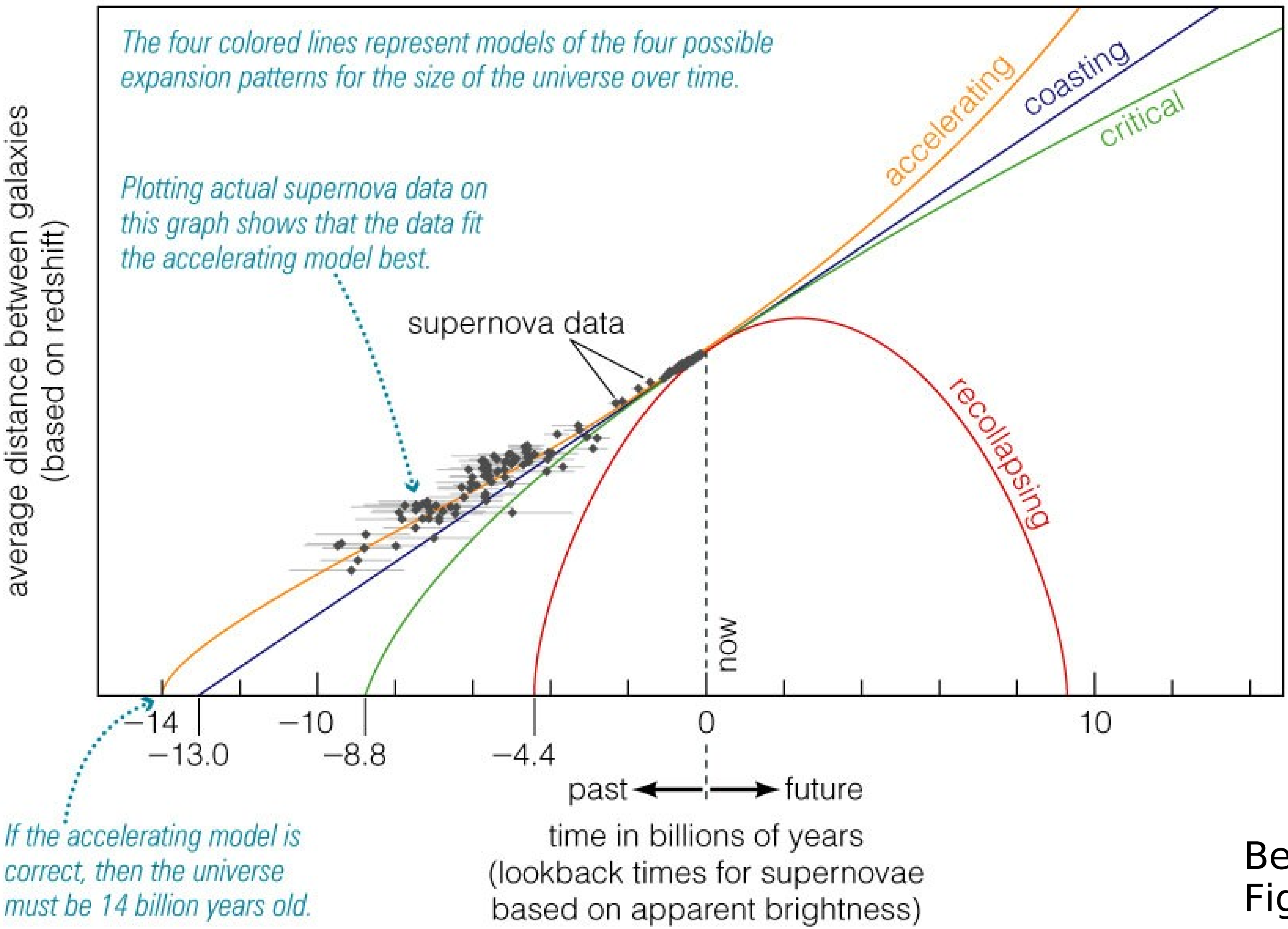
So we must measure distances quite accurately!

Zooming Out:

Possible Expansion Histories (Big Crunch not shown)



Expansion History From SNe Ia



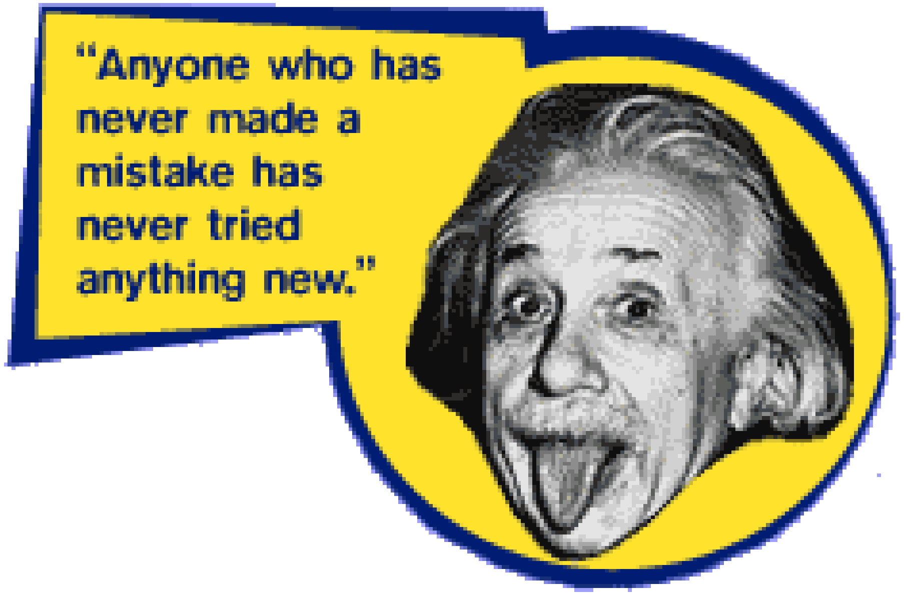
Bennett
Fig 22.17

Big News

- In 1998, two independent groups studying SNe Ia announced that the universe is accelerating!
- We have *no idea* what is causing the acceleration, so we call it “dark energy”
- Dark energy is the biggest unsolved problem in physics today!
- But some people were not so surprised...

Einstein's Greatest Mistake

- ~1920, Einstein assumed the universe was static, but his equations said gravity would not allow that.
- He suggested a mysterious repulsion called the "cosmological constant" which prevented it from collapsing.
- After Hubble showed that it is not static, Einstein called the cosmological constant his greatest mistake.



“Dark Energy”

- Astronomers agree: the universe is accelerating.
- We have *no idea* why.
- “Dark energy” is just a convenient name. It may not even be any kind of energy or force.
- “Dark energy” is more generic than “cosmological constant”. It need not be constant!
- You will hear it on the news if this problem is solved! Maybe 10, 20 years from now…

The Dark Side
(Dark Energy vs Dark Matter)

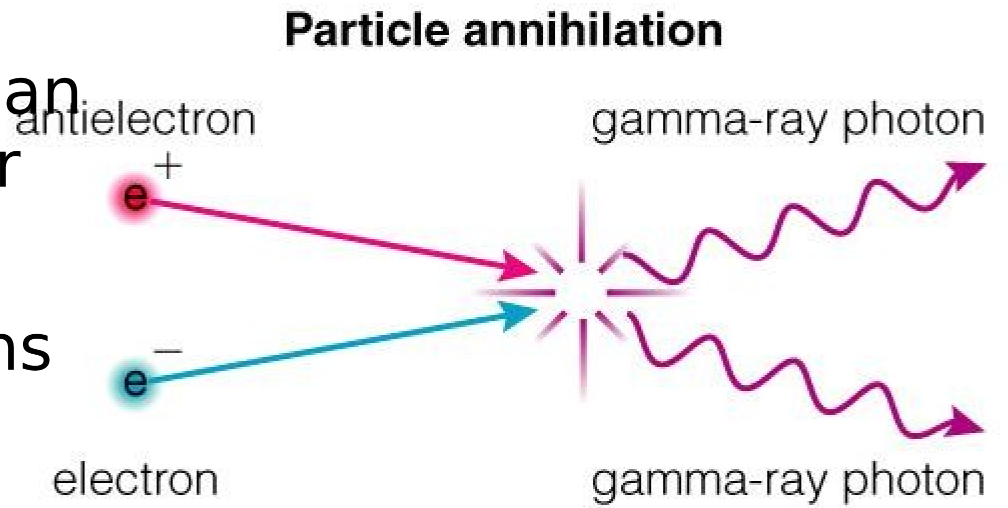
- *there is much more evidence for dark matter.*
- evidence for dark matter cannot be explained by modifying the law of gravity
- the evidence for dark energy *can*
- exciting research aimed at deciding between these two possibilities!
- think of “dark energy” as shorthand for “the unexplained acceleration of the cosmic expansion”
- dark matter is more tangible. An actual dark matter particle could be detected any day now.

The Very Early Universe

- Review: extrapolating backward in time:
  - universe was all plasma (CMB, t~300,000 yr)
  - age of nucleosythesis (elemental abundances, first 3 minutes)
  - formation of neutrons and protons (first seconds)
  - inflation thought to occur from 10^{-38} s to 10^{-36} s
- Further back: matter/antimatter annihilation
- And: unification of forces:

Antimatter

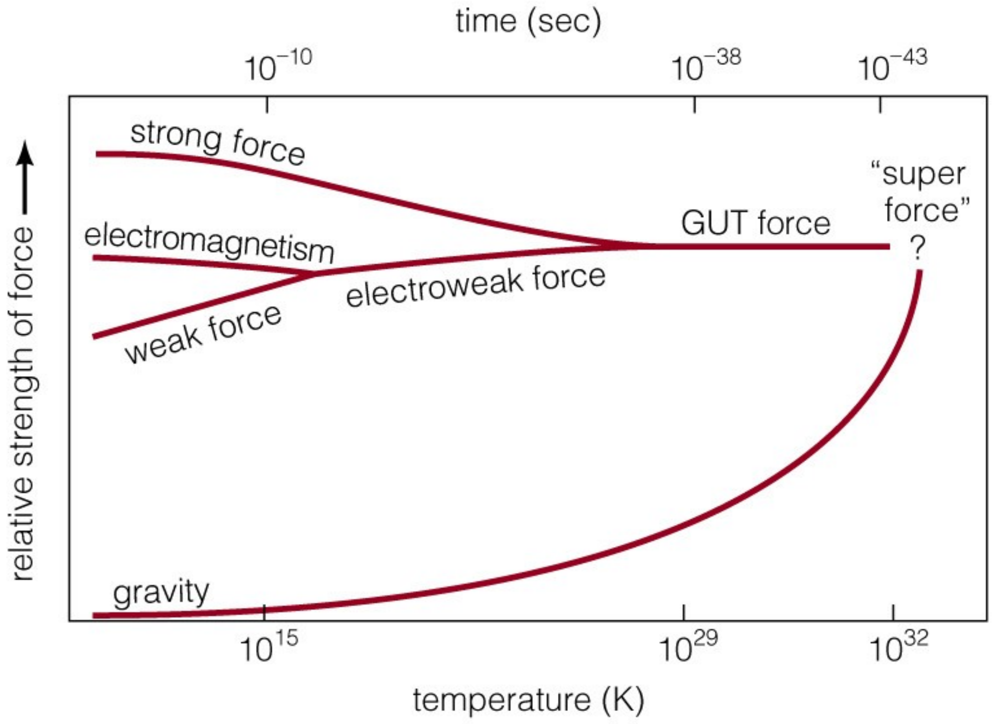
- e- and e+ (for example) can annihilate into photons, or vice versa
- at high temp, reaction runs both ways



- at low temp (after first millisecond), only e+ and e- should remain.
- big mystery: why so much more e- than e+? (And more protons than antiprotons, etc?
- Physicists are actively looking for the origin of this *matter-antimatter asymmetry*! (The asymmetry can be small…)

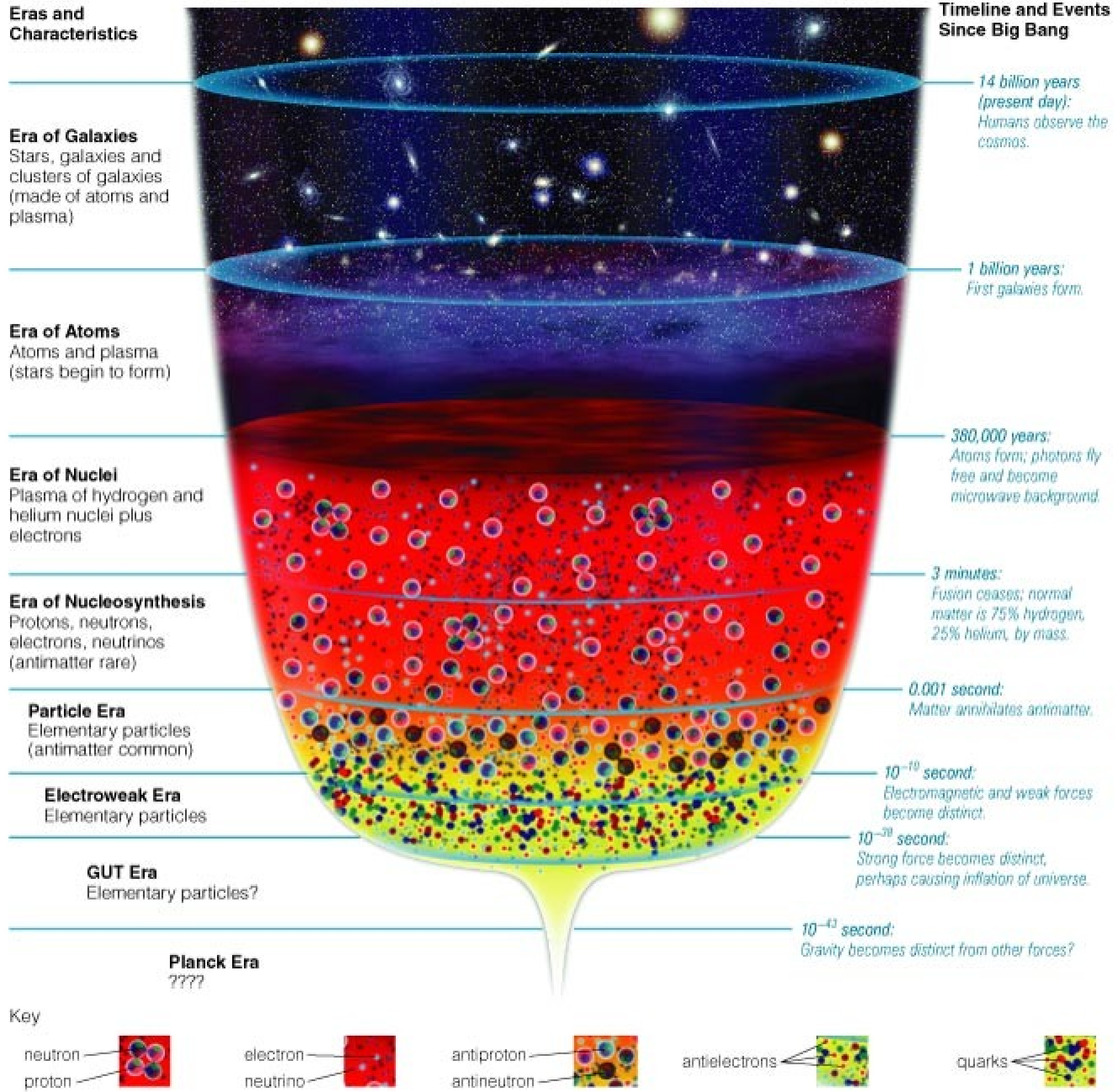
Unification of Forces

- GUT = Grand Unified Theory, includes all forces except gravity.
- Example: supersymmetry is a candidate GUT which will soon be tested at CERN.
- ToE = Theory of Everything, includes gravity. Much more ambitious!
- Example: string theory. Only works in 11 dimensions!
- Difficult to test. Earthbound experiments will never reach these temperatures!



Planck Limit

- At 10^{-43} s, the universe was so small that we need to combine quantum mechanics and gravity.
- We don't know how to do that yet! *We cannot extrapolate back before 10^{-43} s*!!
- The most solid astronomical evidence (p/n ratio) takes us back to ~1 s
- Particle accelerators recreate conditions at ~10^{-10} s. Well understood with some notable exceptions.
- Good arguments, some evidence for inflation at 10^{-38} s to 10^{-36} s
- Before that, very speculative!


Eras and Characteristics
Timeline and Events Since Big Bang
14 billion years (present day): Humans observe the cosmos.
Era of Galaxies
Stars, galaxies and clusters of galaxies (made of atoms and plasma)
1 billion years: First galaxies form.
Era of Atoms
Atoms and plasma (stars begin to form)
380,000 years: Atoms form; photons fly free and become microwave background.
Era of Nuclei
Plasma of hydrogen and helium nuclei plus electrons
3 minutes: Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Era of Nucleosynthesis
Protons, neutrons, electrons, neutrinos (antimatter rare)
0.001 second: Matter annihilates antimatter.
Particle Era
Elementary particles (antimatter common)
10^{-10} second: Electromagnetic and weak forces become distinct.
Electroweak Era
Elementary particles
10^{-38} second: Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
Elementary particles?
10^{-43} second: Gravity becomes distinct from other forces?
Planck Era
????
Key
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

Review: What We Don't Know

- What is dark matter?
- Is “dark energy” a form of energy, or a misunderstanding of gravity?
- If energy, what are its properties? (Time evolution, spatial variation, etc.)
- If modified gravity, how so? Are there extra dimensions we can't see?
- How do we combine gravity and quantum mechanics? (Relevant to Big Bang and black holes.)
- Did inflation really happen and what are the details?
- Why is there matter and not antimatter?