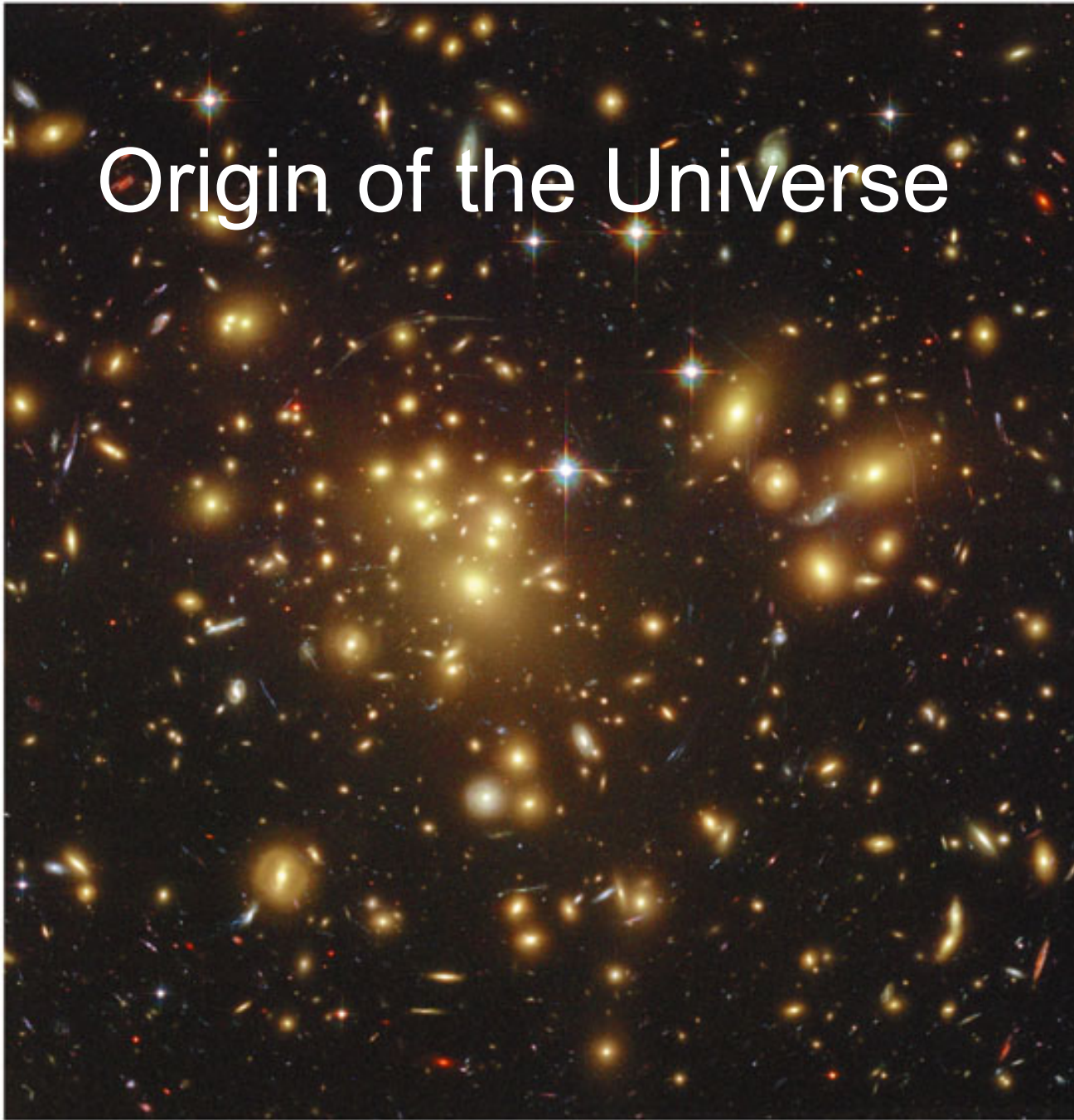


Origin of the Universe

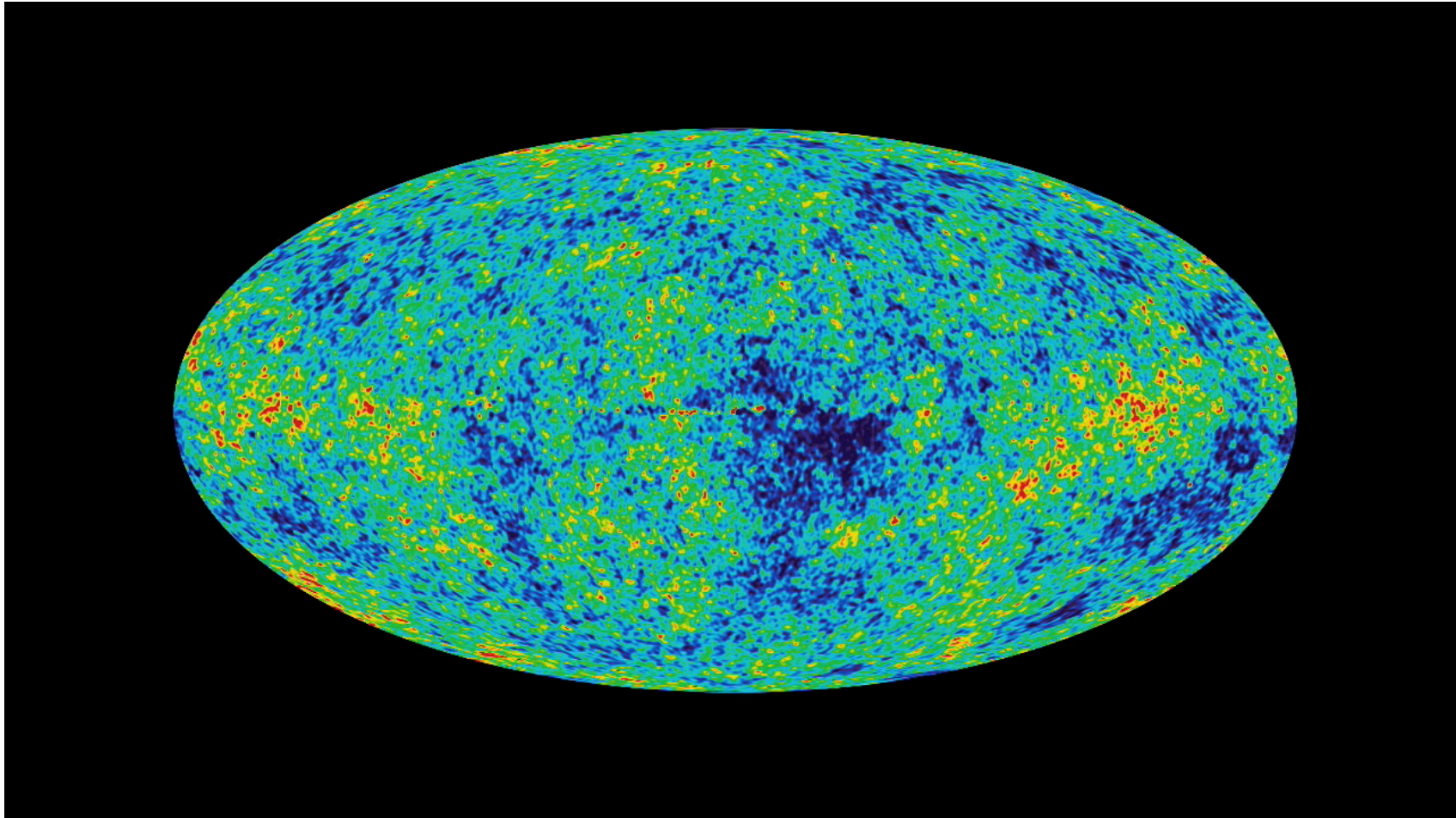


Shortcomings of the Big Bang Model

- There is tremendous evidence in favor of the Big Bang
 - Cosmic Microwave Background Radiation
 - Abundance of Deuterium, Helium, Lithium, all cooked in first 3 minutes
- Prior to 1980, cosmologists had identified three (4) major questions which the theory was unable to answer:
 1. Where does the large scale structure come from?
 2. Why is the large-scale Universe so smooth (homogeneous)?
 3. Why is the density of matter almost critical ($\Omega \sim 1$)?
 4. Why aren't we dominated by magnetic monopoles?

WMAP results

fluctuations are 10^{-5} of CMB intensity

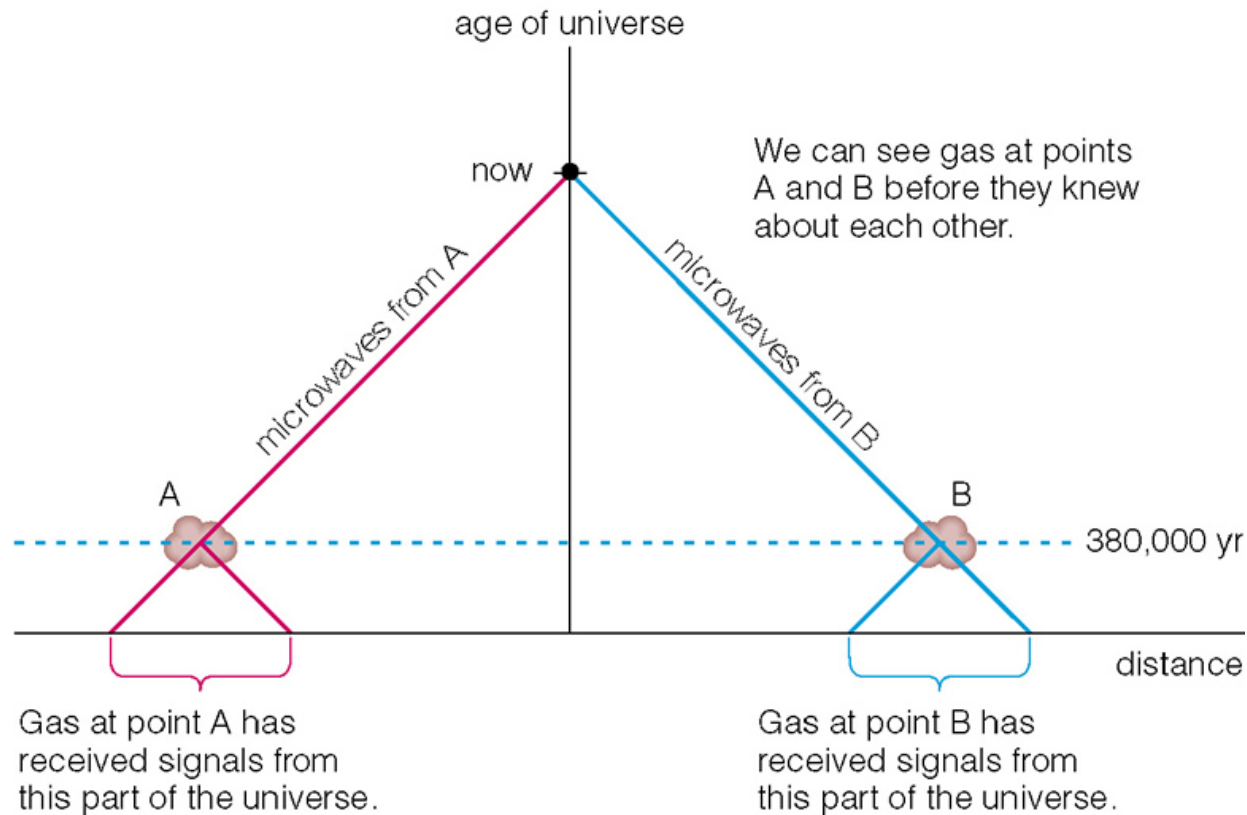


Inflation of the Expansion Rate

- In 1981, physicist Alan Guth realized that the Grand Unified Theories could hold the answers to these questions.
- When the strong force froze out of the GUT force...
 - If the separation involved “latent heat” (e.g. the heat of freezing water)
 - Then there is a phase of **false vacuum** that dominates expansion rate, causing *acceleration*.
 - This phase is termed **Inflation**
 - *Note that recent observations of distant SNe suggest we are entering a new phase of cosmic acceleration!!*
- Inflation works to solve these mysteries!!

Why is the Large-Scale Universe so Smooth?

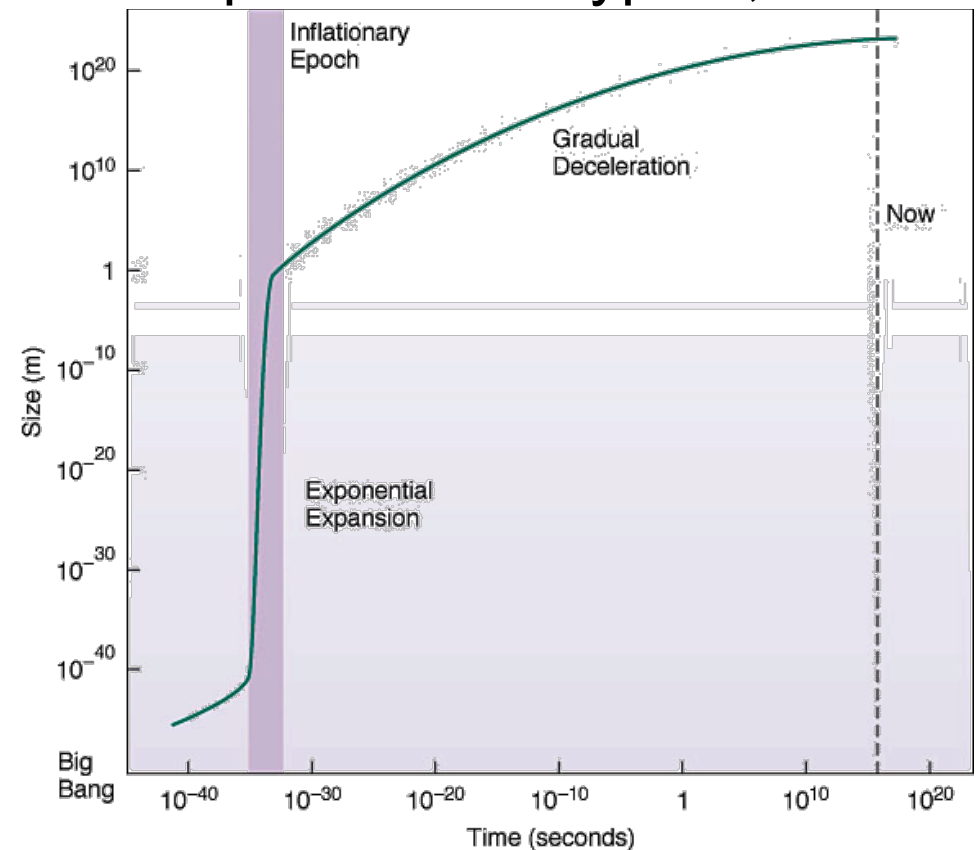
- In all directions, the Cosmic Microwave Background is uniform.
- Traditional Big Bang model can not explain...
 - how two disparate parts of the Universe, beyond each other's cosmological horizon, can have the same temperature



Two possible solutions to the cosmological puzzles:

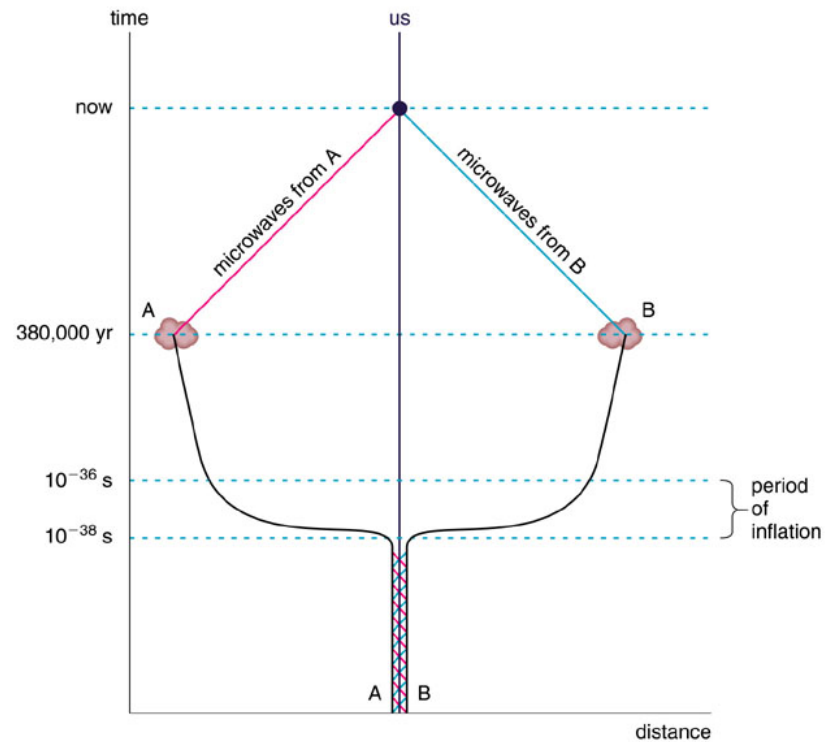
- 1. Accept that the Universe was simply created this way. (will of God)
- 2. Search for a dynamical, physical explanation.
- In 1980, Alan Guth suggested an explanation of type 2, which is called **INFLATION**.

•Conceptually simple:
Instead of a **decelerating** Universe, imagine what would happen if there were some period of an **accelerating expansion**



In an accelerating Universe, particles are all in causal contact at beginning, but then rapid expansion moves particles across **event horizon**, the surface at which particles are receding from each other faster than light speed.

- In inflationary Universe, our present, decelerating phase is replaced by early phase of an accelerating Universe, so that particles start out in causal contact, leave contact with each other, and then come back into contact later.



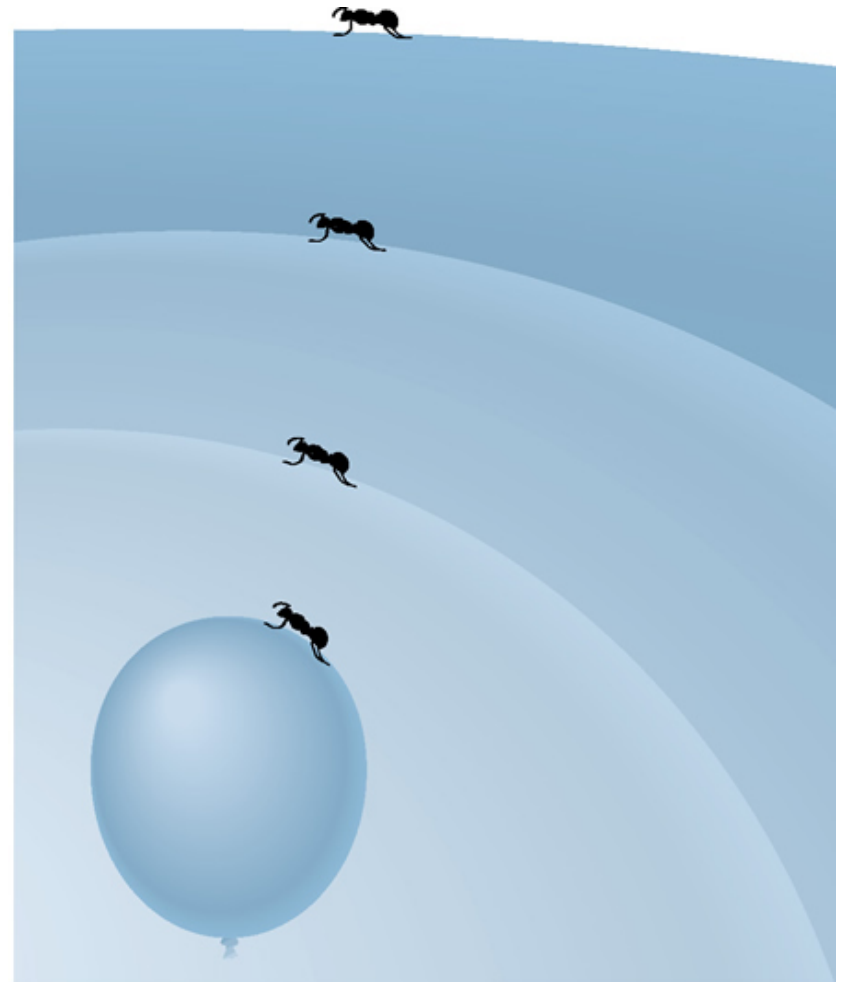
False vacuum and its Relation to Inflation

- During all these phase transitions, the nature of the "vacuum" is not necessarily the same as we imagine now.
- A box of vacuum is something that does not change if we expand or contract the box. Normally we attribute 0 energy density to a vacuum.
- So expanding a box takes no energy. But vacuum state of early phase of Universe might have had different, **non-zero** energy density! As universe expands, vacuum energy density can come to dominate over radiation and matter.
- Guth realized that vacuum dominated phase would correspond to accelerating Universe (according to General Relativity)
- This could occur during a phase transition in early Universe, such as at end of Grand Unified Epoch, or perhaps earlier. **Perhaps the folding up of extra dimensions of string models causes inflation?**
- *It is **again** occurring in the Universe!! That's what we mean by **dark energy**.*

Inflation Flattens the Universe

Why does Universe have $\Omega \sim 1$ (i.e. negligible flatness)?

- $\Omega \sim 1$ is not a natural solution, because for Universe to have expanded 10^{40} requires initially that $\Omega = 1$ to precision of 10^{-80} !! This is asking a lot!
- Ant notices curvature on small balloon before inflation
- But if balloon is blown up a lot, curvature seems to disappear (like curvature of Earth from ant's perspective)
- Solves flatness problem, homogeneity problem!



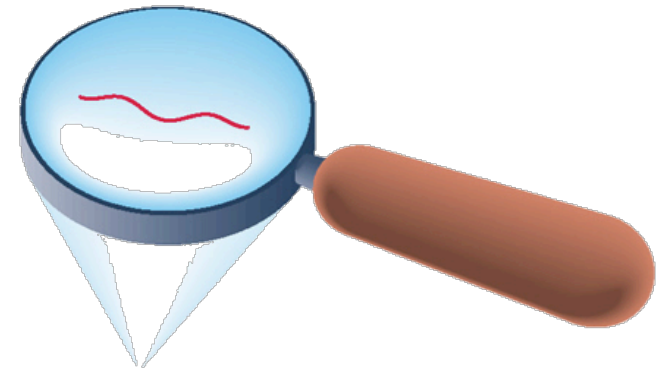
Why is the Density of Matter Almost Critical?

- The gravitational pull of the Universe almost balances the kinetic energy of its expansion...
Why?
 - if matter were at least 10% denser, Universe would have already collapsed
 - if matter were at least 10% less dense, galaxies would have never formed
- According to General Relativity, an imbalance of these energies imposes a curvature of spacetime.
 - but when they balance, we say that spacetime is “flat”
- The effect of rapid inflation is to flatten spacetime.
 - thus, inflation imposed the balance of these energies

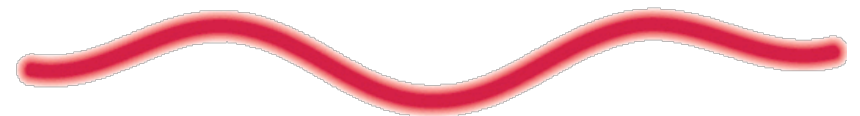
Where Does Structure Come from?

- The density of matter in the early Universe had to differ slightly from place to place.
 - otherwise, galaxies would never have formed
 - traditional Big Bang model does not tell what caused density enhancements
- Quantum Mechanics: energy fields must fluctuate at a given point.
- Energy distribution is irregular...
 - on microscopic spatial scales
- These quantum ripples would be greatly magnified by inflation.
- Large ripples in energy are the seeds for the density enhancements.
 - they imposed a pattern about which structure formed

size of ripple before inflation = size of atomic nucleus

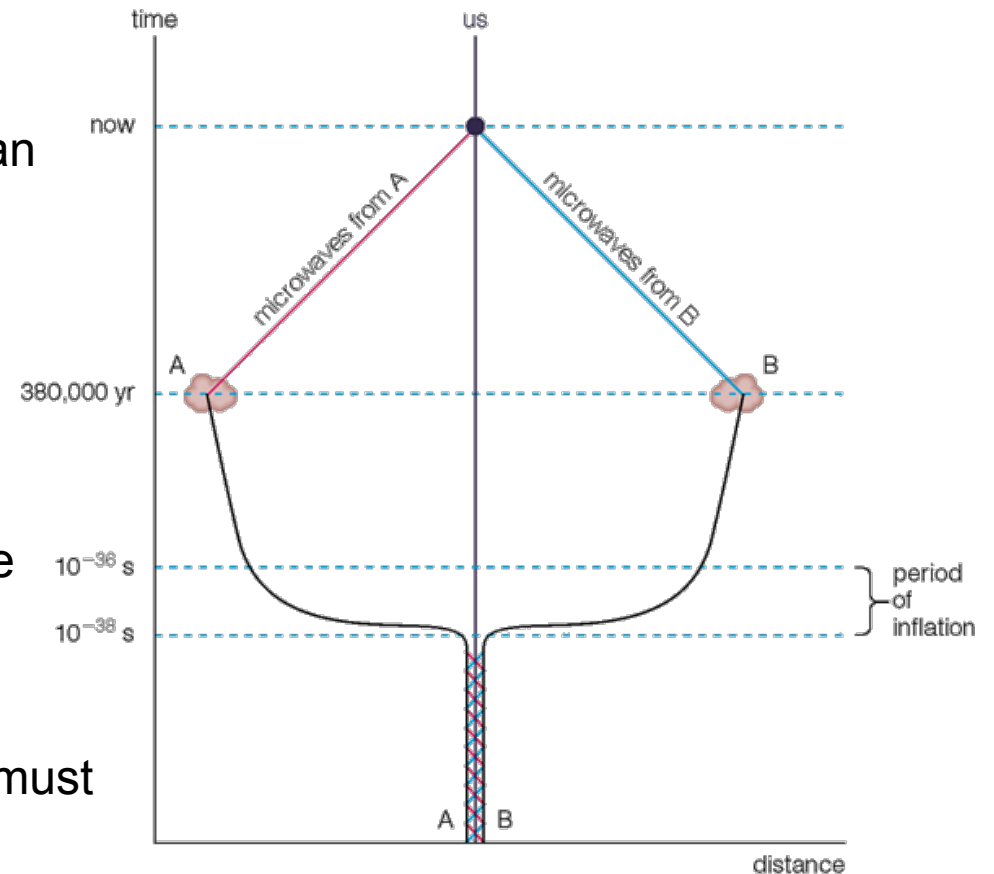


size of ripple after inflation = size of solar system



Why is the Large-Scale Universe so Smooth?

- Inflation can solve this problem.
 - the entire Universe was less than 10^{-38} light-second across
 - radiation signals could reach all points in the Universe
 - temperatures were equalized
 - **then** inflation expanded the Universe so quickly
 - that many points in the Universe went out of communication with each other
 - Points A and B *were* in causal contact, which implies Inflation must have occurred some time ago.

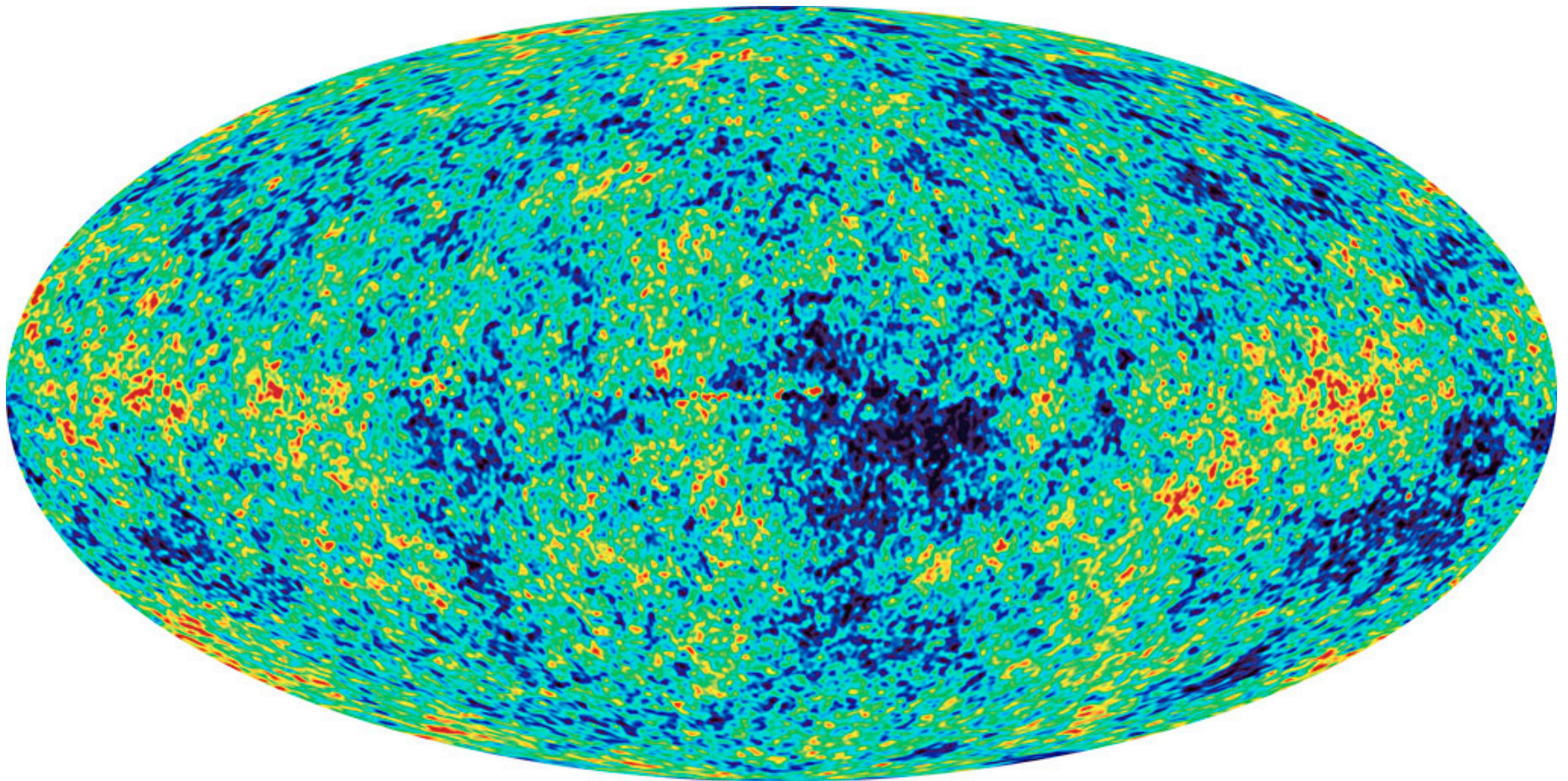


- Key point is that inflation is an episode in cosmic acceleration --*like today!*

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New Evidence for Inflation

- In 2002, the *Wilkinson Microwave Anisotropy Probe* (WMAP) measured the Cosmic Microwave Background with much more precision than COBE.
- It detected far more subtle, small-scale temperature variations.



Inflation implications

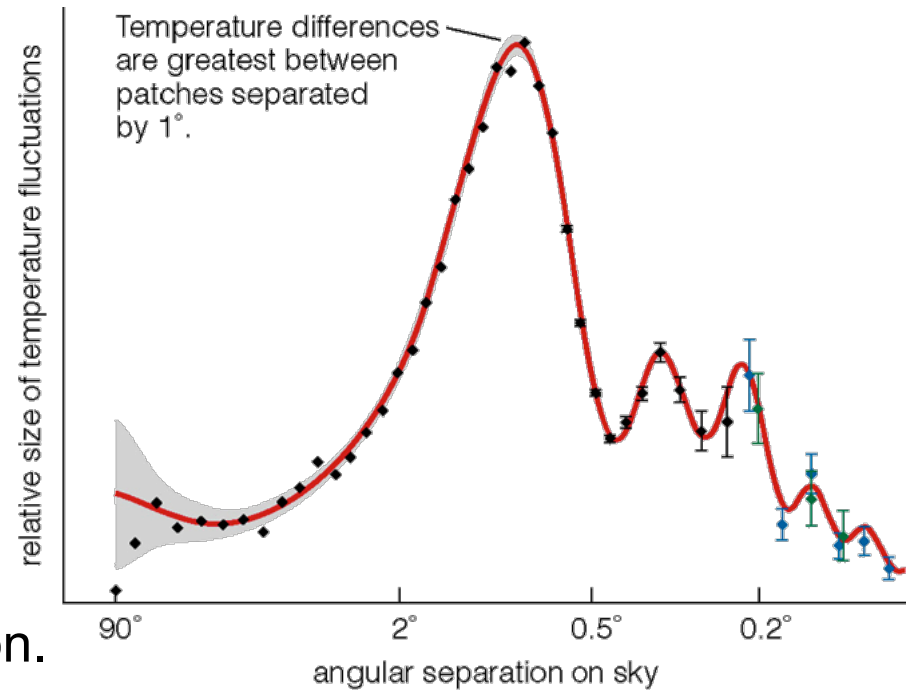
- Spectrum of Large scale fluctuations seen in CMBR are consistent with expectations of inflation!!!! *A remarkable achievement!*
- But inflation predicts $\Omega = 1$, of which 70% is another field of same sort that drove inflation. **WHY??**
- Inflation is an idea that can be incorporated in many different models of early Universe. A topic of intense research, but unclear how we shall ever decide which model is right.
- Note the old adage, that you can't get something for nothing is turned on its head:
- *In an inflationary Universe, the curvature is flat, so the total energy is $E=0$. The entire Universe may well have been made out of a single vacuum bubble which was part of the chaotic foam of space-time at the very beginning. Conditions were right in this bubble to inflate, and to generate our entire Universe out of quite literally, **nothing**.*
- **The Universe is thus the ultimate free lunch.**

Connecting CMBR fluctuations to LSS

- Consider a stereo receiver with knobs for tuning amplitude of different frequencies, bass, midrange, treble, etc. Adjusting these knobs tunes the *spectrum of sound waves*.
- Difference between a viola and a piccolo playing the same note is the higher frequency harmonics and anyone can tell the difference.
- Similarly the spectrum of *inhomogeneous matter waves* in the Universe is tuned by different types of dark matter, different cosmological models.
- Observations of Large Scale structure and CMBR fluctuations seen by COBE and WMAP **are perfectly consistent with cold dark matter models. Current situation is that models are essentially perfect. This was a big triumph!**

New Evidence for Inflation

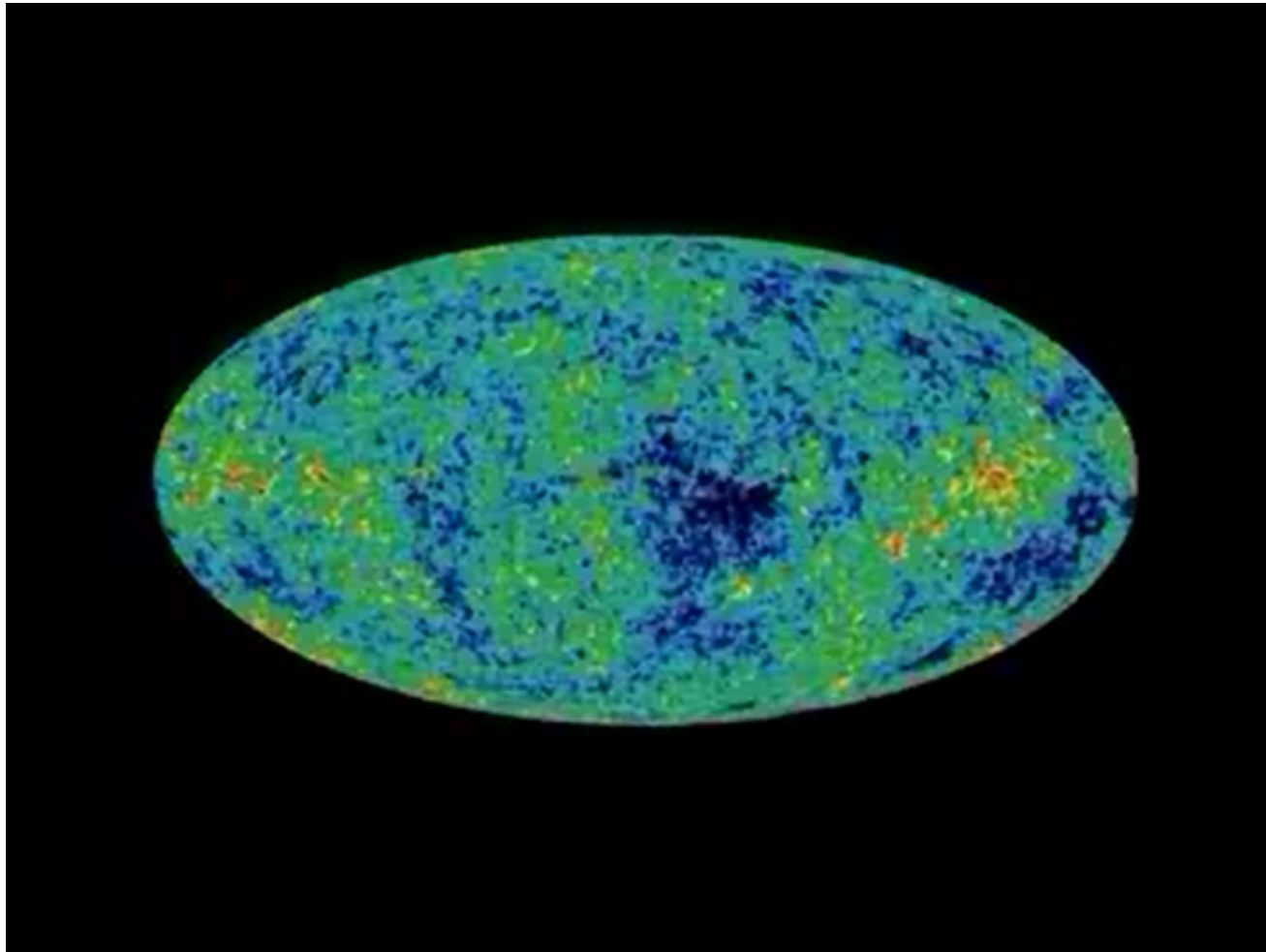
- A Big Bang model with inflation was fitted to:
 - temperature variations plotted as angular separation on the sky →



- Spectrum fully consistent with Inflation.
- Overall geometry of the Universe is flat.
- Total matter density is 27% of the critical density.
 - in agreement with M/L in clusters of galaxies
- Density of baryonic (ordinary) matter is 4.4% of critical density.
 - in agreement with observed abundance of Deuterium
- Flat geometry + matter density < critical implies dark energy.
 - in agreement with accelerating expansion from white dwarf supernovae
- Age of the Universe is 13.7 billion years.

Evolution of a Universe

- Temperature variations in the 380,000 year-old Universe serve as a “genetic code” for the structure of the Universe today!

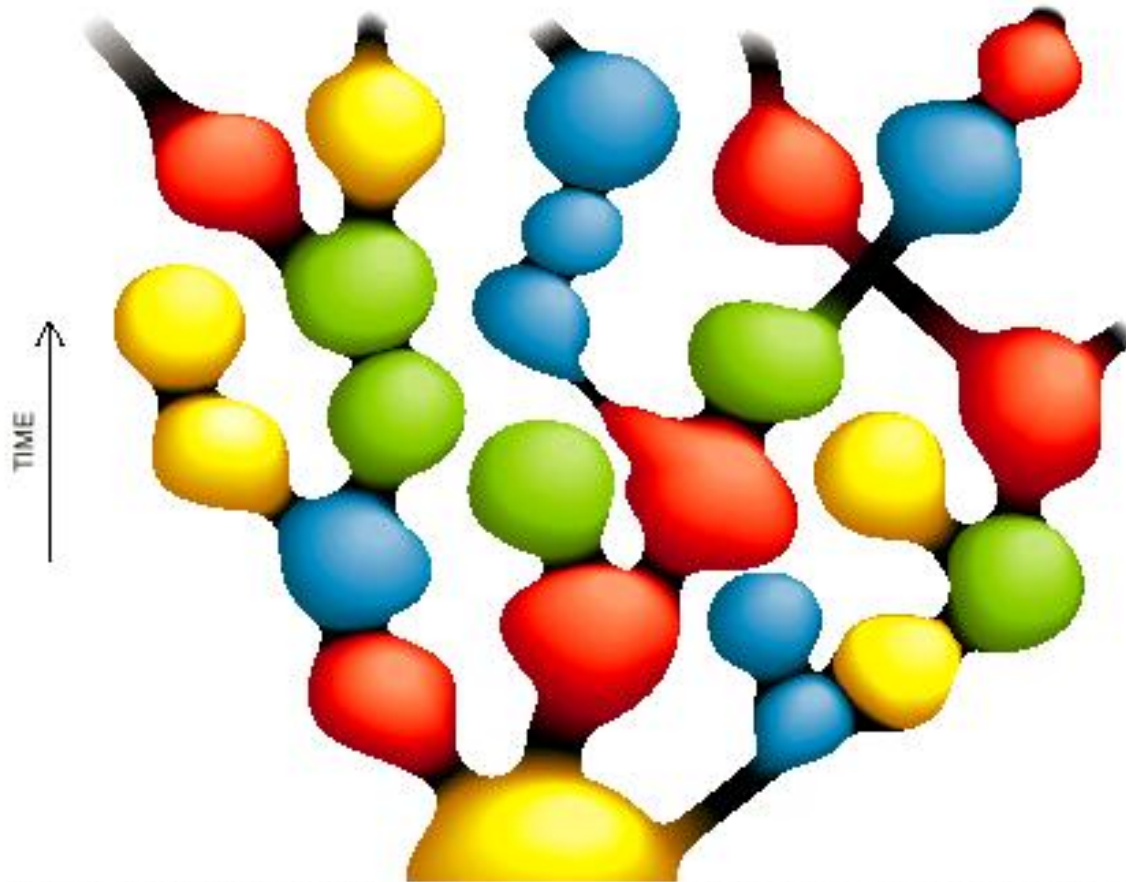


Eternal Inflation— Higher dimensions

- Inflationary phase might be associated with Grand Unification of physical law.
- Much work by theoretical physicists suggests that fundamental physical law should be described by 11 dimensional space-time (**maybe more**)
 - *Other dimensions are curled to unobservably small size, like rolling a sheet of paper to a long, thin tube.*
 - *Is there a unique method to roll-up extra dimensions?*
 - *was thought to be the case, but now estimated to be 10^{500} different ways to fold up extra dimensions!!*
- During inflation, density of Universe is dominated by the false vacuum field, which like all quantum fields, has fluctuations
 - *These fluctuations generate the seeds of cosmic structure!!*
 - *Inflation, once begun, will be **eternal**, spawning daughter Universes continuously, each with its own compactification, and possibly distinct physics.* (first suggested by A. Linde)

Self-reproducing Universes

Eternal Inflation



SELF-REPRODUCING COSMOS appears as an extended branching of inflationary bubbles. Changes in color represent "mutations" in the laws of physics from parent universes. The properties of space in each bubble do not depend on the time when the bubble formed. In this sense, the universe as a whole may be stationary, even though the interior of each bubble is described by the big bang theory.

Alan Guth

Professor of Physics, MIT

Inventor of Inflationary
Cosmology



Andre Linde

Professor of Physics, Stanford

Inventor of chaotic, eternal
inflationary models



Testing predictions of Inflationary cosmology

- Spectrum of Perturbations generated in inflation and observed in ripples of the CMB
 - Matches inflationary prediction !
- Universe should be flat
 - Recent studies of CMB suggest flat Universe !
 - But observed matter density appears to provide only $\Omega \approx 0.3$
 - 30% of that needed to make Universe flat!
 - Study of distant supernovae suggests the Universe is now accelerating, not decelerating
 - Dominant form of matter in universe today must have negative pressure, like in inflationary phase of early Universe

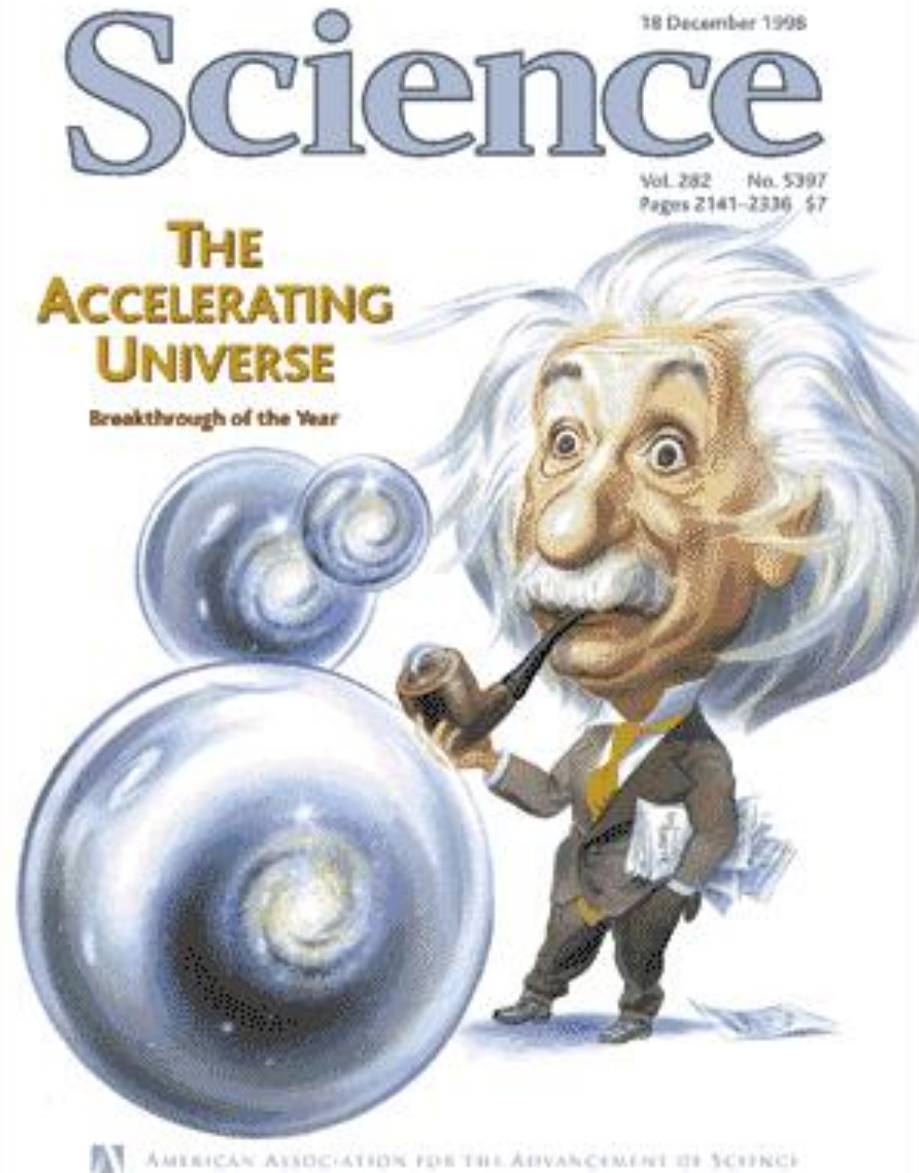
Modern epicycles

- Contents of Universe today:
 - Radiation
 - Neutrino background
 - Ordinary matter (~4% closure density)
 - Dark Matter of unknown nature (~26% closure density)
 - Dark Energy (with negative pressure) ~70% of closure density.
- This seems awfully complicated!
 - Are we in the position of Kepler, who having discovered that Mars orbited as an ellipse, not the perfect circle as the ancient Greeks assumed, despaired over why God had constructed such a complicated cosmology?
 - It took the genius of Newton to provide natural explanation of elliptical orbits.
 - **Who will be our next Newton!!**

Science Story of the Year-1998

Evidence suggests the universe today is accelerating its expansion.

- *Does this mean we are entering a new era of inflation??*
- *What is nature of the dark energy that generates this acceleration??*
- *What can one do to further test such predictions?*



Time and Matter in Cosmological Models

- **Steady State:**
 - Infinite age of Universe
 - Continuous Creation of Matter
- **Big Bang:**
 - Universe has finite age ~14 billion years
 - Conservation of Matter-Energy
- **Inflationary Big Bang:**
 - Finite age of *our* Universe
 - Creation of all matter-energy from conversion of false vacuum at end of inflation.

The March of Progress in Cosmology

The ongoing Copernican Revolution!

- Earth is not center of Universe
- Sun is not center of Universe
- Our galaxy is not center of Universe
- Our type of matter is not dominant constituent of Universe ?

- Our Universe (seen and unseen) is not the only Universe ??
- Our Physics (at low energy) is not the only physics ??
- Our 3+1 dimensional Universe is not the only possibility ??

Quotes of Einstein

- Reality is merely an illusion, albeit a very persistent one.
- The difference between what the most and the least learned people know is inexpressibly trivial in relation to that which is unknown.
- Things should be made as simple as possible, but not any simpler.