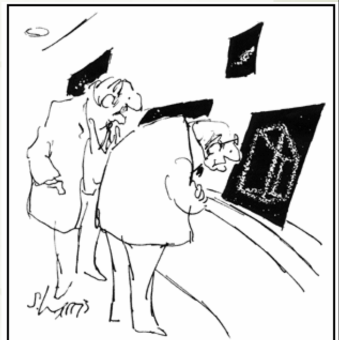
Lecture 22 : Four cosmic puzzles and Inflation

- The cosmic jigsaw
- Four puzzles…
- How inflation solves these puzzles

Reading: Chapter 16 of text (inflation)



"You've seen spiral galaxies, you've seen elliptical galaxies..."

© Sidney Harris

Reminder #1

- Review session: Tuesday May 10th
- Final is Monday May 16th at 10:30am in this room

Reminder #2: Course Evaluation

- Open through Wednesday, May 11

http://www.CourseEvalUM.umd.edu

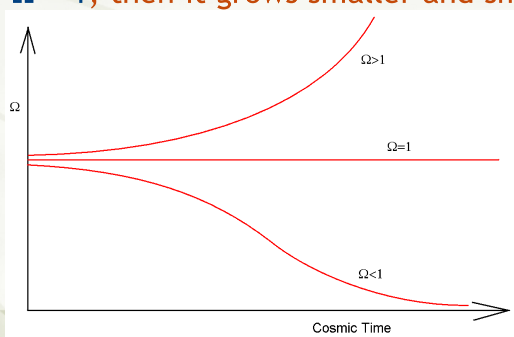
- Note: The evaluations are confidential, I will not be able to identify who has submitted an evaluation, only the participation rate.
- Goal is to achieve >70% response rate
- We are currently at 45% response rate. Thanks for participating!

I : THE FLATNESS PROBLEM

- Universe with a flat geometry is a very special case…
  - $\Omega = 1$ (for standard models)
  - $\Omega + \Lambda = 1$ (for models with cosmological constant)
- Our universe is almost flat…
  - We measure Ω_M approximately 0.3
  - CBR results suggest that $\Omega_M + \Omega_\Lambda \approx 1$ to within 1 percent or better!
- Why are we so close to this special case?
- Also remember that $\Omega = 1$ is a universe with zero total energy: kinetic and gravitational potential energy (negative sign) balance each other!

In fact, problem is much worse…

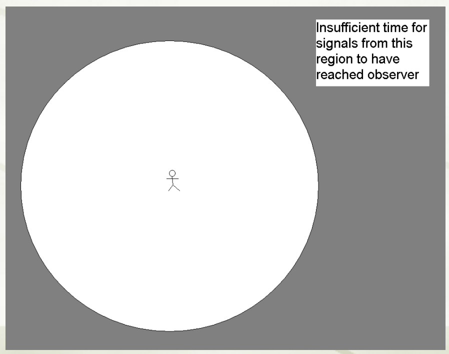
- If $\Omega \neq 1$, then value changes with cosmic time…
  - If $\Omega > 1$, then it grows larger and larger
  - If $\Omega < 1$, then it grows smaller and smaller



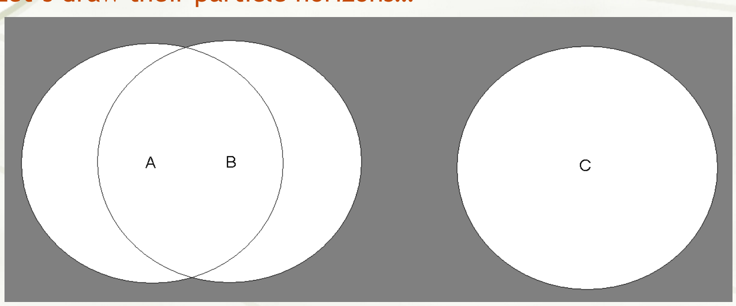
- If the universe is approximately flat now, it had to be very, **very** flat at early times…
  - $\Omega \approx 1$ now means Ω (t = 1s) differed from 1 by less than 10^{-16} !!
  - At the Planck's time, Ω differed from 1 by less than 10^{-60} !!
  - So, very special conditions were needed in the early universe to give approximate flatness now.
  - If the Universe were not nearly flat, we would not be here…
    - If Ω had been much above 1, it would have recollapsed very early before making galaxies
    - If Ω had been much below 1, it would have expanded so rapidly that structures would not have formed
  - This requires a lot of fine tuning!
  - It is known as the **flatness problem**

II : THE HORIZON PROBLEM

- Concept of the particle horizon:
  - The sphere surrounding a given point (e.g., the Earth) which is causally connected to that point



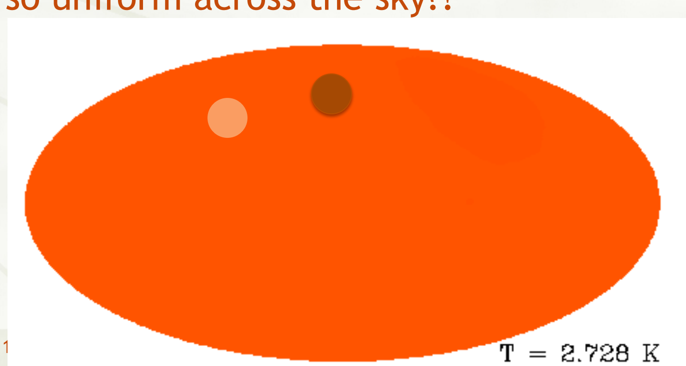
- Consider 3 locations in space; A, B and C.
- Let's draw their particle horizons…



- So, in this example, A and B are causally connected to each other. But C is not causally connected to either A or B.

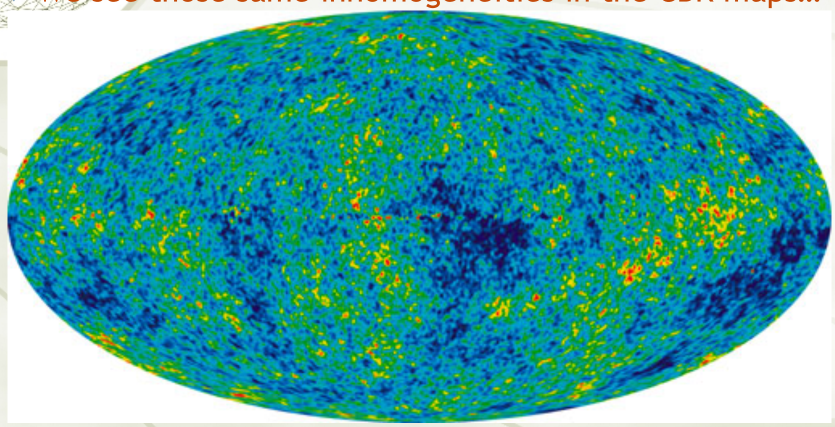
- Consider the "epoch of recombination"
  - Occurred ~400,000 yrs after big-bang
  - At that time, particle horizon would be roughly 10^6 light years across.
  - This size-scale at the redshift of decoupling ($z = 1000$) corresponds to an angle of about 1° on the sky…
- So, patches of the CBR that are separated by more than 1 degree should not have been in causal contact at the time of decoupling
- This gives the **horizon problem…**

- There were a million causally-disconnected regions on sky at the time of last scattering
- How does the CBR "know" that it has to be so uniform across the sky?!



III : THE STRUCTURE PROBLEM

- Structure in the universe (galaxies, clusters of galaxies etc.) came from inhomogeneities in the early universe
- We see those same inhomogeneities in the CBR maps…

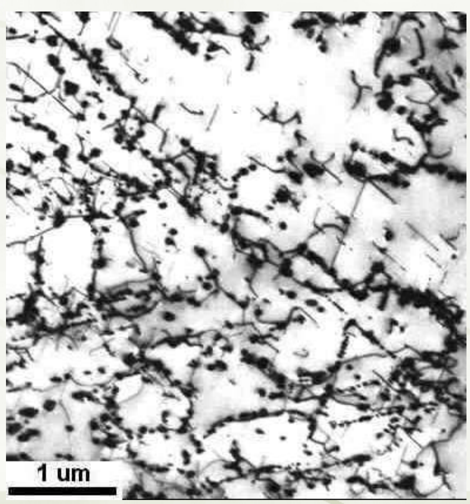


- How did those inhomogeneities get there?
- Why are they just the right magnitude and size to produce the structures we see today?
- How is it possible to have the same kind of inhomogeneities spread throughout the whole universe, despite the lack of causal contact between different parts of the early universe?
  - CBR is statistically the same in all directions
  - Galaxies, etc., that formed are similar in properties, on opposite sides of the Universe
- This is the **structure problem**.

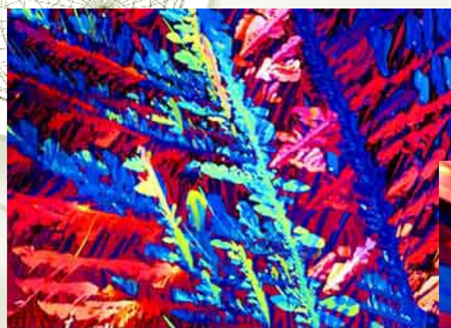
IV : THE RELIC PROBLEM

- Analogy: consider the cooling of a liquid (e.g., water)
- Once liquid reaches freezing point…
  - Freezing does **not** occur smoothly and uniformly
  - Freezing starts at certain locations, and the crystals start growing.
  - When crystals eventually merge to form the solid, there will be dislocations where the individual crystals meet…
  - The process of freezing is called a "phase transition" (matter changing from one phase to another).

Dislocations in steel



Beer crystals (Bud)...



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- What does this have to do with the Universe?
- "Quantum fields" related to particles and forces in the very early universe can undergo phase transitions (i.e., they "freeze").
- As Universe cools…
  - The temperature falls to the point where certain phase transitions can occur
  - Phase transitions will start at particular points in space and grow at light speed
  - Can get "dislocations" produced in the universe as a result of different regions meeting

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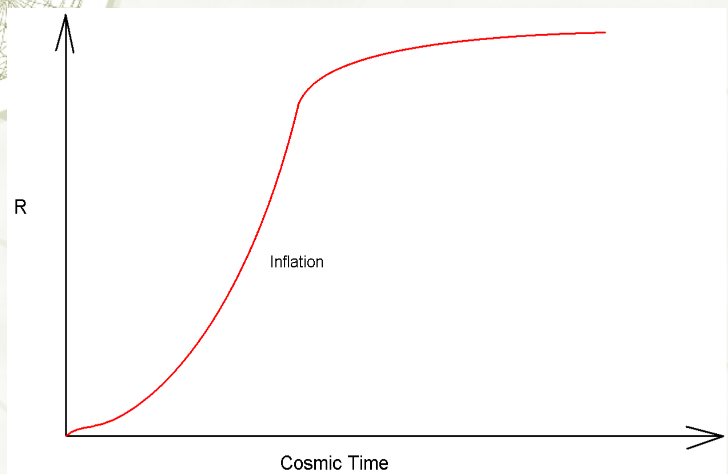
- This would produce exotic structure called topological defects…
  - Domain walls (2-d sheet-like structures)
  - Cosmic Strings (1-d string-like structures)
  - None of these structures have been seen in the observable universe (good limits from CBR data – strings would gravitationally lens the background)
- GUTs predict exotic particles produced at these domain walls in the early Univese
  - Look like magnetic monopoles
  - Never yet detected… and they don't reveal their presence in any observed phenomena. Limits are very good. These objects have to be very very very rare.
- The absence of monopoles (and other relics predicted by particle physics theories) is called the **relic problem**

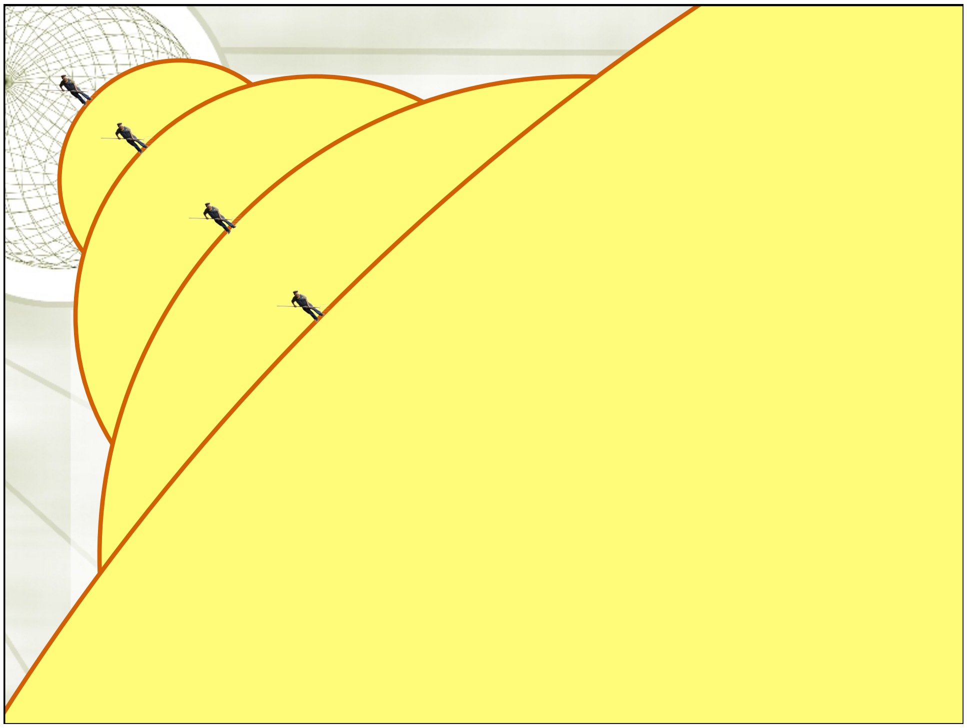
I. BASIC IDEA OF INFLATION

- Theory of cosmic "inflation" was first proposed by Alan Guth in 1982
- Guth postulated an **Inflationary Epoch**
  - Very-rapid, exponential expansion of Universe
  - Occurs during interval $t=10^{-37}-10^{-32}$ s
  - Universe expanded by a factor of $10^{40}-10^{100}$ during this time!
- What caused inflation? We'll get to that later…



II : SOLVING "COSMOLOGICAL PROBLEMS" WITH INFLATION

- The Flatness Problem
  - Imagine taking any (reasonable) curved surface
  - Now expand it by an enormous factor
  - After the expansion, locally it will look flat
  - So, inflation predicts a Universe that is indistinguishable from being flat



The Horizon Problem

- Prior to inflation (at t ≈ 10^{-37} s), the particle horizon has radius of $r \approx 10^{-29}$ m
- A sphere of this radius is the maximum volume that is *causally connected* at t ≈ 10^{-37} s (i.e. in which there can be a mutual influence)
- After inflation (at t ≈ 10^{-32} s), this region has exploded to 10^{11} – 10^{70} m
- "Normal" expansion then takes over… Universe expands by another factor of 10^{22} between end of inflation and recombination/decoupling (t = 400,000 yr)
- So, *at time of decoupling, causally connected volumes have radii* ***at least*** *$r_c = 10^{33}$ m!*
- *This is much larger than today's particle horizon: r~13.7 billion light years ~10^{26} m*

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The structure problem

- The initial inhomogeneities are due to quantum fluctuations during the inflationary epoch.
- Virtual particle pairs that formed would be separated by inflationary expansion before they could annihilate, creating uneven densities
- Inhomogeneities were continually created, and then stretched to much larger scales -- outside the horizon
- Naturally gives a characteristic spectrum of inhomogeneities
  - This is the "Harrison-Zel'dovich spectrum"
  - Equal amplitude for fluctuations on all scales
  - Equivalent to "white noise" in acoustics: **"static"**

Relic problem

- Suppose exotic particles or structures (cosmic strings, magnetic monopoles etc.) were created in very early universe
- They would become very diluted during the inflationary epoch, because space would expand so much
- The probability that we see a "relic" exotic particle in our current universe would then be very, very small.
- *Inflation solves the relic problem!*

Baryons

- But what about baryons? Wouldn't the probability of finding them also be small?
- No, provided that *baryogenesis occurred after inflation stopped*: vacuum energy is converted to regular matter (including baryons) and radiation

- OK… inflation can solve many "cosmic problems"
- But **why** did inflation happen?
- We believe the answer lies in the behavior of **quantum fields.**

Fields and particles

- Quantum view of EM radiation:
  - Basic entity is the electromagnetic field (which permeates all of space)
  - Photons are **excitations** (ripples) of field with certain wavelengths and frequencies
  - Energy/momentum of the excitations in the field is quantized… can only add or take away energy/momentum from field in discrete amounts equaling the energy in a single photon
- Every particle has its own field
  - Electron Field (excitations = electrons)
  - Quark Fields (excitations = quarks)
  - Gluon Fields (excitations = gluons)
  - etc. etc.
- Position and momentum of a particle cannot both be known simultaneously, but obey certain probabilistic rules related to the field's wave behavior

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IV: FALSE VACUUMS AND VARIOUS INFLATION MODELS

- Alan Guth's original idea…
  - In early universe, there was an exotic particle (called "inflaton") and a corresponding scalar quantum field
  - As the very early universe evolved, this field got stuck in a high-energy state
    - Analogous to a marble resting on top of an upside-down bowl, or a pencil balanced vertically on its point
  - This created an enormous "false vacuum" energy that drove the inflation of the Universe.
  - Similar to "dark energy" which is making the Universe expand now!
  - Eventually, field gets "unstuck" and evolves to a lower-energy state corresponding to "true vacuum", so that inflation ends.

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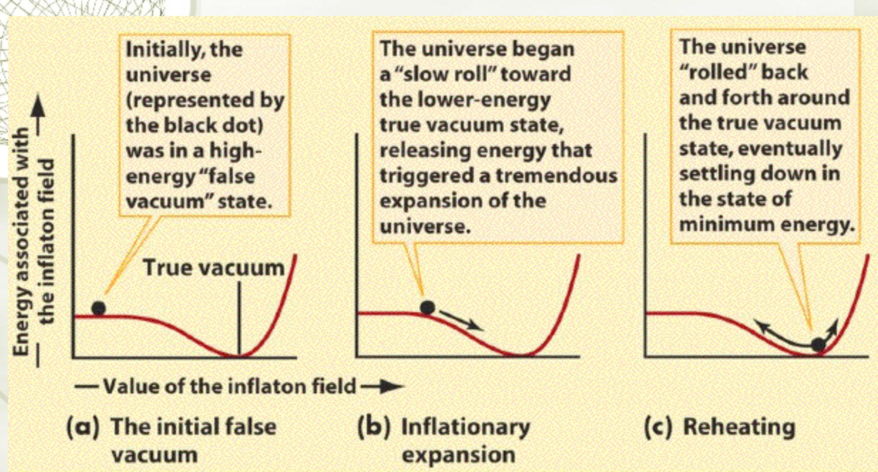
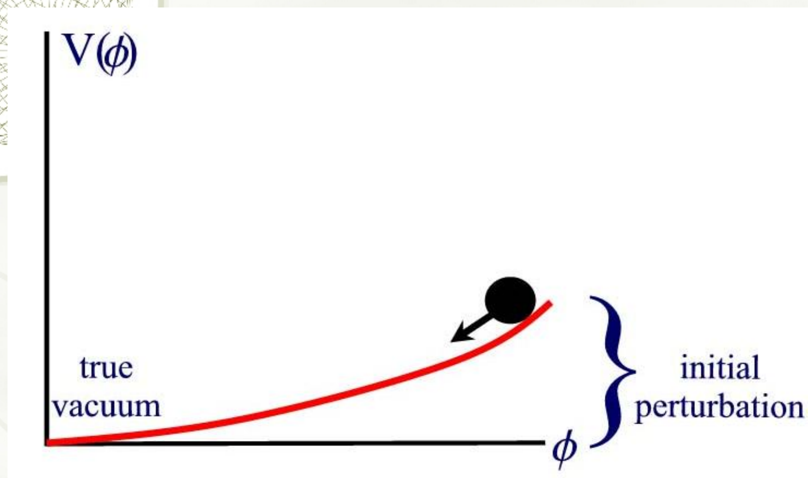
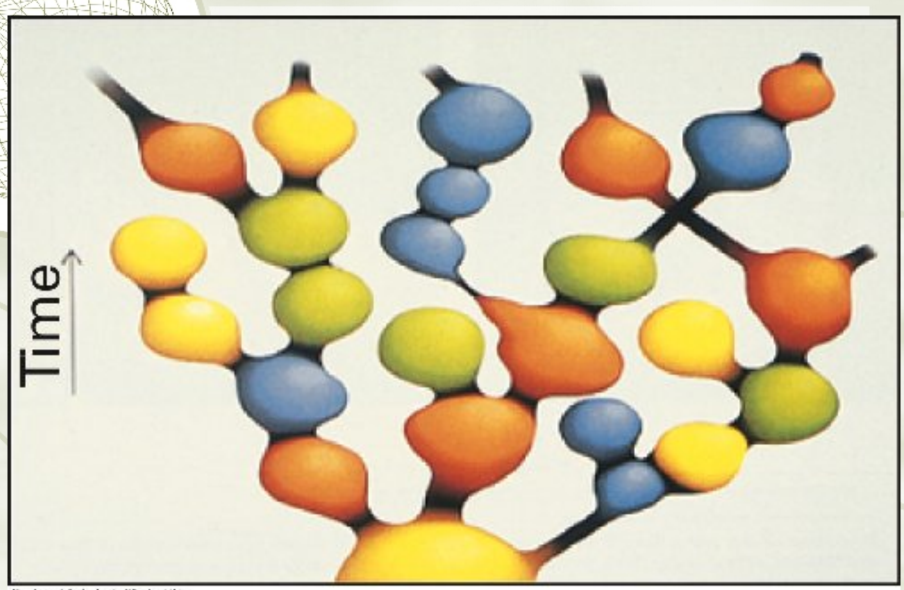
- Guth originally thought the Higgs Boson (a massive particle related to baryogenesis) would work as the "inflaton"
- Guth's original model turned out not to work because inflation would not stop
- "New" inflation or Chaotic inflation
  - Proposed independently by Linde and Steinhardt
  - Inflation occurs during slow rolling of field down a potential. The field is non-zero initially due to quantum or thermal fluctuations

Old inflation, produced by a phase transition



New Inflation: chaotic inflation





Courtesy of Andre Linde (Stanford U.)

Universe starts simple but becomes very complex!

- Final philosophical remarks:
  - Universe evolves form order (low entropy) to disorder (high entropy), but in special places in the universe order wins
  - Life and intelligent life around stars is possible because radiation from the sun is used and degraded to higher entropy thermal radiation
  - A brain is certainly a very low entropy system (in most people)