Lecture 25 : *Inflation*

- Inflation
- How inflation solves the puzzles
- Physical motivation of inflation: quantum fields

"I'll tell you what's beyond the observable universe -- lots and lots of unobservable universe."

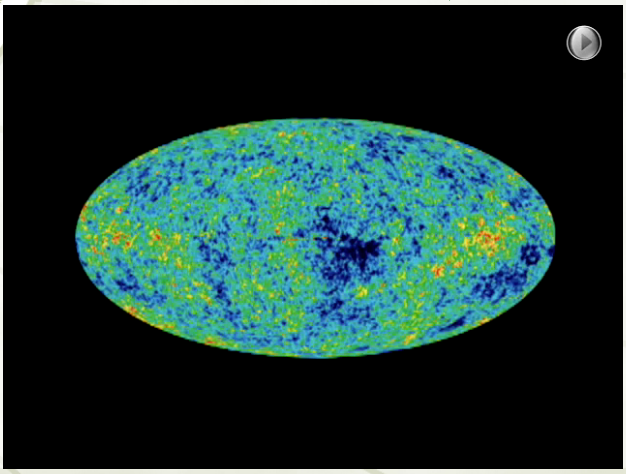
© Sidney Harris

Reading: Chapter 16 of text

Quiz!

- What are Pop III stars? Why/how are they different?

The sequence of structure formation



Four cosmic puzzles

- Puzzles:
  - flatness problem
  - horizon problem
  - structure problem
  - relic problem
- Inflation
  - Basic idea
  - How it solves the cosmological puzzles

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?

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It's worse than that: Ω changes with time

- $\Omega = \Omega_M+\Omega_\Lambda$
- $|1-\Omega|=|k|c^2/[H(t)^2R(t)^2]$
- For a matter-dominated Einstein-de Sitter universe, $|1-\Omega| \sim t^{2/3}$
- For a radiation-dominated universe, $|1-\Omega| \sim t$
- So, if Ω is close to 1 today, it had to be much much closer to 1 in the past!

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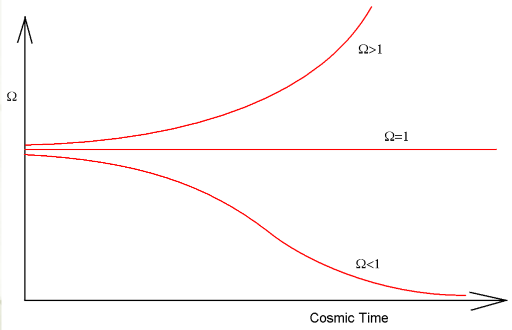
Evolution of omega

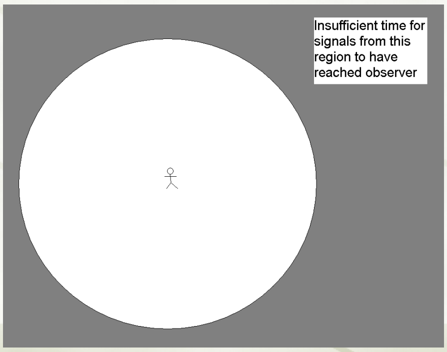
- If $\Omega \neq 1$, then value changes with cosmic time…
  - If $\Omega > 1$, then it grows larger and larger
  - If $\Omega < 1$, then it grows smaller and smaller



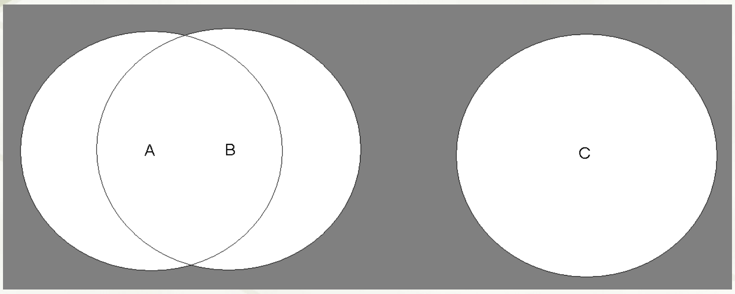
- If the universe is approximately flat now, it had to be very, **very** flat at early times…
  - $\Omega \approx 1$ now means Ω (t = 1s) differed from 1 by less than 10^{-16} !!
  - At the Planck's time, $|1-\Omega| \sim 10^{-60}$!!!!!!!!!!!!!!!!!!
  - So, very special conditions were needed in the 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

- Remember 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…



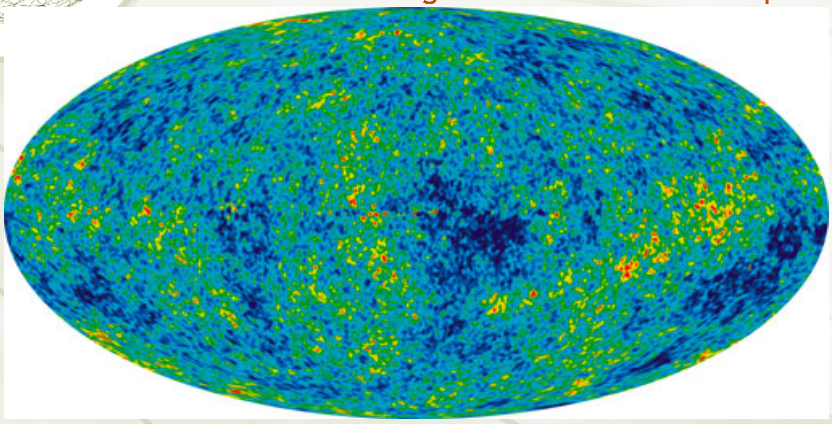
- So, in this example, A and B are causally connected to each other. But C is not causally connected to either A or B.

- Consider the "decoupling epoch"
  - 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 ($z = 1100$) 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…

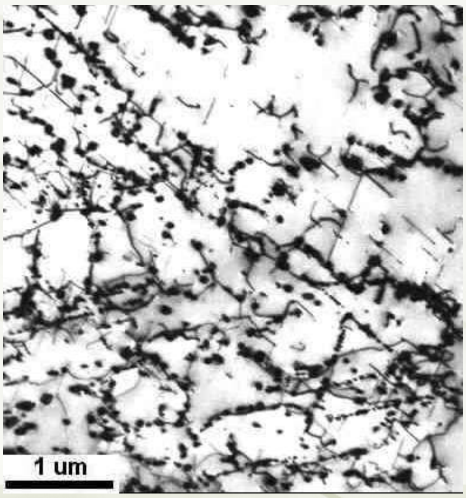


- How did those inhomogeneities get there?
- Why are they just the right magnitude and size to produce the structures we see today?
- How is it possible to have the same kind of inhomogeneities spread throughout the whole universe, despite the lack of causal contact between different parts of the early 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.**

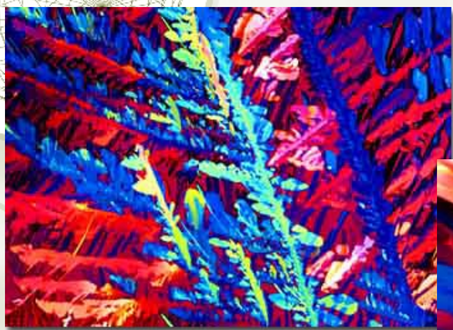
IV : THE RELIC PROBLEM

- 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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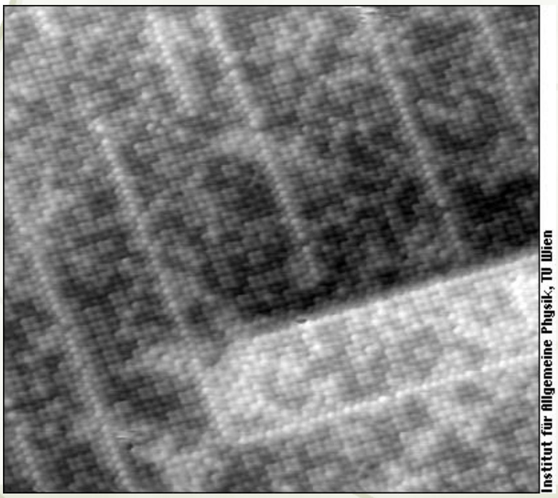
The atomic structure…



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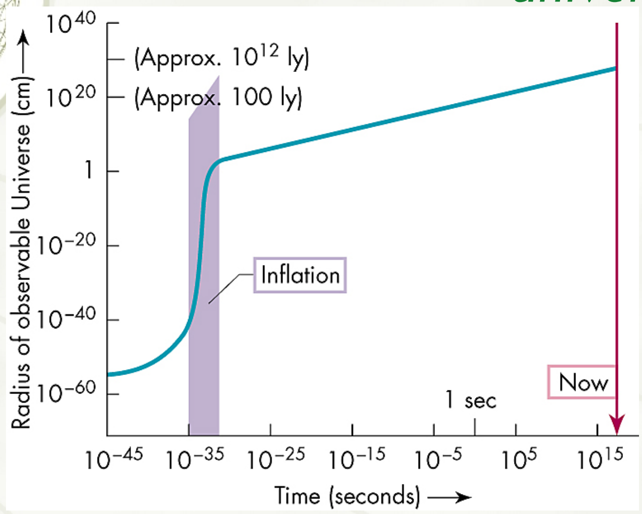
- What does this have to do with the Universe?
- "Quantum fields" related to particles and forces in the very early universe can undergo phase transitions (i.e., they "freeze").
- As Universe cools…
  - The temperature falls to the point where certain phase transitions can occur
  - Phase transitions 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

- 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

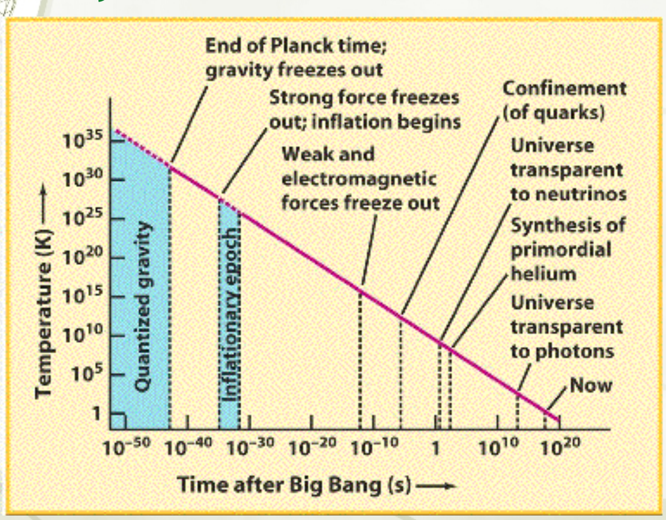
- Theory of cosmic "inflation" was first proposed by Alan Guth in 1982
- Guth postulated an **Inflationary Epoch**
  - Very-rapid, exponential expansion of Universe
  - Occurs during interval $t=10^{-37}$-10^{-32} s
  - Universe expanded by a factor of 10^{40}-10^{100} during this time!
- What caused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

Inflation and the radius of the universe



Graphics: Arny, *Explorations*, McGraw-Hill

Inflation in the timeline



- Does this rapid expansion imply a violation of relativity (no speed exceeds c)?
- No, because it is *space itself* that is expanding (*R(t)*), rather than material particles moving apart at high speed in a fixed, stationary space

II : SOLVING "COSMOLOGICAL PROBLEMS" WITH INFLATION

- The Flatness Problem
  - Imagine taking any (reasonably) 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

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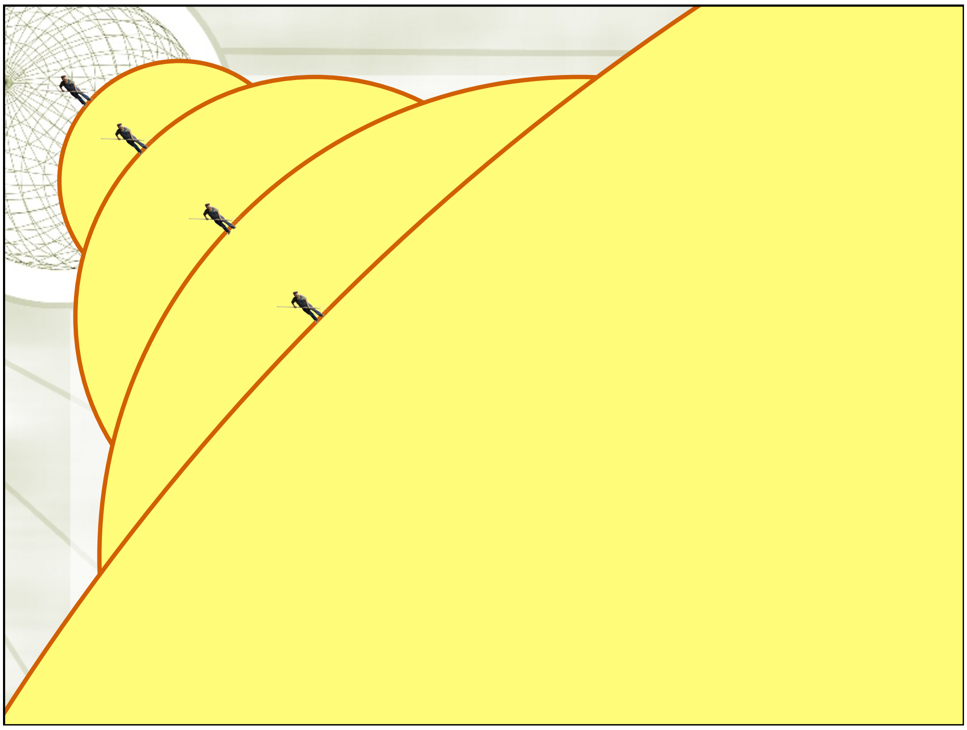
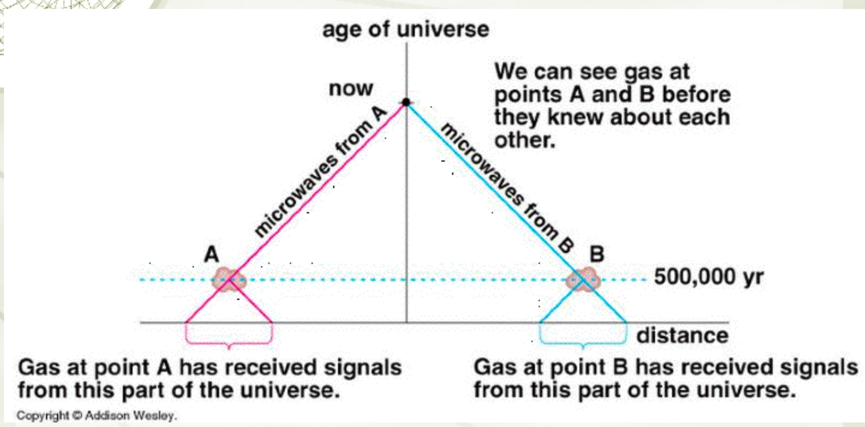


- Mathematically, consider Friedmann's equation with a vacuum energy V_I

$$H^2 = \left(\frac{dR/dt}{R}\right)^2 = \frac{8\pi G V_I}{3} - \frac{kc^2}{R^2}$$

- During inflation, the vacuum energy density V_I stays nearly constant …
- … but, R increases by an enormous factor
- Hence, the last term in the equation (the curvature term) becomes negligible compared to the vacuum energy density term (which is converted into matter and radiation after inflation)
- *Therefore, Universe is well described as being **flat** after inflation*

The horizon problem without inflation



How inflation solves 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!*

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- Cosmic scale factor has increased by a factor 10^3 since decoupling (z = 1100), so causally-connected radius now would be at least $r_c = 10^{36}$ m
- Current horizon of Universe (observable radius) Universe at present time is about $r_H = 10^{26}$ m
- Since $r_H < r_c$ (by at least 10 orders of magnitude) inflation says that the whole observable universe originated within a small *causally-connected* patch of the early universe!
- Since opposite sides of the Universe **now** were in fact in causal contact at t < 10^{-37} s, this explains why the CBR (and everything else) is statistically uniform on large scales
- *Inflation solves the horizon problem!*

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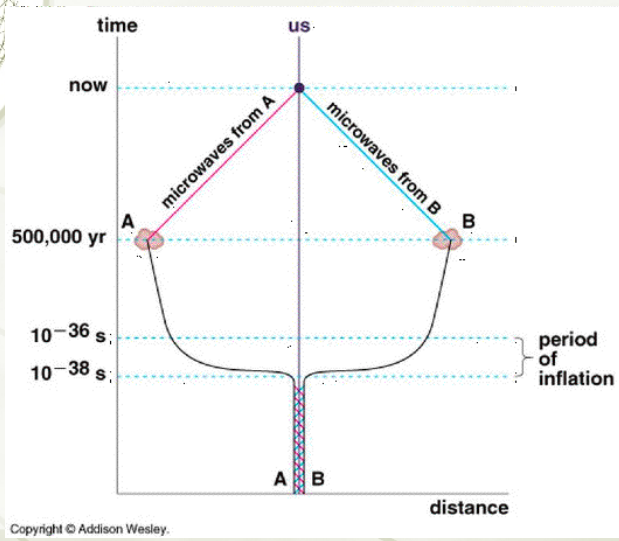
Inflation and causality



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
- It turns out that this naturally gives a characteristic power spectrum of inhomogeneities
  - This is the "Harrison-Zel'dovich spectrum"
  - Equal amplitude for fluctuations on all scales
  - Equivalent to "white noise" in acoustics: "**static**"

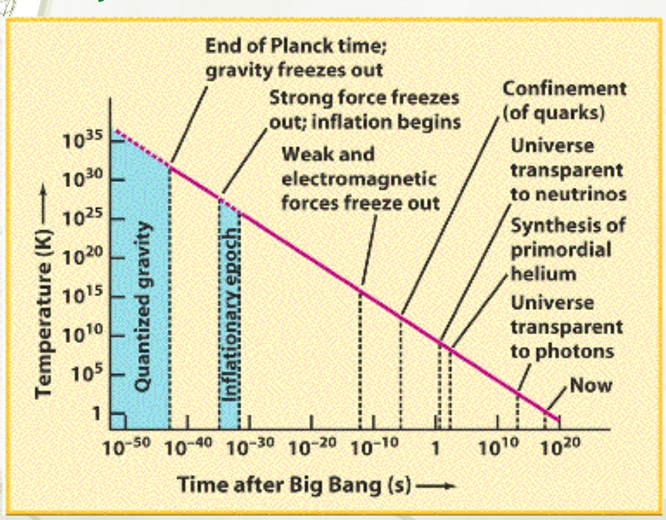
- Any fluctuation created by inflation can only grow at much later times, after the horizon has expanded so that it is larger than the size scale of that fluctuation
- Since the horizon scale increases in time, smaller-scale fluctuations grow first (after inflation)
- Harrison-Zeldovich spectrum is consistent with what we see now, in terms of the observed structure that has grown
- Largest present-day structures (superclusters, voids, filaments) are the result of quantum fluctuations that originally occurred on sub-microscopic scales!

- 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

Inflation in the timeline



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

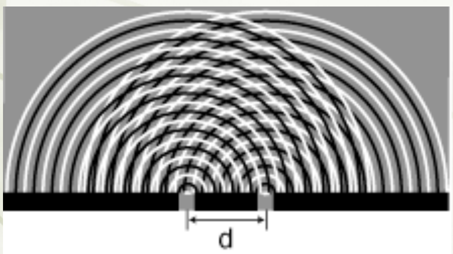
III : QUANTUM FIELD THEORY

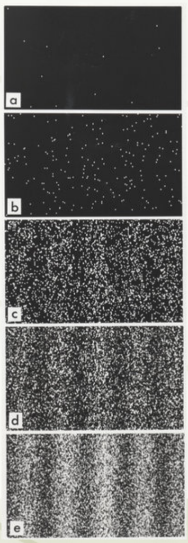
- To understand inflation, we must consider a little more physics about matter and forces.
- Modern theories of matter and forces are called "**Quantum Field Theories**"
- A difficult subject
  - Even basic concepts are very abstract
  - Advanced math needed to study it in any detail.
- Here we just touch on the basic principles.

E/M radiation… particles or waves?

- Electromagnetic radiation (light) can behave as:
  - Waves of electric & magnetic field
    - E.g., see reflection, refraction, diffraction effects
  - Particles (photons)
    - E.g. can detect them individually on a CCD
  - The same EM energy shows both aspects of its behavior: photons can follow a wave pattern
  - Just one of the weird aspects of quantum theory!

Wave interference by two slits





From *Wikipedia*

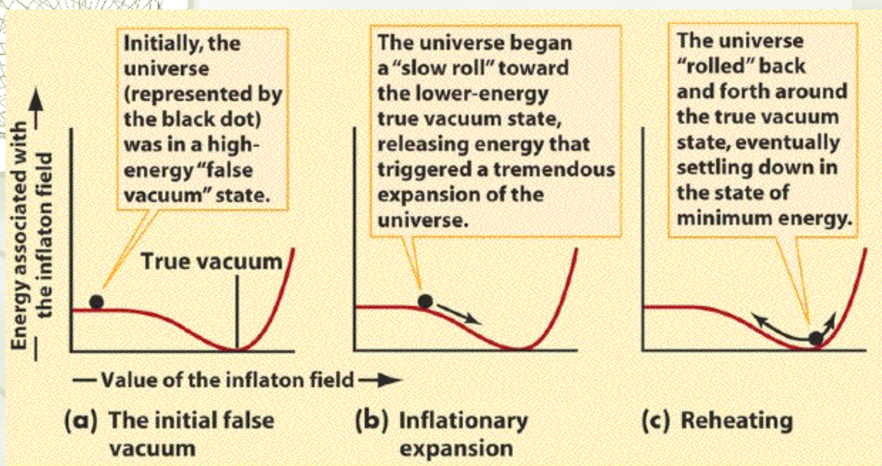
Fields and particles

- 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

IV: FALSE VACUUMS AND VARIOUS INFLATION MODELS

- Alan Guth's original idea…
  - In early universe, there was some an exotic particle (called "inflaton") and a corresponding 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.

- 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
  - Proposed independently by Linde and Steinhardt
  - Inflation occurs during transition from false to true vacuum
  - Quantum field gets "unstuck" slowly



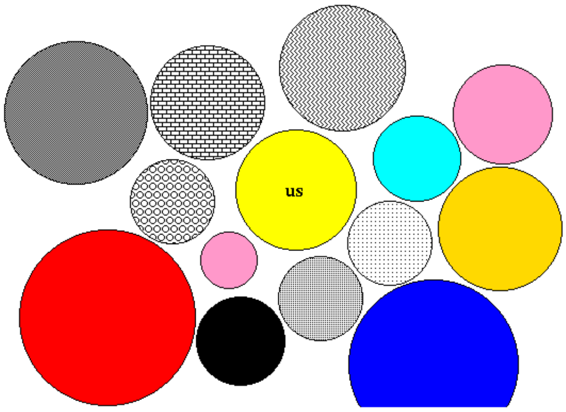
- During inflation, temperature plummets because *T* is inversely proportional to the cosmic scale factor *R(t)*
- After inflation ends, vacuum energy is converted into ordinary particles and radiation, which reheat the universe: *T* rockets up again
- Subsequent evolution is just as in the radiation-dominated, followed by matter-dominated, usual stages that we've discussed

Chaotic inflation

- This is currently considered the "standard" inflationary model
- Idea is that inflation occurs due to fluctuations in some quantum field in the early universe
- So, some regions inflate and some don't; our whole observable universe is a sub-part of one of the "bubbles" that did inflate
- Larger "super-universe" may be continually spawning new bubble universes within it
- Think of boiling water as an analogy: bubbles form some places, but not in others; then expand or collapse
- Unsatisfactory side: loss of predictability. Why do "constants" have the values they have? It's just whatever happened for our patch of the multiverse!

Bubble Universes

after the inflation era, our Universe became just one of many bubbles in the Big Bang substratum



although these other bubble universes may exist theoretically, we will never be able to observe or communicate with them since they are outside our horizon

Graphics: University of Oregon Physics Dept

V: INFLATION AND US

- Inflation solves many problems about the observed parameters and properties of our universe…
  - Space is flat because any original curvature was inflated away
  - Well-separated regions on the horizon look similar to each other because they were neighbors before inflation
  - The perturbations in the CBR which evolved to create structure in the universe has the power spectrum it does because it was imprinted during inflation due to quantum fluctuations
  - There are no strange relics around because the volume per weird particle (monopoles, etc) became very large during inflation epoch

- …and chaotic inflation may help explain why "we are here"
  - There may be many regions in the larger universe (hyperuniverse?) that have different properties
  - Humankind could only have evolved in a bubble that has the properties that "our universe" has!
  - There may be other interesting bubbles out there, but it's beyond the realm of science to know what they are like (they are causally disconnected from us)…
  - This provides a possible answer to the "Why 13.7 Gyr ago?" question if we're in a youngish bubble in an older hyperuniverse.