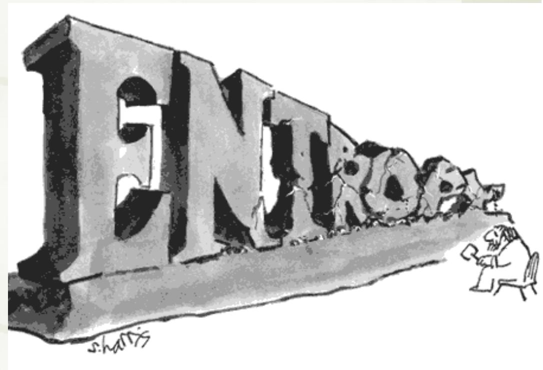
Lecture 25 : Inflation

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



Reading: Chapter 16 of text

FINAL EXAM

- *<u>Friday</u>, 15 May, 8:00-10:00*
- Exam is in this room
- Cumulative, but with emphasis on material after the midterm
- No notes or books allowed
- **<u>Bring calculator</u>**

- **Review session in class May 12**

Please fill in your course evaluation!-

- www.CourseEvalUM.umd.edu
- Have you been challenged and learned new things? Have I been effective, responsive, respectful, engaging, etc?-or dull,boring, stodgy, unprepared?
- Your responses are strictly anonymous. I only see the statistics.
- Helps me and future students!
- Deadline to fill it in is May 13

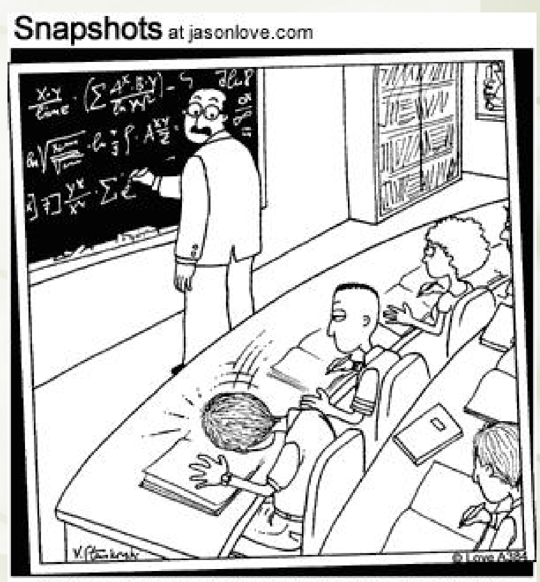
- The evaluations are confidential
- the summarized results are at the same location.
- the system does not identify to you whether or not they submitted an evaluation
- Please do this !- However I will not resort to bribery

instructor evaluation day

- The most popular reason respondents gave for not participating was that they were too busy and/or ran out of time

Difficulty of Material

- 'Cosmologists are often in error, but never in doubt.' Lev Landau
- these are VERY difficult concepts...please ask questions!



Professor Herman stopped when he heard that unmistakable thud -- another brain had imploded.

Some Philosophy

From 10^{-10} seconds to today the history of the universe is based on well understood and experimentally tested laws of particle physics, nuclear and atomic physics and gravity. We thus have confidence about the events shaping the universe during that time

Before 10^{-10} seconds, the energy of the universe exceeds the capabilities of the highest energy particle accelerators (~10 TeV the LHC) and thus there is little direct experimental guidance (Cosmic rays have energies up to 10^{10} TeV). The physics of that era is therefore as speculative as it is fascinating.

The Big Bang has a singularity at t=0; things break down ... not physical?? or new physics??

More Philosophy

Physicists want to understand things at the **most** fundamental level: (those nasty how, why questions; we have concentrated on the what, where and when)

Why is the universe isotropic and homogenous?
How do the ~20 free parameters of the standard quantum physics model occur? (mass of particles, strength of interactions)
How to reconcile General Relativity and quantum mechanics ? (quantum gravity)
What do the indications of physics beyond the standard model mean?

But we want solutions that are general- not fine tuned

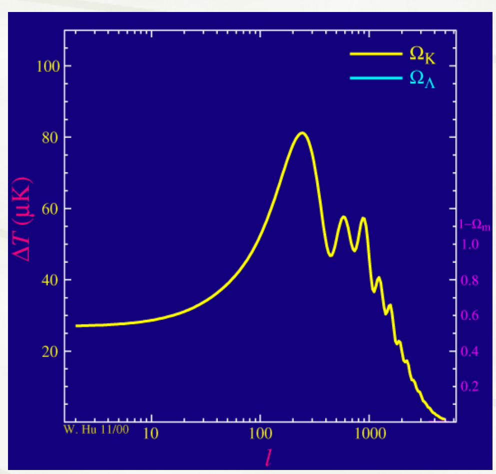
Four puzzles to solve

- The Flatness Problem.
- The Large-Scale Smoothness Problem.
- The Small-Scale Inhomogeneity Problem
- The Magnetic Monopole/Relic Problem.
- To solve these requires 'fine tuning' or *a very improbable initial state of the universe*
- Of course there are others too...

Reading: Chapter 16 of text (inflation)

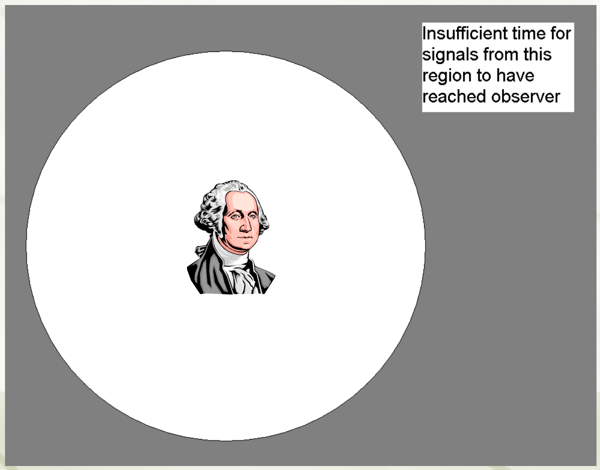
CMB Measures Flatness

- The first peak in the power spectrum of the CMB is very sensitive to the flatness of the universe

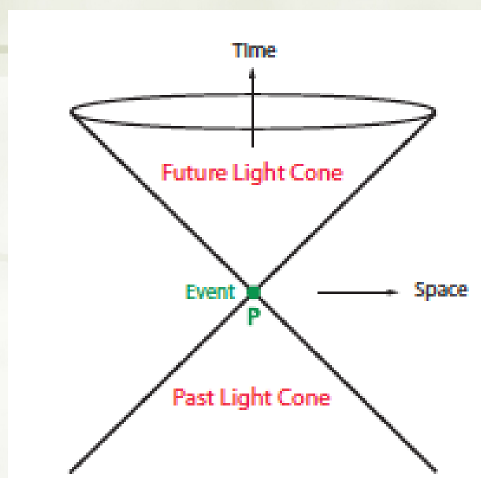


II : THE HORIZON PROBLEM

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



- the conventional Big Bang model `begins' at a finite time in the past and at any time in the past the particle horizon was finite (~twice the Hubble length 8 Gpc), limiting the distance over which spacetime region could have been in causal contact.
- This feature is at the heart of the `big bang puzzles'.



Interior of cone is casually connected

(see text pg 465-467)

- The microwave background radiation from opposite directions in the sky is characterized by the same temperature to within 0.01%, but the regions of space from which they were emitted at 500,000 years after the big bang were more than the light transit time apart and could not have "communicated" with each other to establish the apparent thermal equilibrium - they were beyond each other's "horizon".
- Analogy:

If you have a big gas burner (the big bang), and put two saucepans with water on it, we expect the water in both pans to heat up and boil at *almost, but not exactly* the same time, because the flame is not exactly the same everywhere. There has to be "communication" or heat exchange between the two saucepans for them to heat up in exactly the same way. -

poor man's view of quantum fluctuations

Size of the 'Observable' Universe

- The size of the lightcone ($r_{horizon}$) contains all of the universe that we can see or measure- *but this size changes with time.*
- $r_{horizon}$=2c/H= 8Gpc- but H=(dR/dt)/R

for a flat universe $R(t)=R(0)(t/t_0)^{2/3}$ and thus

$H \sim 1/(t/t_0)$ - the size of the horizon is smaller at earlier times (exact values depend on k and Λ) .

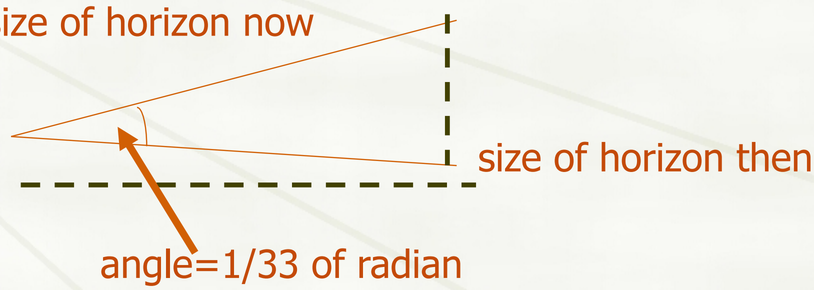
- Or (using eq 10.11- always true) $R_{now}/R_{then}=1+z$ and since recombination occurs at z=1100 ; R is only 8Mpc then
- Using a cosmologically correct calculation for a matter dominated universe the angle in the sky (today) for which blobs of the universe are connected at recombination (when the CMB formed) is $\theta \sim (\Omega_0/1+z_r)^{1/2} \sim 1.7\, \Omega_0^{1/2}$ degrees

Ω_0 is the present value of Ω

Where Does This Formula Come From?

- $R \sim t^{2/3}$ or $t \sim R^{3/2}$
- distance=(velocity)x(time) =dt/dR *c = c $R^{1/2}$
- size of horizon at recombination/size now= $(R_{recombo}/R_{now})^{1/2} = (1+z_R)^{-1/2}$

$= 1100^{-1/2} = 1/33$ radian



Say it again Sam

- The uniformity of cosmic background radiation--varying by < 1 part in 10,000, where ever you look--is a major problem for Standard Big Bang cosmology.
- At the time the universe began 14 billion years - look to the west, and measure the CMB: turn our radio antennas to the east, the CMB is at exactly the same temperature.
- The radiation from the east and the radiation from the west are separated by 28 billion light years.
- the radiation from the east could not possibly be causally connected to that from the west, because information cannot travel faster than the speed of light (the universe is too young). Nor could the regions they traveled from ever have been in communication.
- It's as if 200 students one in a huge introductory classes were taking a test and each student scores exactly 93% on the test. There had to be some cheating going on. But how?

- http://archive.ncsa.illinois.edu/Cyberia/Cosmos/HorizonProblem.html

Structure Problem

- How did those inhomogeneities get there?
- Why are they just the right magnitude, size and distribution in 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?
  - Galaxies, etc., that formed are similar in properties, on opposite sides of the Universe
- This is the **structure problem.**
- Partly similar in concept to the horizon problem- why are things so similar everywhere when they have never been in contact.

- Limitations of the Big Bang Theory

The Big Bang theory successfully explains the "blackbody spectrum" of the cosmic microwave background radiation and the origin of the light elements, but it has several significant problems:

- The Flatness Problem:

CMB shows that the geometry of the universe is nearly flat. However, in Big Bang cosmology, curvature grows with time. A universe as flat as it is today requires extreme fine-tuning of conditions in the past, an major coincidence.

- The Horizon Problem/Structure Problem

Distant regions of space in opposite directions of the sky are so far apart that, assuming standard Big Bang expansion, they could never have been in causal contact with each other. This is because the light travel time between them exceeds the age of the universe. Yet the uniformity of the cosmic microwave background temperature indicates that these regions must have been in contact with each other in the past.

The fluctuations are the same everywhere in the universe

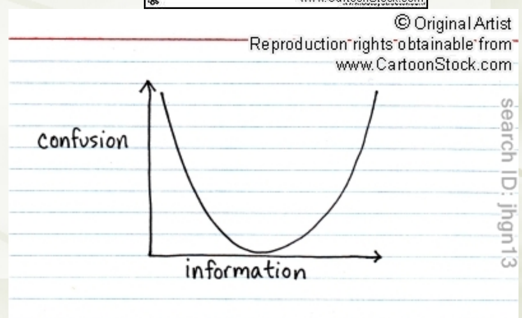
- The Relic/Monopole Problem:

Big Bang cosmology predicts that a very large number of heavy, stable "magnetic monopoles" should have been produced in the early universe. However, magnetic monopoles have never been observed, if they exist at all, they are much rarer than the Big Bang theory predicts.

Here We Go Again ...

Even for quantum physicists this is hard stuff

- We are going beyond the bounds of present day certainty
- these are VERY difficult concepts...please ask questions!



http://www4.ncsu.edu/unity/lockers/users/f/felder/public/kenny/papers/inflation.html

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…

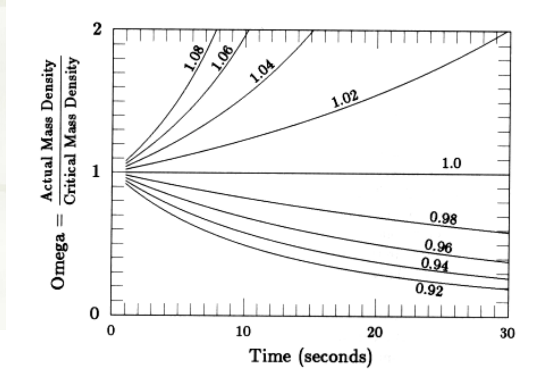
http://www.nature.com/news/2009/090415/full/458820a.html

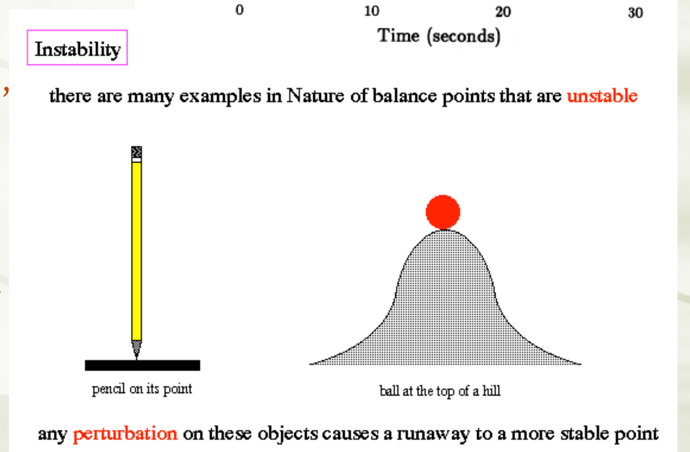
Problems Inflation was Invented to Surmount

- The conventional Big Bang theory has an initial conditions problem: the universe as we know it can only arise for *very special* and *finely-tuned* initial conditions.
- an early period of accelerated expansion (inflation) solves this initial conditions problem and allows our universe to arise from generic initial conditions.

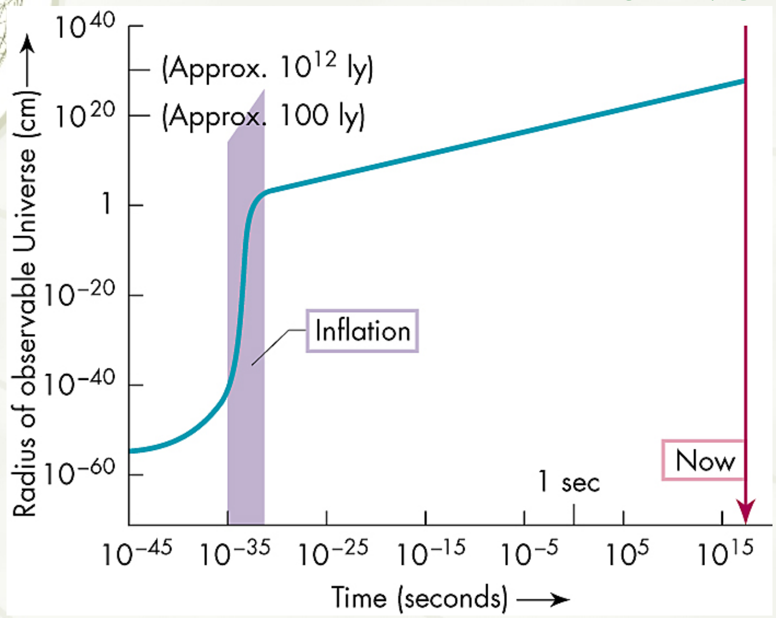
Instability - or fine tuning

- Values of Ω slightly below or above 1 in the early Universe rapidly grow to much less than 1 or much larger than 1 as time passes (like a ball at the top of a hill).
- as time passes, Ω would have **quickly grown, or shrunk**, to present-day values of much, much more, or much, much less than 1.
- the Universe must have a value of Ω exactly equal to 1 for stability. Therefore, the flatness problem is that some mechanism is needed to produce a value for Ω to be exactly one (to balance the pencil)





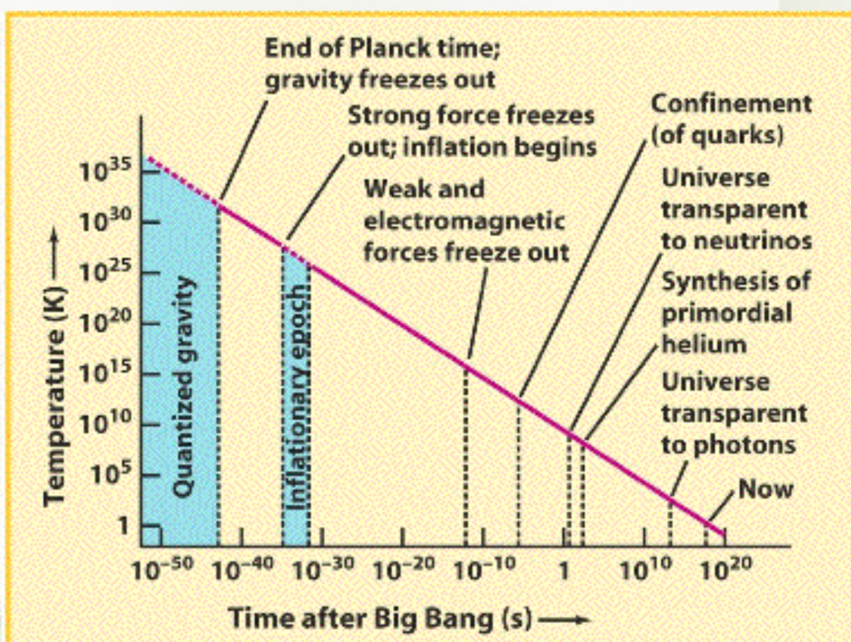
Inflation and the radius of the universe



Graphics: Arny, *Explorations*, McGraw-Hill

Inflation in the timeline

We do not understand quantum gravity- nor the true nature of inflation



- 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
  - Nothing can travel through space faster than light. *However, in general relativity, space itself can do whatever it likes.*

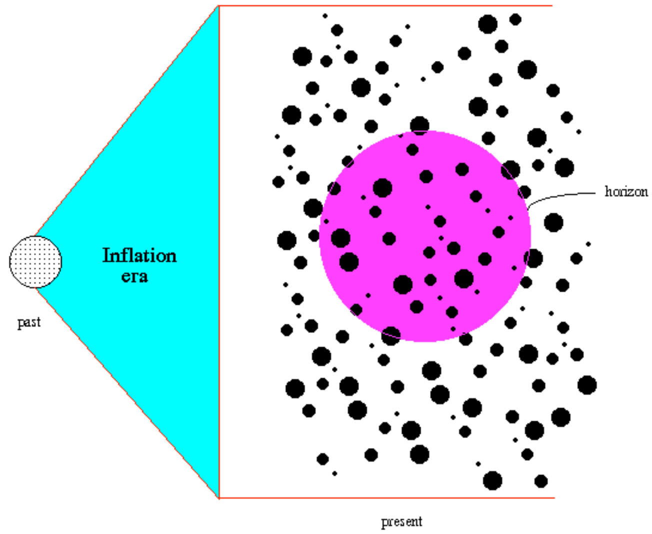
Summary of Inflations Effects

- Before the inflationary period, the universe's constituents would have been in contact with one another, so they could have reached the same temperature.
- Rapid inflation would make the universe's expansion appear very flat, in the same way that the surface of a balloon blown up by such a huge factor would resemble the Great Plains. Inflation ended (and needs to end) ~10^{-30} seconds after the Big Bang,
- Since then the universe has expanded <u>just as it would have in the standard big-bang model.</u>

- Only a small part of the original big bang is within our horizon- OUR universe

Inflation

under inflationary cosmology, the Universe underwent a phase change at the GUT era and expanded faster than the speed of light (the spacetime itself expanded, so there is no violation of special relativity)



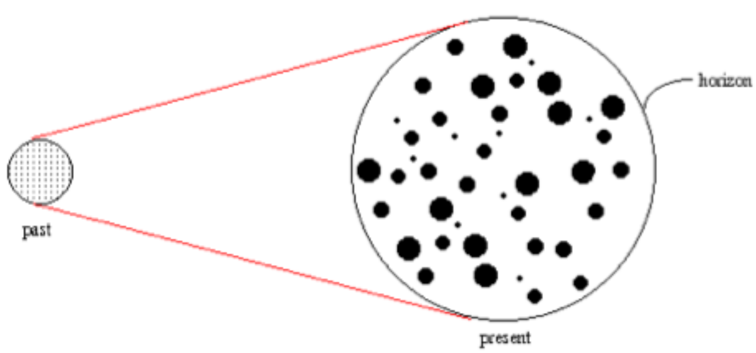
the result is that only a small part of the original Big Bang is within our horizon, what we call our Universe.

http://abyss.uoregon.edu/~js/ast123/lectures/lec18.html

Normal Expansion

Normal Expansion

normal expansion is when the Universe expands at less than the speed of light such that all the Universe is within our horizon either now or sometime in the future



http://abyss.uoregon.edu/~js/ast123/lectures/lec18.html

II : SOLVING "COSMOLOGICAL PROBLEMS" WITH INFLATION

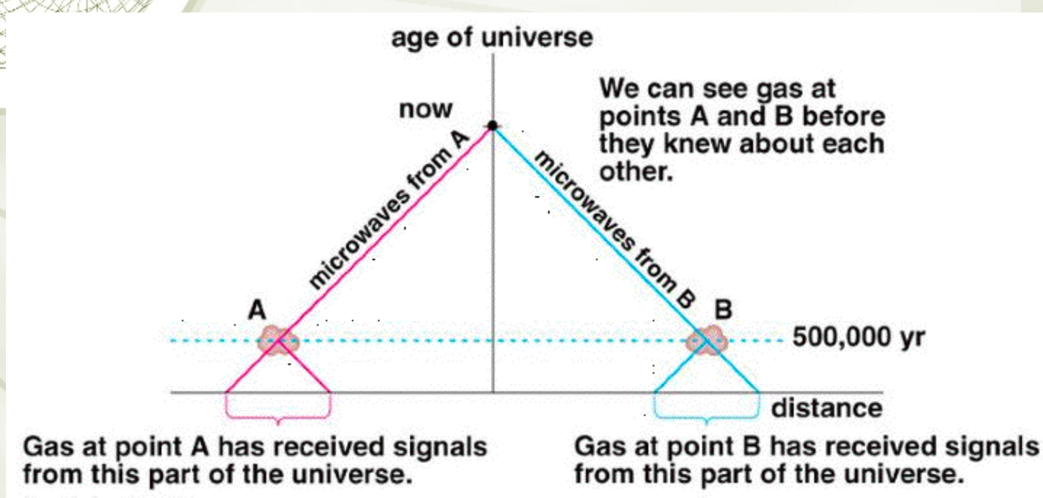
- The Flatness Problem
  - Imagine taking any (reasonably) curved surface
  - Now expand it by an enormous factor
  - After the expansion, locally it will look flat
  - So, inflation predicts a Universe that is indistinguishable from being flat

- 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 - see text pg 478*

The horizon problem without inflation

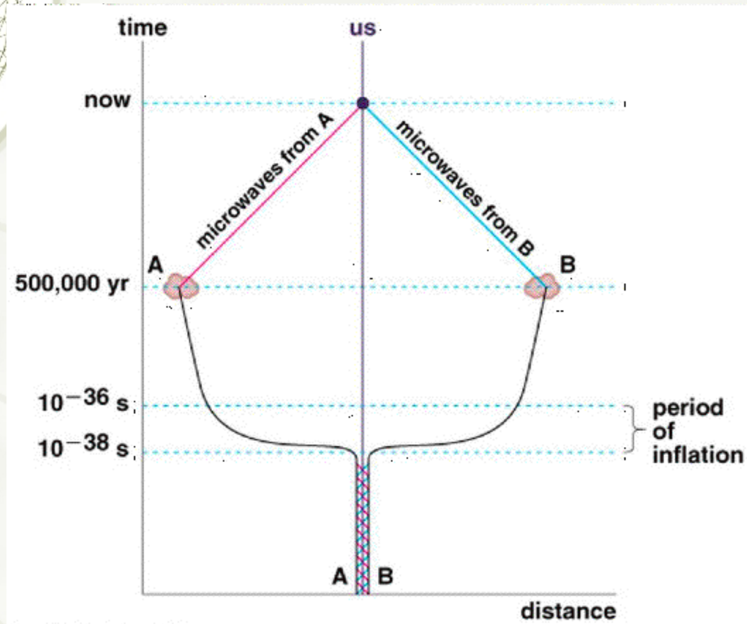


How inflation solves the horizon problem

- Prior to inflation (at $t \approx 10^{-37}$ 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 $t \approx 10^{-37}$ s (i.e. in which there can be a mutual influence-l=ct)
- After inflation (at $t \approx 10^{-32}$ 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!*

- 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!*

Inflation and causality

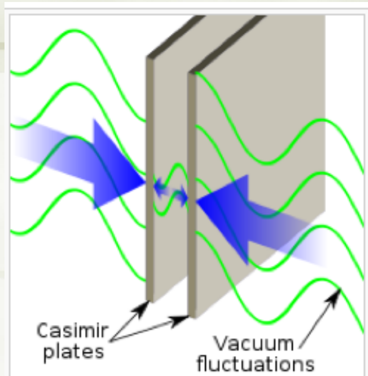


The structure problem

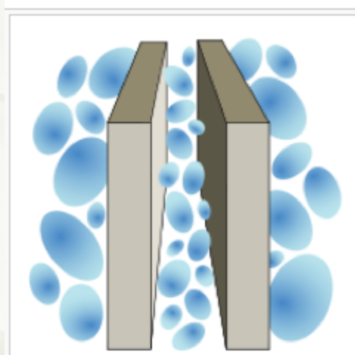
- The initial inhomogeneities are due to *quantum fluctuations* during the inflationary epoch.
- Virtual particle pairs that formed would be separated by inflationary expansion before they could annihilate, creating uneven densities
- Inhomogeneities were continually created, and then stretched to much 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!
- http://www.scientificamerican.com/article.cfm?id=inflation-creates-infinity-universes

- The properties of the Universe come from `nothing', where nothing is the quantum vacuum
- `empty' space is not truly empty, it is filled with spacetime. Spacetime obeys the laws of quantum physics and is filled with potential particles, pairs of virtual matter and anti-matter units, at the quantum level.
- Casimir effect - the vacuum pushes



Casimir forces on parallel plates


Casimir forces on parallel plates

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!*

Additional Bonus Prize

Inflation also explains the origin of structure in the universe.

- Prior to inflation, the portion of the universe we can observe today was microscopic, and *quantum fluctuations* in the density of matter on these microscopic scales expanded to astronomical scales during Inflation.
- while inflation tries to make the universe absolutely uniform, quantum mechanics prevents it from doing so; there is always a small amount of fluctuation in the amount of energy from place to place that no amount of inflation can erase.
- the rules of quantum mechanics predict what kinds of fluctuations should arise from inflation. The result is a set of perturbations of approximately equal strength at all distance scales - these are precisely the kind of fluctuations needed to explain the observed anisotropies of the CMB
- Over the next several hundred million years, the higher density regions condensed into stars, galaxies, and clusters of galaxies.

http://map.gsfc.nasa.gov/universe/bb_cosmo_infl.html

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

The Flatness Problem:

- Imagine a bug living on the surface of a soccer ball (a 2-dimensional world). Its obvious to you that this surface was curved and that you were living in a closed universe. However, if that ball expanded to the size of the Earth, it would appear flat to you, even though it is still a sphere on larger scales. Now imagine increasing the size of that ball to astronomical scales. To you, it would appear to be flat as far as you could see, even though it might have been very curved to start with. *Inflation stretches any initial curvature of the 3-dimensional universe to near flatness.*

The Horizon Problem:

- Inflation supposes a burst of exponential expansion in the early universe, thus regions that are now distant are much closer together prior to Inflation than they would have been with the standard Big Bang expansion and could have been in causal contact prior to Inflation and could have attained a uniform temperature.

The Monopole Problem:

- Inflation allows for magnetic monopoles to exist *as long as they were produced prior to the period of inflation*. During inflation, the density of monopoles drops exponentially, so their abundance drops to undetectable levels.

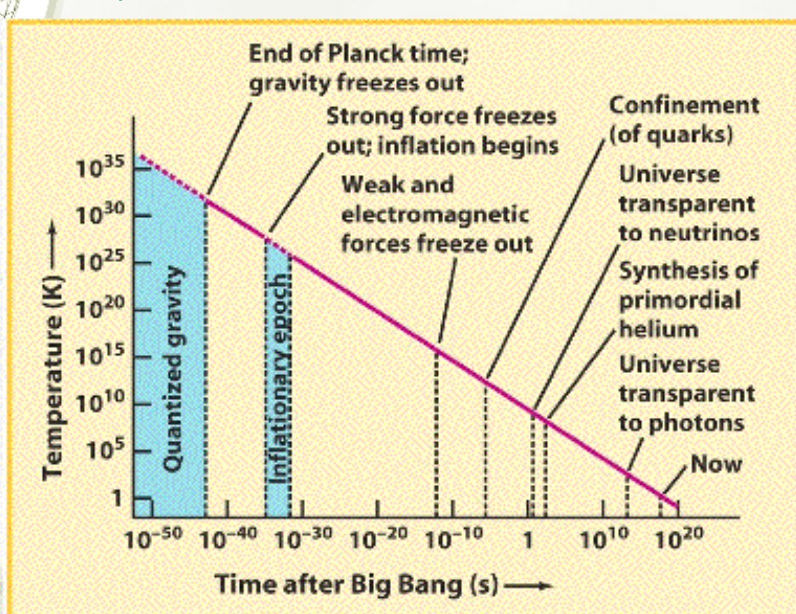
Structure Problem:

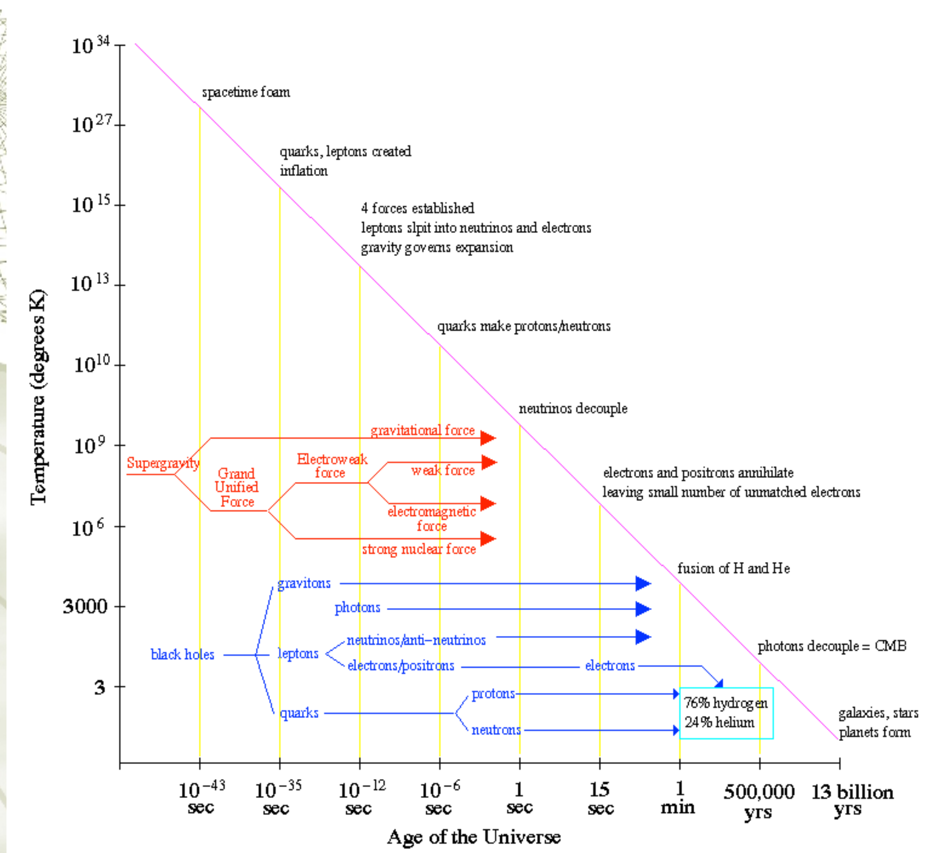
- As a bonus, Inflation also explains the origin of structure in the universe. Prior to inflation, the portion of the universe we can observe today was microscopic, and quantum fluctuation in the density of matter on these microscopic scales expanded to astronomical scales during Inflation. Over the next several hundred million years, the higher density regions condensed into stars, galaxies, and clusters of galaxies.

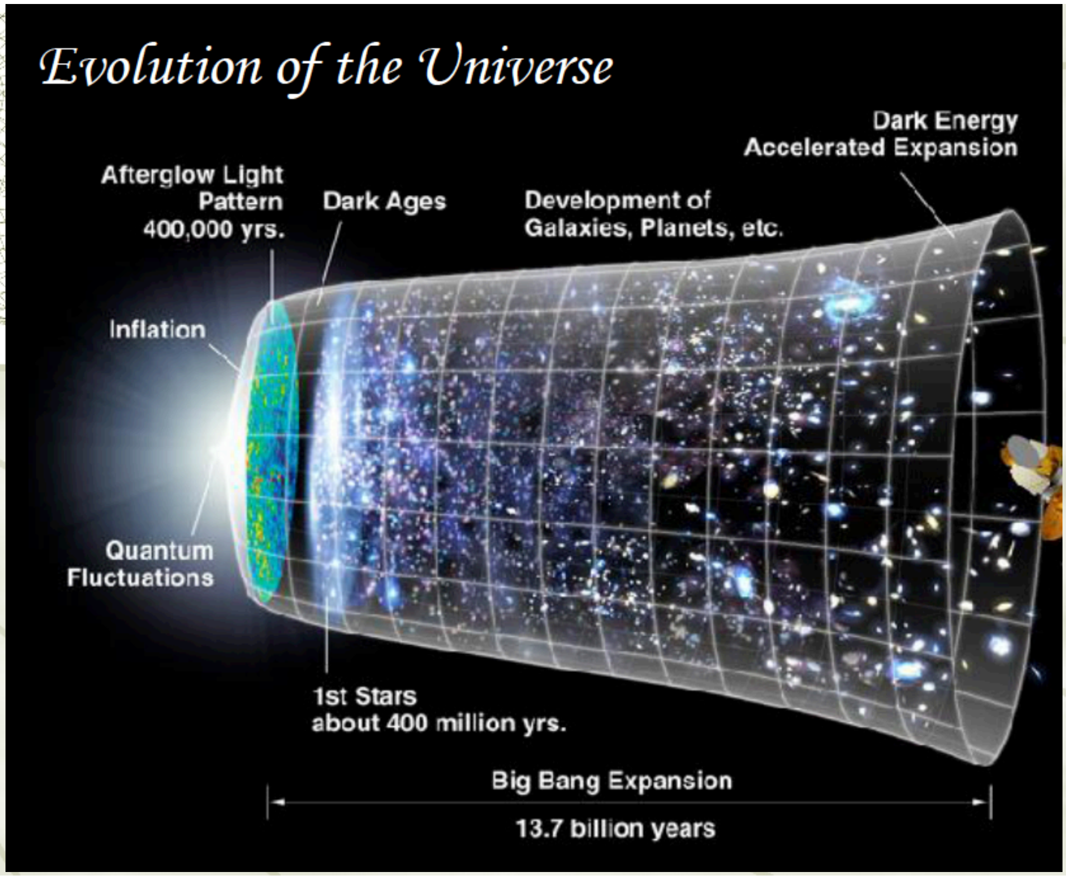
Structure Problem - pg 479

- The initial quantum fluctuations are stretched by inflation, become larger than the local horizon and are 'frozen' in.
- When inflation stops these fluctuations 're-enter' the horizon
- It turns out that this process 'naturally' produces the right shape of fluctuations as seen in the CMB and needed to start the formation of galaxies.
- Its amazing that quantum mechanics - the science of the very small, predicts the fluctuations that are needed to produce the largest things in the universe!

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 ***VERY*** 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!

Fields and particles

- Quantum view of EM radiation:
  - Basic entity is the electromagnetic field (which permeates all of space)
  - Photons are **excitations** (ripples) of a 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

Quantum Fluctuations

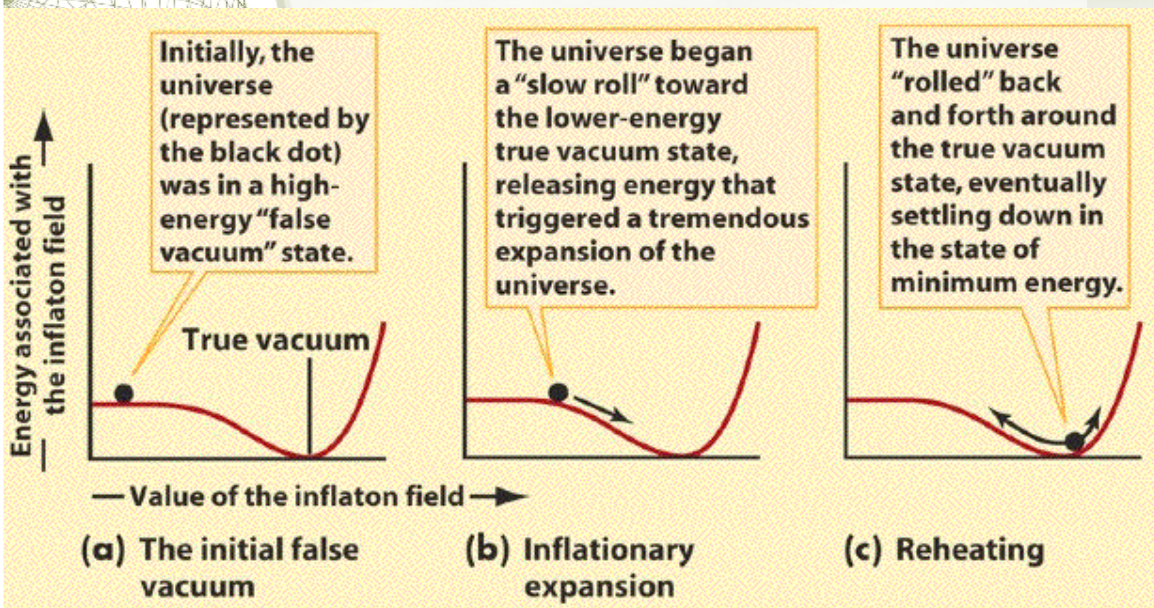
- The properties of the Universe apparently come from `nothing', where nothing is the quantum vacuum, which is a very different kind of nothing.
- `empty' space is not truly empty, it is filled with spacetime, for example.
- Spacetime has curvature and structure, and obeys the laws of quantum physics. Thus, it is filled with potential particles, pairs of virtual matter and anti-matter units, and potential properties at the quantum level.

http://abyss.uoregon.edu/~js/ast123/lectures/lec17.html

IV: FALSE VACUUMS AND VARIOUS INFLATION MODELS

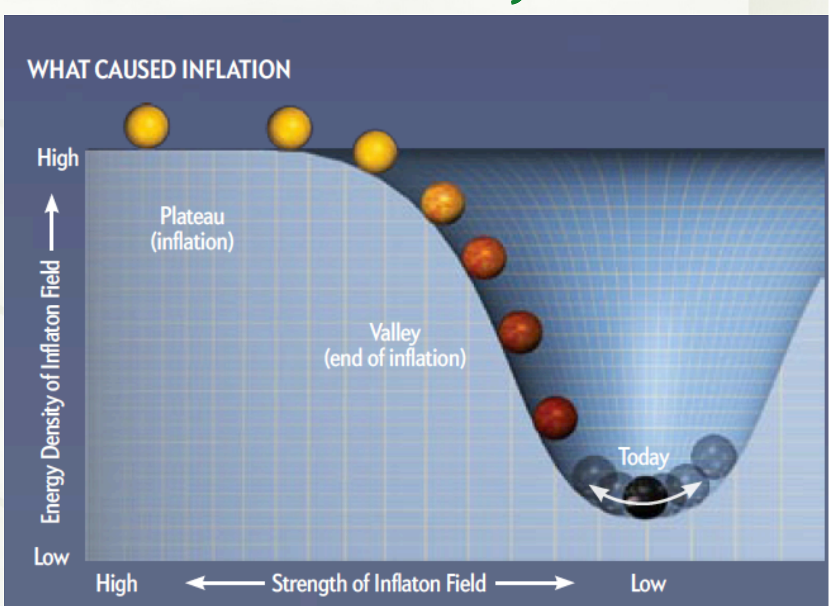
- Alan Guth's original idea…
  - In early universe, there was an exotic particle (called "inflaton") and a corresponding quantum field
  - As the very early universe evolved, this field got stuck in a high-energy state
    - Analogous to a marble resting on top of an upside-down bowl, or a pencil balanced vertically on its point
  - This created an enormous "false vacuum" energy that drove the inflation of the Universe (see text pgs 471-477).
  - 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



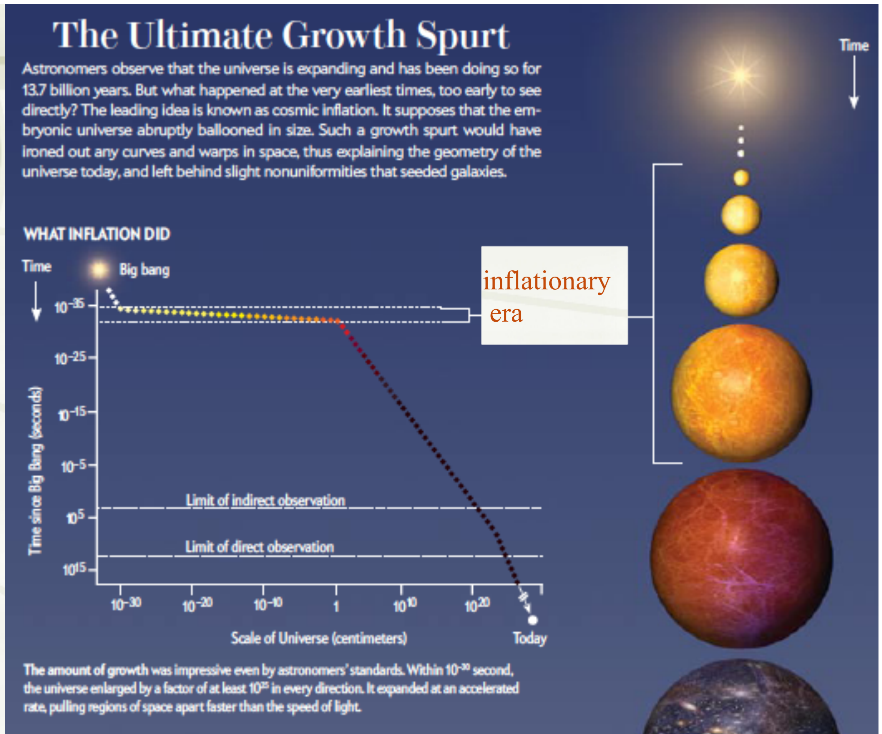
What Caused Inflation

- the equations are similar to those of a ball rolling down a hill of the same shape as the potential energy curve
- P.Steinhardt -Scientific American 2004



A relative of the magnetic field, the "inflaton" generated a repulsive gravitational force that drove space to swell rapidly momentarily. For that to occur, the field's energy density had to vary with strength such that it had a high-energy plateau and a low-energy valley. The field evolved like a ball rolling downhill. On the plateau, it exerted the repulsive force. When it hit the valley, inflation ended.

- **Inflation** relies on a special ingredient known as inflationary energy, which, combined with gravity, can drive the universe to expand by an huge amount in an instant.
- see fig 16.6 in text

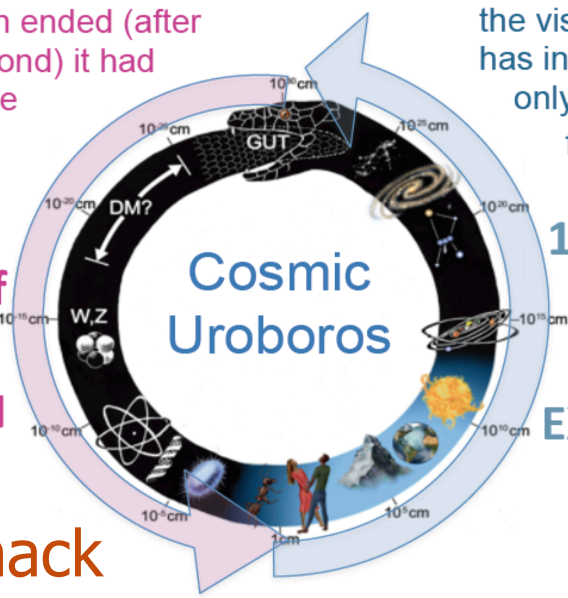


- The inflationary energy must be hugely dense, and its density must remain nearly constant during the inflationary epoch.
- It must repel rather than attract causing space to swell so rapidly.
- theorists have identified many possible sources of such energy

According to Cosmic Inflation theory, the entire visible universe was once about 10^{-30} cm in size. Its size then inflated by a factor of about 10^{30} so that when Cosmic Inflation ended (after about 10^{-32} second) it had reached the size of a baby.

During its entire subsequent evolution, the size of the visible universe has increased by only about another factor of 10^{29}.

10^{-32} seconds of COSMIC INFLATION



13.7 billion years of COSMIC EXPANSION

J. Primack

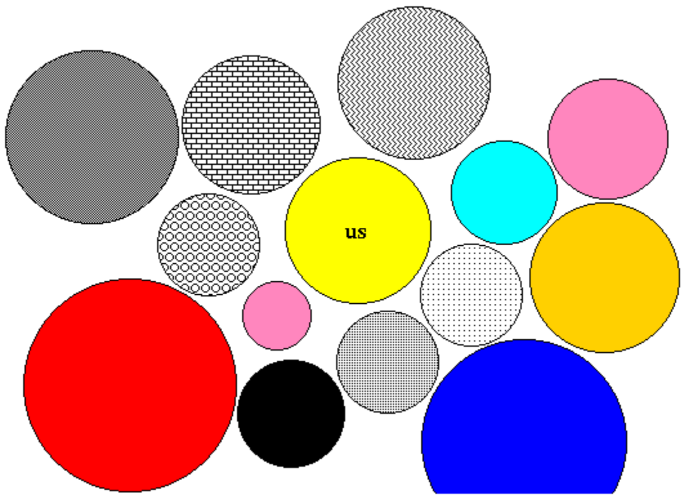
- During inflation, temperature plummets because *T* is inversely proportional to the cosmic scale factor *R(t)*
- After inflation ends, vacuum energy is converted into ordinary particles and radiation, which reheats the universe: *T* rockets up again
- Subsequent evolution is just as in the radiation-dominated, 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

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

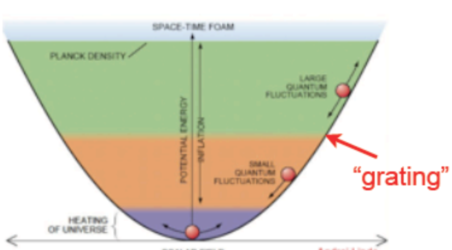
Graphics: University of Oregon Physics Dept

THE COSMIC LAS VEGAS

J. Primack

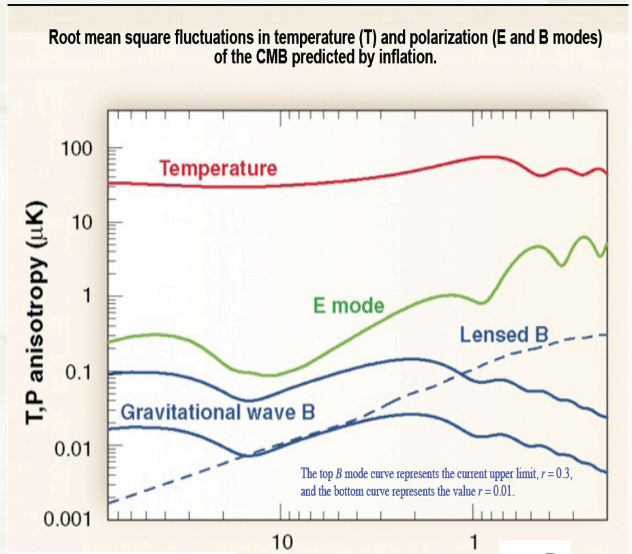
Coins constantly flip. Heads, and the coin is twice the size and there are two of them. Tails, and a coin is half the size.

Consider a coin that has a run of tails. It becomes so small it can pass through the grating on the floor.



Testing Inflation

- Inflation makes a few strong testable predictions
  - The fluctuations have a particular pattern- they are Gaussian (Bell curve shape) (√)
  - A particular type of polarization in the CMB- B modes (produced by gravity waves)-tiny effect
  - Shape of fluctuations is a power law in amplitude (√)



The Planck satellite is looking for the B modes NOW... results anticipated in 1 year

Testing Inflation

- All theories, no matter how wonderful they seem need to be tested... they **need** to
  - make new predictions which can be observationally checked and
  - should 'fit in' with the rest of understood and tested physics
  - not have 'ad hoc' parameters which just produce the desired effects or be fine tuned

There is a lot of discussion about whether chaotic (eternal) inflation can be checked with data- BICEP2 result ! Prediction of gravitational waves checked!

Perhaps need something more

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.