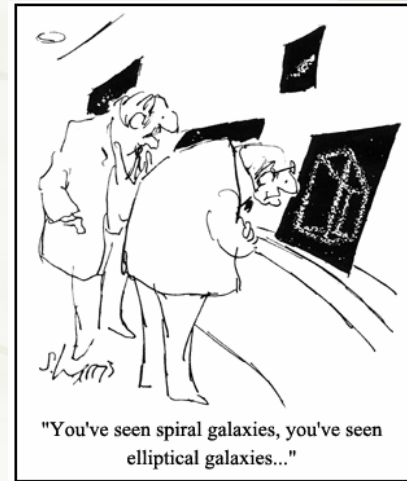


## Lecture 23 : Four cosmic puzzles

### ★ Four puzzles...

Reading: Chapter 16 of text (inflation)



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## 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 perfectly flat...

- ★ We measure  $\Omega_M = 0.315$
- ★ CMB results suggest that  $\Omega_M + \Omega_\Lambda \approx 1$  to within 1 percent or better! ( $\Omega_k = -0.0005 \pm .07$ )

### ★ Why are we so close to this special case?

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## It's worse than that: $\Omega$ changes with time

- ★  $\Omega = \Omega_M + \Omega_\Lambda$
- ★  $|1 - \Omega| = |k| c^2 / [H(t)^2 R(t)^2]$  eq 16.6- so if  $k$  is not *identically* zero
- ★ 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  $\Omega$  is close to 1 today, it had to be much much closer to 1 in the past!

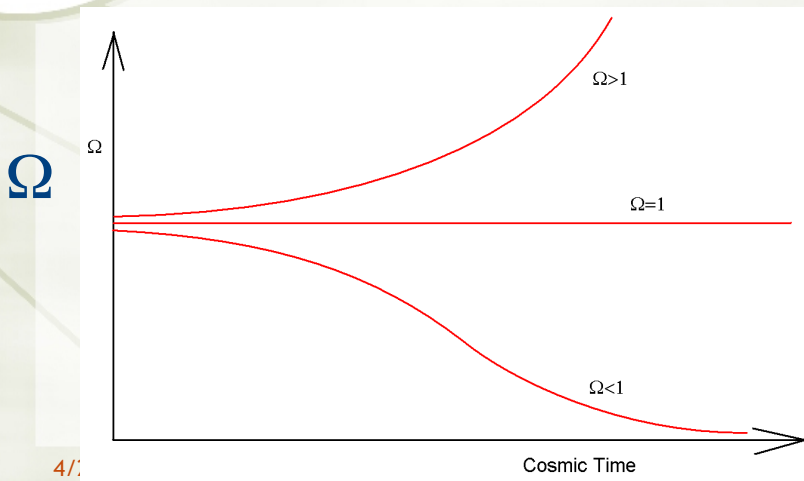
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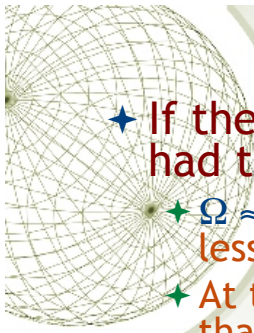
## In fact, problem is much worse...

- ★ 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



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- ★ If the universe is approximately flat now, it had to be **very, very flat** at early times...
- ★  $\Omega \approx 1$  now, means  $\Omega$  (at  $t = 1s$ ) differed from 1 by less than 1 part in  $10^{-16}$  !!
- ★ At the Planck's time,  $\Omega$  differed from 1 by less than 1 part in  $10^{-60}$  !!
- ★ 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  $\Omega$  had been much above 1, it would have recollapsed very early before making galaxies
  - ★ If  $\Omega$  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**

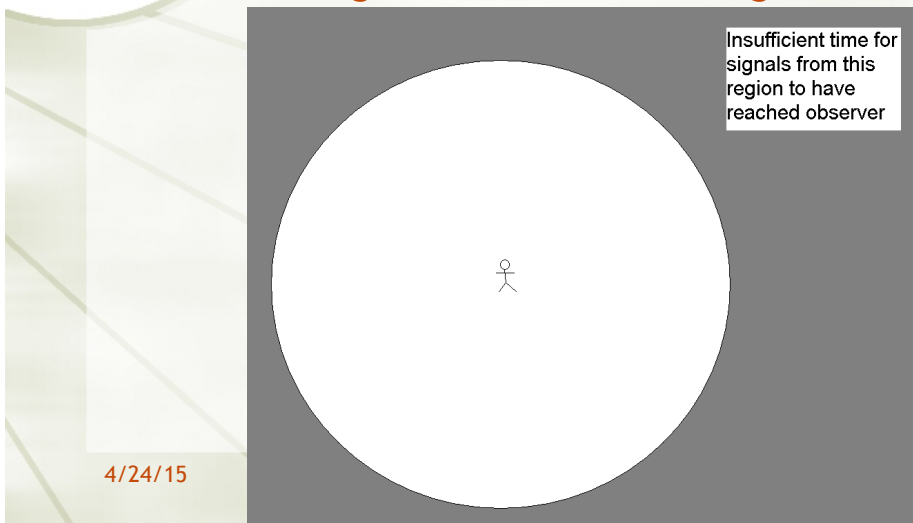
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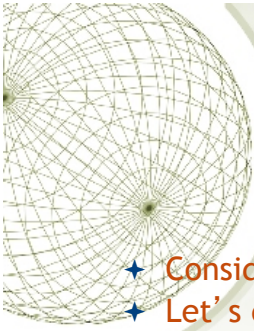
## II : THE HORIZON PROBLEM

- ★ Concept of the particle horizon:
  - ★ The sphere surrounding a given point (e.g., the Earth) which is causally connected to that point- remember Minkowski diagrams from 10 weeks ago?

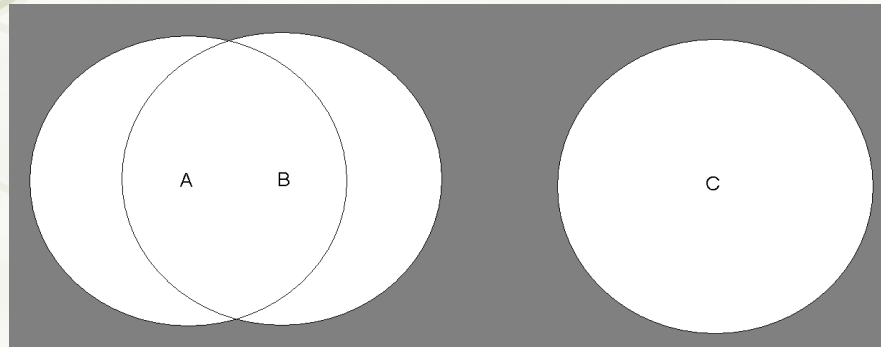


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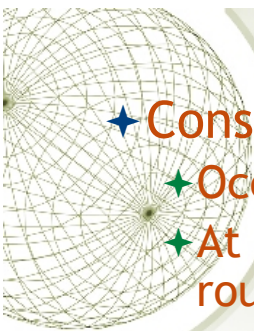
- ★ Consider 3 locations in space; A, B and C.
- ★ Let's draw their particle horizons...



- ★ So, in this example, A and B are causally connected to each other. But C is not causally connected to either A or B at the time of observation.

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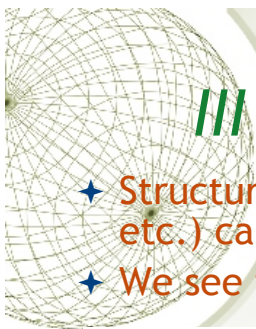
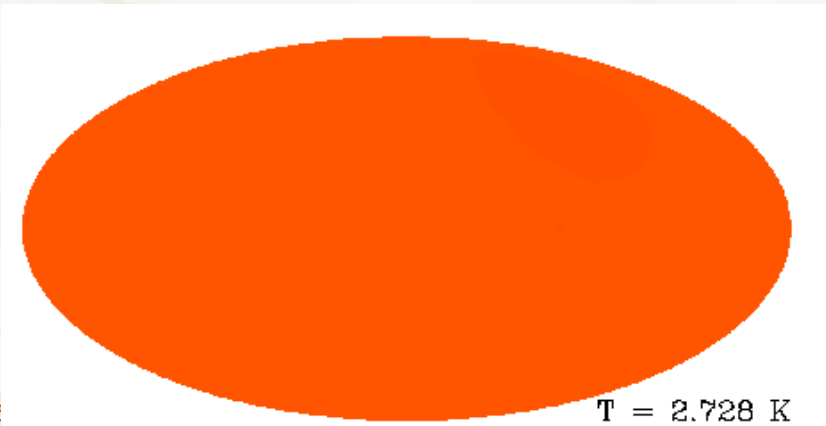
- ★ Consider the “epoch of recombination”
  - ★ Occurred ~400,000 yrs after big-bang
  - ★ At that time, particle horizon would be roughly  $10^6$  light years across.
  - ★ This size-scale at the redshift of decoupling ( $z = 1100$ ) corresponds to an angle of about  $1^\circ$  on the sky...
- ★ So, 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...**(pg 467 in textbook)

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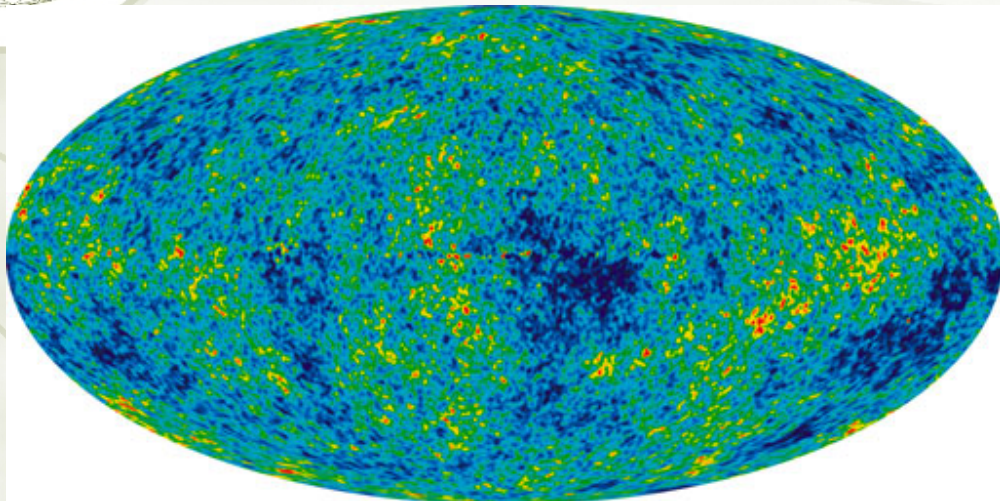


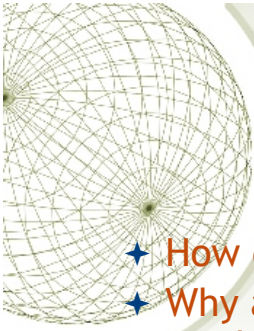
- ★ There were a million causally-disconnected regions on sky at the time of last scattering
- ★ How does the CBR “know” that it has to be so uniform across the sky?!



### 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 CMB maps...

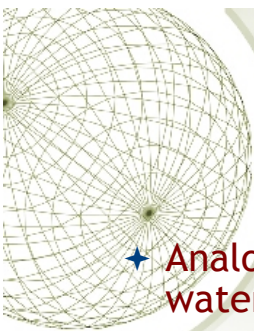




- ★ How did those inhomogeneities get there?
- ★ Why are they just the right magnitude and size to produce the structures we see today?
- ★ How is it possible to have the same kind of inhomogeneities spread throughout the whole universe, despite the lack of causal contact between different parts of the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

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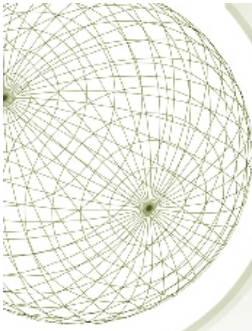


## *IV : THE RELIC PROBLEM*

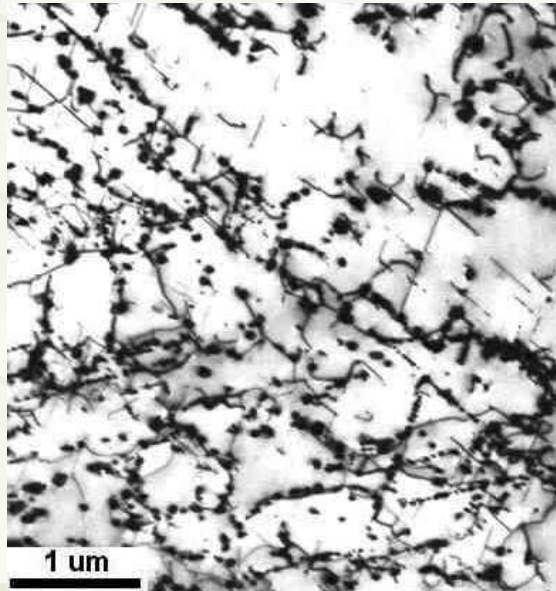
- ★ Analogy: consider the cooling of a liquid (e.g., water)
- ★ Once liquid reaches freezing point...
  - ★ Freezing does **not** occur smoothly and uniformly
  - ★ Freezing starts at certain locations, and the crystals start growing.
  - ★ When crystals eventually merge to form the solid, there will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

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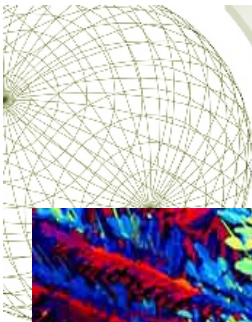


## *Dislocations in steel*

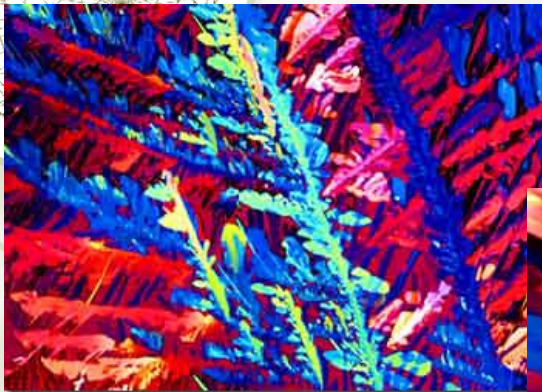


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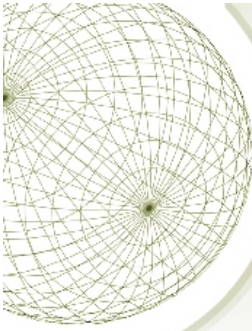
## *Beer crystals (Bud)...*



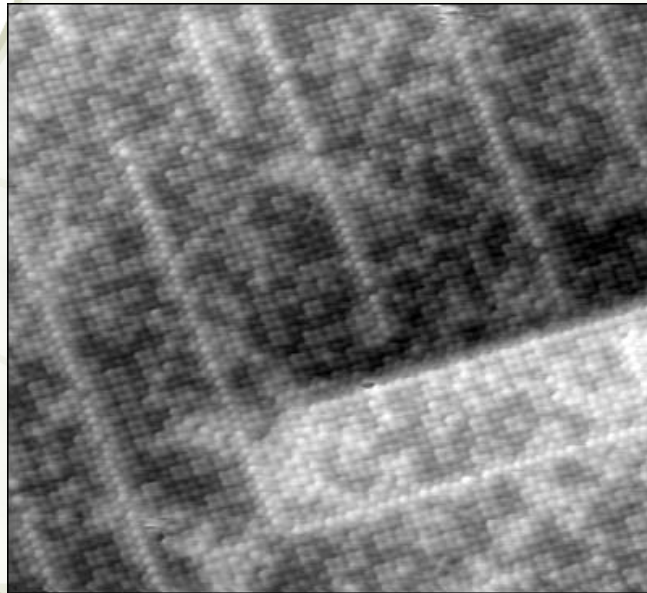
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<http://www.microscopy.fsu.edu/beershots/beerphotos.html>

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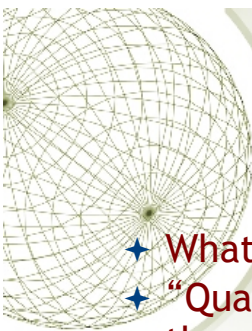
## The atomic structure...



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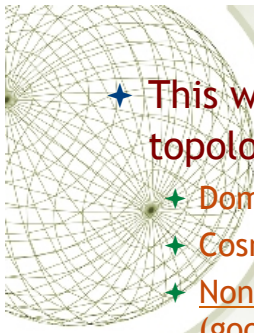


- ✦ What does this have to do with the Universe?
- ✦ “Quantum fields” related to particles and forces in the very early universe can undergo phase transitions (i.e., they “freeze”).
- ✦ As Universe cools...
  - ✦ The temperature falls to the point where certain phase transitions can occur
  - ✦ Phase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

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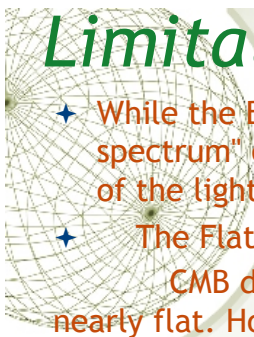


- ★ This would produce exotic structure called topological defects...
  - ★ Domain walls (2-d sheet-like structures)
  - ★ Cosmic Strings (1-d string-like structures)
  - ★ None of these have been seen in the observable universe (good limits from CBR data - strings would gravitationally lens the background)
- ★ GUTs predict exotic particles produced at these domain walls in the early Universe
  - ★ Look like magnetic monopoles
  - ★ *Never 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**

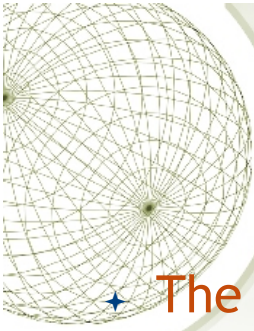
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## Limitations of the Big Bang Theory



- ★ While the Big Bang theory successfully explains the "blackbody spectrum" of the cosmic microwave background radiation and the origin of the light elements, it has significant problems:
- ★ The Flatness Problem:
  - ★ CMB data has determined the geometry of the universe to be nearly flat. However, under Big Bang cosmology, curvature grows with time. A universe as flat as we see it today would require an extreme fine-tuning of conditions in the past, which would be an unbelievable coincidence.
- ★ The Horizon 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 tells us that these regions must have been in contact with each other in the past.



## ★ The Monopole/Relic 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, so if they exist at all, they are much more rare than the Big Bang theory predicts.



## *Inflation Theory to the Rescue*

- ★ Inflation Theory, developed by Alan Guth, Andrei Linde, Paul Steinhardt, and Andy Albrecht, offers solutions to these problems and several other open questions in cosmology.
- ★ It proposes a period of extremely rapid (exponential) expansion of the universe prior to the more gradual Big Bang expansion, during which time the energy density of the universe was dominated by a cosmological constant-type of vacuum energy that later decayed to produce the matter and radiation that fill the universe today.



## Inflation Continued

- ✦ Inflation was both rapid, and strong.
  - ✦ It increased the linear size of the universe by more than 60 "e-folds", or a factor of  $\sim 10^{26}$  in only a small fraction of a second!
  - ✦ Inflation is now considered an extension of the Big Bang theory since it explains the above puzzles so well, while retaining the basic paradigm of a homogeneous expanding universe. Moreover, Inflation Theory links important ideas in modern physics, such as symmetry breaking and phase transitions, to cosmology.

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## How Does Inflation Solve these Problems?

### The Flatness Problem:

- ✦ Imagine living on the surface of a soccer ball (a 2-dimensional world). It might be 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:

Since Inflation supposes a burst of exponential expansion in the early universe, it follows that distant regions were actually much closer together prior to Inflation than they would have been with only standard Big Bang expansion. Thus, such regions could have been in causal contact prior to Inflation and could have attained a uniform temperature.

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★ 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.

★ 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 fluctuations 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 us.