Lecture 26 : *The End*

- Time
- Alternatives to Inflation
- Final musings

Reading: Chapter 16 of text

FINAL EXAM

- *Monday, Dec 17, 1:30-3:30 pm*
- Exam is in this room
- Emphasis on material after the midterm
- No notes or books allowed
- **Bring scientific calculator**
- Q&A review session in class, Dec 6

Fill in your course evaluation!

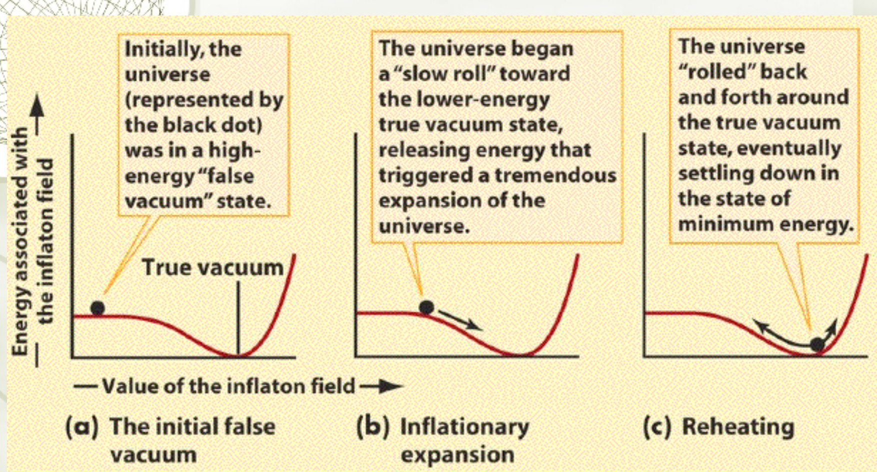
- www.CourseEvalUM.umd.edu

- Course evaluations are open
- Have you been challenged and learned new things? Have I been effective, responsive, respectful, engaging, etc?

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



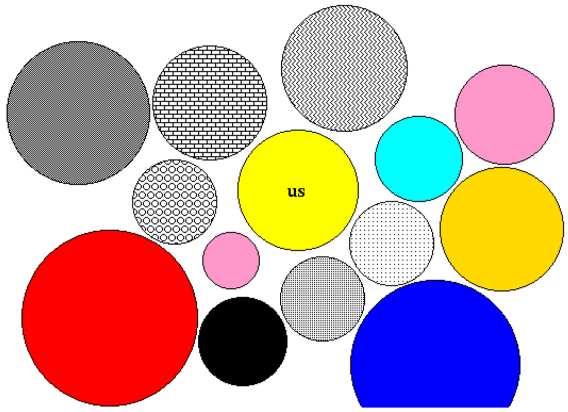
- During inflation, temperature plummets because *T* is inversely proportional to the cosmic scale factor *R(t)*
- After inflation ends, vacuum energy is converted into ordinary particles and radiation, which reheat the universe: *T* rockets up again
- Subsequent evolution is just as in the radiation-dominated,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

Time

- We live in a 4D universe: three spatial dimensions (*x*, *y*, *z*), and one of time (*t*)
- The four are mingled but space and time are not quite the same
  - Time always increases, but we can move freely in space
  - Invariant interval:

$$ds^2 = c\,dt^2 - (dx^2 + dy^2 + dz^2)$$

- *Almost* all Physics is symmetrical in time
- But time is one-way

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Should we even think in time?

- Maybe we should find something more fundamental than time to mark the development of the universe.
- What about the scale factor of the universe *R*(*t*), or the temperature *T*(*t*)?
- Universal time as defined as observed from a frame at rest with respect to the universe as a whole is difficult to deal with when the universe is so small that quantum effects are important.
- Temperature as a record is unambiguous: start at infinite temperature, approach zero temperature in the distant future.

Entropy

- Almost all Physics is reversible in time; entropy is a notable exception.
- Entropy is a measure of how fully a system occupies the states available to it, or of disorder.
- The Second Law of Thermodyamics: the entropy of a closed system never decreases.
- Unless some process is reversible, entropy always increases: a system becomes more "diffuse," occupying an increasing number of states. Disorder increases.
- Relating time to entropy, a concept from thermodynamics, makes sense. So the universe's temperature may be seen as more fundamental than time.

We actually do think of time in terms of entropy

- Organized systems become less organized
  - Life forms die and decompose
  - Pencils break
  - It's funny to watch movies running backwards

The universe's entropy

- A system that is disordered today is likely to have been disordered yesterday
- So the initial conditions on entropy are more interesting than entropy itself: only this way do we see an increase of entropy
- How could the universe start with low entropy? Its entropy increases with time (decreasing background radiation temperature) as stars and galaxies form and then dissipate.
- The universe's entropy must have been (relatively) low for us to mark its increase. (This is an argument against a cyclical universal history)
- Why was this? It must have something to do with the universe's quantum mechanical properties during the Planck era. Another reason to understand quantum gravity!

The origin

- Really hot, rapidly expanding ball of energy

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The end

- No more stars: cold and dark
- Leftover black holes, cold stellar cores, freezing planets, eternally cryogenically preserved bugs…
- Rapidly-increasing separations of these husks due to ever-increasing acceleration by dark energy

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So it's settled?

- Well, no. It shouldn't be – it's science! Despite inflation's successes, a number of people (including Steinhardt of "new inflation" fame) raise some questions:

Philosophical and scientific rationale for alternatives

- Competition is good for theories; it focuses attention on unresolved problems and flaws
- For some, chaotic inflation is a weasely way to explain things:
  - Inflation has fine-tuned parameters; why are they just right?
  - But *why* did inflation start 13.7 Gyr ago?
  - Is this all just luck in chaotic inflation? The strict anthropic principle can't be tested (why not?), so can it be part of a *scientific* theory?
- And suddenly dark energy shows up without even a theoretical whisper that it might? This makes for three independent ideas: inflation, "normal" expansion, and dark energy acceleration. No matter how successfully they're stitched together, are these "epicycles?"

An alternative: the ekpyrotic proposal

- Ekpyrotic: the universe is created in a distributed and sudden burst of high but finite temperature
- Ekpyrotic universes can be cyclical, helping solve the "why just then?" problem.
- This proposal uses superstring theory; here the Universe appears to be four dimensional, but the four are embedded in a larger 5 dimensional spacetime (with more dimensions curled up so we can't easily see them)

Strings and branes

- Strings are long and skinny, and particles are manifestations of string vibrations
- Branes (think membranes) have more dimensions

Brane universe

- Here's the idea: the Universe is a brane; particles move in a 3D brane
- They can't cross the extra dimension to neighboring branes; there's a little gap.
- The EM, strong, and weak force are also confined to the brane
- But gravity isn't; it can (weakly) couple neighboring branes

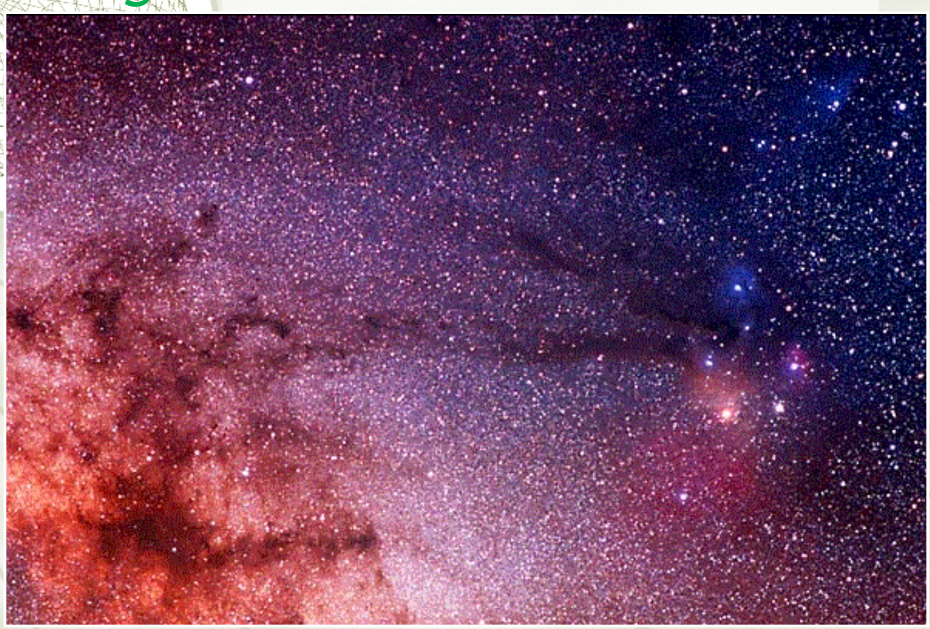
So what's ekpyrotic about this?

- Replace inflation by something quite different: the face-face collision of two neighboring branes.
- Dark energy stretches the branes flat flat flat before collision, but quantum fluctuations leave little wrinkles that later turn into structure (e.g. galaxies).
- The collision releases energy nearly simultaneously throughout the universe (ekpyrosis!), and the branes bounce apart.
- Then the usual expansion of spacetime, temperature evolution, nucleosynthesis etc. runs on afterwards.
- In some models gravity and vacuum (like the Casimir force) forces can make the branes collide cyclically.

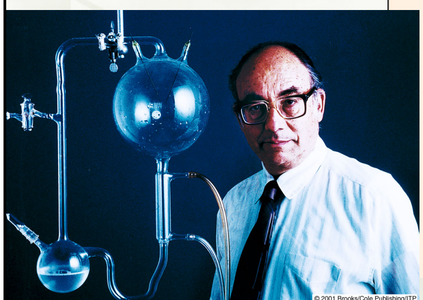
Features of this explanation

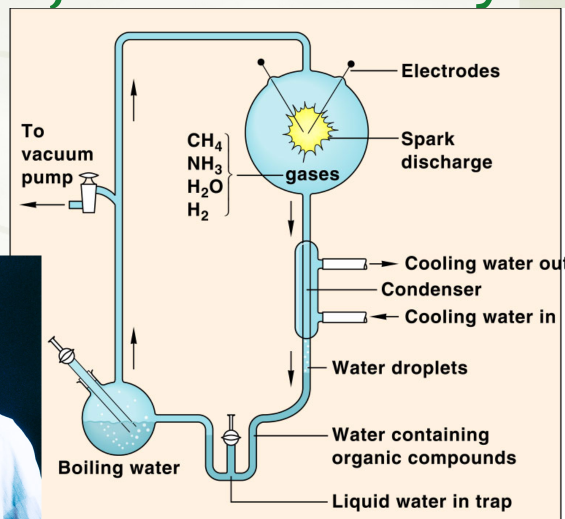
- Produces a homogeneous, isotropic, and flat universe without relic problems
- One story for the whole time development of the universe, includes dark energy
- Cyclical models allow many (maybe infinite) recurring "big bangs," answering the "why then, and just once?" question
- Dark matter could be the usual particles on nearby branes (or, just as well, dark matter particles in our brane)
- In cyclical models, can solve some entropy problems

Organic Molecules in Gas Clouds

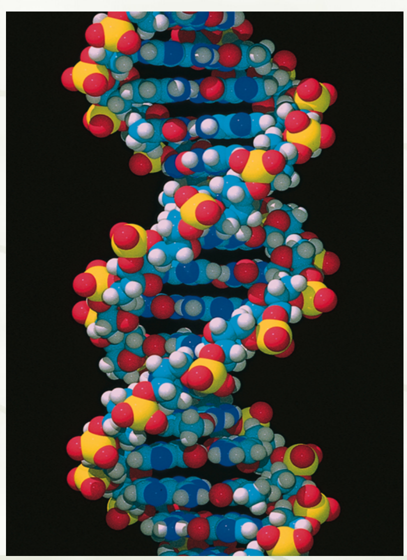


Urey-Miller experiment: amino acids formed naturally



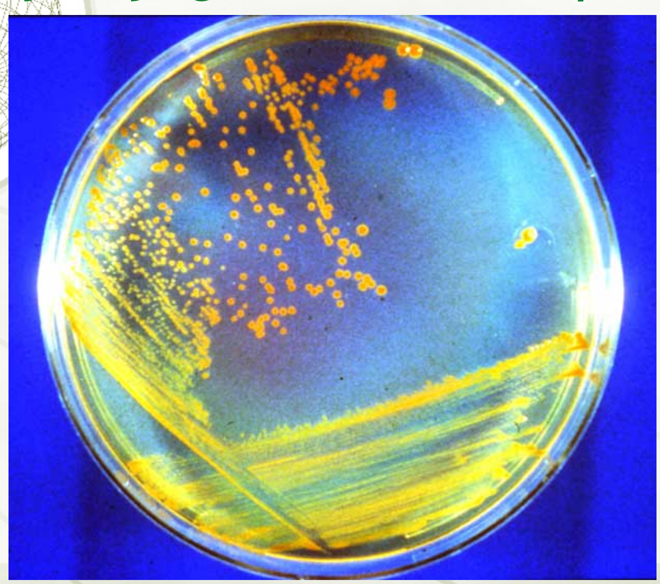


Structure of a DNA molecule



Non-terrestrial amino acids in meteorites

Tiny voyagers? Extremophiles



Tardigrades

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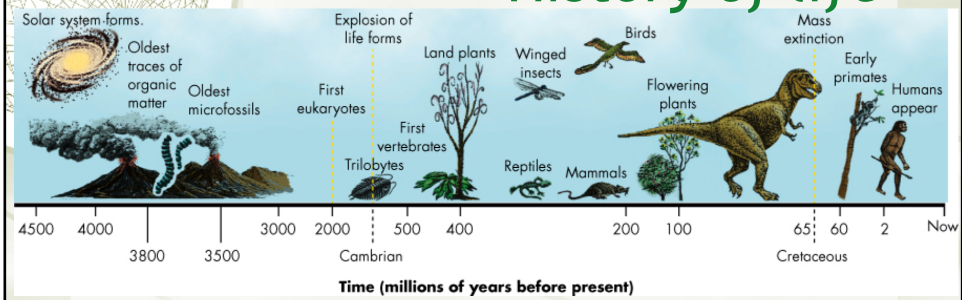
History of life



Life On Earth: How Long it Took to Develop

Stage	Development	Elapsed time [Myr]
1	Microbial life	<500
2	Oxygen atmosphere	1000
3	Multicellular life	2000
4	Life on land	100
5	Animal intelligence	150
6	Human intelligence	3

Development of Complex Life

- Took more than 3 BILLION years after development of first microbial life
  - Using Earth as our guide, this suggests development of complex life may require an environment that remains hospitable for billions of years

Things that had to be, or we wouldn't be here

- A star with just the right mass
  - Two times larger: its lifetime would be too short
  - Two times smaller: for liquid water, Earth so close to star that rotation tidally locked
    - Roast by day, freeze by night
- A benevolent Jupiter
  - Shields us from many impacts (extinctions)
  - Bad Jupiters drive interior planets into star

Things that had to be, or we wouldn't be here

- Right place in Galaxy
  - Nearer nucleus, too many supernova, gamma ray bursters
  - In halo & globular clusters, few heavy elements
- Large Moon
  - Keeps tilt of Earth's axis relatively steady
    - Otherwise widely varying seasons

Things that had to be, or we wouldn't be here

- Planet with the right mass and composition, initially near outer edge of "habitable zone"

Things that had to be, or we wouldn't be here

- The right universe!
- Right kind and strengths of the four fundamental forces: Gravity, Electromagnetic, Strong, Weak
- Favorable values for Ω and Λ

Can this be coincidence?

- Yes
- Think properly: what is the chance that we find ourselves orbiting the Sun, one star out of 10^{10} in the galaxy, and that's just this galaxy
- Statistics can't be applied to individuals in a simple way!

Complexity

- Making a star is simple: gravity
- Making life has more steps, but not infinitely many more
- Confusion about how much humans understand and what is possible
- Nature opens many possibilities

Fermi's Paradox

- Where is everybody?
  - Are there processes that make life or intelligence or a technical civilization less likely?
  - Are we not listening properly? Quarantined? Nobody is transmitting?

So where are we?

- For us:
  - We are not at the center of the universe. Rats!
  - Ordinary planet, star, galaxy, maybe universe.
  - Space and time depend on our point of view (reference frame).
- We understand a tremendous amount about the *characteristics* of our universe
  - Flat universe, expands forever.
  - Started with a rapid expansion of space and time, a hot "Big Bang."
  - Still expanding, even accelerating.
  - Gravity is a puzzle.
  - Time itself is a puzzle.
- Rapid initial self-organization, slow evolution
  - Structure, stars, galaxies
  - Life

Universe starts simple but becomes very complex!

- Form order to disorder, but in special places in the universe order wins
- Life and intelligent life around stars is possible because of the sun: we create a lot of entropy but locally entropy can decrease!