An expanding cosmos
Most important discovery in astronomy?

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Einstein’s misgivings on change

- Rejected dynamic universe, claiming it to be “unphysical”
  - Implies universe starting from a single, infinitely dense and infinitesimally small point (called a singularity)
  - But, like Newton and Kant’s universes, Einstein’s static universe was also inherently unstable (he missed it in his math)
  - Believed as Ernst Mach did that there is a natural reference frame established by averaging over all matter in the universe. An overall flat space-time background from scattered masses exists

- Chinks in his armor appear (early 20th century)
  - Karl Schwarzschild finds first solution to Einstein’s equation from general relativity, and it is applicable to a black hole (singularity)!
    - Useful approximation far away from slow, heavy objects like Sun
    - Uncomfortable: a single mass embedded in flat space-time
  - Willem de Sitter solution: expansion, and with no matter-energy!
    - Philosophical plus scientific conundrum: space without matter?!
  - Alexander Friedmann metric: expansion plus matter
Vesto Slipher discovered that most of galaxies are redshifted.
- We know that means they are all moving away from the earth.
- Only major exception, the blueshifted Andromeda Galaxy (local gravitational pull can overcome expansion of universe).
- No/small shift, or a random set of shifts expected by some.
- Friedmann had theoretical prediction first, with general relativity.

Edwin Hubble generalized the discovery into “Hubble’s Law”.
- Linear relationship between distance to galaxy and its redshift.
- Can use to work out age of universe: earlier estimates were ~10-20 billion years (we have more precise knowledge today).
- Furthermore, the farther a galaxy is away, the faster it is moving outward relative to us (expansion of space is by percentage).
- No center of expansion (alternatively, everyone is at the center!)

Let’s flip back to the title slide: linearity not guaranteed in all cosmological models (recall dangers of extrapolation!).
Gravity, which is attractive, could eventually reign in growth.
Galaxies do not move apart from each other in all directions *within* space as in the traditional sense of motion. (After all, gravity pulls them together: recall Newtonian universe)

Instead, it is the “fabric” of the space-time continuum itself (the universe itself) that is stretching/elongating, with galaxies and galaxy clusters simply coming along for ride!

- Quantified by the Hubble constant $H_0$ in units of km/(s*Mpc), the slope of the line a.k.a. constant of proportionality (~50-100)
- Homogenous universe in all directions, from anywhere (overall)

Expanding universe conserves energy in the standard sense

Since space is 3D not 2D, better way to visualize over balloon example may be raisins within a loaf of rising raisin bread

- [https://www.youtube.com/watch?v=wYwkGoktdVA](https://www.youtube.com/watch?v=wYwkGoktdVA)

A dynamic universe can still be infinite. Question is what kind: “traditional” (if you pick a direction and go, you’ll keep going forever) or curved like the surface of the earth
Group discussion question: debate!

- Big bang theory versus unchanging, uncreated universe

- Choose a side and come up with every single argument you can (from assigned reading, your own past knowledge, or your own reasoning) in favor, as well as arguments against the case of the opposing viewpoint

- OR come up with your own explanation for the origin of the universe (avoiding the Divine/supernatural: you must have a testable hypothesis, with either current or potential future technology and also be consistent with known data)

- I will play Devil’s Advocate and “attack” all of your points
In the beginning...

- Hypothesis of the primordial atom: brainchild of Belgian Catholic (Jesuit order) priest Georges-Henri Lemaître, mathematician, astrophysicist
  - Spewed the universe like radioactive decay (known then)
  - Replicated like a living cell

- Met with extreme resistance!
  - Though popular press went wild
  - Einstein pulled 180-degree turn

- Theory outpaced experiments. No proof for many decades

- (Religion and science clearly not always at odds, as in past)
The primordial fireball of Creation

- Von Weizsäcker: elements through hot, dense nuclear fusion
- Nothing (NO THING) “before” the beginning of the universe: space, time, matter, energy born (critics said too religious)
- Good theories need to make predictions: Gamow, Alpher, and Herman made one, a ~5 K (-270 °C) afterglow (relic light)
- Astronomer Fred Hoyle coined phrase “Big Bang” as insult; it stuck. He found Lemaître and Gamow’s ideas repugnant
  - Insisted (like Aristotle) universe is eternal: always was and always will be. Became loudest proponent of the steady state theory
  - Never gave up, rejecting the Big Bang theory to his dying day
  - Suggested there is a “creation field,” a real force of nature like the gravitational and electromagnetic fields, obeying some physics
- So what caused observed expansion? An initial explosion, the big bang! Or, new atoms being born and crowding out old?
Alternative: the steady state theory

- A decades-long, bitter fight within scientific community: Hoyle, Bondi, and Gold, eventually alone

- Continuous creation of new matter (new atoms) from nothingness (the vacuum of space) just as expansion was creating new space-time

- Thermodynamic “heat death” of our universe, running down like a wound-up clock, thereby avoided

- Natural explanation for sameness of the universe over both time AND space, different vantage points

- NO sudden beginning, no end, and with constant laws of physics. No time period of ignorance, forever beyond theoretical understanding

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Big Bang Model

OR

Steady State Model

Density of galaxies falls as universe expands (remember: not expanding INTO space, in either picture)

Density of galaxies remains more or less constant as universe expands (spaces filled in by new galaxies)

(rate of formation of new matter too small to detect experimentally)
Big Bang for the win? Yes!

- Age of the universe not a problem for either approach
  - The expansion of the universe solves Olbers’ paradox even if universe is “static,” uniform, infinitely old, and infinitely large (unobservable universe outside the light horizon)
  - Initially, Big Bang theory faced problems with age of earth, sun

- The abundance of the chemical elements (periodic table)

- Distribution of matter across space-time (remember: everyone agreed that speed of light finite, so we look back in time when we look out into the cosmos, even if the steady state theory of the universe correct). Young vs. old universe

- The temperature of space (dilution of initial heat)
  - Discovery of the cosmic background radiation settled question once and for all (although steady staters made no prediction, so technically anything would work: must take in full picture)
Cosmic Microwave Background

- Discovered by accident in spring of 1964 by Penzias and Wilson (who later both received the Nobel Prize for this scientific triumph)
- Test of bouncing radio waves off satellite for communication, unexpected support for Big Bang
- Originally thought to be bird poop: 3.5 degrees Kelvin microwave signal from all parts of sky. Call in astronomers (friends), it’s from space!
- Scooped astrophysicists planning to look for it
- Primeval radiation, the ‘echo’ of the Big Bang!
- In 1990s, first evidence of tiny non-uniformities, the “seeds” of galaxy clusters
- An entire class period will be devoted to the CMB (~2/29), 2nd only to expanding universe in importance to history of cosmology?

CMB has in past two decades ushered in era of “precision cosmology,” an exact science suddenly
Homework Assignments

- Read for next class this Wednesday: Ch. 1 of *Journeys to the Ends of the Universe* by Kitchin

- Should have already read Chapter 3, “The Expanding Universe,” from *Wrinkles in Time* by George Smoot (Nobel prizewinner for CMB “wrinkles”) for today’s lecture

- Do the (shorter) HW #4 for Monday

- Study for the test, which is *this* Friday

- A joke to end today’s class:
  
  [https://www.youtube.com/watch?v=OKnpPCQyUec](https://www.youtube.com/watch?v=OKnpPCQyUec)