AY1 Announcements

- Quiz 4: Thursday June 8 (last day of class)
- Final: June 14, 4pm -7pm

Tonight: Mandel Lecture

Dr. Jess McIver

Mandel Lecture June 2017

Einstein, Gravitational Waves and Black Holes

Dr. Gabriela Gonzales

Thursday, June 1, 2017

7:30 pm

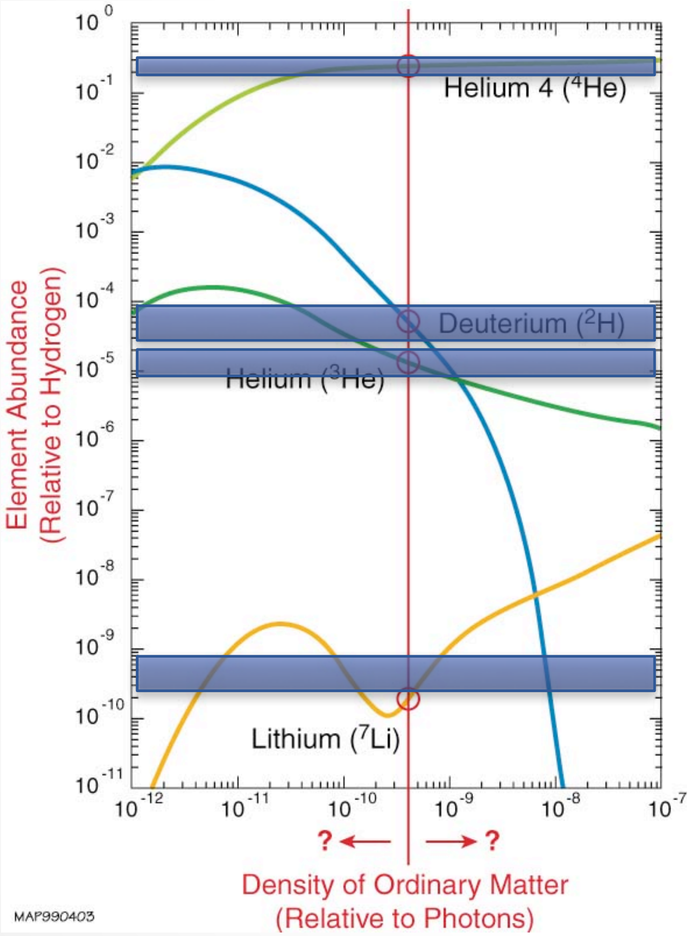
Rio Theatre - 1205 Soquel Avenue, Santa Cruz

Admission is FREE and open to the general public.

No tickets or reservations will be required for entry. Seating availability is on a first come basis. Theater will be open for seating starting at 7:00 pm.

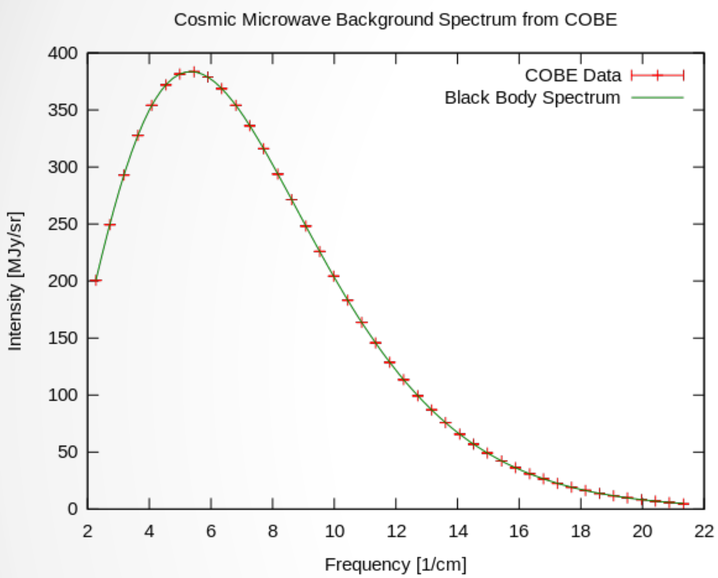
From last time

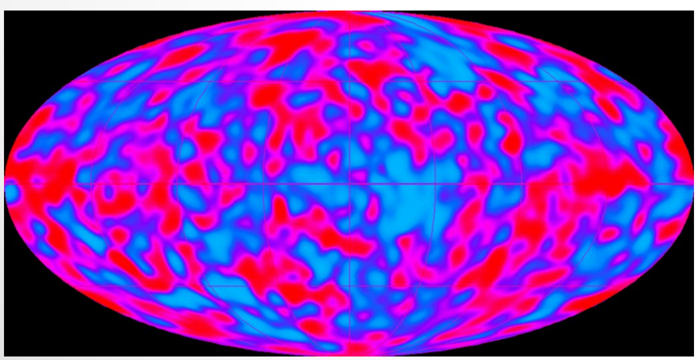
HBB Nucleosynthesis



- Hot Big Bang Nucleosynthesis calculations predict that the HBB only produced Hydrogen, Helium and a tiny smattering of Lithium
- Observations of chemically deficient old stars and gas in the early Universe and the detailed predictions of He^4/H, He^3/H and H^2/H match observations very closely

Cosmic Microwave Background

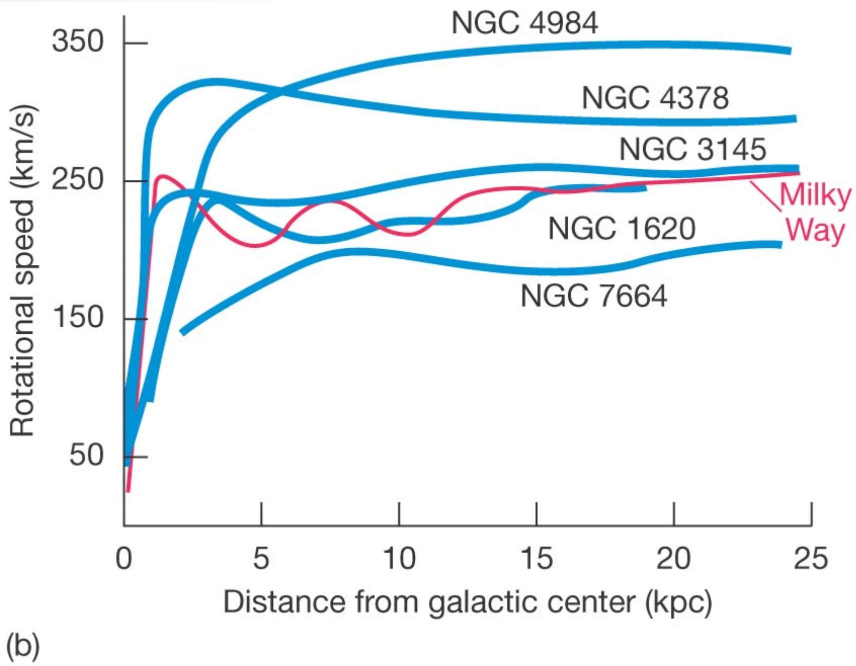




Second test of the Hot Big Bang theory is the presence of the 3K microwave background:

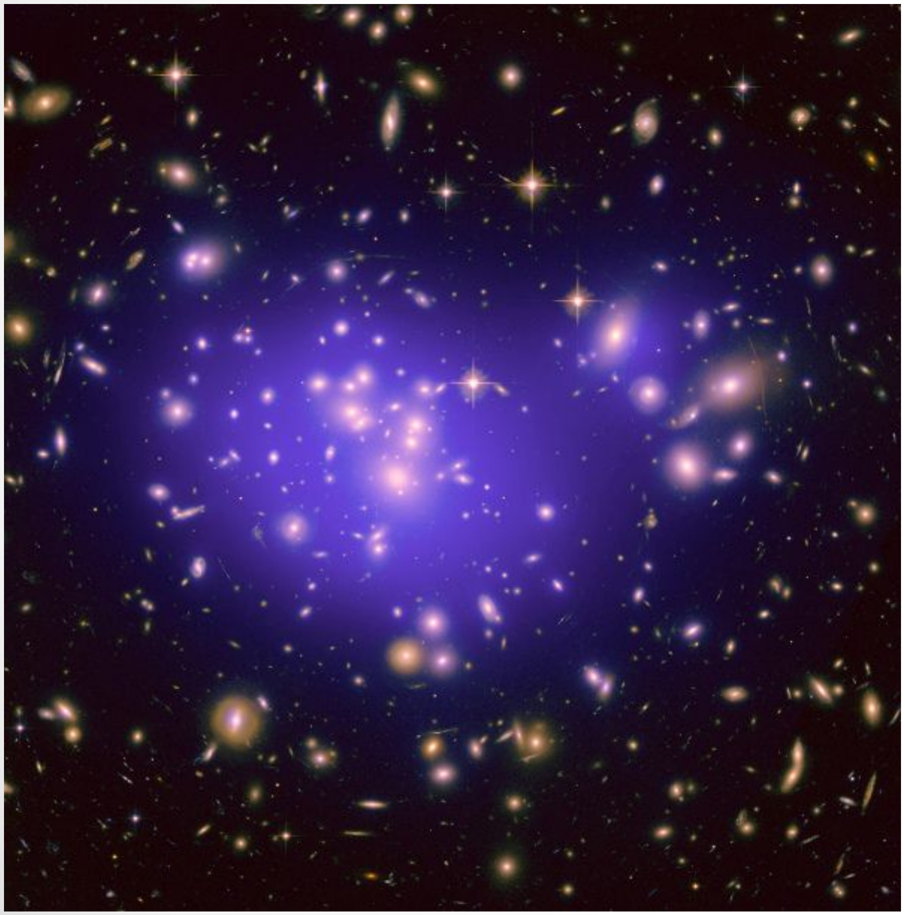
- Universe was ionized and "foggy" till the time where it cooled below 3000K at around 380,000 years after the HBB
- If we look back in spacetime, we see in every direction the radiation from that 3000K "surface of last scattering" but it has been redshifted by a factor of 1100 to look like a 3K plasma
- The presence of structure in the Universe today implies very low level fluctuations in the CMB that were measured by the COBE satellite

Dark Matter I



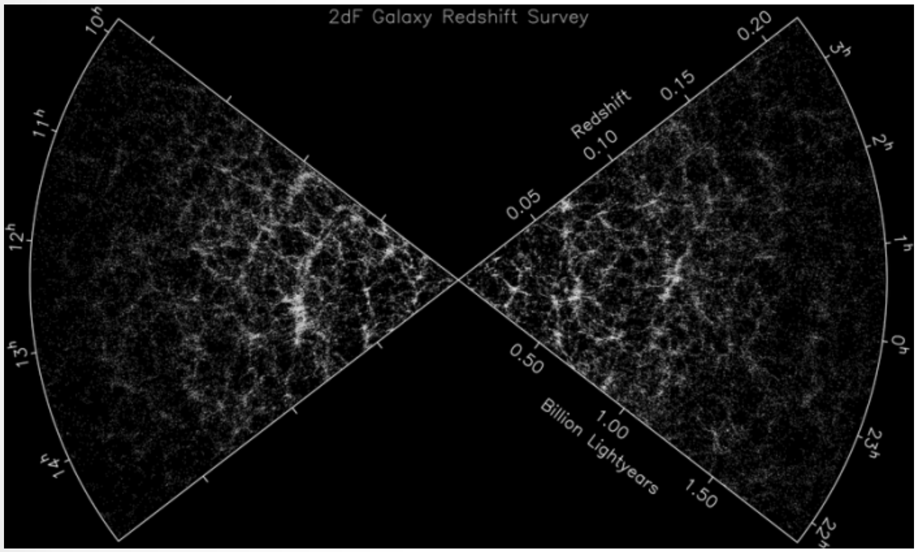
- Rotation curves of galaxies required an extended halo of non-luminous mass to keep the stars at larger radii bound to the galaxies

Dark Matter II



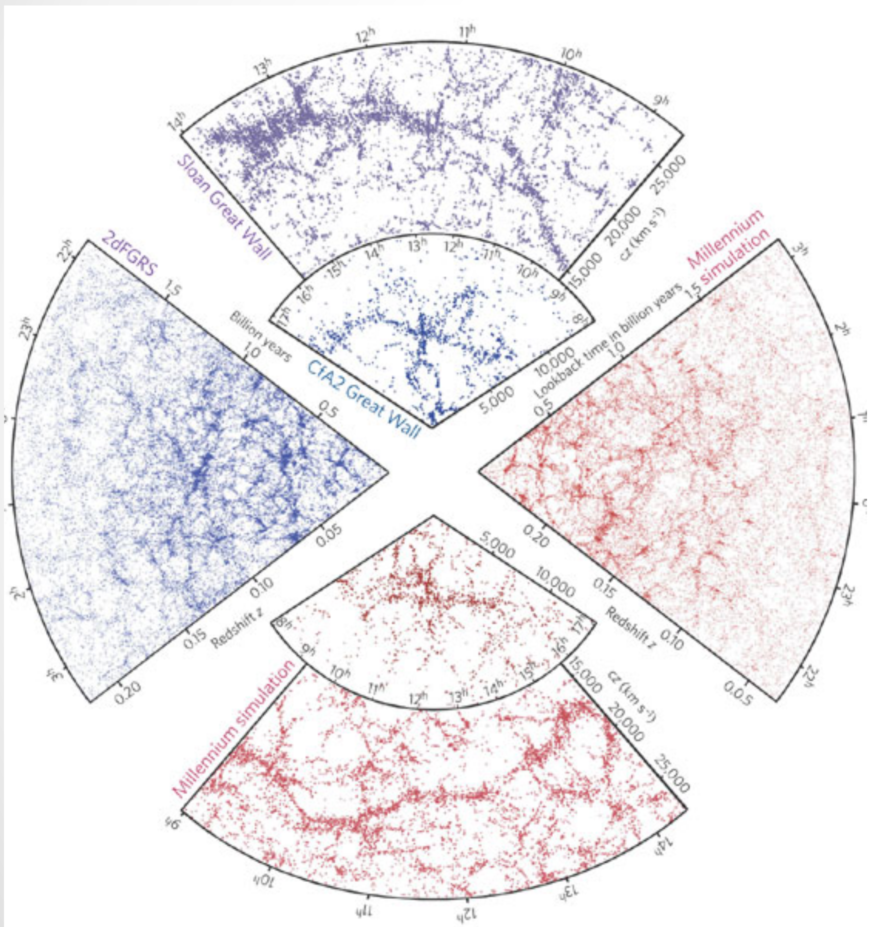
- Dark matter was also required on a larger scale to explain galaxy clusters
  - The "velocity dispersion" of galaxies in a cluster is so high they would fly into space without dark matter contribution
  - Retention of hot gas
  - Presence of gravitational lenses

Dark Matter III



- 3-D maps (using redshifts to estimate distances) of the distribution of galaxies showed far more structure than expected
- To match "large scale structure" required dark matter on a third larger scale

Dark Matter III



- Best match to observations for dark matter is:
  - Cold (not neutrinos) implying relatively massive
  - Weak interaction cross-section (photons and matter)
  - Does not emit or absorb radiation
  - ~30% of the mass/energy of the Universe (ordinary matter is only 4%)

review article

Nature **311**, 517 - 525 (11 October 1984); doi:10.1038/311517a0

Formation of galaxies and large-scale structure with cold dark matter

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[†]Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA
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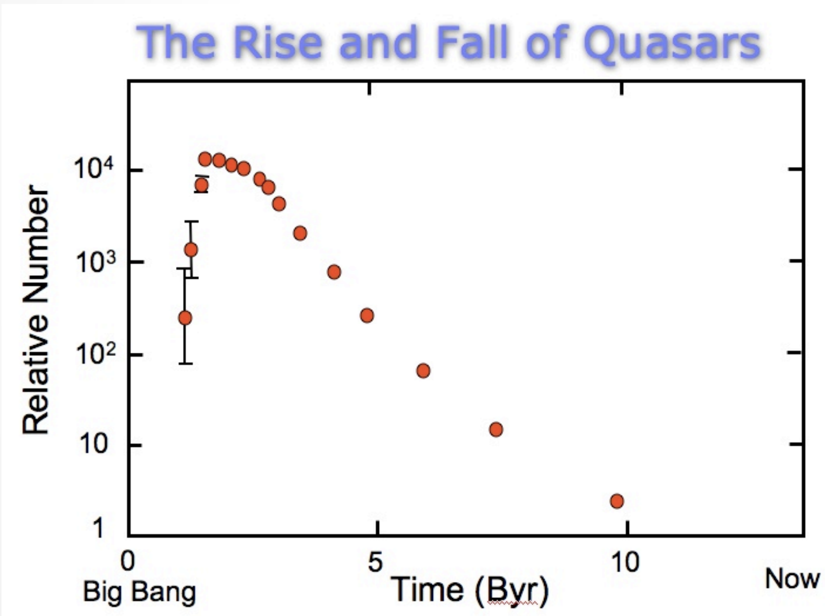
The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich ($|\delta_k|^2 \propto k$) spectrum of primordial fluctuations.

Quasar/SMBH History of the Universe



- If you measure the cosmic history of quasars activity and star formation you get similar plots that peak in the first third of the history of the Universe
- Likely this is related to galaxy-galaxy interactions being more common early in the Universe

Age of the Universe

$$H_0 = 72\text{km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$$

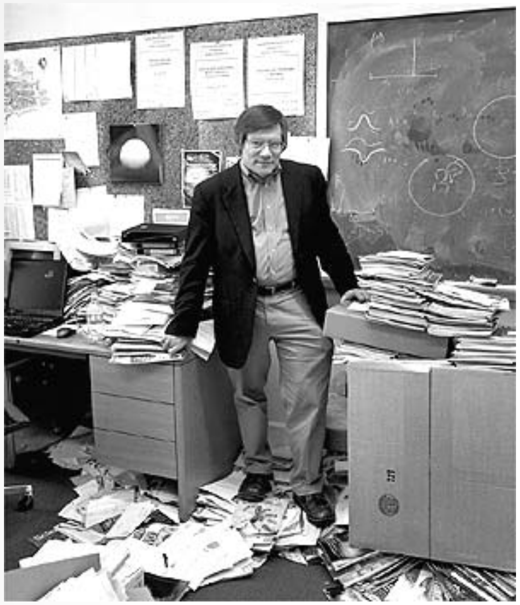
$$\frac{1}{H_0} = \frac{1}{72} \frac{\text{s} \cdot \text{Mpc}}{\text{km}} \times \frac{3.1 \times 10^{19}\text{km}}{1\text{Mpc}} = 4.3 \times 10^{17}\text{s}$$

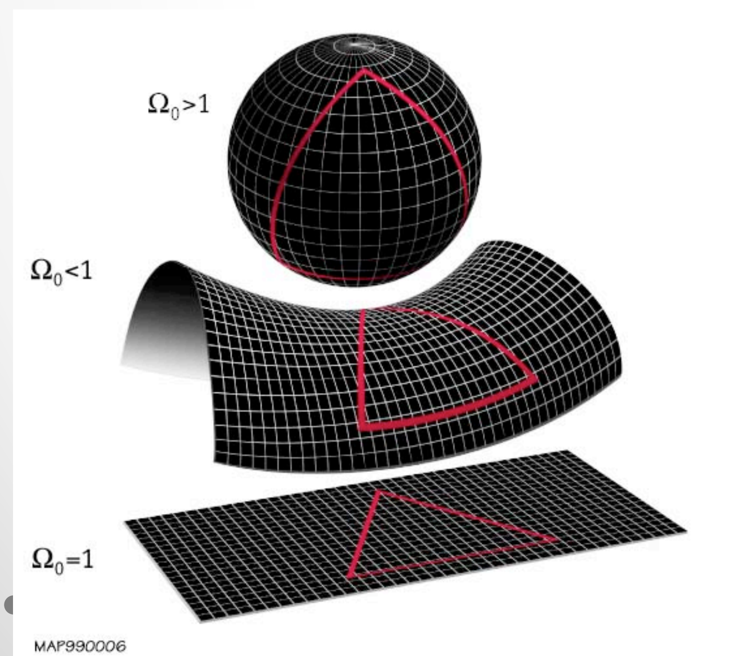
$$4.3 \times 10^{17}\text{s} \times \frac{1\text{year}}{3.15 \times 10^{7}\text{s}} = 13.6 \times 10^{9}\text{years}$$

- If H_o was constant for all time the "expansion age" of the Universe is simply $1/H_o$
- H_o=72 (km/s)/Mpc
- km and Mpc are distance units so H_o has units of 1/seconds

New Material

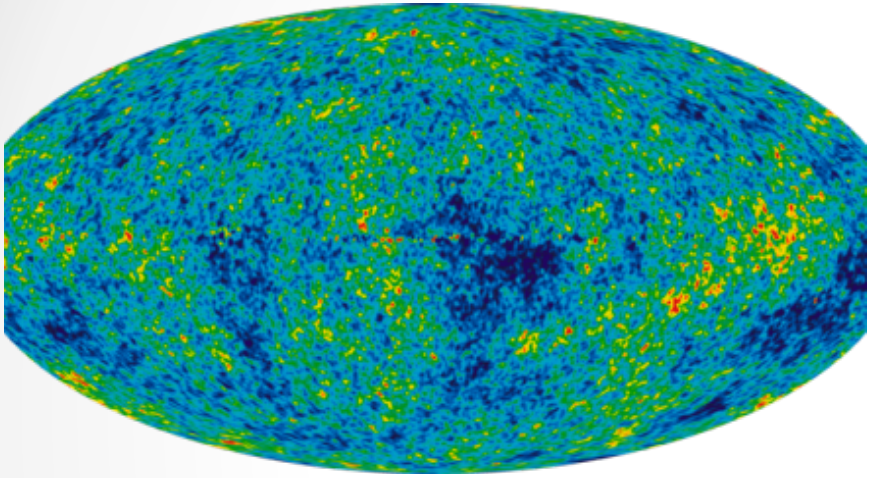
Are Astronomers Inflating the Truth?

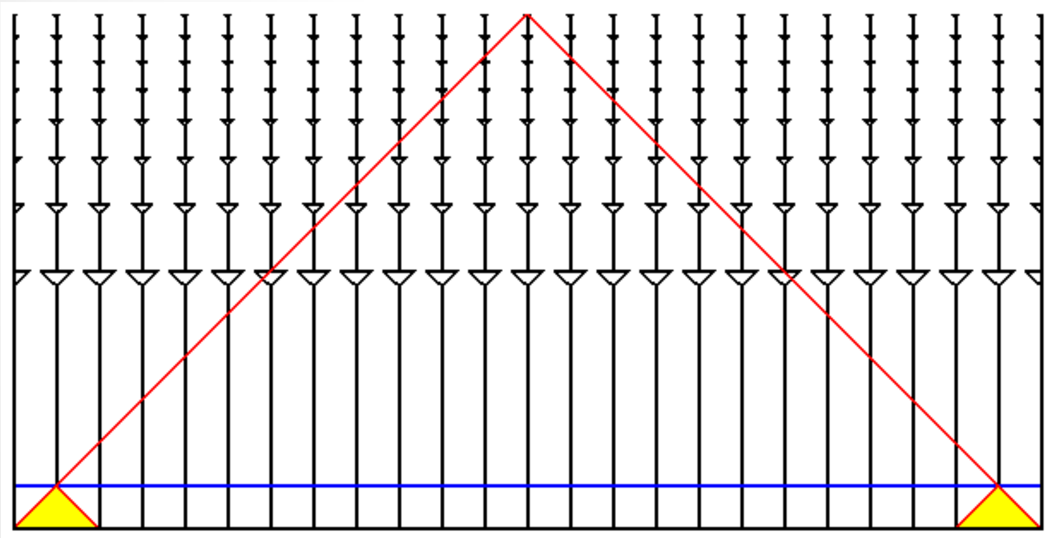




- In the 1970s three problems with the Big Bang were widely discussed:
  - Horizon problem
  - Flatness problem
  - Relic monopole problem
  - Origin of cosmic structures
- Alan Guth proposed the inflaton field and cosmic inflation to solve all these at once
- Universe expands by 10^{26} between 10^{-36} and 10^{-32} seconds after the Big Bang

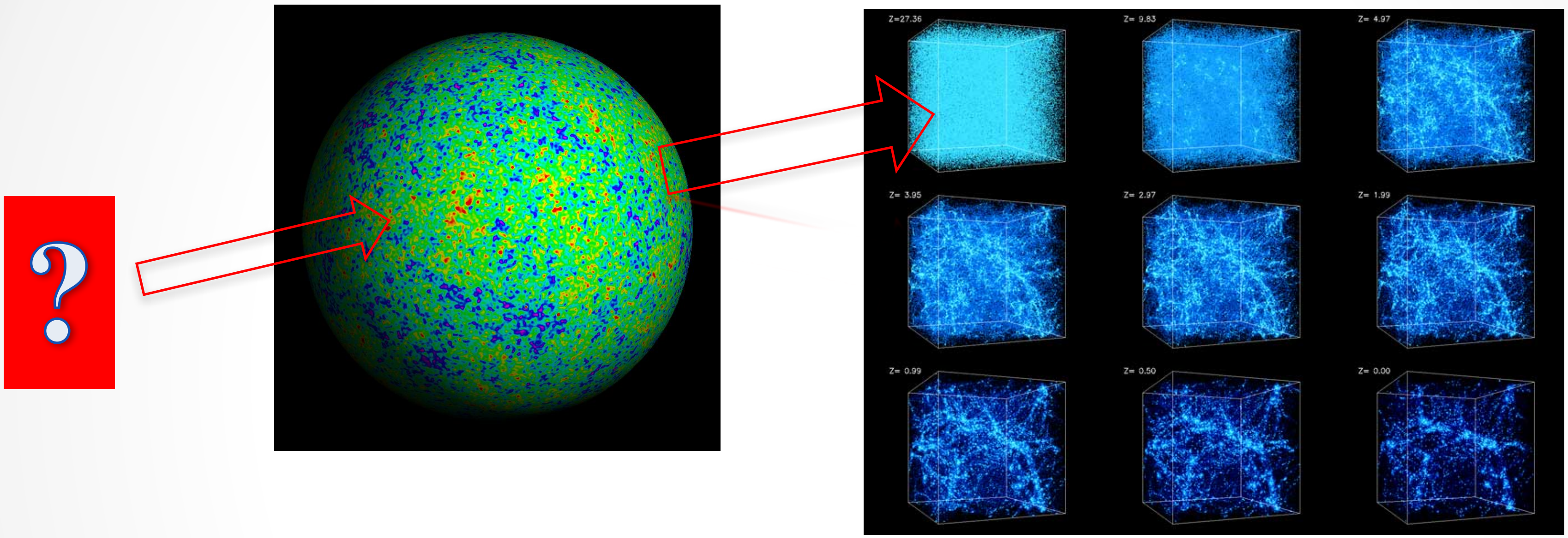
Horizon Problem





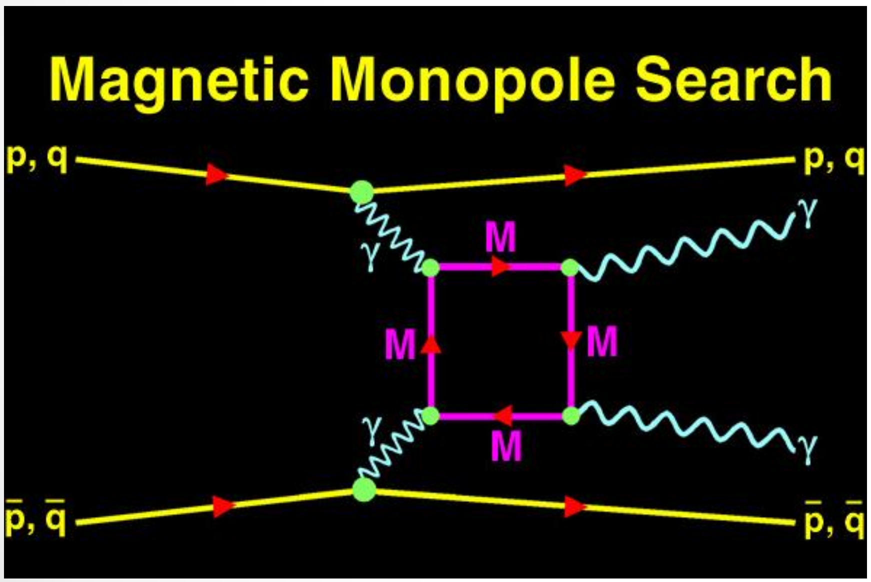
- Cosmic Microwave Background looks the same (statistically) in every direction
- But, the opposite sides of the sky should not have been in "contact" at 380,000 years after the HBB
- How could they be the same temperature to 1 part in 100,000?

Seeds of Galaxies



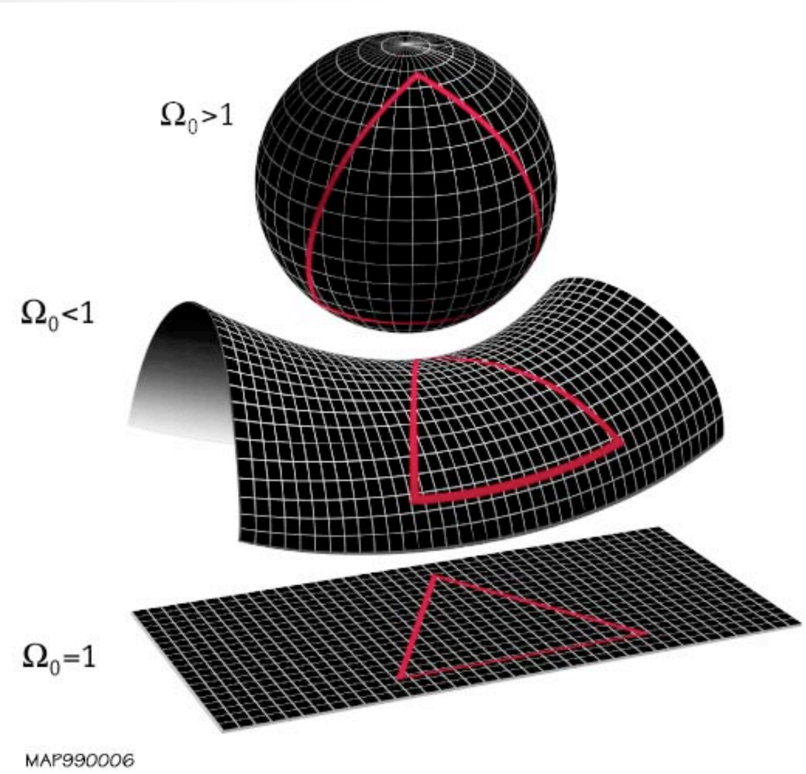
- We can grow the ripples seen in the CMB into the galaxies and large scale structure we see today (with Dark Matter) but what is the origin of the initial inhomogeneities?

Magnetic Monopoles



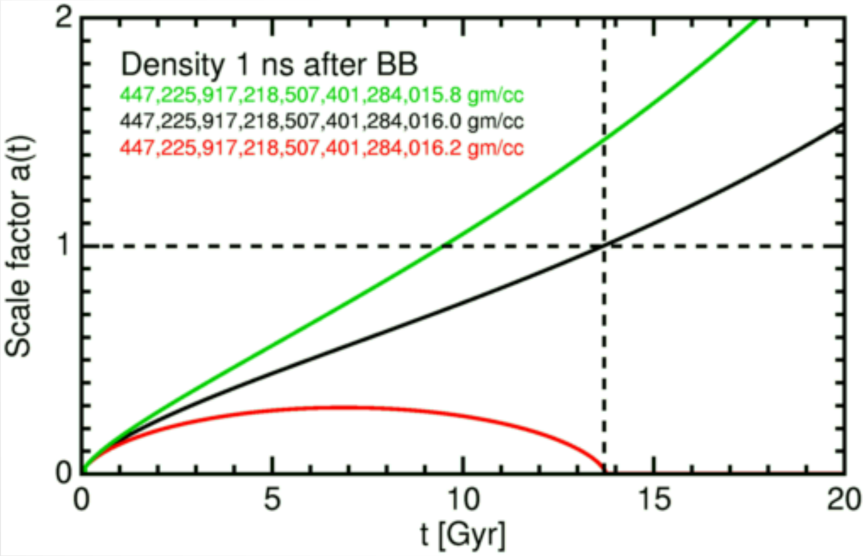
- Predicted by Dirac to explain discrete electric charges in 1930s
- A part of modern String Theory and other GUTS theories predict the presence of massive monopoles that should exist at early times and be stable
- None found: density 10^{-29} that of protons

Flatness Problem



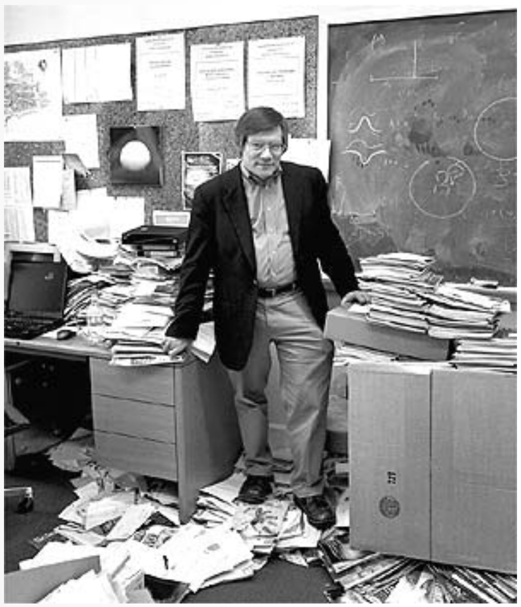
- The mass/energy in the Universe causes an overall "warp" in space time
- There is a critical density of mass/energy that makes the Universe spatially "flat"
- "Ω"= ratio of mass/energy density to the critical mass for a flat universe
  - Ω_M is the contribution of matter (and photons) to the density

Flatness Problem



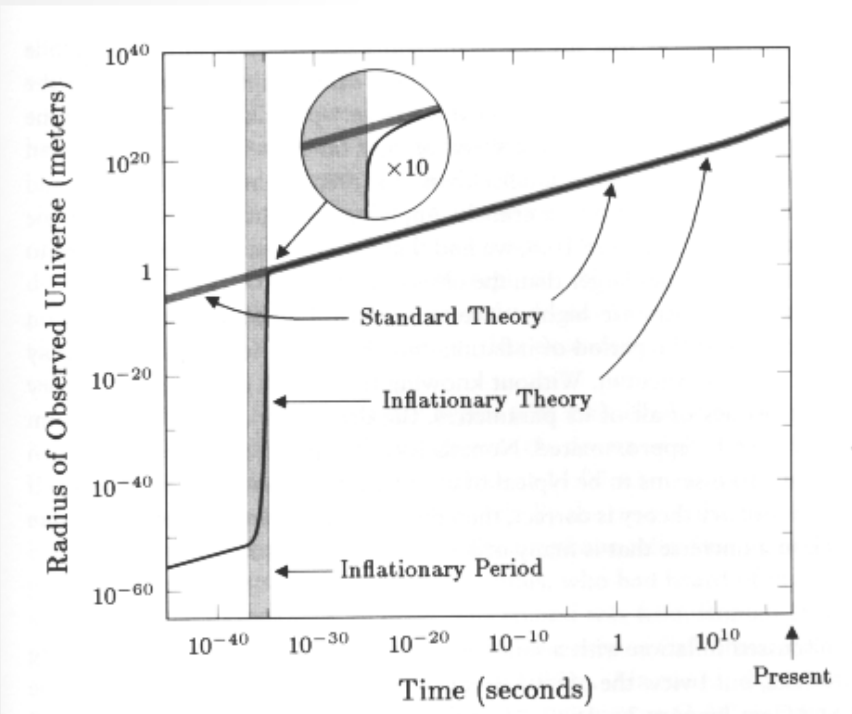
- One of several "fine tuning" problems
- If Ω had been different from 1 by 1 part in 10^{59} early on then the Universe would have collapsed long before now or have expanded too quickly for galaxies/stars/planets to form
- Anthropic Principle?

Are Astronomers Inflating the Truth?

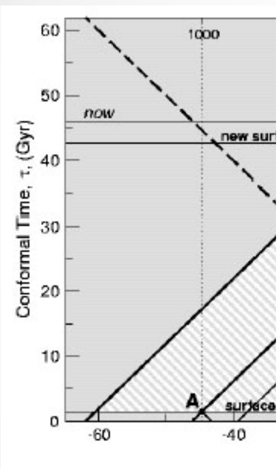


- In 1980 a particle physicist names Alan Guth proposed the "inflaton field" and an era of cosmic inflation to dilute the magnetic monopole density at every early times
- Universe expands by a factor of 10^{26} between 10^{-36} and 10^{-32} seconds after the Big Bang

Inflation: Monopoles



- Monopoles formed before/during inflation at the time that the strong nuclear force separates from electricity and the "weak" force
- Like a phase transition with energy released
- With the 10^{78} increase in volume of the Universe, monopole density was enormously diluted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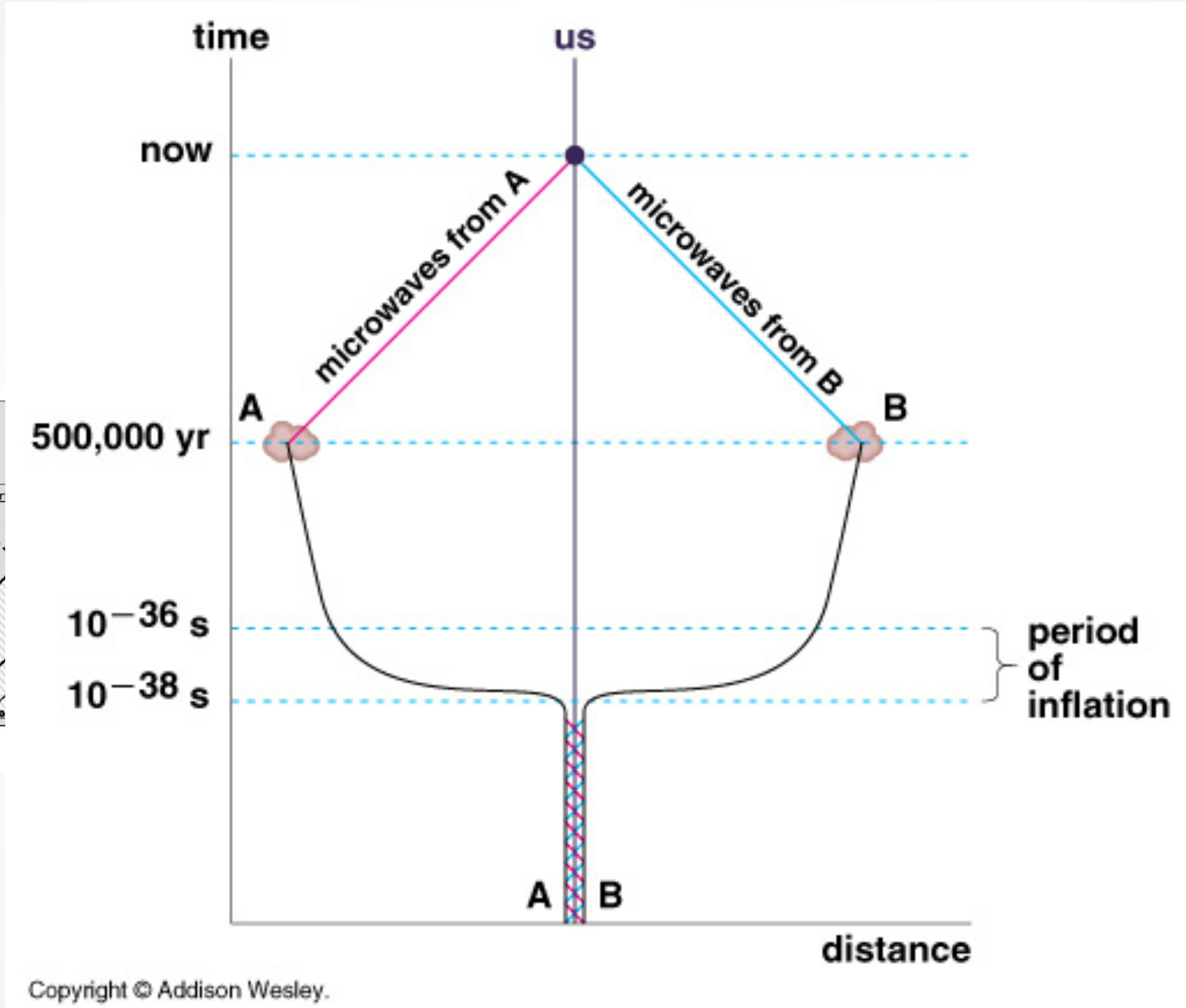
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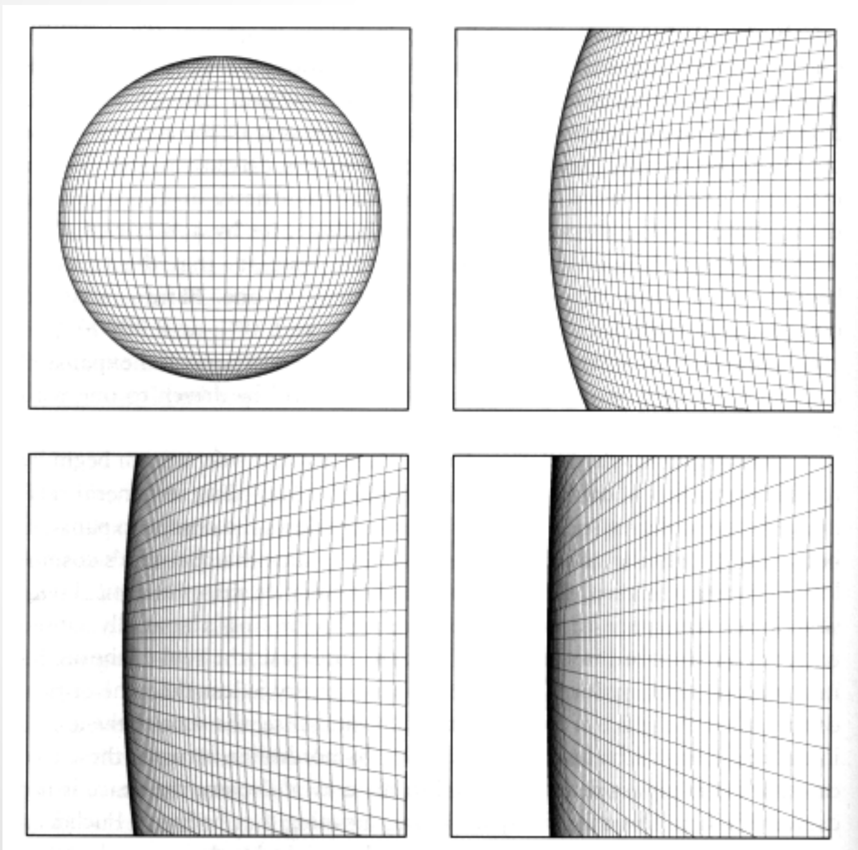
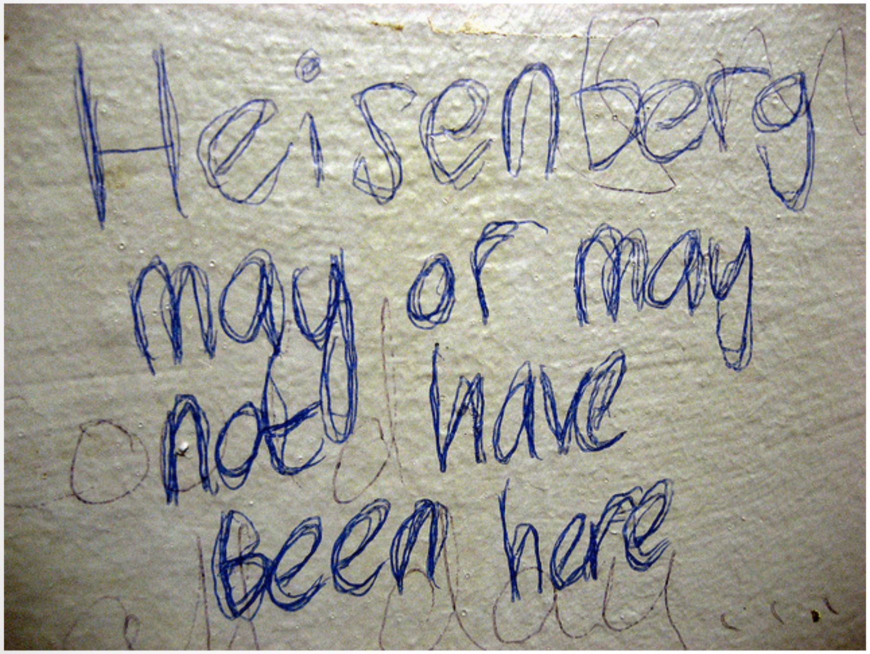
Inflation: Flatness



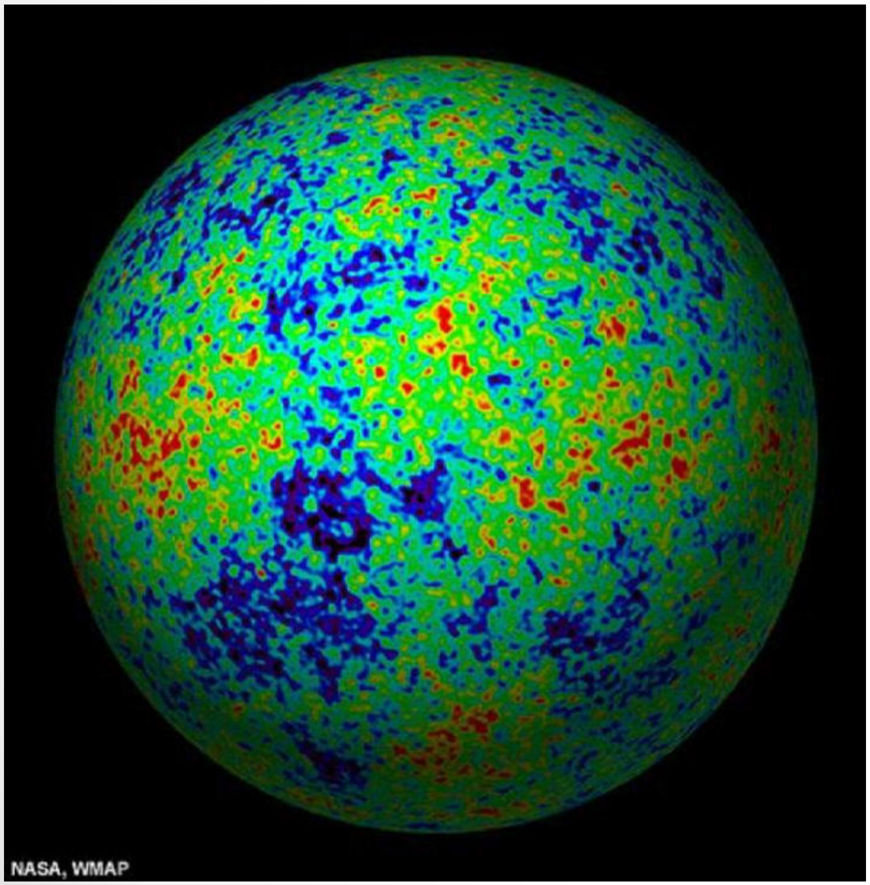
- Huge increase in radius drove the universe extremely close to a flat geometry

Inflation: Seeds of LSS



- In the pre-inflated Universe there were the usual “quantum fluctuations” associated with the Heisenberg Uncertainty Principle
- These tiny fluctuations were expanded to macroscopic scales by inflation

Inflation: Seeds of LSS

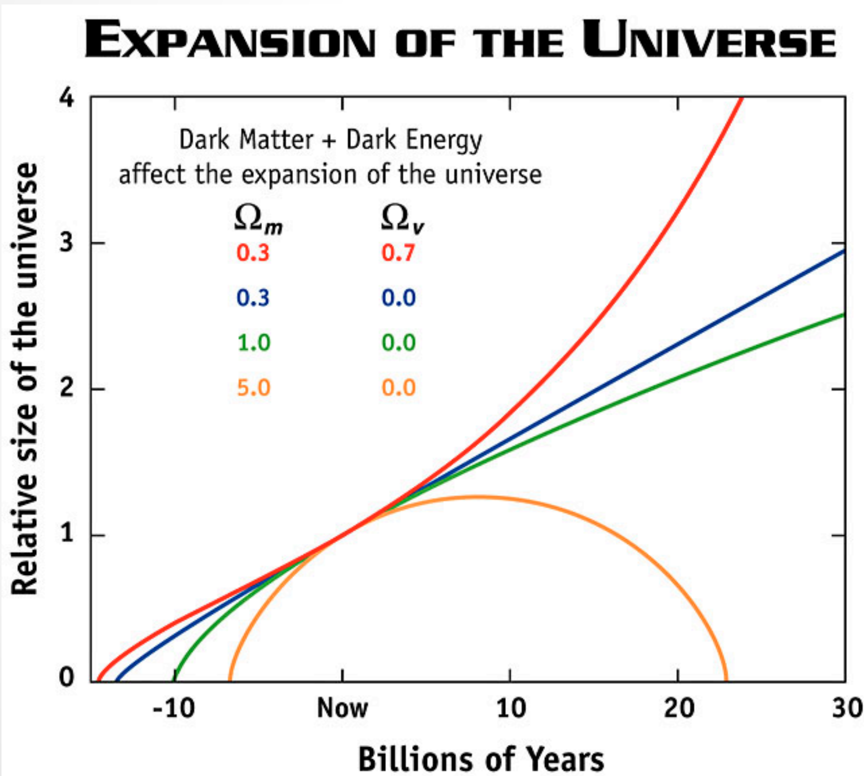


- These tiny fluctuations were expanded to macroscopic scales by inflation
- Seen in the cosmic microwave background and grown to 1 part in 100,000
- These were then the seeds of higher-than-average density regions around which dark matter clustered and galaxies formed

Inflationary, Cold Dark Matter Universe

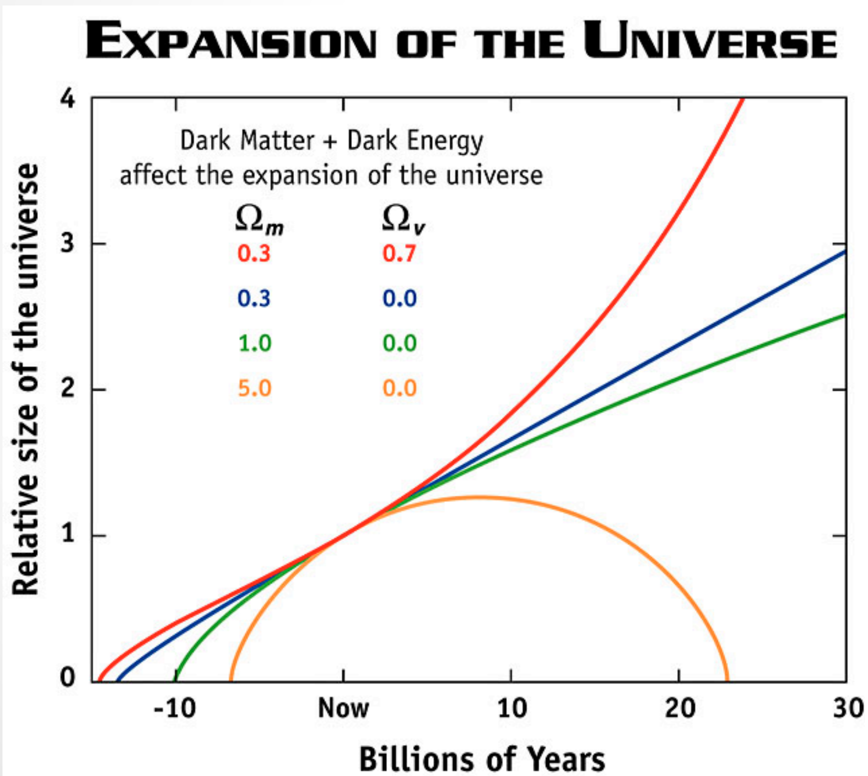
- This model that has evolved over the past two decade matches very well to many, many observations
  - Hot Big Bang
  - Inflation (and spatially flat structure)
  - "Normal" matter small component, dark matter dominates
- Looked great with only a small issue about the age

Age of the Universe



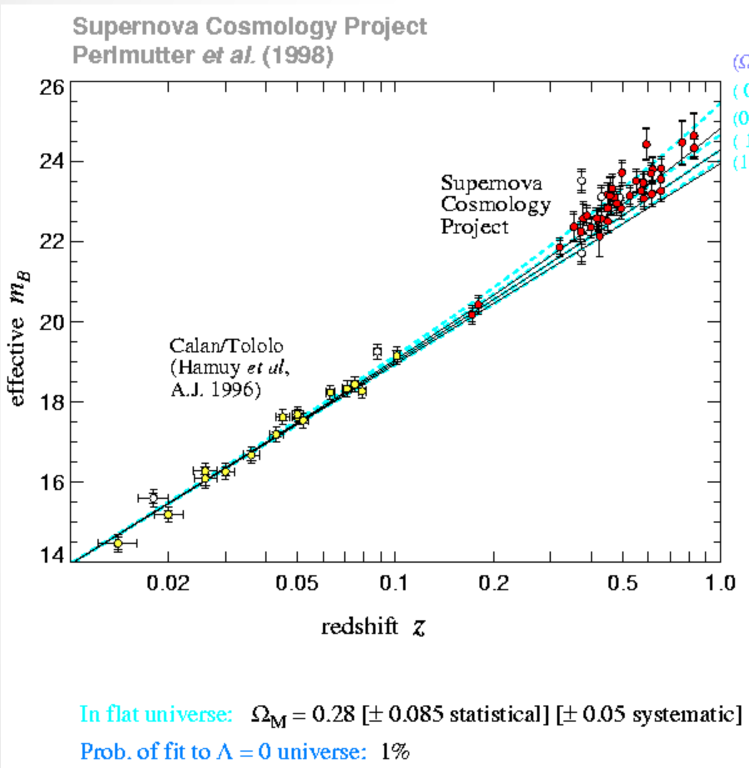
- The expectation was for the expansion of the Universe to be slowing down because of all the matter in the Universe
- Using current H_o this gives a lower expansion age that we measured for stars
  - 8.5 billion years vs 13 billion years from stars

Age of the Universe



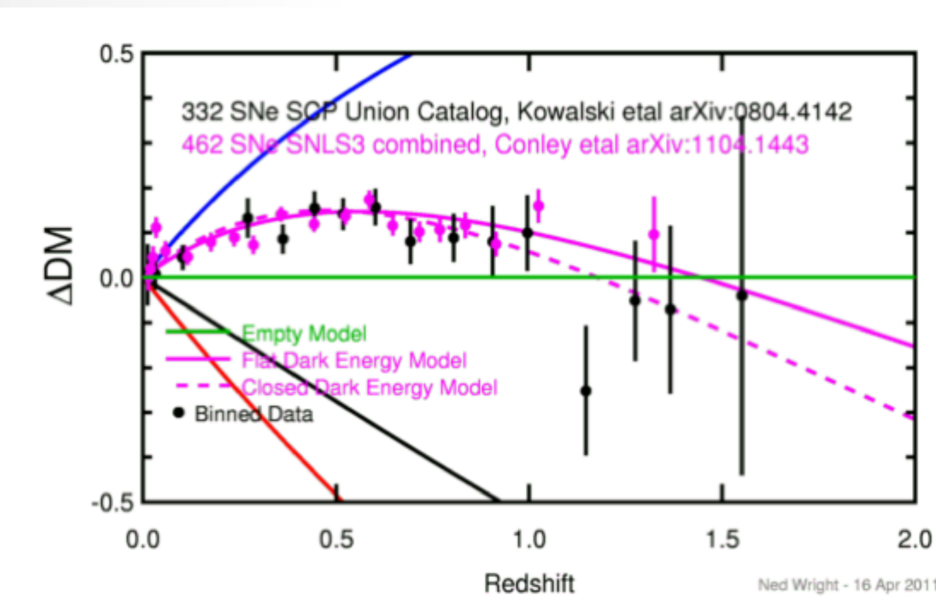
- One proposed idea from the mid 1990s was that instead of slowing down, the Universe was accelerating in its expansion and therefore the expansion age was larger than $1/H_o$
- Initiated programs to measure H (not $_o$) at earlier times to see directly if the expansion had slowed or speeded up

Dark energy



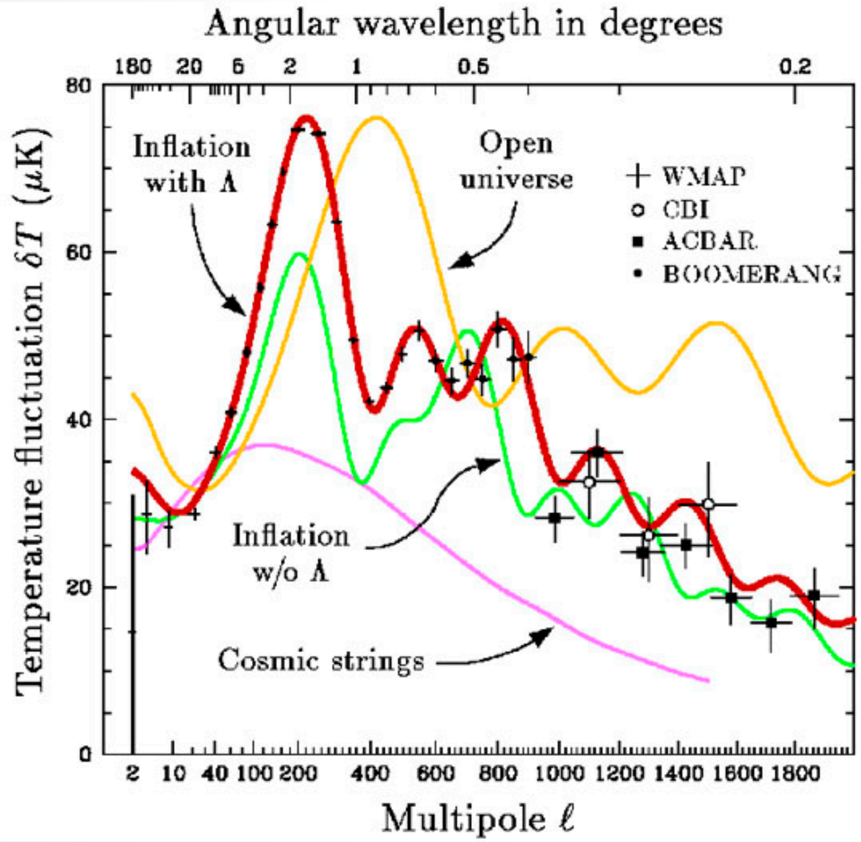
- To the surprise of many the result was that the expansion was slower in the past
- Λ, the cosmological constant was not zero, but rather had a value of ~0.72: consistent with that need to reconcile the Universe expansion age and stellar ages

Dark Energy



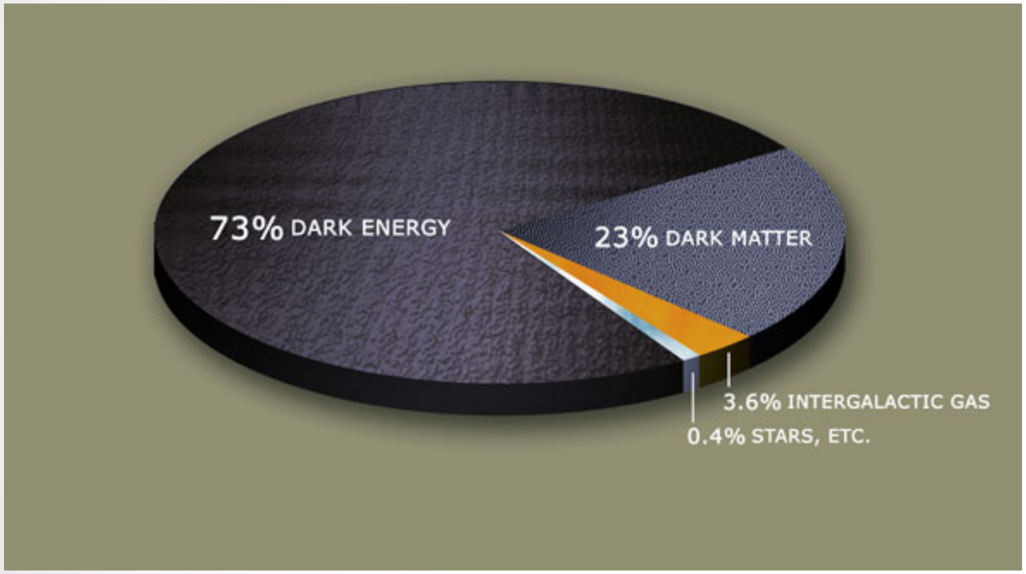
- 2011 Nobel Prize went to the teams who verified the acceleration of the expansion of the Universe
- Possibly the energy of the vacuum
- Much more mysterious than Dark Matter

ΛCDM Universe



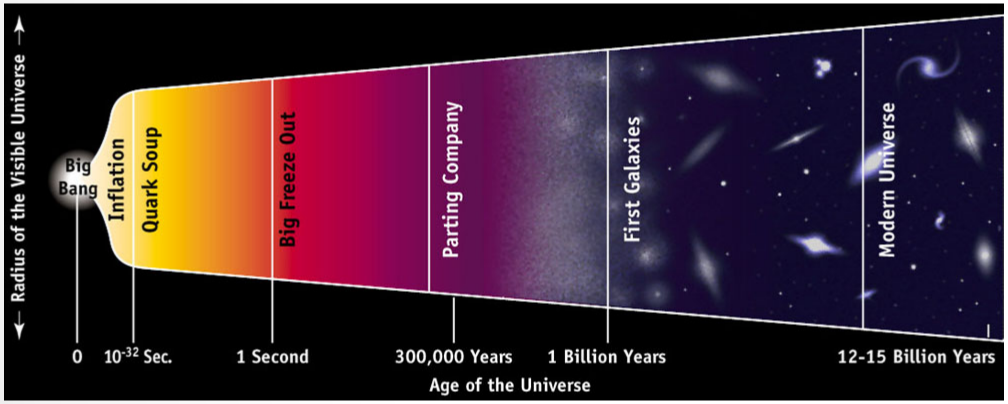
- Combining all these concepts and comparing with the distributions of the CMD flucutuations makes the outcome pretty clear

The Universe



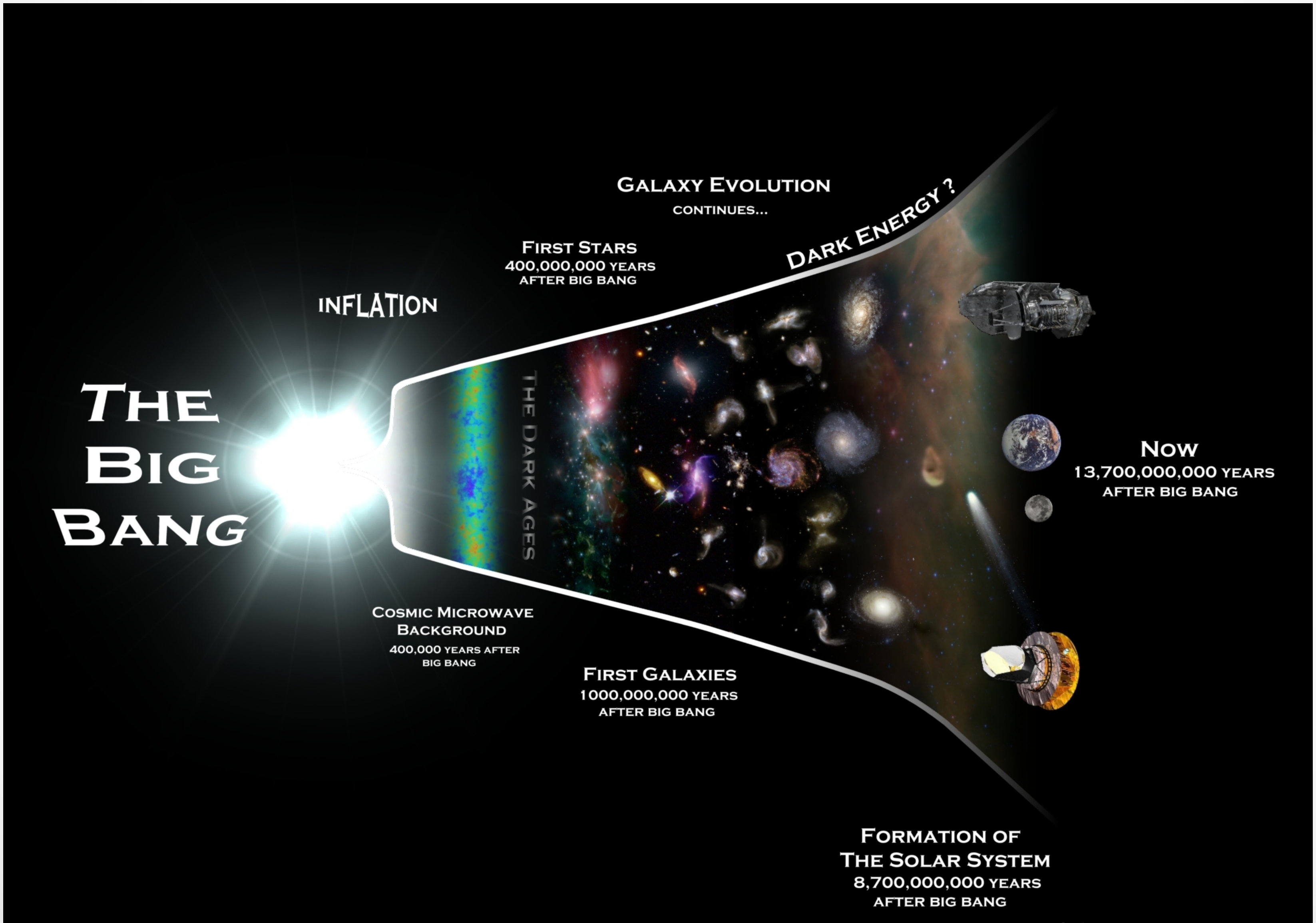
- The mass/energy budget of the Universe is now well established
- Dark Energy dominates, Dark Matter a distance second
- Everything else is just a smattering

Leaves a few questions

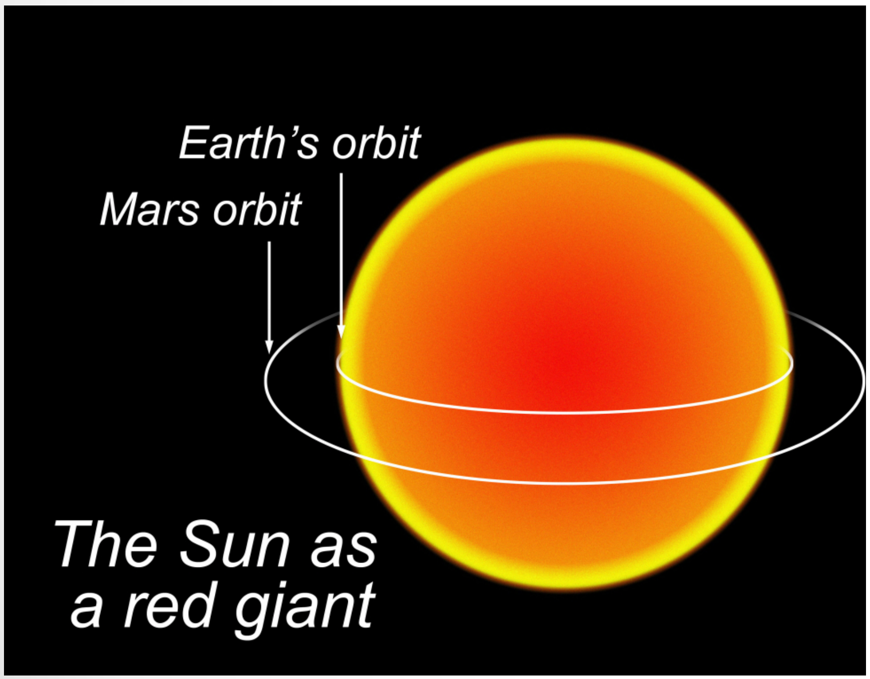


- Nature of Dark Matter
- Nature of Dark Energy
- End of the Cosmic Dark Ages
  - How did Supermassive Black Holes form so early?
- What happened before the Big Bang?

Better version for 2013

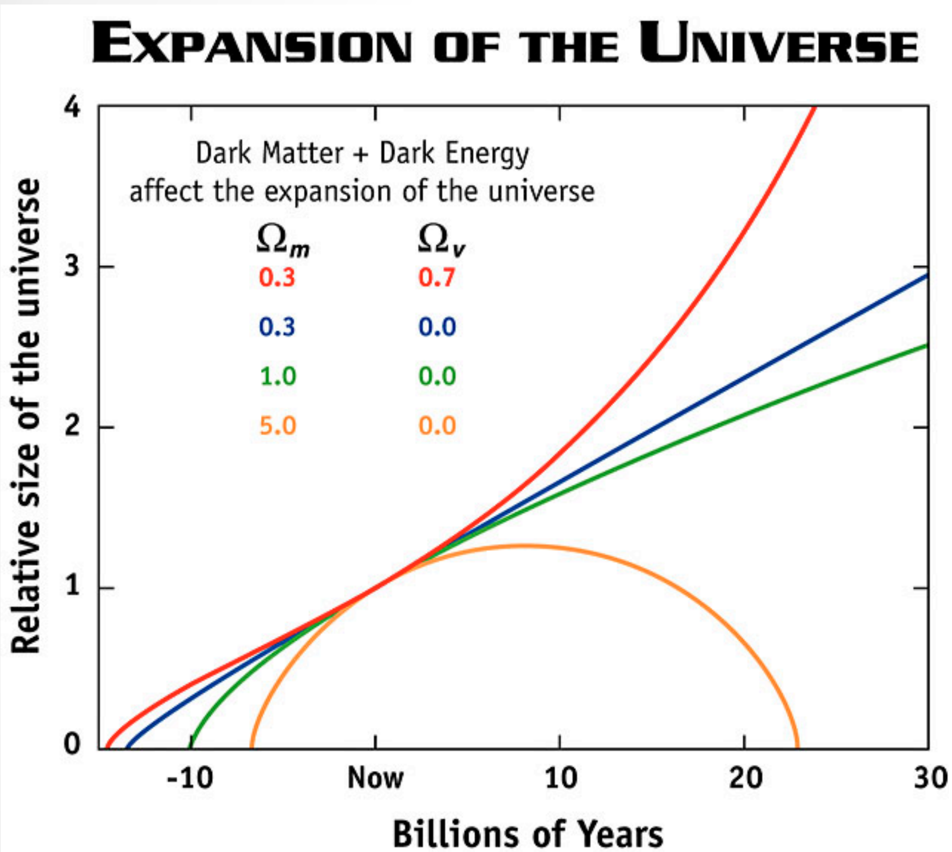


The "local" future



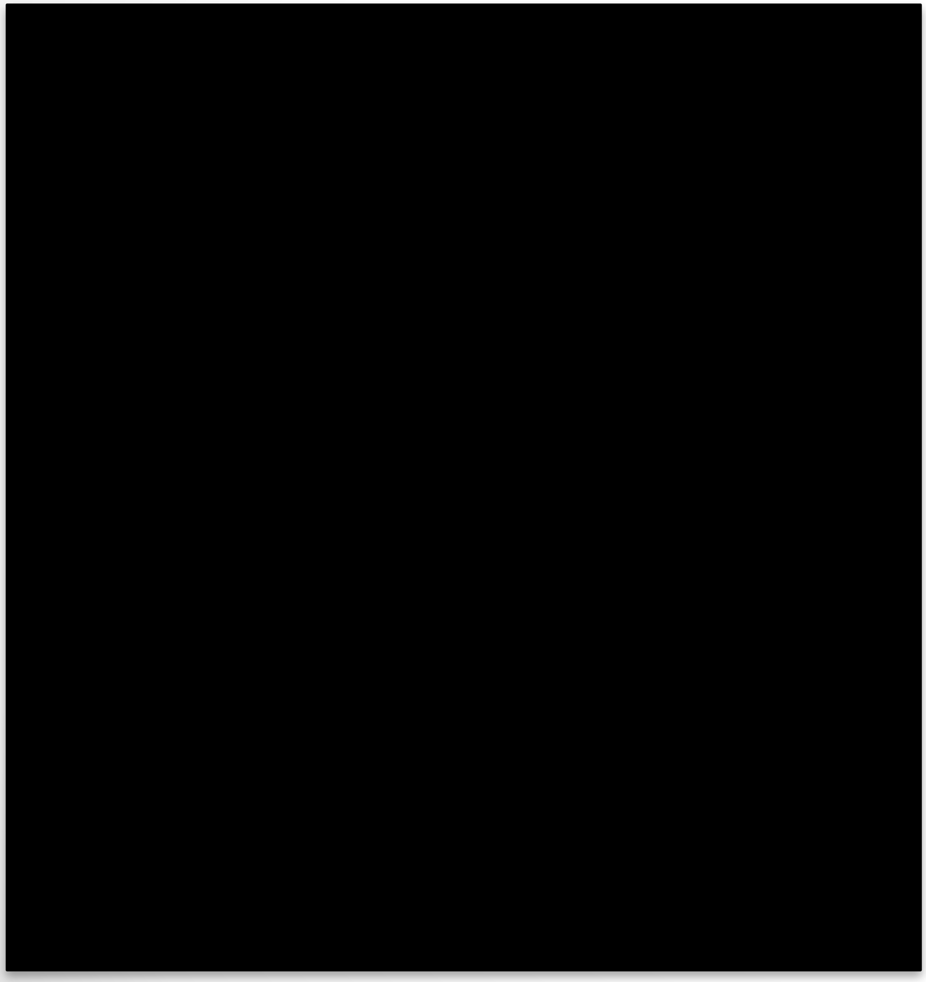
- Major events in Earth's future
  - Sun will expand and incinerate the Earth (4 billion years)
    - Oceans evaporate in 1 billion years
  - Andromeda Galaxy will collide with Milky Way (4 Billion years)
  - Many > 10 km meteor impacts
  - Many nearby supernovae events
  - Disruption of the solar system through chaos or close encounter with star
  - Andromeda Galaxy will collide with Milky Way (4 Billion years)

Future of the Universe



- Expansion of the Universe accelerates for the rest of time
- 100 billion years, all galaxies outside of the Local Group expand outside of our visual horizon
- 1 trillion years, gas is exhausted and star formation ends
- 100 trillion years, last star completes fusion reactions

Future of the Universe



- What happens after 100 trillion years depends on the stability of protons and dark matter, the nature of dark energy and the evaporation of black holes
- Best bet based on what we know in 2013 is a very cold, dark future