An introduction to the Big Bang

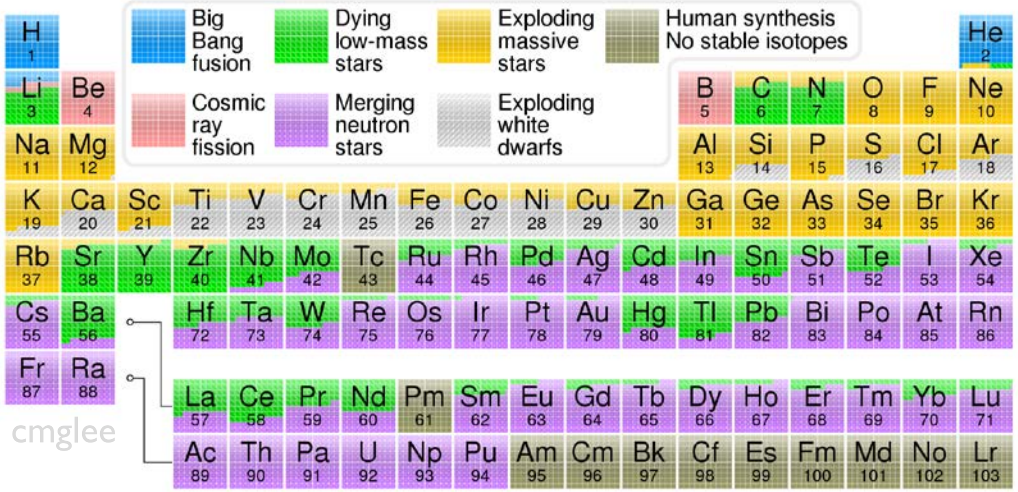
Zach Meisel
Ohio University - ASTR1000

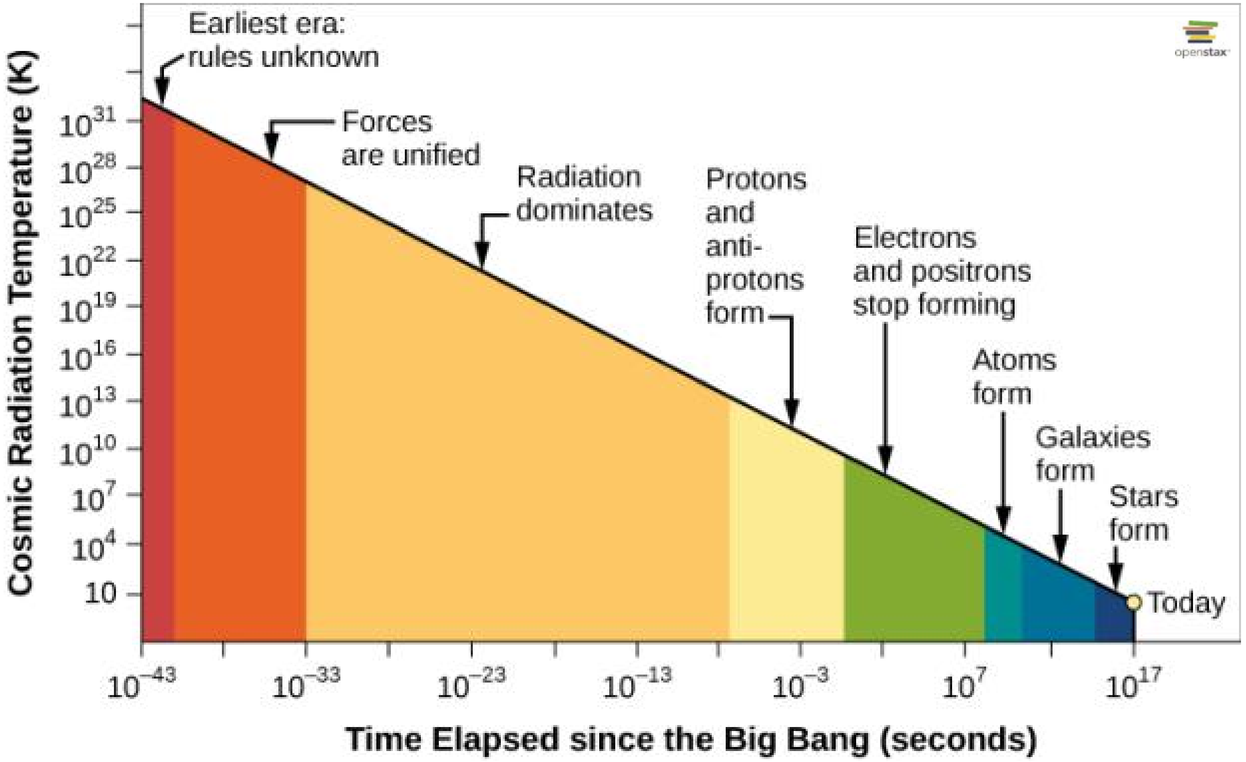
In the beginning…

- The observable universe was an infinitesimal point
  (not necessarily the "whole" universe, whatever that is)
- Suddenly, it rapidly expanded

“*The first three minutes*”

- Traditionally, Big Bang theory describes the first 3 or so minutes of the universe’s history, when the universe formed the first chemical elements

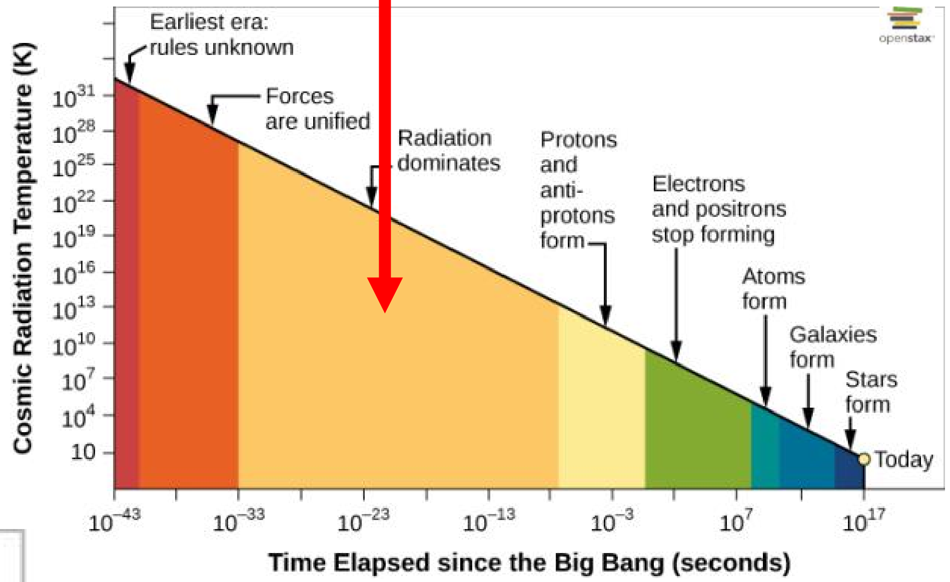


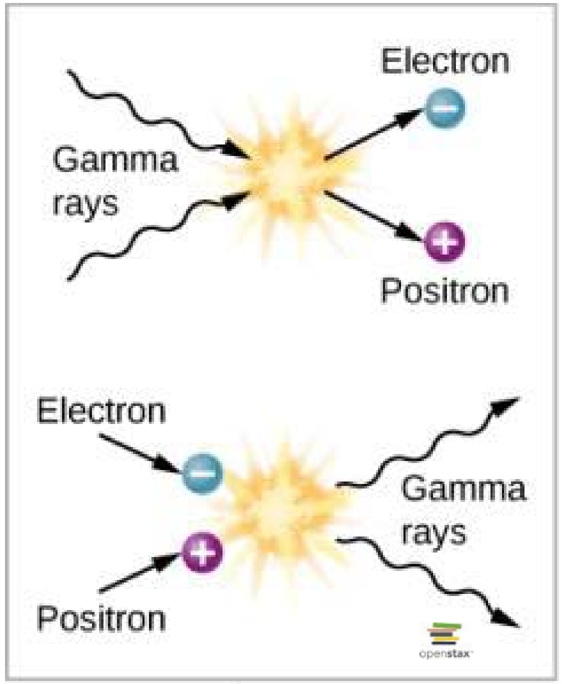


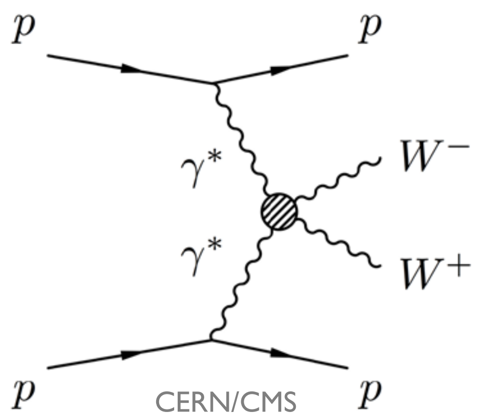
- This may not sound like much, but a lot happened, cooling from “infinite” temperature to a mere billion degrees and decompressing from “infinite” density to roughly Earth’s atmosphere (~1kg/m^3)

A radiation-dominated universe (briefly)

- You're familiar with Einstein's matter-energy equivalency, $E=mc^2$.
  Practically, matter can be converted to energy and vice versa
- At extremely high temperatures, this conversion happens readily.
  Photons combine to make particles and
  particles collide with anti-particles to make photons
- Most of the energy in the universe at this point was in the form of photons, and photons drive the physics at this point,
  hence the "radiation dominated era"

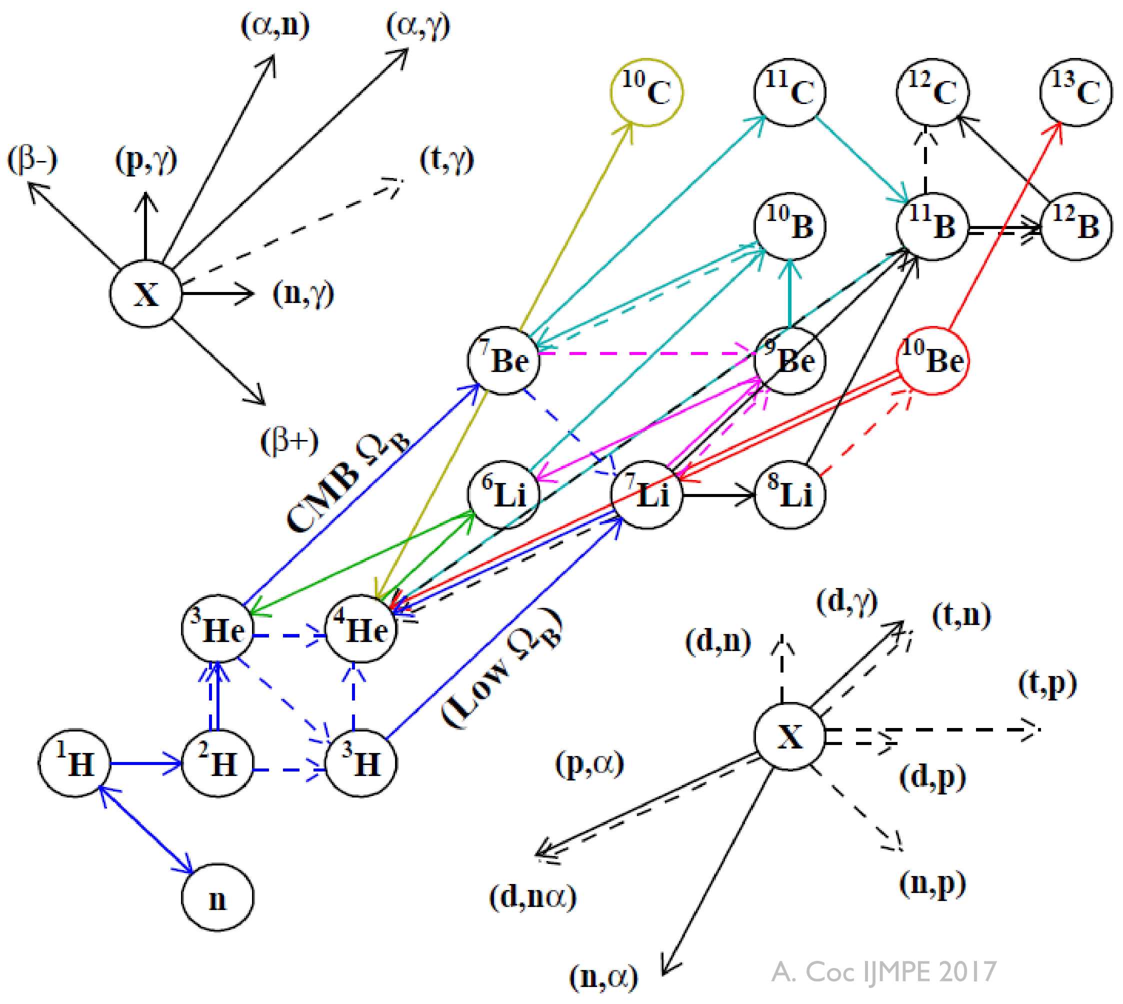






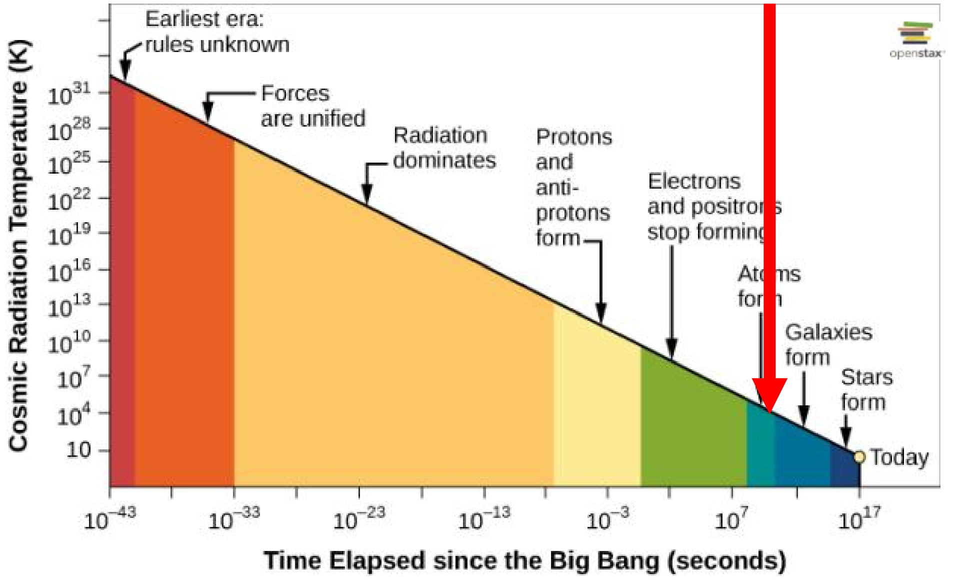
The first atomic nuclei form: *Big Bang Nucleosynthesis*

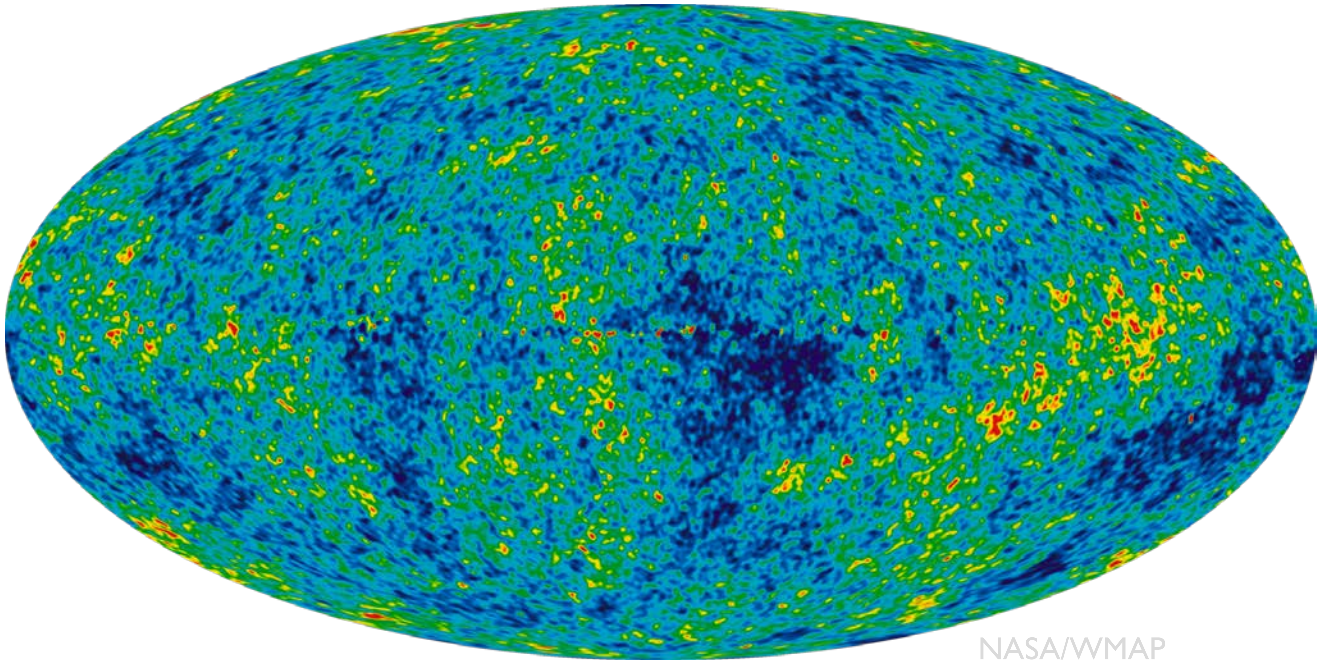
- At just below 1 billion degrees, at ~3min, protons and neutrons can combine to form deuterium (^{2}H), "heavy hydrogen", which could combine to form helium (^{3}He and ^{4}He)
- At ~4min, it was too cool for nucleosynthesis (element formation by nuclear reactions) to occur
- Further nuclear reactions have since processed this hydrogen and helium …but ~99.8% of the universe (at least the solar system) is still hydrogen and helium
- Each of the reactions (arrows in the right figure) are temperature and density sensitive. Observing these "primordial" abundances gives a signature of environment conditions during the Big Bang



The first atoms form

- A short ~300,000 years later it’s finally a cool 3000 K and atoms can form
- More importantly, free electrons are no longer scattering photons (they “decouple’), so photons from that point in time can free stream out into the universe …and some of them eventually reach earth
- The radiation from this point in time is the Cosmic Microwave Background (CMB)
- Due to redshift from expansion, the blackbody temperature of the CMB as observed on earth is ~3K
  - recall $\lambda \approx \frac{2.9\times10^6\ nm}{T[K]} \approx 1\ mm$
  - border of microwave & radio wave



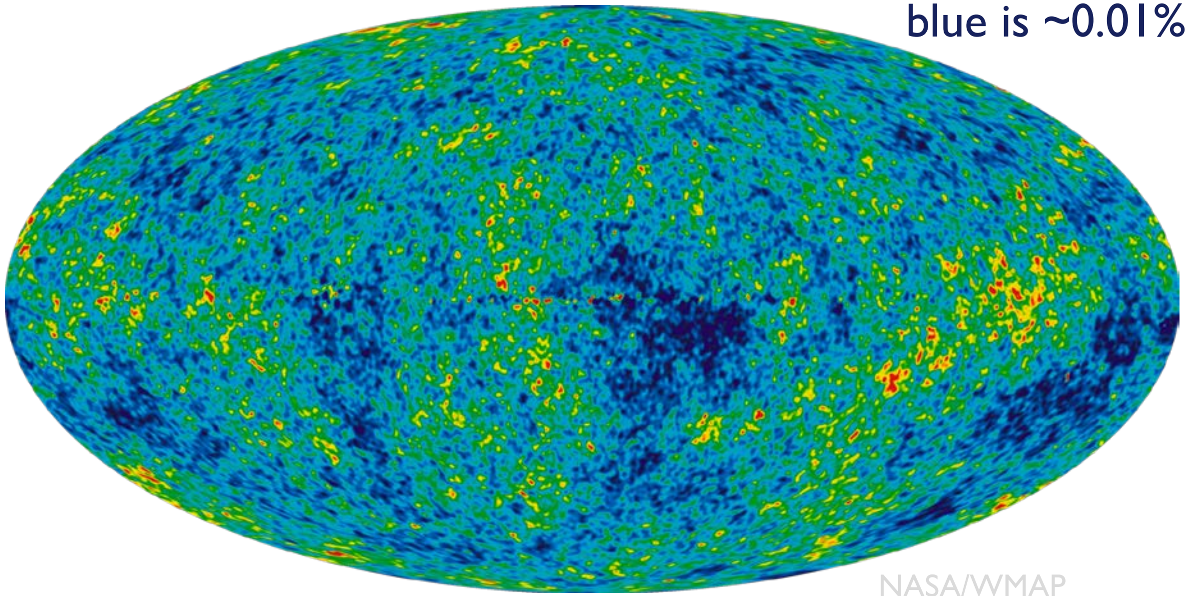


NASA/WMAP

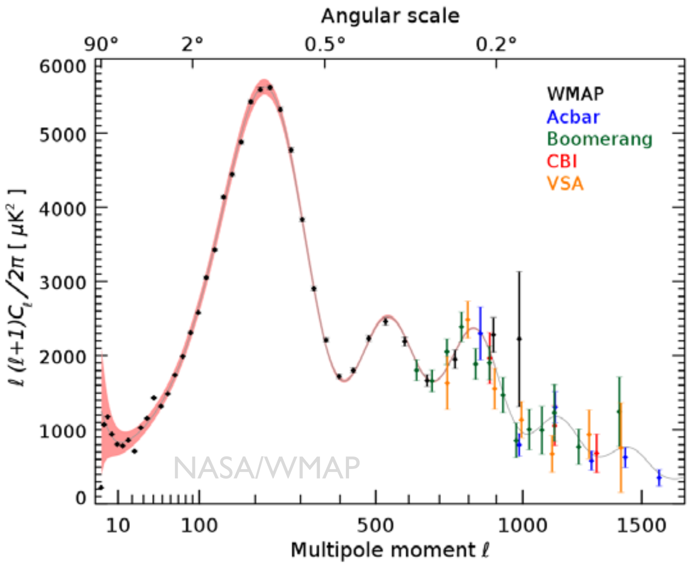
What does the CMB tell us about the Big Bang?

- The universe must have been really uniform, as we expect due to the rapid expansion
- But not too uniform! as we expect from the discrete structures in the universe (e.g. galaxies)
  - Connecting these two is pretty complicated
  - The "power spectrum" is an analysis of the spatial distribution of anisotropies within the CMB

red is ~0.01% hotter
blue is ~0.01% cooler

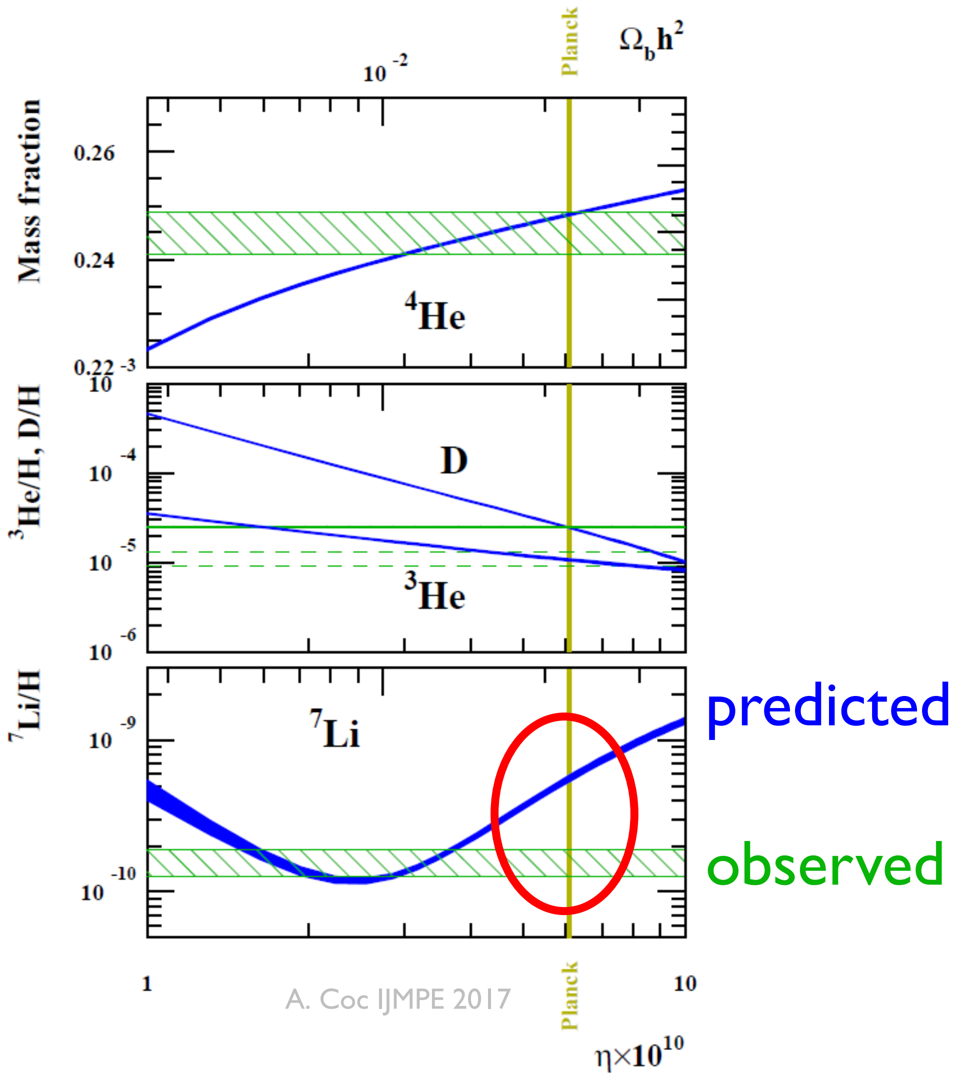


NASA/WMAP

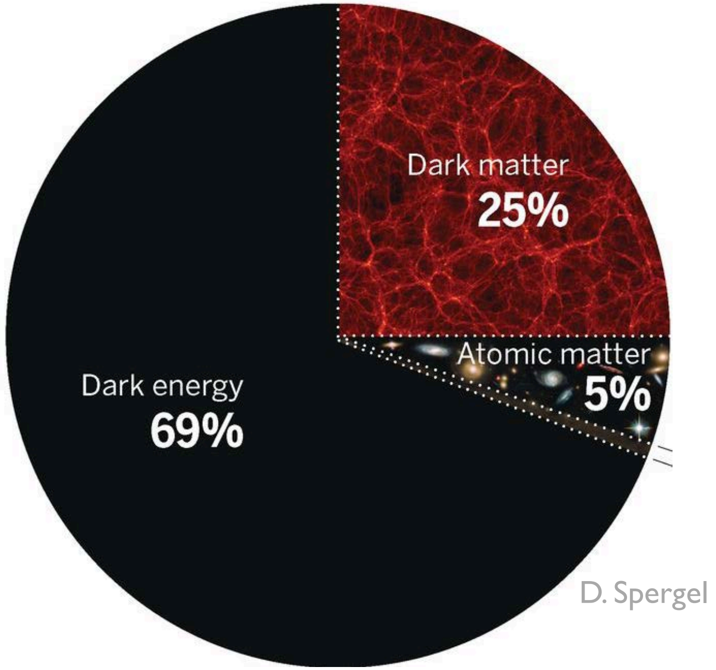


Outstanding Problems of the Early Universe

Why so little lithium?



Why more matter than antimatter?



What is the value of the Hubble constant?