The First Three Minutes
Meeting 10

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March 17, 2021

Meeting 8 – The First Three Minutes

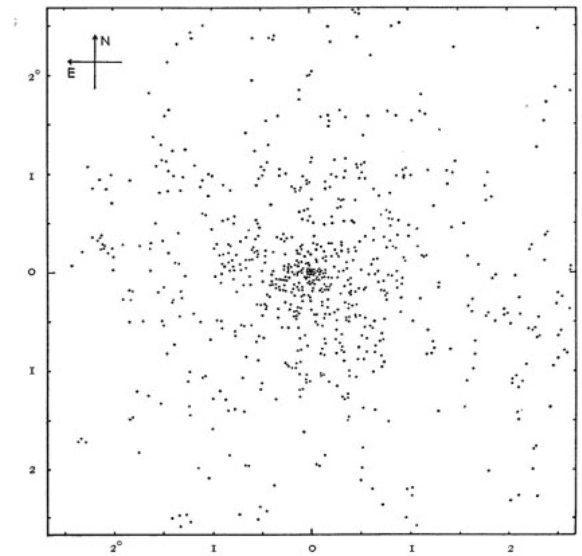
- Announcements
- **Dark Matter**
- Break
- Dark Energy
- Summary

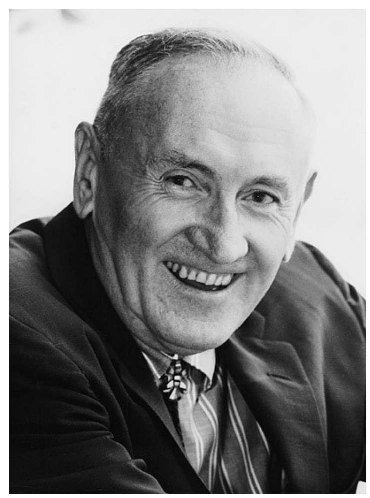
Announcements

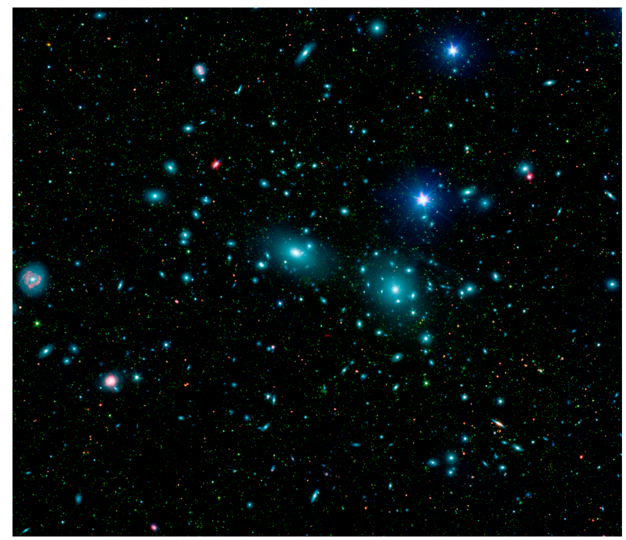
- Notes, slides, etc. on website, tinyurl.com/firstthreeminutes
- Questions
  - Inflation and the critical density – better answer later
  - Pauli blocking – see next slide
  - DM strong, EM, weak interactions
  - Relation between DE and DM

Dark Matter

Astronomer Fritz Zwicky measured the speeds of galaxies in the Coma Cluster and found they were moving too fast to be bound in the cluster. He hypothesized there was Invisible or dark matter providing the gravity to keep the cluster together.



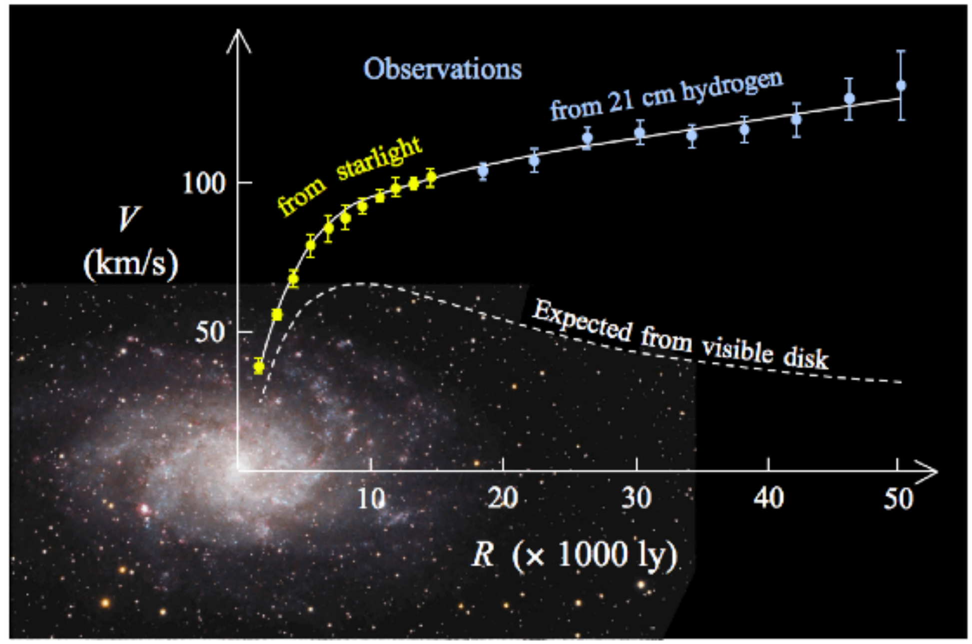




About 35 years passed…

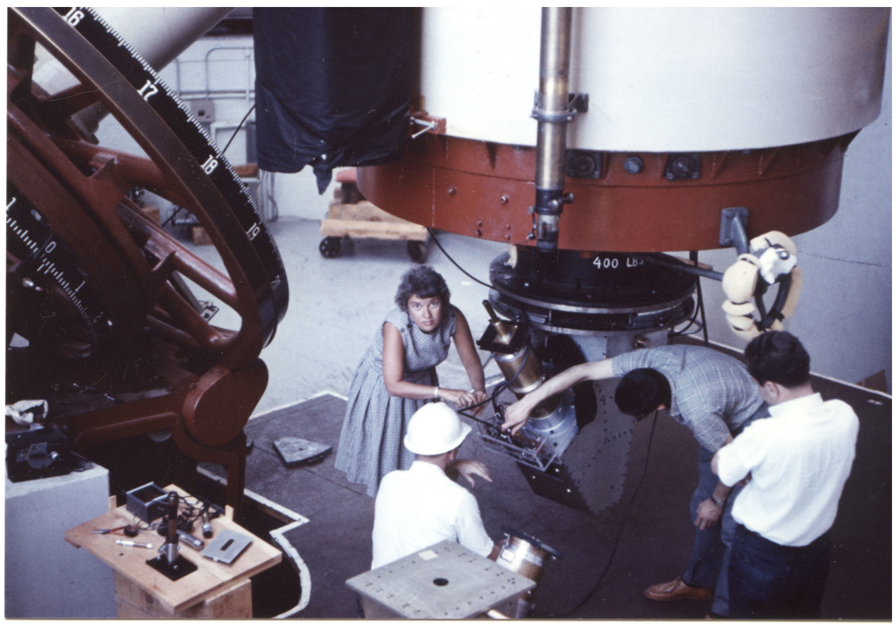
Galactic Rotation Curves

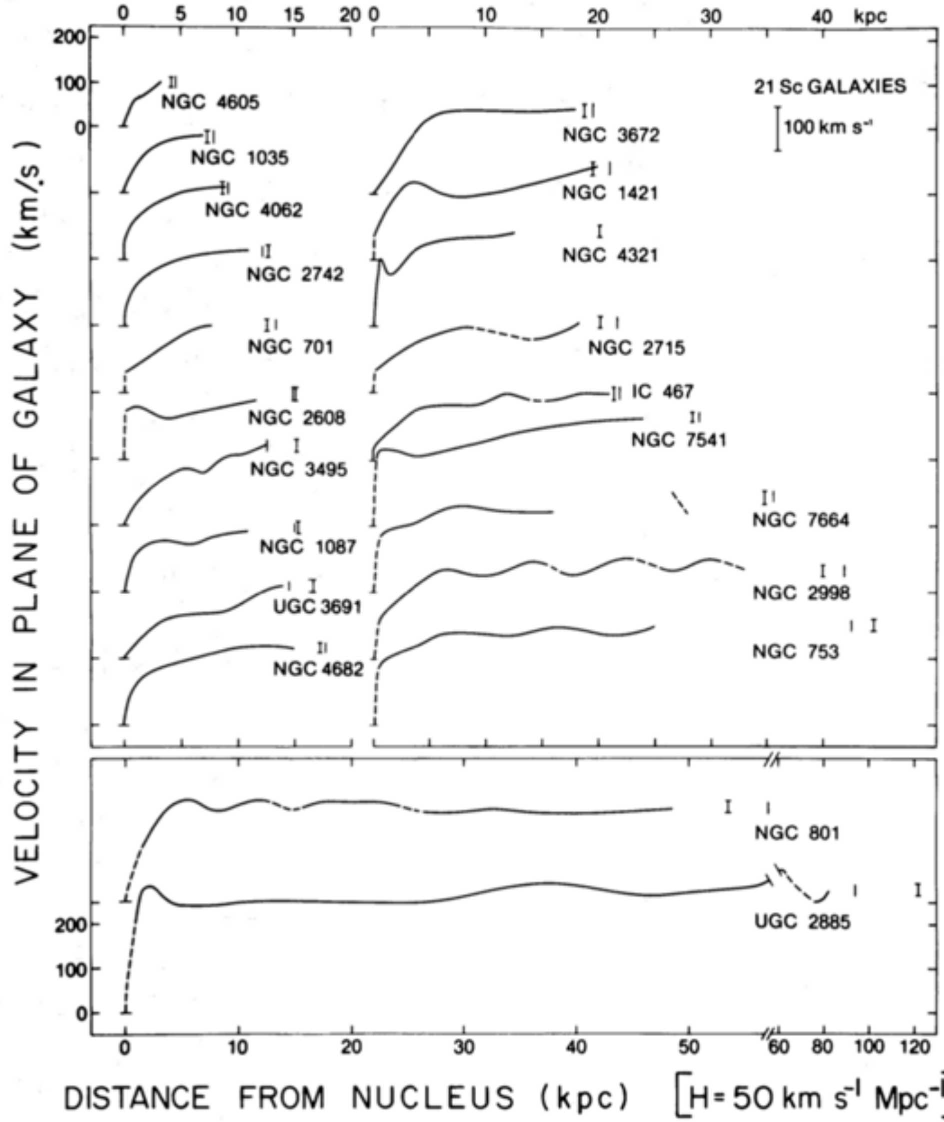
In the 1970's, Rubin, Ford Robinson and others measured the speeds of stars in Andromeda as a function of radius and found they were moving too fast for the amount of visible matter.



Their hypothesis was that the visible stars were surrounded by a halo of dark matter extending far past the visible matter.

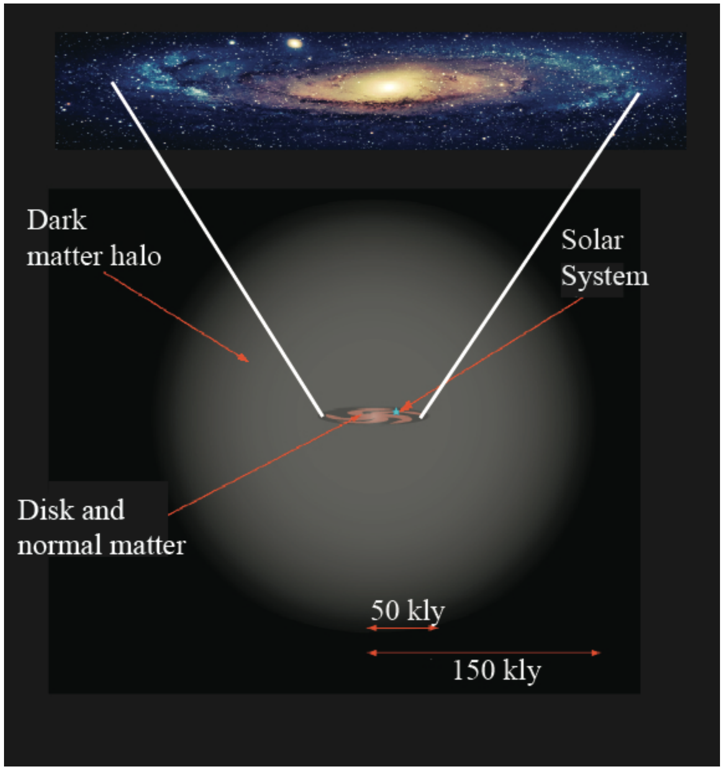
Measurements of rotation curves continued and essentially every galaxy was found to have 90% dark matter





Connection to particle physics

In the early 1980's, theorists found supersymmetry theory predicted neutral particles with 10-1,000 proton masses that could be dark matter.

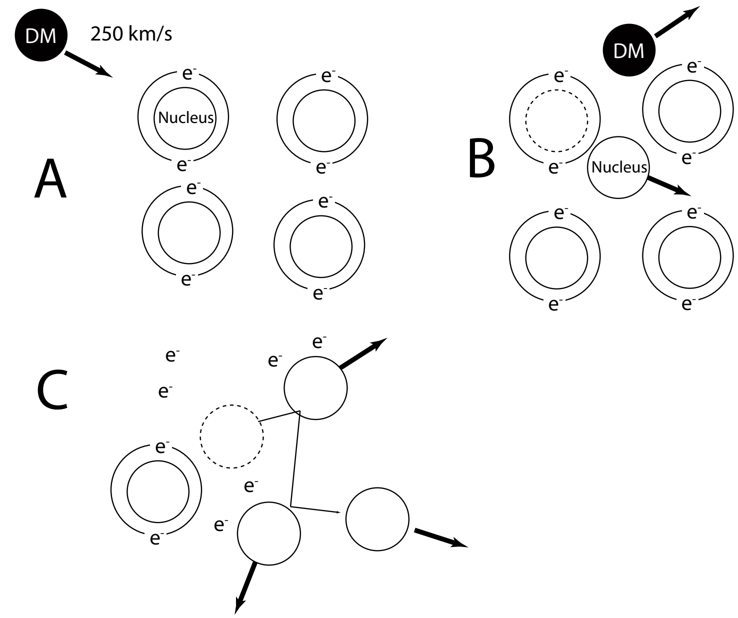


Weakly Interacting Massive Particles (WIMPs).

Other candidates: axions, primordial black holes.

Experiments

WIMP hits a nucleus in an atom, causing it to recoil, detect the energy released in the recoil. Few recoils per kilogram per year.



Fake (background) signals a HUGE problem – gamma rays from material, cosmic rays, and radon case could of fake DM signals at 10,000 times DM rate.

Experiments had to operate 2 km below ground and all the materials had to be screened for radioactivity.

St. Gotthard Road Tunnel

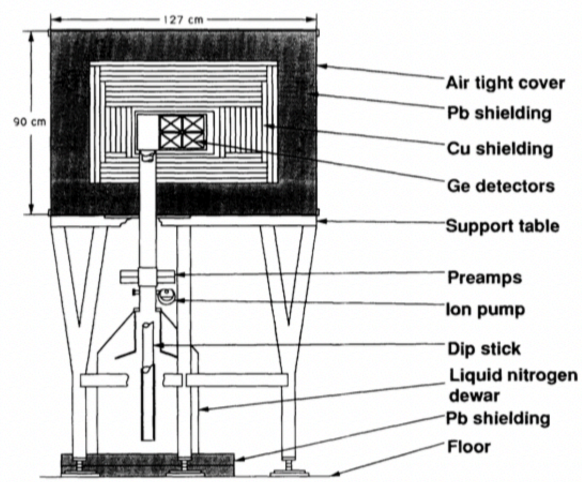
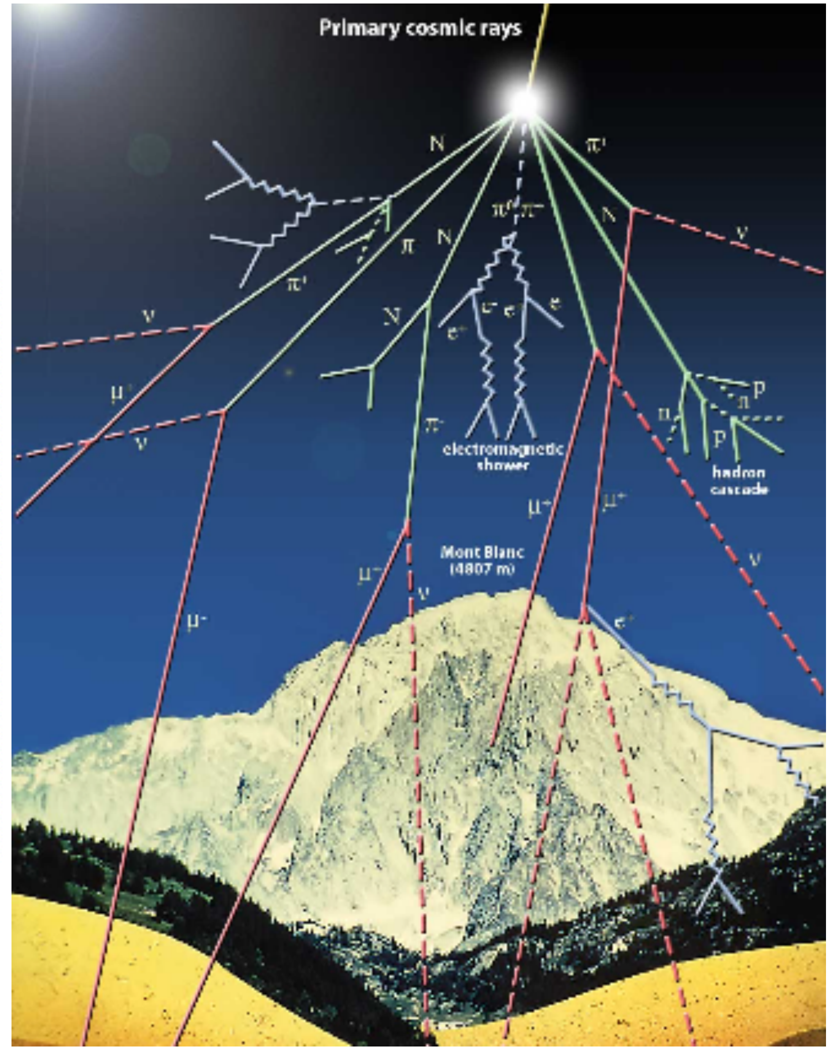
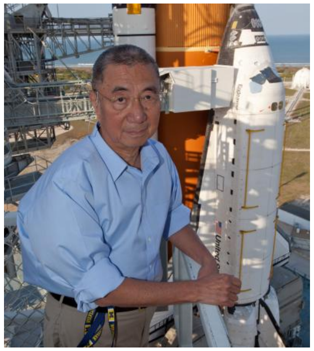


FIG. 1. Schematic view of the experimental setup showing the eight-crystal detector and its shielding.



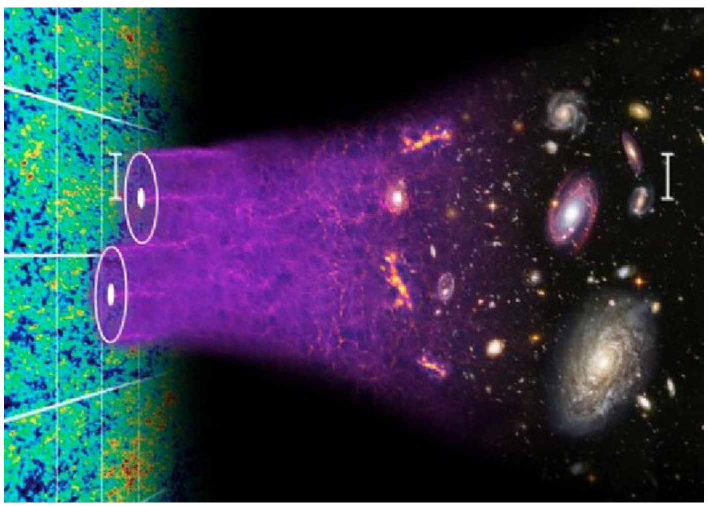
Current

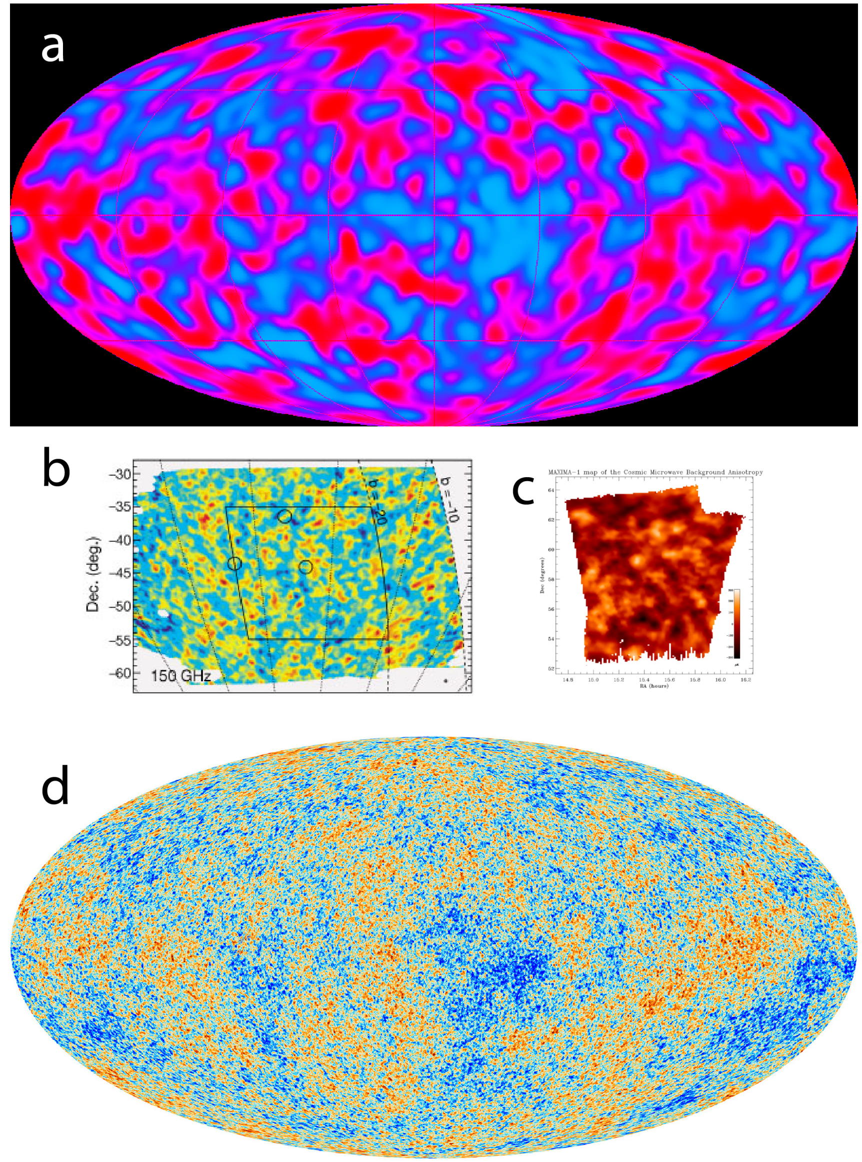
Largest experiment is Xenon1t, with Xenon10t coming. To date, no experiment has definitive proof of observing dark matter on Earth or in space.



CMB

All sky maps of the CMB show patches where excess DM concentrates. The patches seed the formation of galaxy clusters.

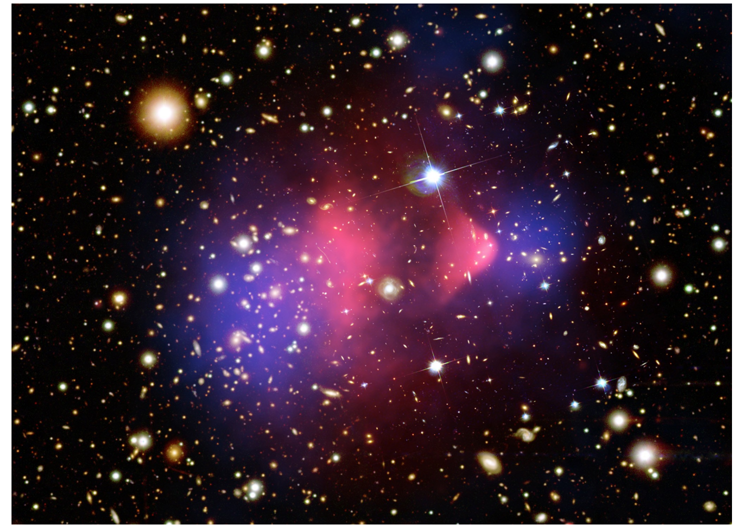


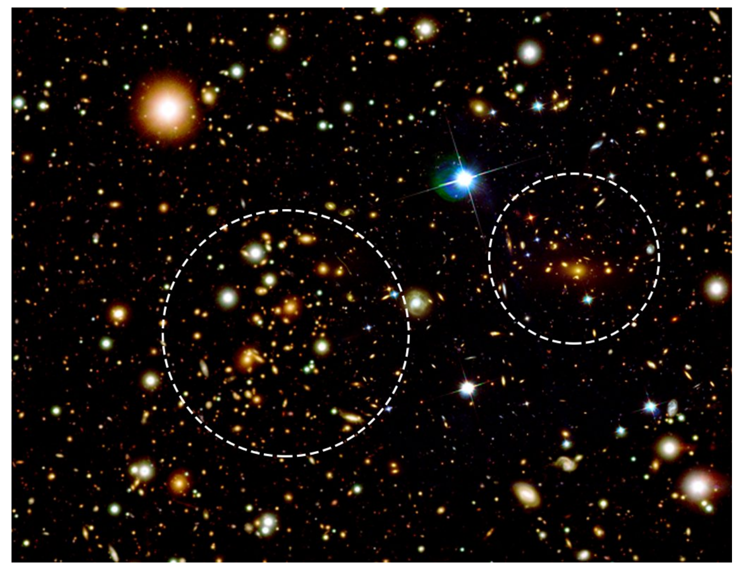


Bullet Cluster

Two clusters of about 25 galaxies each passed through each other. The gas between the galaxies interacted, giving off X-rays. The DM distorted the images of galaxies behind the cluster and shows the DM separated from the gas.

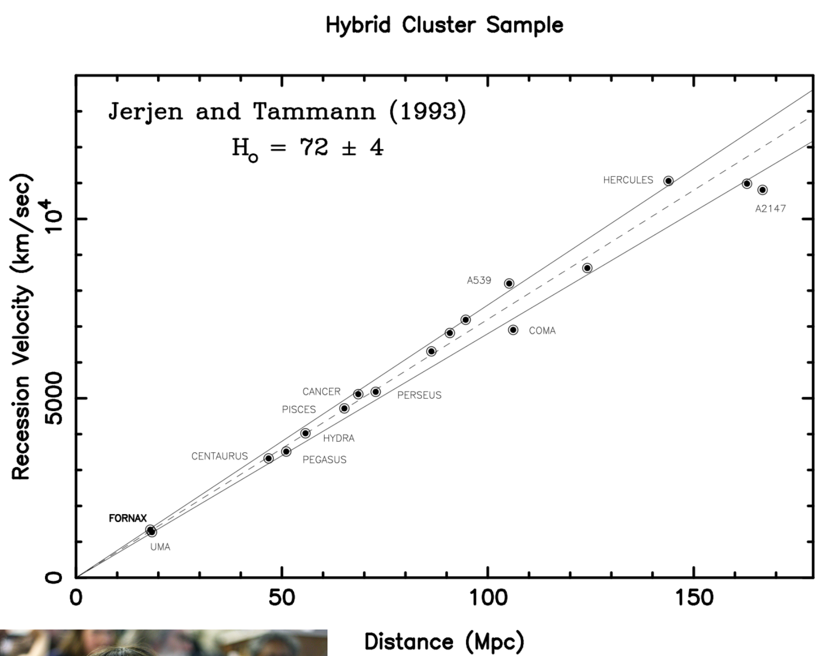
Other examples…





5 m Break

Dark energy



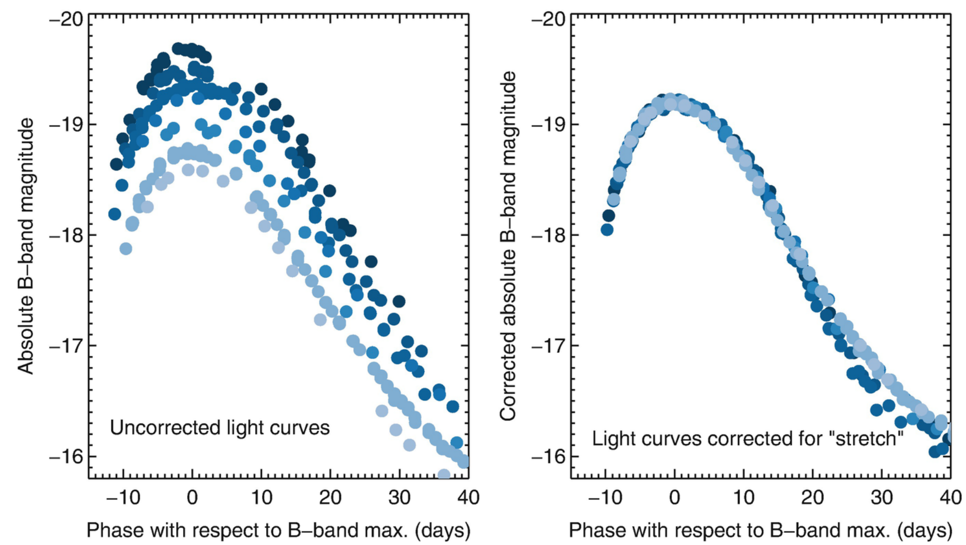
Hubble law measurements continued using Cepheids and, later, galaxies sizes (statistics very tricky).

To go further, need an astrophysical object of known lights output, link the Cepheids, bright enough to be seen 6 Gly away

Type 1A Supernovas

In a binary star system, one star burns its hydrogen until it collapses to a white dwarf with one Solar mass in one Earth radius.

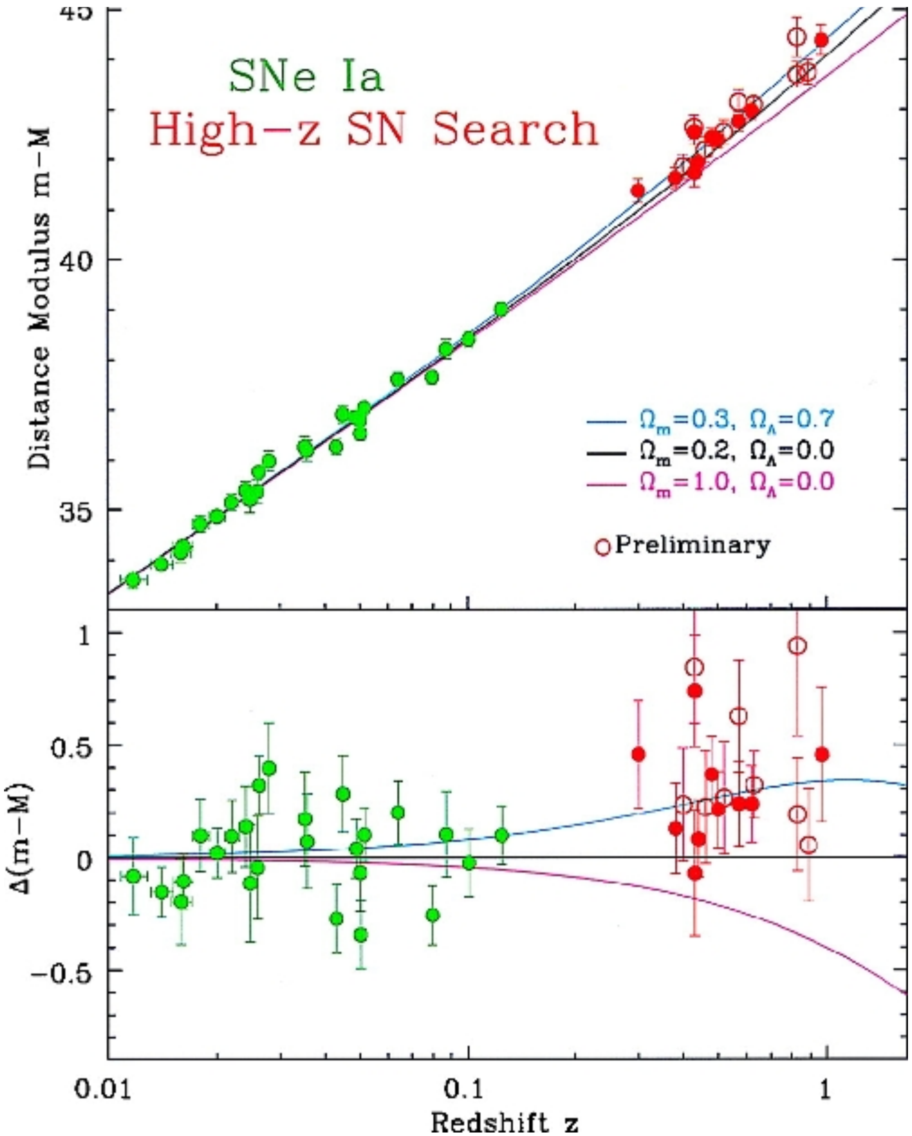
It’s intense gravity pulls in mass from its partner until it reaches 1.44 solar masses, then it explodes.



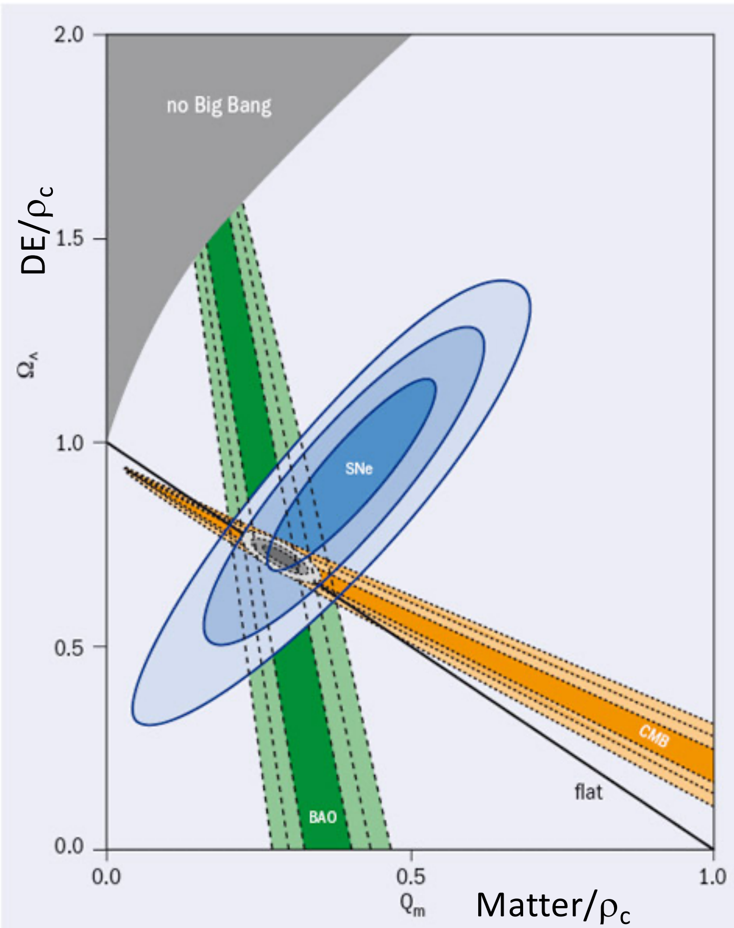
Hubble Diagram

The Type 1A SN's are visible half way across the universe and, with observations over weeks, have a predictable light output.

Measurements of distant Type 1A's in the late 1990's indicated they were dimmer than expected from Hubble's law.



Dark Energy



The dimness of the distant SNs was best explained by dark energy causing the universe to expand more rapidly starting 6 Gy ago.

Dark energy, a constant energy density in the universe, was a natural explanation.

Combining CMB, SN, and other data gave a consistent picture, SM: 4%, DM: 23%, DE: 73%,

Dark Energy

Not a lot to know:

$$\begin{pmatrix}\text{Structure of}\\ \text{space} - \text{time}\\ \text{at a point}\end{pmatrix} = G\begin{pmatrix}\text{Total density}\\ \text{of matter}\\ \text{at the same point}\end{pmatrix}$$

Dark Energy

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Summary

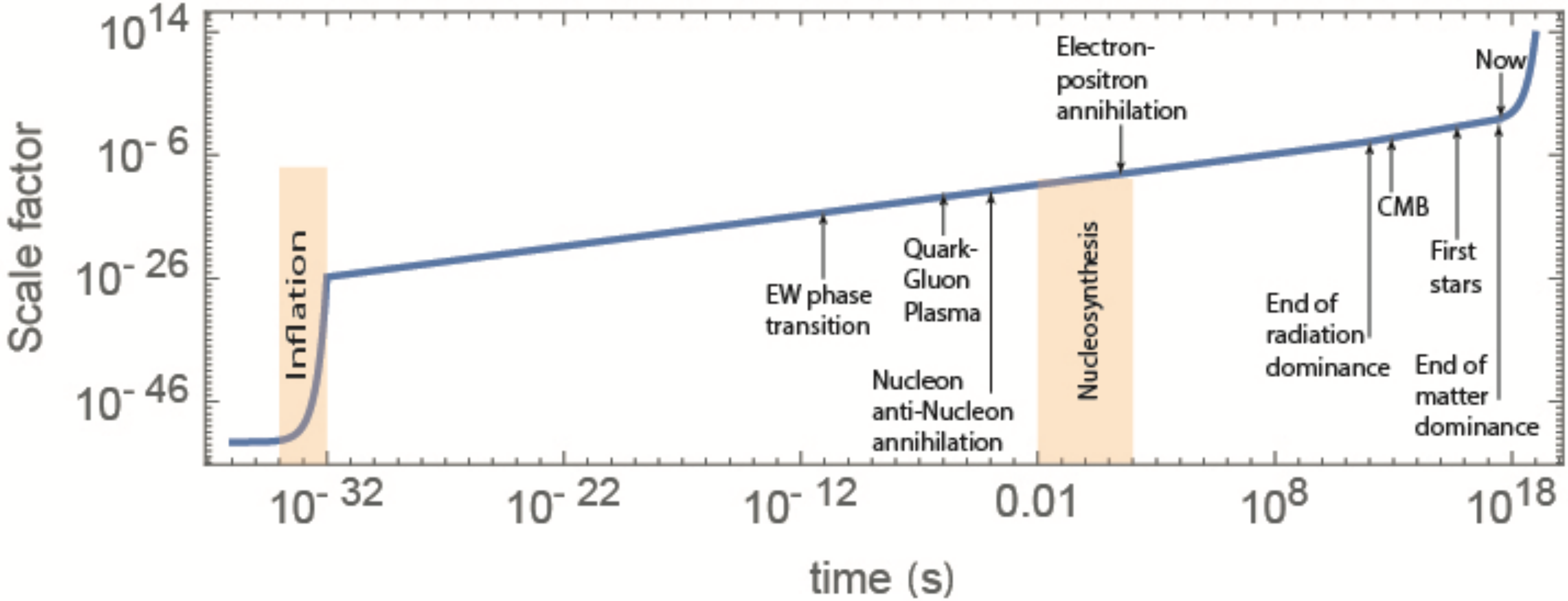
The Universe

Putting together

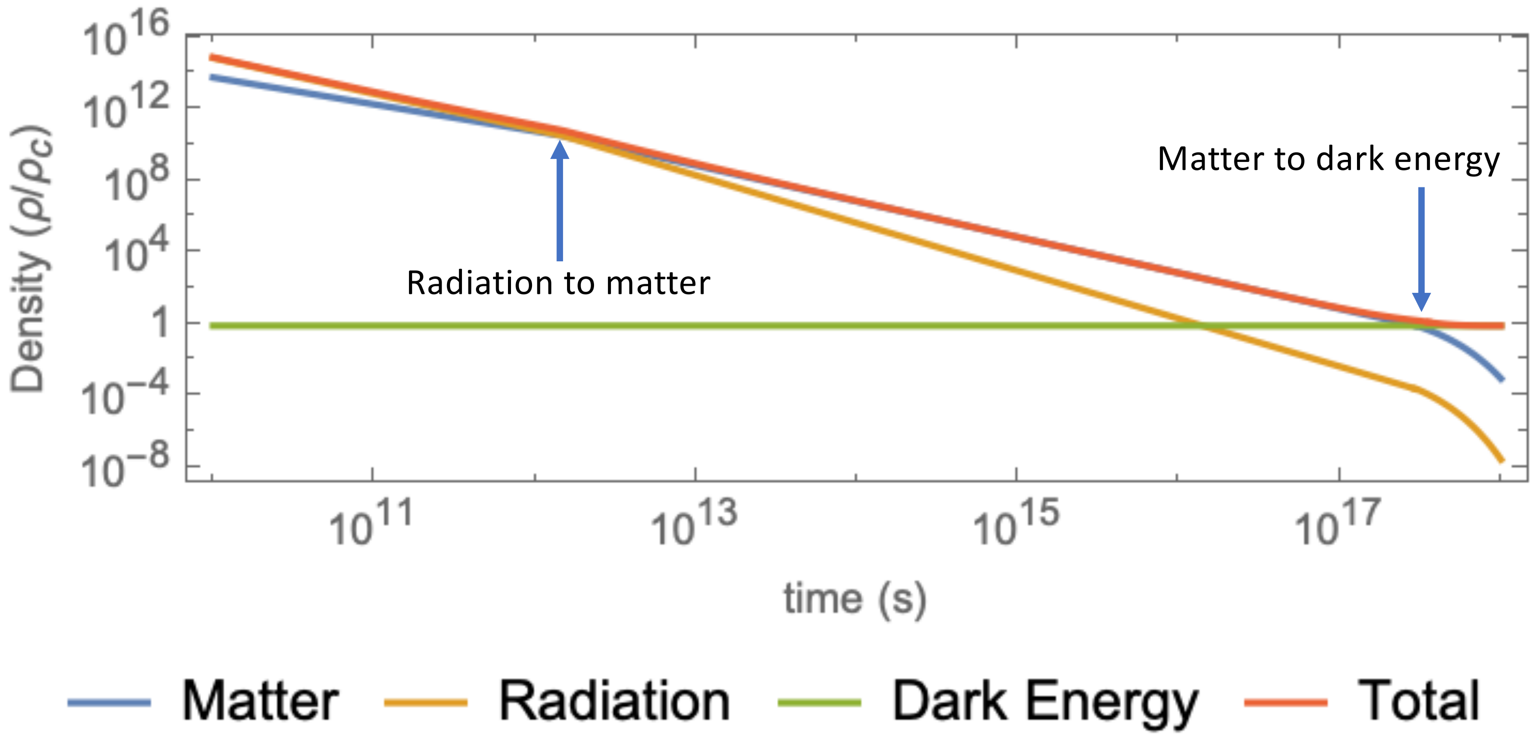
- Inflation (not a theory, but simple parameterization based on physical ideas)
- The Standard Model of Particle Physics
- Big Bang Nucleosynthesis
- Dark Matter
- The Cosmic Microwave Background
- Dark Energy

gives a complete picture of the large scale structure and history of the universe

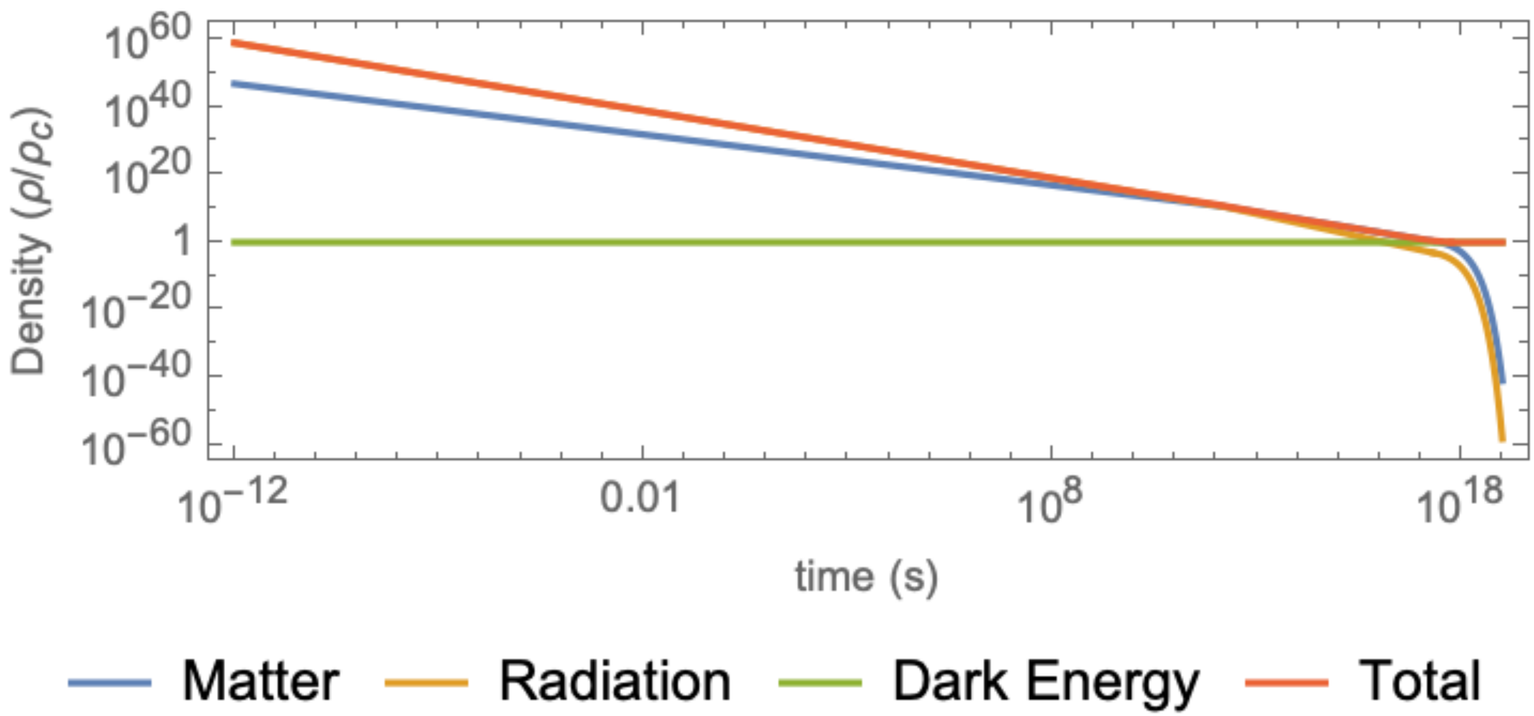
Expansion – scale factor determined by density



Density determined by scale factor

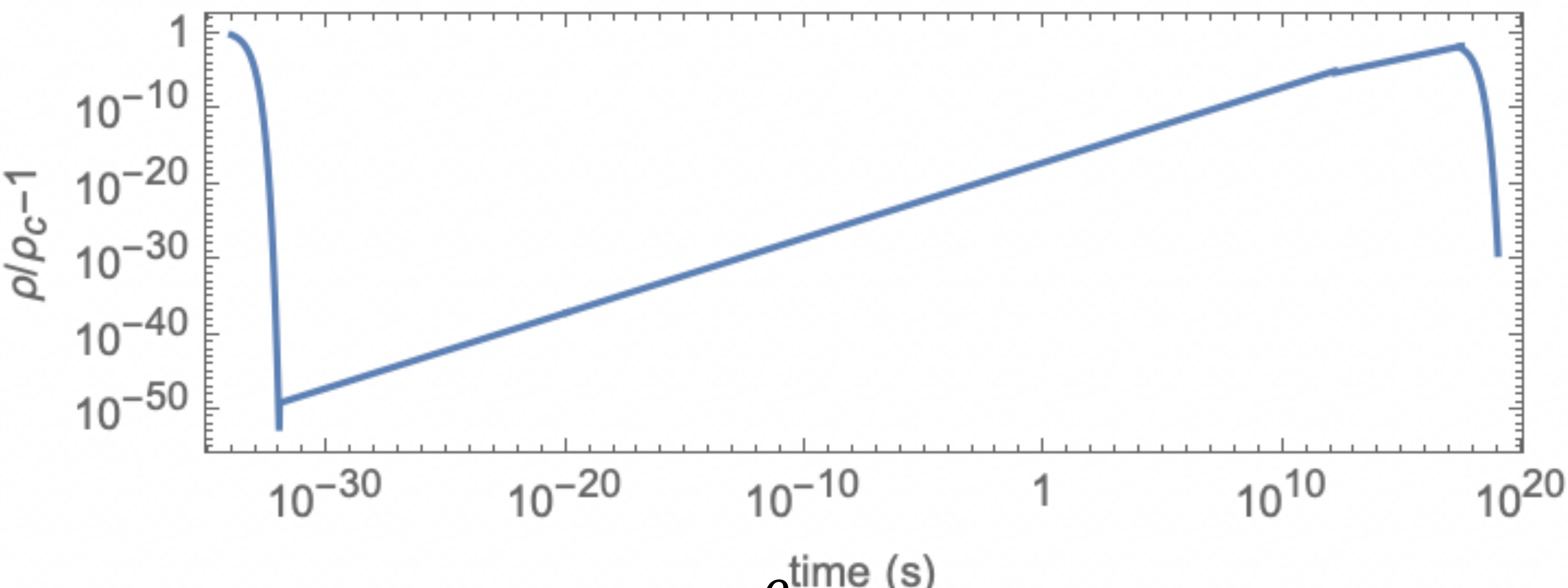


Density



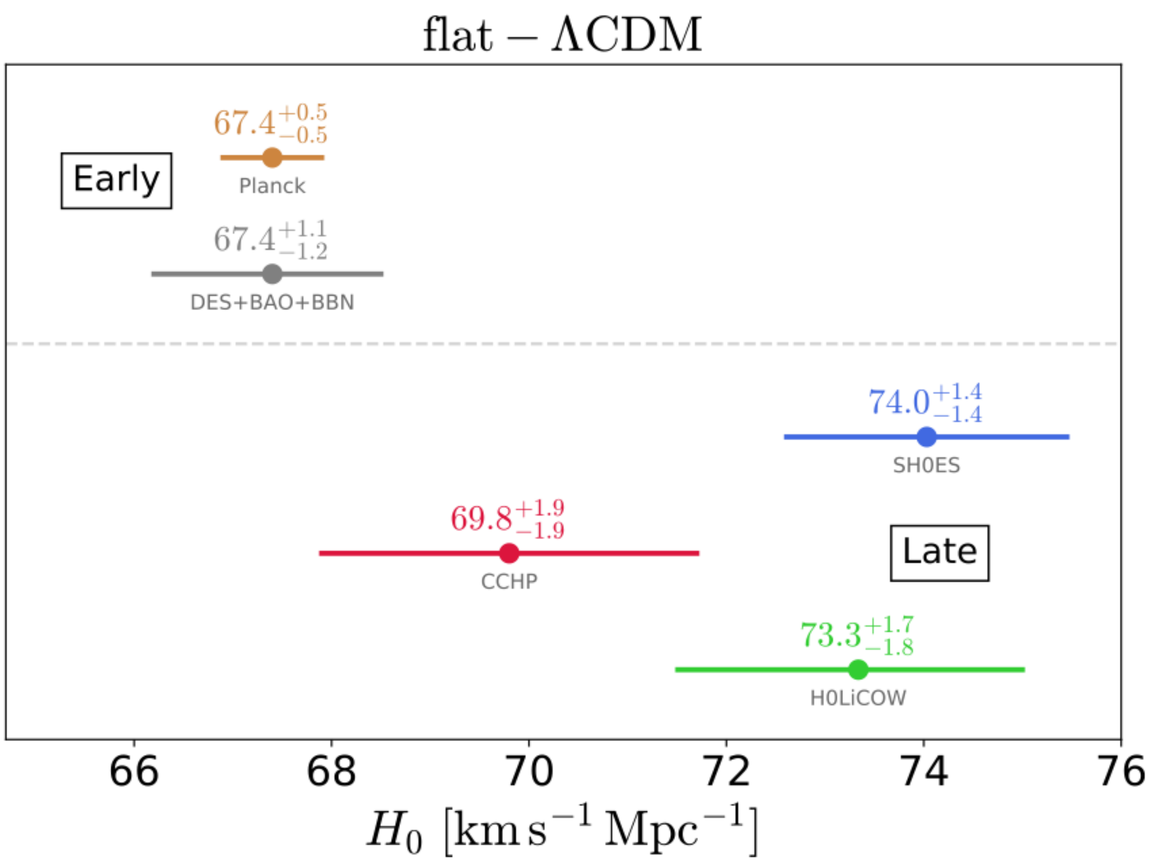
10^{60}
10^{40}
10^{20}
1
10^{-20}
10^{-40}
10^{-60}
Density (ρ/ρ_c)
10^{-12}
0.01
10^{8}
10^{18}
time (s)
Matter
Radiation
Dark Energy
Total

Inflation and density – deviation from critical density proportional to (1/time rate of change of scale factor)^2



Current measurement: $\frac{\rho}{\rho_c} = 1.01 \pm 0.006$

Hubble Constant



The struggle continues…

Numbers

Age of universe	13.797 +/- 0.023 Gy
Hubble constant	67.4 +/- 1.0 km/s/Mpc (Far)
	72.4 +/- 1.1 km/s/Mpc (Near)
Baryon fraction	0.0493 +/- 0.006
Dark matter fraction	0.265 +/- 0.007
Matter fraction	0.315 +/- 0.007
Dark energy fraction	0.685 +/- 0.007
Helium fraction	0.245 +/- 0.004
Baryon to photon ratio	5.8-6.5 x 10^{-10}

Final Thoughts – Weinberg 1977

It is very hard to realize that this all is just a tiny part of an overwhelmingly hostile universe. It is even harder to realize that this present universe has evolved from an unspeakably unfamiliar early condition, and faces a future extinction of endless cold or intolerable heat. The more the universe seems comprehensible, the more it also seems pointless.

But if there is no solace in the fruits of our research, there is at least some consolation in the research itself. Men and women are not content to comfort themselves with tales of gods and giants, or to confine their thoughts to the daily affairs of life; they also build telescopes and satellites and accelerators, and sit at their desks for endless hours working out the meaning of the data they gather. The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy.

JFK, Rice Commencement – "…But why, some say, the Moon? Why choose this as our goal? And they may well ask, why climb the highest mountain? Why, 35 years ago, fly the Atlantic? Why does Rice play Texas?

We choose to go to the Moon. We choose to go to the Moon…We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our energies and skills,…"

Final Thoughts - 2021

Humans have managed to comprehend the early universe using logic, observation, and perseverance – cosmology is an endeavor that inspires us to tackle our immediate problems the same way.

The goal of this course has been to gain an appreciation of cosmology and take inspiration for our own work.

Having this course has been a lifeline for me in the last weeks.

Thank you for your attention and enthusiasm.