Weighing the Universe, and the need for dark matter

Constraints on the baryon density parameter Ω_B

The importance of measuring the **total** density parameter Ω

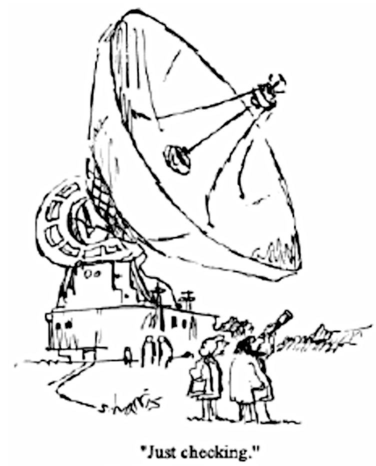
Measuring the mass of the Universe

- Mass to light ratio
- Mass of luminous stars
- Masses of galaxies and galaxy clusters

Non-baryonic dark matter

– why ?

- This week: Chapter 14-15



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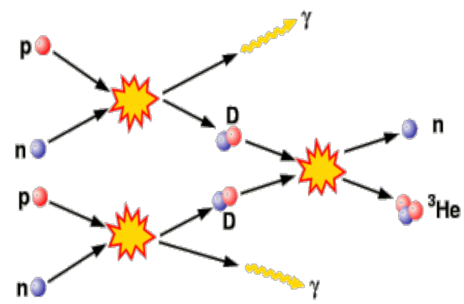
Big Bang Nucleosynthesis

- As the universe cools, the matter content changes - new particles are formed out of the preexisting ones, such as protons and neutrons forming out of quarks.
- From about one second to a few minutes cosmic time, when the temperature has fallen below 10^{10}k, protons and neutrons combine and form certain types of atomic nuclei. This phase is called **Big Bang Nucleosynthesis.**
- While the early universe is totally unlike our everyday world, the basic nuclear physics at the appropriate energies is well understood and allows detailed predictions.

Nucelosynthesis in the BIG BANG Era

- After the universe cools down the particles interact via nuclear reactions
- While these are proceeding, supply of "free" neutrons is decaying away (neutron half life is 611sec).
- So, speed at which nuclear reactions occur is crucial to final mix of elements
- What factors determine the speed of nuclear reactions?
  - Density (affects chance of p/n hitting each other)
  - Temperature (affects how hard they hit)
  - Expansion rate of early universe (affects how quickly everything is cooling off and spreading apart).

one of many sets of reactions



http://www.einstein-online.info/spotlights/BBN article by Achim Weiss,

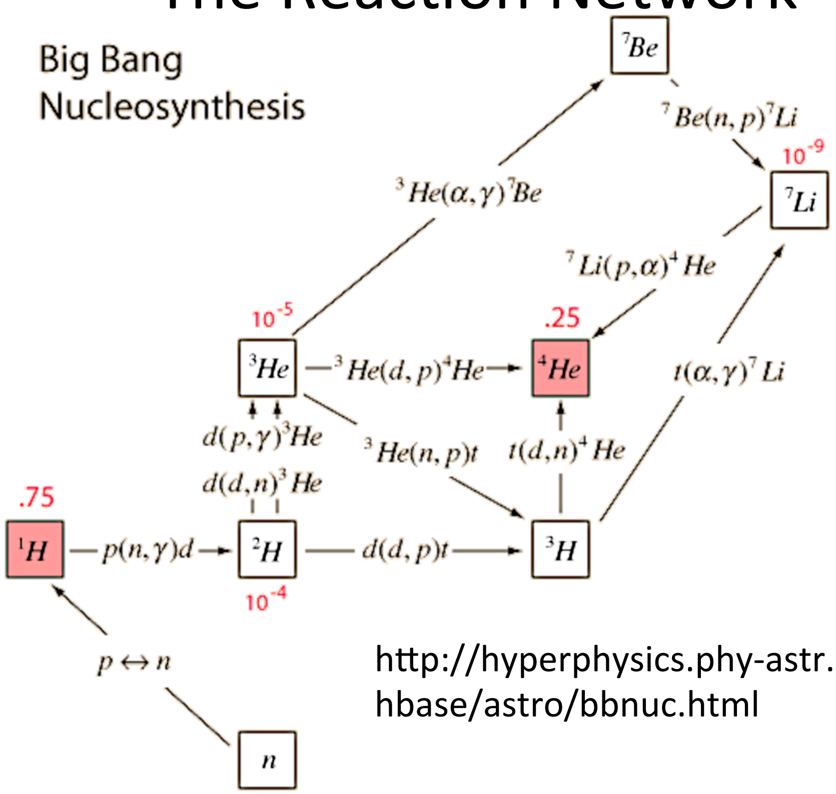
*No*t the Big Band Era

GLENN MILLER and HIS ORCHESTRA

BBN Calculations

- Full calculations are complex. Need to:
  - Work through all relevant nuclear reactions
  - Take account of decreasing density and decreasing temperature as Universe expands
  - Take account of neutron decay
- Feed this into a computer…
  - Turns out that relative elemental abundances depend upon the quantity $\Omega_B H_0^2$
- Here, Ω_B is the density of the baryons (everything made of protons+neutrons) relative to the critical density, H_0 is the Hubble constant
- $\Omega_B = \rho_B/\rho_{crit} = \rho_B/[3H_0^2/(8\pi G)]$

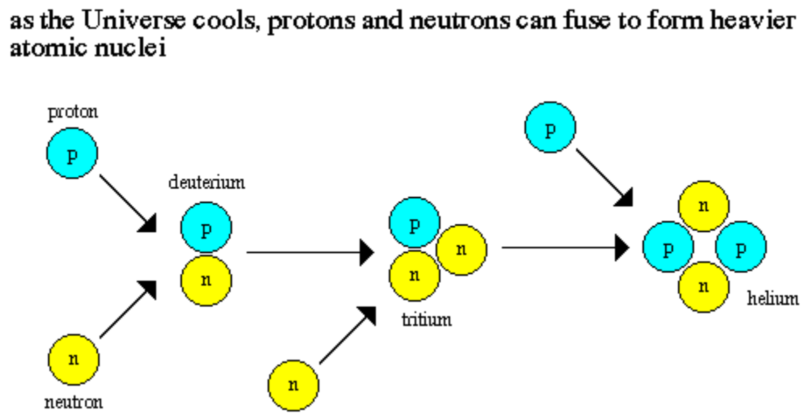
The Reaction Network

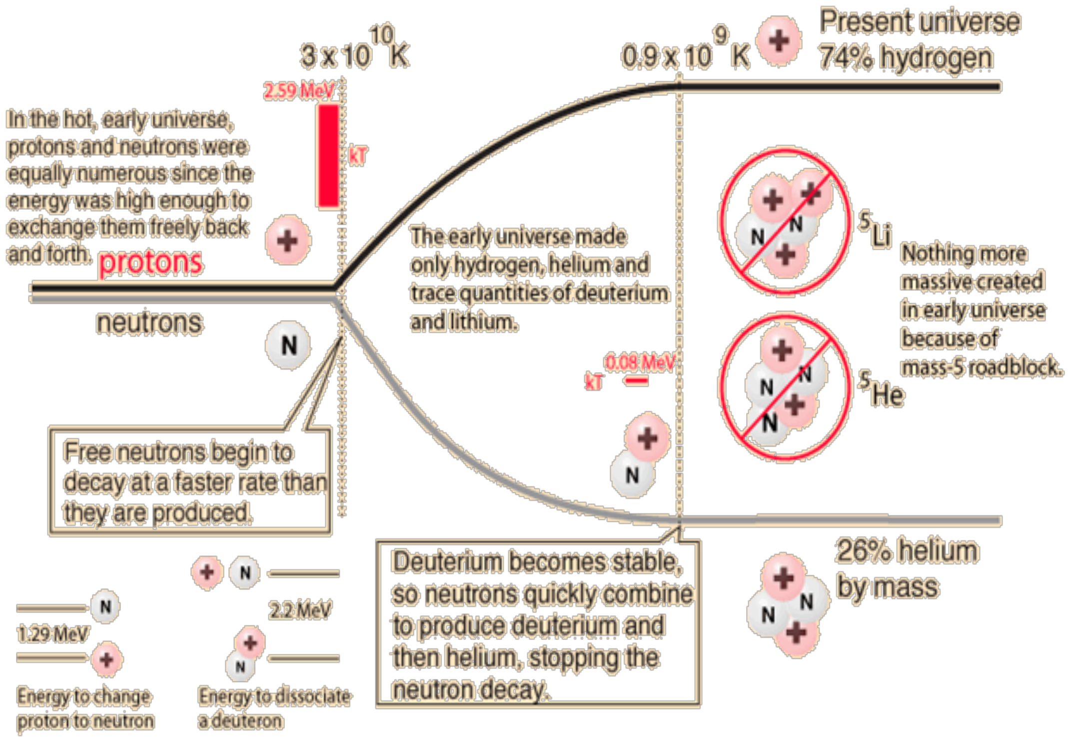


http://hyperphysics.phy-astr.gsu.edu/hbase/astro/bbnuc.html

What Results?

- Ratio of hydrogen to helium is extremely sensitive to the density of matter in the Universe (the parameter that determines if the Universe is open, flat or closed).
- The higher the density, the more helium produced during the nucleosynthesis era.
- The current measurements indicate that 75% of the baryonic mass of the Universe is hydrogen, 24% helium and the remaining 1% in the rest of the elements

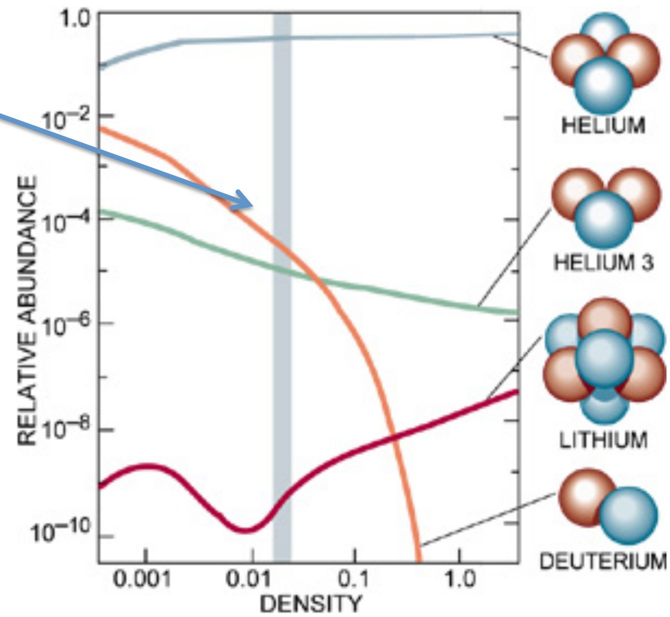




http://hyperphysics.phy-astr.gsu.edu/hbase/astro/bbnuc.html

Dependence of Elemental Abundances on $\Omega_B h^2$

Observations



Astronomers measure the amounts of He^4, He^3, Li^7 and D in the universe by a wide variety of means

All the measurements lie in the gray vertical line area

M.White UCB

- Astronomers use the spectra of stars and gaseous nebulae to measure abundances of elements
  - These need to be corrected for reactions in stars
- By measuring the abundance of H, D, ^3He, ^4He, and ^7Li, we can test the consistency of the big bang model -- are relative abundances all consistent?
- Use the results to measure $\Omega_B h^2$

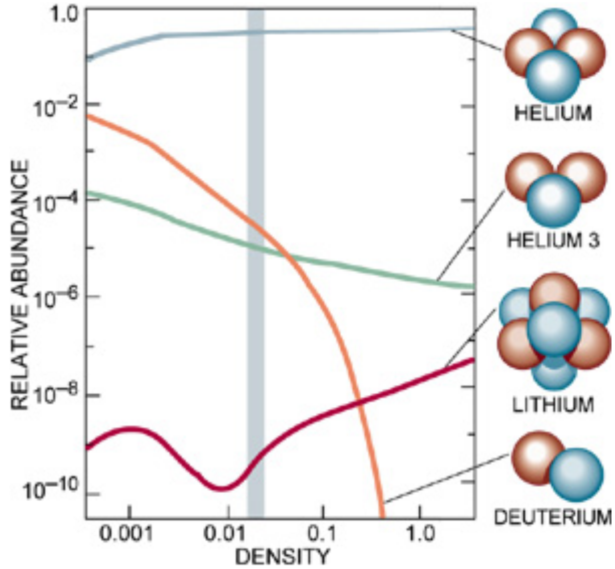
- Best fit gives $\Omega_B h^2 \approx 0.019$
- If H_0=72km/s/Mpc, h=0.72

  $\Omega_B \approx 0.04$

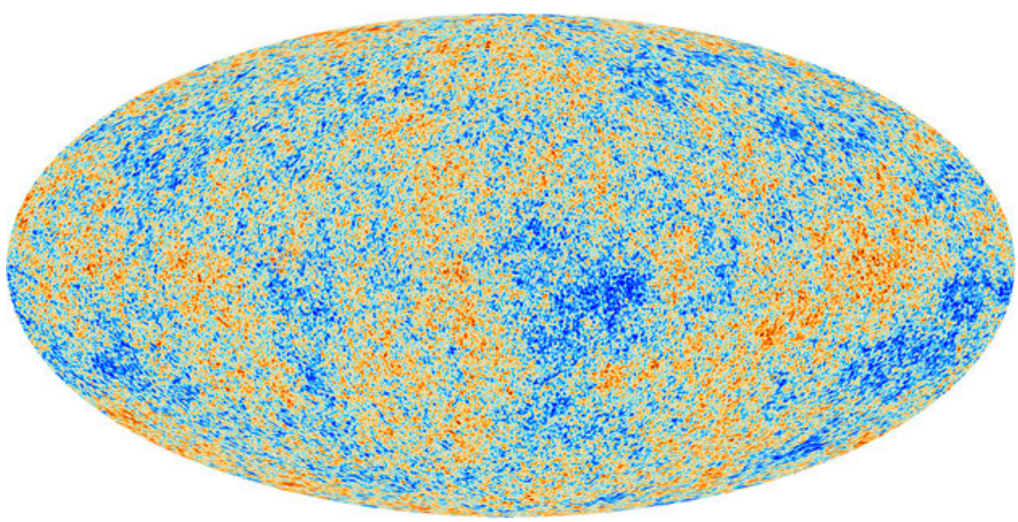
This is far below Ω=1!

- Baryons **alone** would give **open universe**
- remember need $\Omega \geq 1$ for a closed universe.

Results



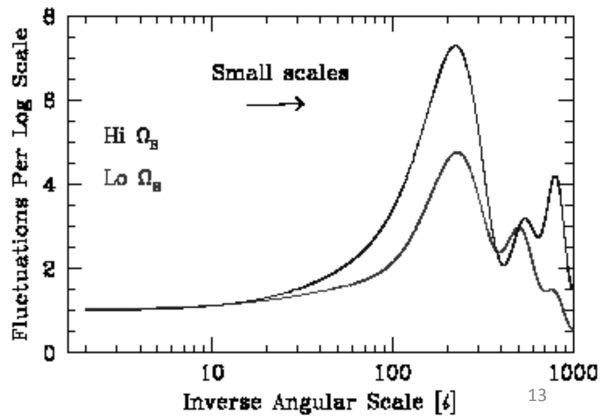
Planck Map 2014



http://www.esa.int/Our_Activities/Space_Science/Planck/Planck_and_the_cosmic_microwave_background

Effect of baryons on CMB

- Baryonic fraction changes the amplitude of the peaks in the power spectrum of the CMB
- comparing the heights of the first two peaks gauges the relative strengths of gravity and radiation pressure in the early universe.
- The observed ratio indicates that baryons had about the same energy density as photons at the time of recombination and hence constitute about 5 percent of the critical density today.



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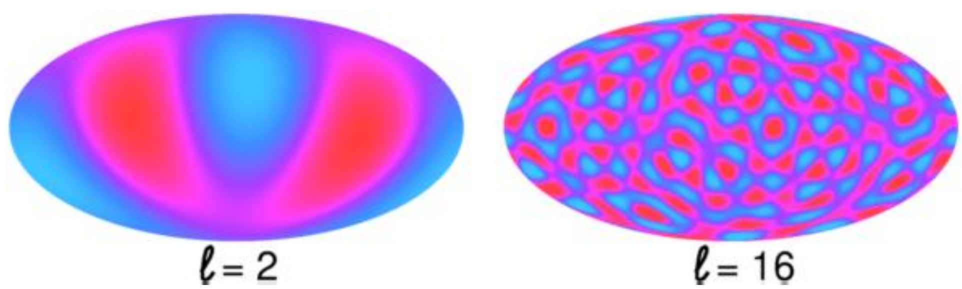
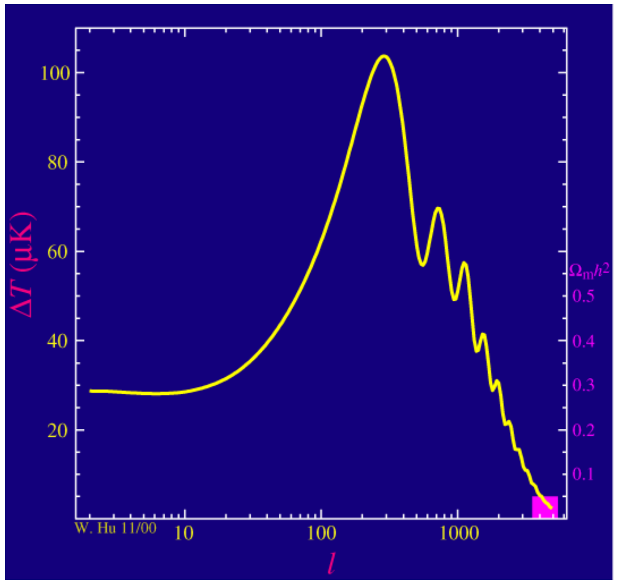
Power Spectrum of CMB

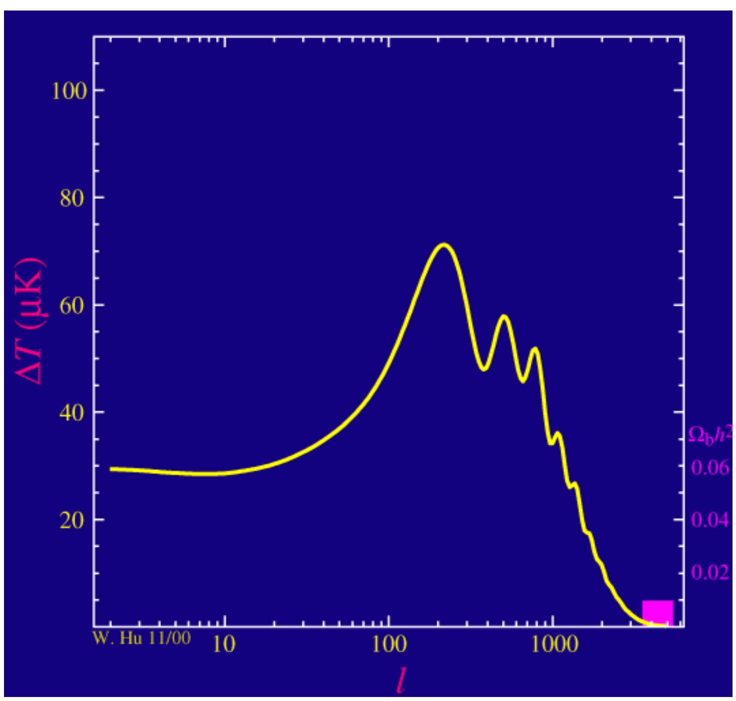


- A representation of the bumps in the CMB
- Angular power spectrum is a plot of how much the temperature varies from point to point on the sky (the y-axis variable) *vs.* the angular frequency *l* (the x-axis variable).
- ℓ =10 means that there are ten cycles in the fluctuation around the whole sky, while ℓ=100 means that there are 100 cycles around the sky.

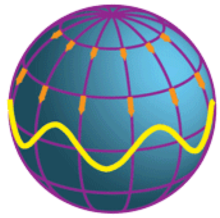
http://www.astro.ucla.edu/~wright/CMB-DT.html

How the Spectrum of the CMB Changes When $\Omega_m h^2$ changes





http://background.uchicago.edu/~whu/

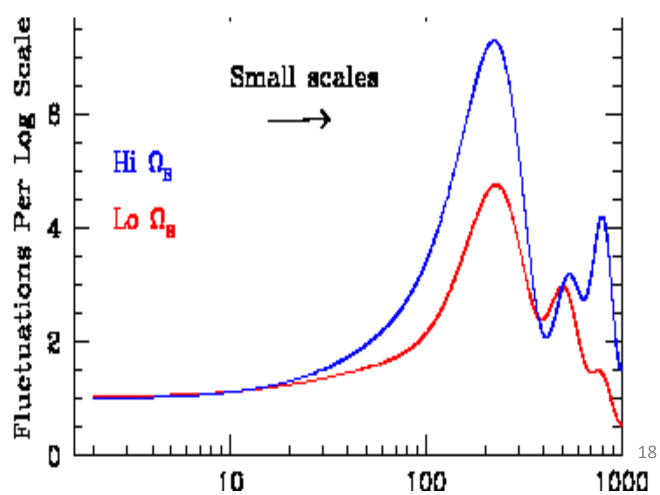


Effect of baryons on CMB

- The result is in spectacular

agreement with the number derived from studies of light element synthesis by nuclear reactions in the infant universe Hu and White 2004

Scientific American .

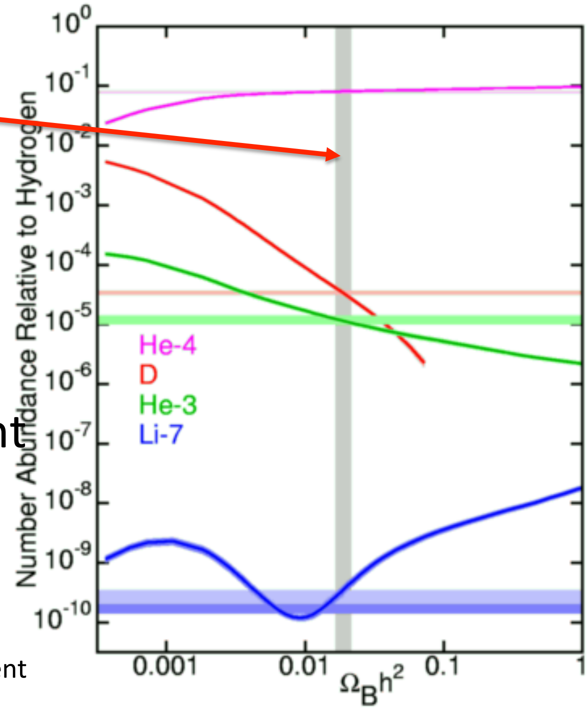


Value from CMB

Ω_b=0.049 +/-0.00028

if fix the value of H_0= 69

Two completely independent and different methods come to the exact same conclusion



Error in Li measurement

Error in He^3 measurement

- http://www.astro.ucla.edu/~wright/BBNS.html

So… where are we?

- We have described the first ~10 mins of the Universe's life…
- Origin of matter (well within first second)
- Origin of H,He,Li (within first few mins)
- Universe continues to expand and cool…

  t=70,000yr : Radiation ceases to be dominant over matter

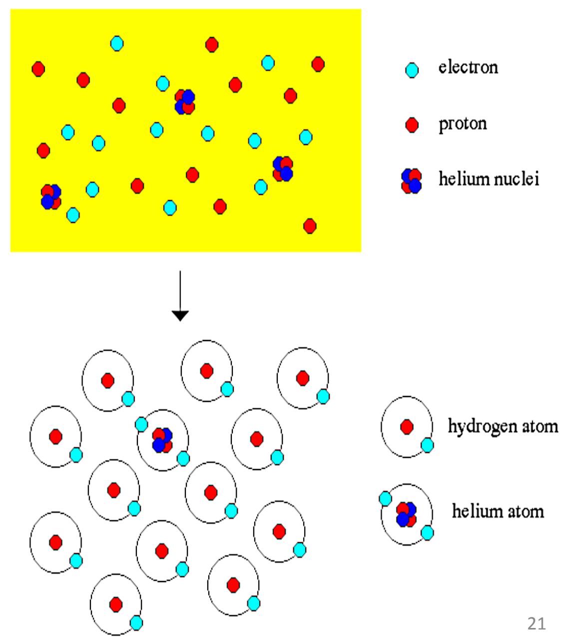
  t=380,000yr : Universe cools to the point where neutral hydrogen can form
- EPOCH OF RECOMBINATION

  Universe suddenly becomes transparent… photons free stream, redshift and are observed today as the CMB!!
- Until now, there's essentially no structure in the Universe. To discuss emergence of structure, we need to look harder at contents of Universe

Universe keeps expanding and cooling until electrons can be bound to hydrogen and helium

Recombination

As the Universe expands and cools, protons and electrons combine to form hydrogen (the most abundant element). And helium nuclei combine with electrons to form helium atoms. This process is called recombination.



http://abyss.uoregon.edu/%7Ejs/ast123/lectures/lec21.html

- Remember the **density parameter** as $\Omega=\rho_{total}/\rho_{crit}$
- Value of Ω very important for determining the geometry and dynamics (fate) of the Universe
- Constraints from nucleosynthesis

To get observed mixture of elements, we need the **baryon density parameter** to be $\Omega_B \approx 0.0.045$

- If there is only baryonic ("normal") matter in the universe, then this tells us that $\Omega \approx 0.045$.
- Thus, the Universe would be open (hyperbolic)

Where and What is the Mass in the Universe?

- Start with the accounting of all forms of mass/ energy in the Universe…
- Baryonic matter- stars, gas, dust
- Other types of matter?
- Radiation

I : THE MASS OF STARS IN THE UNIVERSE

Stars are the easiest things to see and study in our Universe…

Can study nearby stars in detail

Can see the light from stars using "normal" optical telescopes even in distant galaxies.

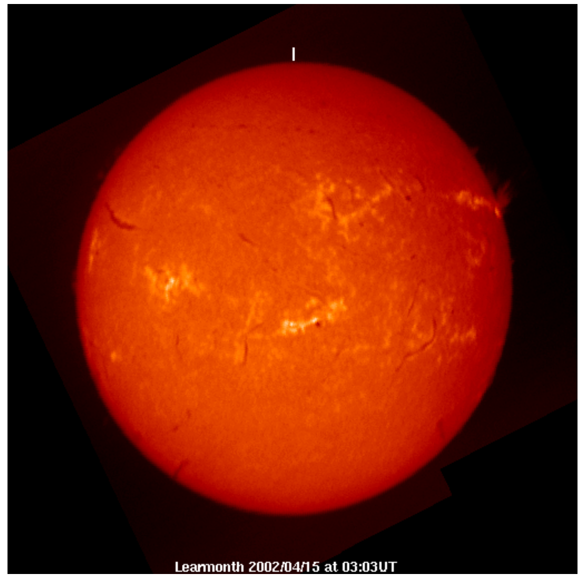
Of course, what we see is the light, and what we're interested in is the mass…

need to convert between the two using the mass to-light ratio M/L.

The Sun

- M_{sun}=2x10^{30} kg
- L_{sun}=4x10^{26} W
- Actual numbers not very instructive…
- From now on, we will reference

mass to- light ratios to the Sun (M_{sun}/L_{sun}).



But life is more complicated than that…

- Much evidence shows that Ω_M may be 5 or 10 times larger than Ω_B , yet still Ω_M <1
- Additional evidence suggests that nevertheless, the Universe is flat, with $k = 0$ so $\Omega_k = 0$
- (i.e. neither hyperbolic nor spherical geometrically)
- This implies the cosmological constant Λ must be nonzero…and in fact, there is observational evidence for accelerating expansion!
- We'll start with the accounting of all forms of mass in the Universe…

Other stars

- Different types of stars have different mass-to-light ratios
  - Massive stars have small M/L (they shine brightly compared with their mass).
  - Low-mass stars have large M/L (they are very dim compared with their mass).
  - We're interested in an average M/L
- Averaging regular stars near the Sun, we get $M/L \approx 3\ M_{sun}/L_{sun}$

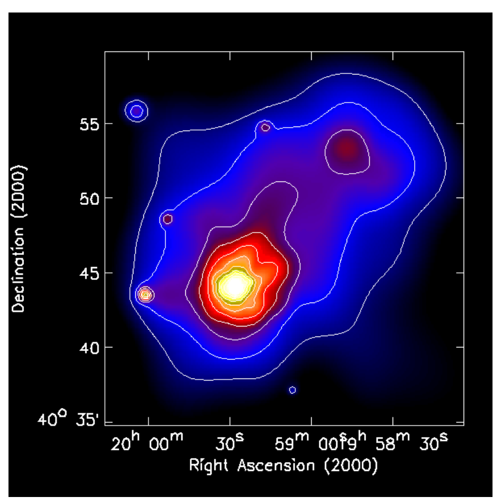
- But, we also need to include effect of "dead" stellar remnants…
  - white dwarfs, neutron stars, black holes.
- …and also sub-stellar mass objects
  - Called "brown dwarfs"
  - Interior gravity is too low to compress gas and initiate fusion $\Rightarrow$ very low luminosity
- All of these have mass M, but very little light L.
  - They add to the numerator of the average M/L, but not to the denominator
  - Including the remnants and (smaller) brown dwarf contribution, this would increase the mass-to-light ratio for spiral galaxies to about

$$M/L \approx 7\ M_{sun}/L_{sun}$$

- So, we can add up the visible star light that we see in the Universe, and convert to a mass in stars (luminous and non-luminous).
  - We get $\Omega_L \approx 0.005\text{-}0.01$
  - **Comparing with $\Omega_B = 0.037$ from nucleosynthesis, we see that most baryons cannot be in stars…**

Where's the rest of the baryonic matter if it's not in stars?

- Galaxy clusters contain a lot of hot gas outside of individual galaxies
  - Gas temperature of 10-100 million K.
  - Can see it using X-ray telescopes.
  - Such gas contains a lot of the baryons
- The rest is believed to be in "warm/hot" (1 million K) gas in intergalactic space.



X-ray emission from the hot gas trapped in the Cygnus-A cluster

THE MASS OF GALAXIES

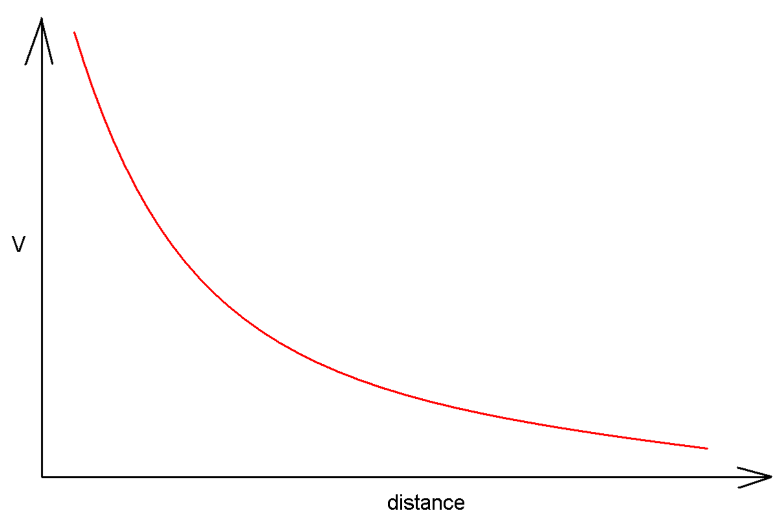
- We can also measure total mass of a galaxy using Kepler's/Newton's laws
- Remember that for planets orbiting Sun, square of period is proportional to cube of distance.

$$P^2 = \frac{R^3}{(GM_{sun}/4\pi^2)} = \frac{(2\pi R)^2 R}{GM_{sun}}$$

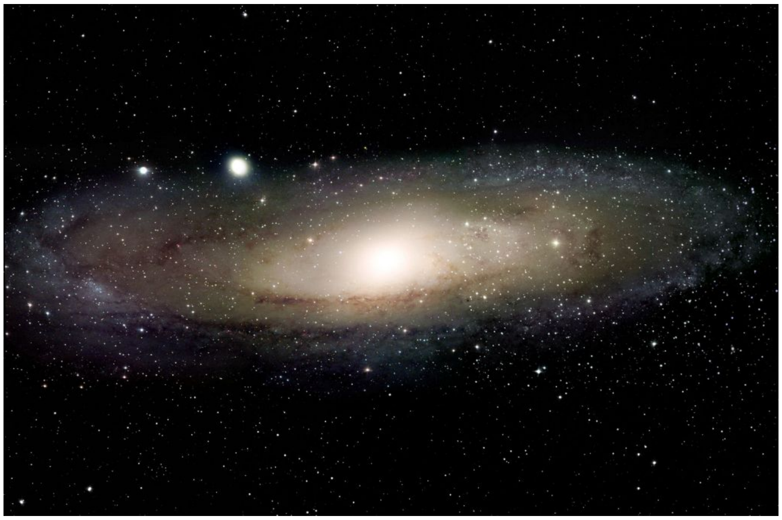
- Can rewrite this as

$$M_{sun} = \frac{(2\pi R/P)^2 R}{G} = \frac{V^2 R}{G} \qquad \text{or} \qquad V = \sqrt{\frac{GM_{sun}}{R}}$$

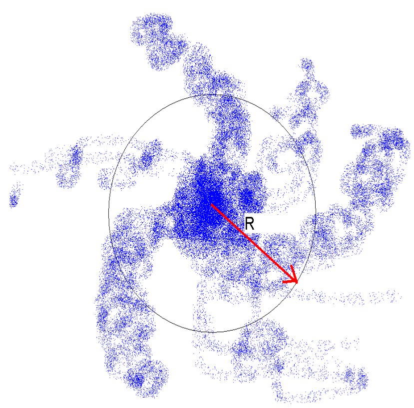
Velocity dependence on radius for a planet orbiting the Sun…



- Apply same arguments to a galaxy…

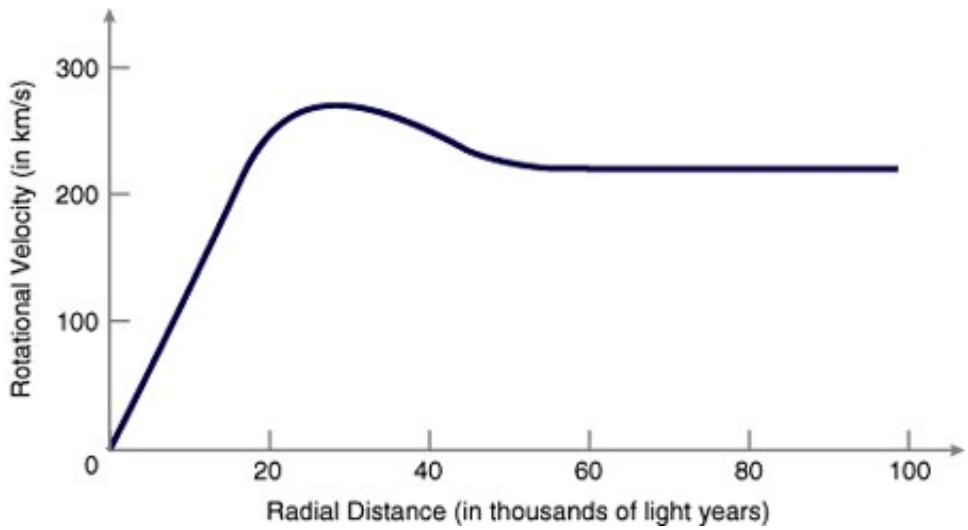


- Consider a star of mass m in the galaxy at distance R from center
- Can measure how fast it's orbiting around the galaxy, V
- Acceleration of star is related to V and R (recall circular orbits have $a = V^2/R$; a is acceleration)
- Then use Newton's law, $F = ma$, with F from the gravity of the rest of the galaxy acting on m
- Turns out that force is mainly due to the mass of the galaxy within the star's orbital radius R, $M_{galaxy}(<R)$
- Thus, can obtain mass of galaxy in terms of V and R:



$$\boxed{M_{galaxy}(< R) = \frac{V^2 R}{G}}$$

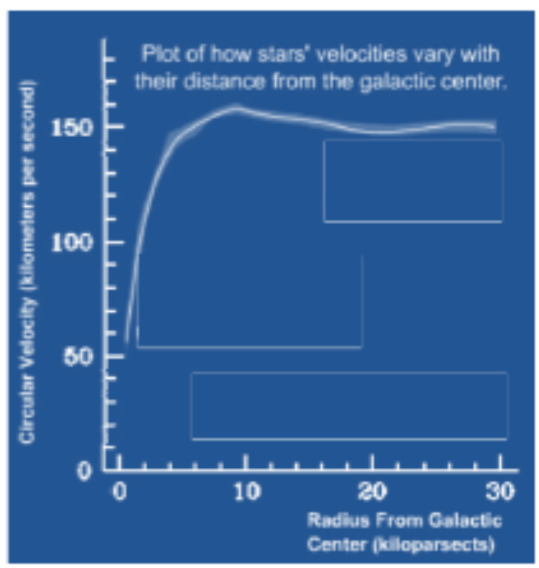
What do we see?

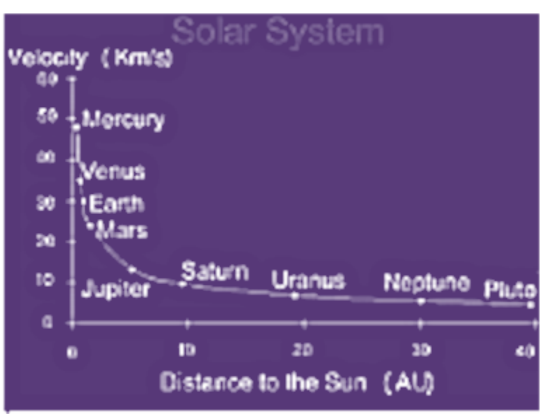


Measuring the mass of a Galaxy

How to measure *how much stuff there is* in various astronomical things

The solar system -measure mass of planets and compare to Newton's laws-works 'perfectly'





So Go out and Measure !

- How to measure how much stuff there is in various astronomical things
- The solar system -measure mass of planets and compare to Newtons laws-works 'perfectly'
- Stars (like the sun) - we understand how these work very well (fusion furnaces) and can relate how luminous they are and their 'color (e.g how hot they are) to their mass very well.
  - This works 'perfectly' (can measure the mass of stars in other ways using the orbits of binary stars)

•Galaxies

roughly speaking galaxies are just assemblies of stars and gas which should be bound by their own gravity

We can measure how much gas there is (both cold and hot) very well

In nearby galaxies we can count the stars (HST) and in more distant galaxies estimate the amount of light very well - QED we can determine the mass of galaxies accurately -WRONG

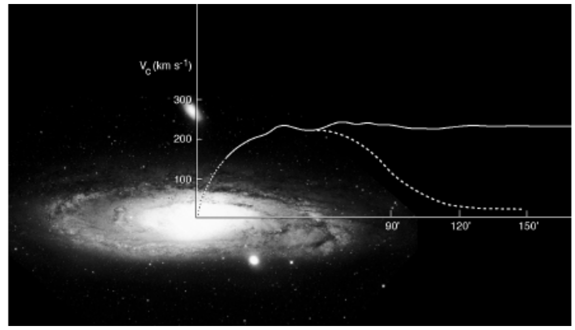
"In a spiral galaxy, the ratio of dark-to-light matter is about a factor of ten. That's probably a good number for the ratio of our ignorance-to-knowledge. We're out of kindergarten, but only in about third grade."—Vera Rubin

Vera Rubin was one of the first 'discoverers' of dark matter- worked at Carnegie Institute of Washington
an 'accidental discovery'- she was trying to understand galaxies
Her papers from 1952-93 are in the Library of Congress Manuscript Division.

Awarded the National Medal of Science for this work

Evidence for Dark Matter

- Galaxy rotation curves (stars and gas)
- Stability of hot gas in elliptical galaxies and clusters
- Gravitational lensing
- CMB results
- Big Bang Nucleosynthesis
- Velocity field of globular clusters and satellite galaxies around big galaxies



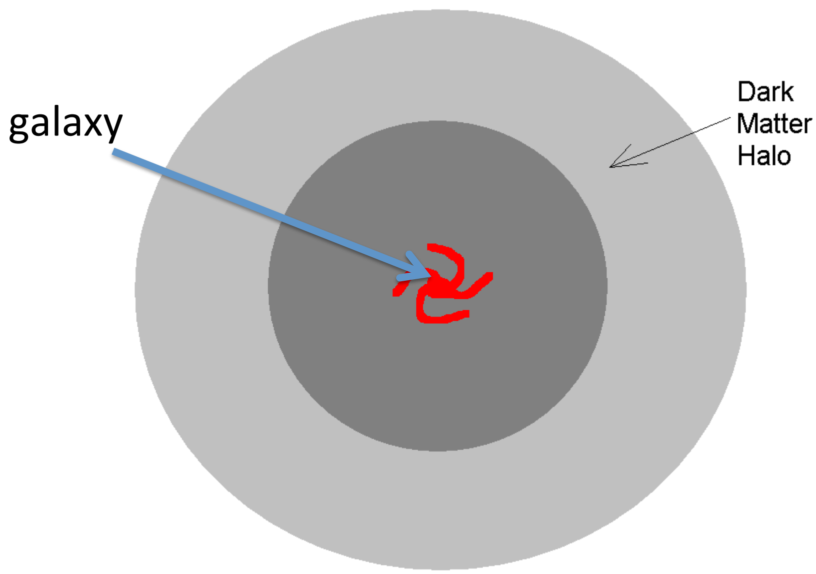
Dark matter is an indispensable ingredient in modern theories of structure formation;

As one goes to larger scales DM gets more and more important-

What Does the Data Show?

- Orbital velocity stays almost constant as far out as we can track it
  - *Means that enclosed mass increases linearly with distance*
  - Mass continues to increase, even beyond the radius where the starlight stops
  - While there is enough diffuse gas out there to track *V*, it adds only a tiny amount of mass
  - So, in these outer regions of galaxies, the mass isn't luminous…
  - This is DARK MATTER.

Called a dark matter “halo”



Halos

- How big are galaxy halos?
  - We don’t know!
  - But they might be huge… maybe 10 times bigger than luminous part of the galaxy!
- Add up all the galaxy halos… how much mass would there be?
  - Uncertain - we don’t know how far out galaxy halos go.
  - Somewhere in range Ω_{halos}=0.1-0.3

Non-baryonic dark matter

- This is our first evidence for non-baryonic dark matter…
  - $\Omega_B = 0.04$ (nucleosynthesis)
  - $\Omega_{halos} = 0.1\text{-}0.3$ (galaxy rotation curves)
- So, there is substantially more mass in the galaxy halos than could possibly be due to baryons!
- Suggests a non-baryonic form of matter may exist… something not based on protons and neutrons.