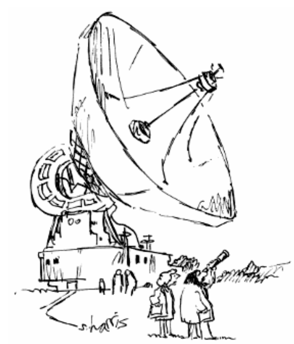
Lecture 19 : *Weighing the Universe, and the need for dark matter*

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 ?



"Just checking."

This week: Chapter 14-15

Nucelosynthesis in the BIG BANG Era

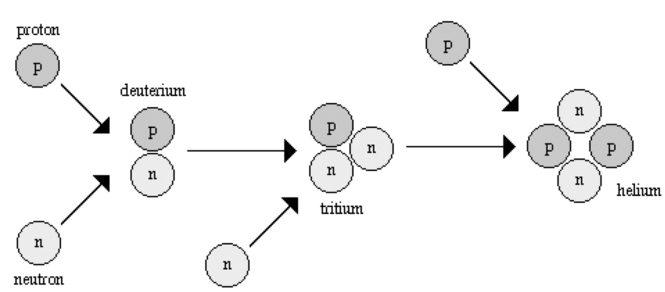
- While the nuclear reactions are proceeding, supply of "free" neutrons is decaying away (neutron half life is 881sec).
- So, speed at which nuclear reactions occur is crucial to final mix of elements
- What factors determine the speed of nuclear reactions?
  - Density (affects chance of p/n hitting each other)
  - Temperature (affects how hard they hit)
  - Expansion rate of early universe (affects how quickly everything is cooling off and spreading apart).

- 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.

$$\Omega_B = \frac{\rho_B}{\rho_{crit}} = \frac{\rho_B}{3H_0^{\ 2}/(8\pi G)}$$

- 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

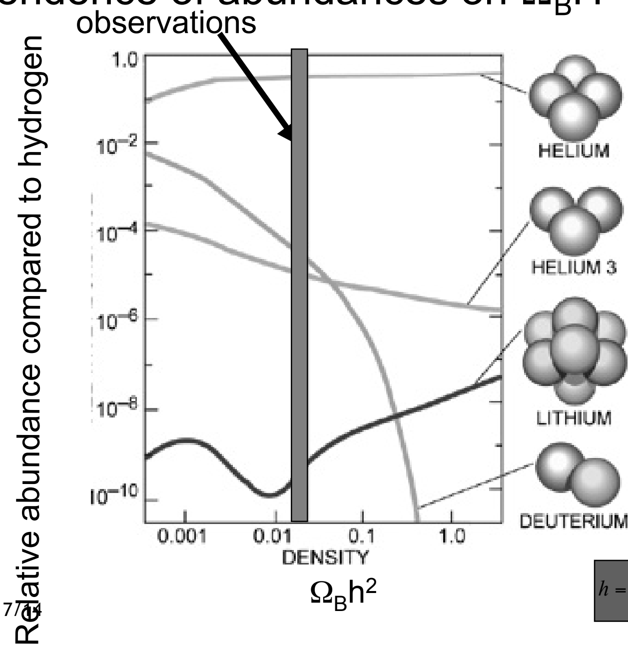
as the Universe cools, protons and neutrons can fuse to form heavier atomic nuclei



http://abyss.uoregon.edu/~js/ast123/lectures/lec21.html

Dependence of abundances on $\Omega_B H^2$

From M.White's webpage, UC Berkeley

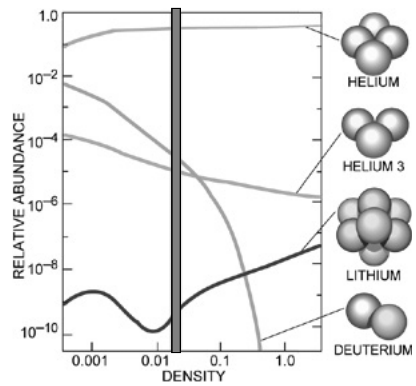


$$h = \frac{H_0}{100 km/s/Mpc}$$

- We can 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 $\Omega_B h^2$

Results

- Best fit gives $\Omega_B h^2 \approx 0.019$
- If H_0=72km/s/Mpc, h=0.72
  - $\Omega_B \approx 0.04$
- <u>This is far below Ω=1!</u>
- **Baryons alone would give open universe- remember need $\Omega \geq 1$ for a closed universe.**

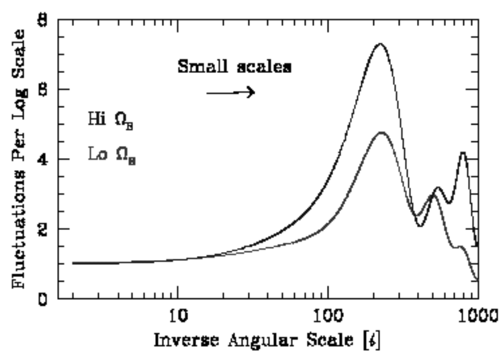


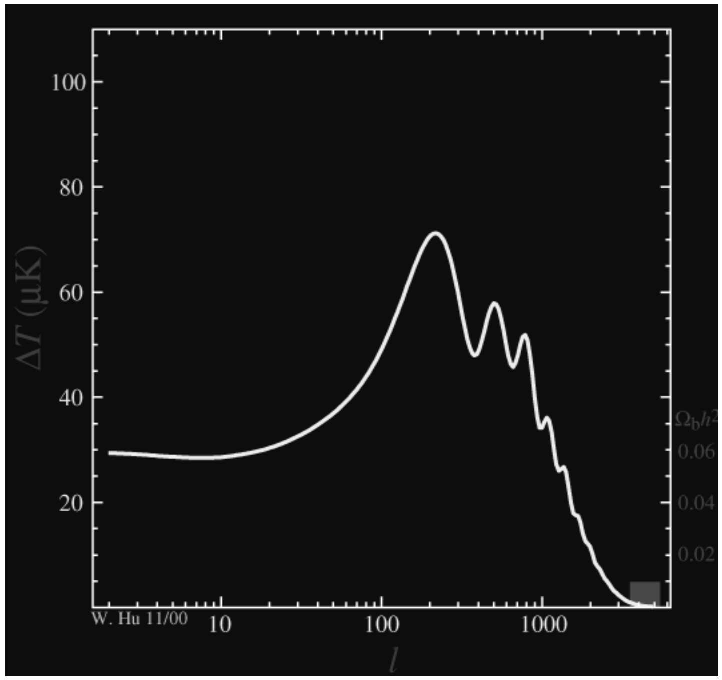
$\Omega_B h^2$

Effect of baryons on CMB

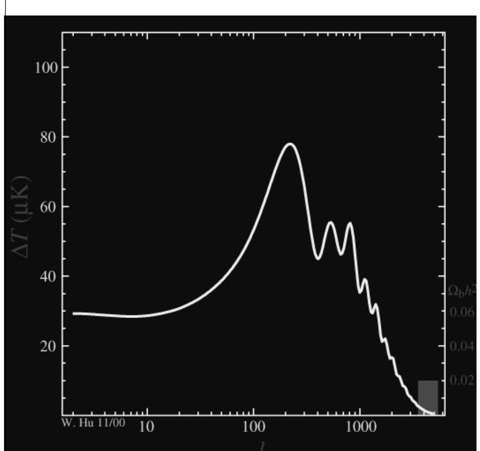
- Baryonic fraction changes the amplitude of the peaks in the power spectrum of the CMB
- comparing the heights of the first two gauges the relative strengths of gravity and radiation pressure in the early universe.
- The observed ratio indicates that baryons had about the same energy density as photons at the time of recombination and hence constitute about 5 percent of the critical density today.
- The result is in spectacular agreement with the number derived from studies of light element synthesis by nuclear reactions in the infant universe

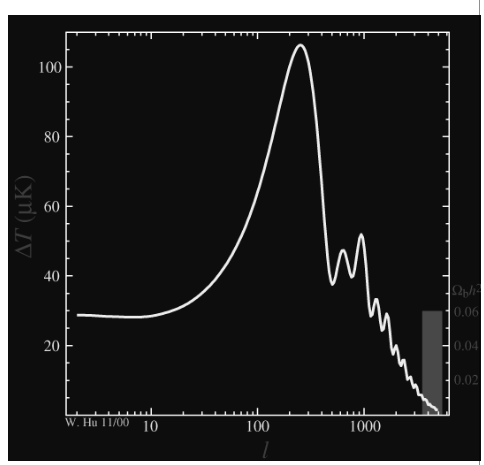
Hu and White 2004 Scientific American .





Sensitivity of CMB to Baryons



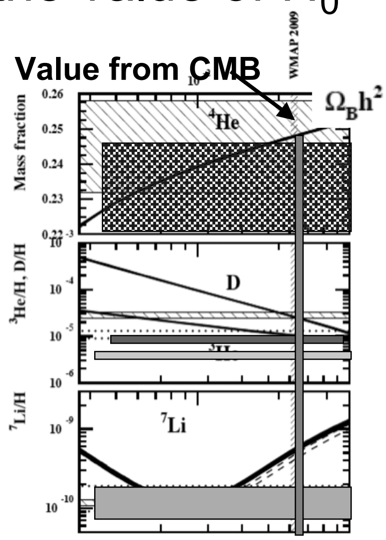


W. Hu http://background.uchicago.edu/~whu/intermediate/baryons3.html

Ω_b=0.0449 +/-0.0028 if fix the value of H_0

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

Notice very different scales on Y axis



Error in ^{4}He measurements

Error in D measurements

Error in ^{3}He measurements

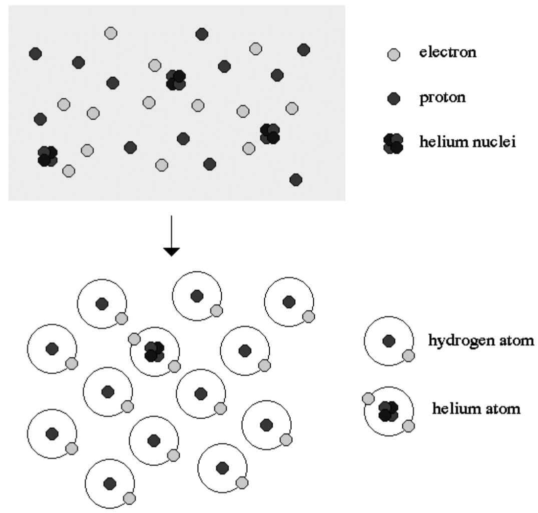
Error in ^{7}Li measurements

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

Recombination

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

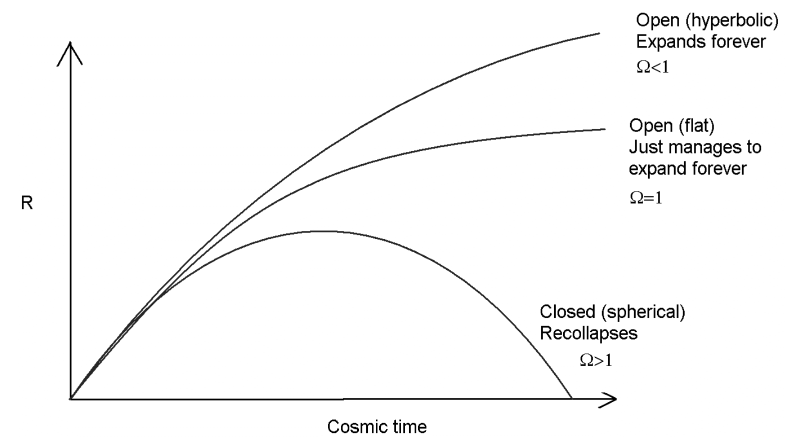


http://abyss.uoregon.edu/~js/ast123/lectures/lec21.html

- Remember the **density parameter** as

$$\Omega = \frac{\rho_{total}}{\rho_{crit}}$$

- 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)
- 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…



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

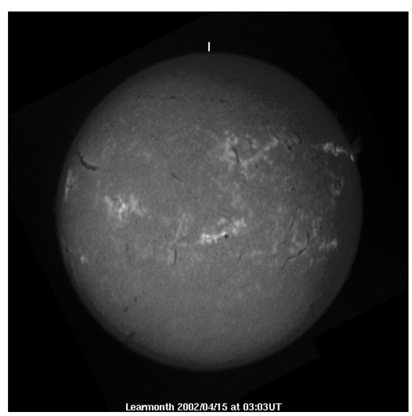
I : THE MASS OF STARS IN THE UNIVERSE

- 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

- $M_{sun}=2\times10^{30}$ kg
- $L_{sun}=4\times10^{26}$ W

- Actual numbers not very instructive…
- From now on, we will reference mass-to-light ratios to the Sun (M_{sun}/L_{sun}).

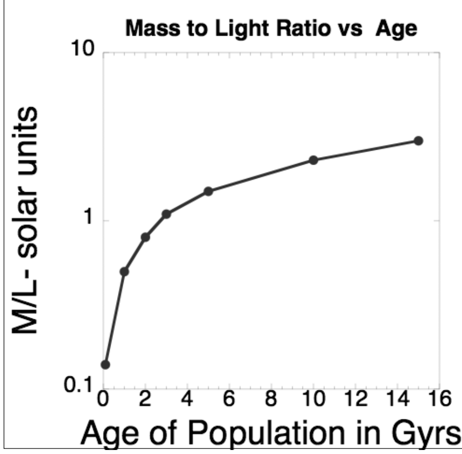


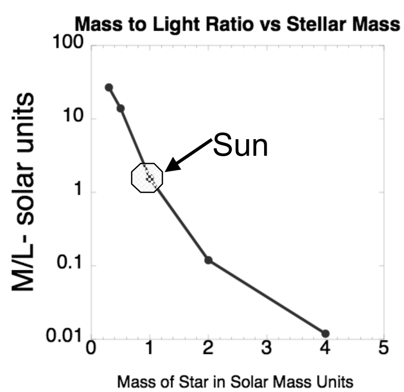
Other stars

- 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 stars near to the Sun, we get $M/L \approx 3\ M_{sun}/L_{sun}$

How Does M/L Change with the Nature of the Stars?

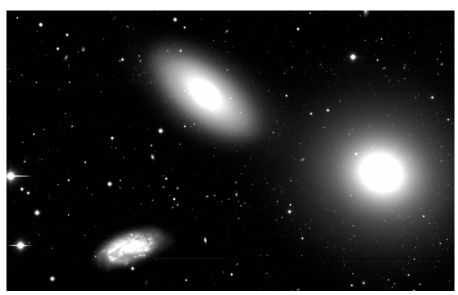
- Low mass stars have less light per unit mass
- For a stellar population the older it is the <u>less</u> light per unit mass





So need to understand stellar populations of galaxies to understand if a given M/L requires additional unseen 'dark matter'

- But, we also need to include effect of "dead" stellar remnants…
  - white dwarfs, neutron stars, black holes.
  - These have plenty of mass M, but very little light L.
  - These have very high ratio M/L
  - Including the remnants, can have mass-to-light ratio as high as $M/L \approx 7\ M_{sun}/L_{sun}$



- So, can add up the visible star light that we see in the Universe, and convert to a mass.
  - We get $\Omega_{star} \approx 0.005\text{-}0.01$
  - Comparing with $\Omega_B = 0.04$ from nucleosynthesis, we see that most baryons cannot be in stars…

II : THE MASS OF GALAXIES

- We can also measure total mass of a galaxy using Kepler's/Newton's laws
- Remember the case for planets…

$$M_{sun} = \frac{4\pi R^3}{GP^2}$$

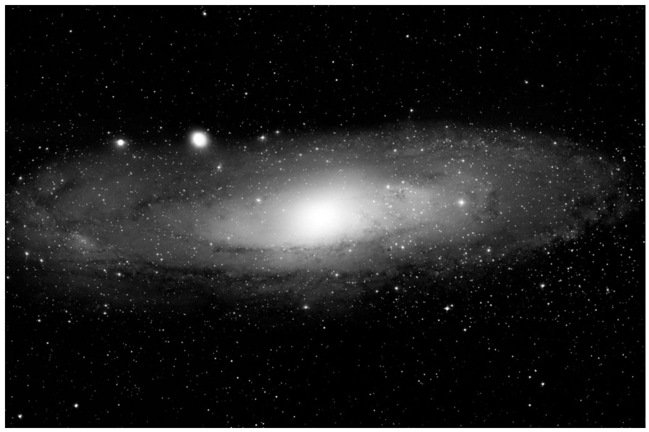
- Can rewrite this as

$$M_{sun} = \frac{V^2 R}{G} \quad \text{or} \quad V = \sqrt{\frac{GM_{sun}}{R}}$$

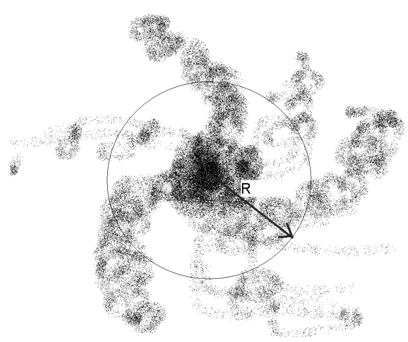
Velocity dependence on radius for a planet orbiting the Sun…

distance from sun

✦ Apply same arguments to a galaxy…



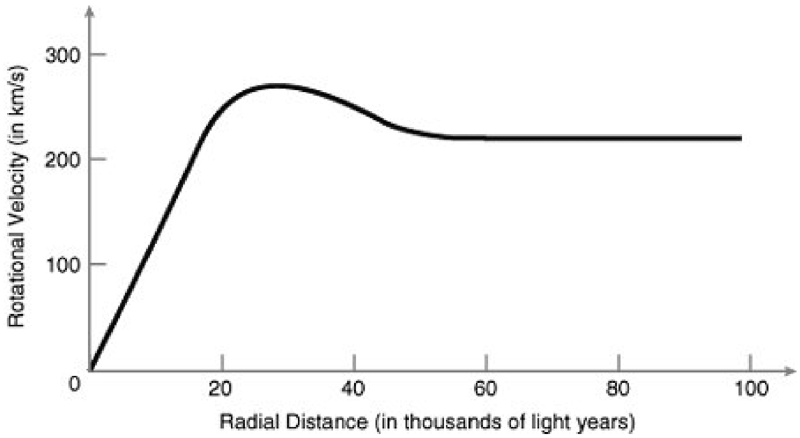
✦ Consider a star in the galaxy at distance R from center
✦ Work out how fast its orbiting around the galaxy
✦ Turns out (Newton figured this out) that relevant thing is mass of that part of the galaxy within radius R, $M_{sun}(<R)$



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

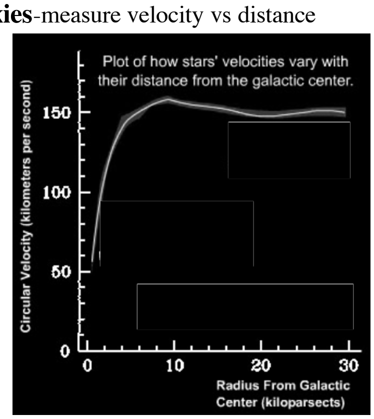
Measure V and R- derive M_{galaxy}

What do we see?

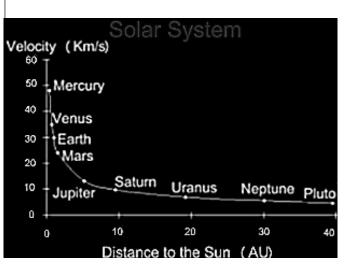


•**Galaxies**-measure velocity vs distance

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'

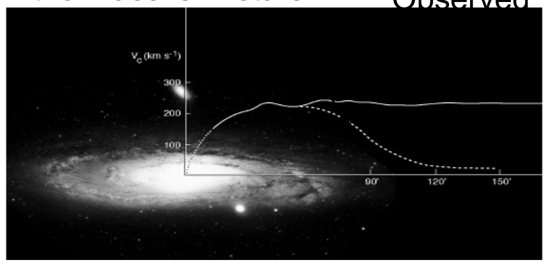


Things Don't Come out right!

- The further out one moves from the center of the galaxy the more 'mass is missing'- lots of mass and no light from stars or indication of gas
- The material that accounts for the 'extra' velocity is ***DARK***
- *Dark matter is a way of expressing our ignorance- the stars and gas do not move like we 'expect'*
- "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

This rotation curve is if all the mass is in stars

Observed



First evidence for 'dark matter' *Galaxies seem to have a lot of stuff where there are no stars or gas-* ***dark stuff- can't smell it, see it or touch it***

Dark Matter

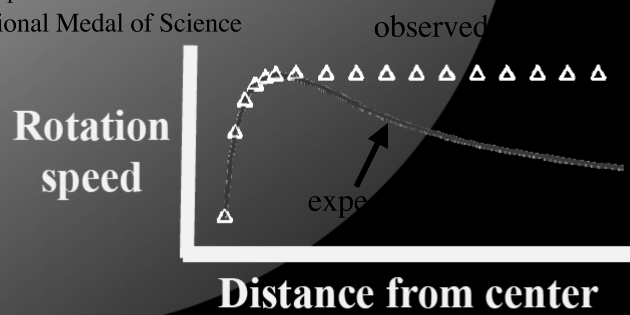
Rubin

Vera Rubin did her work at Carnegie Institute of Washington

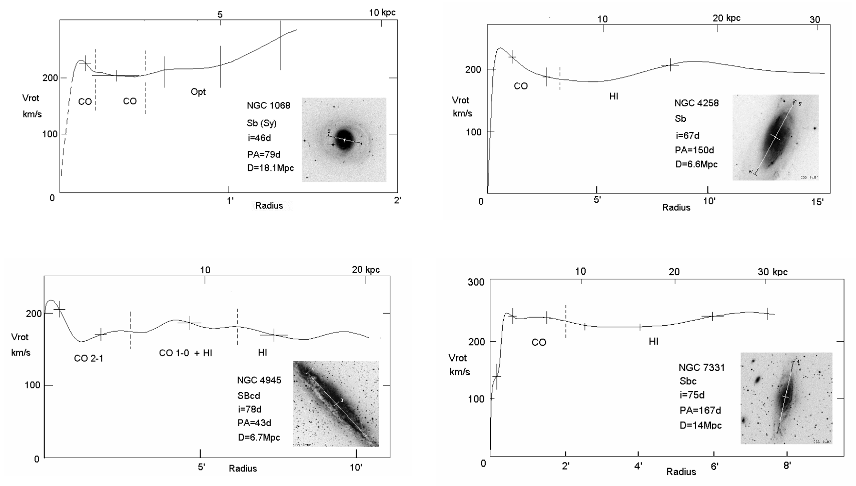
Hers was an 'accidental discovery'- she was trying to understand galaxies

Her papers from 1952-93 are in the Library of Congress Manuscript Division.

awarded the National Medal of Science

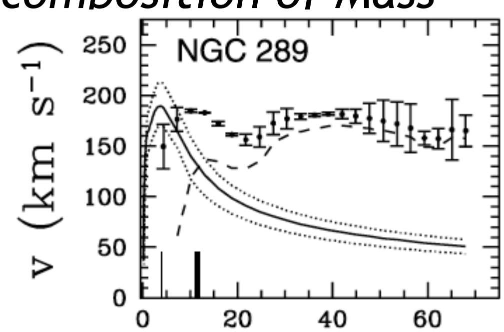


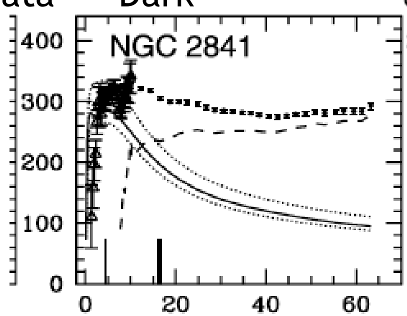
Real measurements



Decomposition of Mass

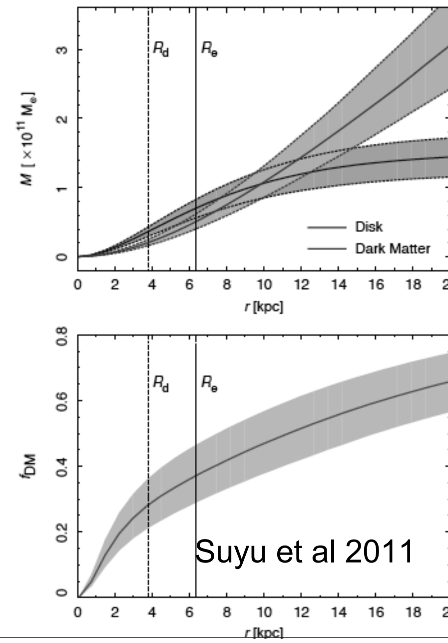
- Solid line is rotation curve from stars
- Dotted line is what 'extra' is needed to fit the data --- Dark matter





Dark Matter Dominates the Outer Regions

- Use of gravitational lensing confirms these results (remember light is bent by gravity so the amount that the light is bent can be used to infer the mass and mass distribution)



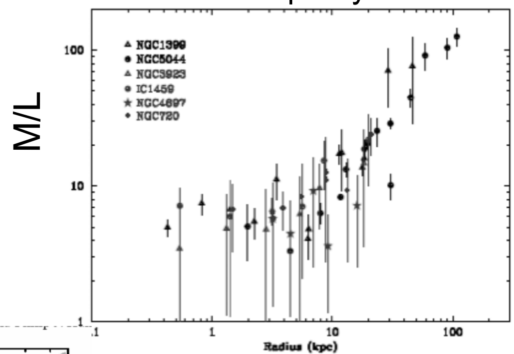
Unexpected mass distribution

- Orbital velocity stays almost constant as far out as we can track it
  - Means that enclosed mass increases linearly with distance… expected?
  - Mass continues to increase, *even beyond the radius where the starlight stops*

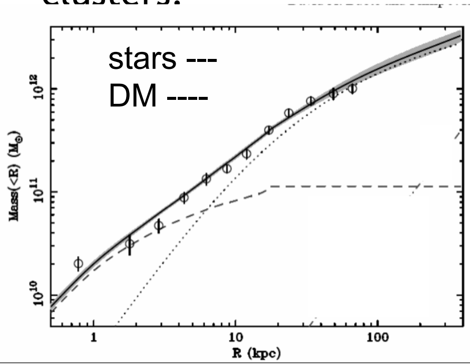
    While there is enough diffuse gas out there to track *V*, it adds only a tiny amount of mass
  - So, in these outer regions of galaxies, the mass isn't luminous…
  - This is **DARK MATTER**.

Elliptical galaxies

Buote and Humphrey 2011



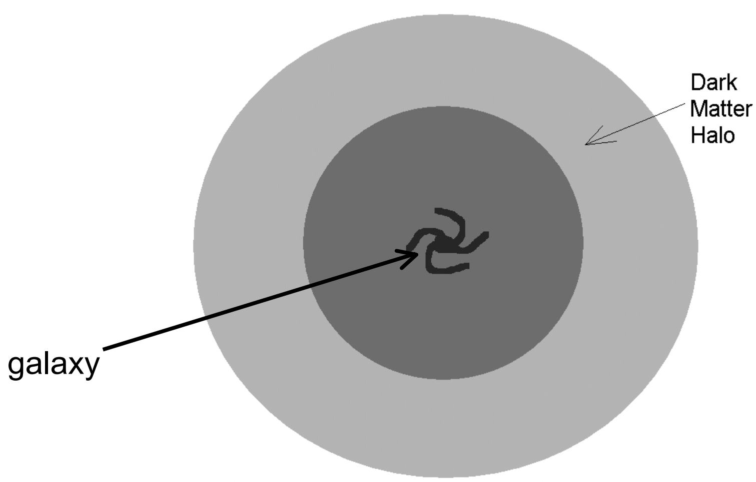
- Trace mass by observing hot gas trapped in potential well, velocities of stars and globular clusters.



In some galaxies see DM "halo" out to >100kpc

Called a dark matter "halo"

3-D distribution of dark matter is roughly spherical



- How big are galaxy halos?
  - We don't exactly 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

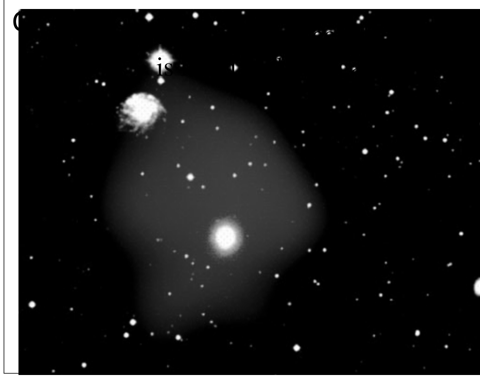
- This is our first evidence for dark matter…
  - Ω_B=0.042 (nucleosynthesis)
  - Ω_{halos}=0.1-0.3 (galaxy rotation curves+velocity dispersion in ellipticals)
  - Since there is more matter than predicted for baryonic matter it is 'non-baryonic'
- So, substantially more mass in the galaxy halos than could possibly be due to baryons.
- Suggests a non-baryonic form of matter may exist… something not made of protons and neutrons.

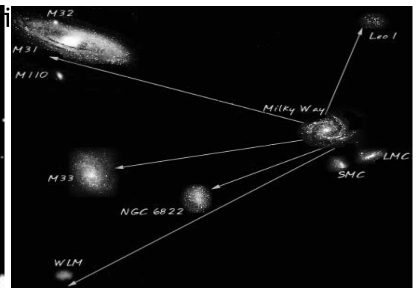
So What about Bigger Things than Galaxies?

Groups of galaxies

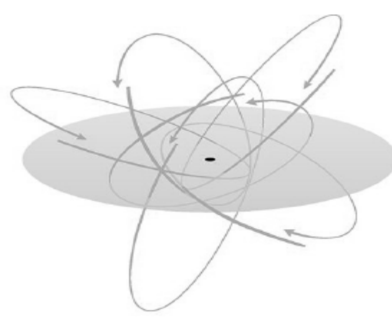
- We use the speed between galaxies in the same way as the stars inside galaxies
- If no dark matter objects fly apart in short time

amount of dark matter determined by galaxy speeds --- higher speed more matter needed.





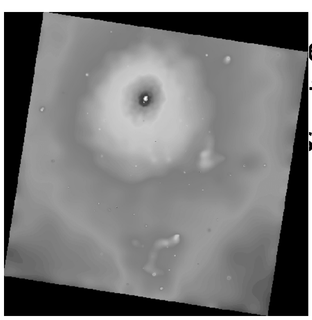
Galaxies Move with Respect to Each Other



III : MASS OF GALAXY CLUSTERS

- Galaxy clusters
  - Large groups of galaxies
  - Bound together by mutual gravitational attraction
  - Let's use same arguments as for galaxies (i.e., based on Newton's laws) to measure mass…

$$M_{gal}(< r) \approx V_{gal}^2 R$$



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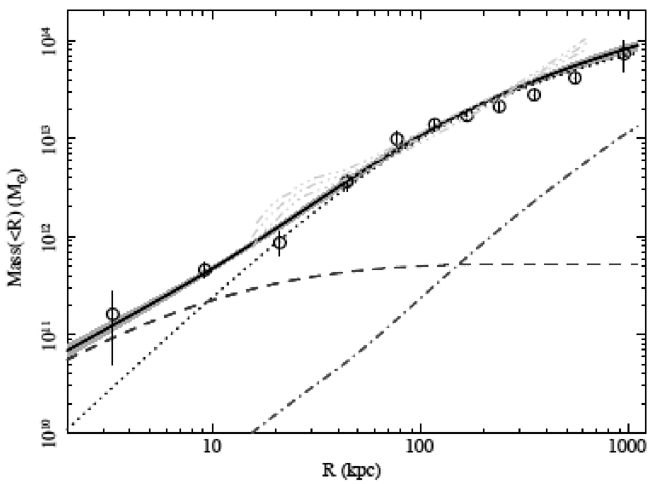
X-ray image of cluster
(Chandra satellite)

Cluster mass has to hold onto hot gas

Clusters are 'really' big ~ 10 million light years across
and massive ~ 10^{15} times the mass of the sun
(10x the number of pennies in the deficit)
And have the same problem: in clusters 86% of the material is dark

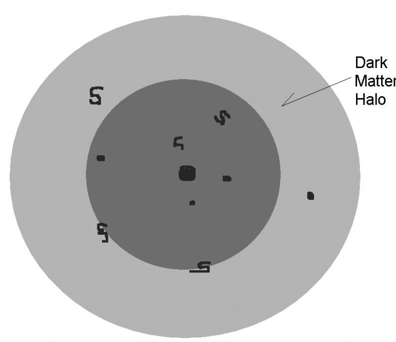
Cluster Mass Profiles



red- stars
purple- gas
blue - dark matter

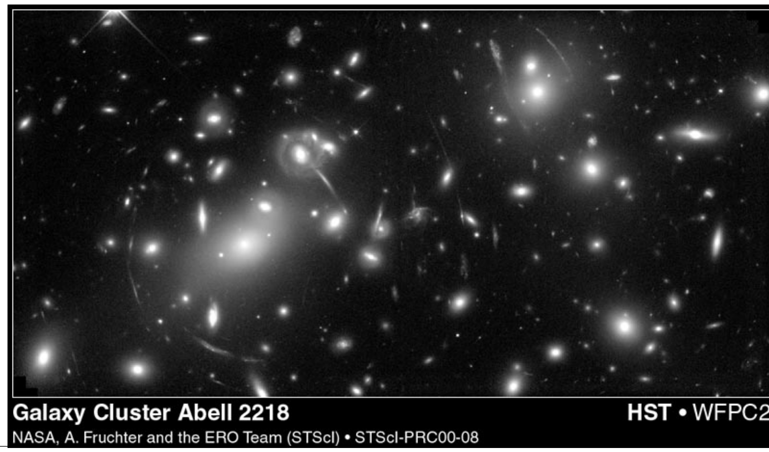
As in galaxies and groups the further from the center the more dark matter dominated - in clusters, gas is the major baryonic component

- Find a similar situation… but with a subtle difference. In clusters 90% of the baryonic matter is in the form of hot gas between the galaxies
- However:
  - There is a giant halo of dark matter enveloping the galaxy cluster
  - in addition to the individual halos that the galaxies possess
  - Add up the mass in these cluster halos…
  - Ω_{clus}=0.3
  - Most of this must be non-baryonic



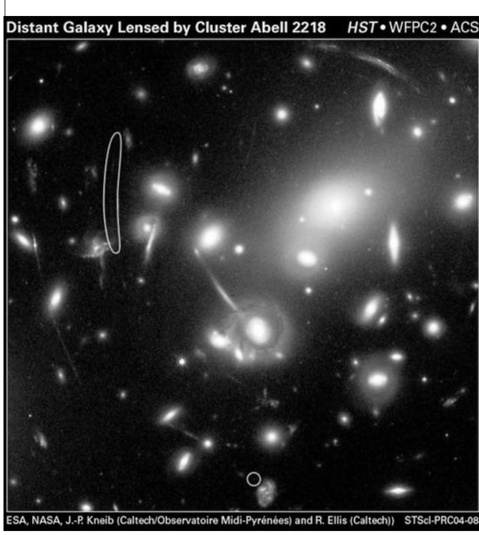
Gravitational lensing…

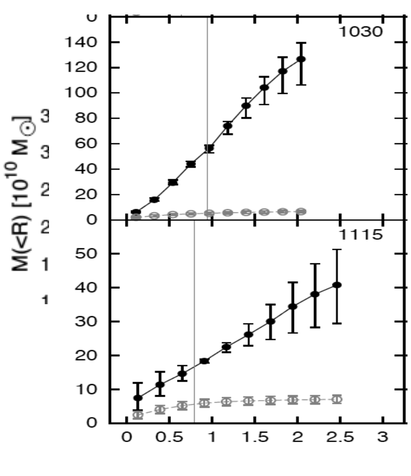
- In some cases, can also measure cluster mass using gravitational lensing.
- Get good agreement with dynamical measurements



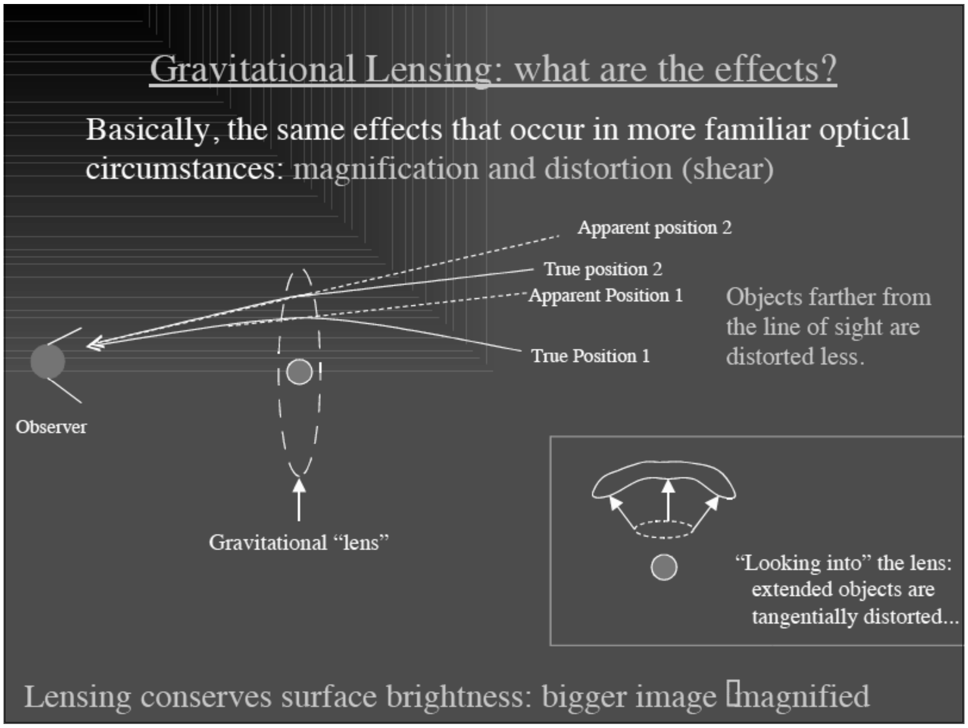
Mass Distribution in Galaxies From Lensing

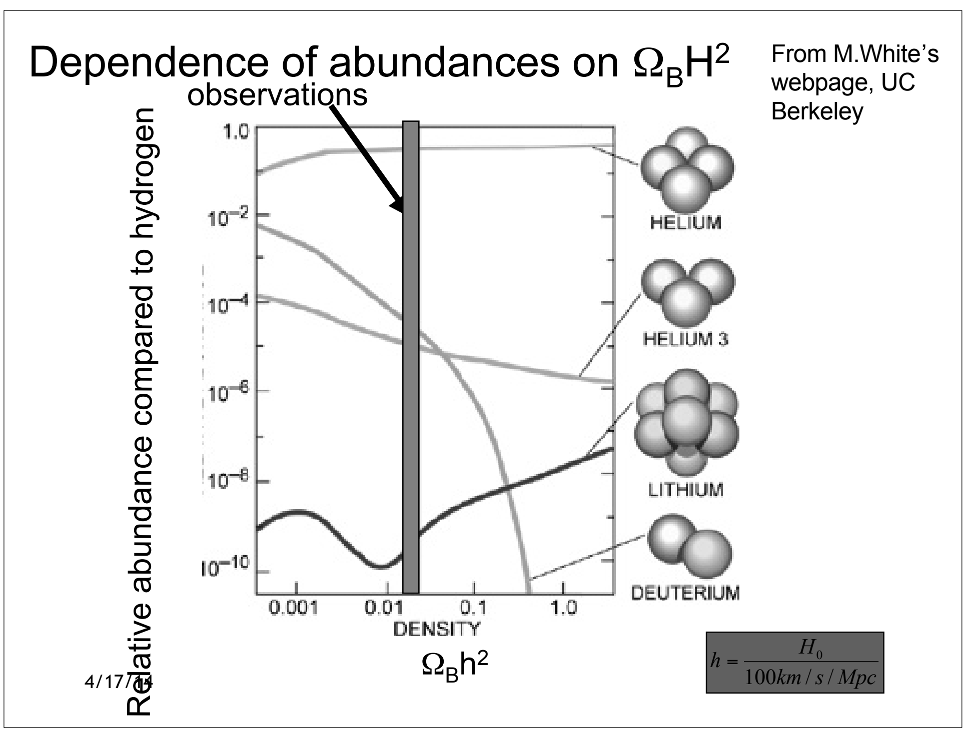
- Black line is the total mass from lensing
- grey line is the mass due to stars
- http://scienceblogs.com/startswithabang/2011/04/how_gravitational_lensing_show.php





Distance from center

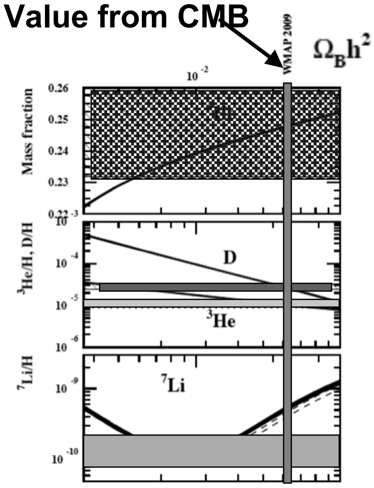

Gravitational Lensing: what are the effects?
Basically, the same effects that occur in more familiar optical circumstances: magnification and distortion (shear)
Apparent position 2
True position 2
Apparent Position 1
True Position 1
Objects farther from the line of sight are distorted less.
Observer
Gravitational "lens"
"Looking into" the lens: extended objects are tangentially distorted...
Lensing conserves surface brightness: bigger image magnified


Dependence of abundances on $\Omega_B H^2$
From M.White's webpage, UC Berkeley
observations
Relative abundance compared to hydrogen
1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0.001
0.01
0.1
1.0
DENSITY
$\Omega_B h^2$
HELIUM
HELIUM 3
LITHIUM
DEUTERIUM
$h = \frac{H_0}{100 km/s/Mpc}$
4/17/14

Ω_b=0.0449 +/-0.0028 if fix the value of H_0

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

Value from CMB



Notice very different scales on Y axis

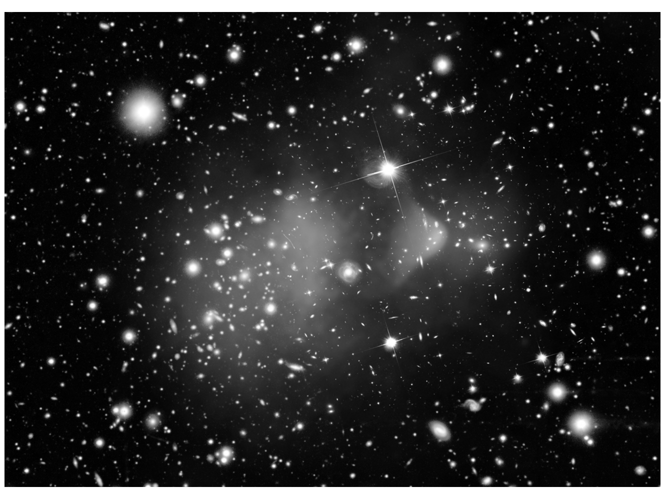
Error in ^{4}He measurements

Error in D measurements

Error in ^{3}He measurements

Error in ^{7}Li measurements

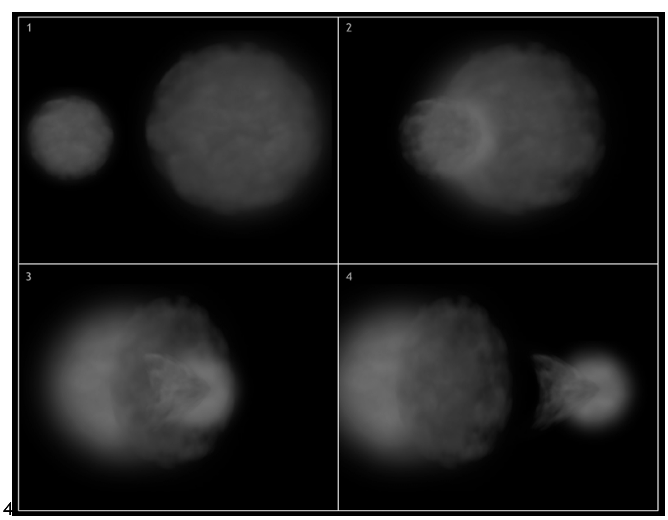
A cosmic collision: the Bullet Cluster



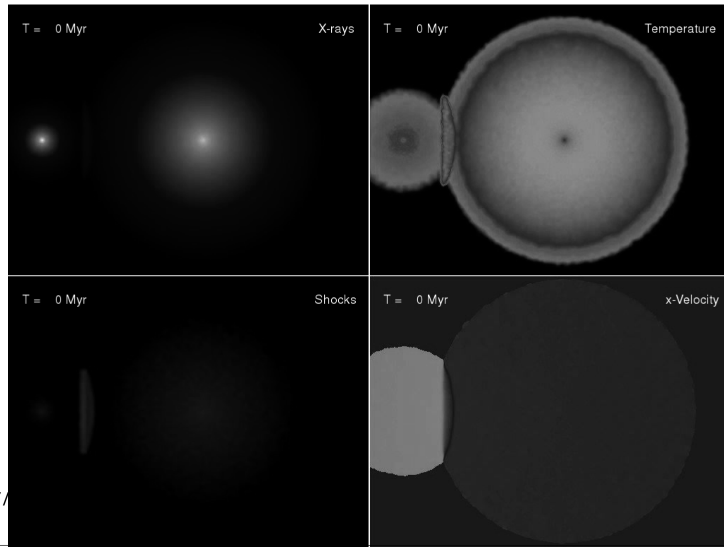
- Red: X-rays (hot gas)
- Blue: Matter from lensing

The mass is not in the baryons

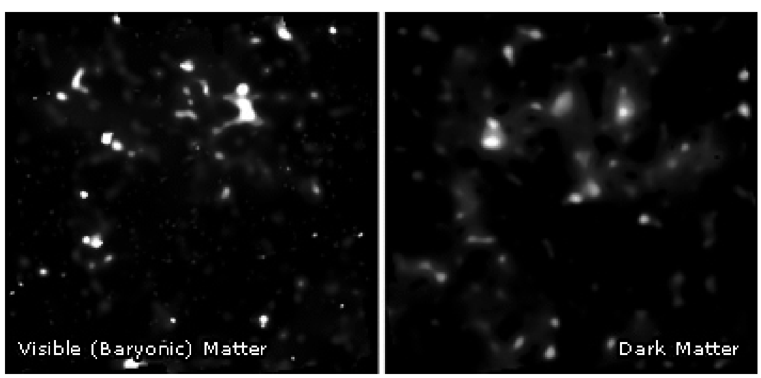
Bullet cluster collision



Bullet cluster collision

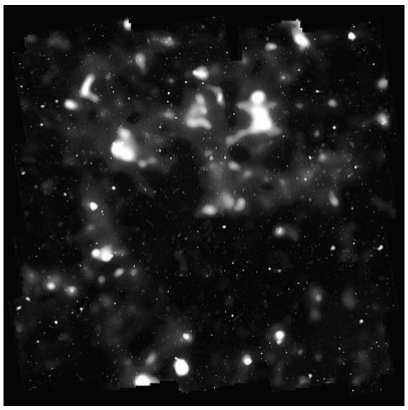


Dark matter map from gravitational lensing from the COSMOS survey



The dark matter is mapped by analyzing weak gravitational lensing of many galaxies.
NASA, ESA, R. Massey

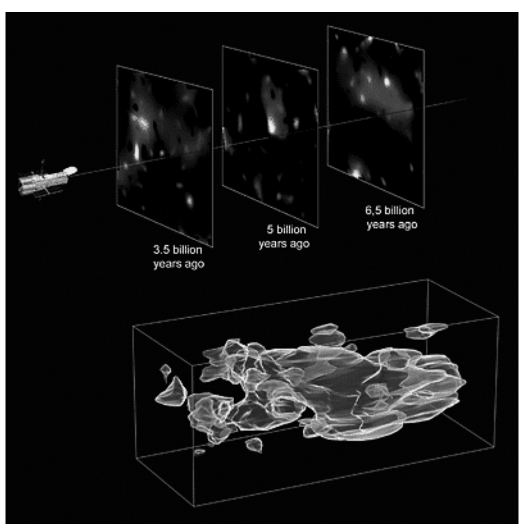
Dark matter map from gravitational lensing from the COSMOS survey



Normal matter (red) from XMM/Newton X-ray observations, dark matter (blue) from gravitational lensing, and stars and galaxies (grey) observed with Hubble.

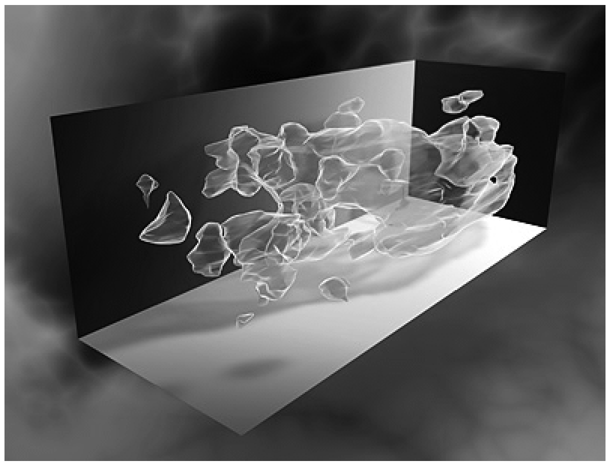
NASA, ESA, R. Massey

Dark matter map from gravitational lensing from the COSMOS survey



NASA, ESA, R Massey

Dark matter map from the COSMOS survey



Best estimates of matter in the universe

Dark sector:	0.954 ± 0.003
Dark energy	0.72 ± 0.03
Dark matter	0.23
Neutrinos	0.0013
Baryon rest mass:	0.04
Warm intergalactic plasma	0.040 ± 0.003
Gas in galaxies	0.024 ± 0.005
Intergalactic gas	0.016 ± 0.005
Intracluster plasma	0.0018 ± 0.0007
Main-sequence stars:	0.0022 ± 0.0004
White dwarfs	0.00036 ± 0.00008

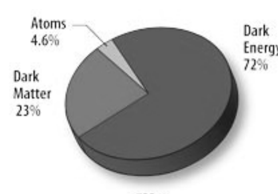
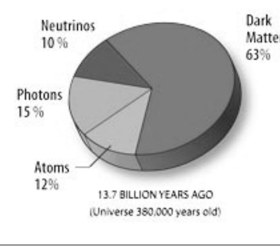


Table 2 Empirical Summary of Baryons in the Universe

Phase	Temperature (K)	$\Omega(z=3)$ Location	Estimate[a]	$\Omega(z=0)$ Location	Estimate[a]
Stars	–	Galaxies	0.005 ± 0.002	Galaxies	0.06 ± 0.03
Molecular Gas	10^2	Galaxies	> 0.001	Galaxies	0.0029 ± 0.0015
Neutral Gas	10^3	Galaxies	0.016 ± 0.002	Galaxies	0.011 ± 0.001
Ionized Gas	10^4	IGM	> 0.80	IGM	$0.17^{+0.2}_{-0.05}$
Warm/Hot Gas	10^6	Galaxies?	> 0.01	Filaments?	??
Hot Gas	10^7	??	??	Clusters	0.027 ± 0.009

[a] Relative to an assumed Ω_b value of 0.043.



IV : NON-BARYONIC DARK MATTER

- Recap again…
  - Nucleosynthesis arguments constrain the density of baryons ($\Omega_B \approx 0.04$)
  - But there seems to be much more mass in galaxy and cluster halos (Ω=0.1-0.3)
  - So, most of the matter in the Universe is not baryonic
- So… what is it?

Evidence for dark matter is overwhelming

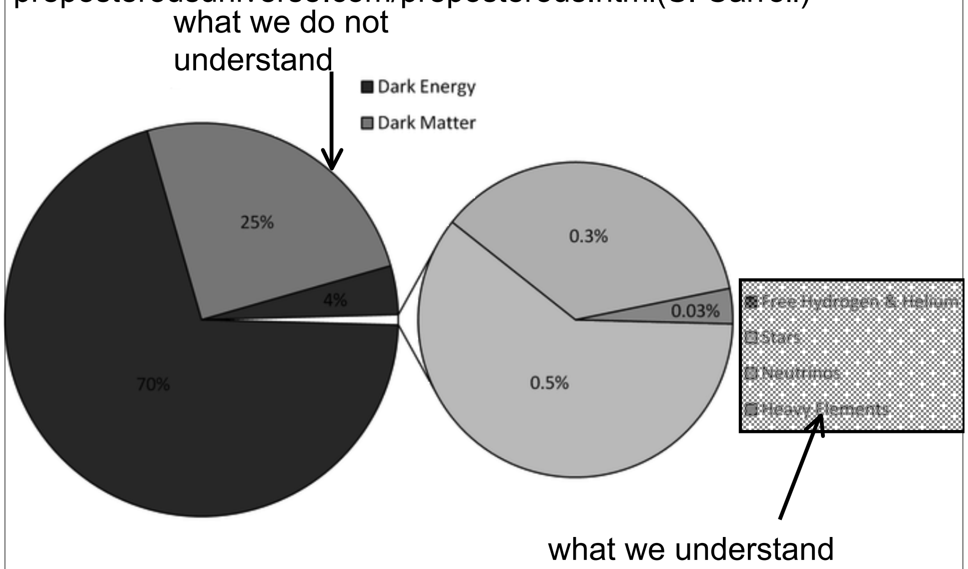
rotation curves
gravitational lensing
microwave background
hot gas in clusters
galaxy velocities in groups and clusters

Properties of dark matter

~85% of all gravitational mass
interacts very weakly with ordinary matter
it is neutral, non-relativistic (a later lecture)
stable or very long lived
Non-baryonic so that it does not participate in Big Bang Nucleosynthesis or interact with photons
slow moving, so that it can clump and form gravitationally bound structures.

Do not know what it is

The Preposterous Universe
preposterousuniverse.com/preposterous.html(S. Carroll)



- Basically, we have to appeal to other kinds of sub-atomic particles.
- Neutrinos ?
  - Already come across neutrinos when talking about nuclear reactions
  - They are part of the "standard model" of particle physics… they have been detected and studied.
  - Maybe the dark matter is in the form of neutrinos?
  - <u>**No…**</u> each neutrino has very small mass, and there just are not enough of them to make the dark mass (only upper limits on mass -measured only very recently)

Possibile dark Matter Candidates

- Particle physicists have proposed literally tens of possible Dark Matter candidates.
- Axions,for instance, are hypothetical particles whose existence was postulated to solve the so called strong CP problem in Quantum theory
- Other candidates include Sterile Neutrinos, which interact only gravitationally with ordinary matter.
- A wide array of other possibilities have been discussed in the literature, and they are currently being searched for with a variety of experimental strategies The most studied class of candidates, however, is that of WIMPs

http://cdms.berkeley.edu/Education/DMpages/essays/candidates.shtml

Non-standard Physics ??

Buzz words: super symmetry and extra Dimensions

- WIMPs
  - Weakly Interacting Massive Particles
  - Generic name for any particle that has a lot of mass, but interacts weakly with normal matter
    - Must be massive, to give required amount of mass in universe (and move slowly... galaxy formation constraint)
    - Must be weakly interacting, in order to have avoided detection
  - occupy a special place, because they arise naturally from new theories that seek to extend the standard model of particle physics and could 'naturally' provide the right amount of dark matter .
  - Many experiments currently on-going- so far no detections

- If Dark Matter is made of WIMPs, we should be able to detect it.
- By observing the interaction of Dark Matter particles with nuclei via
  - measuring the recoil energy of nuclei struck by Dark Matter particles traveling through a detector or
  - through the measurement of the light, the charge or the phonons produced in the target material by the scattering event.
- or we may detect the products of annihilation or decay of these particles,
- Although all the search strategies so far devised have failed to detect Dark Matter particles

Next time…

- Evidence for flat universe (and Λ)
- "Cosmic concordance" parameter set