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 elements (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

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

- Recap –
  - 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

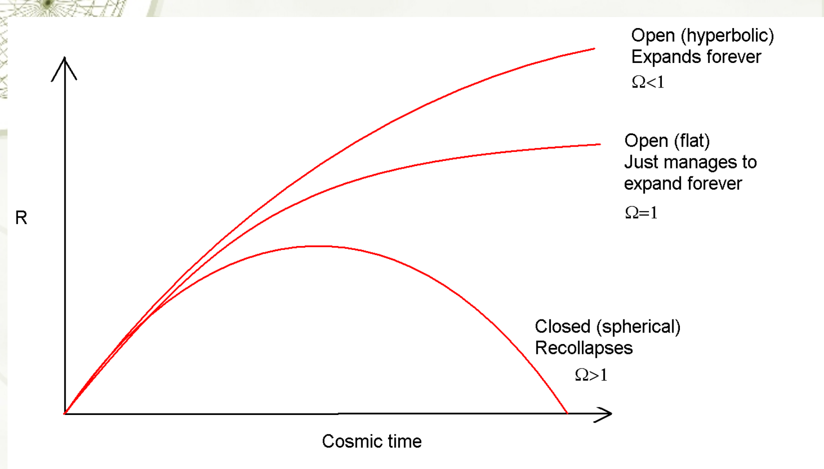
- **[Read Chapter 15 for useful background]**

0 : RECAP

- Define 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 $\Omega_B \approx 0.037$
  - If there is only baryonic ("normal") matter in the universe, then this tells us that $\Omega \approx 0.037$.
  - Thus, the Universe would be open (hyperbolic)
- But life is more complicated than that…



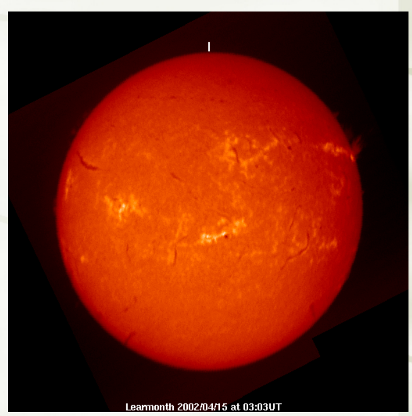
I : THE MASS OF STARS IN THE UNIVERSE

- 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 in even 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 $M/L \approx 3\ M_{sun}/L_{sun}$

- 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 $M/L \approx 10\ M_{sun}/L_{sun}$


- So, can add up the visible star light that we see in the Universe, and convert to a mass.
  - We get $\Omega_{L} \approx 0.005-0.01$
  - Comparing with $\Omega_B=0.036$ 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…

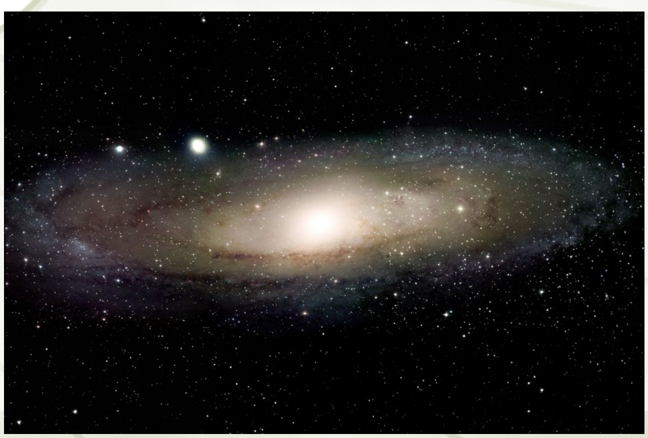
$$M_{sun} = \frac{4\pi R^3}{GP^2}$$

- Can rewrite this as

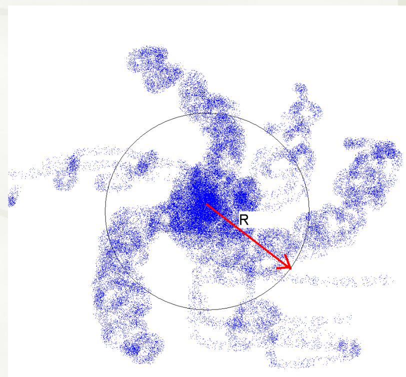
$$M_{sun} = \frac{V^2 R}{G} \quad \text{or} \quad V = \sqrt{\frac{GM_{sun}}{R}}$$

Velocity dependence on radius for a planet orbiting the Sun…

- Apply same arguments to a galaxy…

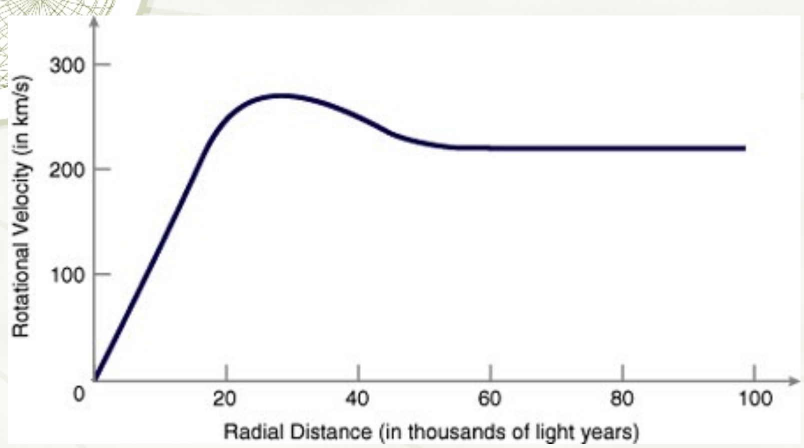


- Consider a star in the galaxy at distance R from center
- Work out how fast its orbiting around the galaxy
- Turns out that relevant thing is mass of that part of the galaxy within radius R, $M_{sun}(<R)$

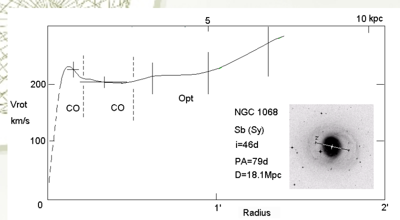


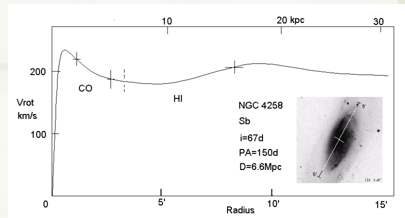
$$M_{galaxy}(< R) = \frac{V^2 R}{G}$$

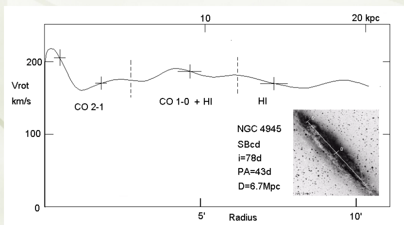
What do we see?

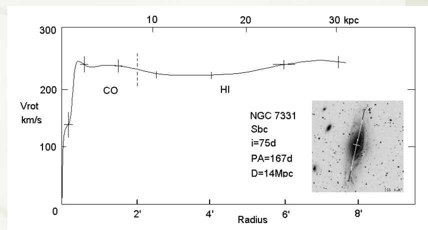


Real measurements









- 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
  - So, in these outer regions of galaxies, the mass isn't luminous…
  - This is **DARK MATTER**.

What is the weight of the Milky Way?

- Using the formula $M=V^2R/G$, with v=200 km/s, $R=6x10^{23}$ cm (that is 200 kpc) and $G=6.7x10^{-8}$ (cgs units) what is the mass of the Milky Way?

a) $\sim 4x10^{33}$ grams

b) $\sim 4x10^{40}$ grams

c) $\sim 4x10^{45}$ grams

d) $\sim 4x10^{47}$ grams

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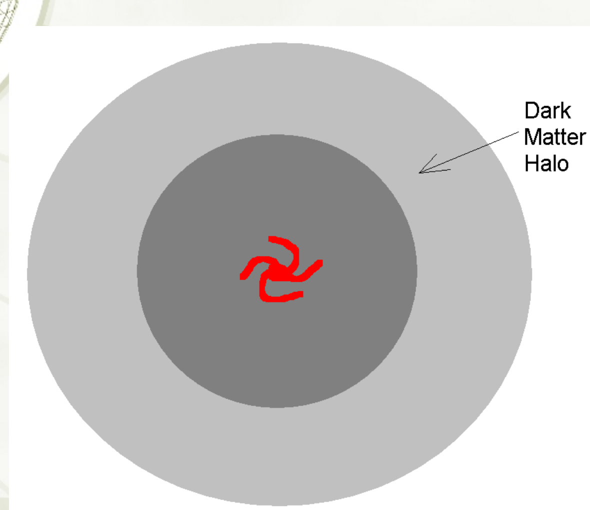
Called a dark matter "halo"



- 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

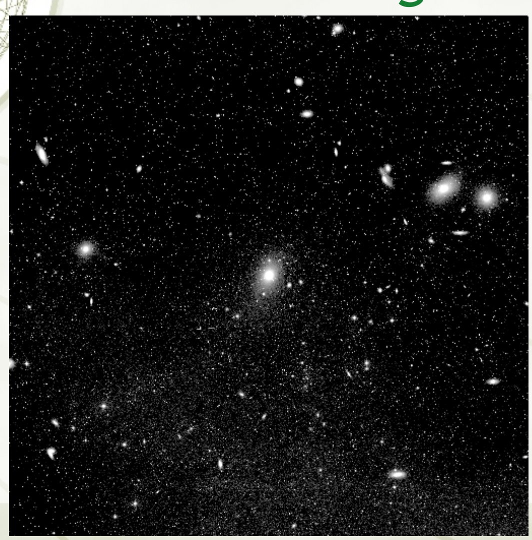
- This is our first evidence for non-baryonic dark matter…
  - Ω_B=0.036 (nucleosynthesis)
  - Ω_{halos}=0.1-0.3 (galaxy rotation curves)
- So, substantially more mass in the galaxy halos than could possibly be due to baryons.
- Suggests a non-baryonic form of matter may exist… something not based on protons and neutrons.

III : MASS OF GALAXY CLUSTERS

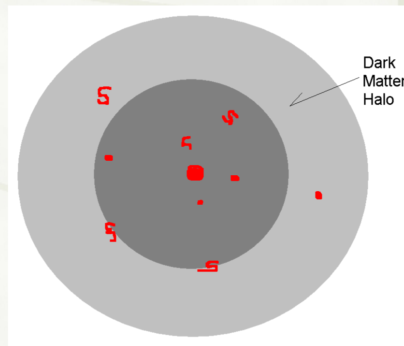
- Galaxy clusters
  - Large groups of galaxies
  - Bound together by mutual gravitational attraction
  - Let's use same arguments as for galaxies (i.e., based on Newton's laws) to measure mass…

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

The Virgo cluster…

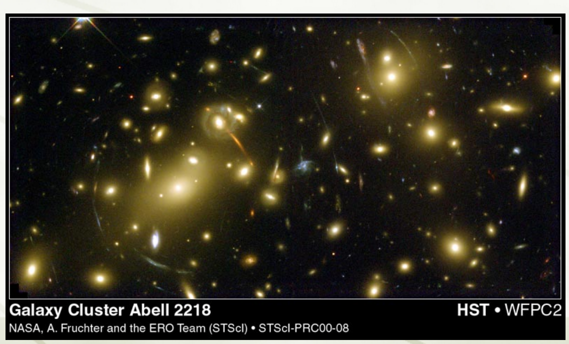


- Find a similar situation…
  - There is a giant halo of dark matter enveloping the galaxy cluster
  - Probably in addition to the individual halos that the galaxies possess
  - Add up the mass in these cluster halos…
  - $\Omega_{clus}=0.3$
  - Most of this must be non-baryonic



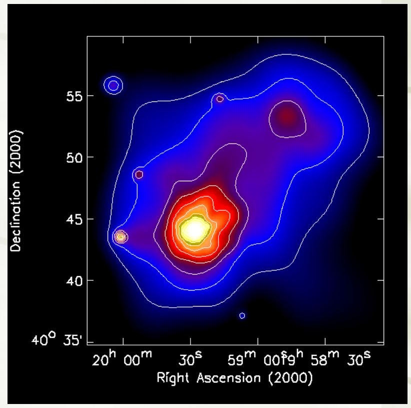
Gravitational lensing…

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



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

- Some of it may be in very low-mass stars (MACHOs)
- Where's the rest?
  - The dark matter halo of galaxy clusters traps a lot of hot gas
  - 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 in "warm" (1 million K) gas in intergalactic space.



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

IV : NON-BARYONIC DARK MATTER

- Recap again…
  - Nucleosynthesis arguments constrain the density of baryons ($\Omega_B \approx 0.037$)
  - 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?

- Basically, we have to appeal to other kinds of sub-atomic particles.
- Neutrinos (a mundane possibility)
  - 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 (mass measured only very recently)

- WIMPs
  - <u>W</u>eakly <u>I</u>nteracting <u>M</u>assive <u>P</u>article<u>s</u>
  - Generic name for any particle that has a lot of mass, but interacts weakly with normal matter
    - Must be massive, to give required mass
    - Must be weakly interacting, in order to have avoided detection
  - Various possibilities suggested by Particle Physics Theory…
    - Super-symmetric particles
    - Gauge bosons
  - Many experiments currently on-going