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

- Baryonic matter and nucleosynthesis
  - Stellar nucleosynthesis
  - 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

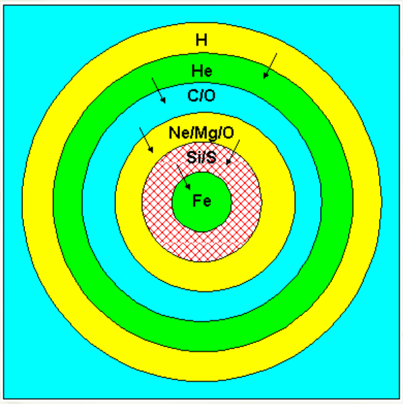
This week: start reading Chapter 13

How are other elements formed?

- Big Bang Nucleosynthesis produces most of the hydrogen & helium observed today.
- But what about other elements?
  - There are naturally occurring elements as heavy as Uranium
  - Some elements (e.g., Carbon, Nitrogen, Oxygen) are rather plentiful (1 atom in every 10^5 atoms)
  - Astronomers believe these elements were formed in the cores of stars long after the big bang
    - Theory of stellar nucleosynthesis was first worked out by Burbidge, Burbidge,Folwer, & Hoyle in 1957

Stellar "burning"

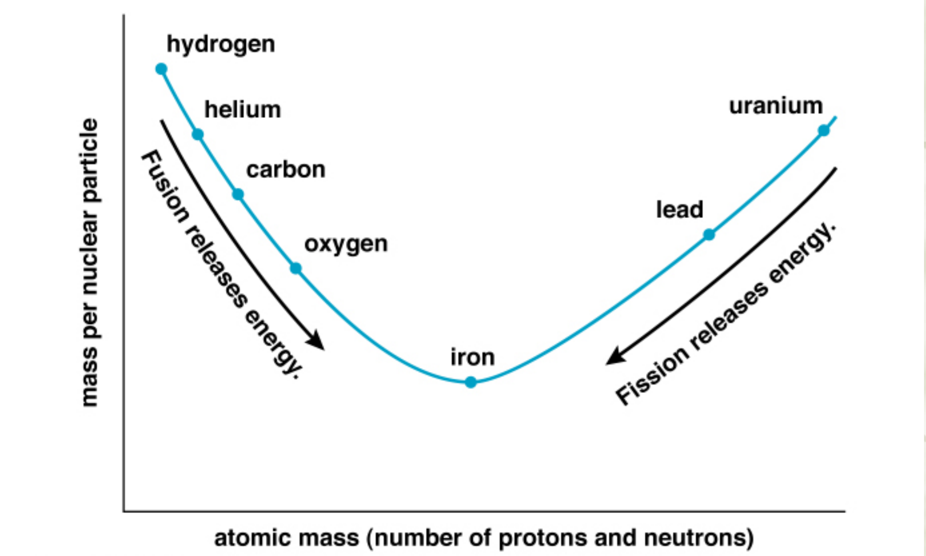
- In the normal life of a star (main sequence)…
  - nuclear fusion turns Hydrogen into Helium
- In the late stages of the life of a massive star…
  - Helium converted into heavier elements (carbon, oxygen, …, iron)
  - "Triple-alpha" process bridges stability gap from Be to C
  - At end of star's life, get an onion-like structure (see picture to right)



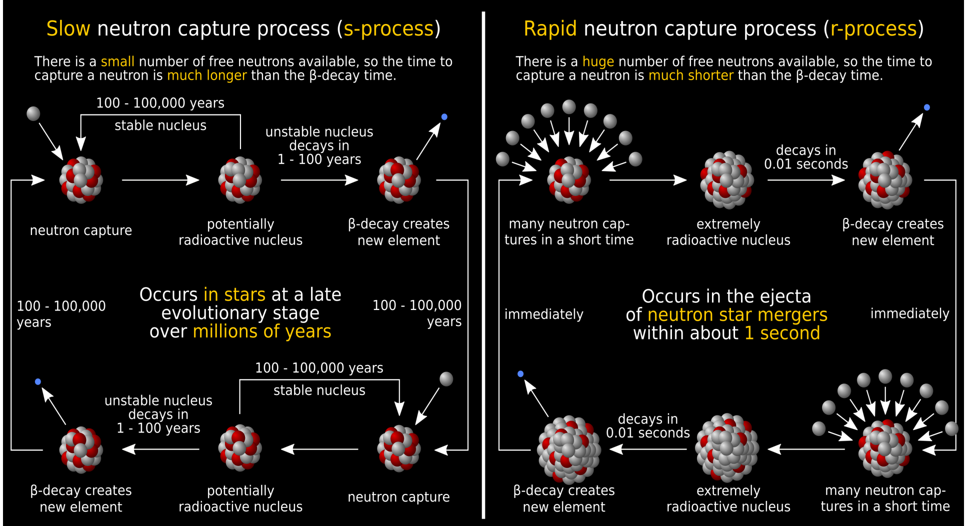
Iron, the most stable nucleus

- What's special about iron?
  - Iron has the most stable nucleus
  - Fusing hydrogen to (eventually) iron releases energy (thus powers the star)
  - Further fusion of iron to give heavier elements would require energy to be put in…
  - Can only happen in the energetic environment of a **supernova** explosion

Fission, fusion, and nuclear

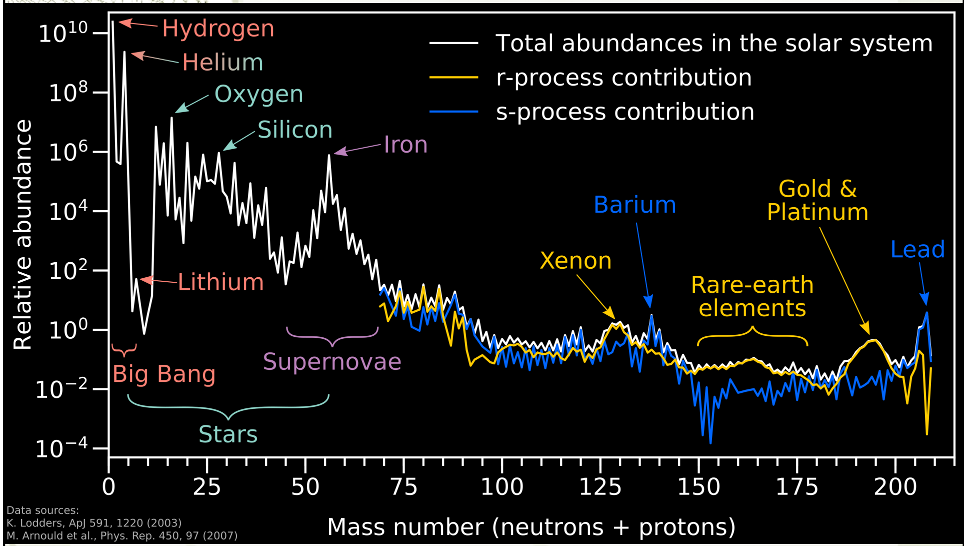


Creating heavy elements by neutron capture



Credit: Lippuner, Jonas
Los Alamos

Creating heavy elements



Credit: Lippuner, Jonas (Los Alamos)

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

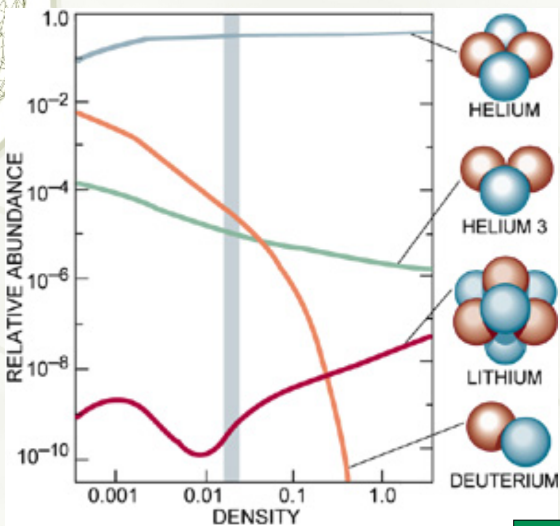
RECAP

- The **density parameter** for matter is defined as

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

- Value of Ω_M very important for determining the geometry and dynamics (and ultimate fate) of the Universe
- Constraints from nucleosynthesis
  - To get observed mixture of light elements, we need the **baryon density parameter** to be $\Omega_B \approx 0.049$
  - If there were **only** baryonic matter ("normal" stuff made of protons, neutrons, & electrons) in the Universe, then this would imply that $\Omega_M \approx 0.049$.
  - In that case, and if Λ were =0, the Universe would be open (hyperbolic) and would expand forever

RECAP

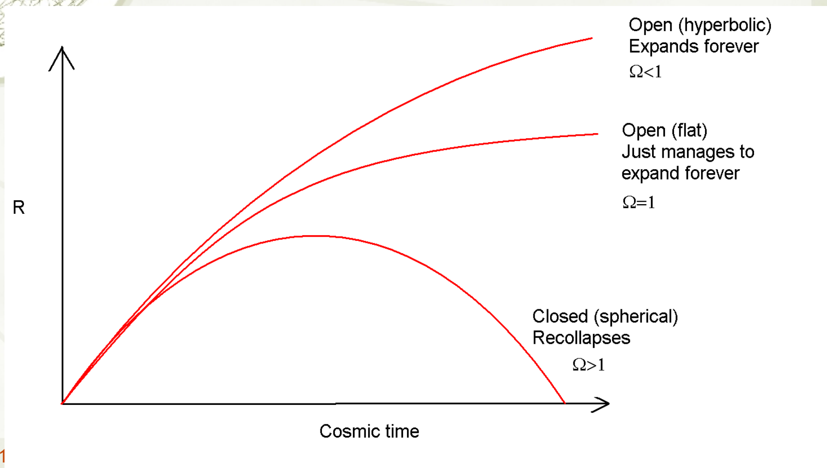


From M.White's webpage, UC Berkeley

$\Omega_B h^2$

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

Standard model evolution diagrams



Preview…

- 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…

Sean Carroll, Discovery Magazine

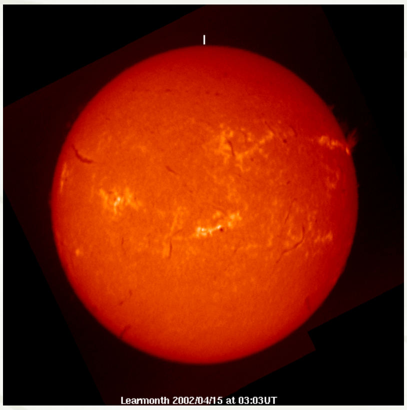
THE MASS OF STARS IN THE UNIVERSE

- 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.
- But…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 regular stars near the Sun, we get $M/L\approx3\ M_{sun}/L_{sun}$

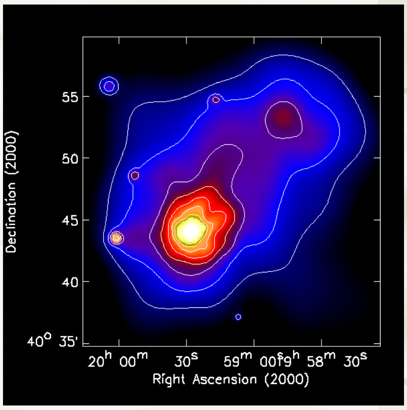
- But, we also need to include effect of "dead" stellar remnants…
  - white dwarfs, neutron stars, black holes.
- …and also sub-stellar mass objects
  - Called "brown dwarfs"
  - Interior gravity is too low to compress gas and initiate fusion ⇒ very low luminosity
- All of these have mass M, but very 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

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

- 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 $\Omega_B = 0.049$ 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. Measuring in MKS,

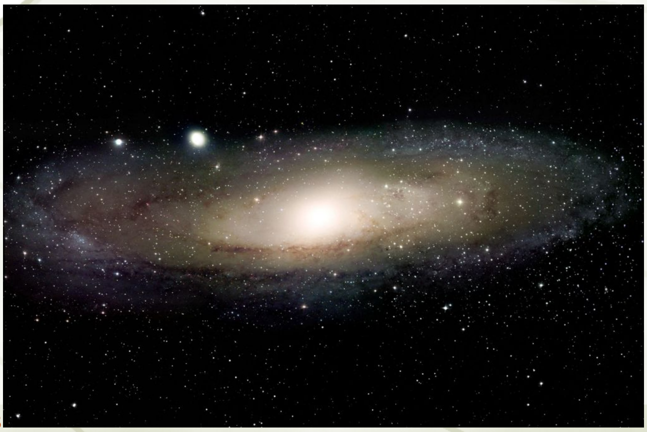
$$P^2 = \frac{R^3}{(GM_{sun}/4\pi^2)} = \frac{(2\pi R)^2 R}{GM_{sun}}$$

- Can rewrite this as

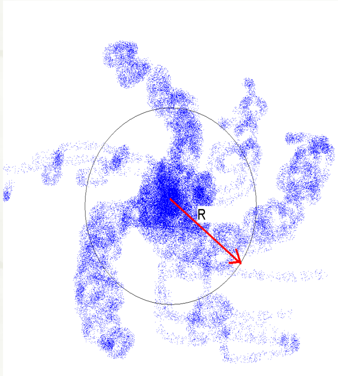
$$M_{sun} = \frac{(2\pi R/P)^2 R}{G} = \frac{V^2 R}{G} \quad \text{or} \quad V = \sqrt{\frac{GM_{sun}}{R}}$$

Velocity dependence on radius for a planet orbiting the Sun…

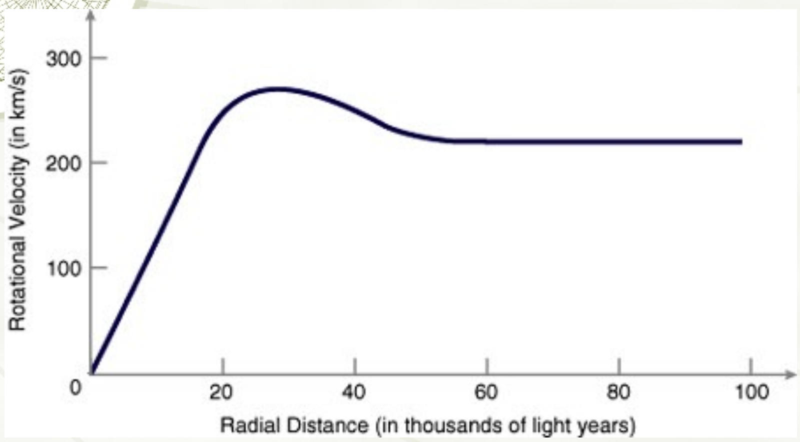
- Apply same arguments to a galaxy…



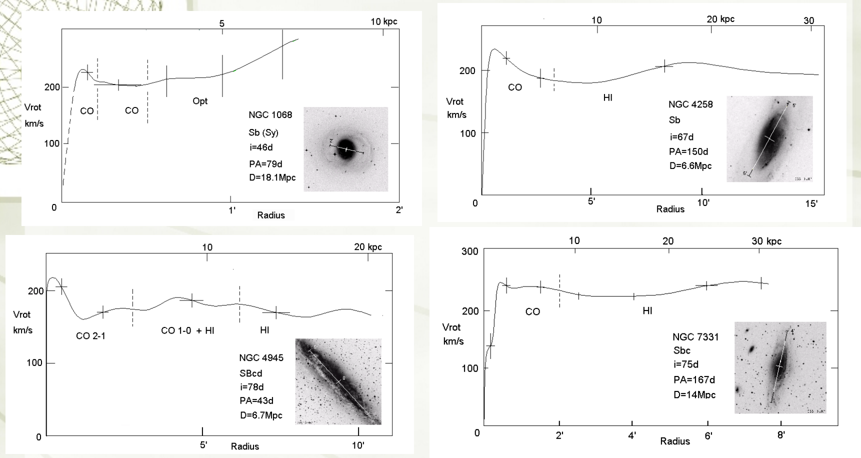
- Consider a star *m* in the galaxy at distance *R* from center
- Can measure how fast it's orbiting around the galaxy, *V*
- Acceleration of star is related to *V* and *R* (recall circular orbits have $a = V^2/R$)
- Then use Newton's law, $F = ma$, with *F* from the gravity of the rest of the galaxy 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*:



What do we see?



Real measurements



In the outermost parts of galaxies, *V* and *R* are based on measurements of hydrogen gas atoms that orbit the galaxy, rather than stars

Funny mass distribution?

- 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**.

Pioneers of dark matter

Vera Rubin
(1928-…)

Fritz Zwicky
(1898-1974)

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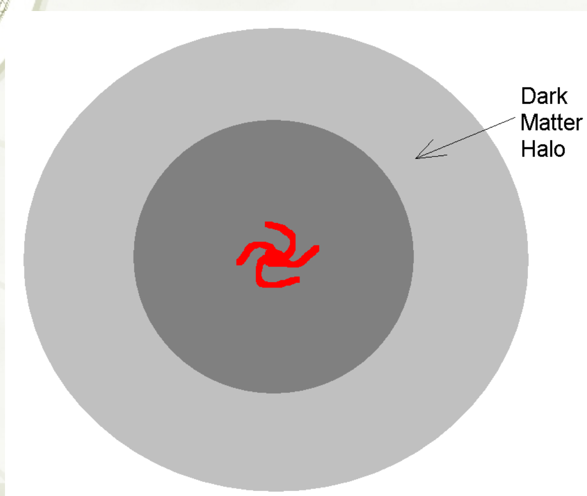
Called a dark matter "halo"



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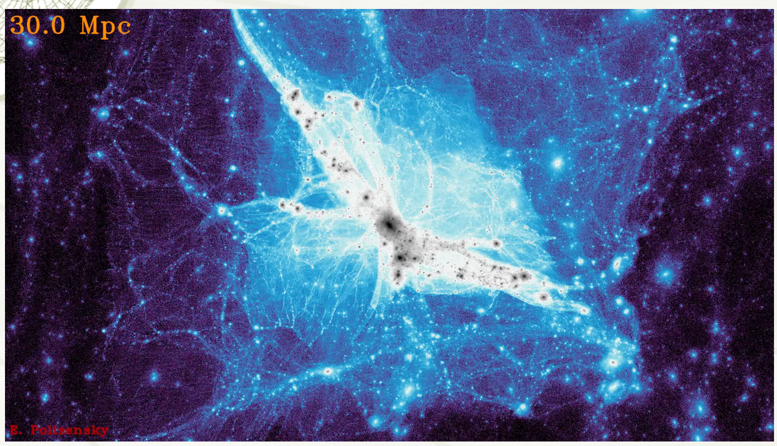
Halos

- 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



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) ~$4x10^{33}$ grams
b) ~$4x10^{40}$ grams
c) ~$4x10^{45}$ grams
d) ~$4x10^{47}$ grams

Non-baryonic dark matter

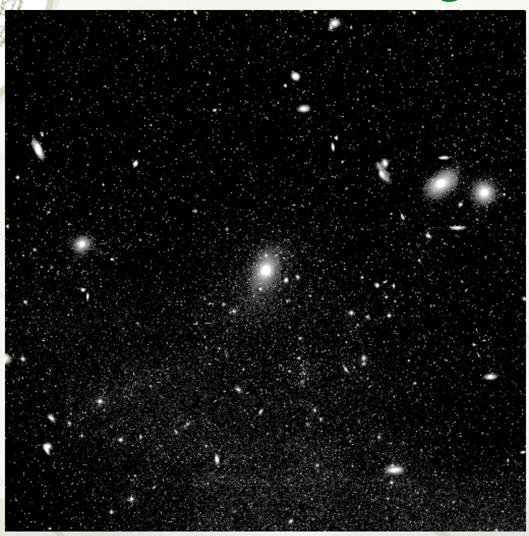
- This is our first evidence for non-baryonic dark matter…
  - Ω_B = 0.05 (nucleosynthesis)
  - Ω_{halos}= 0.1-0.3 (galaxy rotation curves)
- So, there is substantially more mass in the galaxy halos than could possibly be due to baryons!
- Suggests a non-baryonic form of matter may exist… something not based on protons and neutrons.

MASS OF GALAXY CLUSTERS

- Galaxy clusters
  - Large groups of galaxies
  - Bound together by mutual gravitational attraction
  - Let’s use same arguments for velocities and radii of galaxies in cluster as for V and R of stars in galaxies (i.e., based on Newton’s laws) to measure mass…

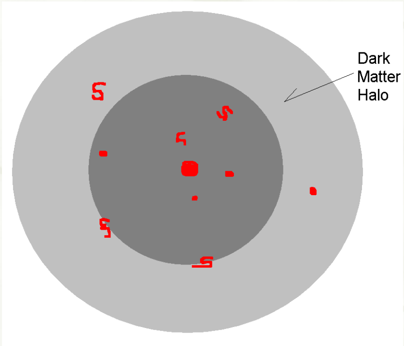
$$M_{cluster}(< R) \approx V_{gal}^2 R / G$$

The Virgo cluster



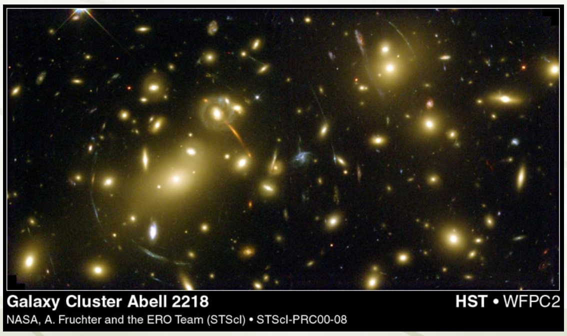
Dark matter in clusters

- Find that here is a giant halo of dark matter enveloping the galaxy cluster
- Includes the individual halos "attached" to each galaxy in cluster
- Also includes dark matter ripped from individual galaxies' halos, or never attached to them
- Add up the mass in these cluster halos…
- $\Omega_{cluster} = 0.3$
- Some of this mass is in hot gas in the cluster (contributing to $\Omega_B = 0.05$ from nucleosynthesis), but most is non-baryonic dark matter



Gravitational lensing…

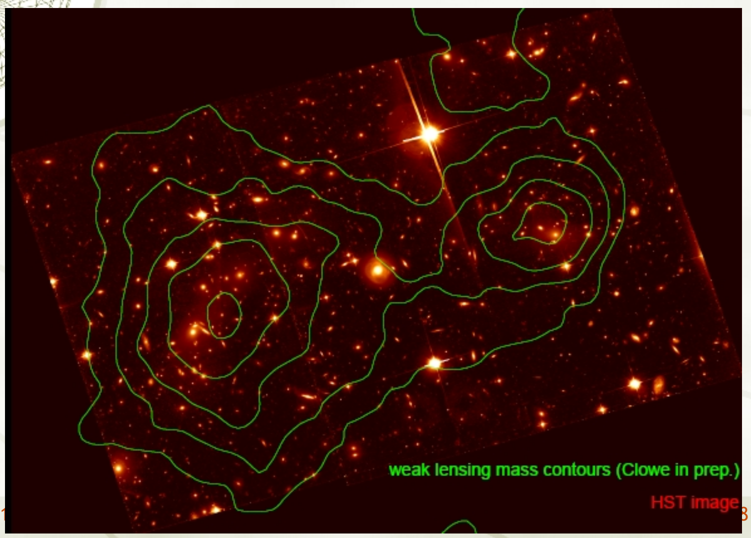
- In some cases, can also measure cluster mass using gravitational lensing.
- Get good agreement with dynamical measurements



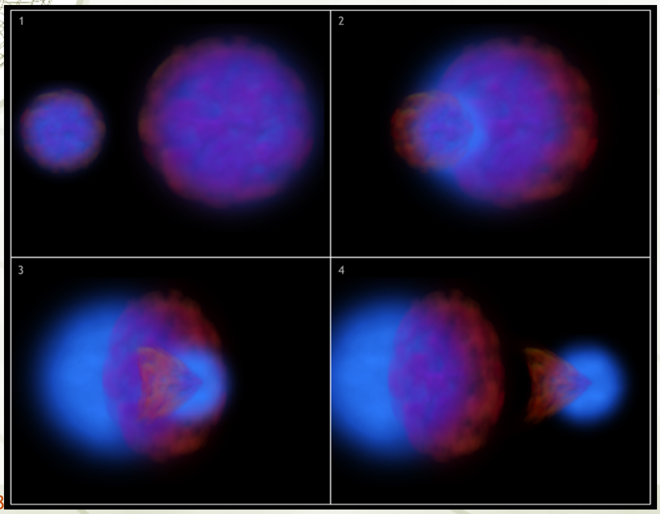
A cosmic collision: the Bullet Cluster

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

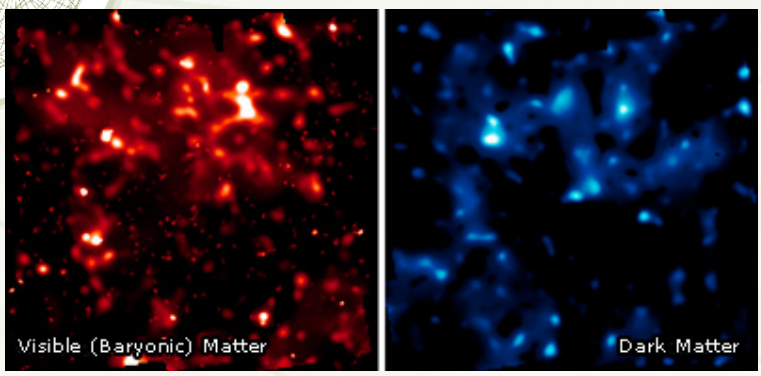
The mass is not in the baryons



Bullet cluster collision

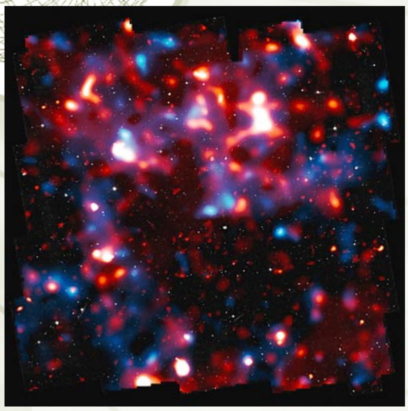


Dark matter map from gravitational lensing from the COSMOS survey



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

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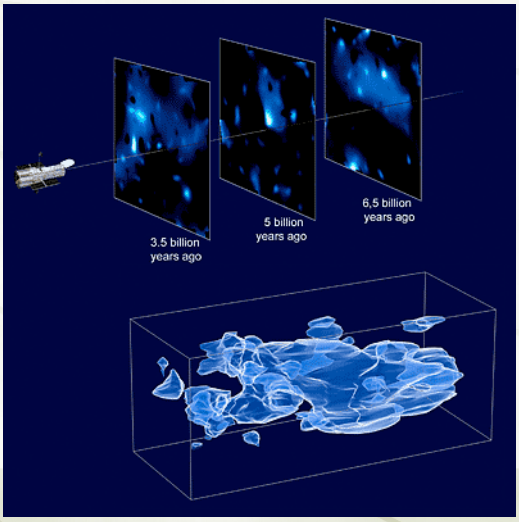
Dark matter map from gravitational lensing from the COSMOS survey



NASA, ESA, R. Massey

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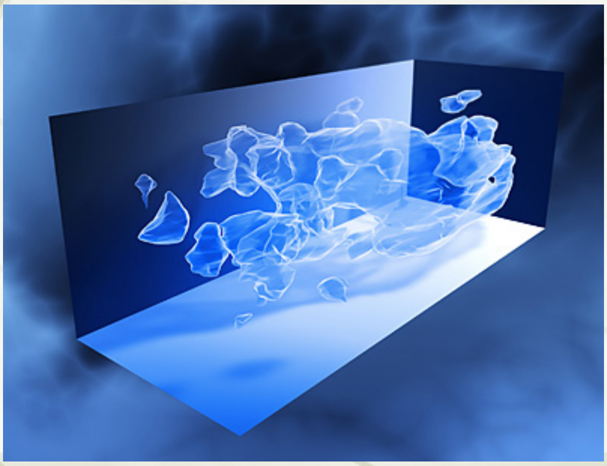
Dark matter map from the COSMOS survey



NON-BARYONIC DARK MATTER: SUMMARY

- Recap again…
  - Nucleosynthesis arguments constrain the density of baryons ($\Omega_B \approx 0.049$)
  - But there seems to be much more mass in galaxy and cluster halos (total $\Omega_{Matter} = 0.3$)
  - So, most of the matter in the Universe is not baryonic!
- what is it????
- We'll discuss candidates for non-baryonic matter later on…

- 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?
  - **No…** 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
  - 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 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

Next time…

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