Black is the Colour ......

So how did it all begin?

- In what follows:

The smallest things we will talk about are galaxies: typically 10 billion (10^{10}) stars and a size of 20 kpc (10^{20} m) M51 in Can Ven: HST picture	

But most of the time we'll be talking about clusters of galaxies: this is Coma cluster. Typically 1 million billion (10^{15}) M_{sun} and a size of 2 Mpc (10^{22} m)

Jim Misti Misti Mountain Observatory

Redshift:

In 1928, Slipher-Hubble-Humason found light from most galaxies is redshifted.

- The Doppler effect gives

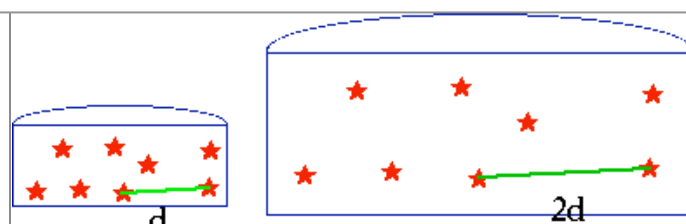
$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\delta\lambda}{\lambda_0}$$

- Velocity of recession: $v = zc$

Hubble found vel. of recession ∝ distance $v = Hd, H = 70\mathrm{km/s/Mpc}$

1 Mpc (megaparsec) = 3×10^{22} m.

Note although all galaxies are receding from us, does not imply we are at the centre: in the currant cake model all currants see all the others as receding



Big Bang (once over lightly)

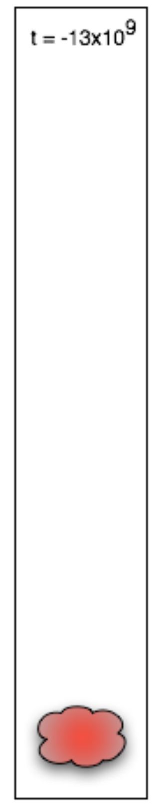
RULE 1 in Physics 100: Never mix your units!

$$H = 70 \times 1000/3 \times 10^{22} \approx 2 \times 10^{-18} s^{-1}$$
$$\Rightarrow \frac{1}{H} \approx 5 \times 10^{17}\mathrm{s} \approx 17 \times 10^{9}\mathrm{yrs.}$$

What does this time represent?

Must be age of universe: if expansion does not change

i.e. 17x10^{9} yr. ago, all the galaxies were in the same place. Universe had a beginning, implied by the big bang. Can run Hubble expansion back: we would like to use this to predict what will happen in the end



Where was the Big Bang?

- 

- A 2-D analog is the surface of a balloon: Note the following:
- It has no centre in 2-D space. Deflating it reduces it to zero size: i.e. at the moment of the big bang, not only matter was created, but also space and time
- The galaxies are not receding from us: space is expanding
- We **require** a curved 2-D surface embedded in a 3-D volume.

- This is a positively curved universe: we can also construct negatively curved ones (harder to visualize)

What's going to happen in the end?

How can we tell if the universe will expand forever?

- As a model, consider this as an escape velocity problem. How hard do we need to throw a galaxy on the "outside" so that it escapes? Note: our calculation had better not depend on r!

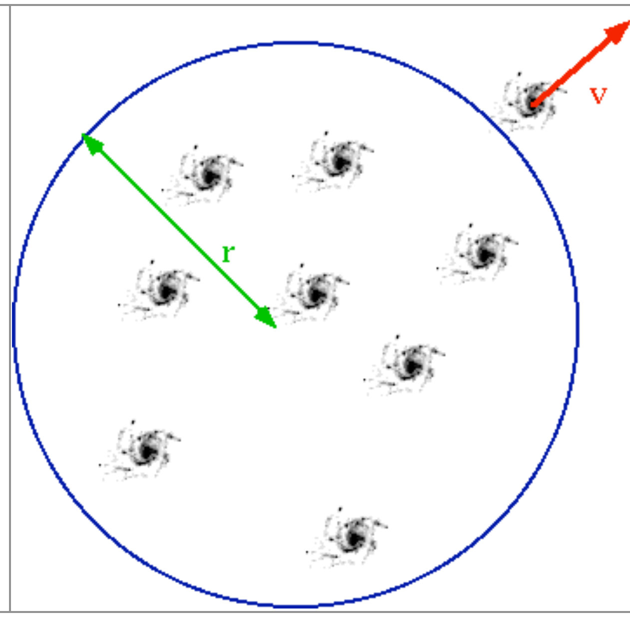
  $$\frac{1}{2}mv^2 - \frac{GMm}{r} = 0$$

  but

  $v = Hr$

  and the total mass of the universe inside

  $M = {}^{4\pi}/_{3}\ \rho\ r^3$



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so...

$H^2 r^2 = 2G\,{}^{4\pi}/_{3}\ \rho\ r^2$

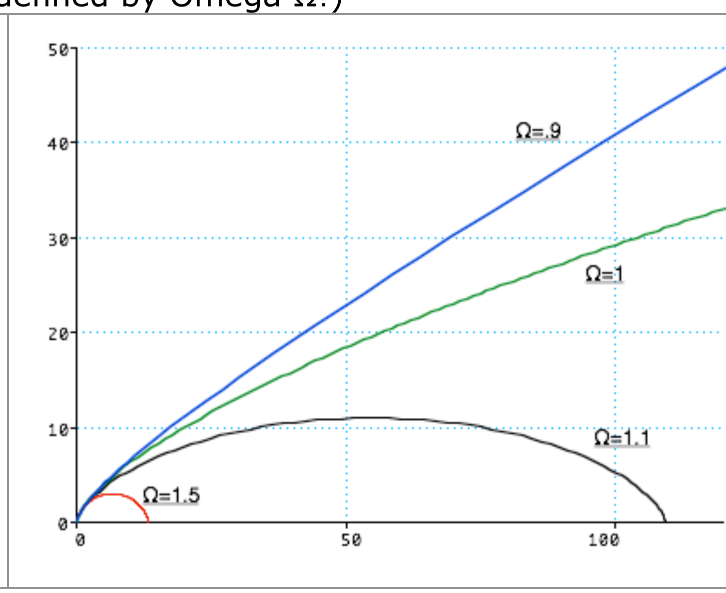
- (we got lucky: the r cancels out!). We can turn this round and write it as an equation for ρ
- $$\rho_0 = \frac{3H^2}{8\pi G}$$
- Hence the critical density
- $\rho_0 \sim 9 \times 10^{-27}$ kg m^{-3} ~ 6 Hydrogen Atoms m^{-3} (Number is flaky).
- We'll use $= \frac{\rho}{\rho_0}$, because some errors cancel out.

The entire future of the universe is given by this one number!!!!!!!!!

(and isn't it nice that the end of the universe is defined by Omega Ω!)

So if

- Ω > 1: Universe come to nasty end in ~ 50 x 10^9 yr.
- Ω = 1: "critical universe")Universe expansion slows down asymptotically
- Ω < 1: Universe expands forever
- More important:we live forever if Ω ≤ 1, (well maybe).



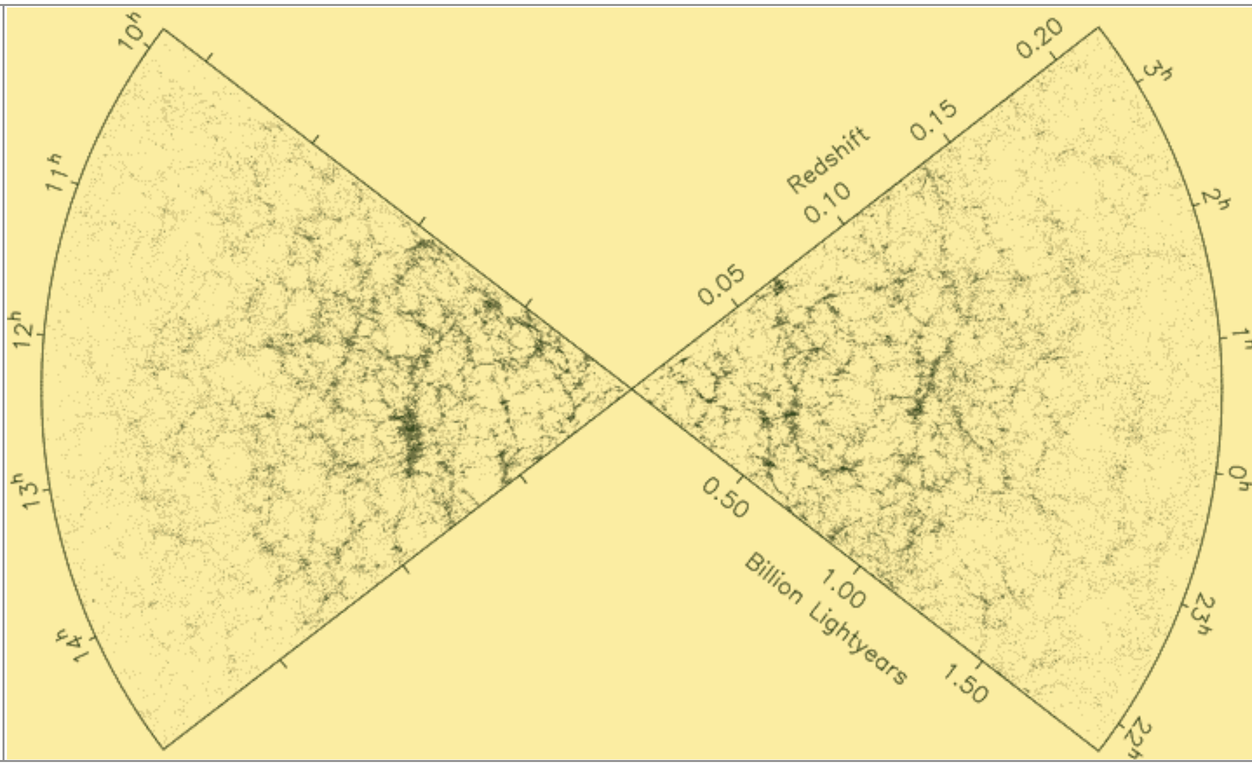
So how do we weigh the universe?

Can only see luminous matter: how much Dark Matter is there?

- First Guess: What you see is what you get!
- Count number of galaxies in a region of space, assume they consist of stars much like the sun, so assume

$$\frac{M}{L} = \frac{M_o}{L_o}$$

- Obviously must average over large enough volume such that universe is smooth R > 100 Mpc, and the universe is a very lumpy place!



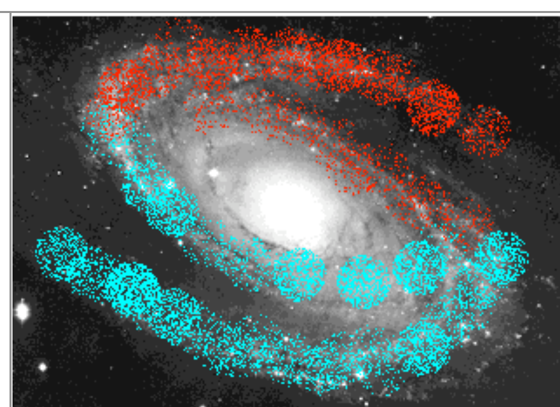
=> Density:

$$\approx .002$$

-
- (Note all these numbers are uncertain to ~ 20%!)
- We live forever!!!
- But wait a moment... How much matter is there we that we can't see?

Masses of Spiral galaxies

- direct observation i.e. measurement of velocities of individual stars in nearby => rotation curves or measurement of hydrogen via 21cm line or estimates of no. of stars



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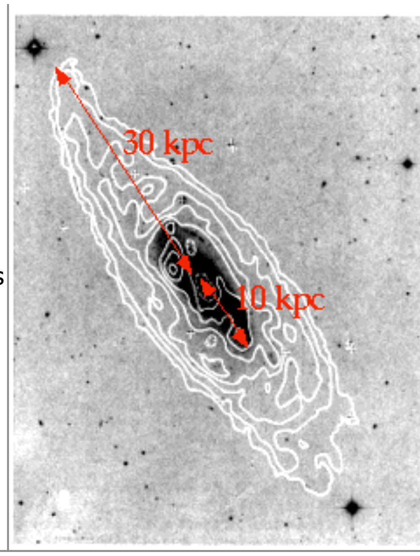
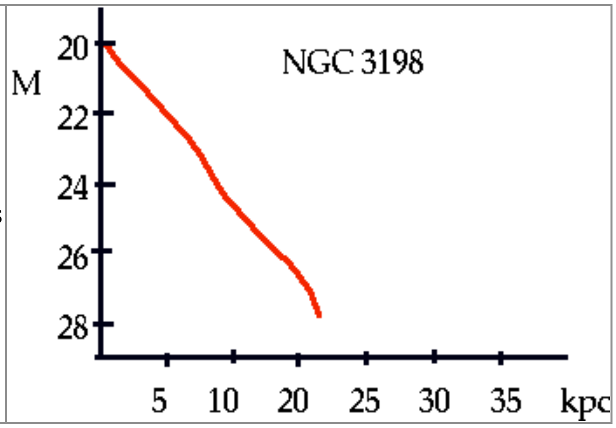
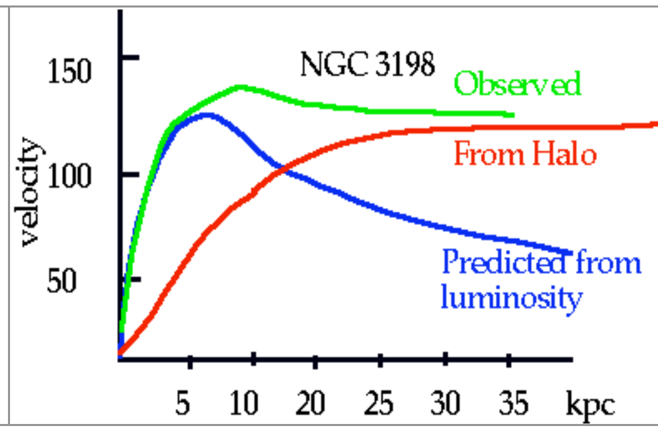
Typical Spiral (NGC3198) R ≈ 20 kpc but outer parts are just seen as H gas



Luminosity of galaxy should reflect mass



- Most of the light is fairly concentrated, so this should be good approx to the mass.
  but the outside part of the galaxy is rotating far too fast: i.e. velocity curve doesn't drop as expected. Means a lot of mass in outside part of galaxy: the "halo"



For spirals

$$\frac{10M_o}{L_o} < \frac{M}{L} < \frac{40M_o}{L_o}$$

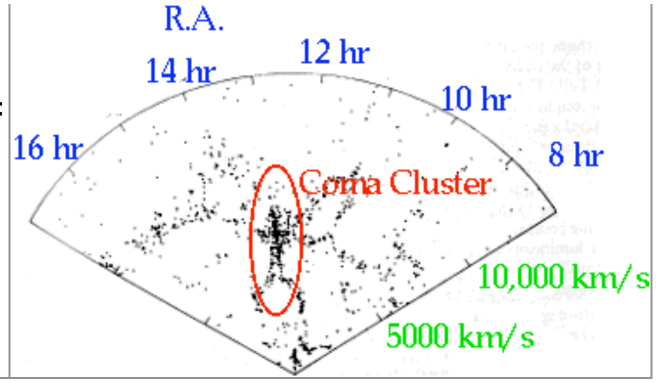
- Implication: Mass of observed galaxy ≈ 10^{10} M_o, R ≈ 2 kpc (for core) Mass of halo ≈ $10^{13} M_o$, R ≈ 100kpc (except that we can't measure out there!)

$$\approx .05$$

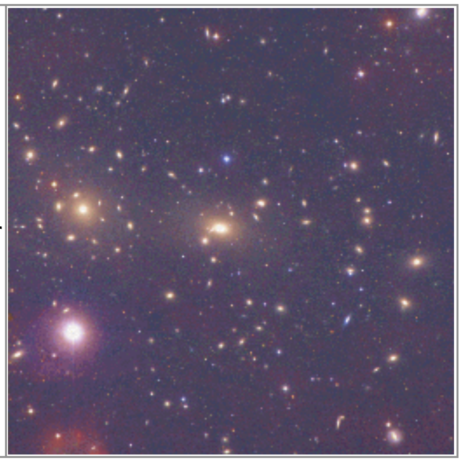
- What do we mean by mass of galaxy? In fact the visible part of the galaxy may just reflect the dark matter.

Large clusters of galaxies:

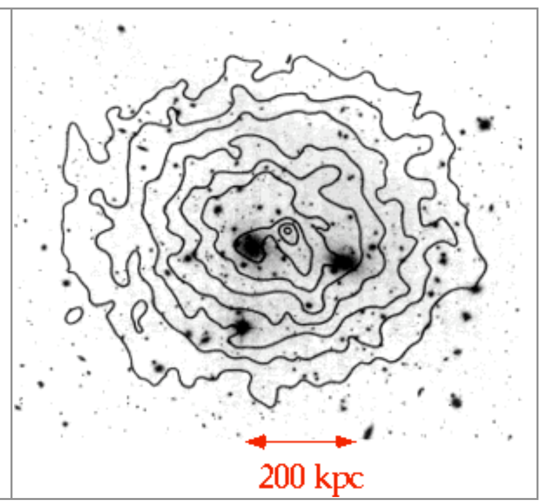
- Can measure speeds of individual galaxies in a cluster:
- faster moving galaxies imply more mass in cluster
- This gives much higher masses than individual spirals
- $\frac{M}{L} \approx 300 \frac{M_o}{L_o}$



A check: The Coma cluster

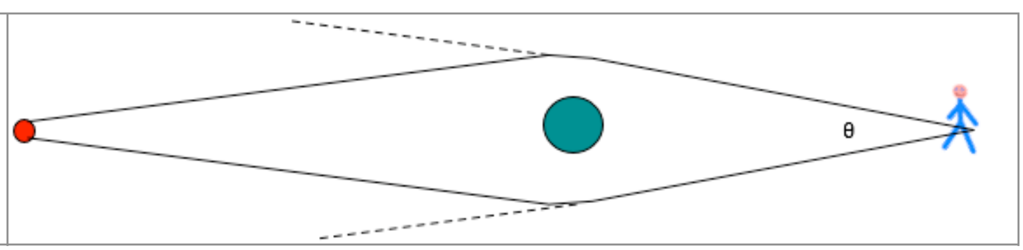


- Large clusters contain a lot of hot gas, which is strong X-ray source. Picture is negative optical + contours of X-rays
- X-ray pictures measure density and temp:

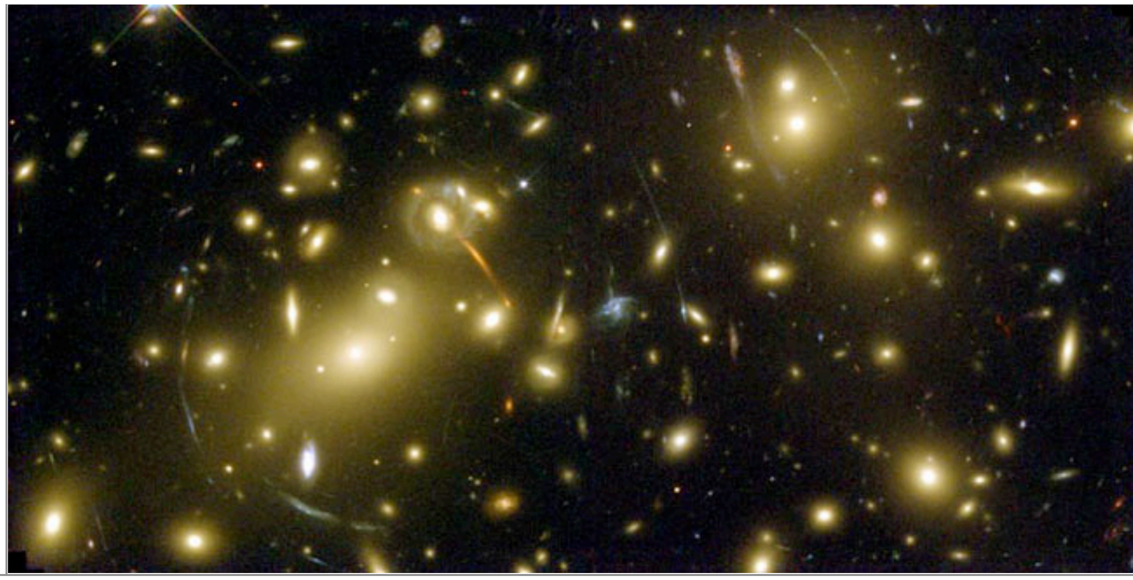


- but the X-rays don't come from where the matter is .....

Also large masses bend light, so large clusters show "gravitational lensing" of very distant objects.



Allows us to estimate the mass. For Abell 2218 we seem to have at least 300 times as much dark matter as luminous matter



The Bullet Cluster

Combination of lensing (blue) and X-rays (red) in the bullet cluster:

Strong evidence for non-interacting dark matter:

- X-ray emitting material is gas, so gets stopped in collision
- dark matter gets carried along

- a) What the hell? i.e. what is the dark matter?
- b) Why the hell? i.e. why is $\Omega \sim 1$ (after all it could be anything?)
- Actually, there is a limit

$$\Omega < 3$$

otherwise the universe would be younger than the earth (wouldn't that make the creationists happy!!)

What the hell:

1. Brown dwarfs
2. Hydrogen gas
3. Jupiters
4. Hydrogen rain
5. Low surface brightness galaxies
6. Maxi Black holes
7. Mini Black holes
8. Neutrinos
9. He H^+
10. Modified $1/r^2$ law
11. Axions
12. Weakly Interacting Massive Particles (WIMPS)
13. Magnetic Monopoles
14. Majorons
15. Photinos
16. E_8 shadow matter
17. Cosmic Strings

Which is it? We don't know! However, all of the above have problems.

The Generic Candidates for Dark Matter :

1. Baryonic (BDM): (we use this as shorthand for "ordinary matter") maybe in some odd form e.g. rocks
2. Hot (HDM) light particles e.g. neutrinos v's

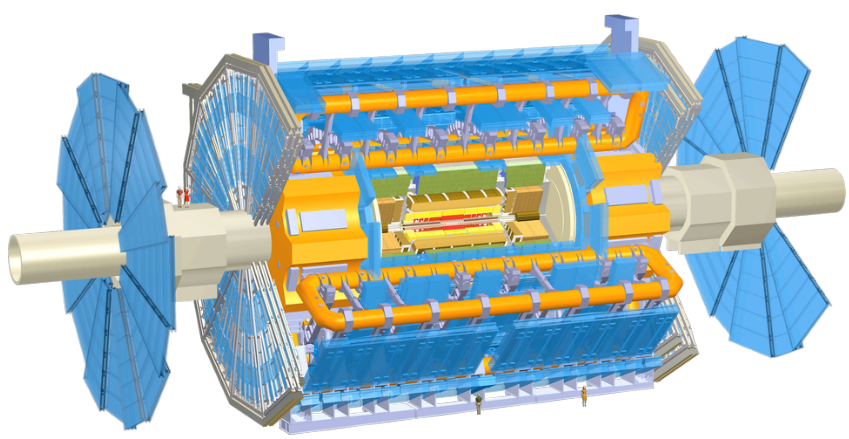
3. Cold (CDM): heavy (usually) particles e.g. WIMPs

What the hell:

- ~~Brown dwarfs~~ Not enough
- ~~Hydrogen gas~~ Would be seen unless it was very diffuse, in which case, not enough
- ~~Jupiters~~ Not enough
- ~~Hydrogen rain~~ Too hot
- ~~Low surface brightness galaxies~~ Doesn't fix the problems in spirals
- ~~Maxi Black holes~~ Only exist at the centre of galaxies: we need halos
- ~~Mini Black holes~~ Not enough
- ~~Neutrinos~~ Part of the solution, but too light
- ~~He H~~ $^+$ Unstable
- ~~Modified $1/r^2$ law~~ Hard to reconcile with Bullet cluster
- ~~Axions~~ Negative searches so far
- Weakly Interacting Massive Particles (WIMPS)
    - ~~Magnetic Monopoles~~ Screw up magnetic fields in galaxy
    - Photinos Will see them in 2008 (maybe)
    - ~~E_8 shadow matter~~ and there is a tooth fairy...
- ~~Cosmic Strings~~Wrong properties

WIMPS

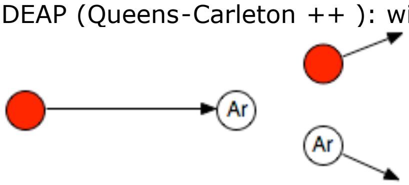
- Heavy particles (say 100 m_{proton}) with interactions like a neutrino
- A lot can be ruled out by "in vitro" experiments (e.g. OPAL: Richard Hemingway and others at Carleton + Alberta +UBC + Victoria + Montreal + 300 others) at CERN
- ATLAS (2008) will be able to rule out a lot more options

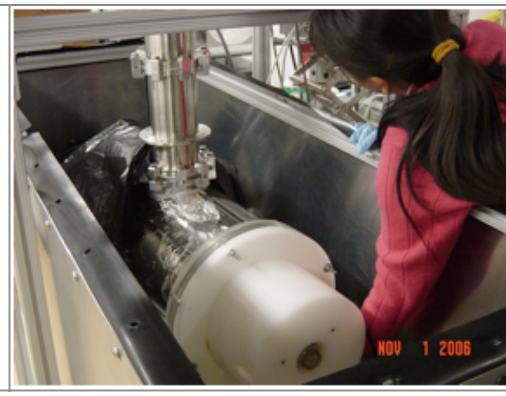


Generic WIMPS can be seen "in vivo" via a variety of low temp. expts.

e.g. Picasso (Queens-Montreal) Nucleus will recoil and transfer energy to super-heated freon liquid and cause transition to gas.

- DEAP (Queens-Carleton ++): will use liquid argon and look at recoil

Where did the galaxies come from?

There is confirmation of the general CDM/WIMP picture from the microwave background measurements: fossil light shows us what the universe was like 300,000 years after the Big Bang

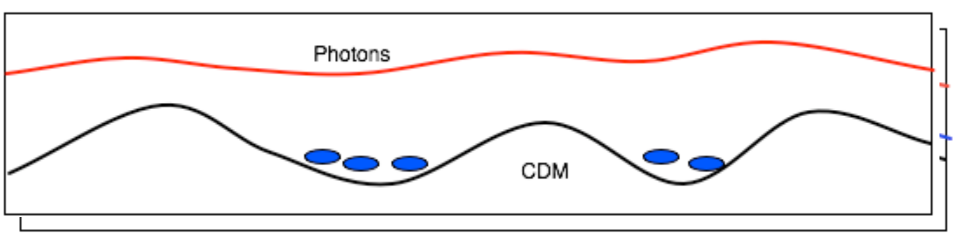
- COBE and WMAP comparison
- But note that the actual variations are tiny: 10^{-5}K

Before galaxies form, Universe is filled with fluid of radiation and matter.

Normally density fluctuations die away (e.g sound waves) but in massive fluid they get amplified by gravity	

Hence Scenario

- CDM decouples
- CDM dominates and clumps
- Atoms (baryons) decouple
- Baryons clump onto CDM
- Galaxies form



Can simulate structure formation on large scale with (massive) n-body computer codes

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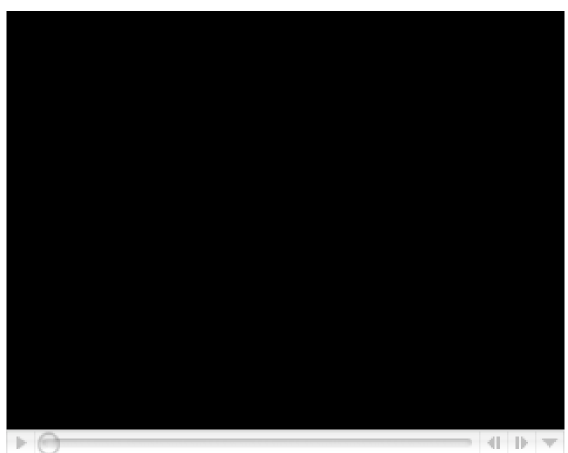
and on scale of clusters.

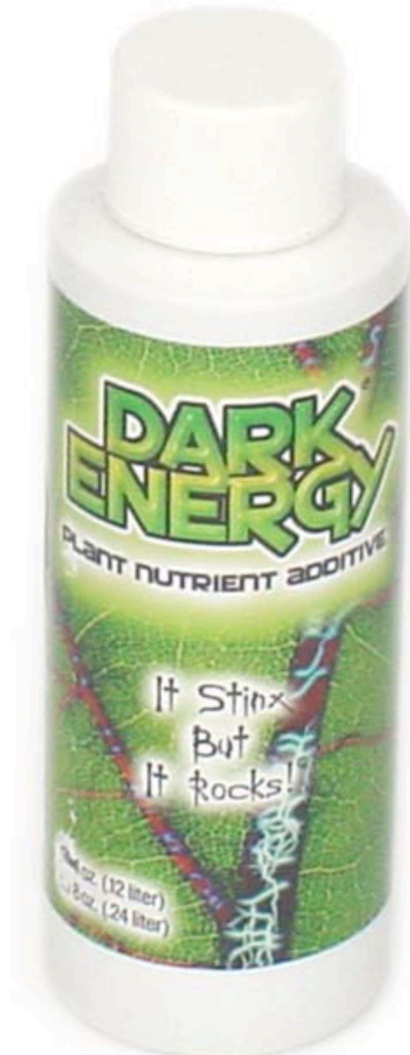
{Performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University).



Dark Energy

And just when you thought it was safe to go out at night....

-

Dark Matter is bad enough, but now dark energy ...	

Luminosity distance "standard candle"

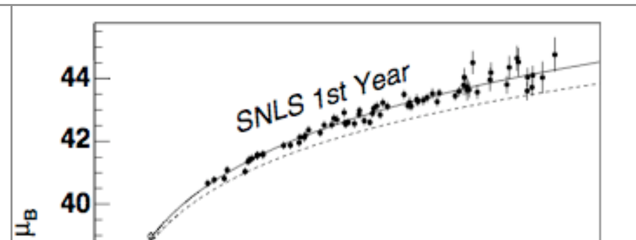
If Luminosity is known, then flux is $f = \frac{L}{4\pi d_L^2}$

Type 1a Supernovae Mv = -20 allows us to measure out to 3000Mpc: LBL High Redshift Supernova Search

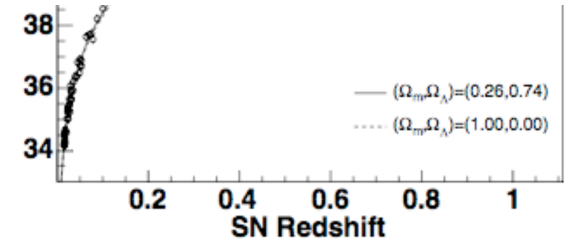
SuperNova Legacy Survey

Canada-France Hawaii Telescope (CFHT)

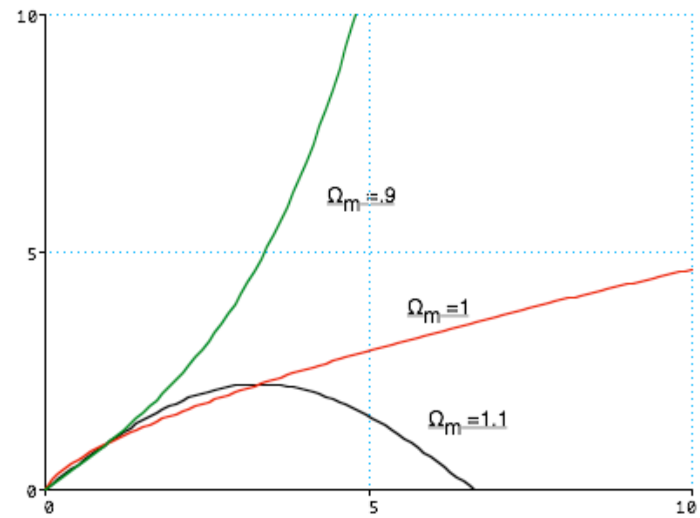
(U of T and others) now provides best data from CFHT: The



implication is that the expansion of the universe is accelerating.



May imply cosmological constant Λ (Einstein's "fudge factor"): in other words vacuum has an energy.



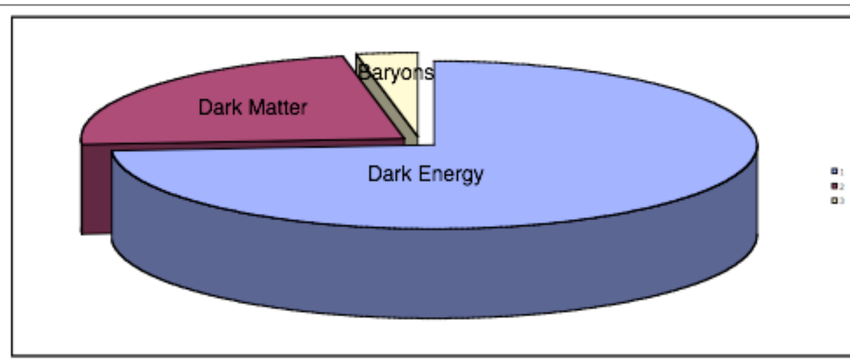
What can dark energy be?

List of all well-motivated models for dark energy

- -
- -
- -
- -
- -

Combining all the data gives "concordance model

- Ω_{Matter} = 0.27 ± .02
- Ω_Λ = 1 - Ω_M



However, there are major problems (what, more?). Simplest model is cosmological constant: i.e. vacuum has an energy: how much?

- Dark energy implies that the vacuum has an energy density:

$$\rho_\Lambda \approx 100\rho_B \approx 10^{-13} JM^{-3}$$

- We could understand $\Omega_\Lambda \equiv 0.$: but....
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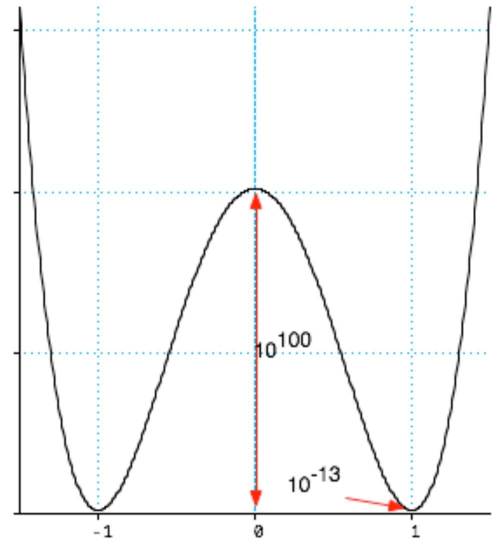
- The only working theory for particles (the standard model) gives $_{\Lambda} = 10^{110} - V_0$ where V_0 is a (unknown) correction. You will notice a discrepancy!



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00000000000000000000.0000000000000
- -99999999999999999999999999999999999999999999999999999999999999999999999999999999
999999999999999999.9999999999999
- = .00000000000001
- get real!
- **Statutory Warnings**
- All of this depends on the assumption that type 1a SN are always the same at $4x10^9$ L_0, even at z = .5. Effect disappears if some (unknown) effect reduces L by 30%
- e.g. Hubble original estimate for H_0 was wrong by factor 7 because 2 different kinds of Cepheids.
- Ω_Λ and Ω_{Matter} are almost equal at present. In the past they would have differed by 10^{40}

Summary/Take Home Message

So......

- We need dark matter
- We need Ω_{DM} ~ .26
- We know $\Omega_{baryons}$ ~ .03
- We have quite reasonable models for DM
- We will (likely) see it by 2010
- If we don't we'll have eliminated a lot of models
- We seem to require dark energy
- We need Ω_Λ ~ .74
- We have no convincing models
- The good models we do have predict nothing like the values we see
- We may not know anything more for 20 years.
- Talk, references and other material at http://www.physics.carleton.ca/~watson/
- Most of the pictures from Astronomy Picture of the Day at http://antwrp.gsfc.nasa.gov/apod/astropix.html