*Lecture 21 : What kind of Universe do *we* live in?*

- What is **our** universe like?
  - Matter content?
  - Geometry (flat, spherical, hyperbolic)?
  - Anything else strange?

© Sidney Harris

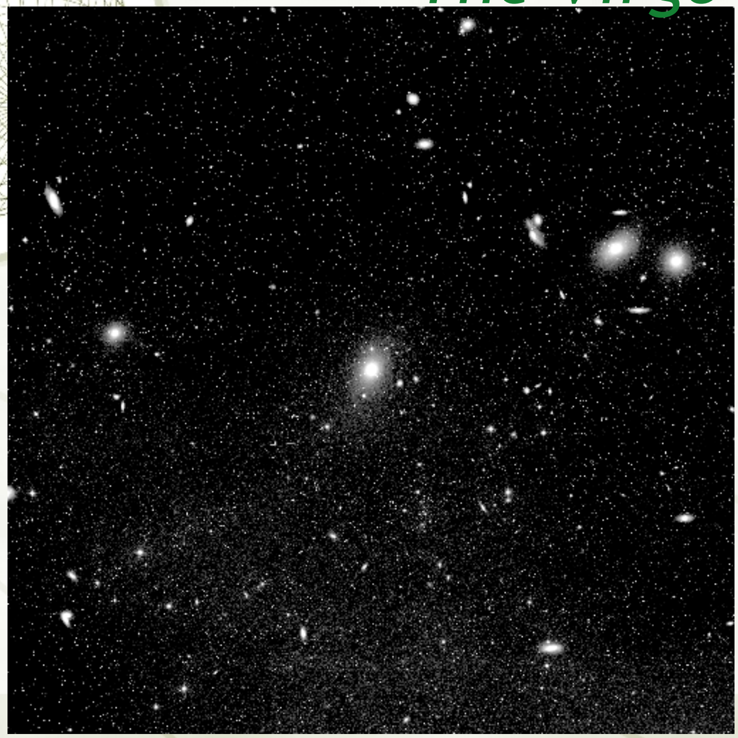
- Remarkable agreement between different experimental techniques: "Cosmic concordance" parameters

Please read Ch. 13 in the textbook

Measurements of the matter content of the Universe (recap)

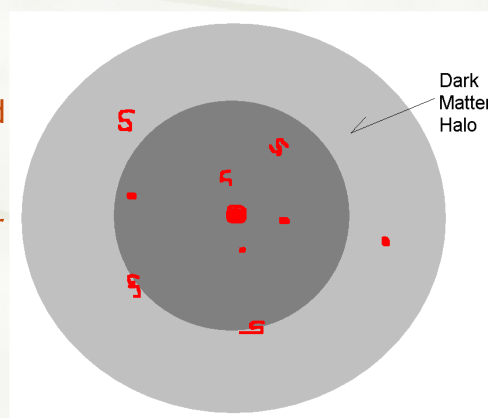
- Primordial nucleosynthesis
  - Theory predicts how present light element abundances (^{4}He, ^{3}He, D, ^{7}Li) depend on mean baryon density
  - Observed abundances $\Rightarrow \Omega_B \approx 0.04$
- Galaxy/galaxy-cluster dynamics
  - Look at motions of stars in galaxies, or galaxies in galaxy clusters… $\Omega_M \approx 0.3$
  - Infer presence of large quantities of "non-baryonic dark matter" ($\Omega_{DM} \approx 0.25$)

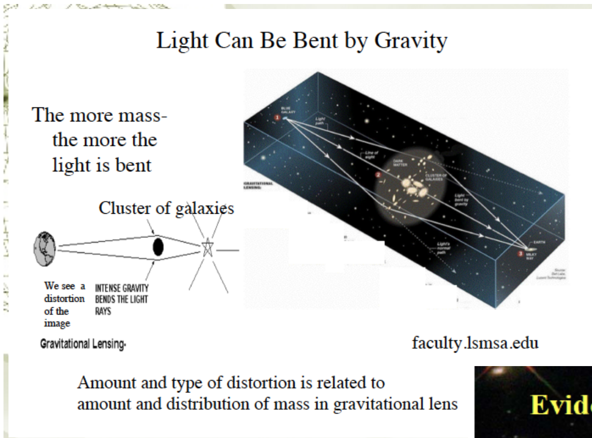
The Virgo cluster



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 $\Omega_B = 0.04$ from nucleosynthesis), but most is non-baryonic dark matter





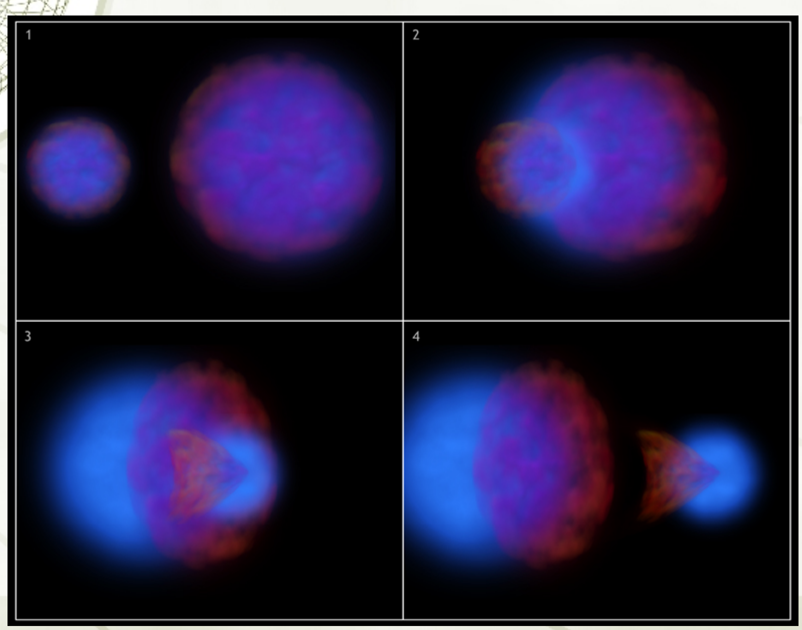
Gravitational lensing…

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

A cosmic collision: the Bullet Cluster

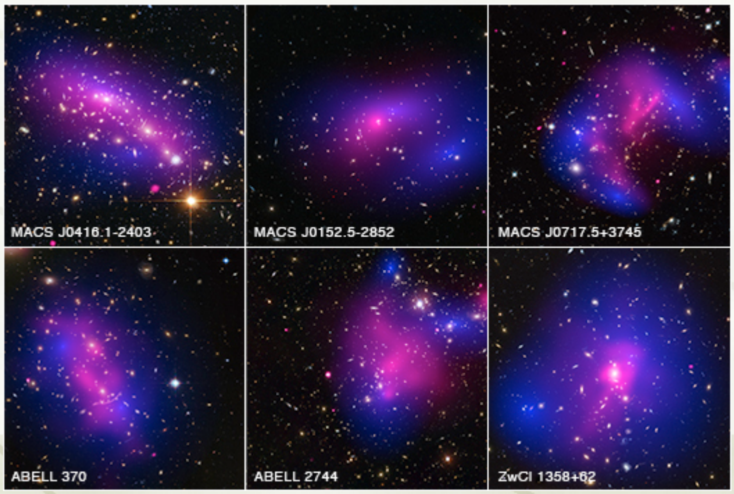
- Red: X-rays (hot gas)
- Blue: Matter from lensing
- White-optical light from stars in galaxies

Bullet cluster collision

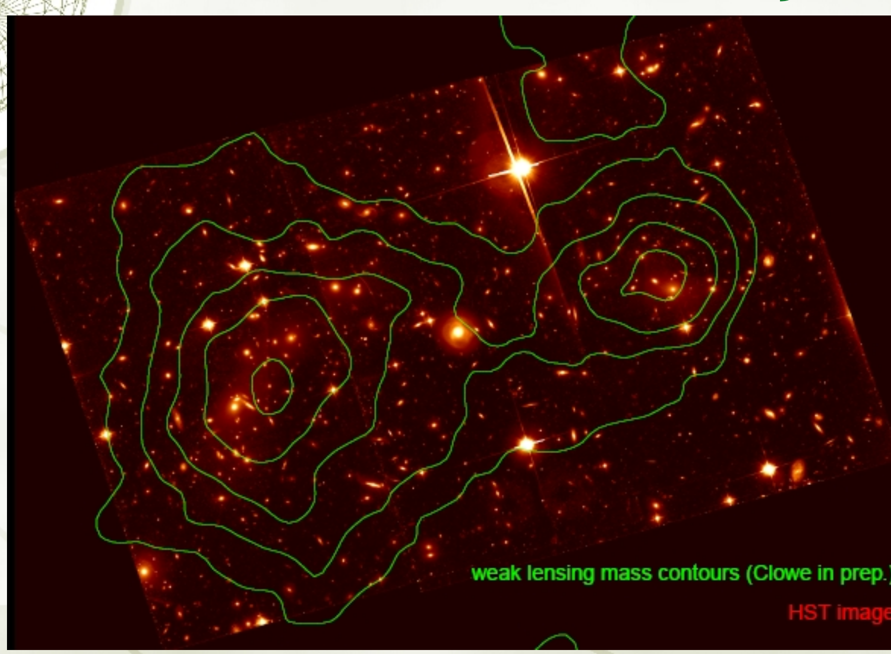


Last week in the news

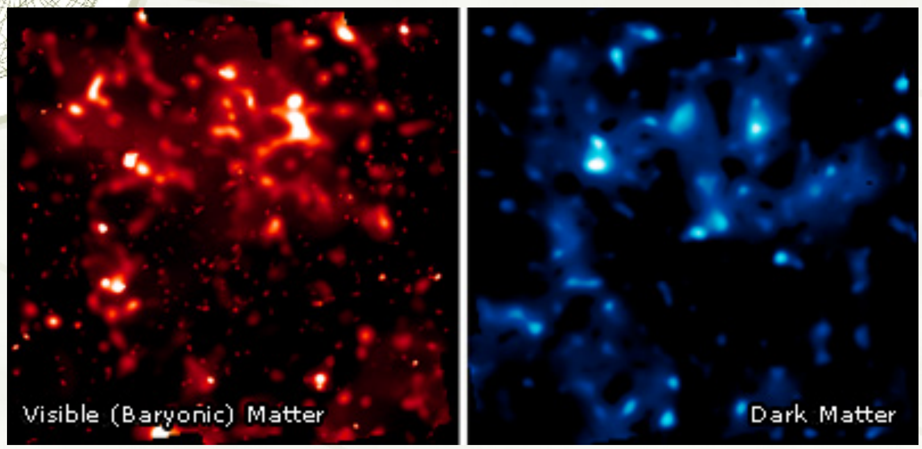
- Dark matter 'ghosts' through galactic smash-ups (http://www.bbc.com/news/science-environment-32066013) **– the Bullet cluster is not alone**



The mass is not in the baryons

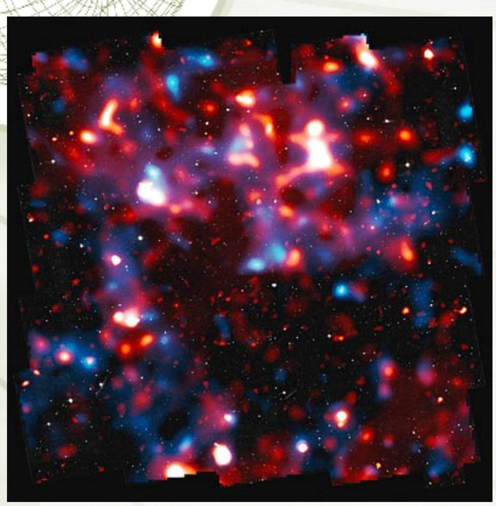


Dark matter map from gravitational lensing from the COSMOS survey



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

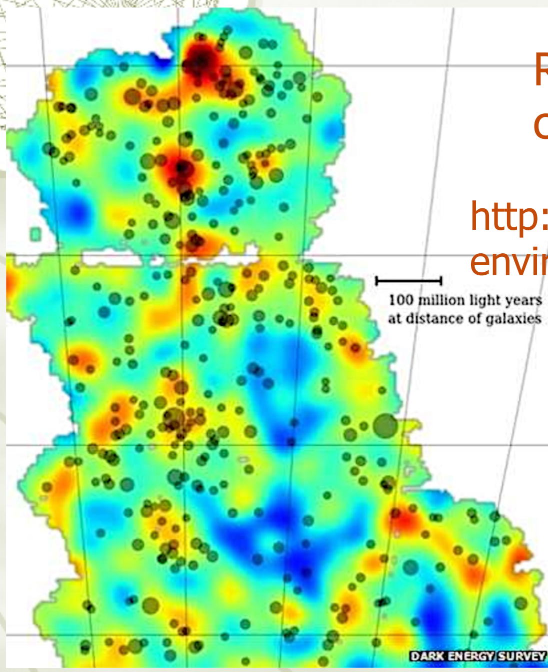
Dark matter map from gravitational lensing from the COSMOS survey



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

Wide Field Lensing Mass Maps from the Dark Energy Survey (DES) Press Release Today



Red-lots of mass from lensing circles- clusters of galaxies

http://www.bbc.com/news/science-environment-32284995

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_M=0.1-0.3)

The CMB also strongly constrains Ω_M =0.3156 ± 0.0091

- So, most of the matter in the Universe is not baryonic
- So… what is it?

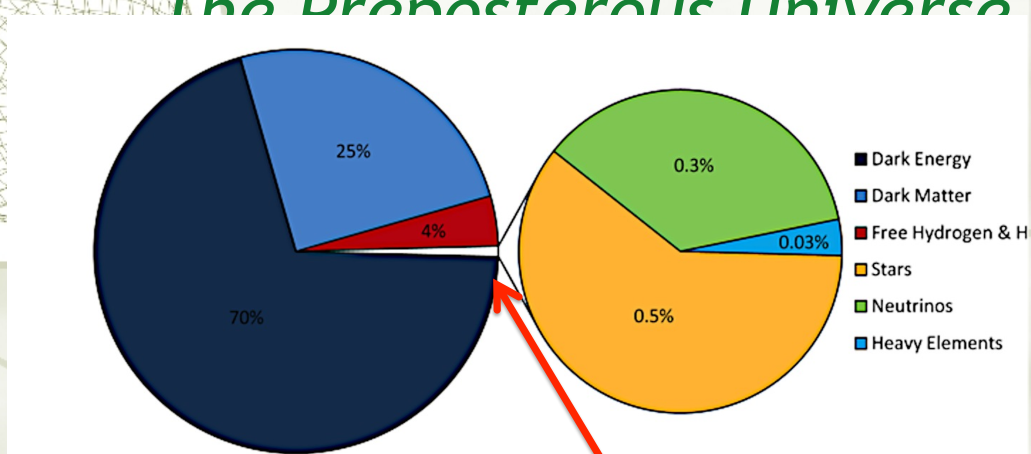
Evidence for dark matter is overwhelming

- 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 in galaxies
- 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



what we understand

preposterousuniverse.com/preposterous.html(S. Carroll)

So What is Dark Matter

- 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- but are very hard to detect

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 (only upper limits on mass –measured only very recently)

Possible dark Matter Candidates?

- Particle physicists have proposed literally tens of possible Dark Matter candidates.
- Axions: 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
- Must 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**

WHAT IS THE GEOMETRY OF OUR UNIVERSE?

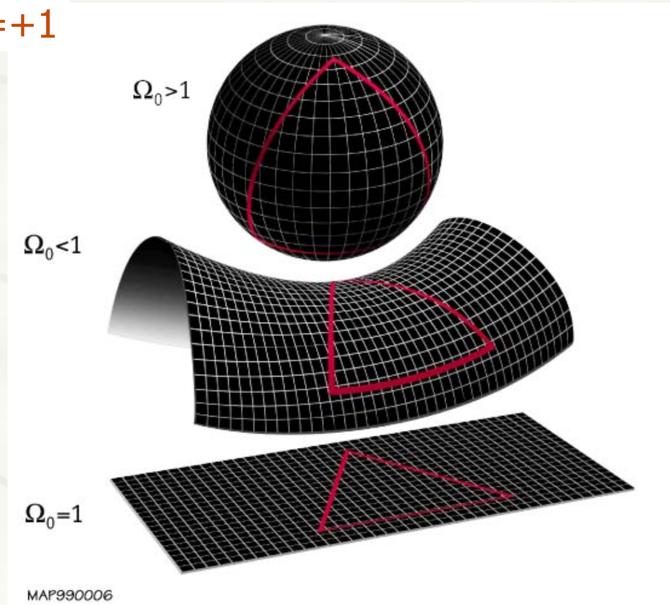
- Recall that universe with different curvature has different geometric properties
- Adding up the angles in a triangle,
  - Flat universe($k = 0$): angles sum to 180°
  - Spherical universe ($k = +1$): angles sum to >180°
  - Hyperbolic universe ($k = -1$): angles sum to <180°
- Similarly, for a known length L at a given distance D, the angular size on the sky varies depending on the curvature of space
  - Flat universe ($k = 0$): angular size $\theta = L/D$
  - Spherical universe ($k = +1$): angular size $\theta > L/D$
  - Hyperbolic universe ($k = -1$): angular size $\theta < L/D$

Graphics: NASA WMAP project

k=+1

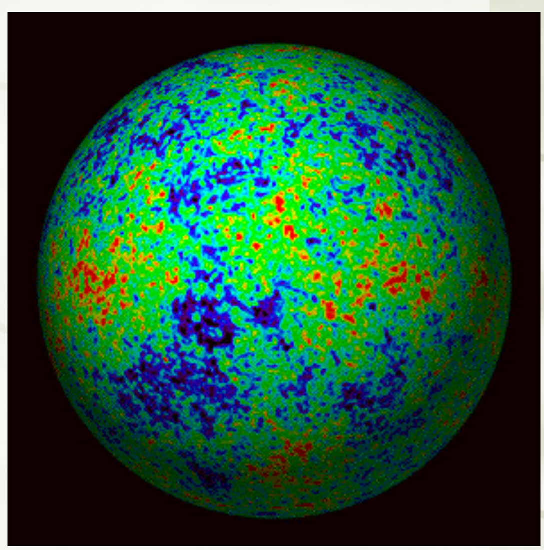
k=-1

k=0



Angular size of fluctuations in the CMB

- Remember the cosmic microwave background…
- It has fluctuations,
  - Average scale of fluctuations is known (associated with sound waves in early Universe)
  - Distance *D* to this "surface of last scattering" is also known
- Can use apparent angular separations of fluctuations compared to *L*/*D* to infer geometry of Universe

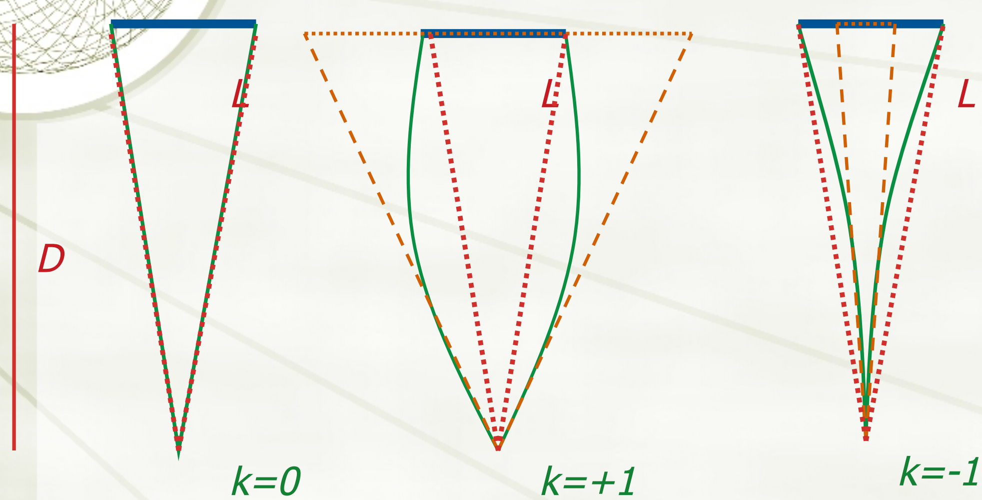


Graphics: NASA WMAP project

Power spectrum peaks and valley

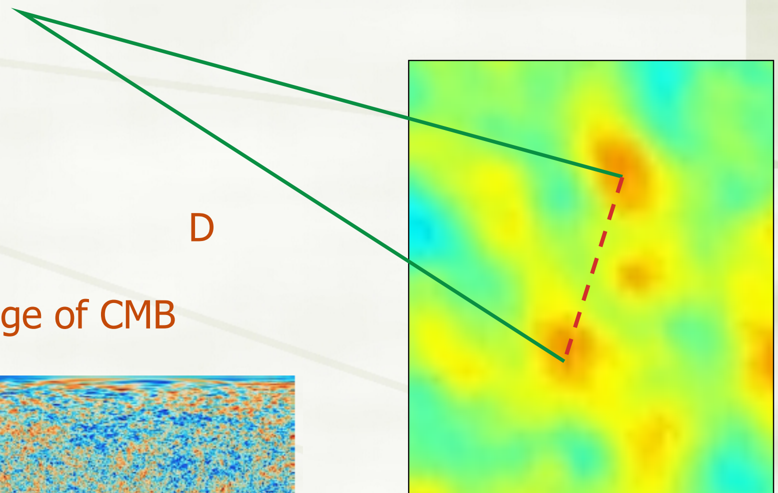
- Angular scale of first (large) peak corresponds to wavelength of sound wave that would have completed half an oscillation within 300,000 years
- This is the "fundamental" peak, at about 1° angular scale
- Peaks at scales <1° are higher harmonics

Curvature affects apparent size or field of view



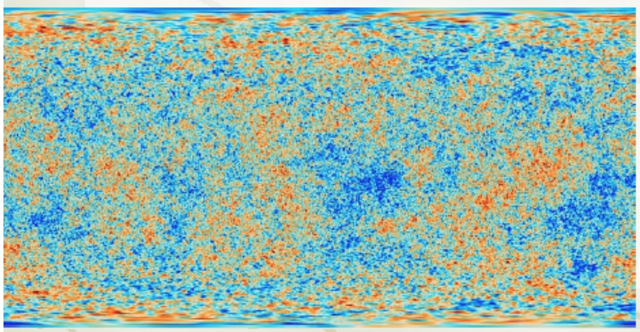
zoom in on CMB wiggles

us



D

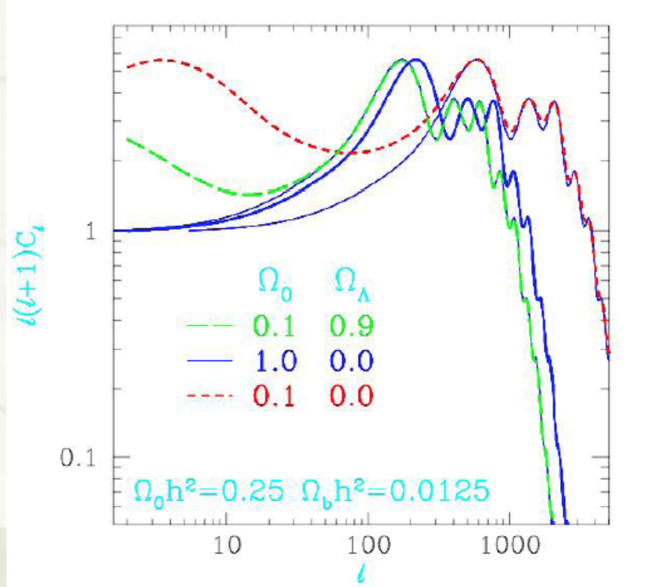
all sky image of CMB



How CMB Spectral changes for varying parameters

Spectra from CMB maps also help constrain other parameters…

Here's how it changes with Ω,Λ



Flat universe!

- Result:
  - The universe is **flat**
  - But, the sum of all known (baryons+dark matter) matter gives $\Omega_M = 0.3$
    - Surely, this implies an open/hyperbolic universe???
  - We must be missing something…
- Remember Einstein's cosmological constant?
  - Cosmological constant corresponds to an energy field that fills space… it is NOT matter, but still contributes to the curvature of the Universe
  - We can get a flat Universe if $\Omega_M + \Omega_\Lambda \approx 1$
  - So, we can reconcile the measurement of mass with flatness of Universe if $\Omega_\Lambda \approx 0.7$
  - What additional effect would this have?
  - This dark energy acts to **accelerate** the Universe!

Remember the Equations

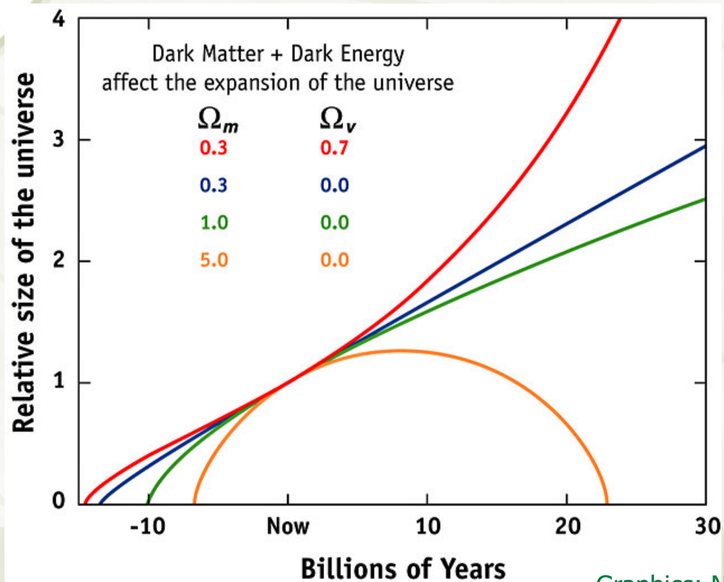
The universe is **flat k=0**

- In terms of omega curvature parameter, $k = 0$ means $\Omega_k = 0$
- Recall that the sum of all three omega parameters as measured at present time must be 1 for the universe to be flat: $\Omega_M + \Omega_\Lambda + \Omega_k = 1$
- How do we reconcile Ωk = 0 with our measurement of the matter density, which indicates $\Omega_M = 0.26$?
- There must be a nonzero cosmological constant, $\Omega_\Lambda = 0.74$!

$$\Omega_M \equiv \rho_0/\rho_{crit} \equiv \rho_0/(3H_0^2/8\pi G) \quad \Omega_k \equiv -kc^2/R_0^2H_0^2 \quad \Omega_\Lambda \equiv \Lambda/3H_0^2$$

Non-zero Λ

- Recall that with a non-zero, positive value of Λ (red curve) the universe expands more rapidly than it would if it contained just matter (blue curve)



Graphics: NASA WMAP project

II : The accelerating Universe

- Huge clue came from observations of Type-1a Supernovae (SN1a)
  - SN1a are exploding White Dwarf stars
  - They are very good "standard candles"
  - Can use them to measure relative distances very accurately… can look for acceleration

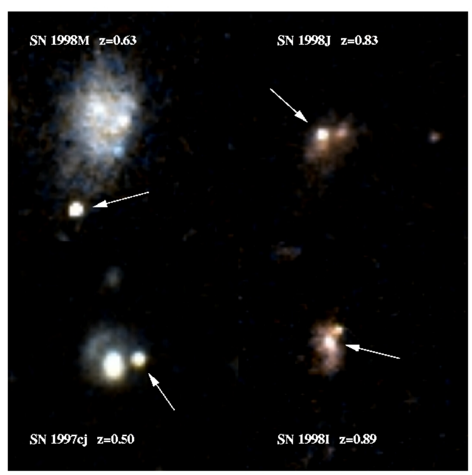
Type 1A Supernovae

- What produces a SN1a?
  - Start off with a binary star system
  - One star comes to end of its life – forms a "white dwarf" (made of helium, or carbon/oxygen)
  - White Dwarf starts to pull matter off other star… this adds to mass of white dwarf (accretion)
  - White dwarfs have a maximum possible mass… the Chandrasekhar Mass (1.4 M_{Sun})
  - If accretion pushes White Dwarf over the Chandrasekhar Mass, it starts to collapse.

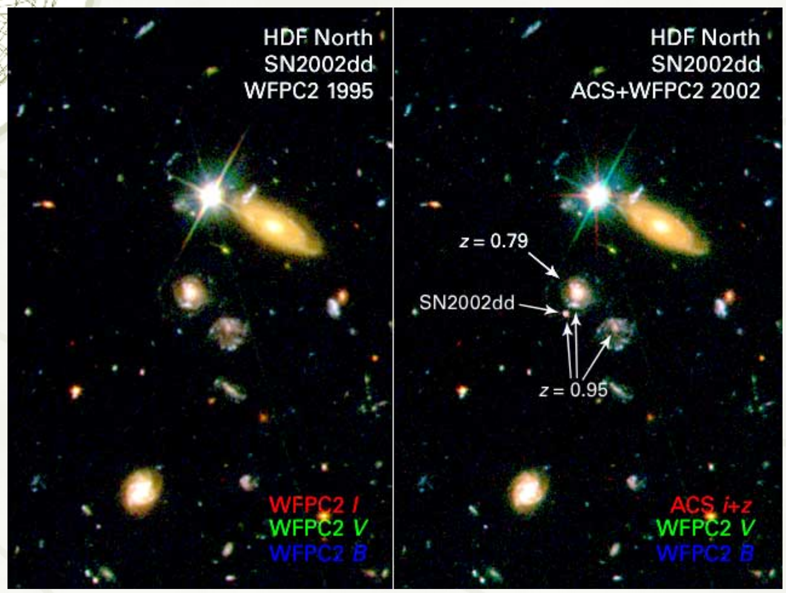
- White Dwarf starts to collapse…
  - Rapidly compresses matter in white dwarf
  - Initiated runaway thermonuclear reactions – star turns to iron/nickel in few seconds
  - Liberated energy blows star apart
  - Resulting **explosion** briefly outshines rest of galaxy containing it… these are the SN1a events
- SN1a
  - No remnant (neutron star or black hole) left
  - Since white dwarf always has same mass when it explodes, these are "standard candles" (i.e. bombs with a fixed yield, hence fixed luminosity)

Cosmology with SN1a's

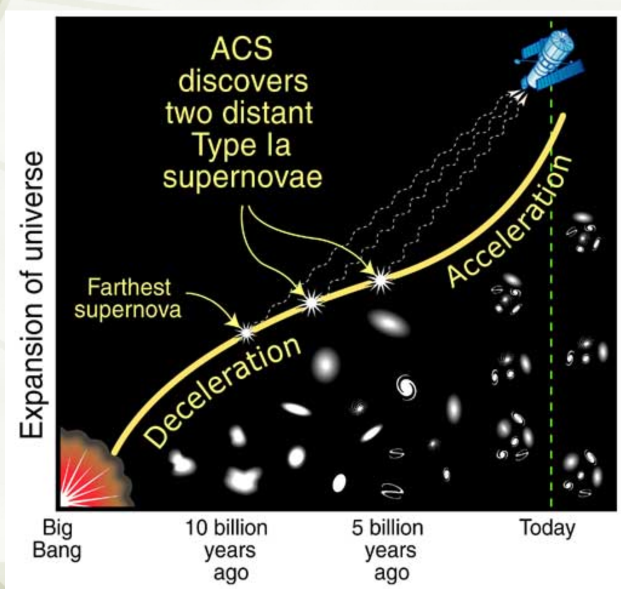
- The program:
  - Search for SN1a in distant galaxies
  - Compare expected power with observed brightness to determine distance
  - Measure velocity using redshift
- "Low redshift" galaxies give measurement of H_0
- "High redshift" galaxies allows you to look for deceleration of universe



Distant supernova

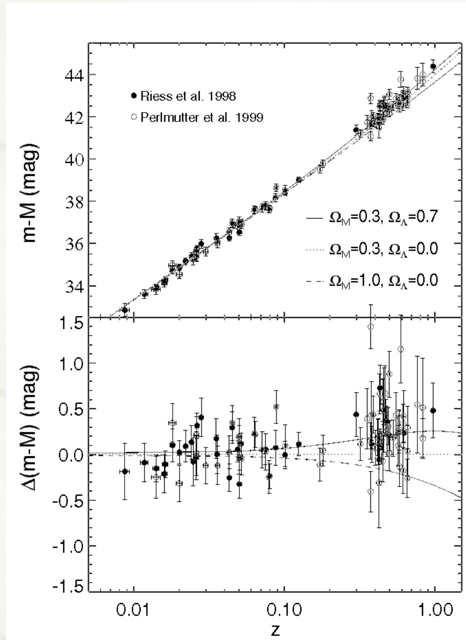


The accelerating universe



The results…

- This program gives accurate value for Hubble's constant
  - H = 72 km/s/Mpc
- Find acceleration, **not** deceleration, at large distance!
  - Very subtle, but really is there in the data!
  - Profound result – confirms existence of Dark Energy!

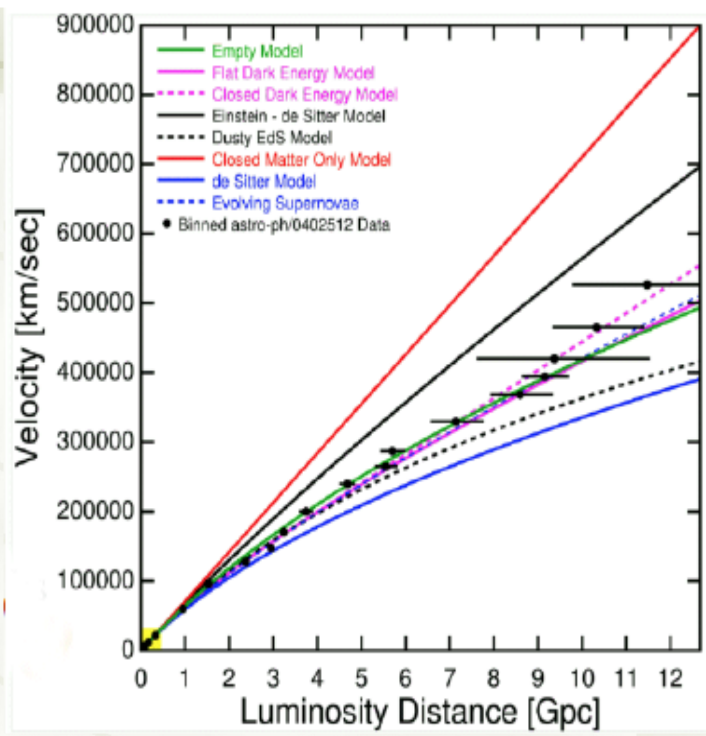


Graphics: Ned Wright, UCLA

Purple curve:
$\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$

Black curve:
$\Omega_M = 1$, $\Omega_\Lambda = 0$

Green curve:
$\Omega_M = 0$, $\Omega_\Lambda = 0$



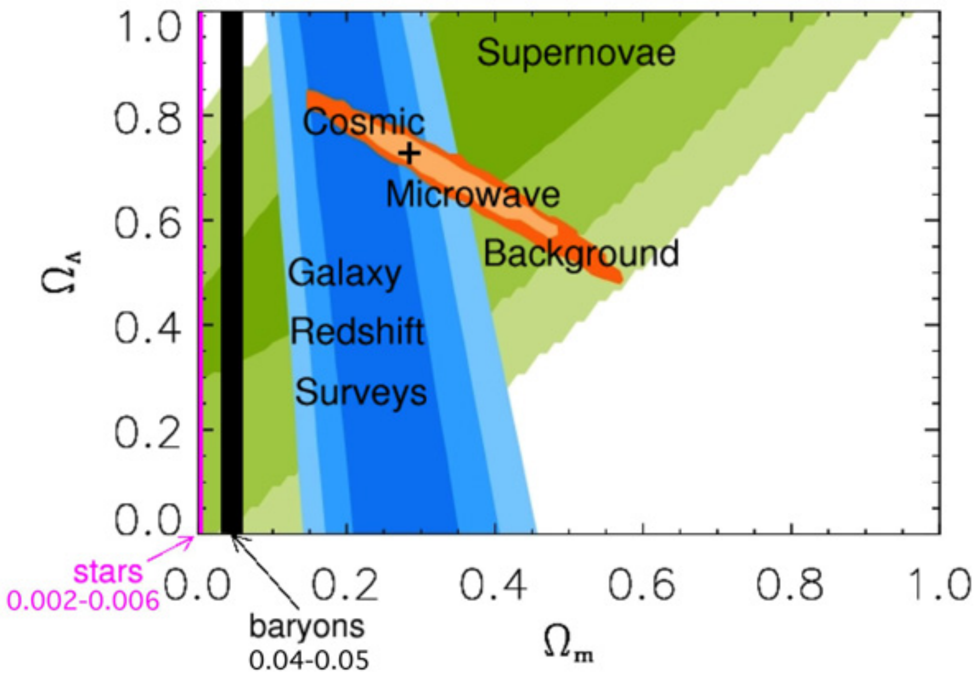
What is "dark energy"?

- An "energy" that is an inherent component of space…
- Consider a region of vacuum
  - Take away all of the radiation
  - Take away all of the matter
  - What's left? Dark energy!
  - But we have little idea what it is…

III :Concordance model

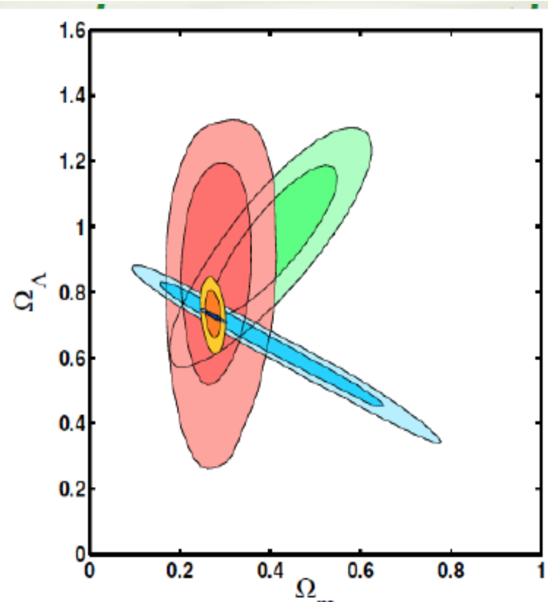
In summary, the parameters for our Universe, using best available data…

- Hubble constant: H_0 = 72 km/s/Mpc
- Geometry: Flat!
- Baryon density: $\Omega_B = 0.04$
- Dark matter density: $\Omega_{DM} = 0.22$
- Cosmological constant: $\Omega_\Lambda = 0.74$
- Age: t_0 = 13.7 billion years



Evidence for 'Dark Energy '

- No one technique definitely 'proves' the existence of dark energy
- The best indicator requires combining different measures
- Physics of clusters (pink) measures Ω_m very well
- CMB measures a combination of Ω_m and Ω_Λ
- and the brightness of type IA Sn a different combination of Ω_m and Ω_Λ



the contours represent the probability that the values lie inside them at the 68 and 90% confidence

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  Take away all of the radiation

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- But we have little idea what it is…

The Age of the Universe

- Using this cosmological model, we can figure out the age of the Universe.
  - Answer – 13.7 billion years
- Prediction…
  - There should be no object in the Universe that is older than 13.7 Gyr.
  - This agrees with what's seen!
  - **This was a big problem with old cosmological models that didn't include dark energy:**
    - e.g age of the universe in Ω_M =1, Ω_k =0, Ω_Λ=0 model is 9 billion years
    - But there are globular star clusters whose estimated ages are 12-14 billion years!
    - This was troubling since universe must be at least as old as the oldest stars it contains!

The final fate of the Universe