*Lecture 20 : What kind of Universe do *we* live in?*

- What is **our** universe like?
  - Matter content?
  - Geometry (flat, spherical, hyperbolic)?
  - Anything else strange?
- Remarkable agreement between different experimental techniques: "Cosmic concordance" parameters

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Please read Ch. 13 in the textbook

Course Evaluation is now open!

- Open now through Wednesday, May 11

http://www.CourseEvalUM.umd.edu

- Note: The evaluations are confidential, I will not be able to identify who has submitted an evaluation, only the participation rate.
- Goal is to achieve >70% response rate
- It will take only a few minutes. Thanks!

O.Measurements of the matter content of the Universe (recap)

- Primordial nucleosynthesis: theory predicts how present light element abundances (^4He, ^3He, D, ^7Li) depend on mean baryon density.
  a) Measuring Helium in stars we can derive $\Omega_B \approx 0.04$
  b) From observations of Deuterium in stars we derive $\Omega_B \approx 0.5$
  c) From observations of Deuterium in intergalactic gas we can derive the density parameter for all kinds of matter
  d) From observations of Deuterium in intergalactic gas we can derive $\Omega_B \approx 0.04$

O.Measurements of the matter content of the Universe (recap)

- How can we weight the universe?
  a) Motions of stars in galaxies, or galaxies in galaxy clusters show the need for "non-baryonic dark matter" ($\Omega_{DM} \approx 0.21$)
  b) Motions of stars in galaxies, or galaxies in galaxy clusters are consistent with the mass we see in stars
  c) The existence of dark clouds of gas can explain the rotation curves of galaxies
  d) Motions of stars in galaxies, or galaxies in galaxy clusters show that $\Omega_M \approx 0.04$, consistent with nucleosynthesis

I : WHAT IS THE GEOMETRY OF OUR UNIVERSE?

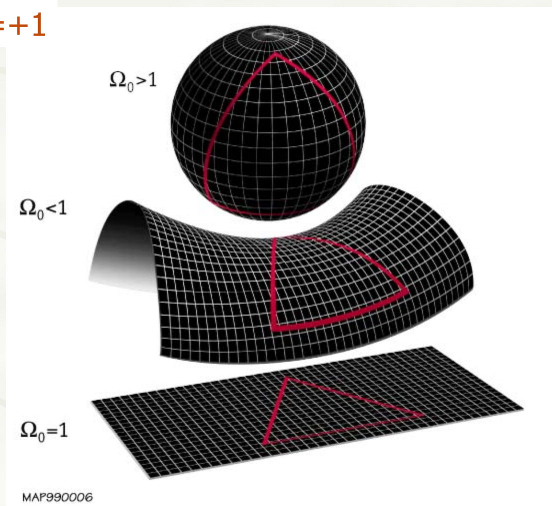
- Recall that universe with different curvature has different geometric properties
- Adding up the angles in a triangle,
  - Flat universe($k = 0$): angles sum to 180°
  - Spherical universe ($k = +1$): angles sum to >180°
  - Hyperbolic universe ($k = -1$): angles sum to <180°
- Similarly, for a known 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

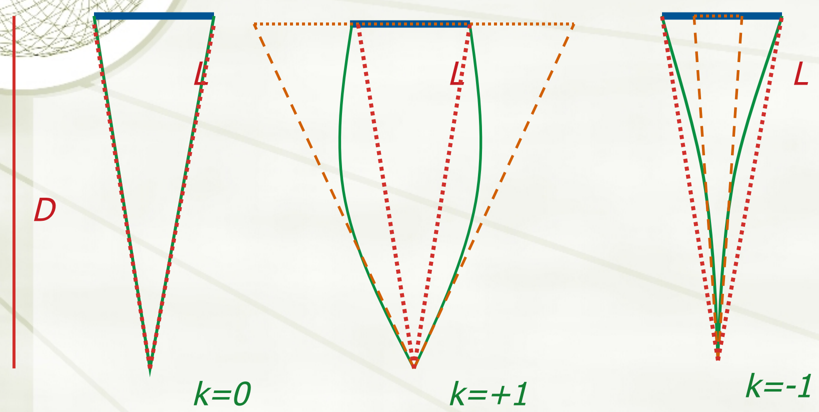
k=+1

k=-1

k=0

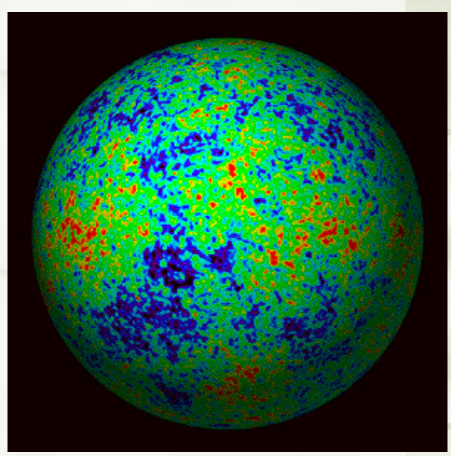


Curvature affects apparent size or field of view

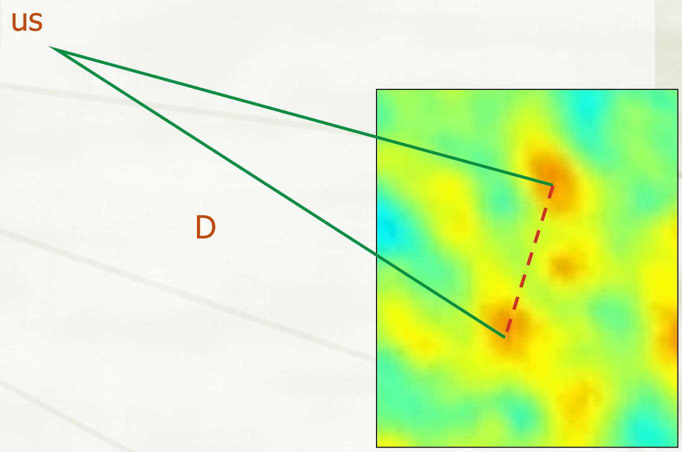


Angular size of fluctuations in the CMB

- 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



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Flat universe!

- Result:
  - The universe is **flat**
  - But, the sum of all known 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!

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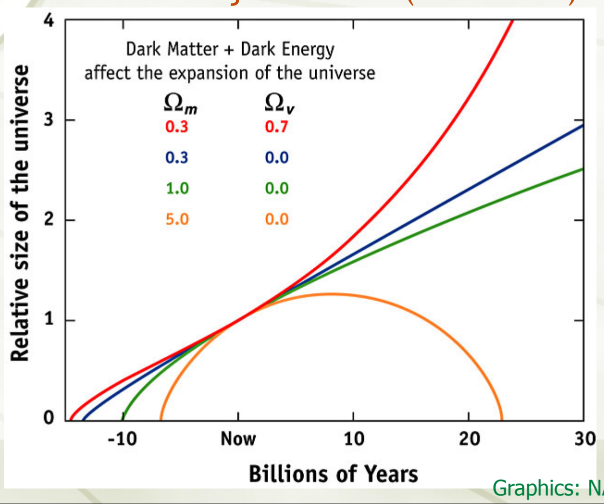
Non-zero Λ

- 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)

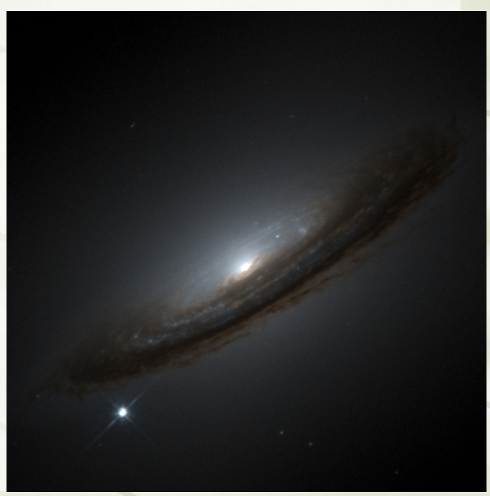


Graphics: NASA WMAP project

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



- 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.

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- 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)

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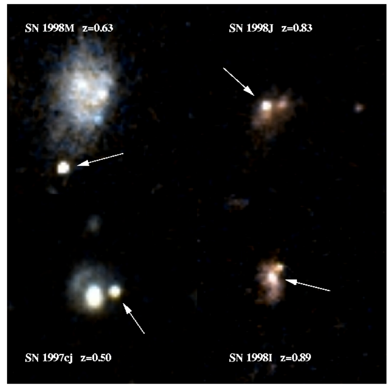
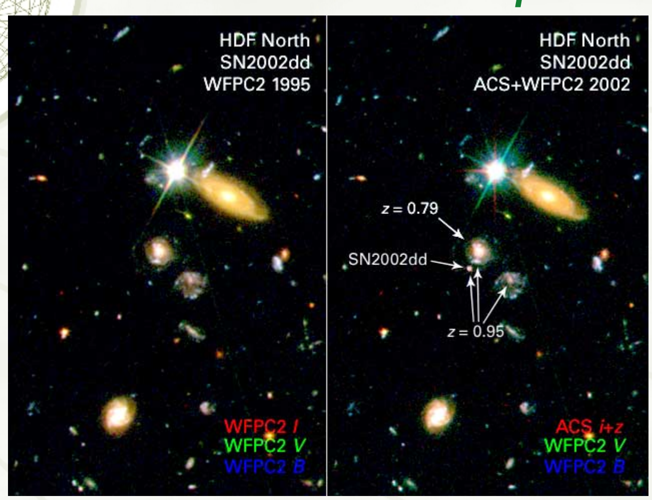
Cosmology with SN1a's

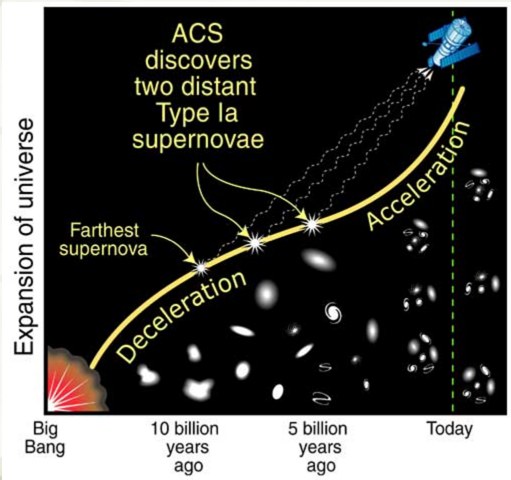
- The program:
  - Search for SN1a in distant galaxies
  - Compare expected power with observed brightness to determine distance
  - Measure velocity using redshift
- "Low redshift" galaxies give measurement of H_0
- "High redshift" galaxies allows you to look for deceleration of universe



Distant supernova

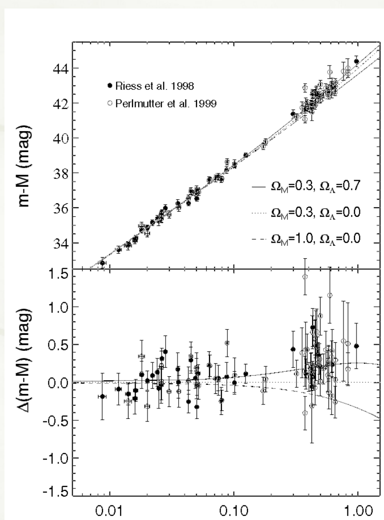


The accelerating universe



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

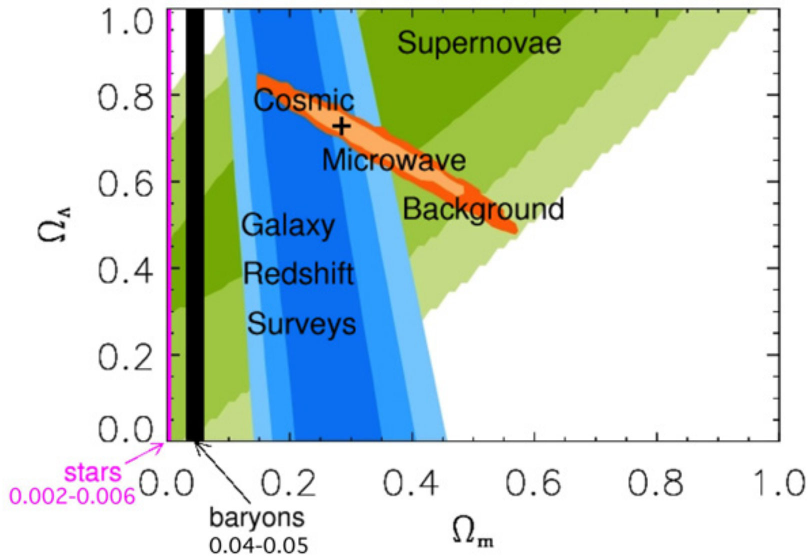
What is "dark energy"?

- 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: Ω_B = 0.04
- Dark matter density: Ω_{DM} = 0.22
- Cosmological constant: Ω_Λ = 0.74
- Age: t_0 = 13.7 billion years



IV : 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!

What is the final fate of the Universe?

a) Expansion slows down and reverse into collapse
b) Expands forever but rate of expansion decreases with time
c) Expands forever and accelerates, galaxies stop forming and become isolated islands
d) Expands forever but all galaxies fall into a single giant black hole