*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

Please read Ch. 13 in the textbook

Measurements of the matter content of the Universe (recap)

- Primordial nucleosynthesis+ CMB Peaks
  - Theory predicts how present light element abundances (^4He, ^3He, D, ^7Li) depend on mean baryon density
  - Observed abundances ⇒ $\Omega_B \approx 0.04$
- 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" ($\Omega_{DM} \approx 0.25$)- that is matter that causes things to move (gravity) but cannot be baryonic

WHAT IS THE GEOMETRY OF OUR UNIVERSE?

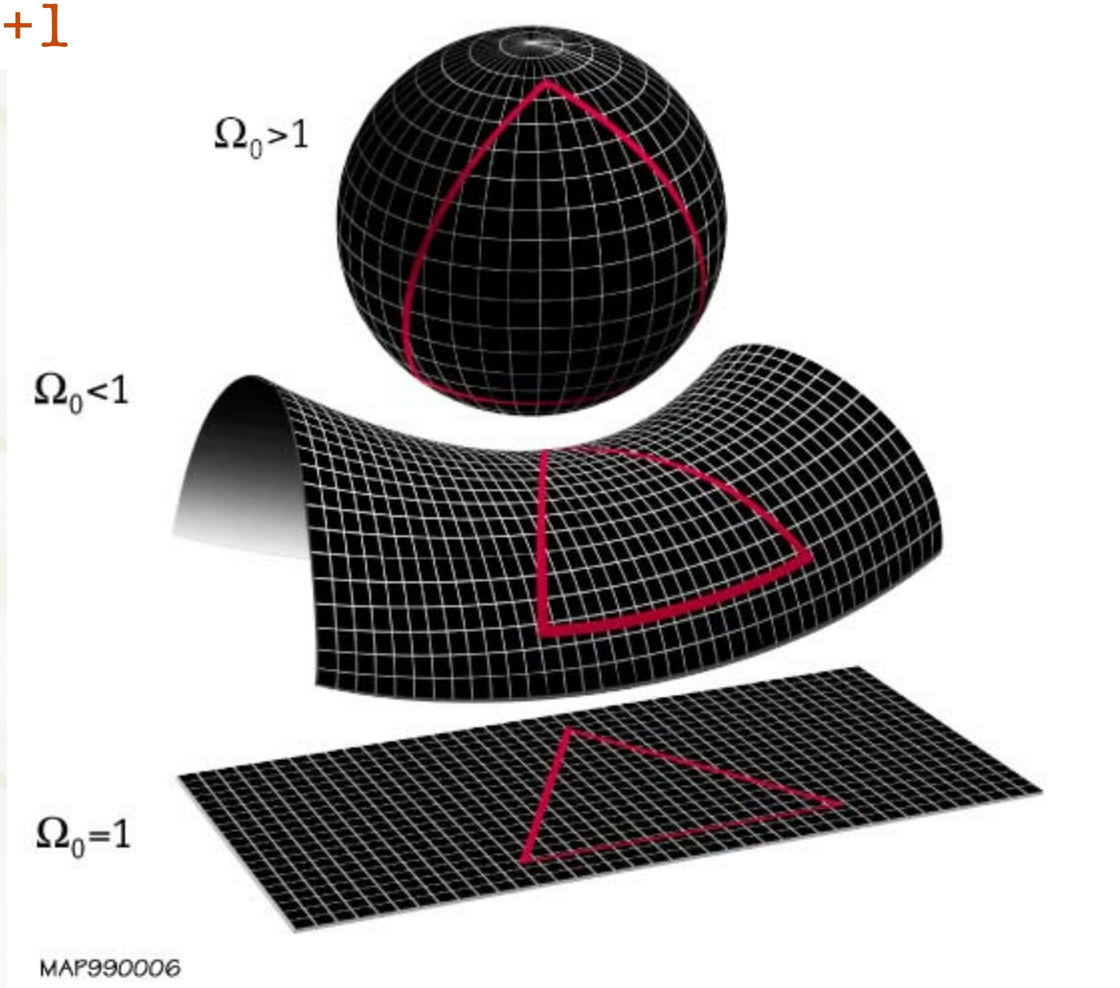
- Recall that universe with different curvature has different geometric properties
- Adding up the angles in a triangle,
  - Flat universe($k = 0$): angles sum to 180°
  - Spherical universe ($k = +1$): angles sum to >180°
  - Hyperbolic universe ($k = -1$): angles sum to <180°
- Similarly, for a known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

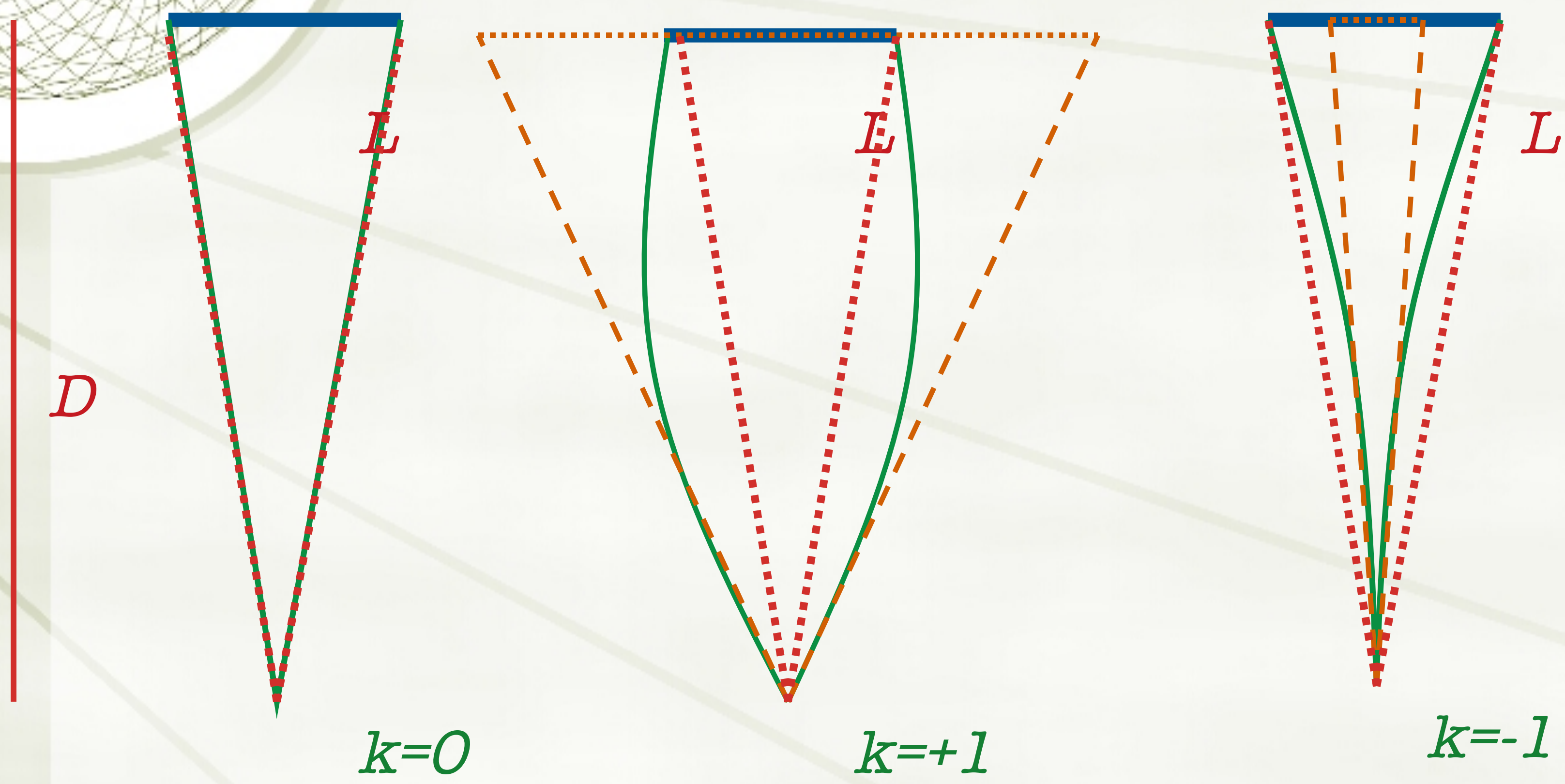
k=+1

k=-1

k=0



Curvature affects apparent size or field of view

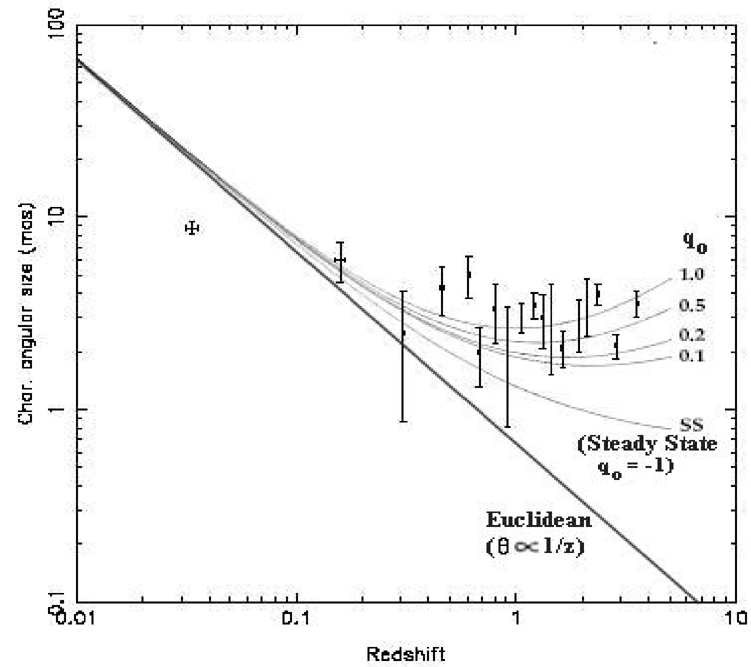


- in the simplest models,
- $q_0 < 0.5$ corresponds to the case where the Universe will expand for ever,
- $q_0 > 0.5$ to closed models which will ultimately stop expanding and contract
- $q_0 = 0.5$ corresponds to the critical case – Universes which will just be able to expand to infinity without re-contracting.

$q_0 = \Omega/2$

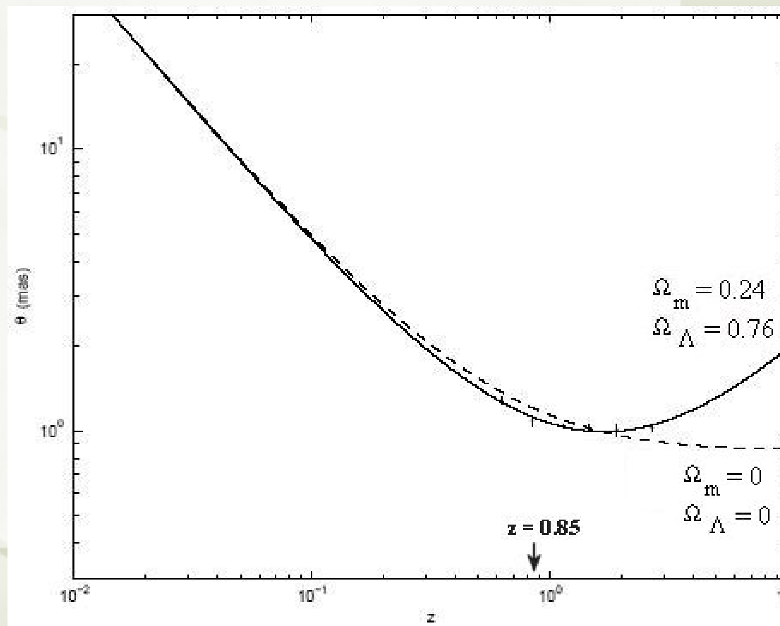
- Λ cosmologies are different

angular size of a fixed rod



redshift

angular size of a fixed rod



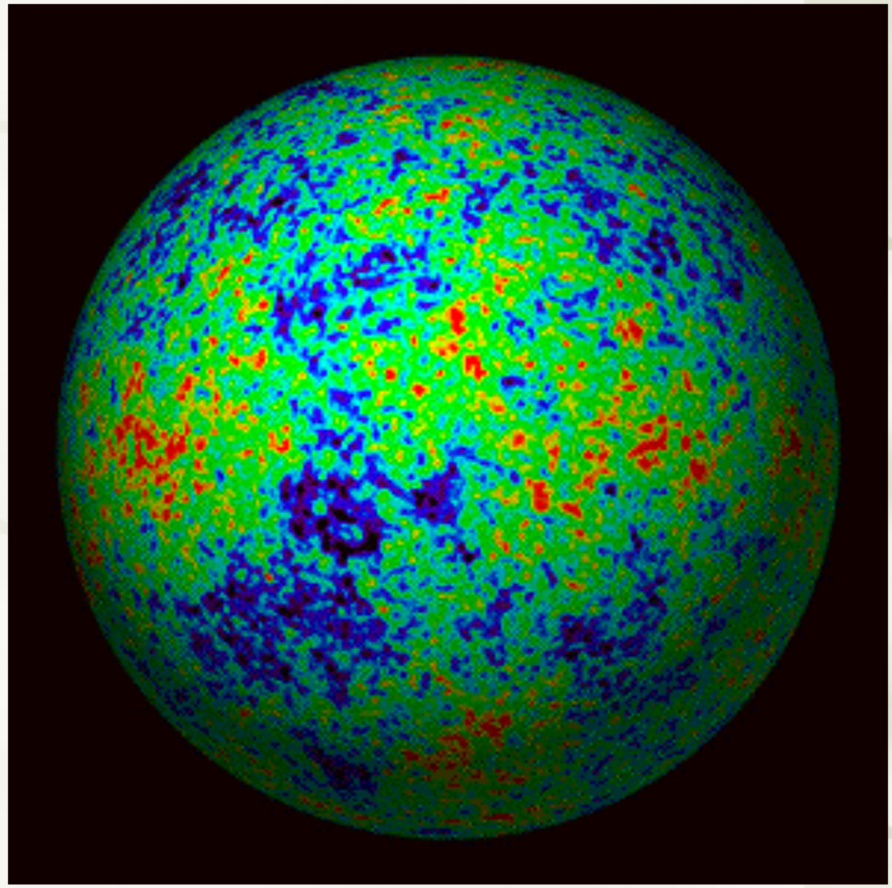
redshift

Power spectrum peaks and valleys

- 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
- At larger scales, waves would have completed less than half an oscillation and no large densities were introduced on those scales
- Peaks at scales <1° are higher harmonics

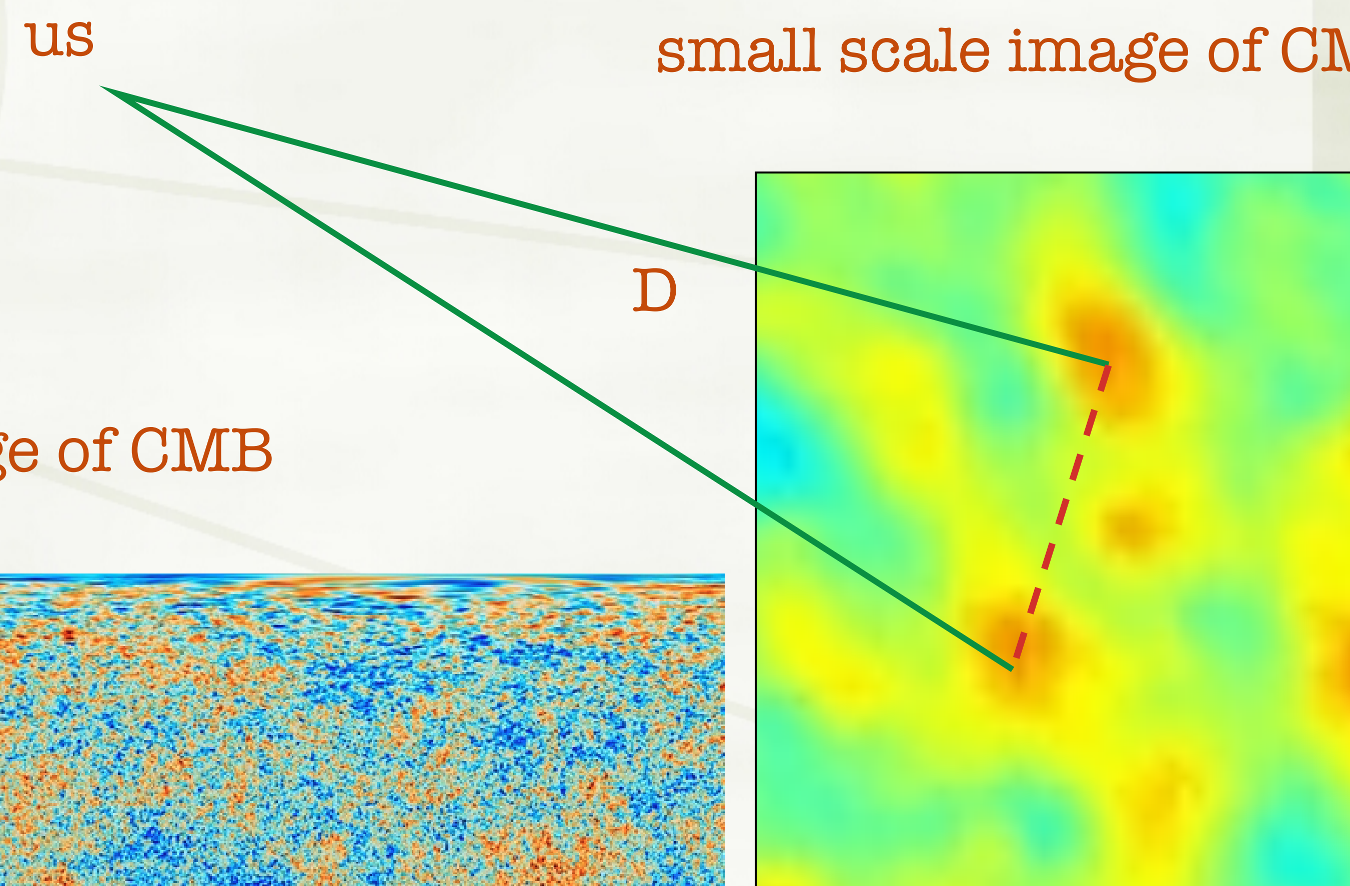
Angular size of fluctuations in the CMB

- 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

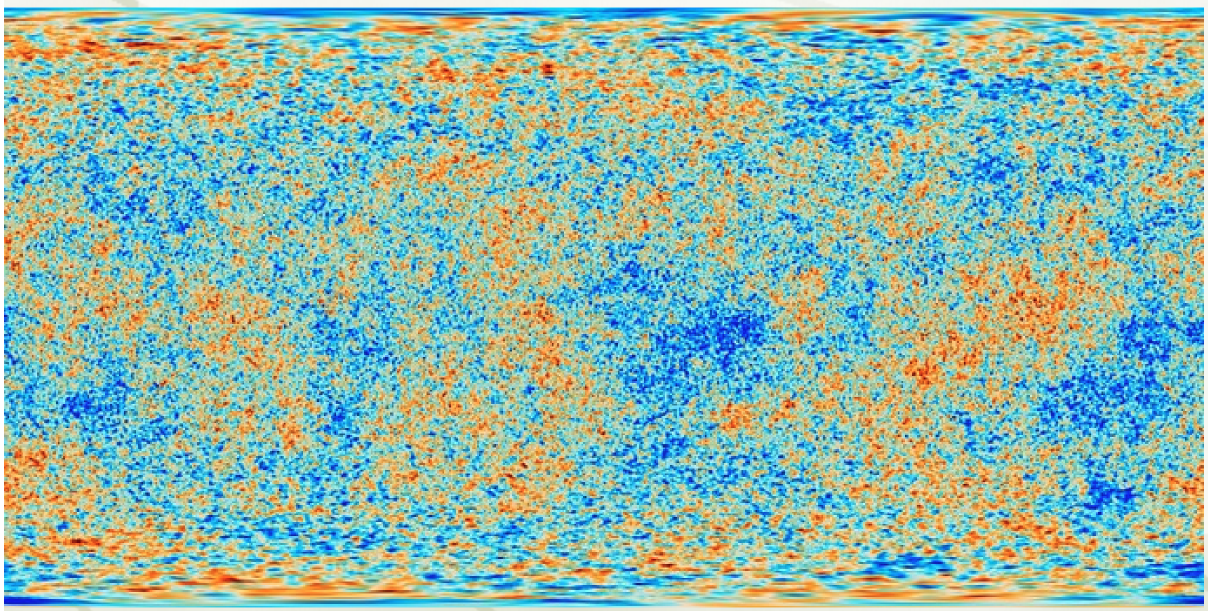


Graphics: NASA WMAP project

small scale image of CMB

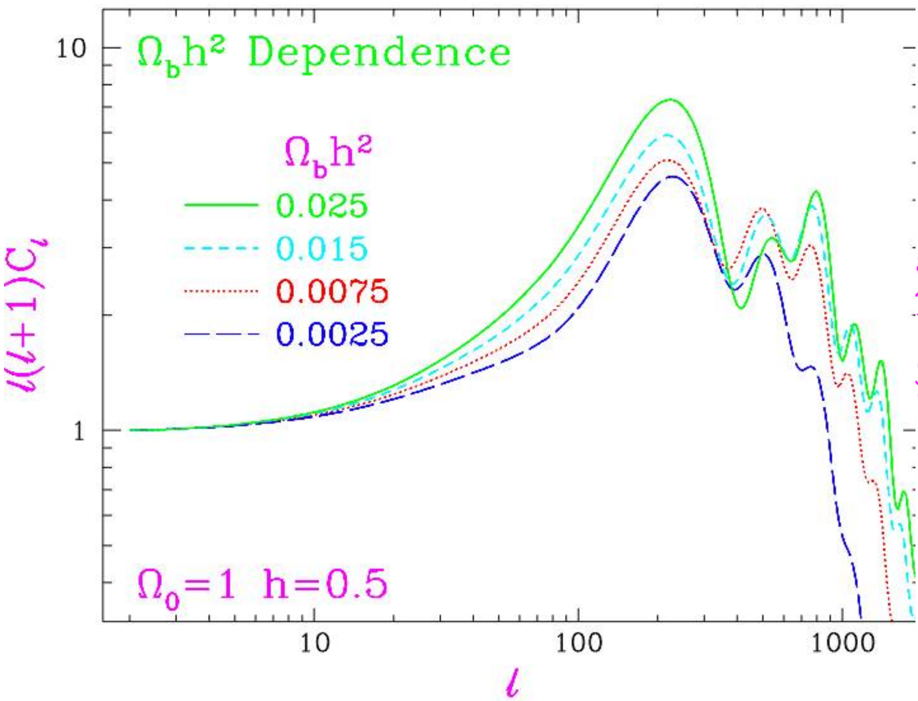


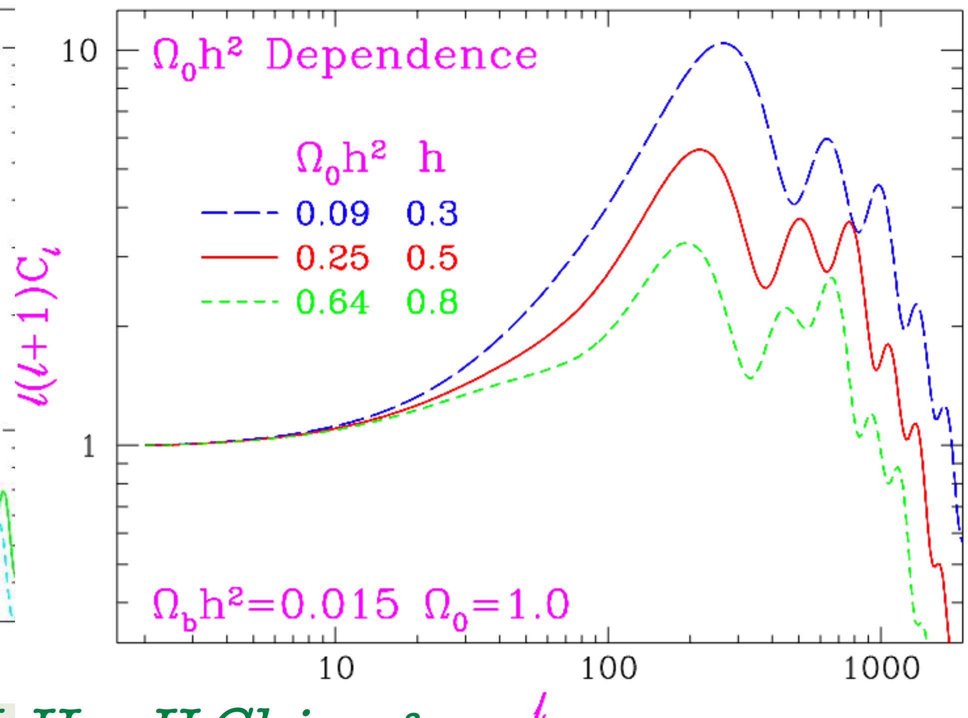
all sky image of CMB



Spectral changes for varying parameters

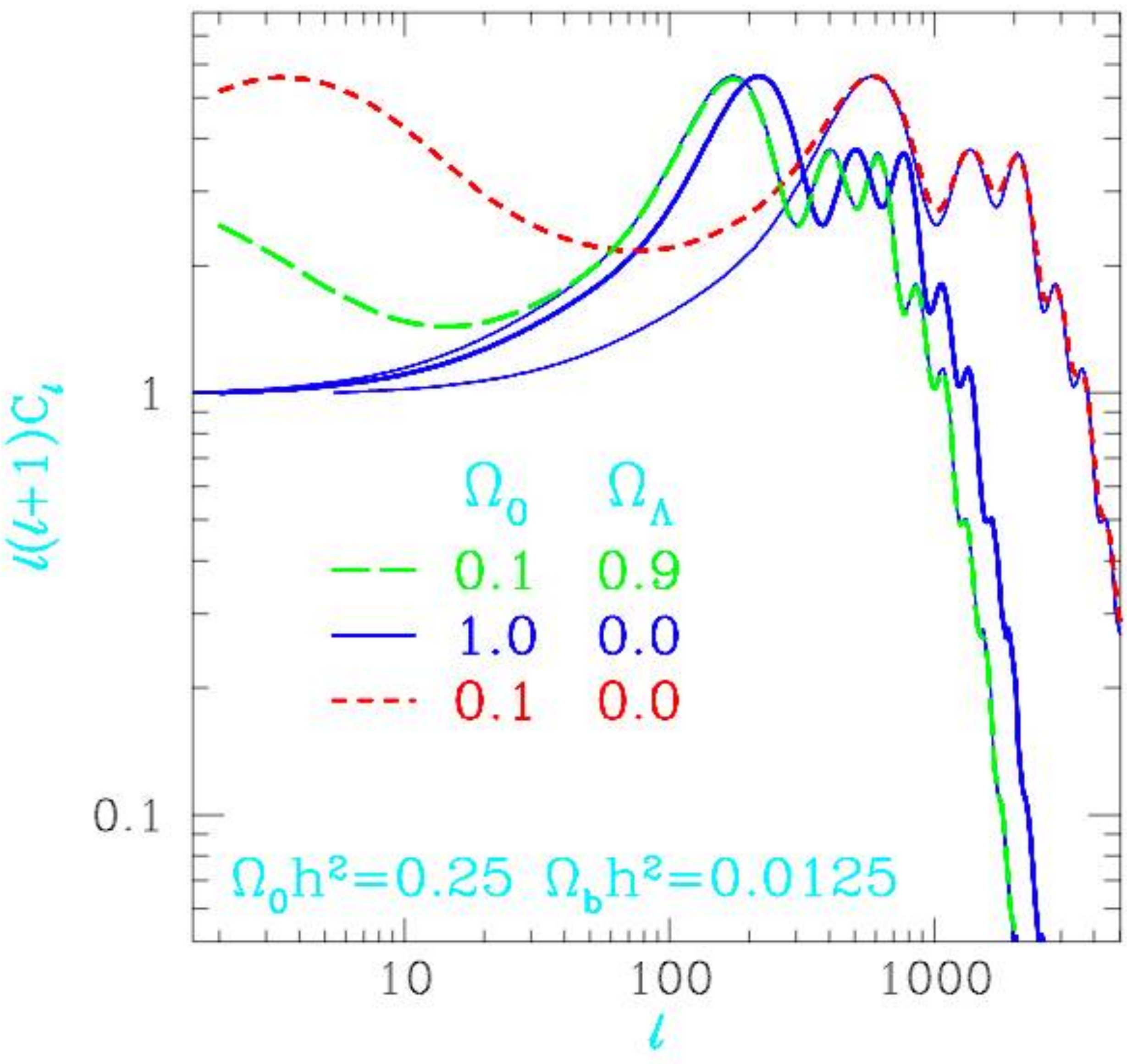
- Spectra from CMB maps also help constrain other parameters…Remember before I showed how the CMB spectrum varied with Ωh^2?





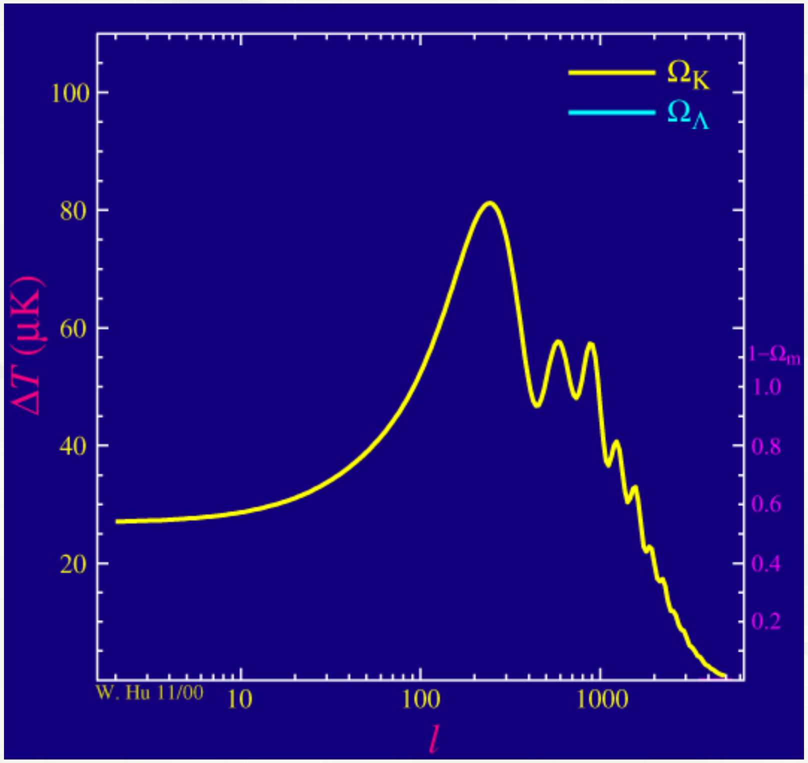
Images: W. Hu, U.Chicago

How the CMB spectrum varies with Ω, Λ



How Curvature Effects the Position of the Peaks in the CMB

- The position of the peaks in the CMB are very sensitive to curvature



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!

Flat universe!

- Result:
  - The universe is **flat**
  - 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:

$$1 = \Omega_M + \Omega_\Lambda + \Omega_k$$

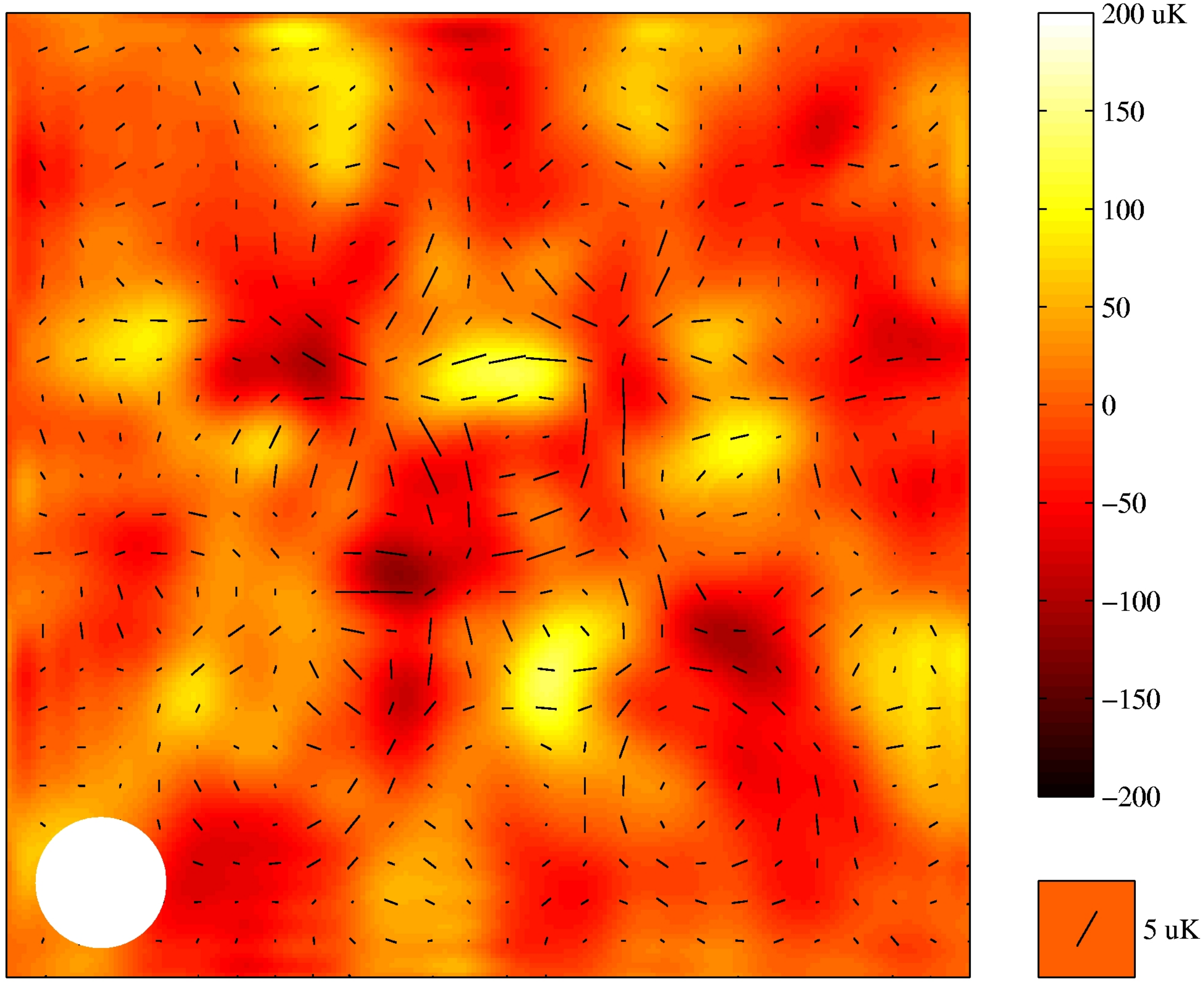
  - How do we reconcile $\Omega_k = 0$ with our measurement of the matter density, which indicates $\Omega_M = 0.26$?
  - There must be a nonzero cosmological constant, $\Omega_\Lambda = 0.74$!

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

More Information on the Early Universe from the CMB Polarization

- Polarization of WMAP data indicates electron density of matter that CMB travels through after leaving surface of last scattering
    - After recombination, free electrons would be produced by star formation
- Evidence from WMAP polarization indicates that star formation began as early as 400 Myr after recombination!

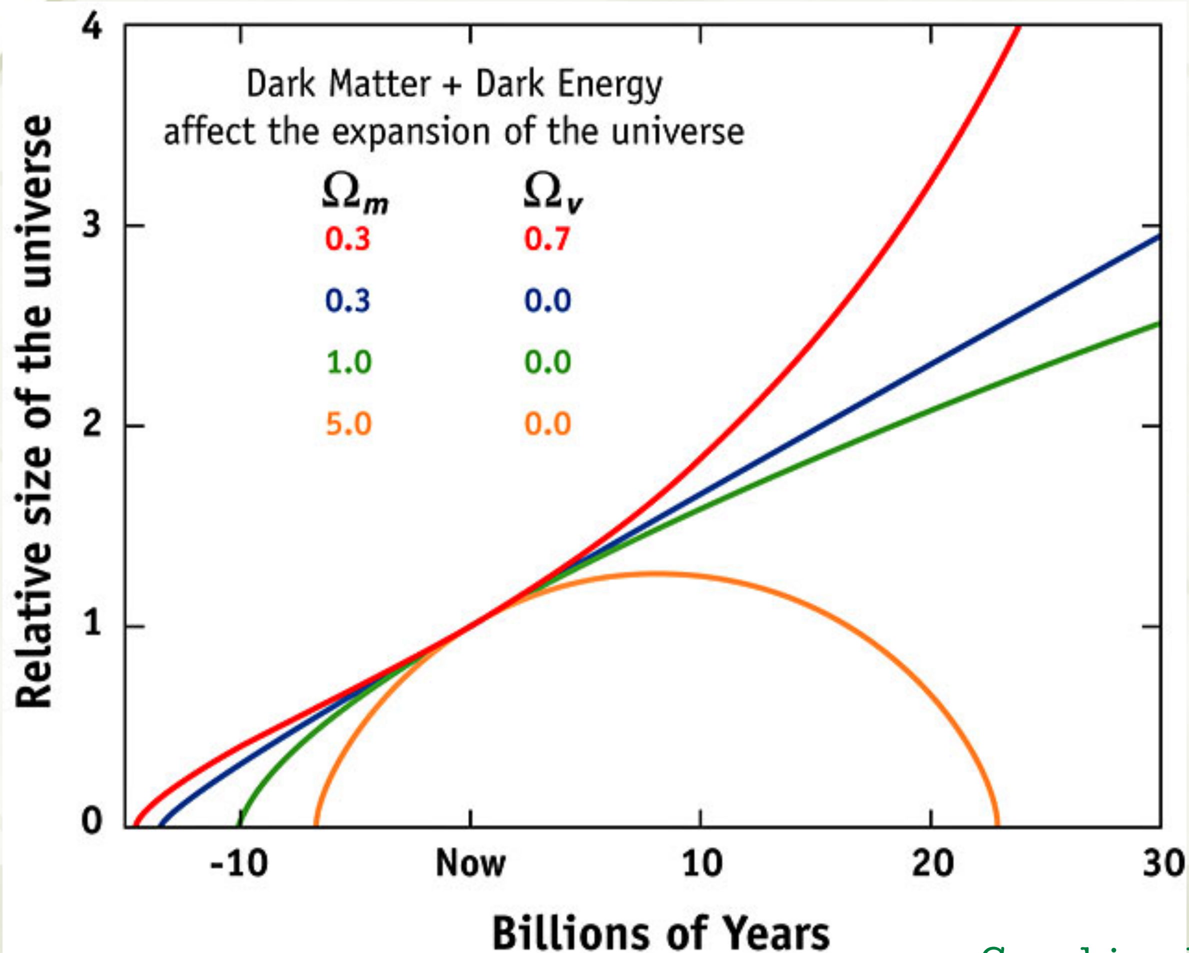
DASI polarization map



Map is 5 degrees square

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 proje

The accelerating Universe Nobel Prize 2011

- 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 out to very large distances… can look for deviations from standard ideas

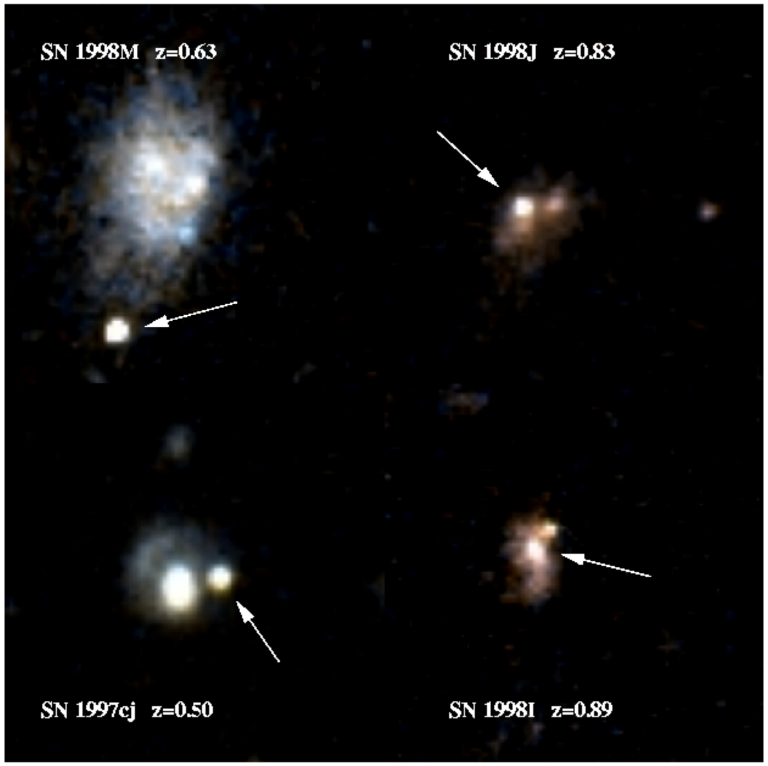
Type 1A Supernovae

- 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.

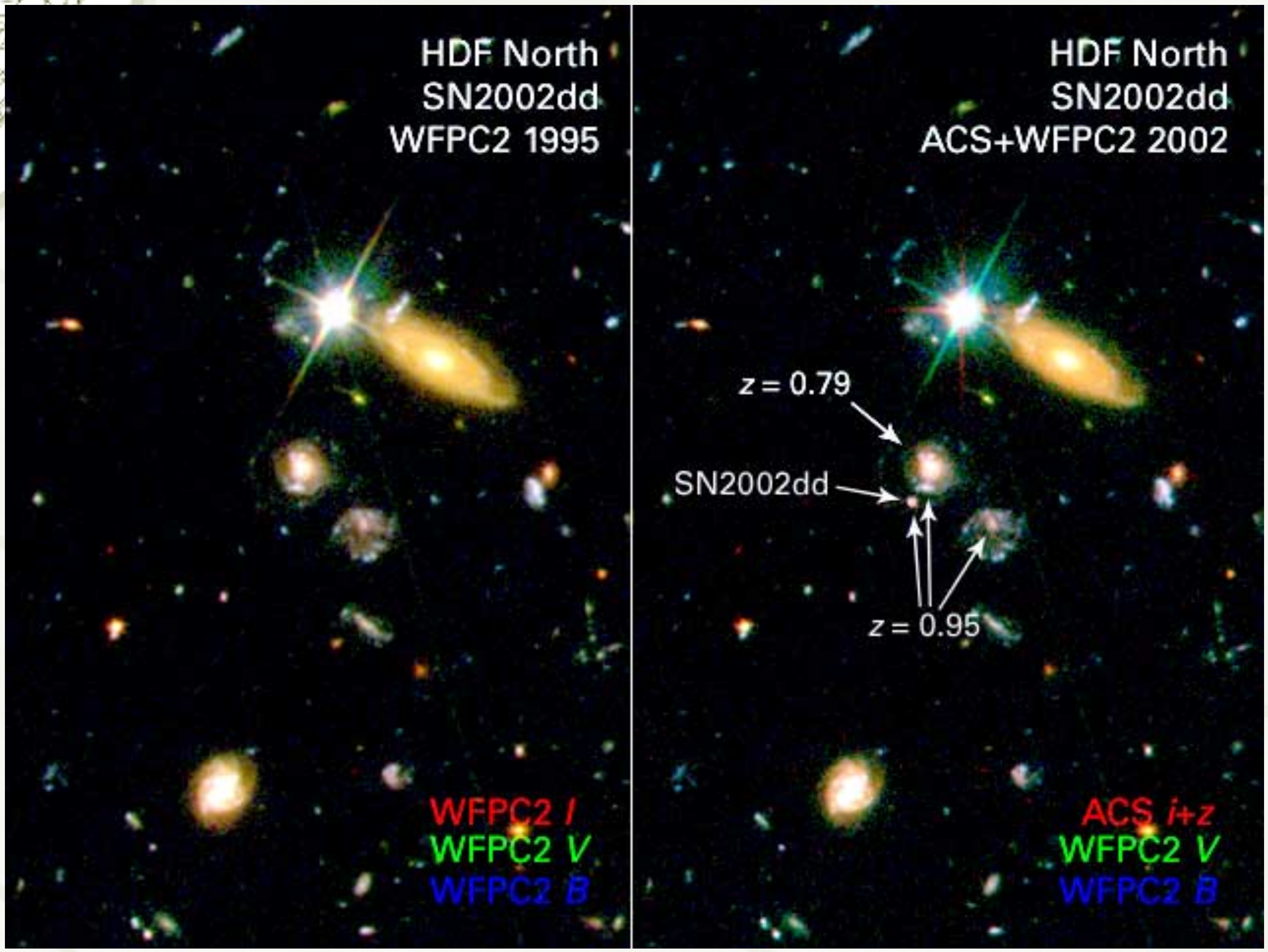
- White Dwarf starts to collapse…
  - Rapidly compresses matter in white dwarf
  - Initiated runaway thermonuclear reactions – star turns to iron/nickel in few seconds
  - Liberated energy blows star apart
  - Resulting **explosion** briefly outshines rest of galaxy containing it… these are the SN1a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

Cosmology with SN1a's

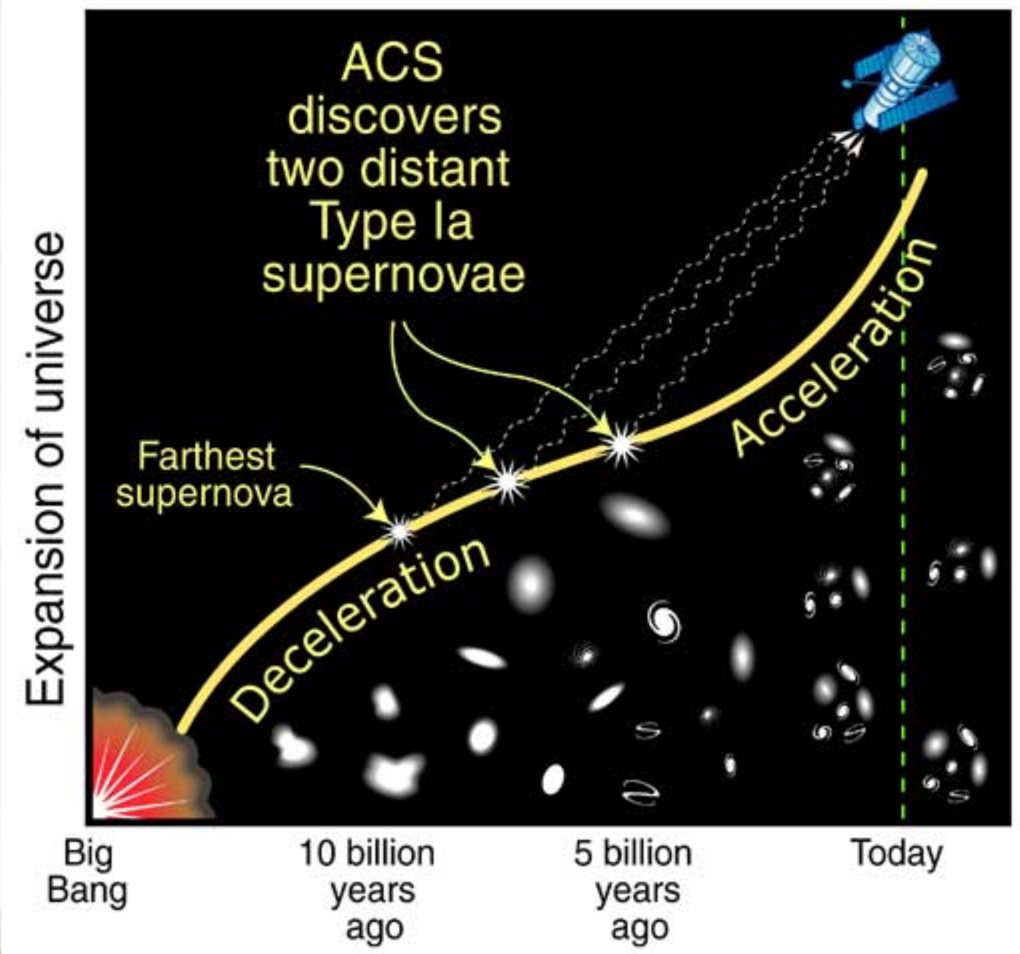
- The program:
  - Search for SN1a in distant galaxies
  - Compare expected power with observed brightness to determine distance
  - Measure velocity using redshift
- "Low redshift" galaxies give measurement of H_0
- "High redshift" galaxies allows you to look for deceleration of universe



Distant supernova

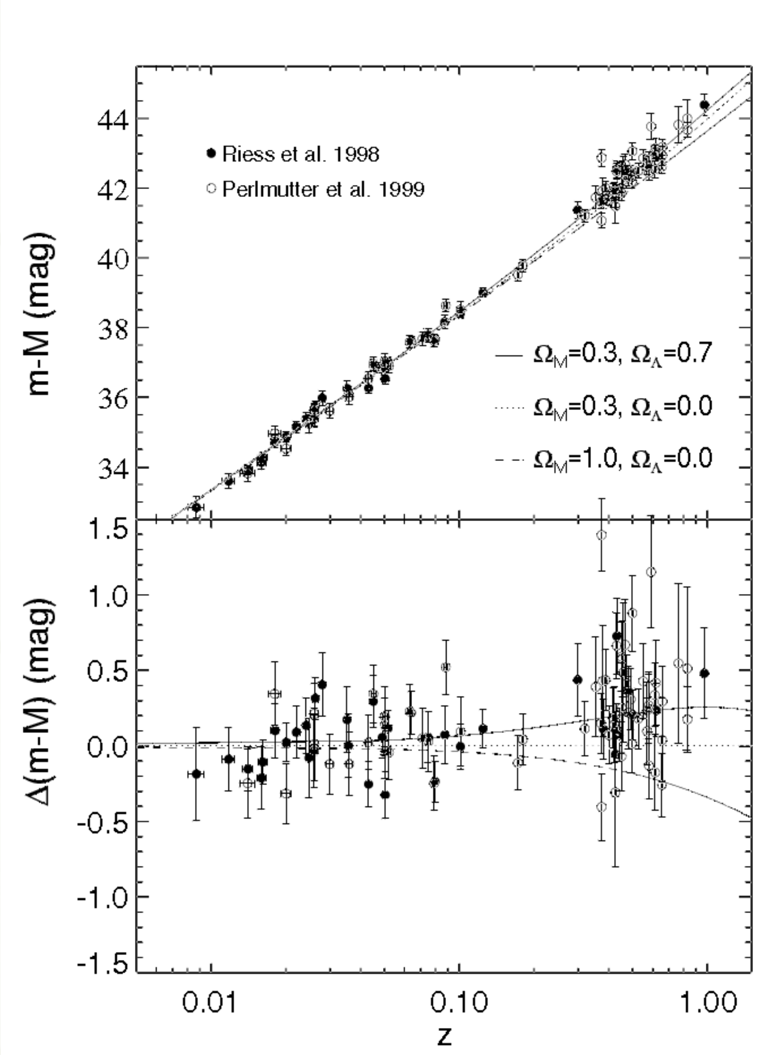


The accelerating universe



The results…

- 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

The results…

- This program gives accurate value for Hubble's constant
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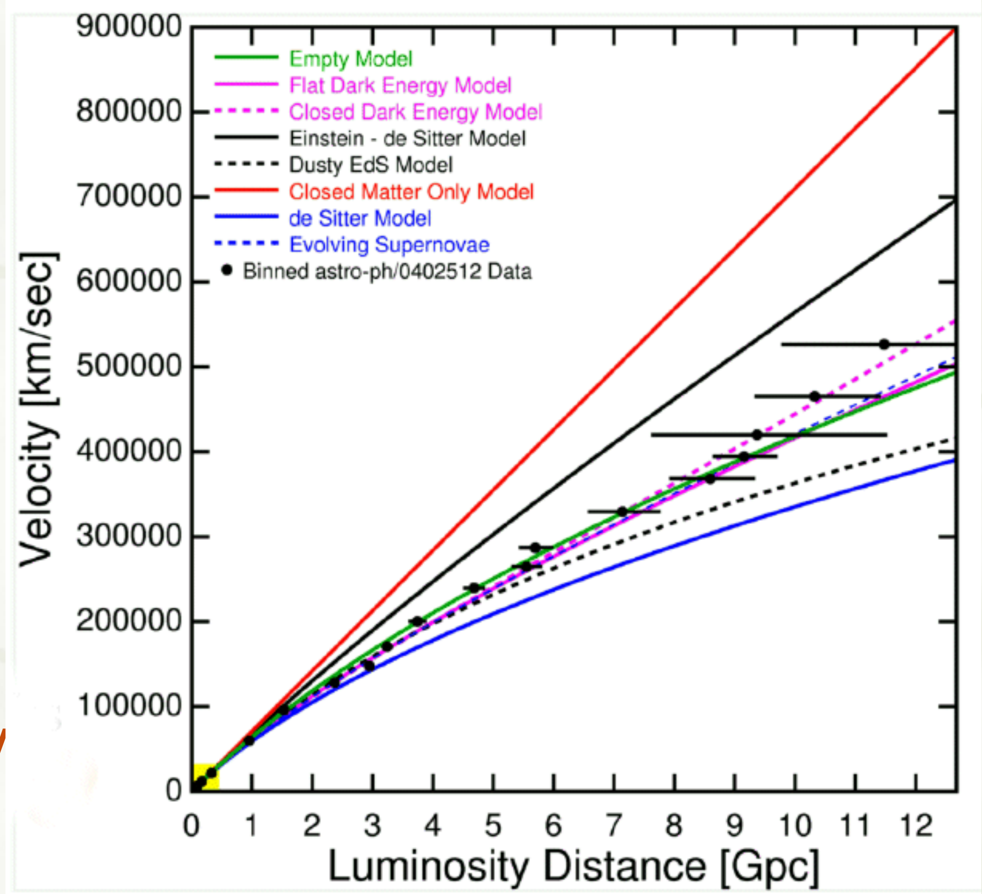
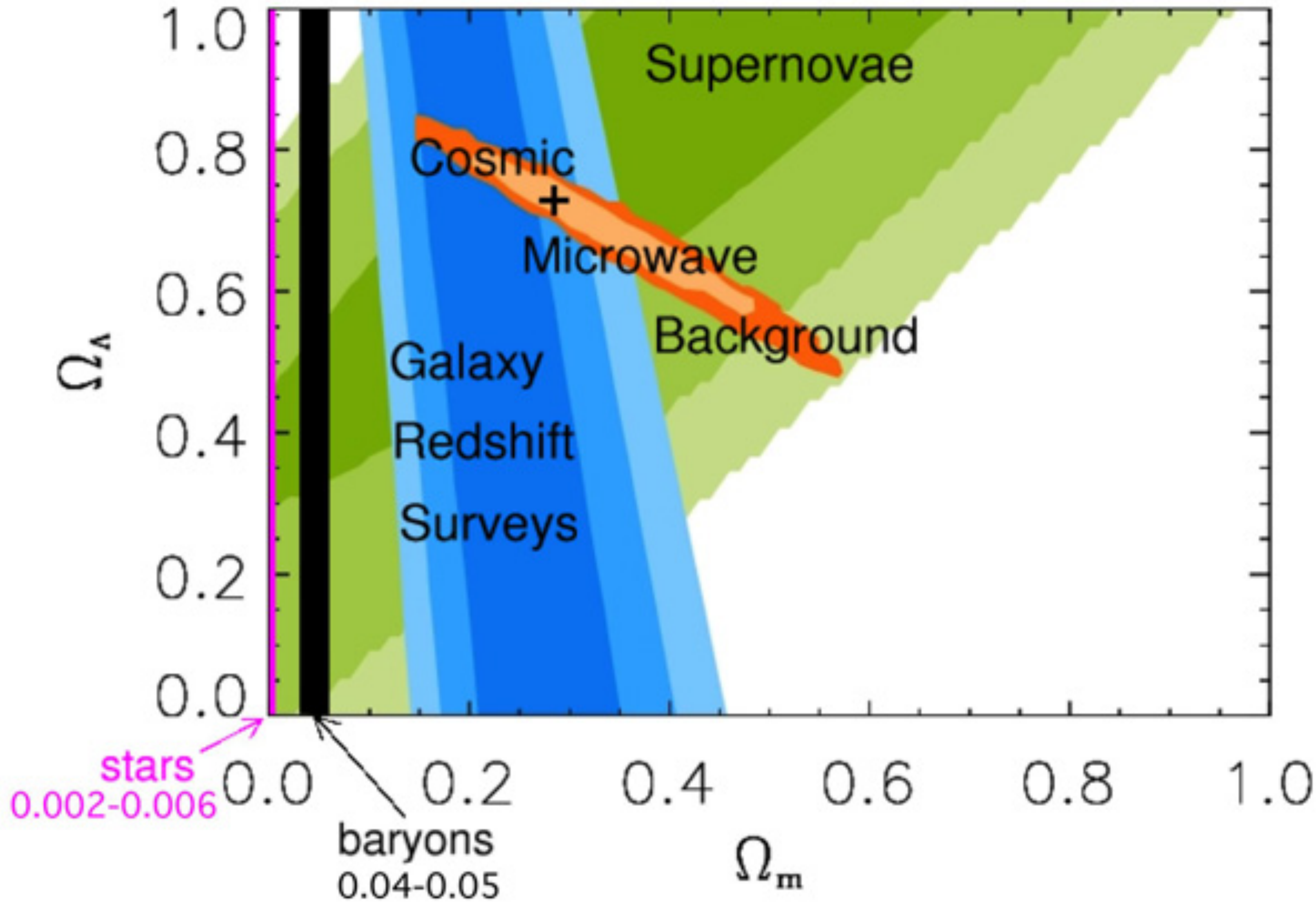


Purple curve: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$

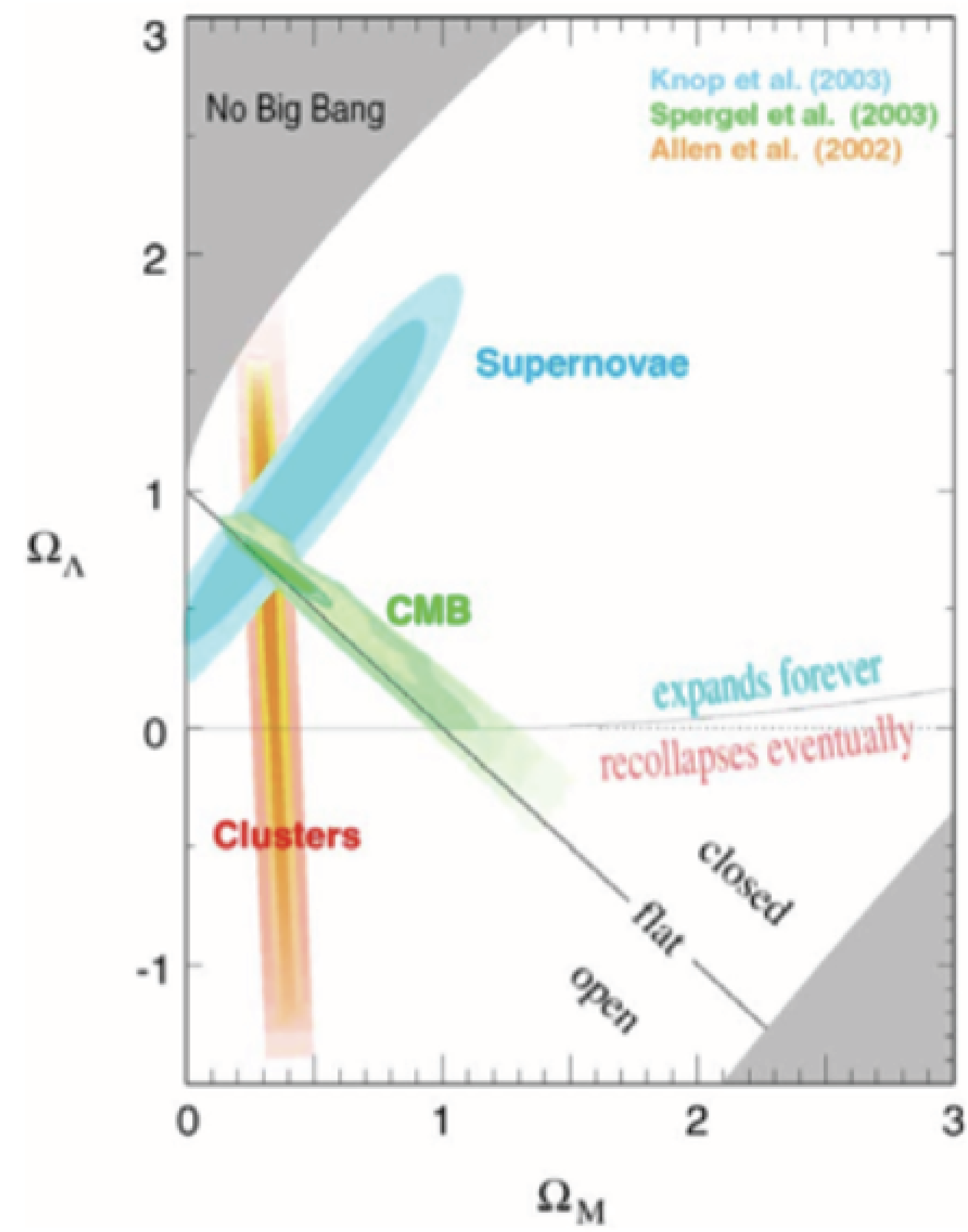
Black curve: $\Omega_M = 1$, $\Omega_\Lambda = 0$

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

Graphics: Ned Wright, UCLA



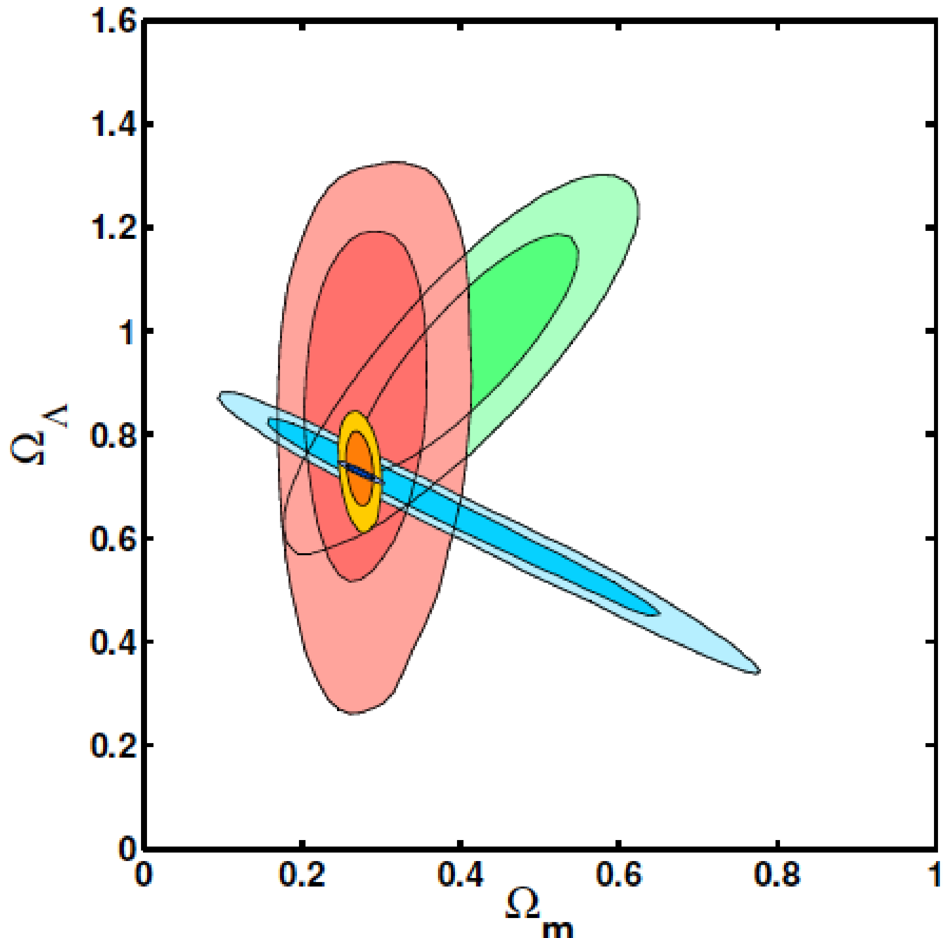
Results ~2001


No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
expands forever
recollapses eventually
Clusters
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

Other Evidence for 'Dark Energy'

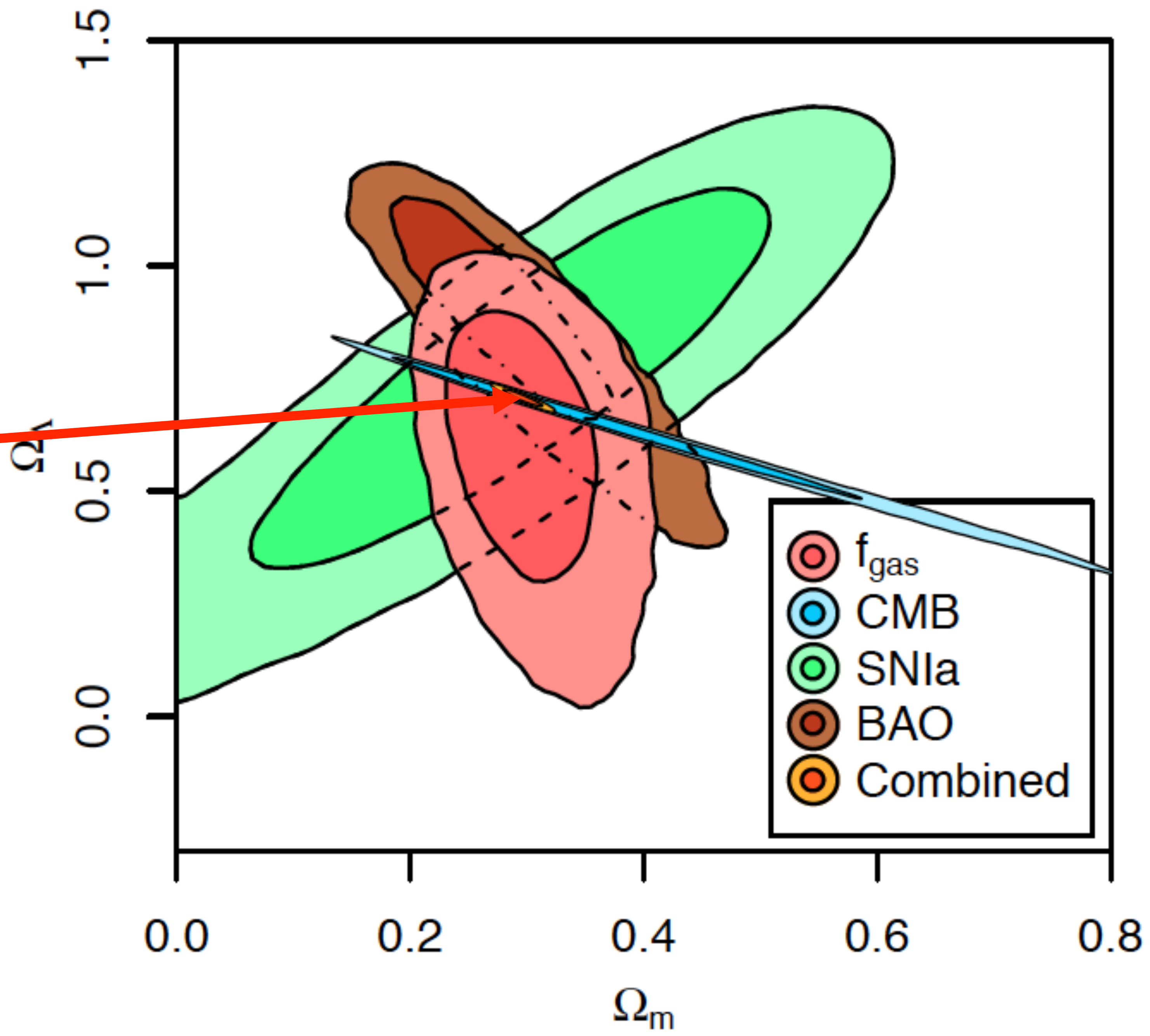
- No one technique definitely 'proves' the existence of dark energy
- The best indicator requires combining different measures
- Physics of clusters (pink) measures Ω_m very well
- CMB measures a combination of Ω_m and Ω_Λ and the brightness of type IA Sn a different

  combination of Ω_m and Ω_Λ



Results ~2010 Rapid progress
Blue-CMB constraints, green supernova and red clusters of galaxies
S. Allen

- Results as of 2014-



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…

Concordance model

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

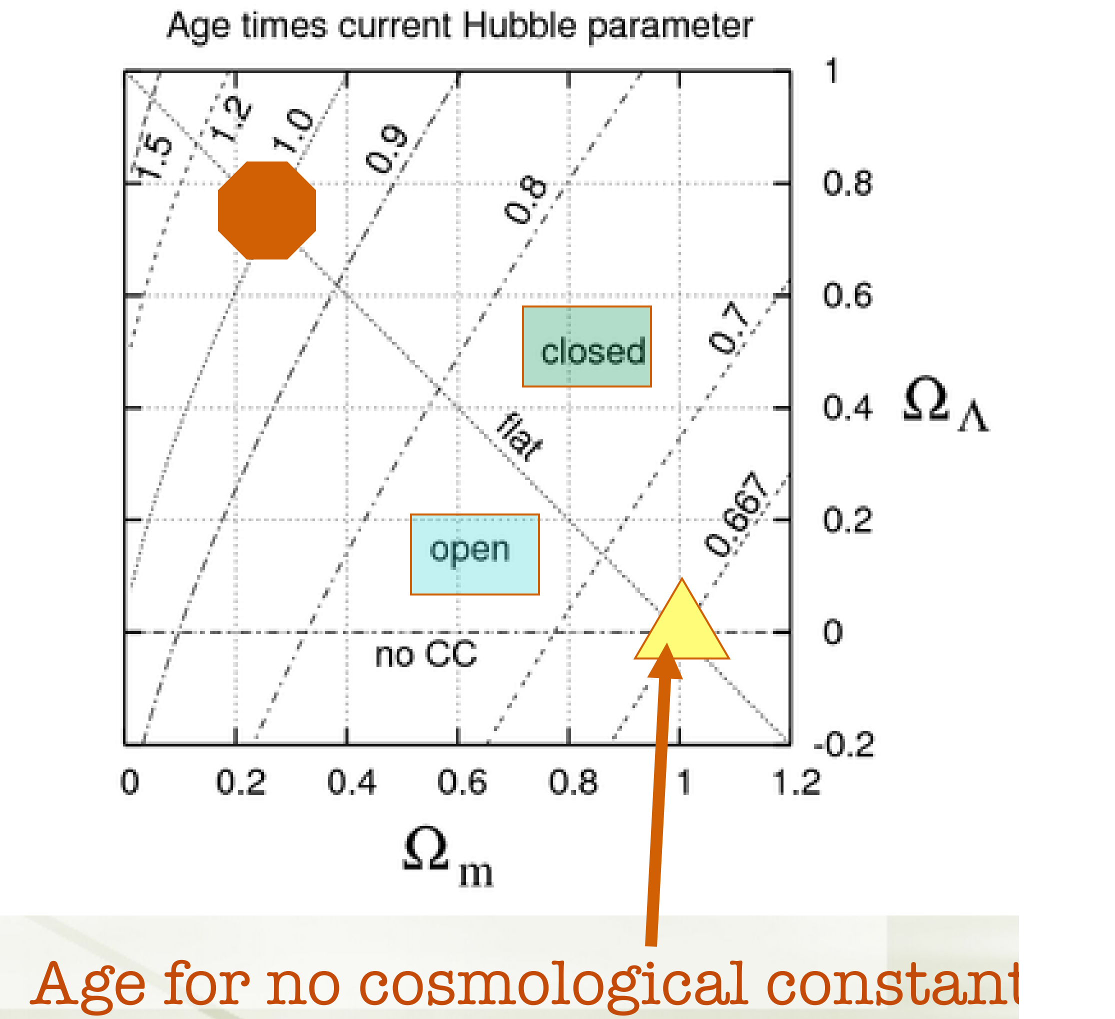
- Hubble constant: H_0 = 70 km/s/Mpc
- Geometry: Flat!
- Baryon density: Ω_B = 0.045
- Dark matter density: Ω_{DM} = 0.26
- Cosmological constant: Ω_Λ = 0.69
- Age: t_0 = 13.798 billion years

The Age of the Universe

- Using this cosmological model, we can figure out the age of the Universe.
  - Answer – 13.8 billion years
- Prediction…
  - There should be no object in the Universe that is older than 13.8 Gyr.
  - 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!

How is the Age of the Universe related to the Cosmological parameters?

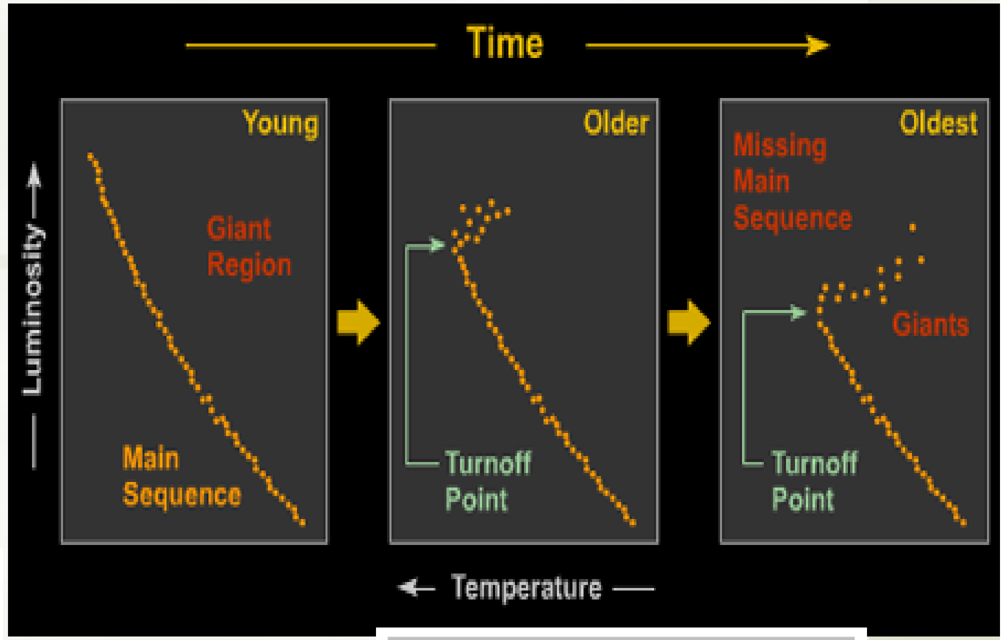
- Remember the Hubble time (~1/H) ~13.8x10[9] yrs
- The figure shows how old the universe is for different values of Ω_M and Ω_Λ and the same Hubble constant

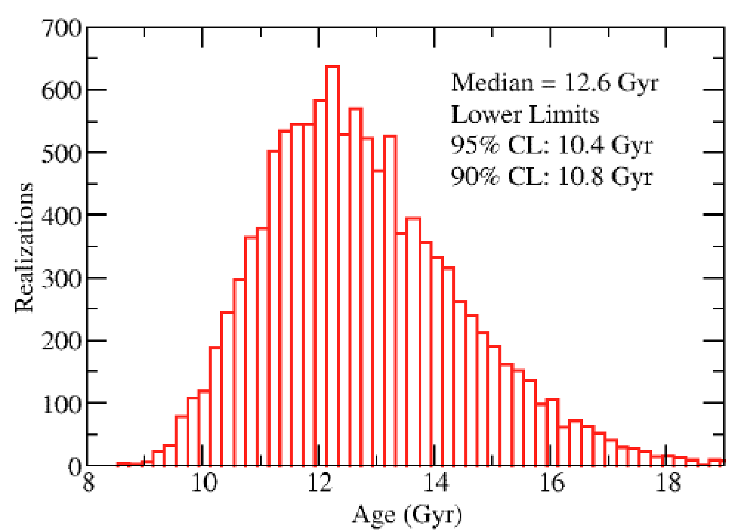



(C) Yuuji Kitahara

Age of Oldest Stars and Globular Clusters

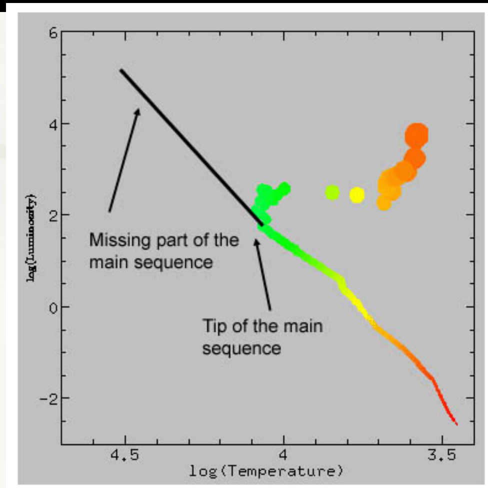
- White dwarfs (dead stars remnants of solar mass stars) cool with age
- Low mass stars (much less than the sun) live for a very long time- they can be dated using our knowledge of stellar evolution



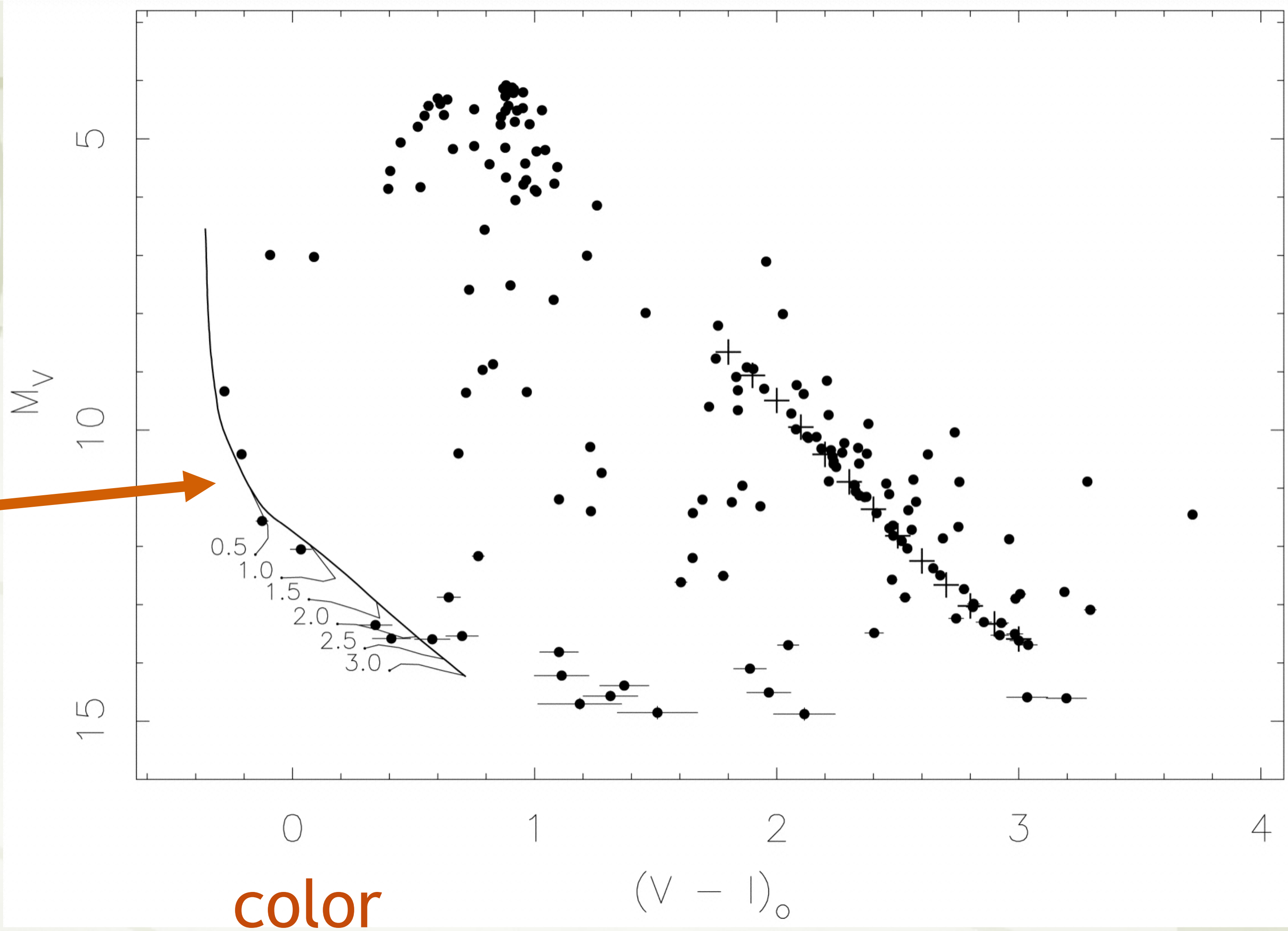


Best fit = 13.2 +/- 1.5 Gyr

Range of possible GC ages (Chaboyer & Krauss 2003)



The older a white dwarf is the dimmer and redder it is (tick marks are the age of the star in Gyrs)

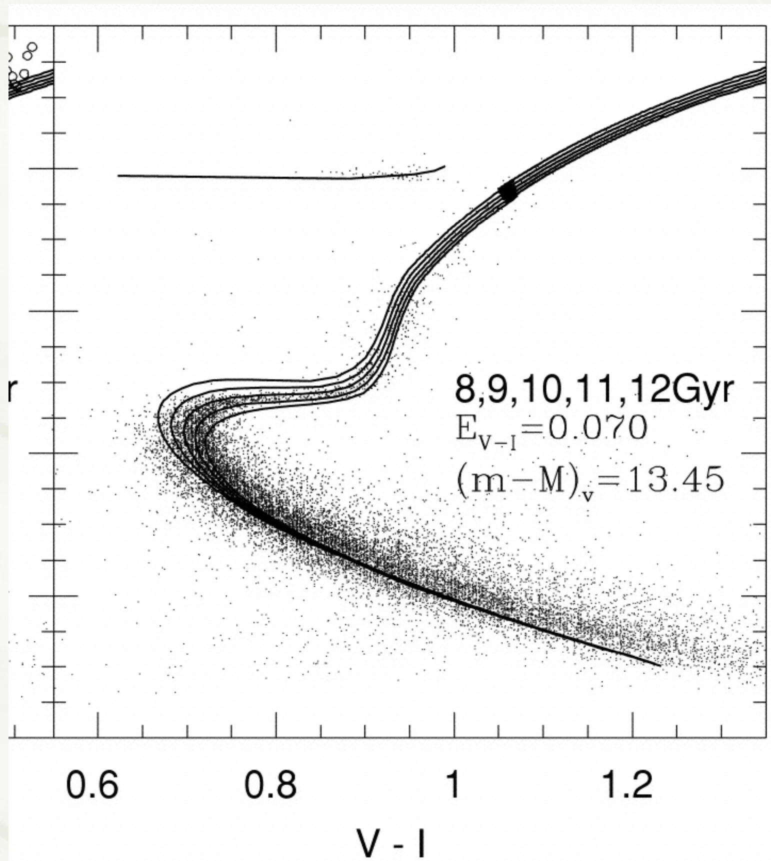


- White dwarf stars in a nearby star cluster-color magnitude diagram

How Does One Date a Globular Cluster

- Luminosity vs color diagram for stars in a globular cluster.
- The lines are theoretical calculations of the relationship of these as a function of age.
- Notice the precision required.

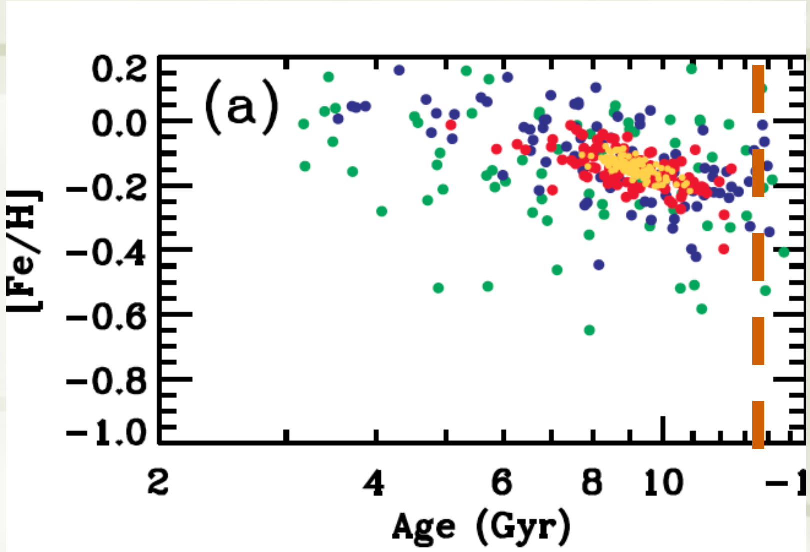
Log Luminosity

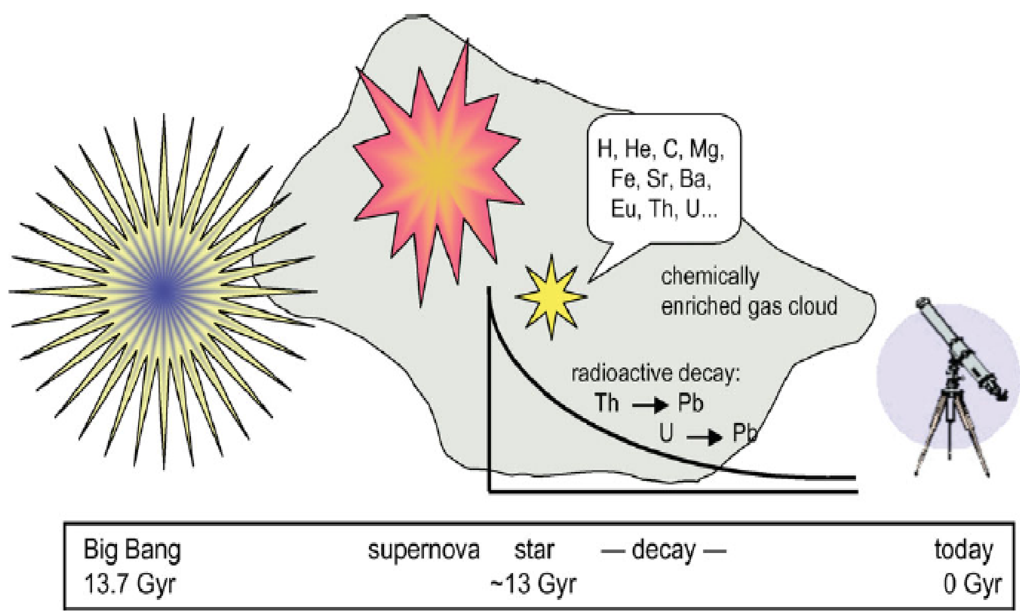


color

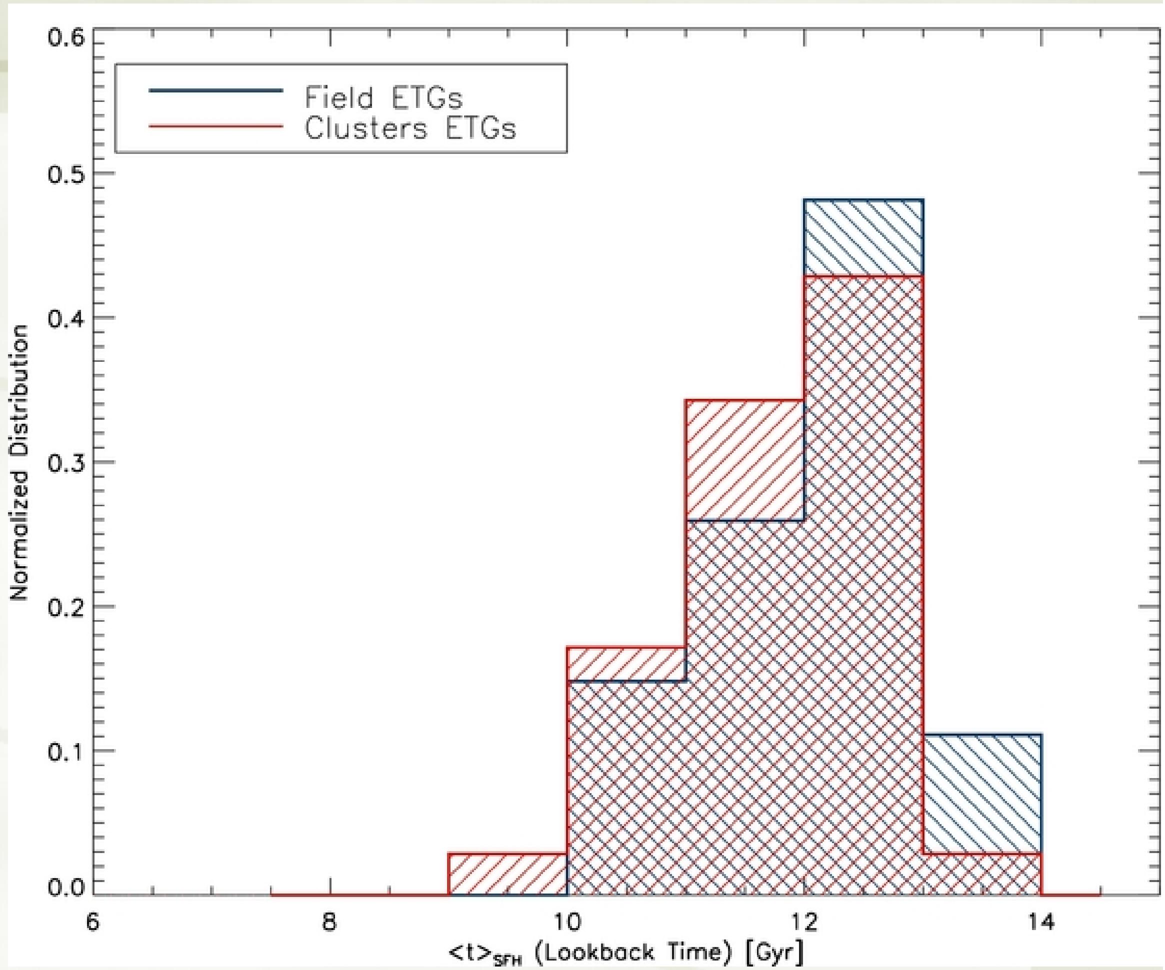
Other Techniques

- Radioactive decay in stars using U and Th
- Ages of galaxies using spectral signatures - at z=0 oldest galaxies seem to be 12Gyr old





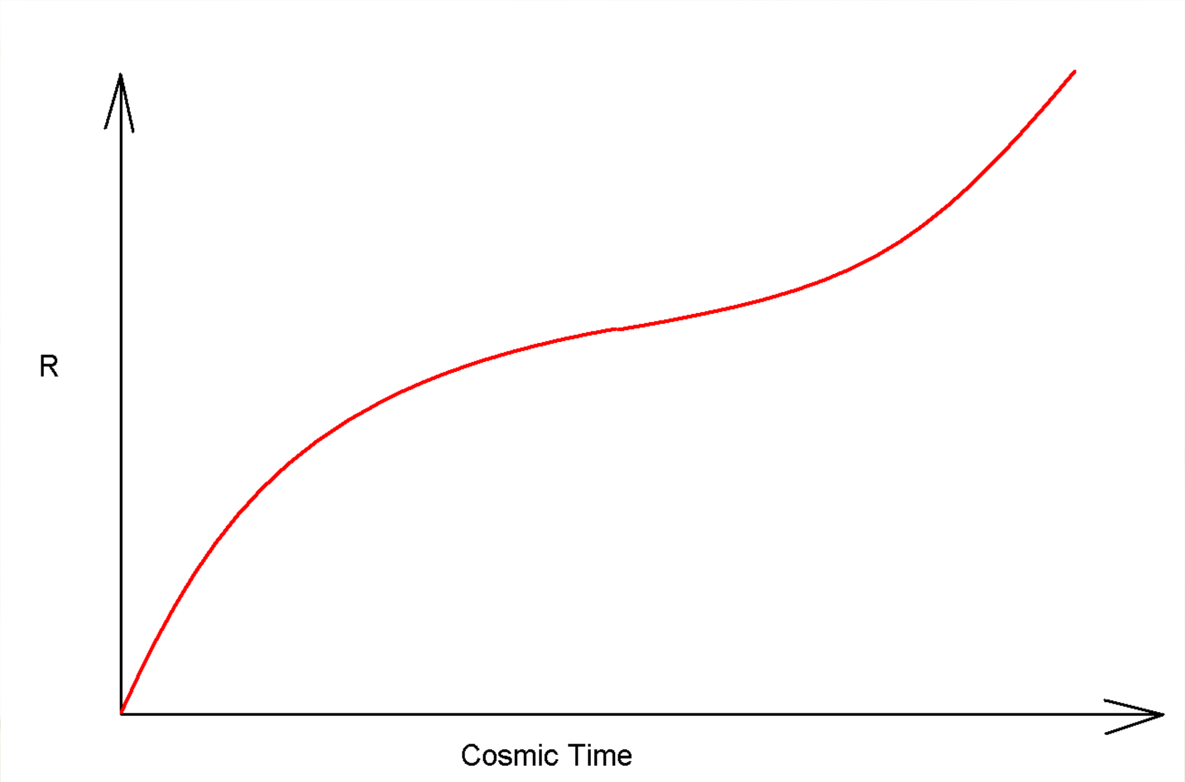
- Ages of galaxies seen at redshift 1.3
- Galaxies and star are younger than the universe- but only if Λ exists !



6 8 10 12 14

time at which galaxy formed

- What does the future hold? Increasingly rapid expansion!



The final fate of the Universe

•In a universe with a significant cosmological constant, the expansion of the universe, the space between clusters of galaxies will grow at an increasing rate. Redshift stretches photons to undetectably long wavelengths and low energies.

• Stars are expected to form normally for10^{12} to10^{14} years, but eventually the supply of gas needed for star formation will be exhausted . Once the last star has exhausted its fuel, stars will cease to shine.

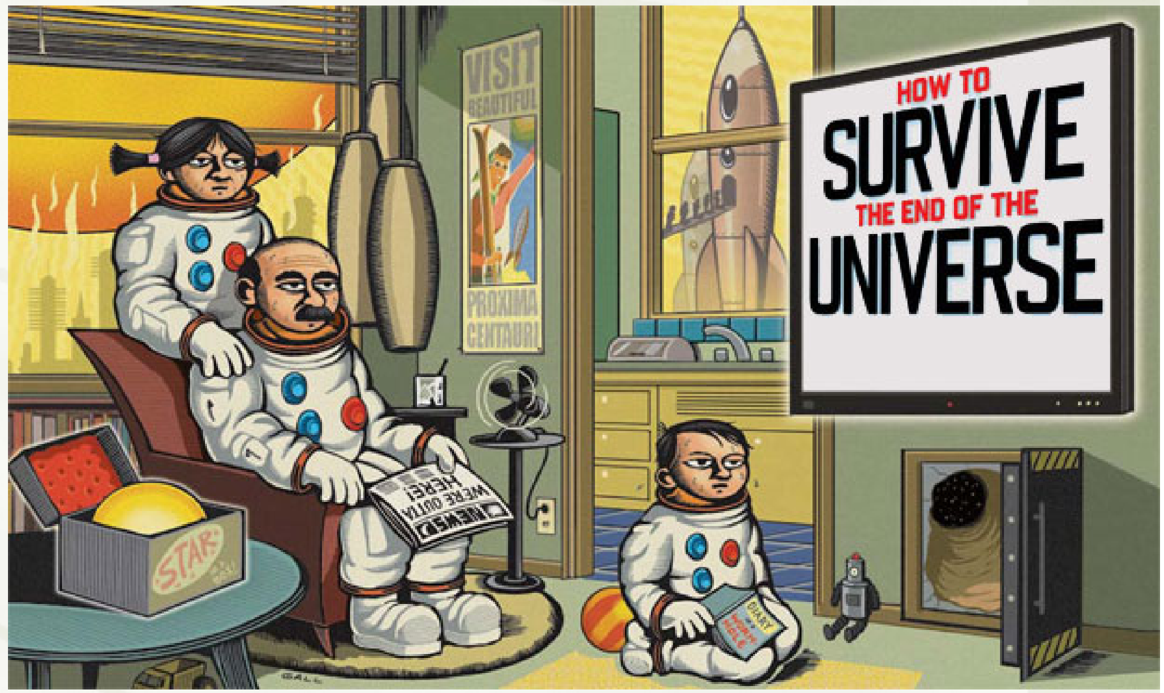
•Our nearest big neighbor M31 ~$2.5x10^{6}$ light years away and the Milky Way are moving towards each other at ~120 km/s. ~$3x10^{9}$ yrs from now, they probably will collide and merge.

•10^{11}-10^{12} yrs from now all the galaxies in the local group will merge.

http://en.wikipedia.org/wiki/Future_of_an_expanding_universe

The END

2x10[12] years from now, all galaxies outside the Local Supercluster will be red-shifted to
such an extent that even gamma rays will have wavelengths longer than the size of the observable universe at that time. Therefore, these galaxies will no longer be detectable in any way



http://discovermagazine.com/2011/dec/16-how-to-survive-the-end-of-the-universe

The final fate of the Universe

Big freeze: 10^{14} years and beyond

- Over a time scale on the order of 10^{14} years or less, existing stars burn out, stars cease to be created, and the universe goes dark
- On a much longer time scale, the galaxy evaporates as the stellar remnants comprising it escape into space, and black holes evaporate via Hawking radiation
- In some grand unified theories, proton decay after 10^{34} years will convert the remaining interstellar gas and stellar remnants into leptons (such as positrons and electrons) and photons.
- Then universe reaches a high-entropy state consisting of a bath of particles and low-energy radiation. It is not known however whether it eventually achieves thermodynamic equilibrium

Dark Energy

- There is an “energy” in the Universe that is making it accelerate
  - Call this “Dark Energy”
  - This makes up the rest of the gravitating energy in the Universe, and causes it to be flat!
  - Completely distinct from “Dark Matter”
- Remember Einstein’s cosmological constant…?
  - Dark Energy has precisely the same effect as Einstein’s cosmological constant
  - So, he was probably 'right' all along!- Well it all depends on what it really is!

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…

…although we are far from understanding all the properties of the Universe, recent observations are bringing us to the "era of precision cosmology!"

Next time…

- How did structure emerge in the Universe? - how did the universe evolve from its 'formless' early state to the stars, galaxies and clusters we see today