### **Cosmological Mysteries:**



### The Dark Energy Wayne Hu

Adler Planetarium, April 2004

### If its not dark, it doesn't matter!

Cosmic matter-energy budget:



Dark Energy
Dark Matter
Dark Baryons
Visib

Visible MatterDark Neutrinos

There is no dark side of the moon really. Matter of fact it's all dark. So How Do We Know?



### Expansion of the Universe

- Apparent recession of objects proportional to distance
- Stretching of the wavelengths of photons





E. Hubble 1889-1953

#### **Recession of Galaxies**

• Linear relationship between recession velocity and distance



Hubble (1929)

Riess, Press, Kirshner (1996)

Modern Day

### Extending the Hubble Diagram

• At extremely large distances or velocities the linearity breaks and indicates the presence of accelerated expansion



Perlmutter et al (1999) Riess et al (1999)

### Charting the Expansion History

- Light from distant objects emitted when the universe was smaller by the ratio of emitted to observed wavelength (color)
- Knowing the distance a photon traveled, infer the time of emission through speed of light - hence expansion in time



## Measuring Distances

### **Measuring Distances**

- Standard ruler: apparent (angular) separation of objects with a fixed physical separation to judge distance
- Standard candle: apparent brightness of objects with a fixed luminosity to judge distance





#### Supernovae as Standard Candles

- Binary system with a giant star and a white dwarf
- Mass transfer from the former to the latter will eventially make it exceed the (Chandrashekar) mass and explode
- Look for the appearance of a "new star"

#### Artists Rendition





#### **Accelerated Expansion**

• At extremely large distances or velocities the linearity breaks and indicates the presence of accelerated expansion



Perlmutter et al (1999) Riess et al (1999)



### **Cosmological Principle**

- "Isotropy": large scale properties look the same in different directions on the sky
- "Homogeneity": large scale properties look the same from different places in the universe
- We do not occupy a special vantange point in the universe



#### Friedmann [Robertson Walker]

- Given homogeneity and isotropy, large scale properties of the universe are described by two quantities
- Geometry: curvature of space
- Expansion history: change in scale of universe in time



#### **Curvature and Gravity**

- Einstein: space-time curvature is gravity gravitational force that bends trajectories is just the bending of spacetime
- Both the geometry and the expansion history are determined by the matter-energy content of the universe



#### Matter-Energy Content

- For space to be flat, the matter-energy density of the universe must be a well specified number called the critical density  $\sim 10^{-29} \text{ g/cm}^3$
- Visible matter falls far short of the critical density: hence if space is flat then must be composed of dark stuff



### Matter-Energy Content

- Ordinary matter exhibits attractive gravity and hence slows down or decelerates the expansion of the universe
- If the expansion is accelerating the matter-energy content must be dominated by dark energy with repulsive gravity



Flat Universe

### In the Beginning...



Hu & White (2004); artist:B. Christie/SciAm; available at http://background.uchicago.edu

# Fade to Black Microwave



### Turn on, Tune in, Drop out

- CMB photons have dropped out of the visible spectrum into the microwaves; a temperature 3 degrees above absolute zero
- Wavelengths in the mm-cm regime, comparable to radio and TV wavelengths



- Tune a TV between channels and about 1% of the static is from the CMB
- Tune a microwave receiver to the peak frequency of CMB photons and they dominate the night sky and come from everywhere at a rate of 10 trillion photons per second per square cm.

### The Microwave Sky



#### Uniform Emission

Penzias & Wilson 1965

### The Microwave Sky



Nigel: but it goes up to 11 no make that 100,000

http://map.gsfc.nasa.gov



- 1 part in 100000 variations in temperature
- Spot sizes ranging from a fraction of a degree to 180 degrees



Selecting only spots of a given range of sizes gives a power spectrum or frequency spectrum of the variations much like a graphic equalizer for sound.

# **Seeing Spots**





### **Observed Power Spectrum**



## Darkness from Light: Recombination

- Reversing the expansion, CMB photons got hotter and hotter into the past
- When the universe was 1000 times smaller and the CMB photons were at 3000K they were energetic enough disintingrate atoms into electrons and protons.



### Seeing Sound

- Colliding electrons, protons and photons forms a plasma
- Acts as gas just like molecules in the air
- Compressional disturbance propagates in the gas through particle collisions
- In the air we experience this as sound hitting the eardrum

- Unlike sound in the air, we see the sound in the CMB
- Compression heats the gas resulting in a hot spot in the CMB

### Piper at the Gates of Dawn

- Blow into a flute or an open pipe
- Spectrum of sound contains a fundamental frequency and harmonic overtones



### Piper at the Gates of Dawn

- Inflation is the source of sound waves at the beginning of time
- Sound waves are frozen at recombination, yielding a harmonic spectrum of frequencies that reach maximum displacement



### Fundamental: Weighing the Universe

- Measuring the angular extent of the fundamental wavelength (spot size) yields the curvature universe is spatially flat
- Einstein says matter-energy density curves space: universe is at the critical density



Dark Matter

### Harmonics: Ordinary Matter

- Competition between gravity and pressure depends on phase of oscillation
- At the fundamental (and odd frequency multiples) gravity assists sonic motion; at second peak (and even multiples) gravity fights sonic motion

Fundamental



### **Ordinary Matter**

- A low second peak indicates baryon or ordinary matter density comparable to photon density
- Ordinary matter consists of ~5% of the critical density today



#### Harmonics: Dark Matter

- What maintains the gravitational potential if the ordinary matter oscillates as a stable sound wave?
- Without matter that does not interact with photons/light or dark matter, gravitational potentials decay once ordinary matter enters into oscillation
- Gravitational enhancement destroyed soon after 1st peak



#### Recombination

#### Dark Matter

- A third peak comparable to second peak indicates a dark matter density ~5x that of ordinary matter
- Dark matter ~25% of the critical density



### Missing Energy

- Ordinary matter and dark matter comprise ~30% of the total density as measured by the first peak
- ~70% of the universe unaccounted for
- Must have negligible contribution at recombination else else seen in the peaks
- New form of energy whose energy density decreases more slowly than matter as the universe expands
- Dub this new form of energy density:

### Dark Energy

#### Cosmic Coincidence?

• Why is it that now (and seemingly only now) is the dark matter and dark energy of comparable density



Sean Carroll: http//pancake.uchicago.edu

### **Structure Formation**

### Gravitational Formation of Structure

- After recombination, CMB photons stop interacting with matter
- Matter fluctuation collapses due to graviational self-attraction
- Grows into the large scale structure of the universe in 14 billion yrs

### Dark Energy & Gravitational Redshifts

- Accelerated expansion halts the growth of structure
- Gravitational potential decays blueshift correlated with galaxies and the large scale structure of the universe





## **Counting Halos for Dark Energy**

- Number density of massive halos extremely sensitive to the growth of structure and hence the dark energy
- Massive halos can be identified by the hot gas they contain



#### Gravitational Lensing by Clusters

- Shearing of galaxy images reliably detected in clusters
- Avoids astrophysical uncertainties; depends only on mass



Cluster (Strong) Lensing: 0024+1654

Colley, Turner, & Tyson (1996)

### Um... What is it?

#### Einstein's Cosmological Constant

- Simplest but perhaps most troubling explanation: Einstein blundered into fundamental property of universe
- Constant energy density, hence increasing net energy as universe expands consistent with data
- Quantum mechanics allows/predicts such phenomena in the form vacuum energy: empty space is alive with virtual particles



 Naive prediction is 10<sup>120</sup> times too big and more sophisticated models still 10<sup>60</sup> off

### Or Was Einstein Fundamentally Wrong?

- Gravity as formulated by Einstein is incompatible with quantum mechanics
- Modern ideas of marrying gravity with quantum mechanics involve extra dimensions that may appear as modifications to gravity on large scales



# We Don't Have A Clue! [A Good Thing]

The Emperor of the South Sea was Fast, the Emperor of the North Sea Furious, the Emperor of the center was Primordial Blob. Fast and Furious were discussing how to repay Primordial Blob's bounty.

All men have seven holes through which they look, listen, eat, breathe; he alone doesn't have any. Let's try boring them.

Every day they bored one hole, and on the seventh day Primordial Blob died.

– Chuang-tzu (c. 350 bc)