



AST 376: Cosmology  
(Spring 2014)



## The Dark Side II: Dark Energy

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## The Dark Side of the Universe

• Big Q: What is the universe made of?



• consensus view of early 21<sup>st</sup> century (WMAP):

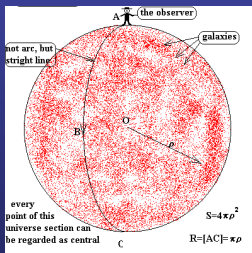
- 4% normal matter ('baryons') (stars, gas, people...)
- 23% dark matter
- 73% dark energy

“Deep into the darkness peering, long I stand there wondering, fearing.” (E.A. Poe, *The Raven*)

• We don't know what > 90% of universe is made of !!!

## Einstein's Cosmological Constant

• 1917: Einstein constructs model of the universe that is eternal and static



• balance between attractive gravity and repulsive cosmological constant (“anti-gravity”)

• finite but without boundary (spatially closed)

## Einstein's “Greatest Blunder” !?

• 1929: Hubble discovers that the Universe is expanding → it is NOT static

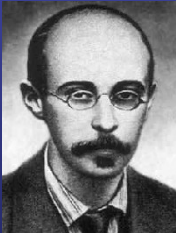


• the repulsive cosmological constant (“anti-gravity”) is not necessary!

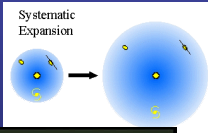
• Cosmological constant ( $\Lambda$ -term) falls into disrepute!

### The Expanding Universe

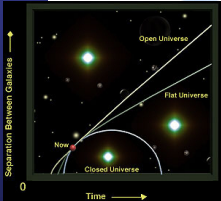
- 1922: an expanding universe (GR without cosmological constant)



Alexander Friedmann  
(1888-1925)



Systematic Expansion




Separation Between Galaxies  
Time


Open Universe  
Flat Universe  
Closed Universe

### The Expanding Universe

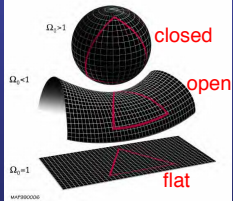
- In Einstein's GR theory: matter density determines geometry of the Universe!



Closed Universe



Open Universe




$\Omega_0 > 1$  closed  
 $\Omega_0 < 1$  open  
 $\Omega_0 = 1$  flat

- Omega: 
$$\Omega = \frac{\text{density of universe}}{\text{critical density}}$$

### Big Q: Which Universe are we living in?

- Task: Determine fate of the Universe by measuring Hubble constant and cosmic mass density!



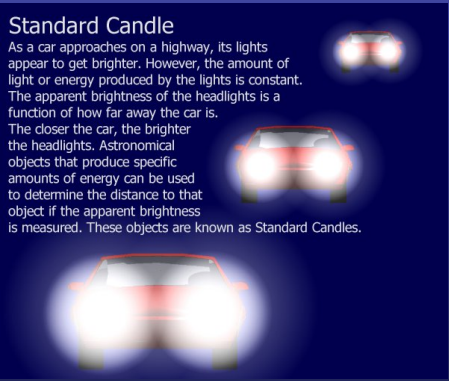
• Allan Sandage  
- born: 1926  
- Hubble's only student

"The Ability of the 200-inch Telescope to Discriminate Between Selected World Models" (1961, The Astrophysical Journal)


### Need Standard Candles to Measure Distances

**Standard Candle**

As a car approaches on a highway, its lights appear to get brighter. However, the amount of light or energy produced by the lights is constant. The apparent brightness of the headlights is a function of how far away the car is. The closer the car, the brighter the headlights. Astronomical objects that produce specific amounts of energy can be used to determine the distance to that object if the apparent brightness is measured. These objects are known as Standard Candles.



### Need Standard Candles to Measure Distances

Galaxy in	Distance in light-years
 Virgo	78,000,000
 Ursa Major	1,000,000,000
 Corona Borealis	1,400,000,000
 Bootes	2,500,000,000

- Need bright source!
- Need standardized one!
- Sandage's idea: Use brightest elliptical galaxies in (galaxy) clusters!

### The Downfall of the Sandage Agenda

- Task: Determine fate of the Universe by measuring Hubble constant and cosmic mass density!



- Beatrice Tinsley (1941-1981)  
- PhD: UT Austin

PhD thesis: "Evolution of Galaxies and its Significance for Cosmology" → galaxies evolve → are not standard candles

### Need Standard Candles to Measure Distances

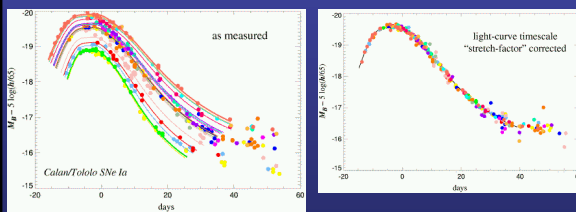
- New idea: Use supernova (SN) explosions!  
→ of Type Ia = exploding white dwarfs



White dwarf

### The Quest to make SN Ia's into Standard Candles

- For nearby Ia's: measure many lightcurves!



→ Corrected lightcurves make for exquisite standard candles!

## Supernova Cosmology: The Big Race

Supernova Cosmology Project

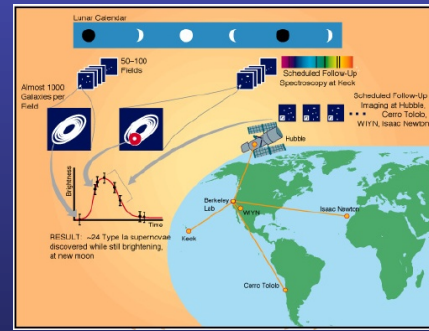


High-z SN Search Team



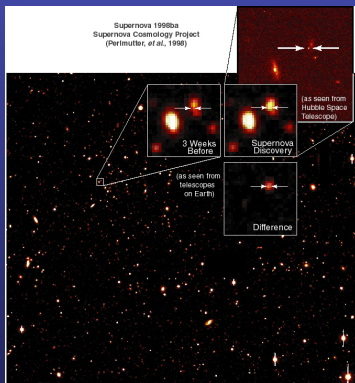
- in mid 1990s: intense rivalry between SCP and HZT

## Supernova Cosmology: The Big Race

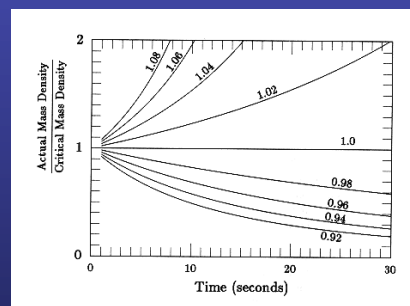


- Large-scale operation: need big teams and the world's best telescopes!

## Supernova Cosmology: The Big Race

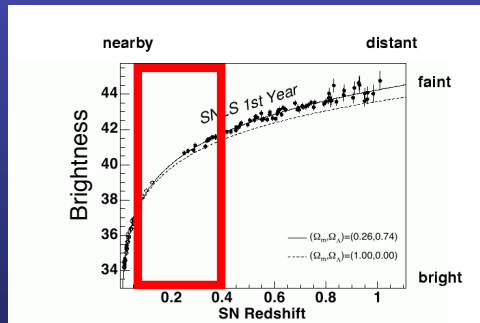


## Theorists already "knew" the answer: $\Omega=1$



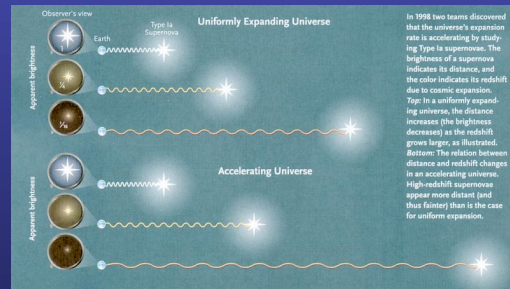
- TINY deviations from  $\Omega=1$  would lead to HUGELY different  $\Omega$ 's VERY quickly!

## Supernova Cosmology: The Answer!



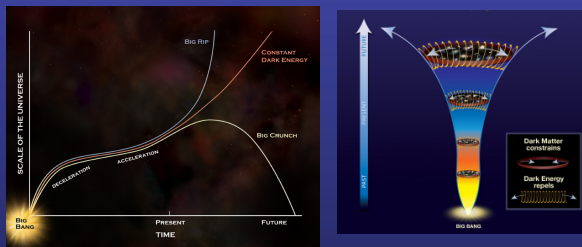
- Far-away SNe appear dimmer as expected!

## Supernova Cosmology: The Interpretation!



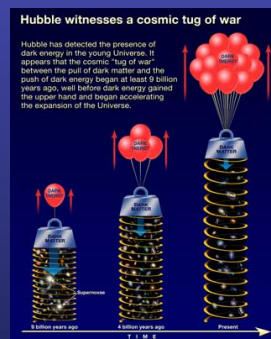
- The Universe's Expansion must be accelerating!

## Supernova Cosmology: The Interpretation!



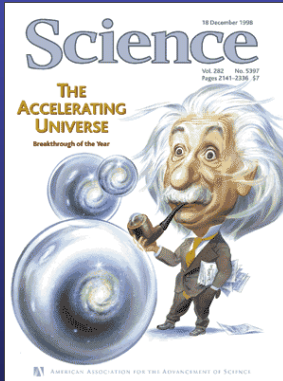
- The expansion of the universe is accelerating!

## Supernova Cosmology: The Interpretation!



- Dark Energy becomes ever more dominant!

## Supernova Cosmology: The Reaction!



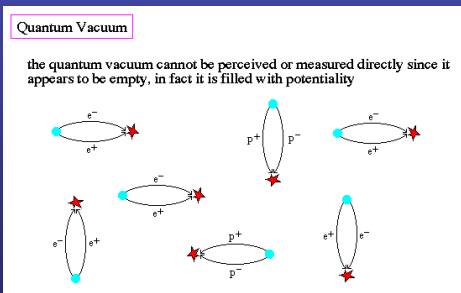
## Through a Universe Darkly

- BIG Q: What is the dark energy?

???

- it could be Einstein's old cosmological constant
- more than 90 years after it was first postulated by Einstein, this remains one of the great unsolved problems in science!

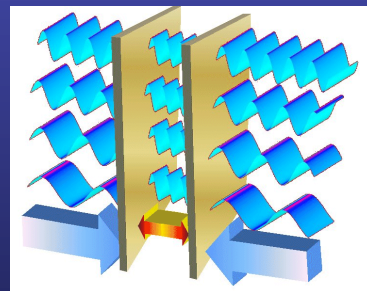
## An idea from particle physics: vacuum energy!



- Virtual particle/anti-particle pairs briefly exist!

## An idea from particle physics: vacuum energy!

→ Observed in lab: Casimir effect!



- The two plates are pushed together!

### An idea from particle physics: vacuum energy!

→ Consider situation in expanding universe!



- Vacuum energy behaves as fluid with **NEGATIVE** pressure!

### In Einstein's theory of General Relativity:

- Gravity has two sources: mass **AND** pressure  
(Pressure is random energy of motion)
- Total gravity = mass density + 3 x Pressure
- If pressure is negative → Total gravity can be negative as well!
- Negative gravity repulses!
- Repulsion eventually wins over attraction!

### To solve the riddle of dark energy:



- UT's McDonald Observatory: Hobby-Eberle Telescope (HET)
- HETDEX: HET Dark Energy Experiment
- measure properties of DE over cosmic time

### Dark Energy and the Accelerating Universe

- **1917: Einstein's Cosmological Constant**
  - acts like repulsive anti-gravity
  - after Hubble discovers expansion of the universe, Einstein the constant (his "Greatest Blunder")
- **1990s: Supernovae Ia made into Standard Candles**
  - if properly corrected, lightcurves are highly standardized
  - huge surprise: SNe appear dimmer as expected
  - only possible explanation: the Universe is accelerating!
- **What is the Dark Energy?**
  - still **VERY** poorly understood
  - maybe related to quantum vacuum energy