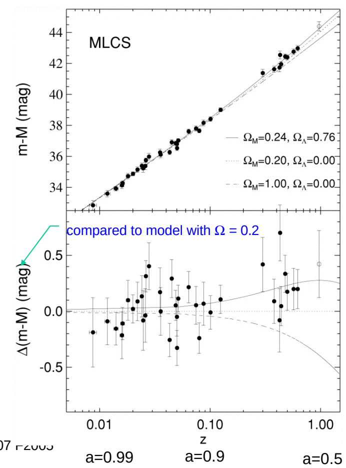
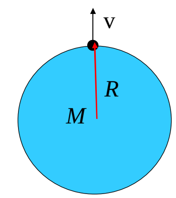
CC—5 Dec

- Distant SN are 15% fainter than model with Ω =0!
  - Longer time to expand than universe having no mass at all!
  - Shorter time means expansion slowed down; longer time means expansion sped up.
- If motion takes longer than model with no mass, need "negative gravity" or "repulsive gravity."
- "Though a good deal is too strange to be believed, nothing is too strange to have happened." —Thomas Hardy



Einstein's General Relativity

- What causes gravity?
- Newton's answer: mass.
  - Force of gravity between what's in the sphere and test mass m
    F = G M m/R².
- Einstein's answer: mass and pressure
  - Force of gravity between what's in the sphere and test mass m
    F = G (M + 3PV/c²) m/R²



Source of Gravity

- Einstein's answer: mass and pressure
  F = G (M + 3PV/c²) m/R².
- Newton's Law of gravity
  F = G M m/R².
- Einstein's Law of gravity
  Curvature of space = 8πG Mass-Pressure
  G = 8πG **T**
  - Object feels curvature of space and changes its momentum
  - **G** and **T** are tensors having 16 components
- Ordinary matter has little pressure because speed is much smaller than c.
  3PV/c² = M (v/c)².
- Radiation has positive pressure
  3PV/c² = M.
  F = G 2M m/R².

$$T_{\text{matter}} = M/V\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & (v/c)^2 & 0 & 0\\ 0 & 0 & (v/c)^2 & 0\\ 0 & 0 & 0 & (v/c)^2\end{pmatrix}$$

$$T_{\text{rad}} = M/V\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & \frac{1}{3} & 0 & 0\\ 0 & 0 & \frac{1}{3} & 0\\ 0 & 0 & 0 & \frac{1}{3}\end{pmatrix}$$

Cosmological Constant

- Einstein's answer: mass and pressure
  Force: F = G (M + 3PV/c²) m/R².
- Einstein's Law of gravity
  Curvature of space = 8πG Mass-Pressure
  G = 8πG T
  - Object feels curvature of space and changes its momentum
- Ordinary matter has little pressure because speed is much smaller than c.
  3PV/c² = M (v/c)².
- Radiation has positive pressure
  3PV/c² = M.
  Force F = G 2M m/R².
- Einstein in 1920s: My equations of gravity allow "cosmological constant"
  - T_{cc} has same mathematical properties as T_{matter} and T_{rad}.

1. Write the force of gravity for the case of the cosmological constant. Watch the signs.

$$T_{\text{matter}} = M/V\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & (v/c)^2 & 0 & 0\\ 0 & 0 & (v/c)^2 & 0\\ 0 & 0 & 0 & (v/c)^2\end{pmatrix}$$

$$T_{\text{rad}} = M/V\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & \frac{1}{3} & 0 & 0\\ 0 & 0 & \frac{1}{3} & 0\\ 0 & 0 & 0 & \frac{1}{3}\end{pmatrix}$$

$$T_{CC} = M/V\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & -1 & 0 & 0\\ 0 & 0 & -1 & 0\\ 0 & 0 & 0 & -1\end{pmatrix}$$

Cosmological Constant

- Einstein's answer: mass and pressure
  Force: $F = G (M + 3PV/c^2)\, m/R^2$.
- Einstein's Law of gravity
  Curvature of space = $8\pi G$ Mass-Pressure
  $G = 8\pi G\, T$
  - Object feels curvature of space and changes its momentum
- Einstein in 1920s: My equations of gravity allow "cosmological constant"
  - T_{cc} has same mathematical properties as T_{matter} and T_{rad}.
  - Pauli: "What is not forbidden is mandatory."

1. Write the force of gravity for the case of the cosmological constant. Watch the signs.
   $F = G (M - 3M)\, m/R^2$
   $F = - G\, 2M\, m/R^2$.
   - Repulsive gravity

$$T_{matter} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & (v/c)^2 & 0 & 0 \\ 0 & 0 & (v/c)^2 & 0 \\ 0 & 0 & 0 & (v/c)^2 \end{pmatrix}$$

$$T_{rad} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} \end{pmatrix}$$

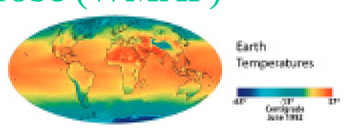
$$T_{CC} = M/V \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

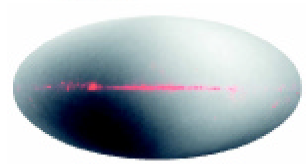
What is the Universe Made of?

- Spherical sample of universe. R=moon's orbit. Sample has
  - 3 oz of ordinary matter
  - 1 lb of dark matter
  - 3 lb of dark energy
- Ordinary matter—protons, neutrons, electrons
  - Stars, gas, dust, planets, us
  - Ω_{matter} = 4%
- Dark matter—not detected except through gravity
  - $\Omega_{dark\ matter}$ = 23%
- Light
  - Mass density is small now. Dominant before universe was 1 Million years old
- Cosmological constant or dark energy
  - Repulsive
  - $\Omega_{cosmological\ constant}$ = 73%
- $\Omega_{matter} + \Omega_{dark\ matter} + \Omega_{cosmological\ constant} = 1$

Weighing the Universe with the Wilkinson Microwave Anisotropy Probe (WMAP)

- Radiation from the Big Bang separated from matter when universe became neutral (not ionized) at a=0.001.
- CBR is a snapshot of U at 300,000 yr.
- Motion: universe expands from a=0.001 to 1
- Timing: Observe the temperature ripples, which have a length (age of Universe)*(speed of light)





Temperature of radiation from BB from WMAP