# Discovery of Dark Energy/ Cosmological Constant —3 Dec

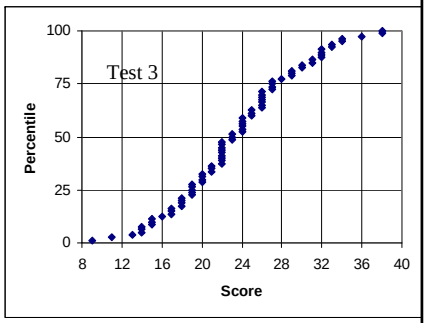
- How do scientists make discoveries?
- Characteristics
  - New ideas
    - Einstein's cosmological constant ca. 1920
  - New instruments
    - Large CCDs to search for SN
  - New wavelengths (NA)
  - Careful design
    - SN are clean, not messy.
  - Serendipity
    - Did not expect to find dark energy
  - Courage to make the measurement (NA)

In a fair sample with R=Moon's orbit
Ordinary matter: 4%, 3oz
Dark matter: 27%, 1lb
Dark energy: 73%, 3 lb



# Grades

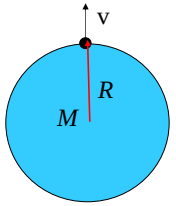
- Average on test 3: 24/40
  - Be certain to pick up both sheets of the answers.
- Provisional grades
  - Pick up sheet
  - Check that your grades have been recorded correctly.
    - A few late hwk will be graded by Fri.
    - I have a Hwk 8 and a Hwk 10 with no name.
  - Your grade may change significantly, because the Final Exam contributes 31% of the course grade.
    - You will be able to pull up missed homeworks.
  - Lowest 3 exercise and lowest homework grades have been dropped.
  - Average grade is 3.1.






# Einstein's General Relativity

- What causes gravity?
- Newton's answer: mass.
  - Force of gravity between what's in the sphere and test mass m
    $F = G\,M\,m/R^2$.
- Einstein's answer: mass and pressure
  - Force of gravity between what's in the sphere and test mass m
    $F = G\,(M + 3PV/c^2)\,m/R^2$






# Source of Gravity

- Einstein's answer: mass and pressure
  $F = G\,(M + 3PV/c^2)\,m/R^2$.
- Newton's Law of gravity
  $F = G\,M\,m/R^2$.
- Einstein's Law of gravity
  Curvature of space = $8\pi G$ (Mass-Pressure tensor)
  $\mathbf{G} = 8\pi G\,\mathbf{T}$
  - Object feels curvature of space and changes its momentum
  - **G** and **T** are tensors having 16 components
  - If on average the material is at rest, then **T** has 4 components. $(M + 3PV/c^2)$ is sum of the 4 terms on the diagonal of **T** V.

$$T = \begin{pmatrix} M/V & 0 & 0 & 0 \\ 0 & P_x/c^2 & 0 & 0 \\ 0 & 0 & P_y/c^2 & 0 \\ 0 & 0 & 0 & P_z/c^2 \end{pmatrix}$$

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

- Ordinary matter has little pressure because speed is much smaller than c.
  $3PV/c^2 = M\,(v/c)^2$.
- Radiation has positive pressure
  $3PV/c^2 = M$.
  $F = G\,2M\,m/R^2$.

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

# Cosmological Constant

- Einstein's answer: mass and pressure
  Force: F = G (M + 3PV/c²) m/R².
  – If on average the material is at rest, then **T** has 4 components. (M + 3PV/c²) is sum of the 4 terms on the diagonal of **T** V.
- Einstein in 1920s: My equations of gravity allow a special tensor. E called it a "cosmological constant"
  – $T_{cc}$ has same mathematical properties as $T_{matter}$ and $T_{rad}$.
  – "What is not forbidden is mandatory"—W Pauli
  – Pressure does not push; pressure sucks.

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

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

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



# Cosmological Constant

- Einstein's answer: mass and pressure
  Force: F = G (M + 3PV/c²) m/R².
  – If on average the material is at rest, then **T** has 4 components. (M + 3PV/c²) is sum of the 4 terms on the diagonal of **T** V.

1. Write the force of gravity for the case of the cosmological constant. (Watch the signs.)
   A. F=G M m/R²
   B. F=G (2M) m/R²
   C. F=G (– 2M ) m/R²
- Ideas:

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

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

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



# 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
- 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."
  – F = G (M – 3M ) m/R²
    F = – G 2M m/R².
  – Repulsive gravity
- Einstein tried to make his theory of gravity prevent expansion or contraction of the universe. The cosmological constant balances gravity of matter.
  – In 1929, Hubble discovered the expansion of the U. Einstein said the cosmological constant was his greatest blunder.
  – Had he lived to 1998, he would have called it his greatest discovery.

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

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

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