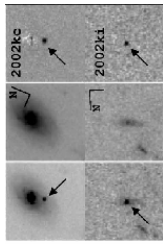
Weighing the Universe—16 Nov

- Weighing the universe means to find mass density
- Why?
  - What is the universe made of? Is there mass that we cannot see?
  - What is the fate of the universe? Will it expand forever or fall back on itself?
- How?
  - Mass in a large sphere surrounding us pulls on a galaxy on the surface
  - Measure how much the galaxy slows.
  - Use supernovae
- What we will find: Galaxies speed up!
  - "Dark energy" is repulsive whereas matter and radiation are attractive.



Distant supernovae
Riess et al, 2004, ApJ 607, 665.

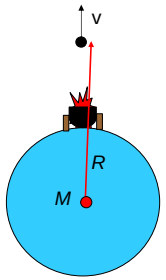
Astronomical Weighing

- Principle for astronomical weighing:
  - Define a motion
  - Time the motion
  - If the motion takes longer, the mass is less.
- To find mass of sun, measure period T & size R of a planet's orbit.
  - Under influence of the gravity of the sun, a planet moves a given distance. If the time is short, the mass of the sun is greater.
- To find mass of a galaxy, measure the speed of gas in orbit & radius of orbit.
  - Under influence of the gravity of the galaxy, a gas cloud moves a given distance. If the time is short, the mass of the galaxy is greater.

Mass	Test object	Motion	Behavior if more massive
Sun	Earth	An orbit	Year is shorter
Galaxy	Gas cloud	An orbit	Speed is faster

Cannon Ball

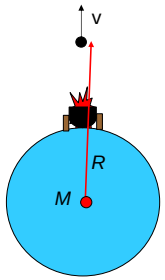
- Cannonball is shot out of cannon at speed v. Cannonball has mass = 1kg.
  - Kinetic energy is ½ v2.
- Gravity pulls on cannonball to slow the motion.
  - Potential energy is G M /R
- What mass & what radius?
  - M is entire mass enclosed by sphere of radius R.
  - Mass outside of R does not count if spherically symmetric.
  - Distance is R between cannonball and center of sphere.



Cannon Ball

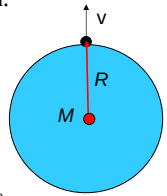
- Cannonball is shot out of cannon at speed v.
  - Kinetic energy is ½ v2.
- Gravity pulls on cannonball to slow the motion.
  - Potential energy is G M /R
- Cannonball will escape if shot fast enough
  - KE ≥ PE
- Define "Density parameter"
  - Ω = PE/KE = 2 G M / (R v^2)

1. A cannonball is shot with Ω=0.7. Will the cannonball escape? Same question for Ω=1.1.



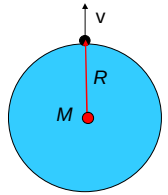
Universe

- Sphere expands and galaxy moves because universe expands.
- Galaxy is moving at speed v.
  - Kinetic energy is ½ v2.
- Gravity pulls on galaxy to slow the motion.
  - Potential energy is G M /R
- Galaxy will escape if moving fast enough
  - KE ≥ PE
- Define "Density parameter"
  Ω = PE/KE = 2 G M / (R v^2)
  Ω = PE/KE = 2 G M / (R^3H^2) Use Hubble's Law
- Mass/volume is mass density ρ
  Ω = PE/KE = $8\pi/3$ G ρ / H^2. Use vol=4/3 π R^3.
- Does not depend on particular galaxy



Does universe expand forever?

- Galaxy is moving at speed v.
  - Kinetic energy is ½ v2.
- Gravity pulls on galaxy to slow the motion.
  - Potential energy is G M /R
- Galaxy will escape if moving fast enough
  - KE ≥ PE
- Define "Density parameter"
  Ω = PE/KE = 2 G M / (R^3H^2) Use Hubble's Law
- Mass/volume is mass density ρ
  Ω = PE/KE = $8\pi/3$ G ρ / H^2.
- Does not depend on particular galaxy



2. Ω=0.7. Will the universe expand forever?
3. Explain why U will not expand forever if mass density is big.
4. Explain why U will expand forever if Hubble's constant is big.

Weighing Universe

- Principle for astronomical weighing:
  - Define a motion
  - Time the motion
  - If the motion takes longer, the mass is less.
- Consider a big sphere centered on us.
  - Contains many galaxies
  - Is a "fair" sample of the Universe.
- Mass inside sphere pulls on galaxy & slows expansion.
- Present speed & present distance are fixed by Hubble's Law.
- To find mass density of the universe, measure the time it takes for the U to expand by a factor of 2. (Other factors are OK too.)

5. (2 pts.) Consider now & time when radius of sphere is ½ present radius. If the time to expand by a factor of 2 is long, the mass density of the U is ___. Explain your reasoning.