

3/27/07



## Agenda

- Announce:
  - Part II of project due Tuesday
  - Observations after Spring Break
  - Extra Credit
- Zwicky
- Bullet Cluster
- The “Big Rip”
- Review Dark Matter/Dark Energy
- Movie: Runaway Universe

## Zwicky



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- fitness freak and used to amaze onlookers by doing one-armed push ups. (wikipedia)
- fond of calling people “spherical bastards”

## Zwicky



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- fond of calling people “spherical bastards”...because they were bastards any way you look at them!

## Bullet Cluster

- Collision of two clusters of galaxies
- Each cluster essentially consists of three things:
  - Stars
  - Hot Gas
  - Dark matter (possibly)
- In this collision we expect certain behaviors....

## Bullet Cluster

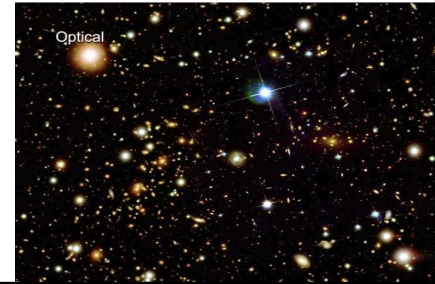
- What we expect:
  - Stars in each galaxy pass right through, hardly affected, but somewhat slowed by gravity
  - Hot Gas would interact with other hot gas (E&M) and be found in the center of the collision
  - Dark matter, if it's present, should pass right through (remember it hardly interacts with anything)

## Bullet Cluster

- How we observe:
  - Stars –look in visible light
  - Hot Gas –look in Xray
  - Dark matter –look for gravitational lensing

## Bullet Cluster

- Visible—galaxies



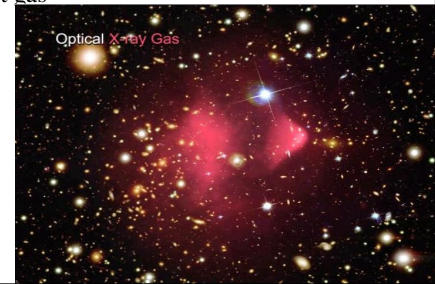
## Bullet Cluster

- Visible—galaxies
- Blue—dark matter



## Bullet Cluster

- Visible—galaxies
- Red—hot gas



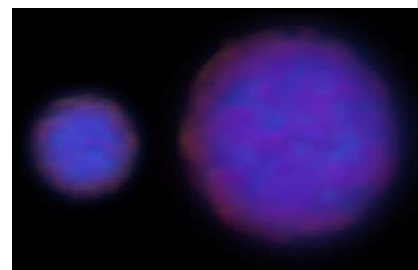
## Bullet Cluster

- Visible—galaxies
- Red—hot gas
- Blue—dark matter



## Bullet Cluster

- Visible—galaxies
- Red—hot gas
- Blue—dark matter



## Bullet Cluster

- Bottom line:
  - If dark matter doesn't exist, then blue regions would overlap red splotches
  - If dark matter exists, blue regions would pass right through each other and be separated from red
- Dark matter exists!

## The “Big Rip”

### Phantom Energy and Cosmic Doomsday

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Cosmologists have long wondered whether the Universe will eventually recollapse and end with a Big Crunch, or expand forever, becoming increasingly cold and empty. Recent evidence for a flat Universe, possibly with a cosmological constant or some other sort of negative-pressure dark energy, has suggested that our fate is the latter. However, the data may actually be pointing toward an astonishingly different cosmic end game. Here, we explore the consequences that follow if the dark energy is phantom energy, in which the sum of the pressure and energy density is negative. The positive phantom-energy density becomes infinite in finite time, overcoming all other forms of matter, such that the gravitational repulsion rapidly brings our brief epoch of cosmic structure to a close. The phantom energy rips apart the Milky Way, solar system, Earth, and ultimately the molecules, atoms, nuclei, and nucleons of which we are composed, before the death of the Universe in a “Big Rip”.

## The “Big Rip”

TABLE I: The history and future of the Universe with  $w = -3/2$  phantom energy.

Time	Event
$\sim 10^{-43}$ s	Planck era
$\sim 10^{-36}$ s	Inflation
First Three Minutes	Light Elements Formed
$\sim 10^5$ yr	Atoms Formed
$\sim 1$ Gyr	First Galaxies Formed
$\sim 15$ Gyr	Today
$t_{rip} = 1$ Gyr	Erase Galaxy Clusters
$t_{rip} = 60$ Myr	Destroy Milky Way
$t_{rip} = 3$ months	Unbind Solar System
$t_{rip} = 30$ minutes	Earth Explodes
$t_{rip} = 10^{-19}$ s	Dissociate Atoms
$t_{rip} = 35$ Gys	Big Rip

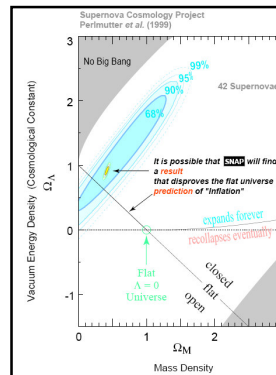
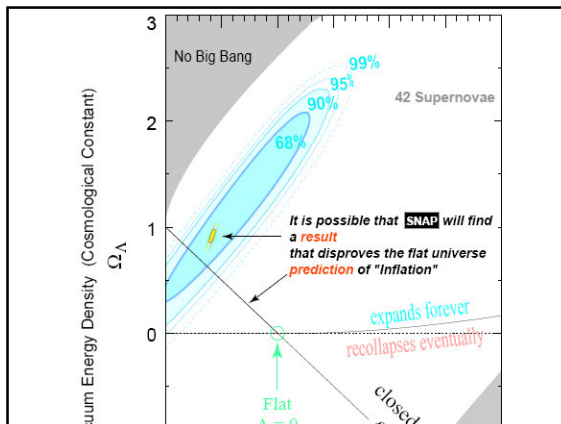


Figure 1: 68%, 90%, 95%, and 99% confidence regions in the  $\Omega_M - \Omega_\Lambda$  plane from the 42 distant SNe Ia in Perlmutter et al. (1999). These results rule out a flat, matter dominated ( $\Omega_M = 1$ ,  $\Omega_\Lambda = 0$ ) cosmology and provide strong evidence (probability  $> 99.5\%$ ) for  $\Omega_\Lambda > 0$ . Also shown is the expected confidence region.



## Evidence for Dark Matter

- Flat rotation curves of galaxies
- Clusters of galaxies:
  - Orbits of galaxies
  - Temperature of hot gas
  - Gravitational lensing
- Fits with computer simulations of galaxy formation
- Fits with other cosmological measurements (WMAP...Universe flat)

## Dark Matter vs. Dark Energy

- |  |  |
|--|--|
| • Can't see w/ light   | • Can't see w/ light   |
| • Attracts via gravity   | • Repels via gravity   |
| • Clumps in galactic halos and cluster cores                                     | • No clumps...smoothly distributed throughout  |
| • Possibly consists of some new particle (WIMPs), likely not dead stars (MACHOs) | • Consists of something very exotic...cosmological constant, quintessence, phantom energy, etc |