AST 376: Cosmology

(Spring 2014)

The Dark Side I: Dark Matter

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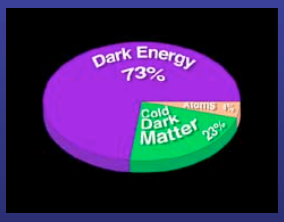
The Dark Side of the Universe

- Big Q: What is the universe made of?

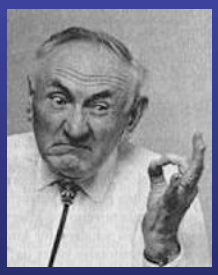


- consensus view of early 21st century (WMAP):
  - 4% normal matter (`baryons') (stars, gas, people…)
  - 23% dark matter
  - 73% dark energy

``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 !!!

Fritz Zwicky: Astronomy's Mad Genius



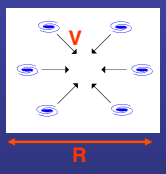
- Swiss national
  1898 (Varna) – 1974 (Pasadena)
- Professor at Caltech (1925+)
- creative genius:
  - **concept of supernova**
  - **neutron stars**
  - **dark matter (`missing mass')**
- intense eccentricity
  ("spherical bastards")

1933: Zwicky and the `Missing Mass'

- Coma cluster of galaxies
  - ~1,000 individual galaxies
  - Radius ~ 5 Mpc
- Zwicky measures average (radial) velocities (from Doppler shift)
  - Result: ~1,000 km/s
- comparison with sum of visible (stellar) mass

- BIG surprise: There must be 10 times more matter !

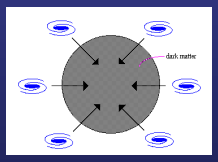
1933: Zwicky and the `Missing Mass'



- measure: V and R
- calculate required mass to hold cluster together:

$$M = \frac{V^2 R}{G}$$

(Newton's constant)



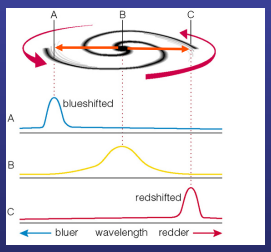
- Result for Coma:
  - need 10 times more mass than is visible!
- For more than 30 years, no one else took this seriously!

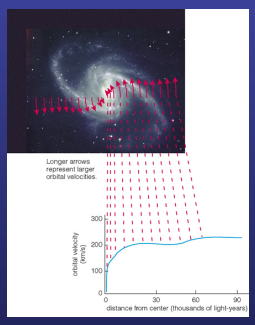
Vera Rubin: The Dark Side of Galaxies

- Born 1928 (Philadelphia)
- 1965: Carnegie Institution (DTM, Washington D.C.)
- firmly established existence of dark matter in individual galaxies (with Kent Ford)
  - **flat rotation curves**
- activist for women's rights in the sciences

Vera Rubin: The Dark Side of Galaxies (1970s)

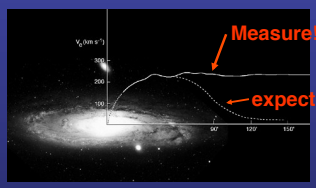
- measure orbital velocity of stars (using Doppler shift)



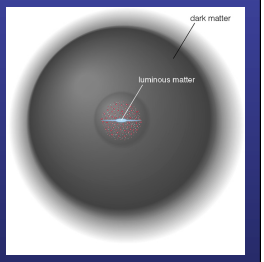


Vera Rubin: The Dark Side of Galaxies (1970s)

- measure orbital velocity of stars (using Doppler shift)



- `flat' rotation curves:
  - galaxies must contain 10 times more non-visible matter!



Through a Universe Darkly

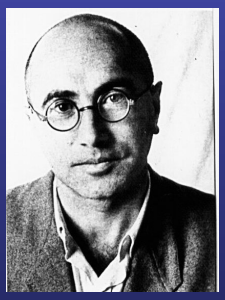
• BIG Q: What is the dark matter?

???

• more than 80 years after it was first postulated by Zwicky, this remains one of the great unsolved problems in science!

• But, by trial and error, we ve gained important clues

Yakov B. Zeldovich: Godfather of Soviet Physics



• 1914 - 1987

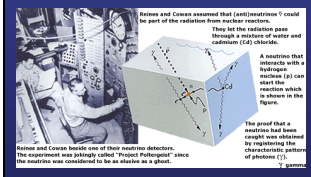
• `father' of Soviet Bomb (Atomic and Hydrogen)

• great astrophysicist:
- **supermassive black holes**
- **no-hair theorem**

• `Zeldovich pancakes' :
- **top-down theory of galaxy formation**
- **neutrinos make up dark matter**

The Neutrino Universe

• neutrinos: - very elusive (weakly interacting)
- they are *known* to exist!

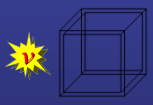


Reines and Cowan assumed that (anti)neutrinos ν could be part of the radiation from nuclear reactors. They let the radiation pass through a mixture of water and cadmium (Cd) chloride. A neutrino that interacts with a hydrogen nucleus (p) can start the reaction which is shown in the figure. The proof that a neutrino had been caught was obtained by registering the characteristic pattern of photons (γ).

Reines and Cowan beside one of their neutrino detectors. The experiment was jokingly called "Project Poltergeist" since the neutrino was considered to be as elusive as a ghost.

The Neutrino Universe

• neutrinos: - produced in Big Bang fireball
- travel (almost) with speed of light



1 cm^3

• n_ν~113 neutrinos plus anti-nu per flavor (e,μ,τ)

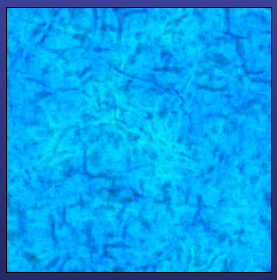
• *If* neutrinos had (tiny) rest-mass:

- total mass of neutrinos in universe huge:

Total Mass = N x mass_nu

The Neutrino Universe

- Briefly after Big Bang: Matter and energy is distributed very smoothly



- but not quite: there are tiny irregularities (`lumps')
- smallest lumps grow fastest under gravity
- What is their fate?

The Neutrino Universe

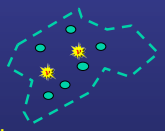
- Q: How much mass is needed to confine (coral in) neutrinos?
- Early on (first 10,000 years), neutrinos move (almost) with speed of light (thus: `Hot Dark Matter')

neutrino

Normal particles

Small mass

→ Small structures are `erased' by neutrino free-streaming!



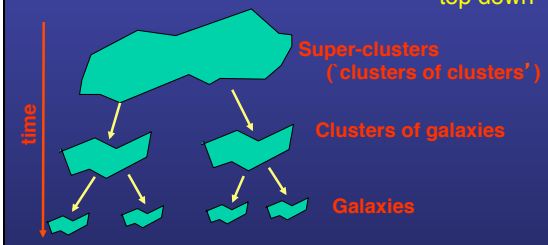
Large mass

~ 10^{15} solar masses

→ mass of a cluster of galaxies (e.g., Coma)

The Neutrino Universe

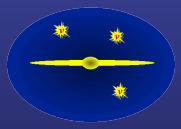
- Zeldovich pancakes: Galaxies form from the `top down'



- Prediction: clusters form *before* galaxies do!

The Neutrino Universe Undone

- early 1980s:
  - dwarf galaxies have dark matter halos, too!
  - clusters of galaxies form late in history of universe, after the galaxies themselves!



- The neutrino universe doesn't work!
- Again: What *is* the dark matter???

The Cold Dark Matter Model

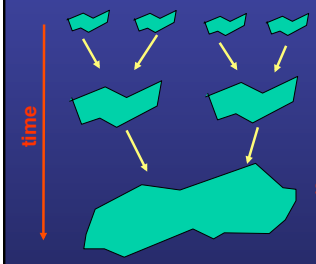
- 1984-86: postulate some mysterious particle that is massive, but only interacts weakly with ordinary matter other than through gravity (Blumenthal, Faber, Primack & Rees; Peebles)
- WIMPs = Weakly Interacting Massive Particles

Normal particle
WIMP

- small lumps survive!
- sub-galactic (million solar mass objects form first)!

The Cold Dark Matter Model

- Galaxies form from the `bottom up' (hierarchical)



Galaxies

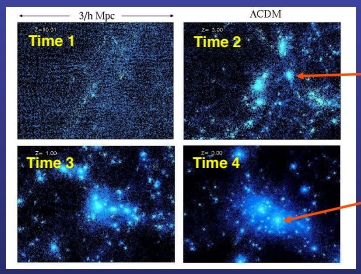
Clusters of galaxies

Super-clusters
(`clusters of clusters')

- Prediction: clusters form *after* galaxies do!

The Cold Dark Matter Model

- Structure forms from the `bottom up' (hierarchical)



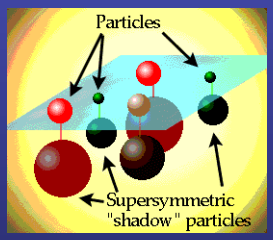
- Evidence: galaxies form before clusters!

The Cold Dark Matter Model

- But what is the WIMP really???
- Has not yet been directly detected!
- But there is a promising candidate:

  - the lightest supersymmetric particle (neutralino)

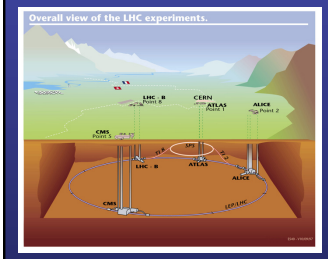
The Cold Dark Matter Model



- for every normal particle, there is a supersymmetric (`shadow') partner
- the lightest one (the neutralino) cannot decay, and would thus have survived from the very early universe!

Hunting down the WIMP:

→ CERN's new Large Hadron Collider (LHC)



- might be able to detect new particles predicted by supersymmetry

Quiz 6:

- (Incorrectly) assume that the sum of all cosmological neutrinos (113 cm^{-3} per neutrino flavor today) *can* make up the dark matter in the universe (recall: critical density $\rho_{crit,0} \sim 9 \times 10^{-30}$ g cm^{-3})
- What would the combined mass-energy have to be:

  $\Sigma m_\nu c^2 = ?$

- Express your result in units of electron-volt (eV);

  recall: 1 eV = 1.6×10^{-12} ergs