The History and Philosophy of Astronomy

(Lecture 26: Modern Developments I: The Dark Side)

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The Dark Side of the Universe

• Big Q: What is the universe made of?

• consensus view of early 21\textsuperscript{st} 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, \textit{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
  - 300 million lightyears away

- Zwicky measures average (radial) velocities (from Doppler shift)
  - Result: ~1,000 km/sec

- 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)
- 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!
• BIG Q: What is the dark matter?

???

• more than 70 years after it was first posulated 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!
The Neutrino Universe

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

~115 neutrinos from Big Bang

1 cm³

• If neutrinos had (tiny) mass:
  - total mass of neutrinos in universe huge:

\[ \text{Total Mass} = N \times \text{mass}_{\text{nu}} \]
The Neutrino Universe

- If \( \text{mass}_{\text{nu}} \sim \frac{1}{10,000} \times \text{mass}_{\text{electron}} \):

  • there would be sufficient mass to `close' the universe
  • Thus: Neutrinos could be very important on cosmic scales!
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')

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

- May 1980: 'Neutrino Spring'
  - Soviet physicist V.A. Lubimov claims that neutrinos have large enough mass to close the universe (~1/10,000 mass_electron)

- Was dark matter riddle solved?
- Alas, no: - Lubimov experiment proved wrong
  - astronomers contradict top-down scenario of galaxy formation
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

• small lumps survive!

• sub-galactic (million solar mass objects form first)!

- Normal particle
- WIMP
The Cold Dark Matter Model

• Galaxies form from the `bottom up’ (hierarchical)

• Prediction: clusters form after galaxies do!
The Cold Dark Matter Model

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

• Computer simulations: 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 (photino)
The Cold Dark Matter Model

- for every normal particle, there is a supersymmetric (‘shadow’) partner
- the lightest one (the photino) cannot decay, and would thus have survived from the very early universe!
The Dark Side of the Universe

• 1930s: Missing mass problem realized (Zwicky)
  - galaxies in Coma cluster move too fast
  - there must be 10 times as much mass as can be seen
  - Zwicky’s prediction largely ignored

• 1970s: Dark halos of galaxies inferred (Rubin & Ford)
  - stars in galaxies continue to rotate quickly, even beyond
    the extent of luminous galaxy
  - again: 10 times as much mass needed
  - this time, the evidence was overwhelming, and dark matter
    was universally accepted

• Hot vs Cold Dark Matter
  - Hot Dark Matter = neutrinos: top-down scenario
  - Cold Dark Matter = WIMPs: bottom-up scenario