Small Dwarfs
Tall Shadows

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Baryons (for example protons and neutrons) are the heaviest particles making up the familiar matter.

Your Universe Needs non-baryonic Dark Matter.
Hot Breath of the Young Universe

378,000 years after Big Bang

difference between cold and hot spots: 1 part in 100,000 of a degree K

Really, just a giant space thermometer
Clustering of galaxies

Redshift gives us the distance to galaxies. For example, a galaxy at redshift $z=0.3$ is 5 billion light years away.

This cartoon shows observations from 1/6 of the sky.
Nothing, Zip.

First stars are born

Hubble Ultra Deep Field

Jimmy Hendrix sets guitar on fire
Nothing, Zip.

First stars are born

Hubble Ultra Deep Field

Jimmy Hendrix sets guitar on fire

to explain this
Jimmy Hendrix sets guitar on fire

First stars are born

Hubble Ultra Deep Field

Nothing. Zip.

to explain this

and this

The Big Bang

- The Universe was filled with ionized gas
- Hydrogen turned to be neutral

The Cosmic Dark Age

- First astronomical objects: formation of galaxies and quasars. Beginning of the cosmic reionization

Renaissance of the Universe - the End of the Dark Age

- Completion of the reionization: inter-galactic medium was ionized

Evolution of galaxies

Formation of the solar system

The Present Universe

Images credit: NASA / WMAP Science Team, Subaru Telescope/NAOJ
Nothing. Zip.

First stars are born

Hubble Ultra Deep Field

Jimmy Hendrix sets guitar on fire

to explain this
and this
and this
and eventually this
We need **Cold Dark Matter**

Nothing. Zip.

First stars are born

Hubble Ultra Deep Field

Jimmy Hendrix sets guitar on fire

*to explain this and this and this and this and eventually this*
Cold Dark Matter: A Recipe for our Universe
5% Ordinary Matter, 25% Dark Matter

Dark: particles don’t interact with light except by gravity
A Cold Dark Matter Universe

- Afterglow Light Pattern 380,000 yrs.
- Inflation
- Quantum Fluctuations
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion

1st Stars about 400 million yrs.

Big Bang Expansion
13.7 billion years

NASA/WMAP Science Team
Λ Cold Dark Matter Simulations of Structure Formation

\[ T = 0.21 \text{ Billion yrs} \]

Millennium Simulation: 10 billion particles, 10 Billion Ly a side!
Λ Cold Dark Matter Simulations of Structure Formation

$T = 5.7$ Billion yrs

Millennium Simulation: 10 billion particles, 10 Billion Ly a side!
Λ Cold Dark Matter Simulations of Structure Formation

T = 4.7 Billion yrs

Millennium Simulation: 10 billion particles, 10 Billion Ly a side!
Λ Cold Dark Matter Simulations of Structure Formation

Millennium Simulation: 10 billion particles, 10 Billion Ly a side!
ΛCDM with Gas and Star Formation: The Formation of Galaxies

Mark Vogelsberger
Harvard-Smithsonian Center for Astrophysics
Institute for Theory and Computation
ΛCDM with Gas and Star Formation: The Formation of Galaxies
Test: Large Scale Structure

Millennium Simulation

SDSS
Test: A Milky Way Simulation

$z = 11.9$

800 x 600 physical kpc

Diemand, Kuhlen, Madau 2006
Test: A Milky Way Simulation
Via Lactea $\Lambda$CDM Simulation
of a Milky Way analog
Image: J. Diemand
Via Lactea ΛCDM Simulation of a Milky Way analog
Image: J. Diemand
How many dwarfs are here?
How many dwarfs are here?
Finding dwarf satellites

This is how sky looks like on a clear night
Finding dwarf satellites

This is how sky looks like on a clear night

Large Magellanic Cloud - the largest of the Milky Way satellites. It is 40 times smaller than our Galaxy
Pushing the frontiers
Pushing the frontiers

The "computers" at the Harvard Observatory in the 1890's were women who examined glass photographic plates containing images of the sky.
Pushing the frontiers

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Actual dwarf galaxy in the constellation of Pegasus

A fingerprint
Dwarf census circa 2004

There are more than 500,000 photographic plates in archives around the world.

Stacks of plates at the Harvard College Observatory.
Dwarf census circa 2004

A total of 11 has been uncovered!

There are more than 500,000 photographic plates in archives around the world.

Stacks of plates at the Harvard College Observatory.

Large Magellanic Cloud

8,000 times smaller than the Milky Way
The Game Changer

Sloan Digital Sky Survey

2.5-meter telescope at Apache Point Observatory, New Mexico

Tens of Tbs of digital images

Hundreds of millions of individual objects (galaxies and stars)

Impossible to eyeball!!!!
What have we found?
What have we found?

*Invisible galaxies!*

Leo I

Bootes I

8,000 times fainter than the Milky Way

2,000,000 times fainter than the Milky Way
What have we found?

*Invisible galaxies!*

Leo I

8,000 times fainter then the Milky Way

Bootes I

2,000,000 times fainter then the Milky Way
Have we found hundreds?
Or thousands?
Have we found hundreds?  
Or thousands?

In 10 years, around the Milky Way we found 15 new dwarfs...

...but we know it’s just a tip of an iceberg

For every discovered dwarf we now know how many are missing!
Comparison!

Satellites around our MW

Image Credit: National Geographic

ΛCDM Simulation of satellites around a Milky Way analog

Image credit: Springel 2001
Soln’s: Not all Dark Matter Halos make stars
• Gas was too hot to have formed stars: Reionization
• Dark matter halos lose their gas, preventing future star formation
Soln’s: Not all Dark Matter Halos make stars

- Gas was too hot to have formed stars: Reionization
- Dark matter halos lose their gas, preventing future star formation
Testable Predictions:

1) There is a lower limit to what we call a galaxy
2) All dwarf galaxies should exist within massive dark matter halos.

**Star Cluster:**
Weighs what you expect

**Dwarf Galaxy:**
Heavier than expected
Mass = Velocity

little dark matter

plenty dark matter

1 kpc = 3,200 ly = 3,000,000,000,000,000,0 km
Mass = Velocity

little dark matter

plenty dark matter

1 kpc = 3,200 ly = 3,000,000,000,000,000 km
Mass = Velocity

little dark matter

Small galaxy forms

plenty dark matter

Fast stars leave

1 kpc = 3,200 ly = 3,000,000,000,000,000,000 km
Mass = Velocity

little dark matter

Small galaxy forms

Fast stars leave

plenty dark matter

1 kpc = 3,200 ly = 3,000,000,000,000,000,000 km
Mass = Velocity

little dark matter

Fast stars leave

Small galaxy forms

Bigger galaxy forms

plenty dark matter

Retains some fast stars

1 kpc = 3,200 Ly = 3,000,000,000,000,000,000 km
Velocities from spectra

\[ \lambda = 1.1 \ \text{Angstrom} = 0.00000000001 \ \text{meter} \]
Velocities from spectra

1 Angstrom = 0.00000000001 meter
Velocities from spectra

Dark matter outnumbers the usual matter by a factor of 100!

1 Angstrom = 0.00000000001 meter
Conclusions

- The sky is littered with invisible galaxies as big as a Moon in angular extent.
- These are relics from the very first episodes of structure formation in the infant Universe.
- These faint dwarfs appear to contain monstrous amounts of Dark Matter.
Small Dwarfs, Tall Shadows

• We have a preferred model to explain the origin of the Universe: Λ Cold Dark Matter

• ΛCDM has passed a lot of tests – the properties of Dwarfs represent the last frontier

→ Predicts too many dwarf satellites

• Solns? :
  – Physics of star formation/death
  – Preventing star formation at small masses
  – Alternative Dark Matter models
Soln’s: Different Dark Matter Models?

**Warm Dark Matter:** Particles move faster than Cold Dark Matter

**Self-Interacting Dark Matter:** Particles can interact with each other
The End