Mysteries of the Dark Universe

**Dark Matter:**
Holds together individual galaxies.

(A new elementary particle?)

**Dark Energy:**
Pushes apart different galaxies.

(The energy of empty space?)
Chemical Elements: (other than H & He) 0.025%

Radiation: 0.005%

Neutrinos: 0.17%

Stars: 0.8%

H & He: gas 4%

Cold Dark Matter: (CDM) 25%

Dark Energy: 70%
The construction of a model... consists of snatching from the enormous and complex mass of facts called reality a few simple, easily managed key points which, when put together in some cunning way, becomes for certain purposes a substitute for reality itself.

Evsey Domar
*Essays on the Theory of Economic Growth*
A Previous Consensus Convergence Dominant Best-Fit Standard Cosmological Model
Dark Matter Goals

Discover dark matter and its role in shaping the universe

Particle Physics
- Discover dark matter and how it is...
  - ... grounded in physical law
  - ... part of a comprehensive model/theory

Cosmology/Astrophysics
- Understand the role of dark matter in structure...
  - ... formation
  - ... evolution
Top Ten Dark Questions

1. Why do we think there is Dark Matter? (Dan Hooper)
Fritz Zwicky 1933 & 1937  Coma Cluster
Dark Matter

Vera Rubin

M33 rotation curve

observed

dark matter

eXpected from stars

\[ v (\text{km/s}) \]

\[ R (\text{kpc}) \]
Dark Matter

Abel 2218 HST
The growth of cosmic seeds

100 Myr

1 M-Myr

5 M-Myr

today

Kravtsov
Top Ten Dark Questions

1. Why do we think there is Dark Matter?
2. How much Dark Matter is there?
**Dark Matter**

Critical density: $10^{-30}$ g cm$^{-3}$

$dynamics$

$lensing$

$x$-ray gas

$cmb$

$simulations$

$power$ $spectrum$

$\Omega_{\text{DarkMatter}} = 0.25$

$3H_0^2 / 8\pi G$
Top Ten Dark Questions

1. Why do we think there is Dark Matter?
2. How much Dark Matter is there?
3. Could it be normal stuff?
Dark Matter

\[ \Omega_B \sim 0.04 \]

QSO 1937-1009

WMAP: \( \Omega_B = 0.0458 \pm 0.00015 \)
Top Ten Dark Questions

1. Why do we think there is Dark Matter?
2. How much Dark Matter is there?
3. Could it be normal stuff?
4. How is it distributed?
simulation

1. a. The action or practice of simulating, with intent to deceive; false pretence, deceitful profession.

1340 Ayenb. 23 And perch wexen vele zennes, ase ariythalf; pet is to wytene: lozengerie, simulacion. c1400 Rom. Rose 7230 He nys no full good champioun That dreith such simaliaccion. 1412-20 Lydgate. Chron. Troy iv. 4504 Amonge hem silege to bringe in tresoun, Feyned troupe and simulacioun. 1542 Udall Erasmus. Apoph. 170 He did with mutual simulacion on his partie cover & kepe secrete the colorable dooyng of the said felse. 1577 tr. Bullinger’s Decades (1592) 319 This precept doth commaunde vs..that..wee doe our neighbor harme..neither by simulation nor dissimulation. 1611 Speed Hist. Gt. Brit. vi. (1632) 114 His nature relishing too much of the Punick craft and simulation. 1692 South Serm. (1697) I. 525 A Deceiving by Actions, Gestures, or Behaviour, is called Simulation, or Hypocrisie. 1711 Steele Tatler No. 213 p1 Simulation is a Pretence of what is not, and Dissimulation a Concealment of what is. 1788 Wesley Wks. (1872) VII. 43 Simulation is the seeming to be what we are not; dissimulation, the seeming not to be what we are. 1836 Landor Pericles & Aspasia Wks. 1846 II. 379, I wish he were as pious as you are; occasionally he appears so. I attacked him on his simulation. 1872 Shipley Gloss. Excl. Terms 71 Fraud.., whether it consists in simulation or dissimulation.

b. Tendency to assume a form resembling that of something else; unconscious imitation.

1870 March Anglo-Saxon Gram. 28 Simulation. The feigning a connection with words of similar sound is an important fact in English and other modern languages: asparagus > sparrow-grass.

2. A false assumption or display, a surface resemblance or imitation, of something.
Dark Matter

Navarro, et al.
Tip of the Iceberg

Most of the matter is dark

and

it’s not even “normal” stuff!
Top Ten Dark Questions

1. Why do we think there is Dark Matter?
2. How much Dark Matter is there?
3. Could it be normal stuff?
4. How is it distributed?
5. Could Newton be wrong?
Dark Matter

- MOND (Modified Newtonian Dynamics)

The Bullet Cluster

Optical Dark Matter X-ray Gas
Top Ten Dark Questions

1. Why do we think there is Dark Matter?
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6. Could astronomy point to the identity of Dark Matter?
Top Ten Dark Questions

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7. Are you really sure it can’t be baryons?
Dark Matter

- MOND (Modified Newtonian Dynamics)
- Planets
- Dwarf stars
- Black holes

MACHOS
Large Magellanic Cloud
150,000 light years distant
100 million stars
brown dwarf

observer
Dark Matter

- MOND (Modified Newtonian Dynamics)
- Planets
- Dwarf stars
- Black holes

MACHOS

Microlensing

```
100
80
60
40
20
0
```

`excluded
or by MACHO
permitted
by MACHO
at 95% CL`

Percent of mass (Mo)
Top Ten Dark Questions

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7. Are you really sure it can’t be baryons?
8. Well, what’s left?
Dark Matter

- MOND (Modified Newtonian Dynamics)
- Planets
- Dwarf stars
- MACHOS
- Black holes
- Particle relic from the big bang
Big Bang Theory,
You've Got To Be Kidding.

-God
Meet two brainiacs with a lot to learn. Leonard and Sheldon can tell their quarks from their quantum physics, but have no clue how women add up. Leave it to their pretty new neighbor, just off a messy breakup, to teach them a thing or two in THE BIG BANG THEORY.
Space and Time

Absolute space ... remains always similar and immovable.

Absolute, true, and mathematical time... flows without regard to anything external...

Isaac Newton, 1687
Philosophiae Naturalis
Principia Mathematica
Space and Time

Space & time are relative.
Albert Einstein, 1905

Space & time can be curved, warped, bent.
Albert Einstein, 1915
Modern Commandments of Genesis

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu} \]

(10 nonlinear partial differential equations)

- space and time
- matter
- radiation
- forces
- cosmological term (dark energy)
Einstein’s Universe 1917–1929

- Gravity ⇔ Geometry
- A stationary universe

Cosmology becomes a science!!!!
Edwin Hubble

University of Chicago         1909 National Champions
Space Expands

Edwin Hubble
1929
Time Machines

Keck Telescope – Hawaii

Hubble Space Telescope

South Pole Telescope

Magellan Telescope – Chile
The Universe Is Radiant

Penzias & Wilson 1965

Temperature of the Universe is 3K (−454 F)
... emerged from a state of high temperature and density 13.78 billion years ago, and is expanding and cooling, evolving and dynamic.
Possible Futures of the Universe

- Sun burns out
- Terror threat red
- FEMA responds
- Hell freezes over
- Cubs win Series
- Universe ends

Cosmic Time Line

Today

13.78 billion years
18 billion years
18 billion years
18 billion years
10 billion years
1000 billion years
billion-billion years
Complete history of the universe (abridged)

- Neutrons
- Protons born
- Nuclei (elements) born
- Atoms born
- Quasars born
- Hot as hell
- Sun born
- Today

Today: Hot as hell
Sun: born
Quasars: born
Atoms: born
Nuclei: (elements) born
Protons: born
Neutrons: born

Today: 1
Aeon: 10^{-3}
Millennium: year
Millennium: day
Millennium: second
Millennium: micro-second
Millennium: nano-second

Temperature: $T^\circ$
Time: $t$
age (seconds) \sim \frac{1}{T(10^{10} K)}
Looking out in space is looking back in time. 

CBR: a snapshot of the universe 380,000 years ago.
DARK MATTER from the Primordial Soup

fraction of a second later

Hot Primordial Soup

380,000 years later
Radiation Last Scattered

13.78 thousand-million years later
Today
<table>
<thead>
<tr>
<th>H</th>
<th>He</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>Be</td>
</tr>
<tr>
<td>Na</td>
<td>Mg</td>
</tr>
<tr>
<td>K</td>
<td>Ca</td>
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<tr>
<td>Sc</td>
<td>Ti</td>
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<td>Ba</td>
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<td>Tl</td>
<td>Pb</td>
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<tr>
<td>La</td>
<td>Ce</td>
</tr>
<tr>
<td>Ac</td>
<td>Th</td>
</tr>
</tbody>
</table>
The Universe today:

73% Hydrogen \((10^{-5}\text{ }^2\text{H}-\text{deuterium})\)
26% Helium \((10^{-5}\text{ }^3\text{He})\)
1% Metals

The Universe 3 minutes AB:

76% Hydrogen \((10^{-5}\text{ }^2\text{H- deuterium})\)
24% Helium \((10^{-5}\text{ }^3\text{He})\)
10^{-8}% Lithium
The Universe 3 minutes AB:

Big bang (rate of change of the temperature)
Nuclear physics (binding energies, reactions)

76% Hydrogen \((10^{-5})^{\text{2H-deuterium}}\)
24% Helium \((10^{-5})^{\text{3He}}\)
10^{-8}\% Lithium
Kepler’s supernova

Observed in 1604 in Ophiuchus
Peak magnitude = $-2.25$
Distance $< 10$ kpc
Top Ten Dark Questions

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8. Well, what’s left?
9. Could it be a particle we know?
Neutrinos

- Neutrinos exist: three active + sterile?
- Neutrinos have mass:
  - Atmospheric ($10^{-2}$ eV)
  - Solar ($10^{-3}$ eV)
- Contribute to $\Omega$
  - hot thermal relic:
    \[ \Omega_{\nu\bar{\nu}} \approx \frac{m_\nu}{45 \text{ eV}} \]
- Not most of dark matter
  - too light!
  - too hot!
Top Ten Dark Questions

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6. Could astronomy point to the identity of Dark Matter?
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8. Well, what’s left?
9. Could it be a particle we know?
10. Then what?
Particle Relic from the Bang

- neutrinos
- sterile neutrinos, gravitinos
- LSP (neutralino, axino, …)
- LKP (lightest Kaluza-Klein particle)
- B.E.C.s, axions, axion clusters
- solitons (Q-balls; B-balls; ….)
- supermassive wimpzillas

**Mass range**

- $10^{-22}$ eV ($10^{-56}$ g) B.E.C.
- $10^{-8} M_\odot$ ($10^{25}$ g) axion clusters

**Interaction strength range**

- Noninteracting: wimpzillas
- Strongly interacting: B balls
**Cold Thermal Relics**

- Particle is stable (or at least has a lifetime greater than $t_U$)
- There is no associated asymmetry (like baryons)
- Particle is in thermal equilibrium at “high” temperature
- Particle remains in LTE until $T < M$ (cold)

* An object of particular veneration.
Smaller annihilation rate → larger $\Omega_X$
Cold Thermal Relics

- Particle is stable (or at least has a lifetime greater than $t_U$)
- There is no associated asymmetry (like baryons)
- Particle is in thermal equilibrium at “high” temperature
- Particle remains in LTE until $T < M$ (cold)
- Particle annihilates
- Calculate freeze-out abundance, depends on annihilation rate
- Contributes to $\Omega_X$
- If annihilation rate depends on $M$, then $\Omega_X$ determines $M$
The WIMP Miracle

Cross section (& mass ?) of order weak scale (10–1000 GeV)

Cold thermal relic: WIMP (Weakly Interacting Massive Particle)

**mir·a·cle**

`´mir-i-kəl`

*noun*

1 : an extraordinary event manifesting divine intervention in human affairs

WIMP Causation or WIMP Coincidence?
WIMPs

$X + \bar{X} \rightarrow q + \bar{q}$

$q + \bar{q} \rightarrow X + \bar{X}$

$X + q \rightarrow X + q$
## WIMPs

Modeling Dark Matter

<table>
<thead>
<tr>
<th>Minimalist</th>
<th>Maximalist</th>
</tr>
</thead>
<tbody>
<tr>
<td>• WIMP is only new particle</td>
<td>• WIMP is one of many newbies</td>
</tr>
<tr>
<td>• Use effective field theory</td>
<td>• Use a motivated model</td>
</tr>
<tr>
<td>• Example: Fermi interaction</td>
<td>• Example: SUSY (Marcela)</td>
</tr>
<tr>
<td>• “Maverick” dark matter</td>
<td>• “SUSY” dark matter</td>
</tr>
<tr>
<td>• “Invent” as little new as possible</td>
<td>• Invent a lot</td>
</tr>
</tbody>
</table>
The Equation that Describes Everything

If I had been present at creation, I would have suggested a simpler scheme.

- Alfonse the Wise
WIMPs

Dark matter is a complex physical phenomenon.

“WIMPs are a simple, elegant, compelling explanation for a complex physical phenomenon.”

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

- Tommy Gold
Direct Detection

WIMPs and Neutrons scatter from the Atomic Nucleus

Photons and Electrons scatter from the Atomic Electrons
Detect Relic WIMPs

WIMP (300 km s\(^{-1}\))

ultrapure material

change in temperature

ionization
Indirect Detection

Supersymmetric neutralinos

Quarks

Low-energy photons

Medium-energy gamma rays

Positrons

Electrons

Neutrinos

Antiprotons

Protons

Decay process

Bosons

Leptons
Detect Relic WIMPs

Galactic Center

Khomas Highland of Namibia
Production in Colliders
Particle Accelerator is a *Time Machine* and a *Telescope*
“KNOWN” INGREDIENTS:
56% QUARKS
16% GLUONS
9% ELECTRON-LIKE PARTICLES
9% W’s AND Z’s
5% NEUTRINOS
3% PHOTONS
2% HIGGS BOSONS (to be discovered any day)

SECRET INGREDIENT:
DARK MATTER
Production in Colliders

**SUSY**

- $g$-pair production with subsequent cascade decays
- $\chi^0$'s escape undetected: missing $E_T$

**Maverick**

- Jet
- Missing $E_T$

Carena
A Decade of Excitement & Confusion

• Is there a WIMP miracle?

• Situation now is muddled (direct hints/indirect hints)

• Ten years from now the WIMP hypothesis will have either:
  Convincing evidence, or
  Near-death experience

• Direct detectors, indirect detectors, & colliders race for discovery

• Suppose by 2015 have credible signals from all three???

How will we know they are all seeing the same phenomenon?

• Lots of opinions (papers)

• *Let’s hope for this problem!!!!*
Other Dark Questions

• Why only one WIMP?

• More strongly interacting:
  — Easier to detect
  — Smaller contribution to $\Omega$

• SuperWIMPs

• Self-interacting WIMPs

• Haze, fog, mist

And this is just for WIMPs!
Dark matter is a ... 

... fuzzy, decaying, repulsive, self-interacting, supermassive, inelastic particle that lives on another brane in a supersymmetric, modified gravity theory.
“To me every hour of the light and dark is a miracle. Every cubic inch of space is a miracle.”

– Walt Whitman

Every cubic inch of space is a miracle!

- cosmic radiation
- dark matter
- dark energy
- virtual particles
- Higgs potential
- extra dimensions
The Dark Side of the Universe

95% of the Universe Is Dark!
“The most beautiful thing we can experience is the mysterious. It is the source of all true art and all science. Those to whom this emotion is a stranger, who can no longer pause to wonder and stand rapt in awe, are as good as dead: their eyes are closed.”

Albert Einstein