What the...?
What is the Universe made of?

alternative talk title: This is not your mother’s Universe
• What is the Universe made of?
• How old is it?
• How has it developed?
• What is its ultimate fate?
What is the Universe made of, circa 450 BC
What is the Universe made of, circa 1969
What is the Universe made of, circa 1869 (here on earth)

Periodic Table of the Elements

"baryonic" matter: made of protons & neutrons
What is the Universe made of, circa 1973

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

**Fermions**

- **Leptons**: Spin = 1/2
  - Electron: Mass = 0.00051, Electric charge = -1
  - Muon: Mass = 0.0002, Electric charge = -1
  - Tau: Mass = 1.777, Electric charge = -1

- **Quarks**: Spin = 1/2
  - Upsilon: Mass = 0.003, Electric charge = 1/3
  - Charm: Mass = 1.3, Electric charge = 2/3
  - Top: Mass = 175, Electric charge = 2/3

**Bosons**

- **Force carriers**
  - Photon: Mass = 0, Electric charge = 0
  - W\(^{±}\): Mass = 80 GeV, Electric charge = ±1
  - Z\(^0\): Mass = 91 GeV

**Properties of the Interactions**

- **Gravitational**
- **Weak**
- **Electromagnetic**
- **Strong**

**Matter and Antimatter**

For every particle type, there is a corresponding antiparticle type, except for a few rare exceptions such as the photon. Particle and antiparticle have identical mass and spin but opposite electric charge and weak isospin. For example, electrons are antimatter.

**Quarks in Mesons and Baryons**

Mesons are hadrons composed of a quark and an antiquark, while baryons are hadrons composed of three quarks. The strong interaction binds quarks together, while the weak and electromagnetic interactions allow quark exchanges.

**Residual Strong Interaction**

The strong interaction is considered the basis for the Standard Model, which is the most successful theory in particle physics. It describes how quarks and gluons interact and how they form hadrons, which are the basis for all matter.

**The Particle Adventure**

For more information, visit the Particle Adventure website: [http://ParticleAdventure.org](http://ParticleAdventure.org).

This chart has been made possible by the generous support of: Fermilab, DOE, NSF, CERN, DOE, NSF, DOE, NSF, DOE, NSF, and DOE.
What is the Universe made of, circa 2007

- Dark energy: 70.0%
- Dark matter: 25.0%
- Gas: 4.5%
- Stars: 0.5%

95% is not on the periodic table or in the standard model
The Universe is filled with galaxies

- Edwin Hubble: first to realize that “nebulae” outside the Milky Way were other galaxies
- Hubble’s breakthrough came from figuring out an accurate way of measuring distances.
The Universe is expanding

• In the 1920’s, Hubble measured the distances to these “spiral nebulae” using very bright stars called Cepheid variable stars

• The absolute brightness of Cepheids is directly related to their variability

• Once their absolute brightness is known, the apparent brightness gives the distance
Measuring the Expansion

- After measuring the distances, Hubble used the spectrum of these galaxies to measure their velocities.
- The wavelength of light (or sound) of objects moving away from us gets longer --> redder.
- Hubble showed that velocity was proportional to distance.

\[ v = H_0 d \]

“the Hubble constant”
Extrapolate this expansion backwards.

Past

- Big Bang
The Big Bang

- Basic idea: The universe is expanding
- In the past, it was much denser. Expansion dilutes the particles
- Since it was denser, it must have been much hotter in the past
- Major evidence for the big bang comes from looking at this process of cooling and diluting
Gravity

- If the Universe is expanding away at a given rate, what will matter do to it?
- slow it down (the more you have, the faster it will slow).
The expansion rate is like a scale

- If you can measure the expansion rate farther away (farther back in time), you can measure the Universe slowing down, and constrain the total amount of matter.
The expansion rate is also like a clock

- If you can measure the expansion rate, you can also measure the age of the Universe by extrapolating backwards.
The Age Problem

• The Hubble time is \( \sim 14 \) billion years, but if there is any matter in the Universe, its age must be shorter.

• For a Universe made of matter, with the critical density, this age is \( \frac{2}{3H} \sim 9.3 \) billion years.

• Oldest things in the Universe are 13-14 billion years old!
General Relativity

- Everything causes gravity and everything is affected by gravity.

- Gravity curves space. This can happen locally (gravitational lensing), or globally (curvature of the Universe).

- One implication: expansion, curvature, and matter density of the universe are all related.
The expansion rate also measures “geometry”
Weighing the Universe with Dynamics

- The amount of stuff we can see from shining stars is only a very small fraction of this “critical density”
- But is what we see all there is?? Light does not necessarily trace mass!
- Just like motion of the whole Universe, motion on smaller scales can measure mass
“Missing Mass” in Galaxy Clusters

- Fritz Zwicky measured velocities for ~1000 galaxies in the Coma Cluster
- Expect $v = \sqrt{M/r}$
- Zwicky found more mass than light, by a large factor!

Zwicky was the first to detect “dark matter”
Dark Matter in a nutshell.

- Lots and lots of observations now indicate that most of the matter in the Universe is “dark”
- The effects of this matter can be “seen” gravitationally on a wide range of scales
- ~85% of the mass
- Doesn’t emit light or radiation; no cooling
- Most likely explanation: a particle we haven’t detected yet.
The Universe is clumpy

image from SDSS
galaxy distribution in SDSS
The clumpy Universe

- How did we get the clumping in the first place?
- Super-luminal expansion in the first fraction of a second of the Universe’s history ("inflation")

The Clumpy Universe at 380,000 years
40 comoving Mpc/h

lookback time (Gyr)

13.3960

simulation:
B. Allgood & A. Klypin
movie:
B. Allgood & C. Heze
The rate of clumping provides another scale

- Gravitational instability: gravity makes small clumps bigger with time
- The more stuff, the faster this process happens
What is the Universe made of, circa 1997

- Dark matter well established to make up 70-90% of the mass.
- However, a bit of a puzzle.
- Theoretical prejudice, based on inflation, for a “flat” Universe
- But a universe with the “critical” density of matter was too clumpy.
A New Standard Candle

- Same idea as Hubble: measure the relationship between velocity and distance.
- Need something brighter than Cepheid variable stars to measure the Hubble diagram at larger distances.

SN 1a: Explosions of massive stars

Surface brightness falls off as $1/r^2$. 
The 1998 breakthrough

- Problem with SN is that they are very rare. (one per galaxy every 5000 years!)
- The breakthrough -- scan large areas of sky quickly, and look for changes
- follow up the interesting things.

Two teams: High-z Supernova search & Supernova Cosmology Project
Surprise!

The Universe is speeding up, not slowing down!

Galaxies are actually accelerating away from us!

Riess et al 98
Science Mag breakthrough of the year 1998
New results in 2003

WMAP satellite

Same picture that gave us the birth of the Universe’s clumpiness can measure the geometry, very accurately. Also gives a very precise age.

Total amount of stuff = amount of matter + amount of energy

mass isn’t enough, but the same stuff that provides the acceleration makes up the difference.
A consistent picture

- Constituents of the Universe quantified: mostly dark matter and dark energy
- Matter density: low
- Shape of the Universe: flat
- Solves the age problem. Age of the Universe: 13.7 billion years
- But we don’t know what 95% of the Universe is!!!
Dark Energy: what the...?

- Universe is dominated by something that isn’t matter
- This component is repulsive, not attractive: makes the Universe expand faster and faster
- Smoothly filling space
- Constant or changing slowly
Vacuum Energy: Nothing is Something!

- Turns out nothing (the vacuum) has energy
- Quantum fluctuations in the vacuum have energy
- This energy is repulsive
Vacuum Energy: Nothing is way too much!

If you try to calculate how much energy you expect from these quantum fluctuations, the answer is $10^{120}$ times bigger than observed.
a strange coincidence

Today

matter density is diluted through the Universe’s expansion, but energy density is not (since it is a property of space itself)

why are these numbers so similar?
Dark Energy: what the...?

- possible explanations
  - a cosmological constant
  - energy of the vacuum
  - a modification of gravity
  - some kind of funny fluid?
  - something else completely unexpected??
Steven Weinberg: 
``Right now, not only for cosmology but for elementary particle theory, this is the bone in our throat"

Frank Wilczek: 
``... maybe the most fundamentally mysterious thing in all of basic science"

Ed Witten: 
``... would be the number 1 on my list of things to figure out"

Michael Turner: 
“... the biggest embarrassment in theoretical physics”
A quiz.

- Are Dark Energy and Dark Matter very similar?
  a) yes
  b) no
  c) only in the distant past

<table>
<thead>
<tr>
<th>dark matter</th>
<th>dark energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>attractive</td>
<td>repulsive</td>
</tr>
<tr>
<td>clumpy</td>
<td>smooth</td>
</tr>
<tr>
<td>made of particles</td>
<td>a property of space</td>
</tr>
</tbody>
</table>
What do they have in common?

Also: can get information about both by measuring the expansion rate and growth of structure.

dark matter  dark energy
Questions about Dark Energy

- Hard Questions:
  - what is it? what caused it?

- Easier questions:
  - Is it a cosmological constant?
  - Does it vary with time or over space?
Dark Energy: The hunt

- **SNAP**
  - [Image of SNAP]
  - SuperNova/Acceleration Probe (SNAP)

- **DES**
  - [Image of DES]
  - 300 million galaxies

- **SPT**
  - [Image of SPT]
  - 3 billion galaxies

- **LSST**
  - [Image of LSST]
Probing Dark Energy

- Main goal is to probe the expansion history of the Universe
  - what is the expansion rate?
    - standard candle (SN1a)
    - standard ruler (BAO)
  - how does the clumpiness grow?
    - evolution of all of the matter (lensing)
    - evolution of the rare objects (clusters)
Some say the world will end in fire,
Some say in ice.
From what I’ve tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To know that for destruction ice
Is also great
And would suffice.

-- Robert Frost
movie by Michael Busha, KIPAC/Stanford
Future fates of the dark-energy universe

Big Crunch
Quintessence in which dark energy reverses

Indefinite expansion
Cosmological constant

Big Rip
Quintessence in which dark energy destabilizes
The Universe’s contents are well quantified, but 95% is not understood.
• Dark Energy: What the...?

• Repulsive energy of the universe, roughly constant over time and space.

• Makes up ~70% of the energy density

• Origin and nature unknown

• Why now? Why so small?

• One of the biggest mysteries in science -- stay tuned!
L’essential est invisible pour les yeux.

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