Don't let the bright lights fool you.
The Dark Side controls the Universe.

**Our Universe**
Stars: 0.5%
Dark Matter: 33%
Dark Energy: 66%

Dark Matter holds it together.
Dark Energy determines its destiny.
The Accelerating Universe
Breakthrough of the Year
Galaxies: Building Blocks of the Universe Today (Hubble 1924)
... GOING BACK IN TIME

10 BILLION YRS AGO

THE BIG BANG

14 BILLION YRS AGO
"REAL" HUBBLE DIAGRAM

$H_0 = 72 \pm 2 \pm 7 \text{ km s}^{-1} \text{Mpc}^{-1}$

$v = H_0 d$

A. Riess et al., 1998

NB: ±5 = 65's resolution ±10 family pet ±15 child ±20 first born male
IS THE UNIVERSE SLOWING DOWN?

TELESCOPE = TIME MACHINE: SEE DISTANT GALAXIES AT EARLIER TIME -- WHEN MOVING AWAY FASTER

HUBBLE'S LAW

\[ v_0 = H d \]

\[ v_0 = \text{velocity today} \]

VELOCITY OF GALAXY

DISTANCE TO GALAXY
Type Ia supernova (SNIa): Thermo-nuclear explosion of 1.4 Mo white dwarf ≤ "std bomb"
Distant Supernova in the Hubble Deep Field
Hubble Space Telescope • WFPC2

NASA and A. Riess (STScI) • STScI-PRC01-09

Riess et al. astro-ph/0104455
Universe is speeding up! ??* Why?

Data sez: Universe is speeding up!
More Evidence for Dark Energy

An Accounting Problem

Cosmic Microwave Background

$\rightarrow$ Critical Density Universe

Matter accounts for $\frac{4}{3}$ Critical Density

Need Dark Energy to Explain Other $\frac{2}{3}$
WMAP: Universe is flat and has the critical density
LOOKING OUT IN SPACE & BACK IN TIME

8.3 MIN AGO  3000 YRS AGO  2,000,000 YRS AGO  2 BYRS AFTER THE BANG  800 MYRS AFTER THE BANG

WMAP
Map of Cosmic Microwave Background

BACK TO THE BEGINNING, BEFORE STARS & GALAXIES, 400,000 YRS AFTER THE BANG
SEEING THE BEGINNING
WITH MICROWAVES

- Quark Soup
- Region of More Matter
- Dark Ages
- Last Scattering
- Formation of Atoms

**0.16 Gyr**
- First Stars

**0.56 Gyr**
- Proto-yelaxies

**1 Gyr**
- First Quasars

**5 Gyr**
- Peak of Galaxy Formation

**10 Gyr**
- Solar System Forms

**Today**
3 Kinds of Big Bang Universes

Two Dimensional Analogues

- Curves back on itself (like the surface of a balloon)
  - High density of matter/energy
- Uncurved
  - "Critical" density
- Curved like a saddle
  - Low density
Repulsive gravity is a feature of Einstein's theory.

... but only really weird stuff has repulsive gravity

"Dark energy"
Quantum Vacuum is Not Empty!

Sea of virtual particles

Whose existence has been detected (shifting of atomic levels in H)

Quantum vacuum is elastic \( \rho = -\rho \) and its gravity is repulsive \( \rho + 3\rho = -2\rho \)

Just what is needed -- but...

Theoretical estimates of amount \( 10^{55} \times \) what is needed to explain accelerating universe

"Houston, we have a problem"
Solving the Dark Energy Problem will require a crazy, new idea!

NB: Not every crazy idea is a solution only?

Cosmology is the best probe of dark energy
A BRIEF EPISODE OF INFLATION
(also known as decaying cosmological constant, quintessence, rolling scalar field)
...mild episodes of inflation are unavoidable
A. GREENSPAN

\( V(\phi) \)

Pressure varies with time, but typically negative
WEIRD DARK ENERGY
or
NEW GRAVITATIONAL PHYSICS?

EINSTEIN'S SURPRISE: NATURAL STATE OF
UNIVERSE IS EXPANSION OR CONTRACTION

NEW SURPRISE: NATURAL STATE OF
"EMPTY UNIVERSE" IS ACCELERATED EXPANSION!
DARK ENERGY MAY BE THE MOST PROFOUNDED PROBLEM IN ALL OF SCIENCE TODAY
With dark energy:

- Continued acceleration
  - Cosmic red out 100 billion yrs

- Decay of dark energy

- Recollapse

- ?? Bounce ??
THE DESTINY OF AN ACCELERATING UNIVERSE

150 billion years: The Hubble Blank Field only 1000 galaxies visible in the entire sky (vs. 100 billion today)

100 trillion years: No More Stars dead w/ no stars forming

$10^{33}$ yrn: Decay of matter

$10^{65}$ yrn: Evaporation of black holes

FINITE ENERGY BUDGET:
COSMIC RECIPE

FLAT UNIVERSE $\pm 2\%$

$\text{AVERAGE DENSITY} = \text{CRITICAL DENSITY}$

$= \frac{1}{3} \text{DARK MATTER} + \frac{2}{3} \text{DARK ENERGY}$

96% IN NEW FORMS OF MATTER & ENERGY

- $C, N, O, \ldots, Fe, \ldots, U$: 0.02%
- Neutrinos: 0.1% - 5%
- Stars: 0.5%
- Ordinary Matter: $(1 \pm 0.8)\%$
- Cold Dark Matter: $(30 \pm 4)\%$
- New Form of Matter
- Dark Energy: $(65 \pm 6)\%$
- New Form of Energy
Connections: Quarks to the Cosmos