The Big Picture

The Dark Universe, 2010

26 September 2010

Michael S. Turner
Kavli Institute for Cosmological Physics
Cosmology is a young science. Its story only begins 90 years ago, 300+ years after the invention of the telescope.
1916-1918: General Relativity & $\Lambda$

PS: Flip-flopper on $\Lambda$
1929: Just One Number K
(error bars not needed, velocity in km)

Hubble & Humanson: few 100 galaxies, z < 0.1
1929: Just One Number K
(error bars not needed, velocity in km)

K (H_0) = 550 km/s/Mpc

Hubble & Humanson: few 100 galaxies, z < 0.1
Gamow’s Hot Big Bang
“alpher, bethe, gamow,” 1948
1948: Steady State Theory
1948: Steady State Theory
1948: Steady State Theory
Cosmology: The Search for Two Numbers... $H_0$ and $q_0$ (Sandage 1970)
Landau on Cosmologists

Often in Error, Never in Doubt!
and at U Mass

The Redbook, a manual for faculty members that explained what a university was, and what it wasn't. It cited two courses one wouldn't find in a curriculum of higher education: witchcraft and cosmology.
Discovery of Cosmic Microwave Background, 1964
ORDINARY MATTER: FROM QUARKS TO US

INFLATION

BARYOGENESIS

Transition from quarks \(\rightarrow\) neutrons, protons

\(10^{-5}\) sec

FORMATION OF ATOMS

Cosmic microwave background

\(100\) sec

Density of matter

\(\Omega = 0.04 \pm 0.002\)

BIG-BANG NUCLEOSYNTHESIS

Formation of H, D, He, He-3, Li

\(\frac{D}{H} = (3.1 \pm 0.2) \times 10^{-5}\)

\(\Omega_B = 0.045 \pm 0.006\)

\(\Omega_B > 0.04\)

CMB

Ratio of first-to-second peaks: 2/1

1 billion yrs

FIRST QUASARS

INTERGALACTIC GAS

Absorption of quasar light by hydrogen

HERE\&NOW

Star, gas, dust...

\(B\nu, N\alpha,\) people...
“The Standard Model”
Hot Big Bang (circa 1972)

“Reality (physics) Based”
• BBN (nuclear physics)
• CMB (atomic physics)
• Structure Formation (grav. physics)
• Begins at 0.01 sec
• $\Omega_0 \sim 0.1$ (baryons)

Big Questions
• “The naughts”: $H_0$, $t_0$, $\Omega_0$
• Large entropy per baryon
• Hadron Wall
• Origin of density perturbations
11 The Very Early Universe

The thermal history of the universe was traced in Section 15.6 back to an era when the temperature was about $10^{12}$K. At this early time, the universe was filled with particles—photons, leptons, and antileptons—whose interactions are hopefully weak enough to allow this medium to be treated as a more or less ideal gas. However, if we look back a little further, into the first 0.00001 sec of cosmic history when the temperature was above $10^{12}$K, we encounter theoretical problems of a difficulty beyond the range of modern statistical mechanics. At such temperatures, there will be present in thermal equilibrium copious numbers of strongly interacting particles—mesons, baryons, and antibaryons—with a mean interparticle distance less than a typical Compton wavelength. These particles will be in a state of continual mutual interaction, and cannot reasonably be expected to obey any simple equation of state.

However, the temptation to try to construct some sort of model of the very early universe is irresistible. There are in fact two extremely different simple models that have been widely considered in recent years, and that reflect two divergent views of the nature of the strongly interacting particles. Although neither model can be taken seriously in detail, the hope is that one or the other of these models may come close enough to reality to lead to useful insights about the very early universe.

The first of these two pictures may be called the elementary particle model. It is supposed that all particles are made up of a small number of elementary
The Fall of "The Hadron Wall"
The Fall of “The Hadron Wall”
1980s: The Go Go Junk Bond Days of Early Universe Cosmology

“Creativity Based”
- Inflation
- Cosmic Strings
- Baryogenesis
- Magnetic Monopoles
- Phase Transitions
- Hot and Cold Dark Matter
- Decaying Particles
- Kaluza-Klein
1990s: Beginning of Data-driven Cosmology

- COBE! and CMB experiments
- Redshift surveys (CfA, IRAS, 2dF, SDSS)
- Large-scale velocity field measurements
- Gravitational lensing
- Big telescopes (Keck, …) with big CCD cameras
- HST, X-ray, gamma-ray, IR, …
1992: COBE
Start of Era of Precision Cosmology

COBE FIRAS

$T = 2.725 \text{ K}$

$\Delta T = 3.353 \text{ mK}$

$\Delta T = 18 \mu\text{K}$
COBE Proves Copernicus Right!

The New Aether: Measuring the Earth's Motion w/COBE

Yearly Temp Variation:

$$\Delta T = 0.275\,\text{mK} \sin \frac{2\pi t}{365\text{d}}$$

Orbital Velocity:

$$V_{\text{orbital}} = \frac{0.275\,\text{mK}}{2.74\,\text{K}} \times c \approx 30.1\,\text{km}\,\text{s}^{-1}$$

(G. Smoot et al, 1991)
Big Glass on the Ground: 4 VLT, 2 Kecks, 2 Geminis and 2 Magellans
More on the way!
Great Observatories in Space: Hubble, Spitzer, Chandra, and Fermi, Herschel
Great Observatories in Space: Soon – JWST
Giant CCD Cameras

100 Megapixel

Gigapixel
Giant CCD Cameras: Dark Energy Camera

0.5 Gigapixel
How far can you see on a clear day? Back to the birth of galaxies.
How far can you see on a clear day with x-ray eyes?
To supermassive black holes at the edge of the Universe!
2000s: Era of Precision Cosmology

"Fisher Based"

- Cosmological parameters
- Tests of inflation, CDM
- Correlating large, complex data sets
- Cosmological Consistency
- Physical parameters (e.g., neutrino mass)
In the midst of a revolutionary period of discovery -- powerful ideas and instruments
The Consensus Cosmology
dark matter, dark energy, inflation inspired
fits a large body of precision data!
The “Consensus Cosmology”

- History from quark soup to nuclei and atoms to galaxies and large-scale structure
- Flat, accelerating Universe
- Atoms, exotic dark matter & dark energy
- Consistent with inflation
- Precision parameters
  - $\Omega_0 = 1.005 \pm 0.006$ (uncurved)
  - $\Omega_M = 0.280 \pm 0.013$
  - $\Omega_B = 0.045 \pm 0.0015$
  - $\Omega_{DE} = 0.72 \pm 0.015$
  - $H_0 = 70 \pm 1.3$ km/s/Mpc
  - $t_0 = 13.73 \pm 0.12$ Gyr
  - $N_\nu = 4.4 \pm 1.5$
$H_0 = 72 \pm 1 \pm 4 \text{ km/s/Mpc}$
... and Dr. Sandage, $H_0$ is now measured and $q_0$ is negative!
Decoding the Cosmic

COBE

DASI

ACBAR

Maxima

BOOMERanG

CBI
The Universe circa 380,000 yrs

WMAP

±0.001% Fluctuations
SEEING THE BEGINNING WITH MICROWAVES

DARK AGES

REGION OF MORE MATTER

REGION OF LESS MATTER

0.1 Gyr
First Stars

0.5 Gyr
Proto-galaxies

1 Gyr
First Quasars

5 Gyr
Peak of Galaxy Formation

10 Gyr
Solar System Forms

TODAY

Last Scattering
Formation of Atoms

$(\delta p/\rho)_{\text{CMB}} \approx (\delta T/T)_{\text{CMB}}$
Curve = concordance cosmology
Curve = concordance cosmology
Large-scale structure: Distribution of $10^6$ galaxies in the Universe today
Tracing the history from a slightly lumpy Universe to galaxies ablaze
The Consensus Cosmology

consistent with an impressive body of data

describes Universe from a burst of inflation through the formation of structure shaped by dark matter to today when dark energy controls the fate of the Universe

but …
The Consensus Cosmology

Rests upon three mysterious pillars
All implicate new physics!
Standard Model of Fundamental Particles and Interactions

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

Fermions

- Matter constituents: spin = 1/2, 3/2, 5/2, ...

**Leptons**
- Spin = 1/2
  - **電子 neutrino** $\nu_e$: Mass $<1\times10^{-8}$ GeV/c², Electric charge 0
  - **電子** $e$: Mass 0.000511 GeV/c², Electric charge -1
  - **μon neutrino** $\nu_\mu$: Mass $<0.0002$ GeV/c², Electric charge 0
  - **μon** $\mu$: Mass 0.106 GeV/c², Electric charge -1
  - **τon neutrino** $\nu_\tau$: Mass $<0.02$ GeV/c², Electric charge 0
  - **τon** $\tau$: Mass 1.7771 GeV/c², Electric charge -1

**Quarks**
- Spin = 1/2
  - **Up quark** $u$: Charge 2/3
  - **Down quark** $d$: Charge -1/3
  - **Charm quark** $c$: Charge 2/3
  - **Strangeness** $s$: Charge -1/3
  - **Top quark** $t$: Mass 175 GeV/c², Electric charge 2/3
  - **Bottom quark** $b$: Mass 4.3 GeV/c², Electric charge -1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \times 10^{-28}$ GeV s. The mass of the proton is $1.67 \times 10^{-27}$ kg.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60 \times 10^{-19}$ Coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron crossing a potential difference of one volt. Masses are given in GeV/c² (remember $m = mc^2$), where 1 GeV = $10^9$ eV = $1.60 \times 10^{-10}$ joule. The mass of the proton is $938$ GeV/c² = $1.67 \times 10^{-27}$ kg.

Bosons

- Force carriers: spin = 0, 1, 2, ...

**Unified Electroweak**
- **Gluon** $g$: Spin 1, Electric charge 0

**Strong (color)**
- **Gluon** $g$: Spin 1, Electric charge 0

Residual Strong Interaction

- The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electric interaction that binds electrically neutral atoms to form molecules. It can be viewed as the exchange of mesons between the hadrons.

Baryons $qqq$ and Antibaryons $\bar{qqq}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

**Property**
- Acts on: Mass = Energy
- Electroweak: Flavor, Electric Charge
- Strong: Color Charge
- Residual: See Residual Strong Interaction Note

Particles experiencing:
- All
- Quarks, Leptons
- Electromagnetically charged
- Quarks, Gluons
- Color-neutral

Particles mediating:
- Graviton (not yet observed)
- $W^+$, $W^-$, $Z^0$

Strength relative to electromagnet for two quarks at:
- $10^{-18}$ m
- $10^{-17}$ m
- Not applicable to quarks

Residual interactions:
- Not applicable to quarks
- 25
- 60
- 20

Matters and Antimatter

- For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless $\gamma$ or $\phi$ charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons ($\omega$, $\varphi$, and $\eta$) are also their own antiparticles.

Figures

- These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

The Particle Adventure

Visit the award-winning web feature The Particle Adventure at http://ParticleAdventure.org

This chart has been made possible by the generous support of:
- U.S. Department of Energy
- U.S. National Science Foundation
- Lawrence Berkeley National Laboratory
- Stanford Linear Accelerator Center
- American Physical Society
- Division of Particles and Fields

Burling Industries, Inc.

©2000 Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 55-308, Lawrence Berkeley National Laboratory, Berkeley, CA 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see: http://CPEPweb.org
### FERMIONS

**Leptons**
- **spin = 1/2**
  - **ν_e** electron neutrino: $<1 \times 10^{-8}$ MeV, massless
  - **ν_μ** muon neutrino: $<0.0002$ MeV, massless
  - **ν_τ** tau neutrino: $0.016$ MeV, massless
  - **e** electron: $0.000511$ MeV, $1/3$
  - **μ** muon: $0.106$ MeV, $1/3$
  - **τ** tau: $1.7771$ MeV, $-1$

**Quarks**
- **spin = 1/2**
  - **U** up: $0.003$ MeV, $2/3$
  - **D** down: $0.006$ MeV, $-1/3$
  - **C** charm: $1.3$ MeV, $2/3$
  - **S** strange: $0.1$ MeV, $-1/3$
  - **T** top: $175$ MeV, $2/3$
  - **B** bottom: $4.3$ MeV, $-1/3$

### BOSONS

**Unified Electroweak**
- **spin = 1**
  - **γ** photon: $0$ MeV, $0$
  - **W^-**: $80.4$ MeV, $-1$
  - **W^+**: $80.4$ MeV, $+1$
  - **Z^0**: $91.187$ MeV, $0$

**Strong (color)**
- **spin = 1**
  - **g** gluon: $0$ MeV, $0$

### Residual Strong Interaction
- **qq** quark-antiquark pairs are produced during strong interactions. Each quark carries color charge but the color charge is conserved. Two types of hadrons have been observed in nature: mesons and baryons.

### Properties of the Interactions

<table>
<thead>
<tr>
<th>Property</th>
<th>Interaction</th>
<th>Gravitational</th>
<th>Weak</th>
<th>Electromagnetic</th>
<th>Fundamental</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass - Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
<td>See Residual Strong Interaction Note</td>
<td></td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### THE HIGGS!?#
No Dark Matter

No Dark Energy

THE HIGGS!?"
Dark Matter/Dark Energy: The Scientific Approach

- Evidence
  - Meets the Sagan Standard

- Ideas
  - Rooted in exciting ideas about extending the standard model of particle physics

- Probes
  - Full court press – answers will come soon!
Carl Sagan:
Extraordinary Claims Require Extraordinary Evidence
Evidence for Dark Matter

- Flat rotation curves of galaxies (galaxies have large, dark halos)
- Clusters are held together by dark matter (galaxy motions, gravitational lensing)
- Without the gravity of exotic dark matter cannot make observed structure
- Airtight evidence for non baryonic nature
  - BBN/CMB census of stuff in the Universe
Airtight Evidence for Nonbaryonic Dark Matter

$\Omega_b h^2 = 0.021 \pm 0.001$

vs.

$\Omega_M h^2 = 0.13 \pm 0.005$

20σ discrepancy
BIG Gap Between Matter and Baryons

Baryons: \(21 \pm 1\)

Matter: \(130 \pm 5\)

→ Most of the matter is not baryons
Dark Numbers

- Stars: 0.5% of critical density
- Atoms: 4.5% of critical density
- Matter total: about 28% of critical density
- Dark Atoms: 4% of critical density

Bottom Line: Atoms can only explain 4% of the Dark Matter, the other 24% must be a new form of matter ("exotic dark matter")
Cosmic Web of Dark Matter Decorated by Stars
Big Dark Questions

• Where are the dark atoms (atoms: 4.5% total vs. in stars: 0.5%)?
  – Probably hot gas; seen in clusters

• Neutrinos: how much of the dark matter is neutrinos?
  – Between 0.2% and 2% (comparable to what exists in stars!)

• What is the Rest of the Dark Matter?
  – Neutralino: Accelerators, Specialized detectors and space
  – Axions: Specialized detectors
Finish the Baryon Story

Confirm Hogan’s Pie Chart
The First Missing Matter Puzzle: Helium

1868: Janssens and Lockyer find evidence for new element, the D3 line

1895: Ramsay solves puzzle by isolating He gas produced by cleveite
National Helium Monument
Celebrating 100th Anniversary of Discovery

Helium Time Columns Monument and Museum

Erected 1968, commemorating the 100th anniversary of discovery of helium in the gaseous atmosphere surrounding the Sun. (The discovery of traces of helium on earth was first announced 1895.)

The four time columns are filled with books, documents, and various artifacts that will tell future generations about life in 1968. After the time columns were filled, the caps were welded on and the contents sealed in a helium atmosphere. In twenty-five, fifty, one hundred, and one thousand years from the time of filling, the four individual columns are to be opened.

Helium is an element which occurs in commercial volume in natural gas produced since 1912 from wells in the Texas Panhandle. In 1929 the first of several helium processing plants began operations near Amarillo. Large quantities of helium extracted from natural gas are stored underground northwest of Amarillo and will provide a valuable source of supply for many years.

Once used only in lighter-than-air craft, helium now serves vital needs in industry, science, and the nation's military and space programs.
National Helium Monument
Celebrating 100th Anniversary of Discovery

Which City Will Be Known As The City Of Dark Matter?
### Dark Matter Candidates

**EXAMPLE:** 100 kg, relic cosmologist

\[ \lambda \sim 10 \mu m \]

\[ 310^9 K \]

**Dark Matter Candidates**

**NB:** Very exotic candidates not listed!

**FOR REFERENCE:**
- \( \rho_{\text{crit}} = 10^{-30} \text{g cm}^{-3} = 10^2 \text{eV cm}^{-3} \)
- \( n_B = 3.2 \times 10^2 \text{ cm}^{-3} \)
- \( n_B = 3 \times 10^2 \text{ cm}^{-3} \)
- \( 1 \text{ yr} = 3.2 \times 10^{26} \text{ deg}^{-2} \)

**Suspect** | **Mass** | **Abundance** | **Birth Site**
--- | --- | --- | ---
Invisible Axion | 10 eV | \( 10^9 \text{ cm}^{-3} \) | \( 5 \times 10^3 \text{ yr} \) 1 MeV
Light Neutrino | 30 eV | \( 10^9 \text{ cm}^{-3} \) | \( 5 \times 10^3 \text{ yr} \) 3 MeV
Axino/Photino/Gravitino/Minor Parity | keV | \( 10^5 \text{ cm}^{-3} \) | \( 10^4 \text{ yr} \) 100 MeV
Heavy Neutrino/Neutralino/Higgsino | GeV | \( 10^5 \text{ cm}^{-3} \) | \( 10^4 \text{ yr} \) 100 MeV
Sneutrino/Axino/Gravitino/| keV | \( 10^5 \text{ cm}^{-3} \) | \( 10^4 \text{ yr} \) 100 MeV
Supernova Magnetic Monopoles | 1 \text{ eV} | \( 10^5 \text{ cm}^{-3} \) | \( 10^4 \text{ yr} \) 100 MeV
Champs | 1 \text{ eV} | \( 10^5 \text{ cm}^{-3} \) | \( 10^4 \text{ yr} \) 100 MeV
Krypto-Baryons | | | |
Superheavy Neutralinos | | | |
Pythons/Maximon | | | |
Perry Maps/Schwarze-Scubs | | | |
Rene/Black Holes | | | |
Primordial Black Holes | \( \sim 10^{13} \text{ g} \) | \( 10^9 \text{ cm}^{-3} \) | \( 10^5 \text{ yr} \) 100 MeV

---

**EXAMPLE:**

F<sub>j</sub> (10 μm) \( \sim 10^{16} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} \)

\( \approx 3 \times 10^9 \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} \) (observed)
Dark Matter Candidates
Moose Diagram of Dark Matter Candidates

Axion
Neutralino
Baryon
WIMP
Full Court Press!!
Produce at an accelerator
Detect them in our halo
Detect annihilation products
AND WE MAY KNOW SOON!
Dark matter factory
Dark matter factory
COUPP
Juan Collar
Soudan Mine
Dark Matter Search
Dark Matter annihilating in our halo produces positrons, neutrinos and gamma rays.
Recent Pamela Positron Data

Confirmed by FGST
Recent Pamela Positron Data

Confirmed by FGST
The neutralino is very attractive, but don’t forget the axion

- Prediction of the most attractive solution to strong CP problem (Peccei-Quinn symmetry)
- Produced coherently in early Universe, with $\Omega \sim 1$ for $m \sim 10^{-6}$ to $10^{-5}$ eV
- Detectable!
The neutralino is very attractive, but don’t forget the axion
**Axion Mass Constraints**

(fa/N) Coupling to Electrons

- 10^{-13} GeV
- 10^{-12} GeV
- 10^{-11} GeV
- 10^{-10} GeV

([GG](DRS))

([GG](Hadronic))

SN 87A

Relic Decays

Windows on the Axion

- fa > 1
- fa (Davis) > 1

- 10^{-5} eV
- 1 eV

\[ \Omega_a = 1 \]

No Inflation & Davis Correct

(Hadronic Only)

(\Omega_a < 10^{-3})
Detecting Cosmic Axions

**Tuning in on Cosmic Axions**

- P. Sikivie 1983

Axion

Magnetic Field

Microwave Photon

Locally $10^{13}$ per cm$^3$

$\sim 30$ conversions per day

Power $\sim 10^{-23}$ Watt

Big Magnet

Microwave Cavity

[Image of research group and equipment]

[Diagram of experimental setup]
The Dark Matter Decade

- Hints (and distractions) in the air: Pamela, Fermi-Haze, WMAP Haze, ATIC, CDMSII
- New capabilities: LHC, Xenon100, Fermi, ...
- Prediction: The WIMP/Neutralino hypothesis will be tested this decade!
Big Surprise? – No Dark Matter

ASTRONOMY

Seeing Through Dark Matter

Stacy McGaugh

Dark matter was proposed to explain galaxy dynamics. A modification of Newton’s law of gravitational force may offer a better explanation.

The universe appears to be dominated by invisible components that astronomers call dark matter and dark energy. The astronomical evidence implicating dark matter has been apparent for a generation (1). The rotational speeds of objects in extragalactic systems exceed what can be explained by the visible mass of stars and gas. This discrepancy has led to the inference that there is more mass than meets the eye. However, this inference requires that Newton’s law of gravitational force be extrapolated well beyond where it was established. In addition, laboratory searches for dark matter have yet to bear fruit. This lack of corroborative evidence, combined with the increasing complexity and “preposterous” nature of a once simple and elegant cosmology, leads one to wonder if perhaps instead gravity is to blame.

Simply changing the force law on some large length scale does not work (2). One idea that has proven surprisingly resilient is the modified Newtonian dynamics (MOND) hypothesized by Milgrom (3) in 1983. Rather than change the force law at some large length scale, MOND subtly alters it at a tiny acceleration scale, around $10^{-10}$ m s$^{-2}$. In systems with gravitational accelerations above this scale (e.g., Earth, the solar system), everything behaves in a Newtonian sense. It is only when accelerations become tiny, as in the outskirts of galaxies, that the modification becomes apparent.

MOND has successfully described the rotation curves of spiral galaxies (see the figure) (4). In case after case, MOND correctly maps the observed mass to the observed dynamics. Why would such a direct mapping exist between visible and total mass if in fact dark matter dominates? Moreover, MOND’s explicit predictions for low surface brightness galaxies have been realized (5). In contrast, the dark matter par
see through dark matter

stacy mcgaugh

dark matter was proposed to explain the rotation curve of newton's law of gravitational force may offer an explanation.

the universe appears to be dominated by invisible components that astronomers call dark matter and dark energy. the astronomical evidence implicating dark matter has been apparent for a generation. for a long time, galactic rotation speeds of objects in extragalactic systems increased above any acceleration scale of order $10^{-10}$ m s$^{-2}$. in systems that exceed this scale cannot be explained by the mass of the stars and gas. this discrepancy has led to the inference that there is more mass than meets the eye. however, this inference requires that newton's law of gravitational force be extrapolated beyond where it was established. in many laboratory searches for dark matter have been fruitless.

this lack of corroboration, coupled with the increasing complexity and "preposterous" nature of a once simple and elegant cosmology, leads one to wonder if perhaps instead gravity is to blame.

simply changing the force law on some large length scale does not work. one idea that has proven surprisingly resilient is the modified newtonian dynamics (mond).

mond successfully described the rotation curves of spiral galaxies (see the figure). case after case, mond maps the observed mass to the observed dynamics. why would such a direct mapping exist between visible and total mass if in fact dark matter dominates? Moreover, mond's predictions for low surface brightness galaxies have been realized. in contrast, the dark matter post
Big Surprise? – No Dark Matter

If MOND is Right
I’ll Eat My
Powerpoint
(laptop included)!

gravity is to blame.
Simply changing the force law on some large length scale does not work (2). One total mass if in fact dark matter dominates? Moreover, MOND’s explicit predictions for low surface brightness galaxies have been realized (3). In contrast, the dark matter par...
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 his destiny
DARK ENERGY MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY
Youbetcha Katie, I believe in Dark Energy – we can see it from Alaska!
Youbetcha Katie,
I believe in Dark Energy – we can see it from Alaska!

Drill for Dark Energy!
A LOT AT STAKE!

Cosmic Destiny (can't understand)

Inflation related?

Narcissistic vacuum

Neutrino mass vs scale

Quantum vacuum energy

Why so small?

Supersymmetry

Supersymmetry

Supersymmetry

New graviton physics

SUSY \implies \rho_{vac} = 0

SUSY \implies \rho_{vac} \neq 0

Surprise??

What is dark energy?

Superstrings

Solution?

So... Swedish gold opportunities
IS THE UNIVERSE SLOWING DOWN?

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

HUBBLE'S LAW

\[ v_0 = H_d \]

\[ v_0 \text{ velocity today} \]
Is the Universe Slowing Down?

Telescope = Time Machine: See distant galaxies at earlier time when moving away faster.

Hubble's Law: \( V_0 = H_d \)

Data says: Universe is speeding up!

Universe is speeding up!? Why?
Discovery! – 1998

Hi z Supernova Team

Supernova Cosmology Project

Mark Philips
Two Technological Enablers:
1. Large (100 Mpixel) CCD Cameras
2. SNe Ia: Bright, Standardizable Candles (1.4 solar mass bomb)
The Discovery Data

Perlmutter et al, 1999

Riess et al, 1998
Carl Sagan:
Extraordinary Claims Require Extraordinary Evidence
1000 SNe from:
the original teams +
SNLS, ESSENCE, SDSS,
CfA, CSP, ...

More data stronger signal
SDSS-II Supernova Survey

~500 Well studied SNe Ia, suitable for framing
SDSS Low-redshift Light curves will lead to better understanding of Type Ia Supernovae
The Universe circa 380,000 yrs

WMAP

±0.001% Fluctuations
 Curve = concordance cosmology

\[ \Omega_0 = 1.005 \pm 0.006 \]
\[ \Omega_M = 0.28 \pm 0.015 \]
only consistent if
\[ \Omega_{\Lambda \text{-like}} = 0.72 \pm 0.015 \]
Baryon Acoustic Oscillations (BAO): Zel’dovich’s Standard Ruler
Baryon Acoustic Oscillations (BAO): Zel’dovich’s Standard Ruler
New stand alone evidence for cosmic acceleration from clusters observed by Chandra

36 Clusters with $z \sim 0.55$ and 49 with $z \sim 0.05$
Fig. 2.— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at \( z = 0 \) adjusted) computed for a cosmology which is close to our best-fit model. The low-\( z \) mass function is reproduced from Fig. 1, which for the high-\( z \) cluster we show only the most distant subsample (\( z > 0.55 \)) to better illustrate the effects. In the right panel, both the data and the models are computed for a cosmology with \( \Omega_\Lambda = 0 \). Both the model and the data at high redshifts are changed relative to the \( \Omega_\Lambda = 0.75 \) case. The measured mass function is changed because it is derived for a different distance-redshift relation. The model is changed because the predicted growth of structure and overdensity thresholds corresponding to \( \Delta_{\text{crit}} = 500 \) are different. When the overall model normalization is adjusted to the low-\( z \) mass function, the predicted number density of \( z > 0.55 \) clusters is in strong disagreement with the data, and therefore this combination of \( \Omega_M \) and \( \Omega_\Lambda \) can be rejected.
Consistent with all observations:

\[ \Omega_\Lambda = 0.71 \pm 0.02 \]
Eddington Criterion
Eddington:

"No experimental result should be accepted until confirmed by theory."
Very elastic stuff \((p < -\rho/3)\) with repulsive gravity is called “dark energy”.

\[
\rho + 3p
\]

( spherical symmetry )

- Black holes when \( \rho \geq \rho/3 \)
- Repulsive gravity when \( p < -\rho/3 \)

GR ALLOWS FOR REPULSIVE GRAVITY:

SOURCE OF GRAVITY IN GR:

FEATURE NOT A BUG!
May 1998
Birth of Funny Energy
But, Focus Groups
Didn’t Like Name
August 1998
Birth of Dark Energy
Third Stromlo Symposium
astro-ph/9811454
Dark Energy

**Defining features:**
- Large negative pressure, $p \sim -\rho$, so that $(\rho + 3\ p) < 0$
- $w = p/\rho$ (equation-of-state parameter) $\sim -1$
- Smoothly distributed
- Not particulate (dark matter has $p \sim 0$)

**Simplest example:**
- Energy of the quantum vacuum: $w = -1$
Defining features:
- Large negative pressure, $p \sim -\rho$, so that $(\rho + 3\ p) < 0$
- $w = p/\rho$ (equation-of-state parameter) $\sim -1$
- Smoothly distributed
- Not particulate (dark matter has $p \sim 0$)

Simplest example:
- Energy of the quantum vacuum

That's pronounced dubya
Dark Energy

Defining features:
• Large negative pressure, $p \sim -\rho$, so that $(\rho + 3p) < 0$
• $w = p/\rho$ (equation-of-state parameter) $\sim -1$
• Smoothly distributed
• Not particulate (dark matter has $p \sim 0$)

Simplest example:
• Energy of the quantum vacuum: $w = -1$
\[ \rho_{DE} \sim (1 + z)^{3(1+w)} \]

\[ w = \text{pressure/energy density} \]
$\rho_{DE} \sim (1 + z)^{3(1+w)}$

$w = \text{pressure/energy density}$
The Gravity of Nothing Is Repulsive

... But How Much Does Nothing Weigh?

Apparently, Way Too Much or Possibly Nothing to be more precise, the answer is nonsensical (infinite) – not as bad as a finite answer that is off by orders of magnitude

$$\rho_{\text{vac}} \approx 3 \times 10^{-11} \text{ eV}^4$$
The Gravity of Nothing Is Repulsive

... But How Much Does Nothing Weigh?

Apparently, Way Too Much or Possibly Nothing to be more precise, the answer is nonsensical (infinite) – not as bad as a finite answer that is off by orders of magnitude

$$\rho_{\text{vac}} \approx 3 \times 10^{-11} \text{ eV}^4$$

\[ dE = -\rho dV \quad \text{(First Law)} \]

\[ \rho_{\text{vac}} dV = -\rho_{\text{vac}} dV \Rightarrow \rho_{\text{vac}} = -\rho_{\text{vac}} \]

\[ T_{\mu\nu} = \rho_{\text{vac}} g_{\mu\nu} \quad \text{(same as } \Lambda) \]

Quantum vacuum is elastic (p = -p)

Quantum vacuum is elastic and its gravity is repulsive!

Just what is needed -- but...

Theoretical estimates of amount

10^{55} x what is needed to explain accelerating Universe

"Houston, we have a problem"
The Gravity of Nothing Is Repulsive

... But How Much Does

\[ \rho_{\text{vac}} \approx 3 \times 10^{-11} \text{ eV}^4 \]

\[ \rho_{\text{vac}} > \rho_{\text{vac}} \]

\[ dE = -\rho dV \text{ (First Law)} \]

\[ \rho_{\text{vac}} dV = -\rho_{\text{vac}} dV \Rightarrow \rho_{\text{vac}} = -\rho_{\text{vac}} \]

\[ T_{\mu\nu}^{\text{vac}} = \rho_{\text{vac}} g_{\mu\nu} \]

(same as \( \Lambda \))

Quantum vacuum is elastic

\[ \rho + 3\rho = -2\rho \]

Quantum vacuum is very repulsive!

Whose existence has been detected

(spinning of atomic levels in H)

Quantum vacuum is elastic

Just what is needed -- but...

Theoretical estimates of amount

\[ 10^{55} \times \text{what is needed to explain accelerating Universe} \]

"Houston, we have a problem"
The Gravity of Nothing Is Repulsive

... But How Much Does Nothing Weigh?

Apparently, Way Too Much or Possibly Nothing to be more precise, the answer is nonsensical (infinite) – not as bad as a finite answer that is off by orders of magnitude.

$$\rho_{\text{vac}} \approx 3 \times 10^{-11} \text{ eV}^4$$

$$\rho_{\text{vac}} dV = -\rho_{\text{vac}} dV \Rightarrow \rho_{\text{vac}} = -\rho_{\text{vac}}$$

$$T^{\mu\nu}_{\text{vac}} = \rho_{\text{vac}} g^{\mu\nu}$$

(same as \(\Lambda\))

Quantum vacuum is elastic \(\rho = -\rho\) and its gravity is repulsive!

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

Just what is needed -- but...

Theoretical estimates of amount

$$\rho_{\text{zero pt}} = \frac{1}{2} \int_0^\infty \sqrt{k^2 + m^2} \frac{d^3k}{(2\pi)^3} = \frac{1}{16\pi^2} k_{\text{max}}^4$$

$$\rho_{\text{zero pt}} < \rho_{\text{crit}} \Rightarrow k_{\text{max}} < 0.03 \text{ eV}$$
Now we have two puzzles:

Why does nothing weighs so little?

&

What is dark energy?

Puzzles could be related or unrelated!
SOLVING THE COSMIC ACCELERATION RIDDLE WILL REQUIRE A CRAZY, NEW IDEA!

NB: NOT EVERY CRAZY IDEA IS A SOLUTION TO A PROFOUND
Vacuum Energy Problem Solved by Supersymmetry or?
Theorists: When in doubt, just add a scalar field
When in doubt, just add a scalar field.

**Rolling Scalar Field**

(aka: decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)

Bronstein 1933 (executed by Stalin 1935)
Hill Schramm Fry 1986
Freese et al. 1987
Patke-Peebles 1988
Friedman et al. 1995
Caldwell et al. 1998

**A. Greenspan 1998:** "... Brief Episodes of Inflation Are Unavoidable."

\[ V(\phi) \]

\[ p = \frac{1}{2} \dot{\phi}^2 + V \]

\[ p = \frac{1}{2} \dot{\phi}^2 - V \]

\[ w = -1 \rightarrow 1 \]

\[ (10^{-2} V)^4 \]

**TRUE VACUUM ZERO ENERGY**
Theorists: When in doubt, just add a scalar field

NB: does not address of the lightness of nothing

A. GREENSPAN 1998: "...Brief episodes of inflation are unavoidable."

$V(\phi) = (10^{-22} \text{eV})^4$

$p = \frac{1}{2} \dot{\phi}^2 + V$

$p = \frac{1}{2} \phi^2 - V$

$w = -1 \rightarrow 1$

TRUE VACUUM
ZERO ENERGY
NO DARK ENERGY
NEW ASPECT OF GRAVITY

"EMPTY" UNIVERSE UNDERGOES ACCELERATED EXPANSION!

AVERAGE MATTER DENSITY TODAY $\approx 10^{-29}$ g/cm$^3$
$\approx 10^{-100} \times$ DENSITY AFTER INFLATION
Dark Theory Summary

1. GR + repulsive gravity of dark energy (Conservative)
   - Quantum vacuum energy/cosmological constant
   - “Quintessence”
   - ?? Something else with negative pressure

2. No dark energy, new theory of gravity (Progressive)

3. No dark energy, no new theory of gravity (Birther)
   - Non linear gravitational effects
   - Center of the Universe
Two Big Dark Questions

Does Dark Energy change with time (i.e., is dark energy vacuum energy)?

Does Cosmic Acceleration require going beyond General Relativity?
Two Big Dark Questions

Does Dark Energy change with time (i.e., is dark energy vacuum energy)?

No, at the 10 to 20% level

Does Cosmic Acceleration require going beyond General Relativity?
Two Big Dark Questions

Does Dark Energy change with time (i.e., is dark energy vacuum energy)?

No, at the 10 to 20% level

Does Cosmic Acceleration require going beyond General Relativity?

Not well tested
Dark Energy:
\[ \Omega_{DE} = 0.76 \pm 0.02 \]
\[ w = -0.94 \pm 0.1 \]
(± 0.1 sys)
New Results 400d Survey
Alexey Vikhlinin et al, CCCP
Known Probes of Dark Energy

- Supernovae: Geometric
- BAO: Geometric + simple physics
- Weak Lensing: Geometric + dynamic
- Clusters: Dynamics + geometric
- Evolution of large-scale structure (dynamic)
  - Must reproduce LCDM
  - Growth factor/red-shift space distortions
- CMB and other precision data that pin down cosmological parameters (provide priors)
Dark Energy Survey
Dark Energy Survey
First Results from the South Pole Telescope

Staniszewski et al, astro-ph/0810.1578
Impressive Array of Dark Energy Projects on the Horizon

- **BAO**: SDSS/2dF, WiggleZ, FMOS, BOSS HETDEX, WFMOS, PAU → EUCLID & JDEM
- **CL**: SZA, SPT, DES, ACT, Chandra → eROSITA
- **SNe**: DES, PanSTARRS → LSST, EUCLID & JDEM
- **WL**: DES, PanSTARRS → LSST, EUCLID & JDEM
- **CMB et al**: WMAP/ACT/SPT/Planck – cosmological degeneracies make many other observations valuable

On the way to few % in $w_0$, 10% in $w_a$, significant tests of underlying gravity theory … and deeper understanding of dark energy
Impressive Array of Dark Energy Projects on the Horizon

- **BAO**: SDSS/2dF, WiggleZ, FMOS, BOSS HETDEX, WFMOS, PAU → EUCLID & JDEM
- **CL**: SZA, SPT, DES, ACT, Chandra → eROSITA
- **SNe**: DES, PanSTARRS → LSST, EUCLID & JDEM
- **WL**: DES, PanSTARRS → LSST, EUCLID & JDEM
- **CMB et al**: WMAP/ACT/SPT/Planck – cosmological degeneracies make many other observations valuable

On the way to few % in $w_0$, 10% in $w_a$, significant tests of underlying gravity theory… and deeper understanding of dark energy.
The New Cosmology

• What we know for sure
  – Quark Soup to Expanding Galaxies
  – BBN, Gravity the masterbuilder, CMB, the phenomena of Dark Matter and Accelerated Expansion

• Knocking at the Door (ie, testing now)
  – Particle dark matter, inflation, dark energy, (baryogenesis)

• Wild Speculation
  – Before the big bang, multiverse, extra dimensions, emergence of space
WE KNOW MUCH

INFLATION

STYLING

COSMOLOGY

HOT BIG BANG

MODEL

DARK ENERGY

COSMIC

ACCELERATION

MAGNETIC

COLD

DARK

MATTER

CAN WE PUT IT ALL TOGETHER?
WE KNOW MUCH

INFLATION

STYLING COSMOLOGY

HOT BIG BANG MODEL

MASSIVE NEUTRINOS

DARK ENERGY

COSMIC ACCELERATION

DARK MATTER

CAN WE PUT IT ALL TOGETHER?

THE BIG PICTURE

OUR UNIVERSE
From Here to Eternity
In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!
In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!

Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!
NANCY KENNIGAN ASKED:

WHY ME?
WHY NOW?

ENERGY

MATTER

DARK ENERGY
DOMINANT

COSMIC ACCELERATION

DARK MATTER
DOMINANT
COSMIC DECELERATION

TODAY

TIME

WHY THE SWITCH OVER
JUST WHEN WE ARRIVED?
Important clue or coincidence?

Why me? Why now?

Why the switch over just when we arrived?
At the very least, we can now say that cosmology is the battle between two dark titans.
Λ’s Checkered History
Λ's Checkered History
• 1917 – 1929
  – Einstein: static, finite, positively curved Universe
    $\rho_M = 2\rho_\Lambda$, $R = 1/(4\pi G \rho_M)^{1/2}$
  – de Sitter (1917): vacuum solution, first derivation of Hubble’s Law
  – Eddington-Lemaitre long lived cosmologies
  – Hubble discovers expansion
  – Einstein: “my greatest blunder”
  – Eddington remains obsessed
1948 – 1970

- Bondi & Gold, Hoyle: Steady State Cosmology: “perfect cosmology”
- Strong signs of evolution: quasars, radio sources and CMB kills a beautiful theory
- Petrosian, Salpeter & Szekeres (abundance of $z \sim 2$ QSOs) and Gunn & Tinsley (data)
- Rise of Standard Cosmology (Hot Big Bang)
Quantum Vacuum Energy: Most Embarrassing Problem in all of Physics

- 1930s: Pauli, “Size of Universe could not reach to the moon”
- 1968: Zel’dovich articulates the problem
- 1989: Weinberg, “Bone in the throat of theorists”
Most Anticipated Surprise Ever

- 1984 on – “Ω problem”
- 1984 – 1995: Λ solution, best fit Universe, COBE and $\Omega_M \sim 0.3$ & triumph of ΛCDM
- 1998: The Accelerating Universe
- 1998: Cosmology Solved Debate
- 1998: Birth of Dark Energy and a new puzzle

Rapid acceptance it is the missing piece of the puzzle
EVIDENCE
for DARK MATTER
ITS GRAVITY IS:
NEEDED TO HOLD
GALAXIES TOGETHER
V. RUBIN ET AL. '70A.

NEEDED TO HOLD
CLUSTERS TOGETHER
ZWICKY '35
Fritz Zwicky

Discoverer of the Dark Side
circa 1935
Vera Rubin and Flat Rotation Curves
Dark Matter Close to Home
The Rise and Fall of Omega

- **1970s**: Mass-to-light ratios on limited parts of the galaxy
- **1980s**: Peculiar velocity measurements probe larger regions
- **1990s**: Cluster fair sample, LSS, peculiar flows
- **2000s**: CMB, LSS, BAO, clusters