COSMIC RECIPE

FLAT UNIVERSE

AVERAGE DENSITY
= CRITICAL DENSITY
= 1/3 DARK MATTER + 2/3 DARK ENERGY

"COSMIC FOOD CHAIN"
Solving the dark energy problem will likely require a crazy new idea.

However, not every crazy new idea will be a solution!

Needed: Probes of dark energy
Quantum vacuum is not empty!
sea of virtual particles

whose existence has been detected
(switching of atomic levels in H)

W. Lamb, ca.1950

Quantum vacuum is elastic \((p=-\dot{p})\)
& its gravity is repulsive!

just what is needed -- but...

Theoretical estimates of amount

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

"Houston, we have a problem"
A BRIEF EPISODE OF INFLATION

(aka decaying cosmological constant, quintessence, rolling scalar field)

...mild episodes of inflation are unavoidable

A. GREENSPAN

\[ V(\phi) \]

\[ m, \dot{m}, \ddot{m} \]

pressure varies with time, but typically negative

\[ \phi \]
WHAT DO WE KNOW ABOUT DARK ENERGY

Dark Energy (dark en'ør jē)
- non-luminaus; energy-like; most of the stuff in the Universe; diffuse; MYSTERIOUS

LOTS OF IT: $\Omega_X = \Omega_0 - \Omega_M \approx 0.67 \pm 0.06$
- CMB: $\Omega_0 \approx 0.33 \pm 0.04$

DOESN'T CLUMP SIGNIFICANTLY:
- $T^\mu_\nu \approx (\rho_x - p_x - p_y, 0)$
- Equ of State: write $p_x = w \rho_x$
- $p_x \propto R^{-3(1+w)}$
  IF $w = \text{const}$

REPULSIVE GRAVITY:
- In GR: source of gravity $\propto (\rho + 3p)$
- $\propto \rho_x (1 + 3w) < 0$ IF $w < -\frac{1}{3}$

NB: Relativists call something $w/10^{10}$ or $10^{11}$ "energy-like"
**NEED** \( w \leq -\frac{1}{2} \) **TO MAKE** "X-MATTER" UNIMPORTANT IN PAST & NOT INTERFERE W/ STRUK FOMATION

**NB:** \( w \uparrow \sigma_0 \downarrow \)

**Graph**: 
- Log (energy density) vs. Log (scale factor)
- \( P_x \propto R^{-3(1+w)} \)
- \( w=1 (\Lambda) \)
- \( \frac{1}{3} \) and \( -\frac{1}{3} \) lines
- Rad and Matter
How can we learn more? Largely from cosmology.

Dark energy controls the expansion of the universe.

\[ H^2 = \frac{8\pi G \rho}{3} = \frac{8\pi G}{3} (\rho_m + \rho_x) \]

\[ H^2 = H_0^2 \left[ \Omega_m (1+z)^3 + \Omega_x (1+z)^{3(1+w)} \right] \]

\[ \Omega_x = 1 - \Omega_m \]

Influences:

Distance to an object at redshift \( z \):

\[ r(z) = \int_0^z \frac{dz}{H(z)} \]

Luminosity distance:

\[ d_L(z) = (1+z)r(z) = \left( \frac{L}{4\pi F} \right)^{1/2} \]
GROWTH OF STRUCTURE:

\[ \ddot{\delta} + 2H \dot{\delta} - 4\pi G \rho_m \delta = 0 \]

Expansion acts like friction that slows the growth of structure.

Total growth relative to \( \Omega_m = 1 \) (EdS).

Recent growth:

Dark energy influences how structure develops.

Sensitivity of cosmology to \( w(z) \).

Sensitivity to \( w(z) \):

The Hubble Law \( r = H^{-1} z \).

Sweet spot:
\[ z = 0.2 \rightarrow 2 \]

Age of universe:
\[ t_0 = \int_0^t \frac{dz}{H_0 (Hz)^{-3}} \]

Less potential.
NEED $w \leq -\frac{1}{2}$ FOR LONG MATTER-DOMINATED ERA
NEEDED TO GROW STRUCTURE

$P_x \propto R^{-3(1+w)}$

$w_x = \frac{1}{45}$
$w = -1$

LOST GROWTH
SUPPRESSED GROWTH OF DENSITY PERTURBATIONS BY SMOOTH COMP

$W \approx -\frac{1}{3}$

"COBE-1354" $\Omega_h = 0.3$

$\sigma_8$ vs $W$

$\sigma_8^{(obs)} = 1.301$
NANCY/KERRIGAN PROBLEM

WHY ME?
WHY NOW?

Mysterious, but crucial

energy density

unimportant

important

dark energy
dominant

scale factor

matter

today
SNAP $n(z)$
Optimal $n(z)$
50% $Z_1 \approx 0.4 Z_{\text{max}}$
50% $Z_2 = Z_{\text{max}}$
AGE FAVORS SMALLER W

\[ t_0 = H_0^{-1} f(w, \Omega_i) \rightarrow H_0^{-1} f(w) \]

\[ \Delta w = 0.35, \quad t_0 = 135 \pm 1.5 \]
\[ H_0 = 70 \pm 7 \]

\[ \text{Halo} = 0.94 \pm 0.14 \]
"DON'T HAVE A CLUE AS TO WHAT THE DARK ENERGY IS!" "RIGHT NOW, NOT ONLY PRL-COSMOLOGY BULKS UP-BLEM. PART. TYPICALLY THIS IS THE BONE IN OUR THROAT" — S. WEINBERG

IT IS SMOOTH, HAS REPULSIVE GRAVITY, & INVOIDS FUND PHYSICS
CHARACTERIZE IT BY $w_x = \frac{\dot{w}}{\dot{x}}$, $w_x(t)$
AS A START

<table>
<thead>
<tr>
<th>CANDIDATE</th>
<th>$w$</th>
<th>$\dot{w}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSMOLICAL CONSTANT ($\Lambda$)</td>
<td>$-1$</td>
<td>$0$</td>
</tr>
<tr>
<td>FLUCTUATED DEFFCTS N=1 (string), L (walls)</td>
<td>$-\frac{\Lambda}{3}$</td>
<td>$\approx 0$</td>
</tr>
<tr>
<td>FALSE VACUUM STATE</td>
<td>$-1$</td>
<td>$\approx 0$</td>
</tr>
<tr>
<td>ROLLING SCALAR FIELD &quot;QUINTESSENCE&quot;</td>
<td>$-1 \Rightarrow 1$</td>
<td>$\frac{\ddot{x} + V(x)}{\dot{x}^2 + V(x)}$</td>
</tr>
</tbody>
</table>

"THE BULK", BREAKDOWN OF FUN COSMOLOGY, ...
**GOAL:** DETERMINE $\Omega$, $\Lambda$

**CMB:** position of first peak($z$)

$l_1 \propto r(\Omega = 1)$

"DEGENERACIES", NO SENSITIVITY TO $\Lambda$

**SNeIa:** "map out" $r(z)$

**SNeIa**, WHICH TELESCOPE? SPACE OR GROUND

**COUNTING GALAXIES, CLUSTERS**

$r(z)$ and $\delta(z)$

**SYSTEMATICS** (E.G. PREDICTING W(z), H - T REL.?) HOW BEST TO FIND

**GRAV. LENSING:** WEAK & STRONG

$\delta(z)$ and $r(z)$

**SYSTEMATICS**, WHICH TELESCOPE, SPACE OR GROUND
Position of First Acoustic Peak

\[ \Delta \xi / \xi = -0.0004 \Delta \omega \]

\[ \phi = 0.3 \]

\[ \Delta \xi / \xi = -0.0004 \Delta \omega \]

\[ \Delta \xi / \xi = 0.25 \Delta \omega \]

\[ \Delta \xi / \xi = 0.20 \Delta \omega \]

\[ \Delta \xi / \xi = 0.30 \Delta \omega \]

\[ \Delta \xi / \xi = 0.40 \Delta \omega \]
Another approach: counting standardizable objects

\[ \frac{dn}{d\Omega dA} = n(z) \times \frac{dv}{d\Omega dA} \]

Observable

Astrophysics: Evolution

Volume element: Cosmology

\[ = n(z)^2 \frac{1}{H(z)} \]

Key systematic: Evolution \( n(z) \)

IE standardizing the objects

Graphs showing the number of galaxies and clusters vs. redshift, with trends indicated by different values of \( w \).
CLUSTER SAMPLE

X-ray selected
1000 $z=0-3$

Contours
1, 2, 3 $\sigma$

$\delta w \approx 0.5$

S-Z selected
100 $z=0-3$

$\delta w \approx 0.4$

Holder et al
astro-ph/0002336
**COSMOLOGICAL OBSERVATIONS CAN ADDRESS** $w, \dot{w} (w(z))$

Evidence that $w \neq -1$ or $\dot{w} \neq 0$ would be a major clue and indicate the presence of something new.

**WORK TO BE DONE!**
- Understand systematics
- Determine optimal approach
- Get new telescopes built

**NEED IDEAS STILL NEEDED**
- Measure slight clumping
- Look for other signs — e.g., long-range forces, variation of constants of nature

**DARK ENERGY IS A MOST IMPORTANT PROBLEM!!**
Cosmology can shed light on its mysterious nature.
SNe Ia can get at the nature of dark energy

SNe determine expansion history thru

\[ d_L(z) = \frac{(1+z)H(z)}{H_0} \]

Distance: \( d_L \) = \( \frac{L}{4\pi} \frac{1}{H_0} \)


\[ r(z) = \int_0^z \frac{dx}{H(x)} \]

\[ H^2 = H_0^2 \left[ \Omega_m(H_0) + \Omega_{\Lambda} \right] \]

\( k = 0, \ w = \text{const} \)

Determine from SNe Ia data

Reconstruct \( w(z) \):

\[ w_x(z) = -1 + \frac{4}{3} H_0^2 \Omega_m(z)^2 \frac{2 + (d^2r/dz^2)/(dr/dz)^2}{H_0^2 \Omega_m(z)^2 - 1/(dr/dz)^2} \]

\( k = 0 \)

On \( V(\phi) \) for scalar field model:

\[ V(\phi) = \frac{1}{8\pi} \left[ \frac{3}{(dr/dz)^2 + (H(z)(d^2r/dz^2)/(dr/dz)^3} \right] - \frac{3}{4\pi} \frac{\Omega_m(H_0)^3}{16\pi G} \]

NEED QUALITY DATA SET!