Implications of Cosmic Acceleration


Need for dark energy

Low mass density of universe observed

But CMB fluctuation spectrum implies critical density, flat geometry

Make up energy deficit with “dark matter” and “dark energy”
Dark energy must resist gravitational collapse

- Not concentrated in clusters of galaxies (dark halos)
- But dominant form of energy, would prevent structure formation
- Requires “tuning:” dark energy negligible in the era of structure formation, becoming significant only now
According to General Relativity, this requirement implies that the dark energy has negative pressure.

- Notice that pressure has the same dimensionality as energy density.

- Ordinary matter
  - Exerts positive pressure on its surroundings
  - Tends to slow cosmic expansion through gravity
Negative-pressure dark energy, on the other hand, causes the cosmic expansion to speed up

- Indicated by use of Type Ia supernovae as standard candles
- Return of the cosmological constant ($\Lambda$), which is equivalent to spatially uniform, time-independent vacuum energy density

Claim: there is no natural explanation for negative-pressure dark energy.

Here are two examples of recent attempts to introduce it in a natural way.
Ferreira & Joyce introduce a scalar field

- Weakly coupled
- Justification in theoretical particle physics
- No experimental evidence for it, though

Field $\Phi$, potential $V = M_P^4 \exp(-\lambda \Phi / M_P)$ with the Planck mass $M_P = (8\pi G)^{-1/2}$, $\lambda > 2$.

Field equations allow a solution with matter and energy coupled to this field through gravity.

This solution is an attractor — a wide range of parameter choices lead to it — so tuning is not needed.
Quintessence $Q$ (Caldwell et al.)

Contribution to cosmic energy density with equation of state $w = p/\rho < 0$

Evolving scalar field stable against catastrophic gravitational collapse

Fluctuations are inevitable; the field has to respond to fluctuations in the matter (satisfies equivalence principle).

“...at least as well motivated by fundamental physics as introducing a cosmological constant.”
Why do $Q$ and matter have similar energy densities today? No explanation yet.

Simulations yield reasonable CMB fluctuations and other observational quantities.
Background on string theory, extra dimensions (Randall)

Provides the only known way to reconcile general relativity with quantum theory (quantum gravity).

Requires that space have additional, unseen, dimensions. Where are they?

How we know we live in three spatial dimensions . . .
Inverse square law of gravity, a consequence of isotropy of space

- Experimentally validated down to 0.1 mm
- If there were more dimensions, force lines would spread out into them and distance dependence of force would be steeper

Kaluza-Klein: extra dimension is wrapped up in little balls

- Radius $r_c \sim 10^{-33}$ cm (the Planck scale)
- Unobservable because too small to resolve — garden hose from a distance
• Space not isotropic; extra dimension is compact, force lines spread only a distance $r_c$ in the extra dimension

(Horizontal lines are 3-D force lines)
But it is not known whether the extra dimensions have to be as small as the Planck length.

Radius $r_c$ as large as 1 mm is consistent with all observations if only gravity exists in the extra dimensions, not the other forces.

This point follows from the existence of branes — another ingredient of string theory
Branes

Flat subspaces (membranes) embedded in a higher-dimensional space

Visualize as 2D but can be 3D or higher

Relevant properties

- Carry energy or tension
Matter and forces can be confined to them; for example, electromagnetism is well known to function in 3 spatial dimensions.

Gravity exists in the full spacetime. Strength of gravitational force decreases exponentially with distance from a brane.

A flat brane requires vacuum energy.

Solution to Einstein’s equations is a 5D anti-de Sitter spacetime (has negative vacuum energy).

The graviton has a tightly bound 4D state, is tightly confined to the brane.
• The hidden (fifth) dimension can be infinite

Force lines are denser near the brane
Idea may lend insight on why gravity is so weak
Steinhardt-Turok cosmology

One brane has positive tension, the other negative

Matter in the visible universe is confined to one brane, gravity is strongest on the other (the Planck brane). Particles on the Planck brane interact with the visible brane only through gravity, acting like dark matter.

The theory’s scalar field, $\phi$, determines the distance between the branes.
The potential, $V(\phi)$, is chosen so that the branes move alternately together and apart: an oscillating cosmology

Departs from GR, but departures are within observational constraints

Passage from approach to moving apart at collision: physical quantities remain finite

Cosmic acceleration (100 orders of magnitude smaller than in inflationary cosmology) is crucial for suppressing density perturbations and diluting entropy and black holes
Acceleration phase is now just beginning

Universe is periodically restored to empty, smooth state

Time scale $\sim 10^{13}$ yr