Dark Energy and the Accelerating Universe

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Questions

• Who can summarize the evidence in favor of the reality of dark energy and its effects for me?

• What is the difference between dark matter and dark energy? Are there any (superficial) similarities?

• What are dark energy’s consequences, in terms of how the universe may one day “die out”?

• What stops dark energy from for example ripping the moon away? Still the case in a billion years?
What is dark energy?

- Honestly, who the heck knows? Astronomers are all baffled.
- All right everyone, nothing more to learn here, let’s go home, class over early today. For Mon. homework go read..
- (Kidding.) There’s quantum mechanics: zero-point energy.
- One decent idea -- We know already for certain that vacuum ISN’T empty (calculations from quantum field theory):
  - Submicroscopic (subatomic-level) quantum fluctuations: virtual particle-antiparticle pairs pop in & out of existence all the time.
  - There is an important catch: dark energy is too small by factor of $10^{120}$!!!!!! (Less of a problem back when we thought it was 0)
The Casimir Effect

• Can borrow a little energy from vacuum, and it doesn’t even have to be a temporary loan (short distance scales)
  • “Virtual” particles have real effects (can carry a force)

• Plates initially uncharged develop calculable electrical potential difference and then attract each other (opposite electric charges, - and +)
  • Very small effect, difficult to measure, but we’ve done it
How did we find dark energy?

• Type Ia supernova (our best “standard candle”) studies
• CMB (Planck) confirms result
• Equation of state $w = -1.0$ exactly as far as we can tell
  • Means constant-energy-density, negative-pressure field (0-point)
  • Just like with the flatness of universe from total density close to critical, a huge coincidence
• Persistent energy -> persistent (an accelerating) expansion


Instead of seeing of turn-down (would be true of standard closed, flat, or even open universe) shocked to see opposite

Hubble’s Law with a vengeance

Where is gravity kicking in?
What is acceleration?

- Means speeding up, while deceleration means slowing down.
- But most often in physics, acceleration is used as a more general term to mean the change in velocity (speed and/or direction) over time.
- Units of length over (divided by) units of time squared (taken to the 2\textsuperscript{nd} power, or multiplied by self).
- Derivative (slope) of velocity w.r.t time, and thus second derivative of displacement vector (distance).

<table>
<thead>
<tr>
<th>Displacement (x)</th>
<th>Velocity (v)</th>
<th>Acceleration (a)</th>
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<tbody>
<tr>
<td>At $v=0$;</td>
<td><img src="" alt="Graph" /></td>
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<tr>
<td><strong>b. Motion with constant velocity</strong></td>
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<td><strong>c. Motion with constant acceleration</strong></td>
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<td><strong>d. Motion with constant deceleration</strong></td>
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Is $\Lambda$ “anti-gravitational”?

- Is not exactly: I’ve told you before it is LIKE anti-gravity
  - But the repulsion is not like objects repelling each other *through* space like two magnets with like poles facing
  - It is space(-time) itself expanding more & more quickly: think like ants on a balloon. As balloon expands they move apart, rather than ants moving away from each other on their own

- Variants on what it is (instead of “cosmological constant,” which is mathematically exactly same as vacuum energy)
  - Temporal variance instead of persistence (quintessence)
  - Spatial variation instead of smoothness (uniform expansion?)
  - Phantom energy (Big Rip), badly motivated theoretically
Alternatives

- In support of dark energy: back in late 1990s, fixed a lot of problems all at once (recall how inflation did)
  - Stars older than the universe itself?!
  - Large-scale structure: too much void
  - Matter sum close to critical amount

- Inhomogeneity: we know universe not as isotropic as we claim in our equations. Acceleration an illusion?

- Tweak Einstein field equation OR introduce extra dimension* (again)

*5D term starts to dominate at the longest distances

Gott and Juric, Princeton
The Homework

- Rich history of CMB study. PICK ONE
  - Planck: [http://www.esa.int/Our_Activities/Space_Science/Planck_overview](http://www.esa.int/Our_Activities/Space_Science/Planck_overview)

- What can the CMB radiation tell us?
  - Dark matter, dark energy, and large-scale structure through its anisotropies
  - Gravitational waves
  - Bubble universes
  - Hubble constant
  - Age of universe
  - Geometry of universe
  - Its great smoothness…

It is probably not too much of a stretch to claim that nearly everything we know so precisely about our beautiful universe is derived in no small way from studying the subtleties of the microwave background.