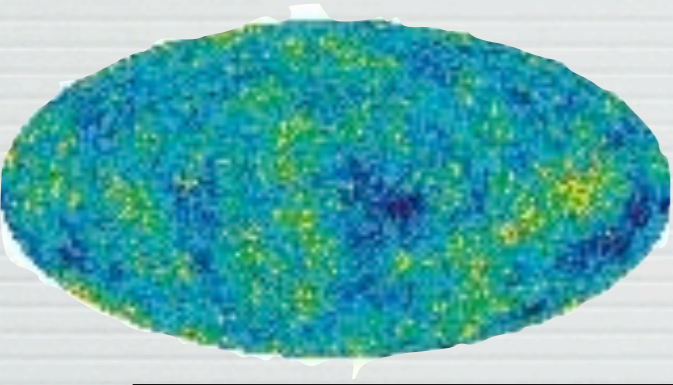


# Dark Energy and the Accelerated Expansion of the Universe

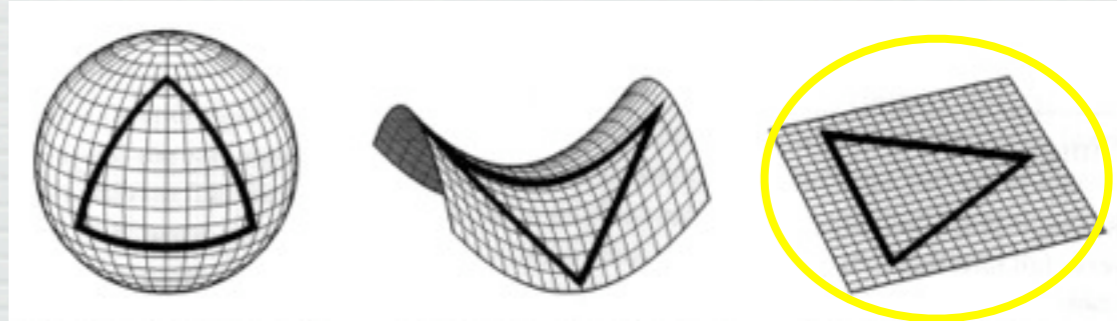
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- Since the 1930s, we've known that **the Universe is expanding** over time. (Hubble, Einstein)
- Normal matter attracts itself — so the expansion **should slow down over time** (“deceleration”).
- But: we observe that **the expansion seems to be speeding up** (“acceleration”)
- We call the substance responsible for this **“Dark Energy”**
- (In fact, Einstein already had this in his theory — **the cosmological constant,  $\Lambda$** )



# Evidence

- Observe overall *flat* geometry

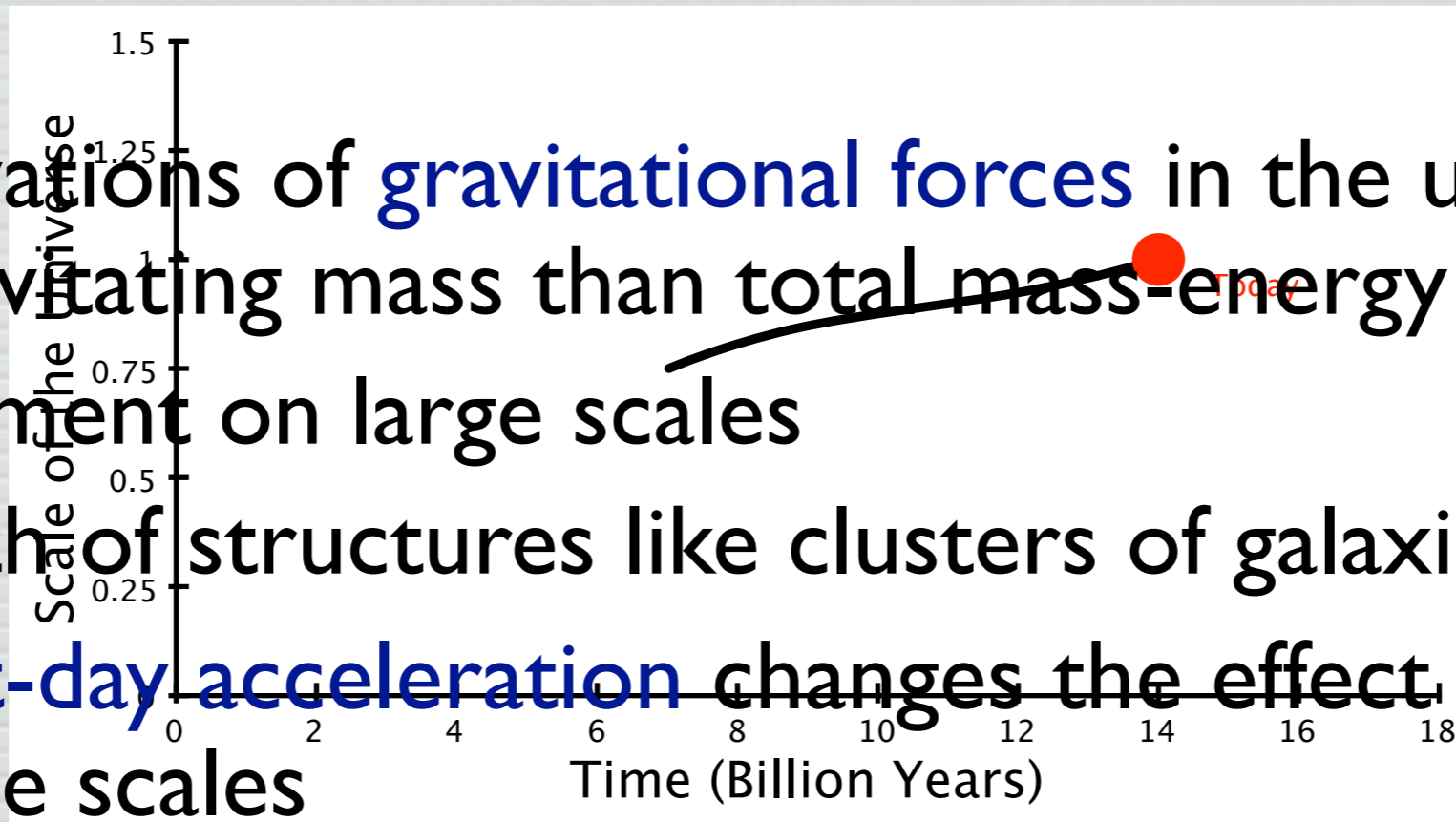


- Relativity  $\Rightarrow$  total amount of mass-energy
- Normal matter: Universe would be 10 billion years old
- **But:** oldest objects  $\sim$  13 billion years old
- Present-day acceleration makes the Universe older
- Need **dark energy** for acceleration

# Evidence

- Observations of distant **exploding stars (supernovae)** are **dimmer** than they would be if the Universe were only composed of gravitating matter
- **Present-day acceleration** makes these objects further away

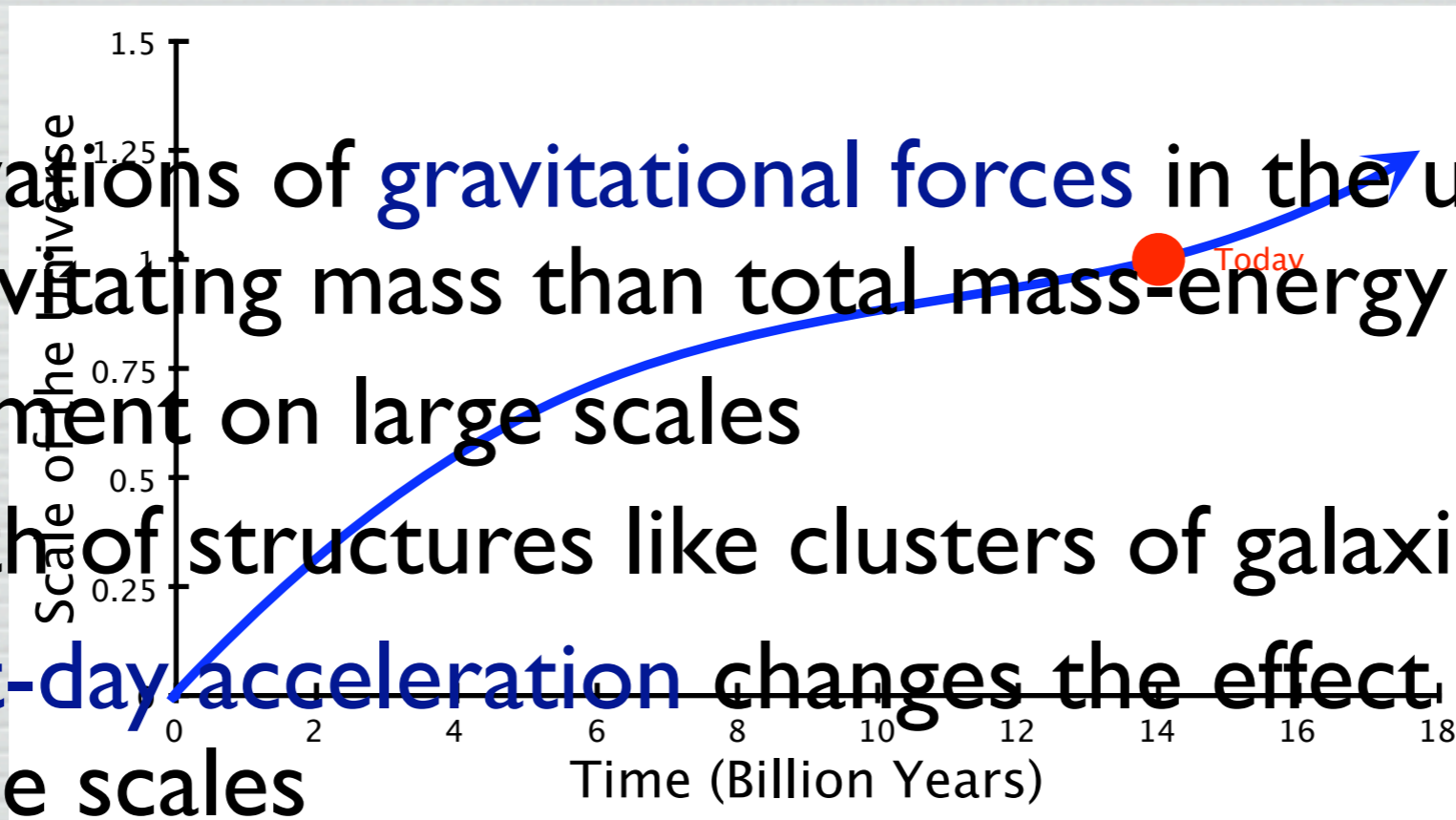
- Observations of **gravitational forces** in the universe: less gravitating mass than total mass-energy
  - movement on large scales
  - growth of structures like clusters of galaxies
- **Present-day acceleration** changes the effect of gravity on these scales



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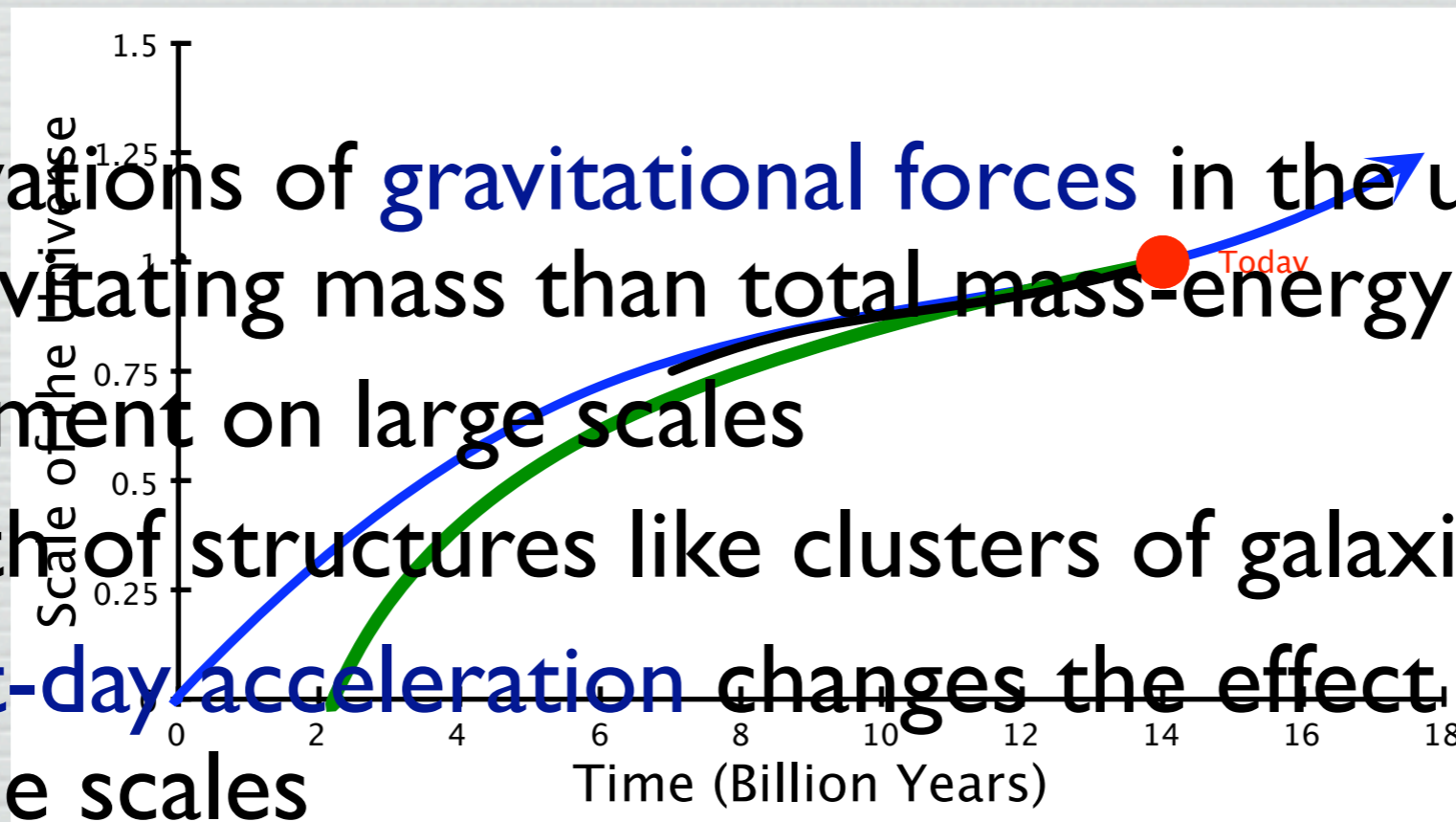
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# Evidence

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# What is the Dark Energy?

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1. **Just a number** that can appear in Einstein's General Relativity?
2. The “**energy of the vacuum**” which *should* appear in *any* theory which links GR with Quantum Mechanics?
  - this gives an explanation for (1) — but our calculations appear to be very, very, very wrong!
3. A quantity having to do with **peculiar** (but possible) **types of matter**?
  - Would still need to explain why 1 or 2 is zero.

# Why the controversy? The Cosmological Constant Problem

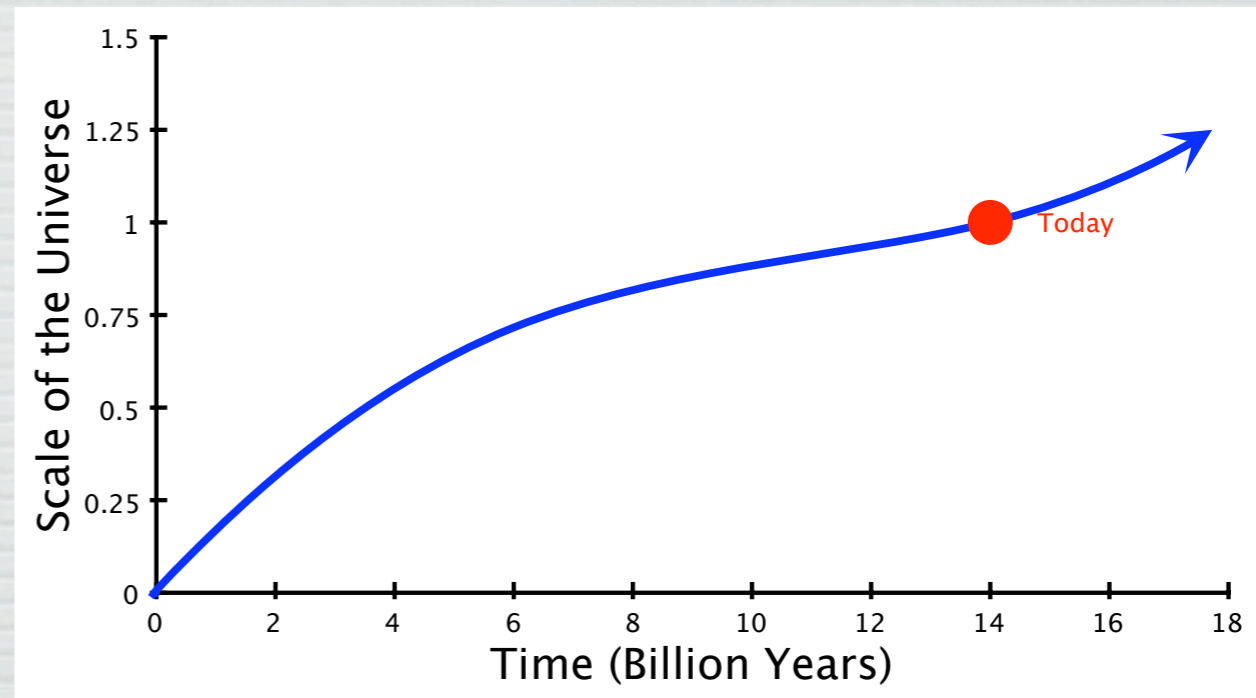
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- Observation:
  - dark energy density  
 $\Omega_\Lambda \approx 0.7$



# The Future of the Universe

- What happens now?



- **Continued acceleration?** Very **boring...** and very **lucky** that we live right now!
- Or something **more complicated?** Depends on the **nature of the Dark Energy** (1, 2 or 3?) — and of the Universe on scales vastly beyond our current observations!