So What?

Mystery of Dark Energy

- The actual value of the cosmological constant turns out to be relatively **small** (more later…) and **positive**. Based on $\frac{\ddot{a}}{a} = \frac{\Lambda c^3}{3}$ (when Λ dominates), this has profound implications for our existence:

    - If Λ were **much larger** than it is (anything remotely close to its predicted value…more later), the universe would have expanded so fast that galaxies, stars, or even atoms could not have formed ⇒ **no life**.

    - If Λ were much larger & **negative**, the universe would have collapsed too soon for life to have evolved ⇒ **no life**.

    - Λ is relatively "**fine tuned**" to allow for the existence of life. Thus, the **question of our existence** is intimately tied to why Λ has the value it does. **Where does it come from?**

Mystery of Dark Energy

- So, what is dark energy?

    - **It is dark:** Or invisible/transparent—we cannot see it. It doesn't appear to interact with matter or radiation (light) at all. (We can "see" **dark matter** by its gravitational interaction with visible matter; not so for **dark energy**.)

    - **It is smoothly distributed:** It does not fall into galaxies or clusters (gravitationally clump), or it would affect the dynamics of those objects (like dark matter does).

    - **It is persistent:** It's density appears to remain constant even as space expands. It **doesn't dilute** (get less dense) like ordinary and dark matter does, when space expands.

    - In short: Dark energy is **not matter**. Unlike matter, it appears to have no dynamics, and does not dilute as space expands. **It is something else.** Hence the name: *dark energy*.

- So, what is dark energy?
  - **Best guess:** Dark energy is "**vacuum energy**":
    - ✓ Observations indicate the dark energy is at least *approximately* uniform and persistent, but is *consistent* with being **perfectly** uniform and persistent
    - ✓ Assuming this is so, that's the definition of **vacuum energy**: an energy associated with space *itself*: space **empty of all matter,** i.e., **vacuum**.
    - ✓ But a vacuum energy means that *if we double the amount of space, we double the amount of vacuum energy*.

Mystery of Dark Energy

- So, what is dark energy?

  - **But wait!** Doesn't this violate *conservation of total energy*?

    - ✓ **Unknown**. Remember, Einstein's theory of space, time and gravity threw a "monkey wrench" into our understanding of "energy". We don't yet properly understand how to include **gravitational energy**, so we don't really know if **total** energy is conserved or not, especially on the cosmological scale.

    - ✓ Certainly, energy of matter **alone** (ignoring gravity) is **not** always conserved. **Example:** The number of CMB photons is fixed, but as space expands, they get stretched to lower-energy photons, so matter (light) energy is lost. **However**, the matter still obeys what's called the "**energy-momentum conservation**" equation (), which includes the effects of the expanding space in the "". Energy loss of photons is a **clear prediction of general relativity**, that has been verified.

- So, what is dark energy?

  - **But wait!** Doesn't this violate *conservation of total energy*?

    - ✓ It can be argued that the *decreasing CMB photon energy* is **no weirder** than the *increasing dark energy*. Both happen because, in general relativity, spacetime *itself* is **dynamical**, and participates in how things evolve over time. See the article by Sean Carroll.

    - ✓ On the other hand, physicists sometimes talk about changes in **negative gravitational energy** compensating for changes in **positive matter/radiation energy**, but this is not completely understood. Rough arguments are even made that the total **negative** gravitational energy in the universe plus the total **positive** matter/radiation energy add up to simply **zero**. If true, the total energy of the universe **is** conserved, and **adds up to exactly nothing**! (We'll come back to this…)

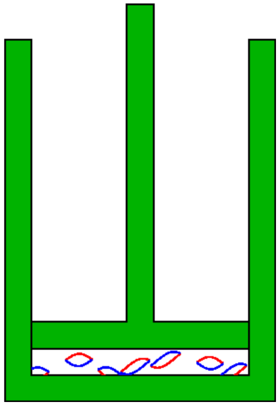
Mystery of Dark Energy

- So, what is dark energy?

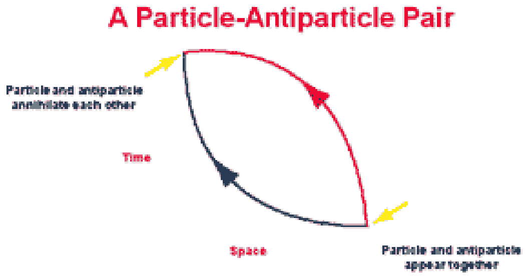
    - **But wait!** Doesn't this violate *conservation of total energy*?

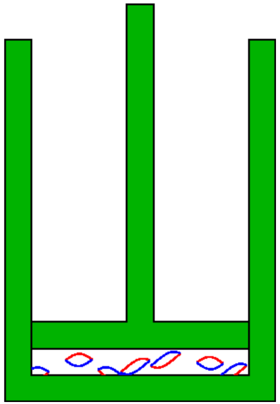
        - ✓ Imagine a cylinder filled with a gas at **negative pressure** (analogous to the negative pressure of dark energy). This will tend to pull in the piston. If we do work to pull it out, we **add positive energy** to the gas, like stretching an elastic band (analogous to more dark energy appearing as space expands).

        - ✓ So **increasing dark energy** & **negative dark pressure** work together to <u>make sense</u>. But what's pulling the piston out? Like , "just the math" of Einstein's theory, : *Negative* pressure drives *positive* accelerated expansion! It seems weird only because we don't have day-to-day experience with it.



- So, what is dark energy?
    - Vacuum energy? **How can empty space have energy?**
        - ✓ Before physicists discovered **quantum mechanics** (more later…) we would have said that the vacuum is *empty*.
        - ✓ But the quantum nature of the universe says that the vacuum is *teeming with activity* in the form of **spontaneous creation and annihilation** of "virtual particle-antiparticle pairs", called *quantum vacuum fluctuations*.
        - ✓ This does **NOT violate conservation of energy**; it just means the vacuum has energy that is greater than zero.





Mystery of Dark Energy

- So, what is dark energy?

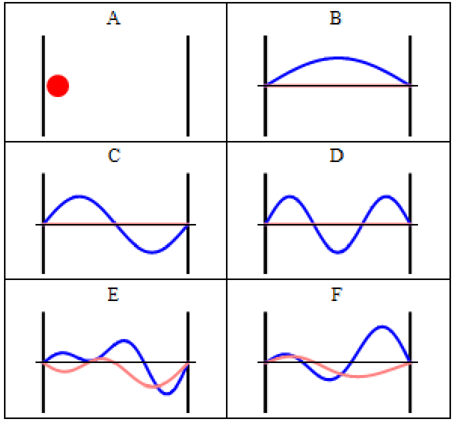
  - Vacuum energy? **How can empty space have energy?**

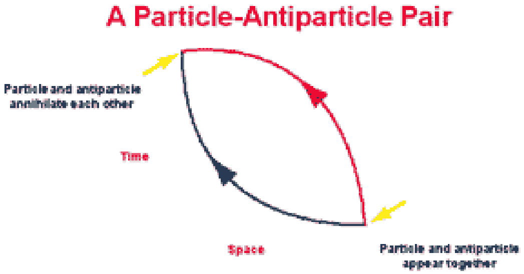
    ✓ **Example:** Particle in one-dimensional box of length L. A is the classical behaviour; B-F are examples of the particle behaving like a wave (quantum behaviour).

    ✓ **Heisenberg Uncertainty Principle** (quantum) says: and so:

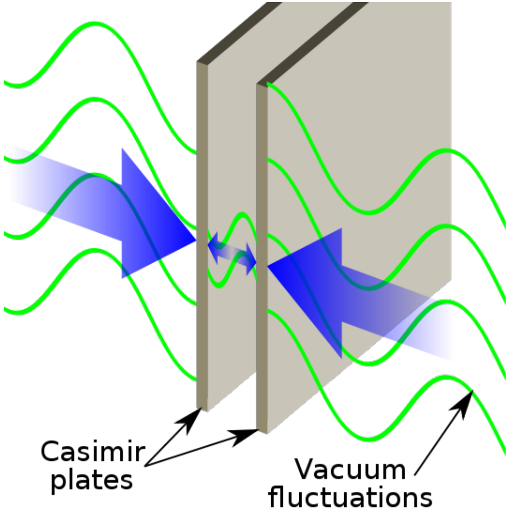
    ✓ The momentum of the particle is **uncertain**: it **cannot have a certain value**, e.g., zero. Thus, it **cannot have zero energy**. The lowest possible energy is > 0.

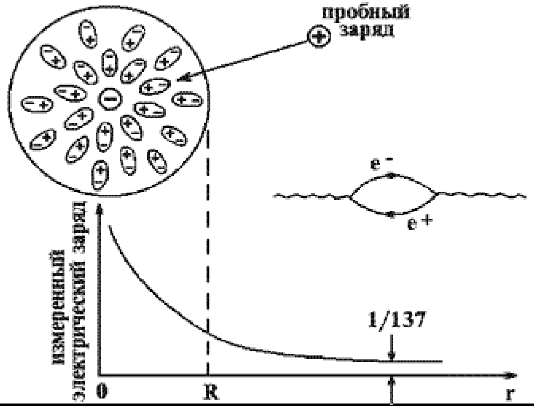
    ✓ Same is true for **fields**: spontaneous creation and an-nihilation of "virtual particle-antiparticle pairs"





- So, what is dark energy?
  - Vacuum energy? **How can empty space have energy?**
    - ✓ This weird consequence of the quantum nature of our universe can be **accurately observed in the lab**:
      - ➢ Casimir effect
      - ➢ Lamb shift
      - ➢ Anomalous magnetic dipole moment of the electron (most accurately predicted and experimentally confirmed quantity **ever**)
    - ✓ Also responsible for **Hawking radiation** (more later…)





- So, what is dark energy?
  - **Can such vacuum energy be the dark energy?**
    - ✓ The vacuum energy of quantum fields has **exactly the right form** to be the cosmological constant, or dark energy: it has contant > 0 and .
    - ✓ **Problem:** Physicists estimate .
      This is the **MOST WRONG** prediction in the history of science!
    - ✓ This is called the "**cosmological constant problem**": What is the origin of this discrepancy? Why is the cosmological constant so many orders of magnitude **smaller than we expect**? If it's that small, then why is it not just **zero**?

- So, what is dark energy?
  - **Can such vacuum energy be the dark energy?**
    - ✓ But is it ***really*** a problem?
    - ✓ Maybe is simply **not a valid prediction**. It accounts for **quantum** effects, but **ignores gravity**, and so should not be expected to have anything to do with the real world.

[is calculated assuming the virtual particles responsible for vacuum energy **do not gravitate** (curve spacetime). But , together with general relativity, tells us they **must**. Ignoring gravity, the vacuum energy can be made to be ***anything***; usually, it's made to be just **zero**…which then doesn't explain the observed Λ.]

Mystery of Dark Energy

- So, what is dark energy?

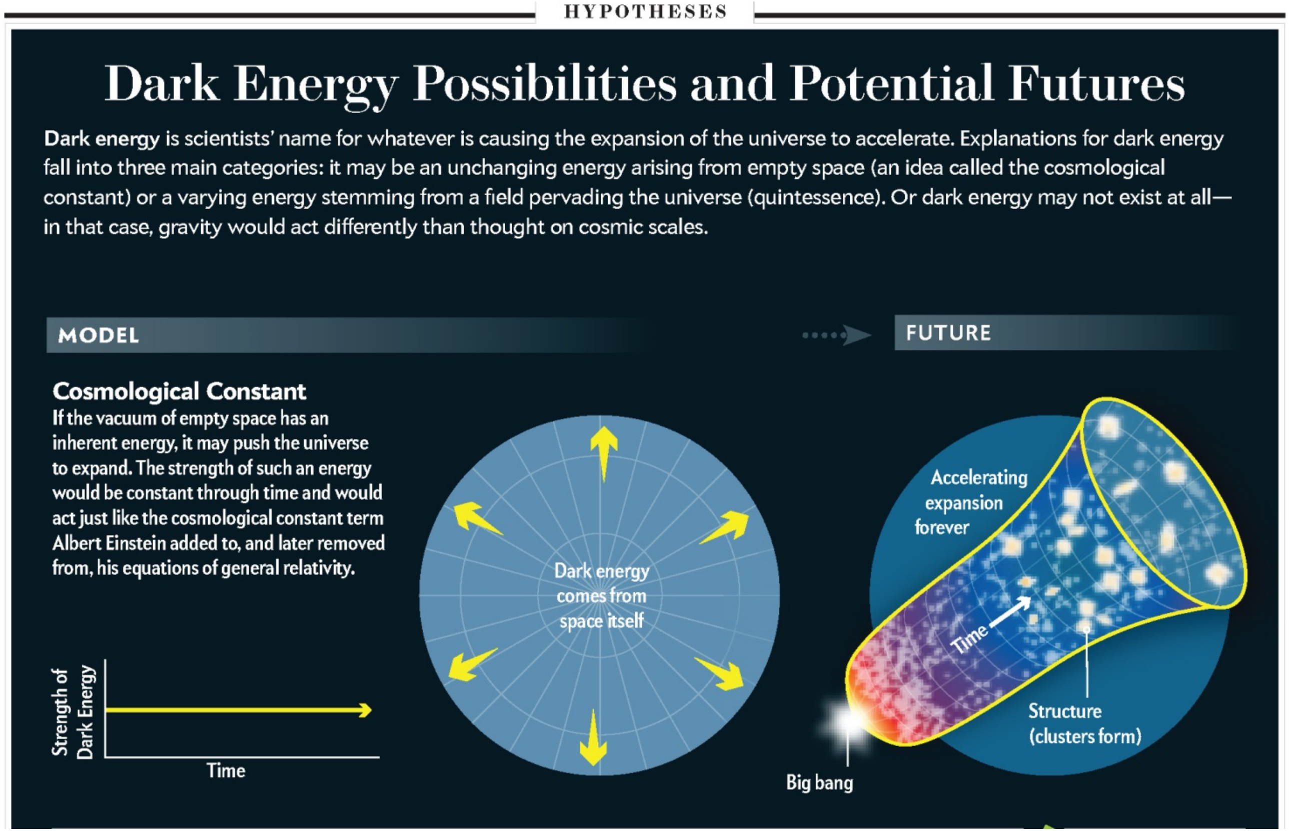
  - **Can such vacuum energy be the dark energy?**

    ✓ But is it ***really*** a problem?

    ✓ In order to get a **valid prediction**, we need a deeper understanding of the universe that properly incorporates *both* its **quantum** and **gravitational** nature. We need a **theory of quantum gravity**, or more generally, a "**theory of everything**".

    ✓ So: understanding the observed value of Λ, and thus **our existence**, is intimately linked to a **theory of everything** (more later…).

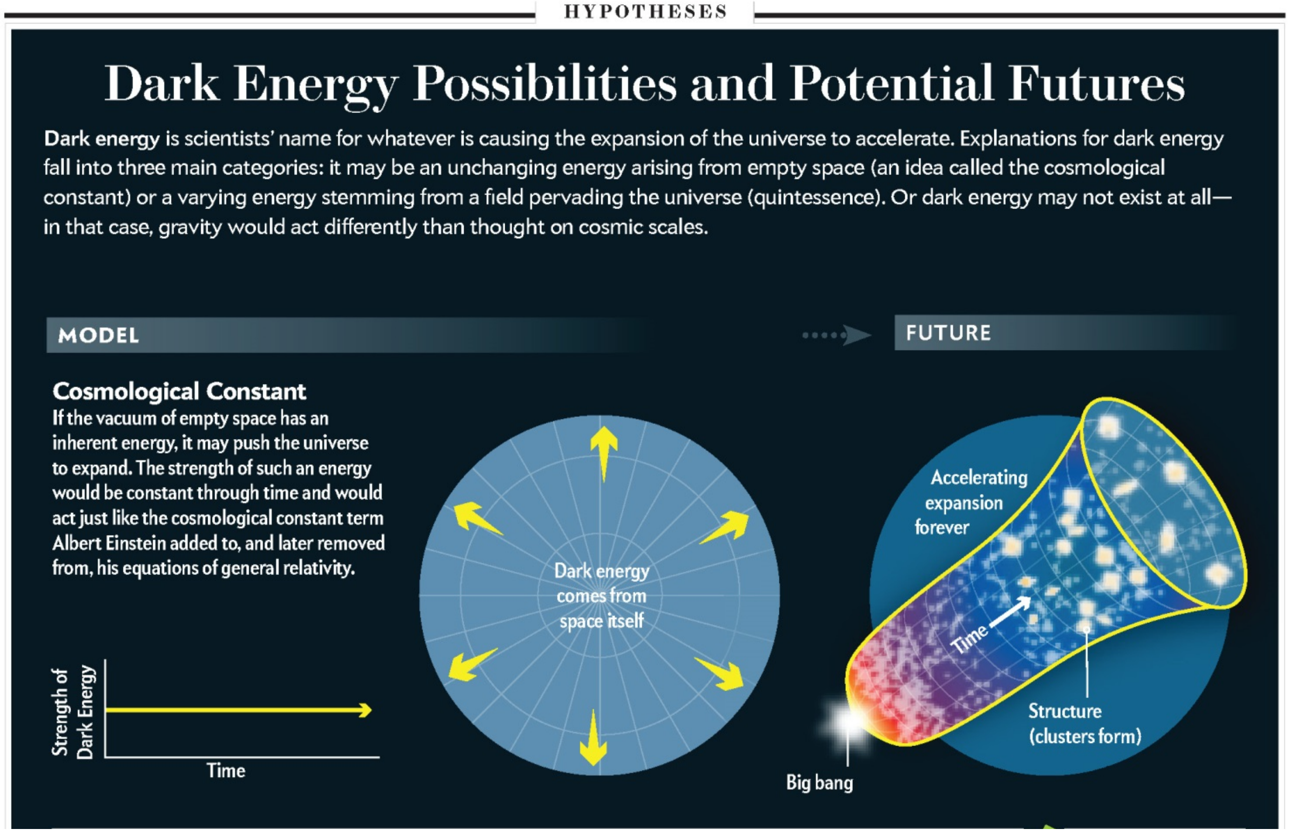
- So, what is dark energy?



Despite its uncertain origin, vacuum energy / cosmological constant is the **leading candidate** for what dark energy might be.

If so, the expansion of space will continue to accelerate; after a **trillion years**, our observable universe will contain essentially just the **Milky Way and Andromeda**; more distant galaxies will be "receding faster than ".

- So, what is dark energy?



Ultimate fate of the universe would be a "Big Freeze"—essentially "**heat death**":

In 1-100 trillion years, **gas to fuel stars** will be exhausted → universe will grow dark.

Most matter will coalesce into BHs (by 10^{40} years), which will **evaporate** in Hawking radiation (by 10^{100} years) → **redshift** to zero.

(More complicated than this...research on your own.)

Mystery of Dark Energy

- So, what is dark energy?

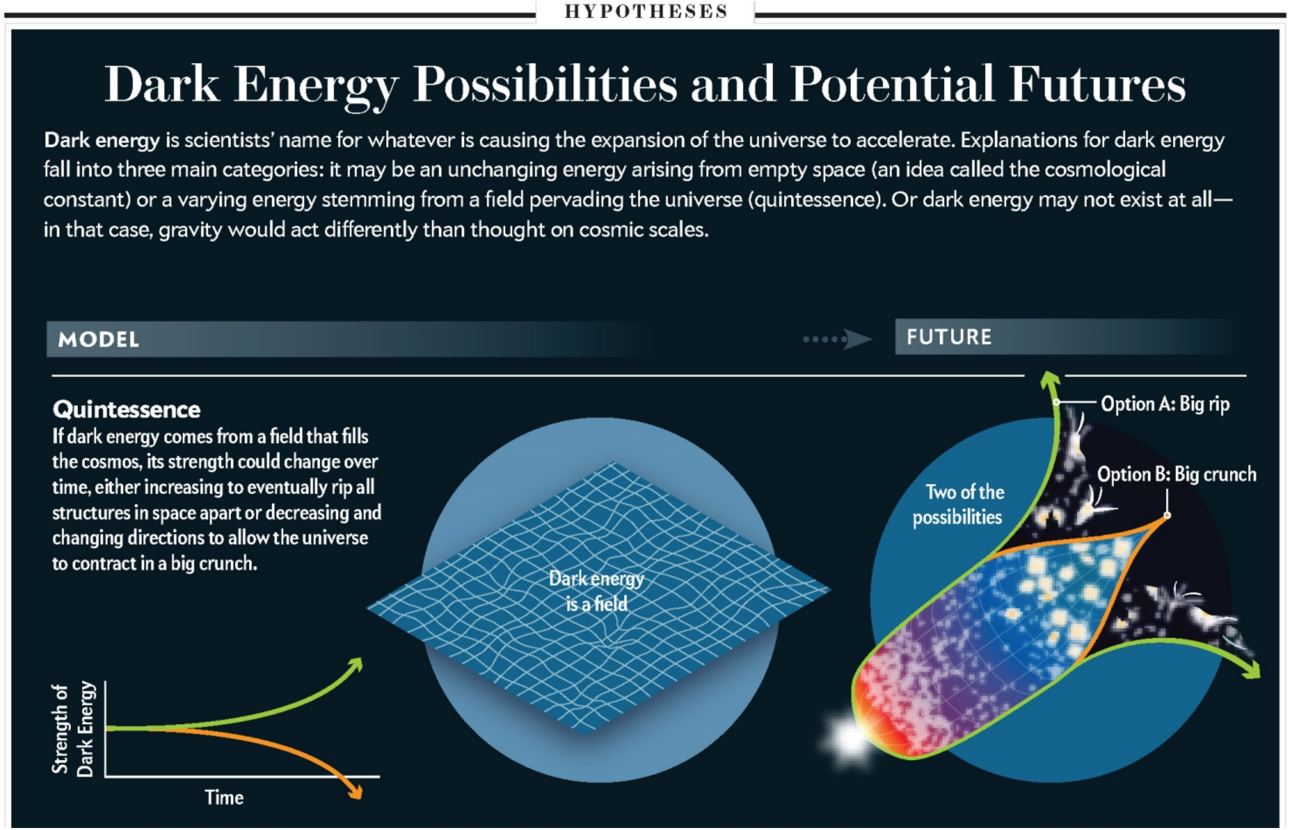
  - Another possible answer: **Dark Energy = Quintessence**

    - ✓ Maybe dark energy is a **dynamical field**, like the electromagnetic field, except **unlike** the electromagnetic field, it does **not** arise from localized sources, and pervades all of space **uniformly** (or almost uniformly).

    - ✓ Named after the **fifth classical element** (beyond earth, fire, water, and air). It was believed to fill all space in the “heavens”; what the gods breathed.

    - ✓ “**Dynamical**” means it can **change with time**, thus changing the rate at which the expansion of space is accelerating. Its strength could change over cosmic time, both into the past and into the future. However, any hypothesized dynamics of such a quintessence field is **purely speculative** at this stage.

- So, what is dark energy?



If dark energy is quintessence the fate of the universe depends on its (unknown) dynamics.

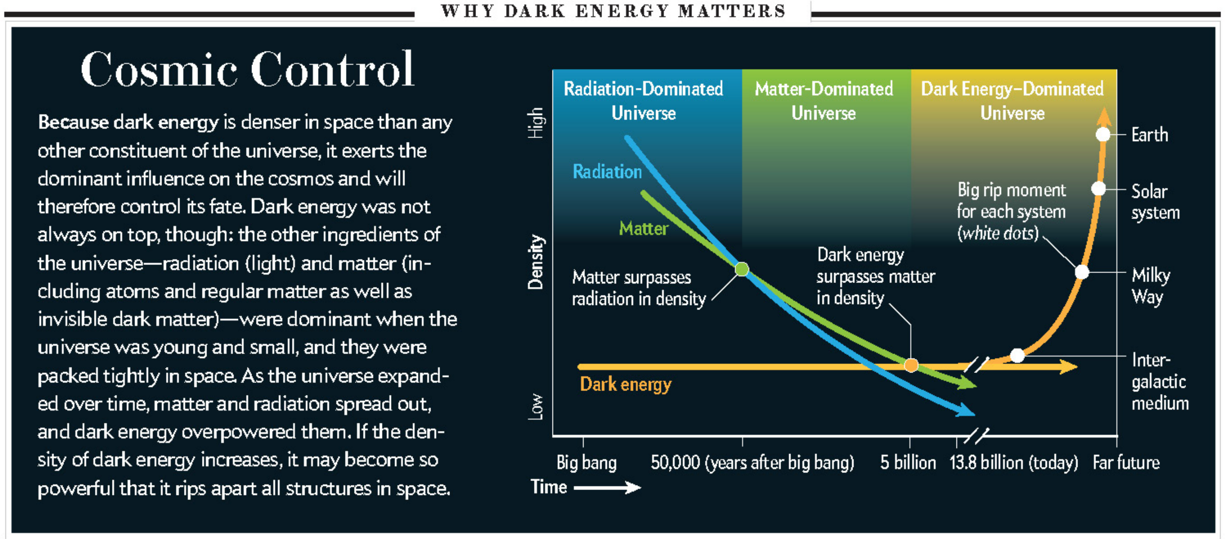
If its strength **decreases** and eventually changes direction → "Big Crunch".

If its strength **increases** enough → "Big Rip".

So the nature of dark energy (cosmological constant or quintessence) is important because it **controls the ultimate fate of the universe.**

The universe was originally dominated by **radiation** (light), then later **matter** (dark & ordinary), and now **dark energy**. The first two **dilute as space expands** (radiation started bigger, but **dilutes faster** than matter); presently, the (at least roughly constant) **dark energy** is left to **dominate**.

If dark energy is **quintessence**, in the “**Big Rip**” scenario, the accelerated expansion of space can be so large that it rips apart first galaxy clusters, then galaxies, then solar systems, then planets, people, atoms, atomic nuclei, etc… (!)



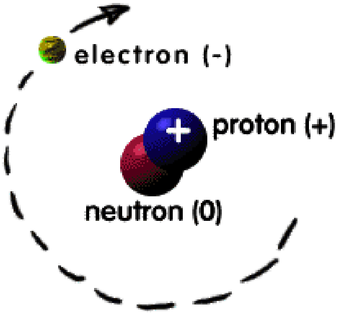
Mystery of Dark Energy

How?

Imagine electron and proton **at rest**, and **turn off** electrostatic attraction. A small, **constant** (accelerated expansion of space) would cause the space between them to expand, faster and faster. Like galaxies, they are **not accelerating**, and there is **no force** between them, but they are accelerating ***relative*** to each other, ***as if*** they are experiencing a very weak "repulsive force".

Now turn on the electrostatic attraction, and add to it this very weak ***effective*** "repulsive force". **Net** effect is a **slightly weaker** attractive force, and hence a **slightly larger** atom (if you put in the numbers, larger by 1 part in)

A small, ***constant*** Λ produces a small, ***constant*** increase in the size of atoms.
Atoms (and people) are **NOT** getting bigger and bigger as space expands!

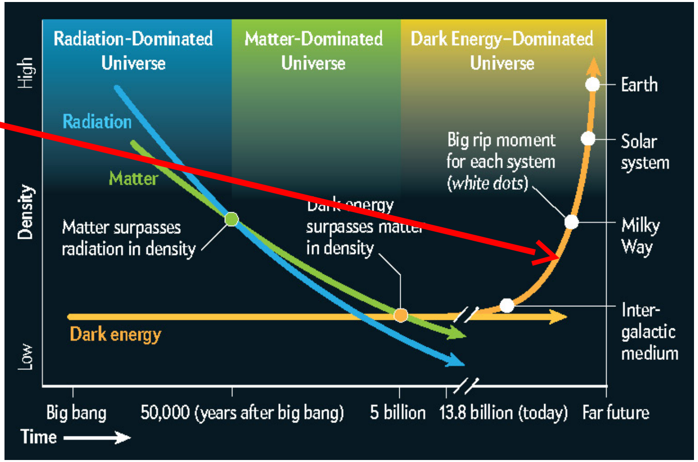


Challenge for physics students: If r_0 is the Bohr radius, then a small, constant Λ will increase r_0 to $(1+\epsilon)r_0$, where ($\lambda = \frac{\hbar}{mc}$ = Compton wavelength):

$$\frac{\epsilon}{r_0} = \frac{1}{3}\frac{\Lambda}{\lambda^2/{r_0}^4} \sim 10^{-68}$$

How?

However, if Λ were to ***increase*** with time (not constant), by ***many orders of magnitude*** (Big Rip scenario), then yes, atoms and people would get bigger with time. First galaxy clusters, then galaxies, then solar systems, then planets, people, atoms, atomic nuclei, etc., would get **ripped to shreds**, everywhere, simultaneously.



A small, ***constant*** produces a small, ***constant*** increase in the size of atoms.

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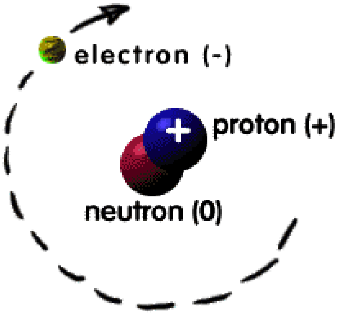
Challenge for physics students: If is the Bohr radius, then a small, constant will increase to , where (Compton wavelength):

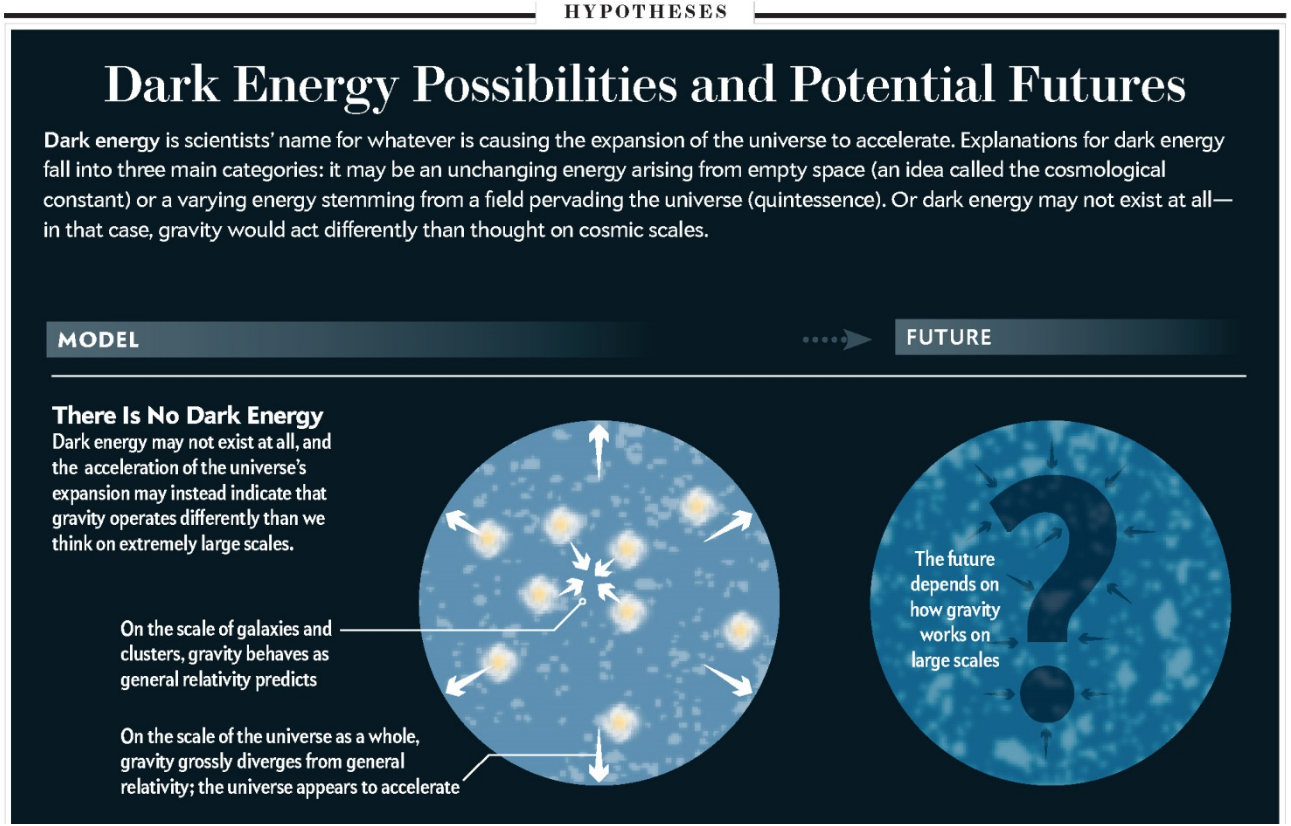


Mystery of Dark Energy

- So, what is dark energy?
  - Another possible answer: **There is no dark energy; it's just gravity**
    - ✓ The expansion of space is **certainly accelerating**: getting faster and faster. Two **completely independent** lines of evidence point to the same thing: Type 1a supernovae measurements, discussed earlier, and rate of galaxy clustering.
    - ✓ But just as there may be no **dark matter**—the observations might instead be explained by a **modified theory of gravity**, maybe there is no **dark energy**—the observed accelerated expansion might instead be explained by modifying our understanding of gravity on the scale of galaxy clusters and larger.
    - ✓ While possible, and currently an active area of research, this is **not** the currently favoured hypothesis.

Mystery of Dark Energy

- So, what is dark energy?



If there is no dark energy, and it's just gravity behaving in an unexpected way at very large scales, then the fate of the universe is **completely unknown**.

"All bets are off," until we discover this new, deeper theory of gravity…

Mystery of Dark Energy

- So, what is dark energy?

  - **No one knows**, but very active research continues.

  - **Main question:** Is the dark energy density really **constant**, or has it **changed** over cosmic time?

  - **New projects** (research on your own):
    - ✓ Dark Energy Survey (DES), begun in 2013
    - ✓ Large Synoptic Survey Telescope (2021?)
    - ✓ Wide-Field Infrared Survey Telescope (mid 2020s?)
    - ✓ ESA's Euclid space mission (2020?)
    - ✓ Etc…

- Dark energy is a **major unsolved mystery** of **huge importance** in the **"bigger picture"**…