Particle physics and the origins of the universe

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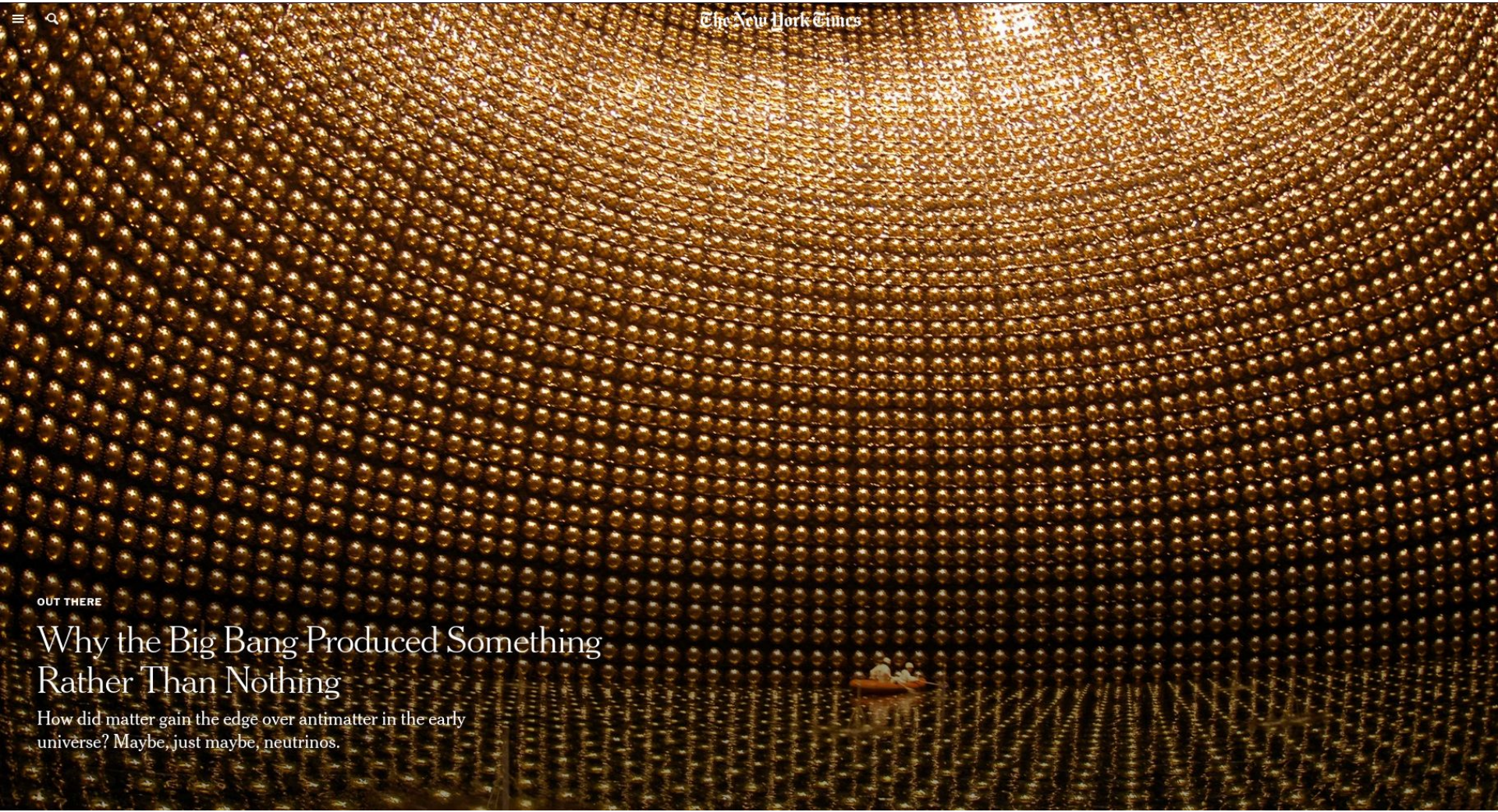
Why is there something rather than nothing?

Spoiler:
Physics/science does not have a satisfying answer



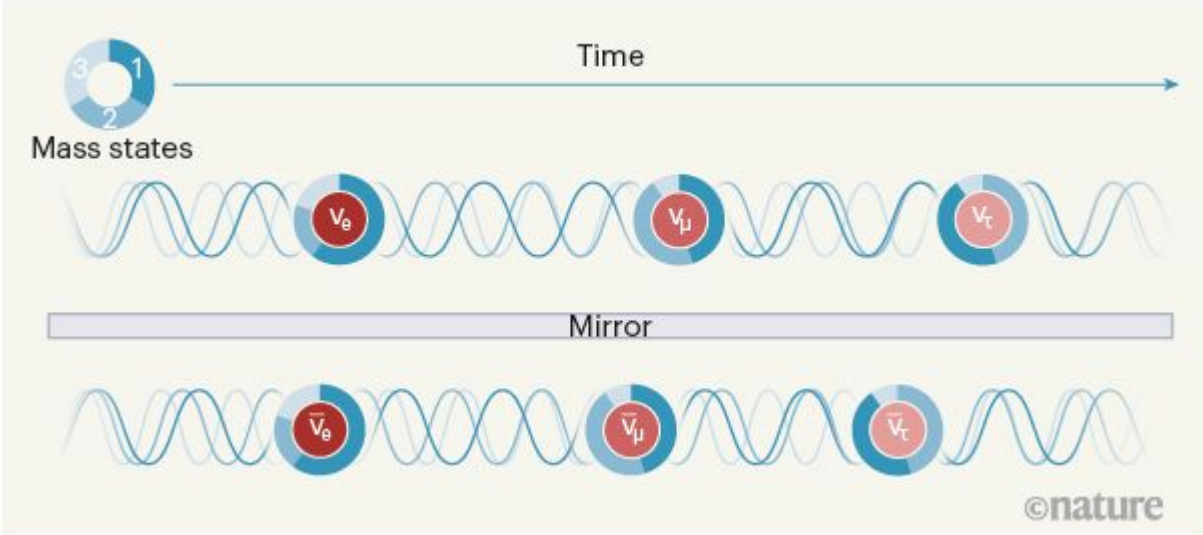
OUT THERE

Why the Big Bang Produced Something Rather Than Nothing

How did matter gain the edge over antimatter in the early universe? Maybe, just maybe, neutrinos.

Matter–antimatter symmetry violated

In a mirror world, antiparticles should behave in the same way as particles. But it emerges that leptons — neutrinos, electrons and their more exotic cousins — might not obey this expected pattern.



OK first, what do we mean by “matter”

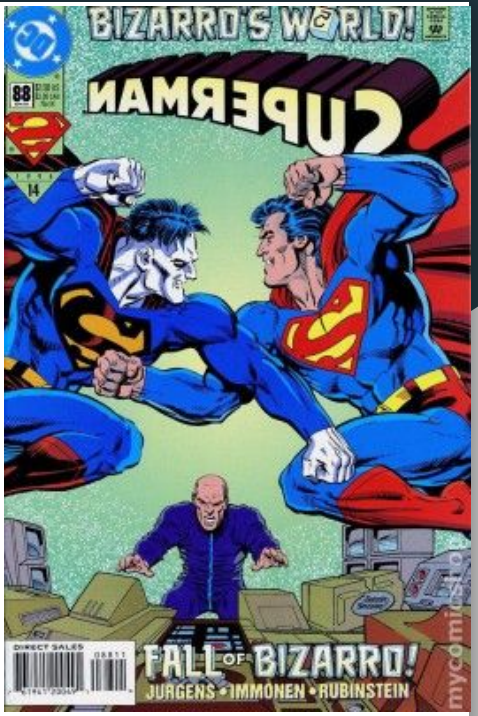
- Matter means stuff, buildings, air, people, the Earth, stars and planets
- Matter means things made of atoms, as well as subatomic particles

Is *light* matter? Is *energy*? *Heat*?

- Debatable
- They're all *real*: measurable, part of our lives, valuable
- But would you be satisfied if the only thing in the universe were light, heat and energy?

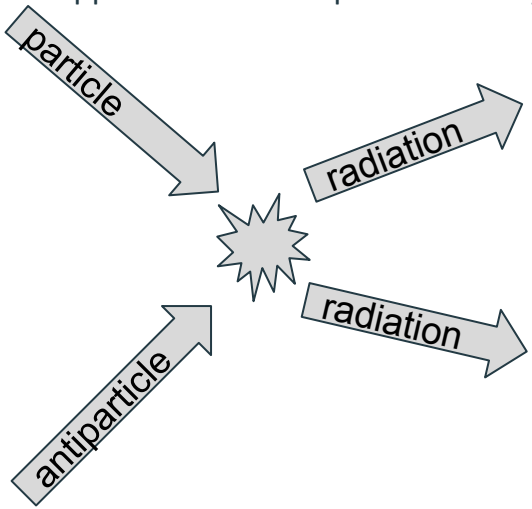
What is antimatter?

- Every type of matter particle has a partner antimatter particle
  - Sort of like Bizarro World in Superman
- We can have anti-atoms and anti-molecules
- Antimatter feels gravity the same way we do (attractive) but feels the opposite electric force compared to matter
- Most scientists treat antimatter as “equal and opposite” to matter
- BUT
- There are also some very slight differences in how matter and antimatter particles are produced and how they decay
- This talk is about those differences



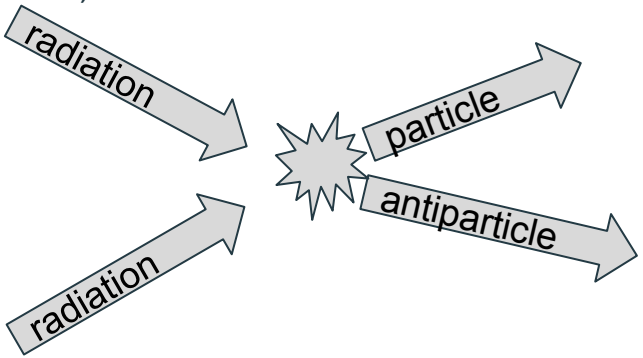
What happens when matter and antimatter meet?

- Annihilation
- Both particles disappear and in their place is usually some form of radiation like gamma rays



How do you make antimatter?

- “Pair production”
- Particle-antiparticle pairs can be created out of high-energy gamma rays
- Or by colliding pretty much any 2 particles together with high energy
- Pair production is the opposite of annihilation
- Fun fact: lightning is powerful enough to create antimatter, and there is a satellite that has detected antimatter produced by lightning



Why is our universe made mostly of matter instead of a balance of matter and antimatter?

A (simplified) history of the universe

In the beginning…

- Everything was really hot and packed close together
- (Very hot: 1,000,000,000,000,000,000,000,000,000 or so degrees)
- Luckily, this period only lasted 0.00000000000000000000000000000001 seconds

These numbers are more commonly written 10^{27} degrees and 10^{-32} seconds

Inflation

- All of a sudden, a powerful force starts applying an outward pressure everywhere in space all at once
  - Kind of like yeast causing bread dough to rise
  - We don't know what force or where it came from or why it decided to start pushing
- All the particles in the universe suddenly had a bunch more room to move around in: everything else was very far away
- How much farther?
- 100,000,000,000,000,000,000,000,000 times farther apart, over the course of a tiny fraction of a second
- So most of the universe is now empty space. But only for an instant

That's 10^{26} times farther

Reheating

- Then inflation stops - the force turns off
- All the energy that was causing inflation is released as heat
- In the form of gamma rays but also all sorts of other radiation particles
- Sort of like a hot plasma of vaporized matter and antimatter

Extra matter is created…somehow…

- This is where those small differences between matter and antimatter come in
- We can add up all the differences in behavior that we know about
- But it’s not enough to create the imbalance that we see today
- Mystery!

Annihilation

- As long as the temperature is hot enough, the rates of pair production and annihilation will balance out
- As the universe continues slowly expanding, it cools and the particles lose energy
- Eventually, there's no longer enough energy for pair production
    - Or for any of the exotic processes that can change the balance between matter and antimatter
- So pretty quickly, all available antimatter finds a matter partner to annihilate with
- And we're left with a bunch more radiation from the annihilations, plus the leftover matter

Atoms form

- The universe is still very hot - hotter than the inside of the sun - and gradually expanding
- The subatomic particles are moving around too fast to bind together and form atoms and molecules
- As the universe expands, things get more space to move around and become less frenetic - they literally cool down
- Eventually, after about 380,000 years, atoms can form without being smashed to pieces by passing radiation

Stars & galaxies form

- The same thing that happened with atoms also happens with stars & galaxies, but on a larger scale
- (more or less)
- The first stars formed around 400,000,000 years after the first atoms formed
- A long time passes where stars and galaxies are happily doing their thing
- The universe is still slowly expanding

Modern universe: accelerated expansion

- After about 9 billion years (9,000,000,000), something interesting happens
- The expansion starts to speed up (accelerate)
- We don’t know a lot about what is causing the expansion to speed up so we call it “dark energy”
- We are currently in this phase of the universe’s life, and we have been for about 5 billion years
- The universe today is about 14 billion years old

Questions & problems

- What caused inflation and why did it stop?
- What is dark energy?
- **What reactions could account for the matter-antimatter imbalance?**

On the culture of physics

- We like being able to explain things as simply as possible
- When antimatter was first discovered, everyone assumed it behaved exactly the same as matter
- That makes things easy to calculate!
- If there is any difference, then we have to start including the difference in our calculations
- And it spoils the simple picture
- So you might hear me describing how people hoped for balance
- Even though we now know that we *need* an imbalance

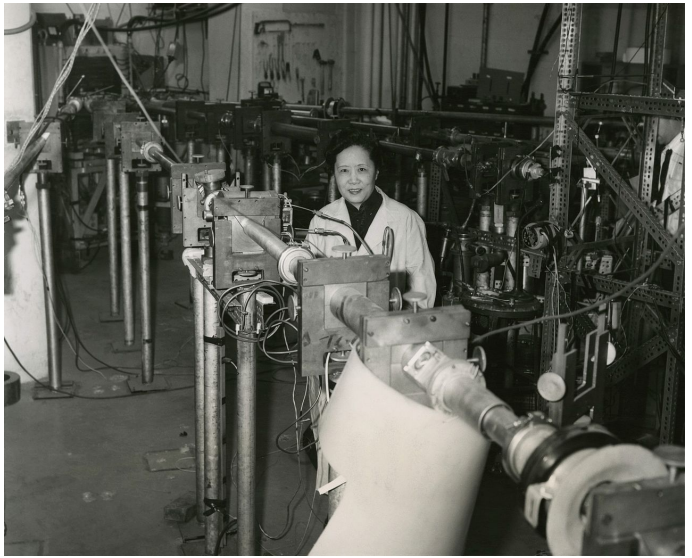
For a while, physicists were stumped

- From the discovery of antimatter until the 1950s, everyone assumed that antimatter would behave exactly the same as matter
- And that matter and antimatter had to be produced in pairs
- So no imbalance was possible

- I already spoiled this — matter and antimatter behave differently sometimes!

The first sign of an imbalance

- Discovered in 1956 by C.S. Wu, a Chinese immigrant who studied at Berkeley and Caltech and was a professor at Columbia
- She was skipped over for the Nobel Prize, which was instead awarded to 2 of her (male) colleagues also involved in the project
- Let’s just take a minute to appreciate her discovery in the context of the current national climate



Introducing the neutrino

- The particle that breaks and/or solves everything
- Neutrinos are subatomic particles that are extremely light - trillions of times lighter than an atom
- They also don’t feel the electric force (they’re neutral and small, hence the name)
- Often described as “the ghost particle” because they fly through walls without leaving a trace
- There are 3 flavors (types) of neutrinos: electron, muon, and tau
- And 3 corresponding flavors of antineutrinos

Neutrinos have spin

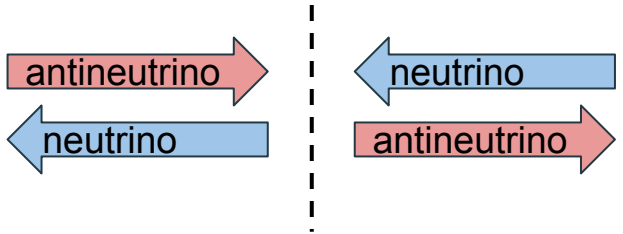
- Like most particles, neutrinos have a property called spin
- The spin of a neutrino can be only in 2 possible directions
- Either forwards (in the direction of motion) or backwards
- A neutrino with “forward” spin is called right-handed
- A neutrino with “backward” spin is called left-handed
- We can measure spin by looking at the direction particles bounce off each other
    - Like how a tennis ball’s spin affects how it bounces off the court surface

So what did C.S. Wu discover?

- Turns out, our universe only contains left-handed neutrinos and right-handed antineutrinos
- This was a huge deal!
- The first sign that the universe doesn’t treat matter and antimatter exactly the same

Physicists tried to come up with a workaround

- Maybe it’s not that matter behaves the same as antimatter
- Maybe instead, left-handed matter behaves the same as right-handed antimatter!
- So you have to swap matter and antimatter, then watch through a mirror



This is called CP symmetry

- If left-handed neutrinos are magically swapped with right-handed antineutrinos, then we would still end up with only the “allowed” types of neutrinos
- So maybe neutrinos obey CP symmetry!

If CP symmetry is obeyed, then we still are forced into a balance

- For every left-handed particle, we would also get a right-handed antiparticle
- So there’s still the same number of particles as antiparticles

The jury is still out on neutrinos and CP

- Maybe left-handed neutrinos behave differently from right-handed antineutrinos
- If neutrinos violate CP symmetry, then they could help contribute to the matter imbalance in the universe!

Wait, do we like CP symmetry or do we want it to be broken?

It depends

- Neutrino CP violation is one of the few plausible ways to generate the matter imbalance in the early universe
- If neutrinos obey CP, that would mean the universe follows a certain pattern, which is convenient and elegant

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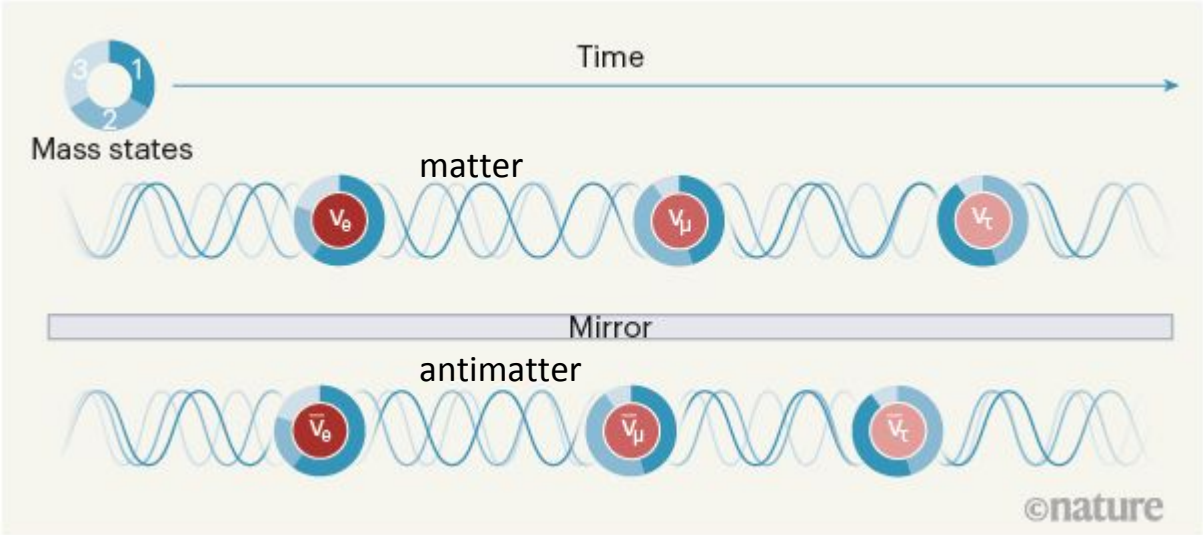

What does all this mean?

- The universe was created in a balanced state
- But the laws of physics favor matter over antimatter
  - VERY SLIGHTLY
- Not enough to create the imbalance we observe
- We need to find more reactions that increase the imbalance
- Neutrinos are a very promising avenue for investigation!

Topics for discussion

- Matter vs. antimatter
- The beginning of the universe / initial conditions
- Inflation
- Symmetry in the laws of physics
- The culture of physics / science
- How physicists study the early universe

See you next week for Yaron’s introduction to Kabbalah!