Beyond Our Five Senses

How we know about the subatomic universe

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Ask-a-Scientist

6 December 2015

Let's talk about coffee.

The USA bought $\sim$23.76 million 60 kg bags of coffee in 2014[1].

23.76 Mbags $\times$ 60 kg/bag $\times$ 0.87 (roasting loss) $\times$ 100 cups/kg

$\approx$ 100 billion cups of coffee!

$\approx$ 1 cup per person in USA per day.

whattoexpect.com

[1] International Coffee Assoc., http://www.ico.org/monthly_coffee_trade_stats.asp

Is coffee healthy?

Let's look at some clinical studies on coffee.

1985, Johns Hopkins	$\geq$5 cups daily linked to heart disease. (Coffee bad.)
2012, NEJM	Statistical link between increased coffee consumption and decreased mortality rates. (Coffee good!)
2013, Mayo Clinic	Positive correlation between coffee consumption and increasing mortality rates. (Coffee bad.)
2014, Ann. Int. Med.	"Regular coffee consumption was not associated with an increased mortality rate. . . The possibility of a modest benefit of coffee consumption on all-cause and CVD mortality needs to be further investigated." (Coffee good?)

Coffee vs. neutrinos

Coffee

- Coffee is everywhere, all the time.
- You experience coffe through your senses:
  - Smells
  - Tastes
  - Sights
  - Warm mugs
  - Burnt tongues. . .
- It looks like we *still* don't know some pretty basic things about it.

Neutrinos

- Neutrinos are *literally everywhere, all the time.*
- They *do not* affect our senses!

MINERνA Beamline (Active!)

- How can we "know" about neutrinos?

We think of our senses as defining reality.

How to square this:

"Seeing is believing."

With this:

- You are awash in particles called neutrinos.
- More than ten trillion neutrinos pass through your body every single second.
- They're invisible and they *almost* never interact with normal matter. (Picture a block of lead. . .)

Ten trillion neutrinos pass through your body every second?!

How big is ten trillion?

- Ten trillion raindrops would fill 10-20 Olympic-sized swimming pools.
- Ten trillion grains of sand would cover a football field to a depth of $\sim$6 inches.
- I am making a HUGE claim about invisible, un-sense-able stuff.
- How are you supposed to believe me?

Our senses are lovely and vital but they are not the whole story.

Beyond our senses: the Ancient Greeks knew a thing or two about this.

Raphael's *School of Athens*, 1509-1511.

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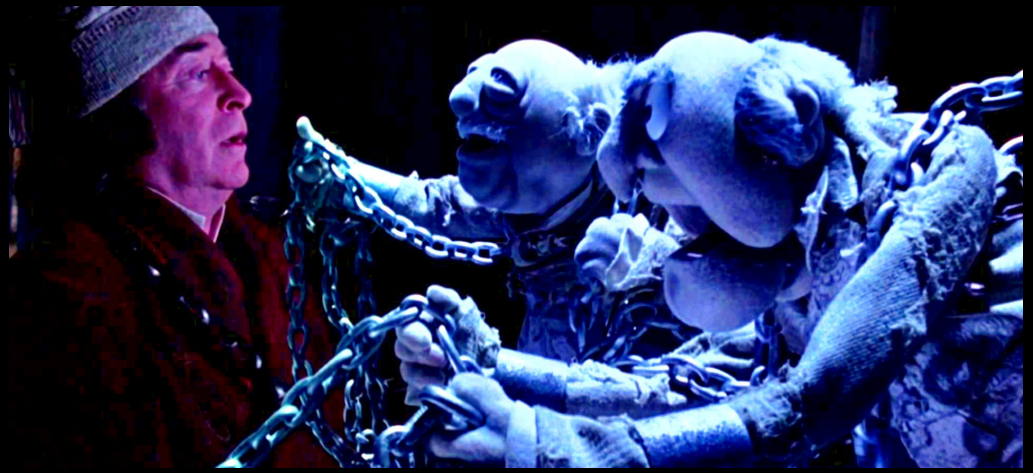
Raphael's *School of Athens*, 1509-1511.

Here's some 2500-year-old wisdom for you.

- You may say that figs taste sweet.
- What if you eat honey right before you eat figs? Do they still taste sweet?
- How reliable are your senses in giving you **truth** about the taste of figs?

http://www.mytravelingjoys.com/2013/09/roasted-turkish-figs-with-polish-honey.html

Charles Dickens will back me up.

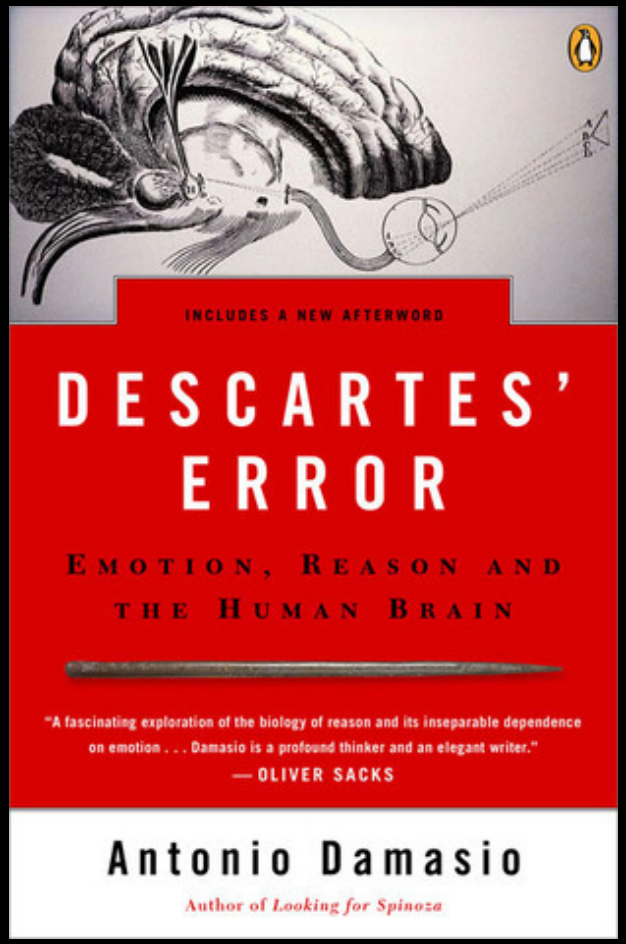


"You don't believe in me," observed the Ghost.
"I don't," said Scrooge.
"What evidence would you have of my reality beyond that of your senses?"
"I don't know," said Scrooge.
"Why do you doubt your senses?"
"Because," said Scrooge, "a little thing affects them. A slight disorder of the stomach makes them cheats. You may be an undigested bit of beef, a blot of mustard, a crumb of cheese, a fragment of an underdone potato. There's more of gravy than of grave about you, whatever you are!"

–Charles Dickens, *A Christmas Carol*, 1843

Have you ever gotten “hangry”?

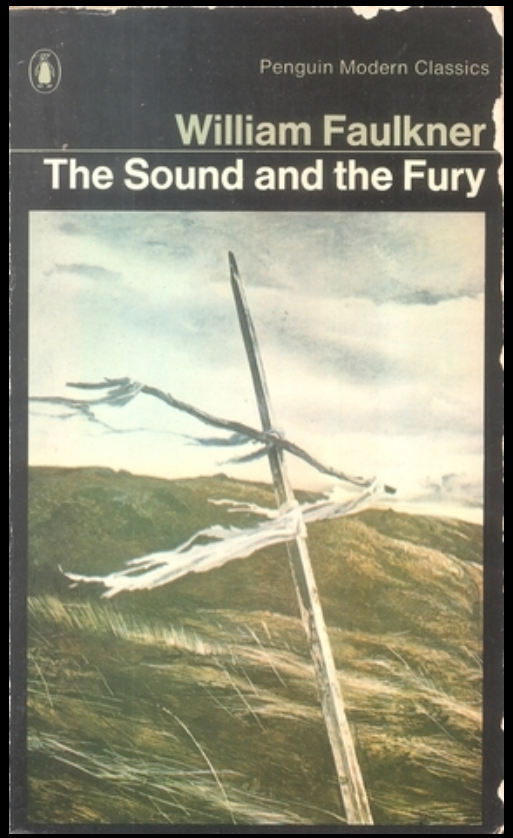
Human perception has a strong emotional component.



A. Damasio, *Descartes' Error: Emotion, Reason and the Human Brain*, 1994.

- Neuroscientist describes patients who have little or nonstandard emotional ability.
- "When would be a good time for our next appointment?" followed by 30 minutes of dispassionate deliberation.
- *The somatic-marker hypothesis* is well-regarded in neuroscience.

Cold objectivity is not our strong suit, anyway.



See also: unreliability of eyewitness testimony in jury trials.

http://www.scientificamerican.com/article/do-the-eyes-have-it/

We have developed a very powerful tool for overcoming the limitations of our subjective experiences.

We have developed a very powerful tool for overcoming the limitations of our subjective experiences.

That tool is called “science”.

First, we'll talk about measuring something familiar and macroscopic. Then, we'll talk about how you can measure something like a subatomic particle.

Measuring something macroscopic: How tall is Daniel?

- Before this talk, I asked some of you how tall I was.
- Two methods: Guesses and measurements.
- We'll use this as a springboard for talking about truth and measurement.

Observation is great, but measurement gives you *certainty*.

http://cheezburger.com/5971932416

Some measurements are better than others. Science gives us a way to measure our measurements, so to speak.

How certain are you that your measurements are correct?

$$\text{standard deviation } \sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

- Let's say you have N measurements.
- The *mean (average) value* is your best estimate of the "real" value.

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i.$$

- $x_i - \bar{x}$: How far away is the measurement x_i from $\bar{x}$?
- $(x_i - \bar{x})^2$: We care about absolute distance from the mean. $x_i - \bar{x}$ might be negative...
- Then take the square root so scale, units balance out.

Some of you estimated my height and some of you measured.

Estimation

i	x_i
0	6’0"
1	6’0"
2	5’7"
3	5’11"
4	5’10"
5	5’10"
6	6’0"
7	0’70"
8	6’0"
9	5’10"

Daniel is 5’10"$\pm$1.50" tall.

Measurement

i	x_i
0	0’71"
1	5’11"
2	0’71"
3	6’0"
4	0’70"

Daniel is 5’11"$\pm$0.63" tall.

Daniels are easy to measure. What about neutrinos?

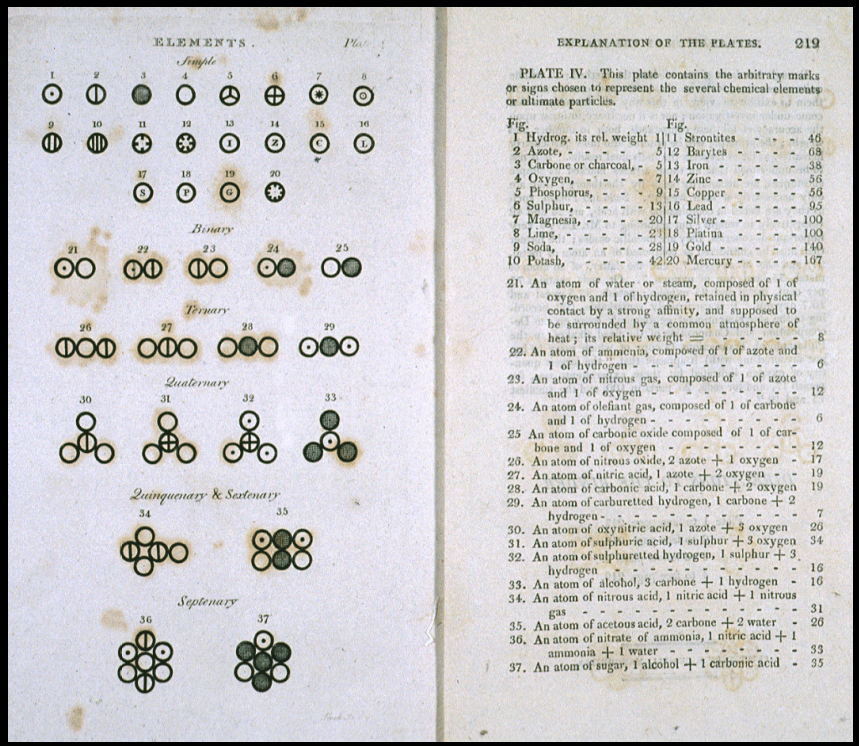
1. Why *should* there be neutrinos? Why did we start looking for them in the first place?
2. How do you detect neutrinos?
3. Why should we care?

We'll build up our argument for neutrinos one piece at a time.

1. Subatomic particles exist.
2. The conservation of energy is a thing.
3. 1930: Some curious observations.
4. Neutrinos exist.

Step 1: Subatomic particles exist.

John Dalton and Amedeo Avogadro did a lot between 1808 and 1811 to bring atomic theory into the scientific mainstream.



ELEMENTS.

Simple

Binary

Ternary

Quaternary

Quinquenary & Sextenary

Septenary

EXPLANATION OF THE PLATES. 219

PLATE IV. This plate contains the arbitrary marks or signs chosen to represent the several chemical elements or ultimate particles.

Fig.		Fig.		
1	Hydrog. its rel. weight	1	11 Strontites	46
2	Azote,	5	12 Barytes	68
3	Carbone or charcoal,	5	13 Iron	38
4	Oxygen,	7	14 Zinc	56
5	Phosphorus,	9	15 Copper	56
6	Sulphur,	13	16 Lead	95
7	Magnesia,	20	17 Silver	100
8	Lime,	23	18 Platina	100
9	Soda,	28	19 Gold	140
10	Potash,	42	20 Mercury	167

21. An atom of water or steam, composed of 1 of oxygen and 1 of hydrogen, retained in physical contact by a strong affinity, and supposed to be surrounded by a common atmosphere of heat; its relative weight = 8
22. An atom of ammonia, composed of 1 of azote and 1 of hydrogen 6
23. An atom of nitrous gas, composed of 1 of azote and 1 of oxygen 12
24. An atom of olefiant gas, composed of 1 of carbone and 1 of hydrogen 6
25. An atom of carbonic oxide composed of 1 of carbone and 1 of oxygen 12
26. An atom of nitrous oxide, 2 azote + 1 oxygen 17
27. An atom of nitric acid, 1 azote + 2 oxygen 19
28. An atom of carbonic acid, 1 carbone + 2 oxygen 19
29. An atom of carburetted hydrogen, 1 carbone + 2 hydrogen 7
30. An atom of oxynitric acid, 1 azote + 3 oxygen 26
31. An atom of sulphuric acid, 1 sulphur + 3 oxygen 34
32. An atom of sulphuretted hydrogen, 1 sulphur + 3 hydrogen 16
33. An atom of alcohol, 3 carbone + 1 hydrogen 16
34. An atom of nitrous acid, 1 nitric acid + 1 nitrous gas 31
35. An atom of acetous acid, 2 carbone + 2 water 26
36. An atom of nitrate of ammonia, 1 nitric acid + 1 ammonia + 1 water 33
37. An atom of sugar, 1 alcohol + 1 carbonic acid 35

A page from Dalton's *A New System of Chemical Philosophy*
https://en.wikipedia.org/wiki/File:Daltons_symbols.gif

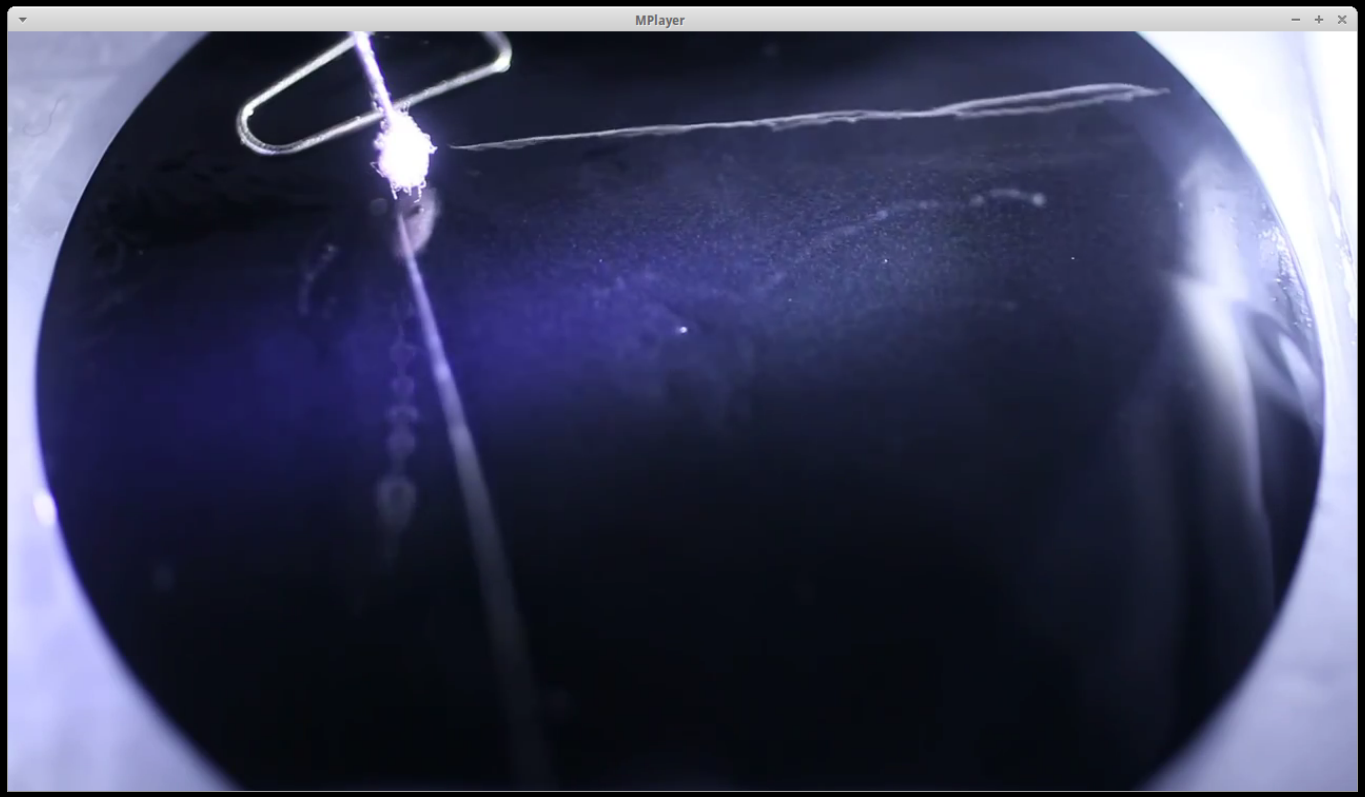
(We don't have time to dig deeper into atomic theory. . .)

Step 1: Subatomic particles exist.

As of 1900:

- Things are made of atoms.
- Atoms have electrons and some $+$ components too.
- Some materials (radium, polonium, etc.) emit “rays”.

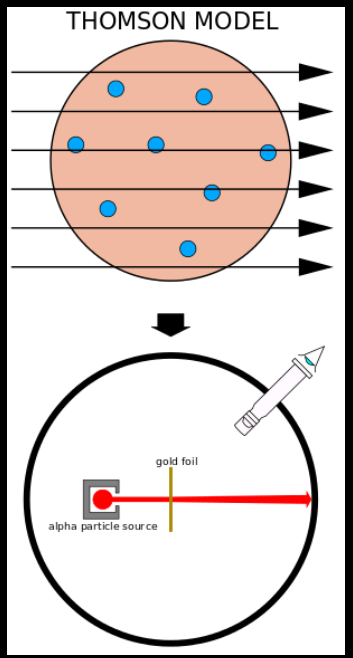
- These rays can interact with atoms in interesting ways.



alpha and beta rays in a cloud chamber by Youtube user 4gokan123,
http://www.youtube.com/watch?v=ZLiXgdymIYE

Atomic theory pre-1911 predicted atoms as “blueberry muffins”.

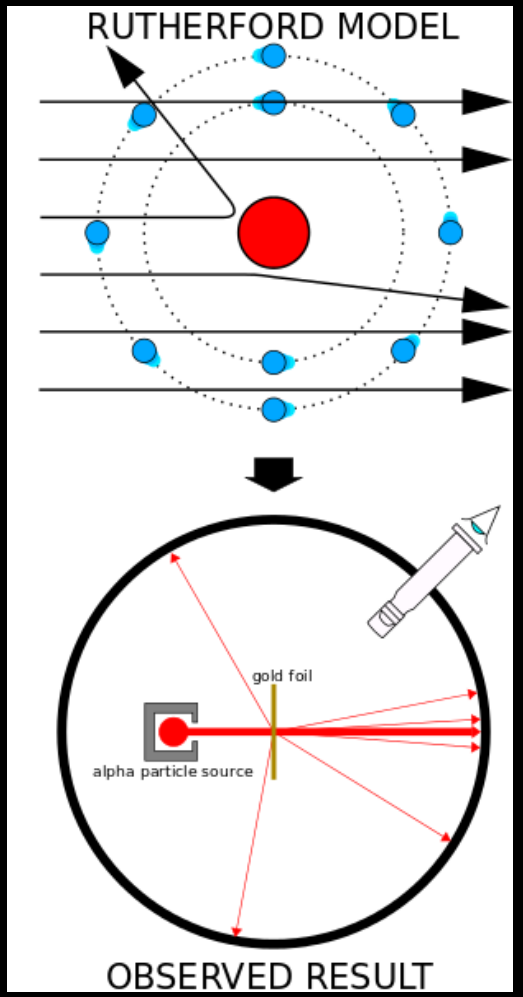
Negatively-charged electrons suspended in a positive blob. If it was correct, alpha particles would pass straight through a heavy atomic nucleus:



https://en.wikipedia.org/wiki/Atomic_theory

Instead. . .

Instead, Ernest Rutherford found this in 1909:



This is how we discovered the atomic nucleus.

To sum up Step 1:

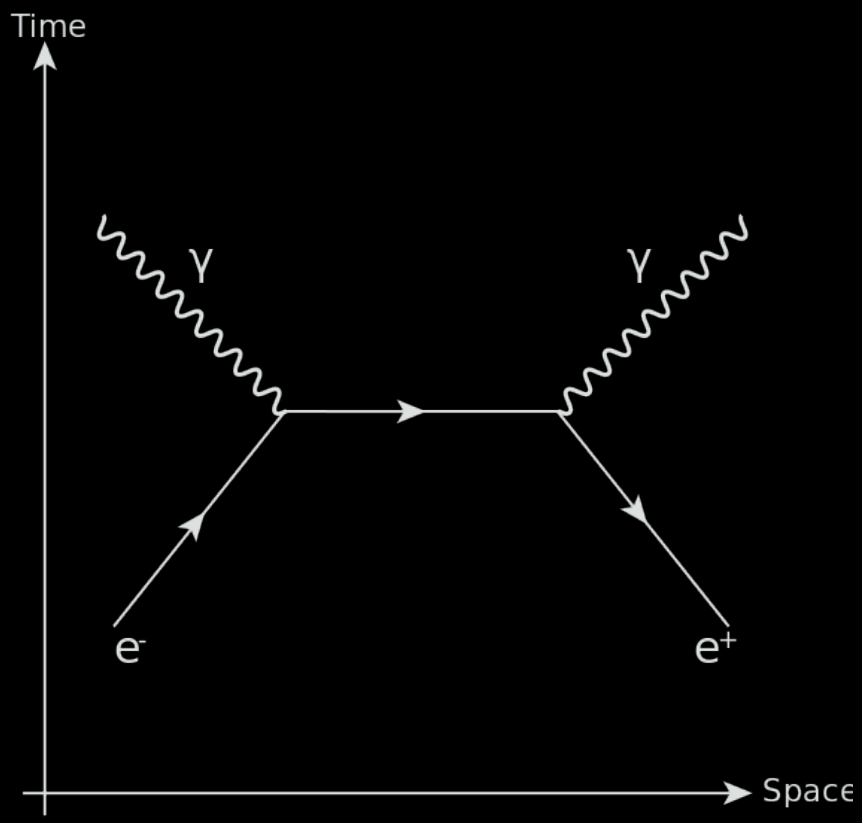
- Things are made of atoms.
- Atoms are made of nuclei, orbited by electrons.
- **We can construct conceptually simple experiments that give vital information about the subatomic world.**

Step 2: The conservation of energy is a thing.

https://commons.wikimedia.org/wiki/File:Bola_%E2%88%9E_%288082754258%29.jpg

- You impart kinetic energy to the cue ball when you shoot.
- The cue ball imparts kinetic energy to the 8-ball when they collide.
- $E^{\text{cue}}_{\text{before}} = E^{\text{cue}}_{\text{after}} + E^{8-\text{ball}}_{\text{after}}$

Step 2: Energy is also conserved by subatomic particles.



$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$E_{e^-} + E_{e^+} = E_{\gamma 1} + E_{\gamma 2}$$

An electron and an anti-electron annihilate, producing photons.

https://en.wikipedia.org/wiki/Pair_annihilation

Step 3: Some curious observations in 1930.

Scientists were trying to study the decay of atomic nuclei – "beta decay", in which a nucleus A falls apart into a lighter nucleus B and an electron. They were observing this:

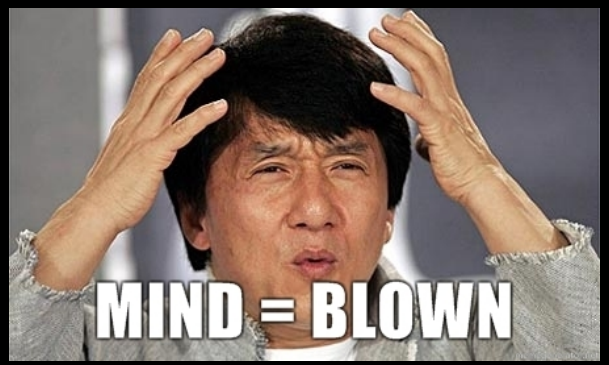
$$A \to B + e^-$$

From the conservation of energy, what would you expect?

$$E_A = E_B + E_{e^-}$$

Instead, they were seeing this:

$$E_A > E_B + E_{e^-}$$

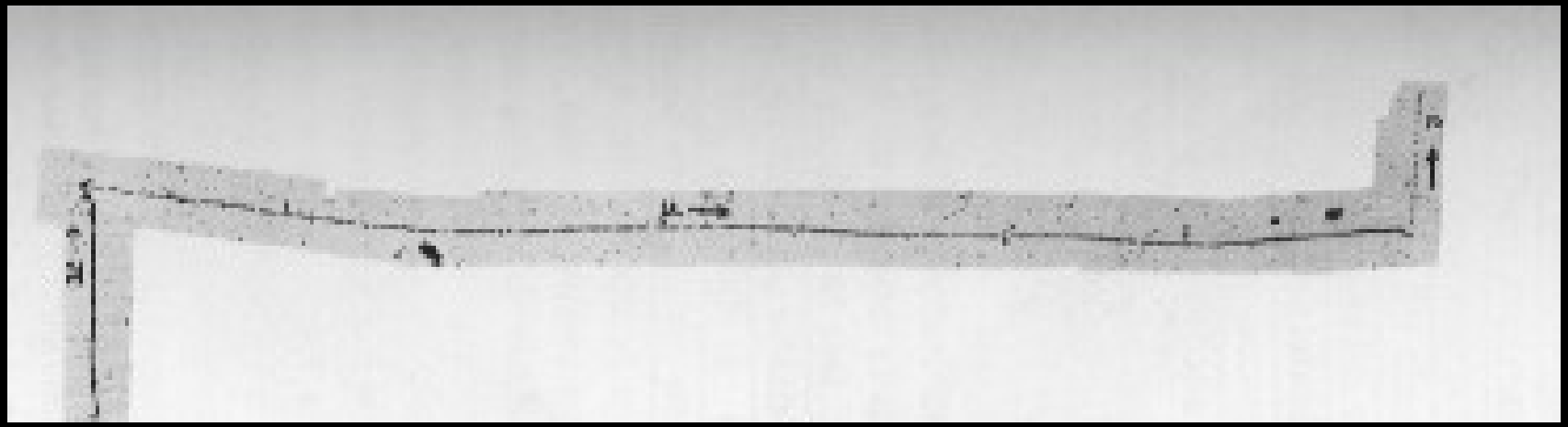


Jackie Chan, *Who Am I?*, 1998.

Niels Bohr:
“Welp, looks like conservation of energy isn’t a thing.”

Wolfgang Pauli:
“What if $A \rightarrow B + e^{-} + X$, and X is just really hard to detect?”

Further indirect evidence by Cecil Powell *et al.* in 1949.



C. Powell *et al., Nature,* **163**, 82 (1949).

Why the sharp right turn? Neutrino emission!

$$\pi \rightarrow \mu + \nu$$

So far, we have *suggestions and indirect evidence* of neutrinos.
How can we get direct evidence?

Reines & Cowan, *Nature* **178**, 446-449 (1956).

What would constitute *proof*?

"If the neutrino is a real particle carrying the missing energy and momentum from the site of a beta decay, then the discovery of these missing items at some other place would demonstrate its reality."

In plain language:

- What sort of particle reaction could *only* be the result of neutrinos?
- Let's design an experiment in which the results of the neutrino reaction are unmistakeable.
- Bonus points if the reaction occurs at your predicted rate.

“Negative beta decay” can happen when a neutrino collides with a proton.

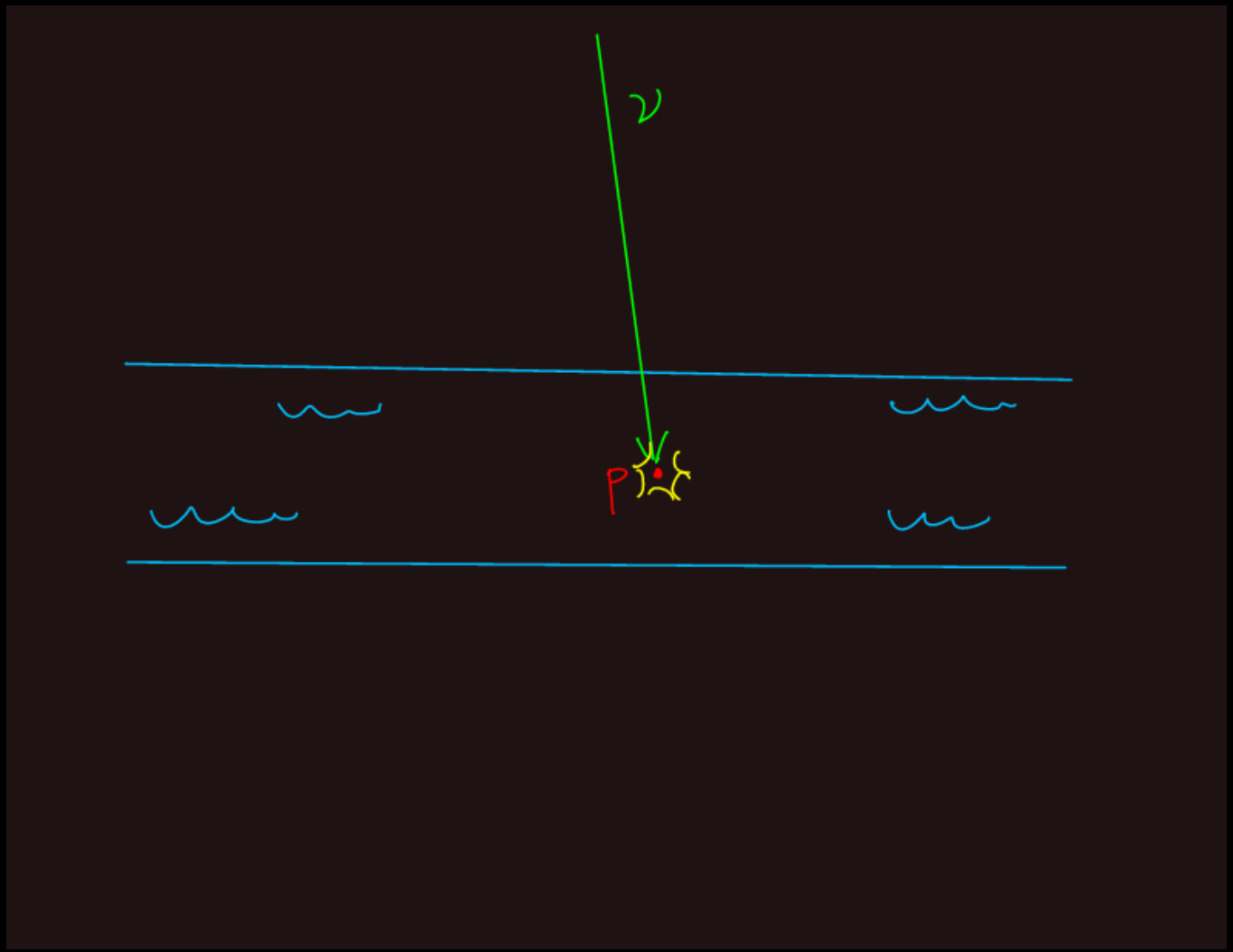
$$\nu + p \rightarrow e^{+} + n$$

Reines & Cowan’s experimental design looked like this:

1. Use a nuclear reactor to generate lots of neutrinos, ν.
2. Put lots of protons, p (i.e. water) near the reactor.
3. Try to observe evidence of positrons, e^{+}, and neutrons, n that look like they came from that reaction.

In practice, their experiment looked like this:

Fill a tank with water and a little cadmium chloride. Wait for ν's.



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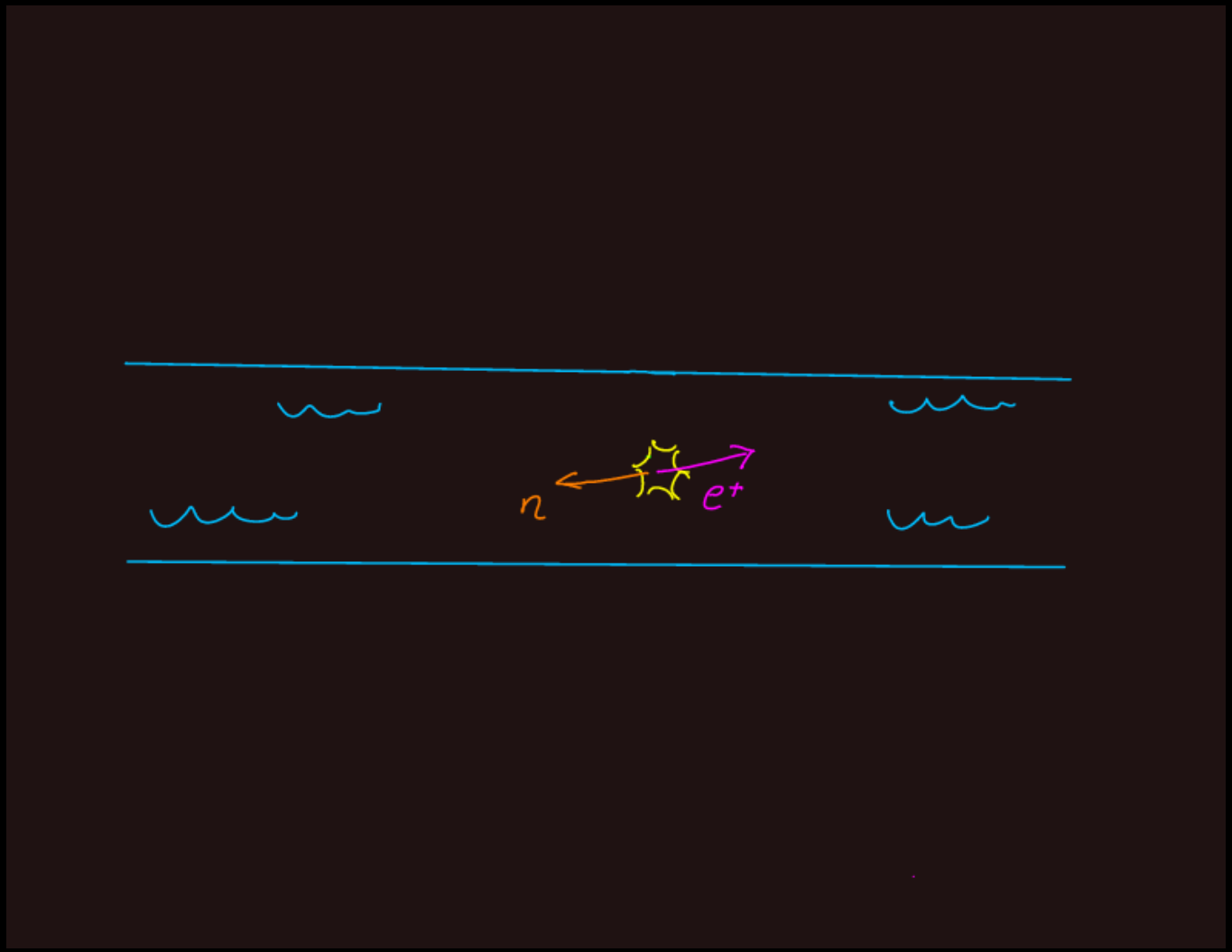

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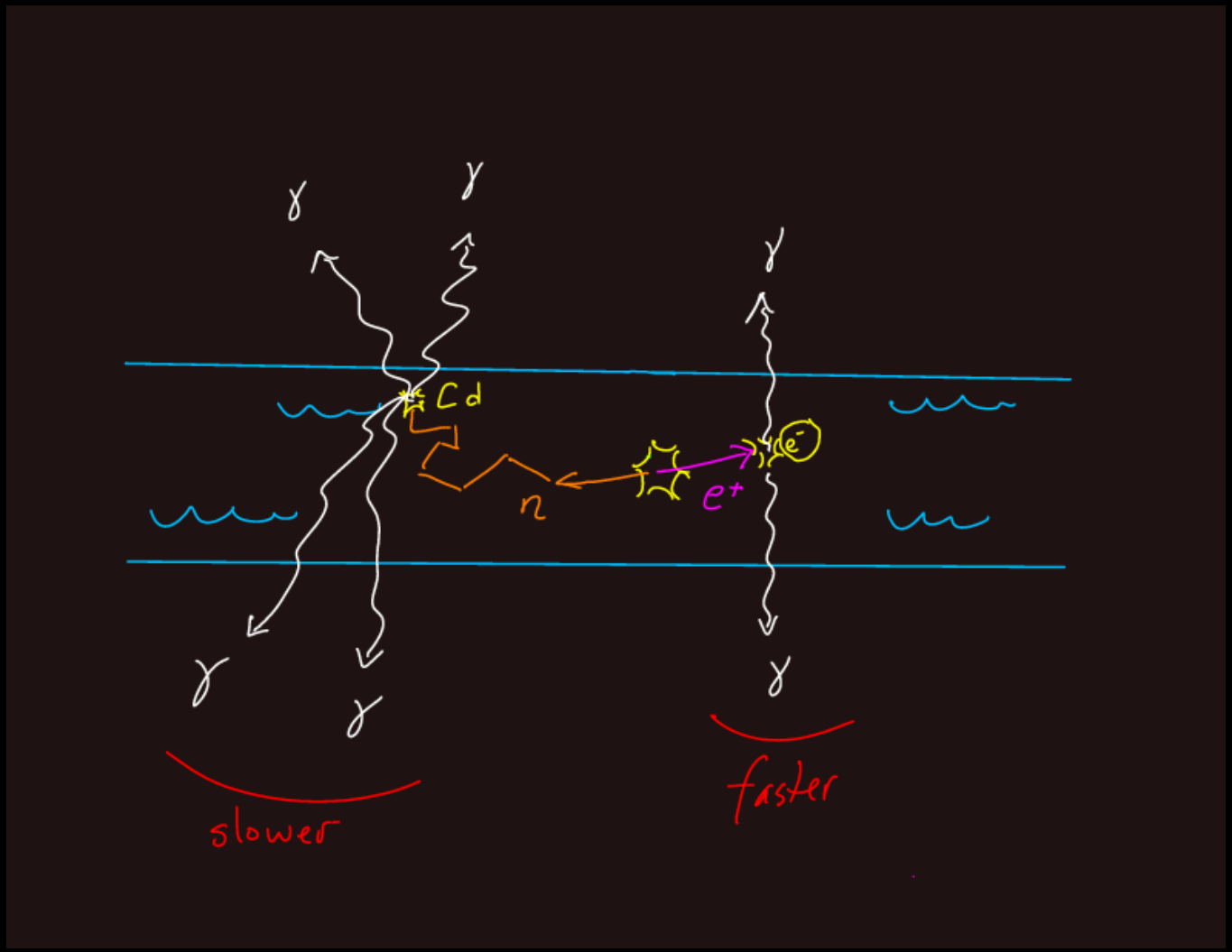

We have “traded” neutrinos (hard) for photons (easy).

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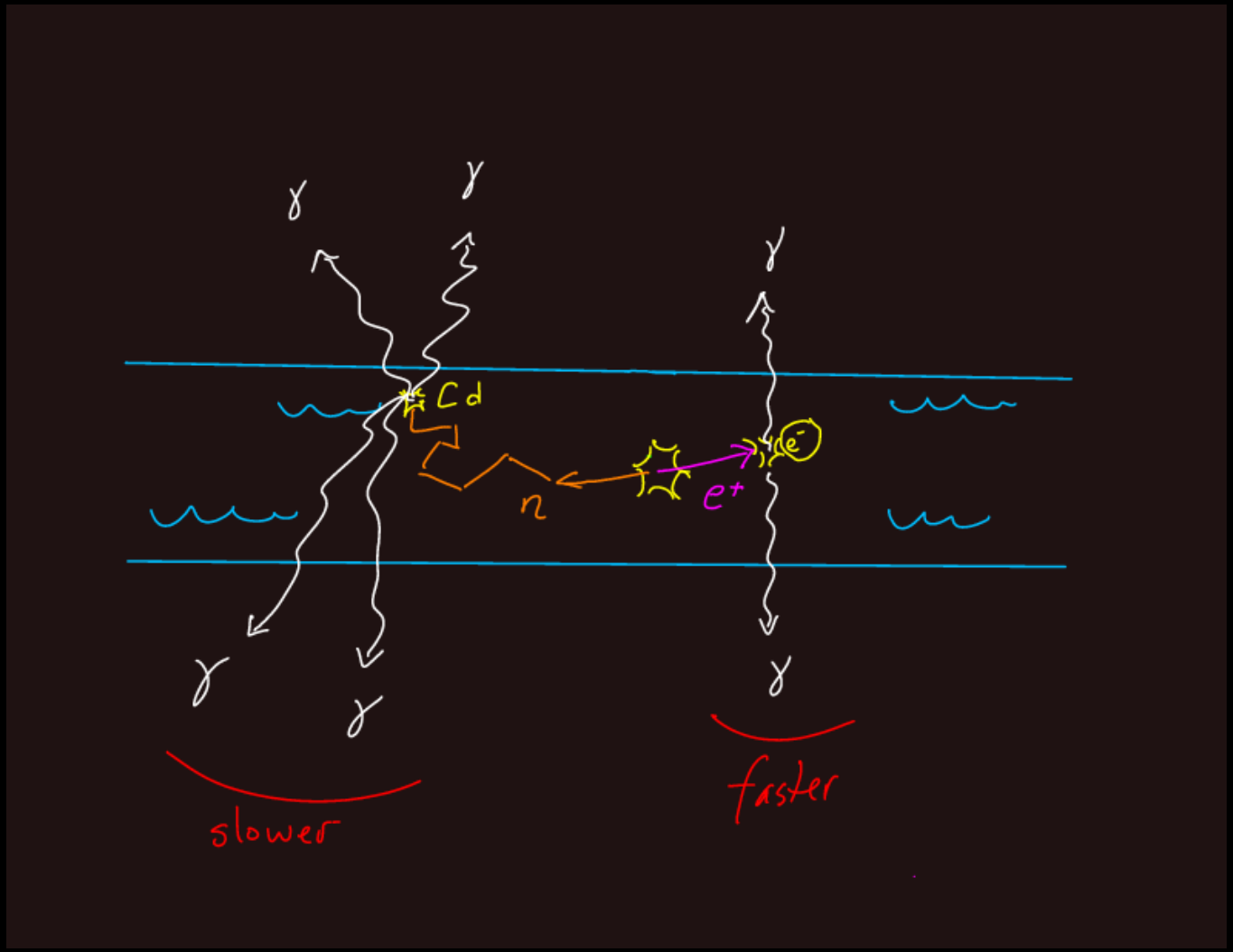

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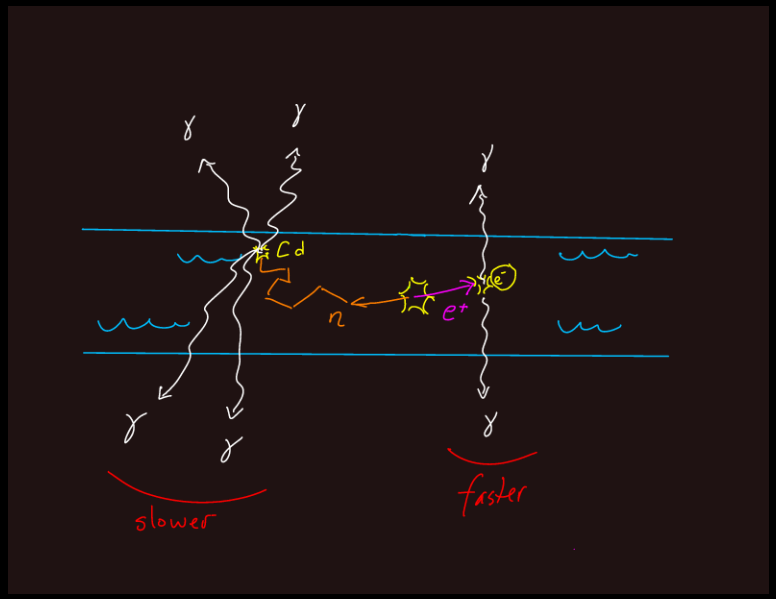


6 photons produced during negative beta decay here. 2 come promptly, 4 come a little after.

“Photomultipliers” take in photons and output small voltages. Aim these at the water tank, look for voltage signals with correct amplitude, timing.

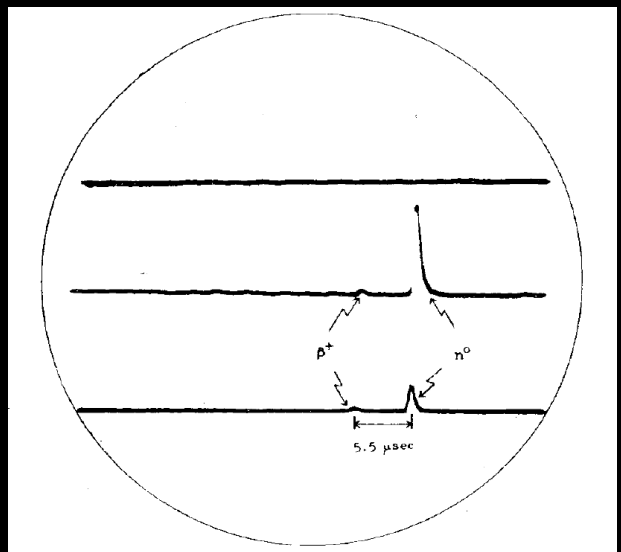
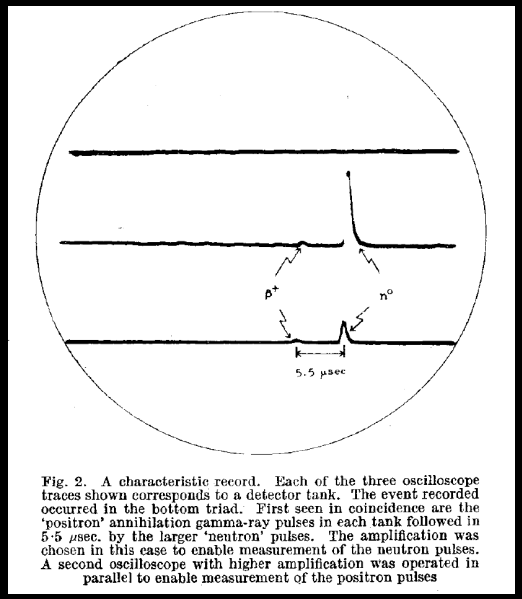


Fig. 2. A characteristic record. Each of the three oscilloscope traces shown corresponds to a detector tank. The event recorded occurred in the bottom triad. First seen in coincidence are the ‘positron’ annihilation gamma-ray pulses in each tank followed in 5·5 μsec. by the larger ‘neutron’ pulses. The amplification was chosen in this case to enable measurement of the neutron pulses. A second oscilloscope with higher amplification was operated in parallel to enable measurement of the positron pulses

How can you be sure your voltage blips aren't accidents?



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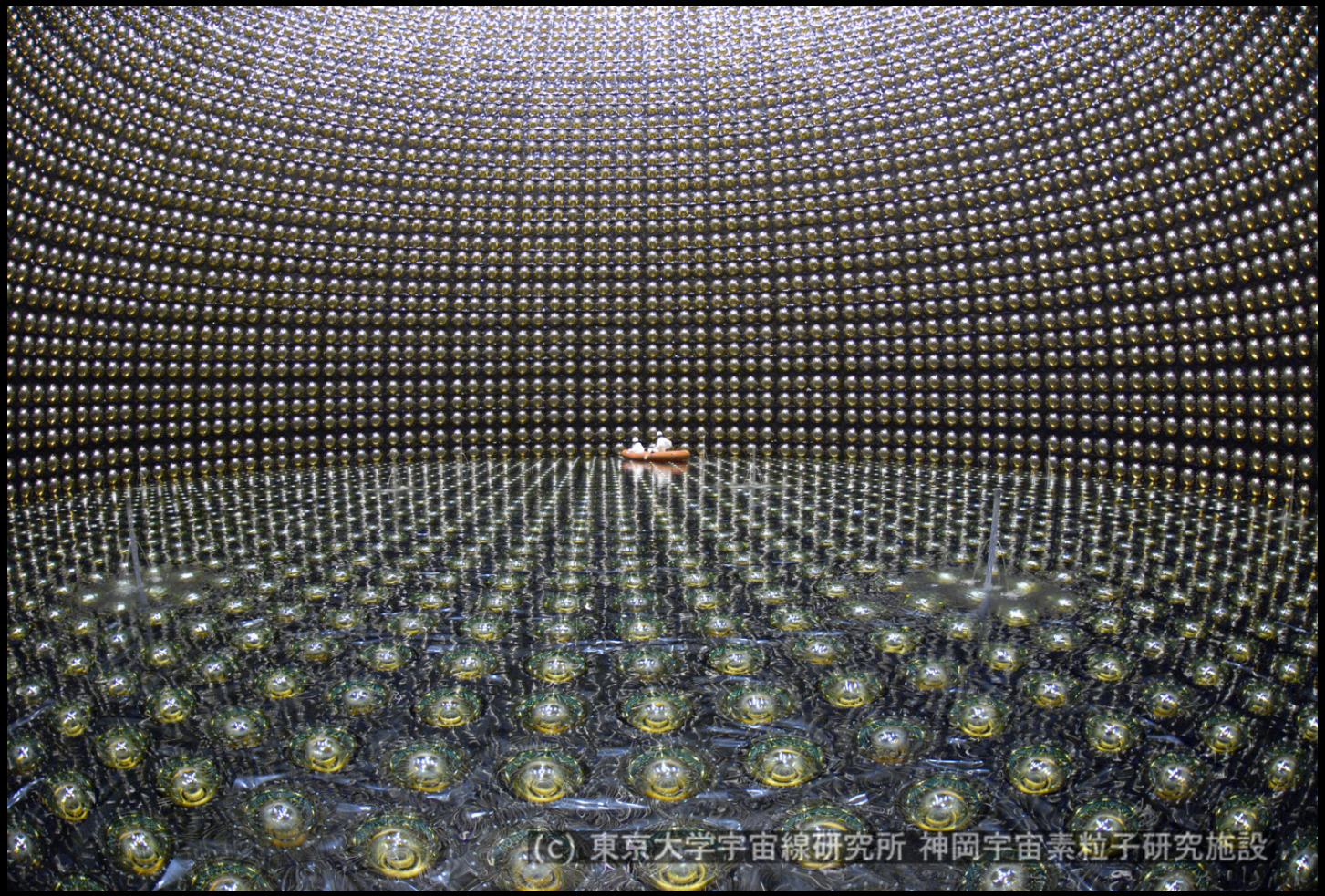
$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\bar{x} - x_i)^2}$$

- You don't stop at just one!
- They ran for 1371 hours (2 months!) and measured 2.88±0.22 counts per hour. ($\bar{x} \pm \sigma$).
- Other checks: Put heavy water in the tank, change density of protons. Does the event rate change? (Yes.)

Frederick Reines got the Nobel Prize for all this in 1995.

Bigger detectors mean more sensitivity. (Those guys in the boat are doing photomultiplier maintenance.)



Super-Kamiokande

http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/image-e.html

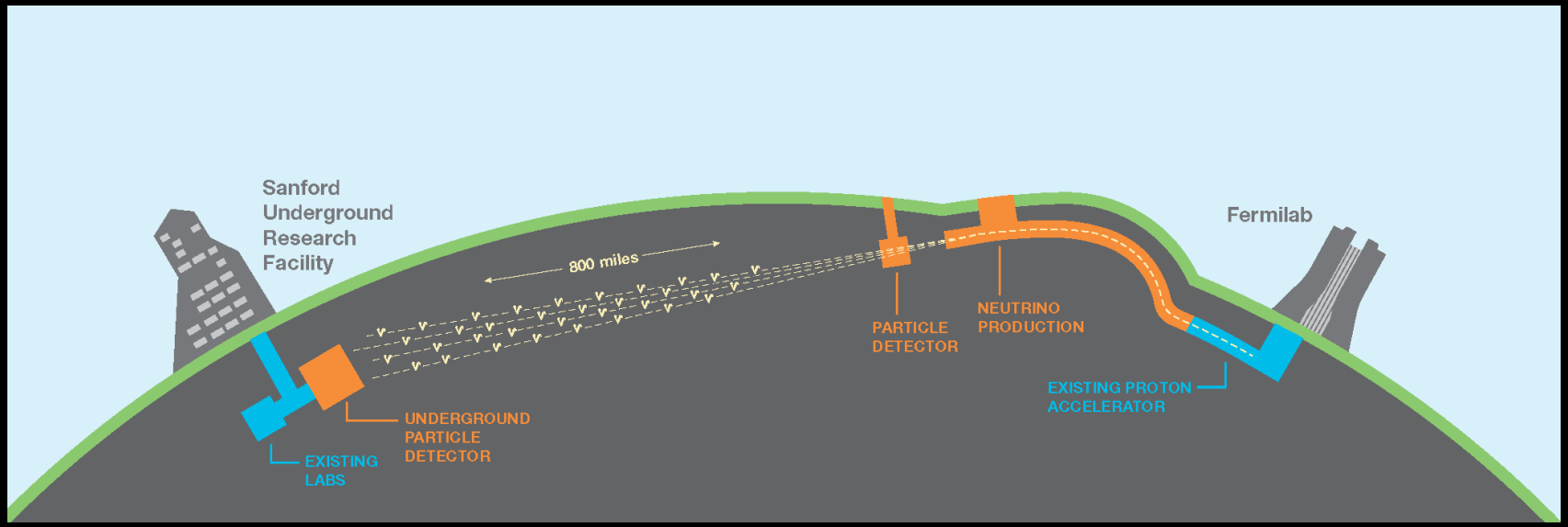
https://en.wikipedia.org/wiki/Deeper,_Deeper,_Deeper_Still

To sum up: neutrinos exist.

Neutrinos exist: so what?

- Our understanding of neutrinos is a remarkable human achievement!
- Neutrino telescopes give us important astronomical information and a probe for dark matter.
  http://icecube.wisc.edu/
- "Why is there stuff?"
  - http://arxiv.org/abs/1108.2694
  - http://www.symmetrymagazine.org/article/february-2013/long-baseline-neutrino-experiment
  - http://www.danielbowring.net/2014/02/03/on-the-craziness-of-neutrinos-or-why-is-there-stuff/
- High-sensitivity neutrino detectors could help us monitor nuclear reactors for "suspicious activity":
  http://physics.aps.org/articles/v7/79

Fermilab is working on this problem in a serious way.

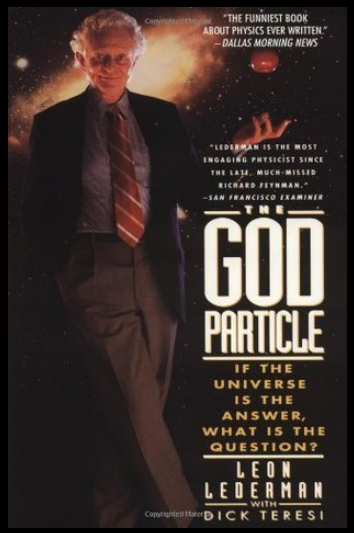


http://www.dunescience.org

Because neutrinos are so “ghostly”, we can send them straight through the Earth to South Dakota. No tunnel, no beam pipe, nothing!

http://lbnf.fnal.gov/env-assessment.html

Parting thoughts from Leon Lederman, a former director of Fermilab:



L. Lederman, D. Teresi, *The God Particle*, 1993.

Excerpt from *The God Particle*

The lady in the audience was stubborn. "Have you ever *seen* an atom?" she insisted. . . . My attempts to answer this thorny question always begin with trying to generalize the word "see". Do you "see" this page if you are wearing glasses? . . . If you are reading the text on a computer screen? Finally, in desperation, I ask, "Have you ever seen the pope?"

"Well, of course," is the usual response. "I saw him on television." Oh, really? What she saw was an electron beam striking phosphorous painted on the inside of a glass screen. My evidence for the atom, or the quark, is just as good.

Thanks for your attention!

References

(It ain’t true just because I say so.)

Coffee statisticts from the International Coffee Association, http://www.ico.org/monthly_coffee_trade_stats.asp

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http://www.whattoexpect.com/forums/june-2013-babies/topic/having-our-morning-coffee.html

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Boffey, Phillip. “New study ties coffee drinking of 5 cups daily to heart disease.” *New York Times* Nov. 12, 1985. http://www.nytimes.com/1985/11/12/science/new-study-ties-coffee-drinking-of-5-cups-daily-to-heart-disease.html

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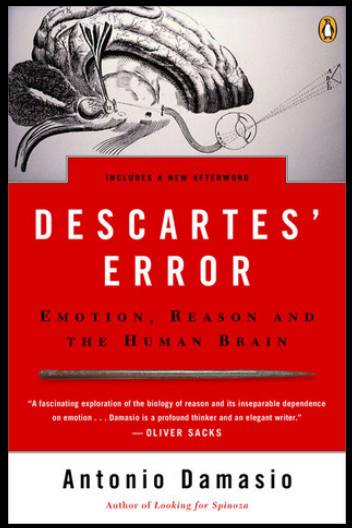
N. Freedman *et al.*, “Association of coffee drinking with total and cause-specific mortality.” *N. Engl. J. Med.* **366**, 20 (2012).

J. Liu *et al.*, "Association of coffee consumption with all-cause and cardiovascular disease mortality." *Mayo Clinic Proc.* **88**, 10 (2013).

204 Ann. Int. Med.

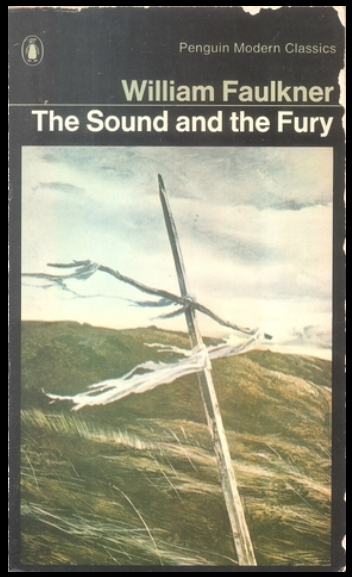
`http://minerva.fnal.gov/`

C. Dickens, *A Christmas Carol*, 1843.



A. Damasio, *Descares' Error: Emotion, Reason, and the Human Brain*, 1994.

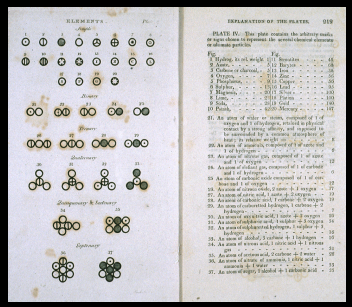
Rashomon. Dir. Kurosawa Akira. Perfs. Mifune Toshiro, Kyo Machiko, Mori Masayui. Daiei Motion Picture Co., 1951.



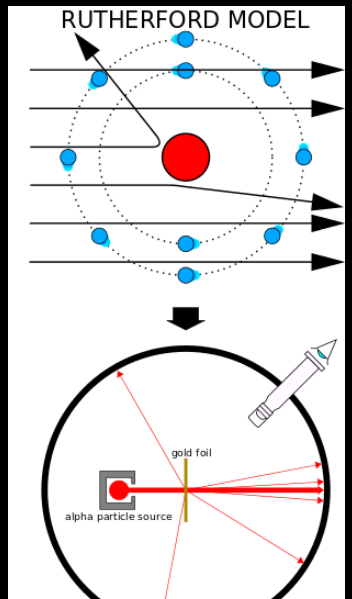
W. Faulkner, *The Sound And The Fury* (London: Penguin Modern Classics, 1964).

Scientific American. “Why Science Tells Us Not To Rely On Eyewitness Accounts”, last modified Jan. 1 2010. http://www.scientificamerican.com/article/do-the-eyes-have-it/

http://cheezburger.com/5971932416



J. Dalton, *A New System of Chemical Philosophy* (Cambridge University Press, 2010).



E. Rutherford, “The scattering of α and β rays by matter and the structure of the atom” *Philos. Mag.*, **6**, p. 21 (1911).

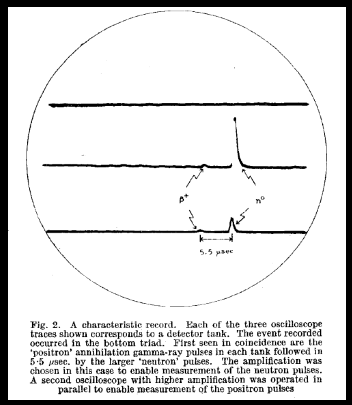
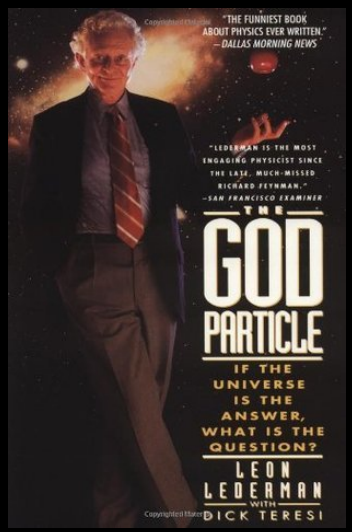


Fig. 2. A characteristic record. Each of the three oscilloscope traces shown corresponds to a detector tank. The event recorded occurred in the bottom triad. First seen in coincidence are the 'positron' annihilation gamma-ray pulses in each tank followed in 5·5 μsec. by the larger 'neutron' pulses. The amplification was chosen in this case to enable measurement of the neutron pulses. A second oscilloscope with higher amplification was operated in parallel to enable measurement of the positron pulses

Reines & Cowan, *Nature* **178**, 446-449 (1956).



L. Lederman, D. Teresi, *The God Particle: If the Universe is the Answer, What is the Question?* (London: Bantam Press, 1993).
