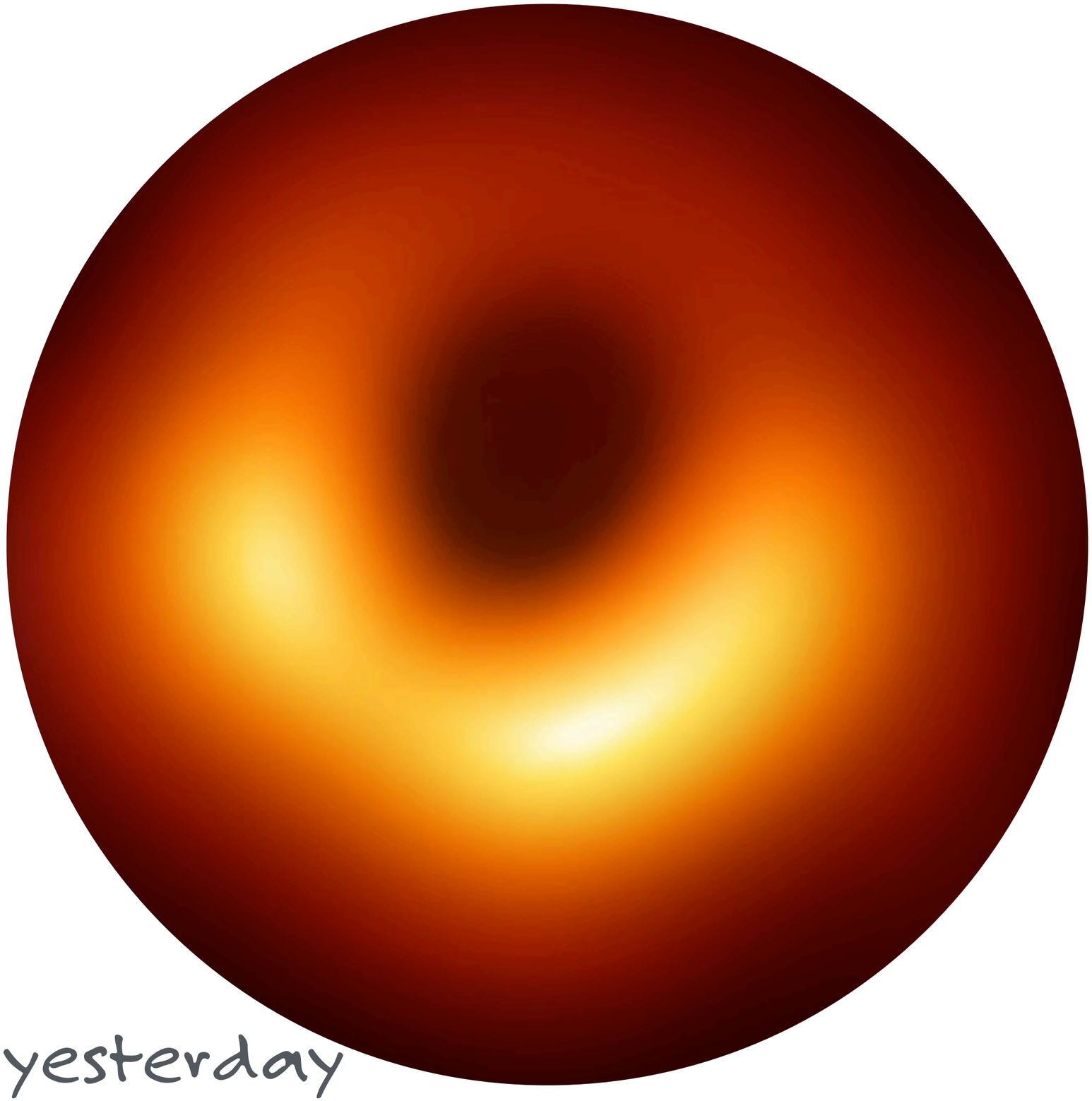
hi

Day 23, 04.11.2019

Quantum Mechanics 6

171 days until the world series

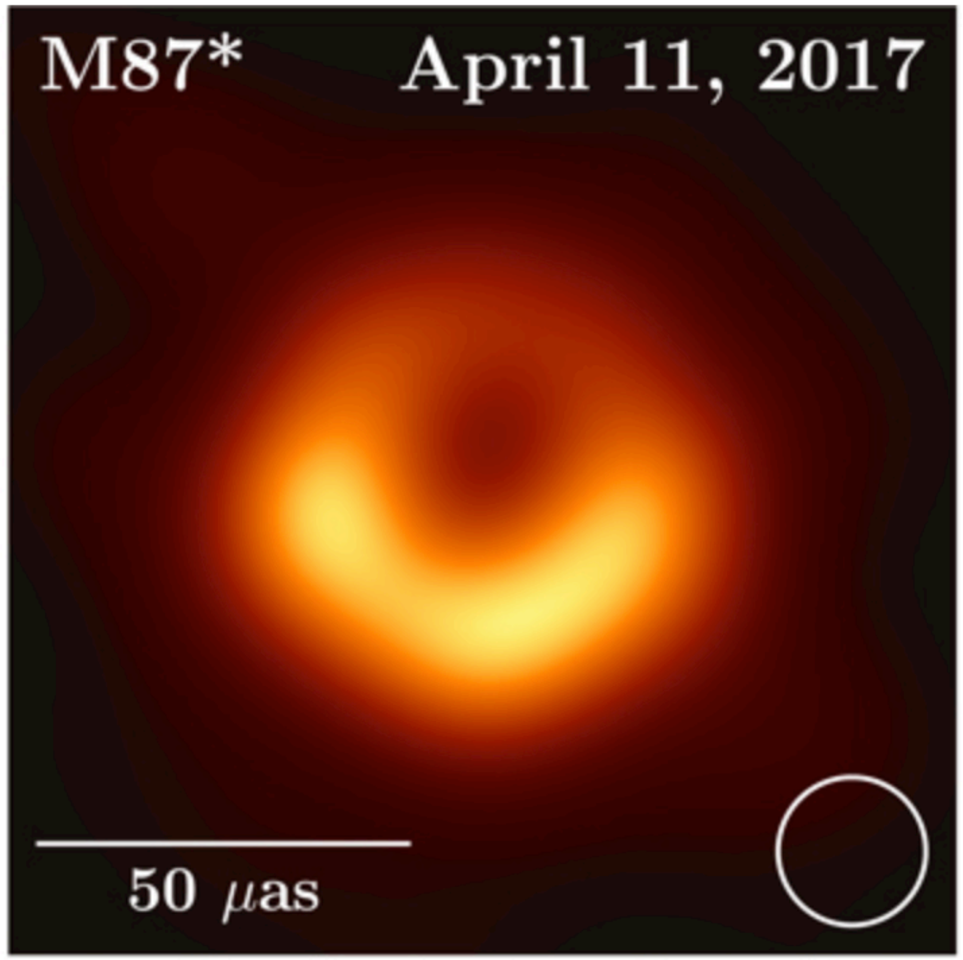
Black Sabbath week



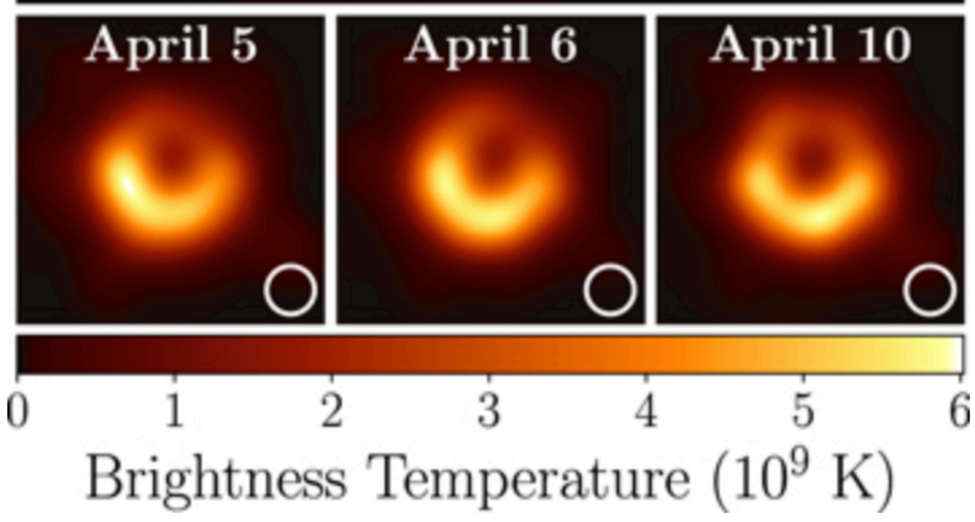
EHT: 0900 yesterday

M87...55 Mly from earth - Black Hole, 7B suns'worth

bright is aimed towards us 58 Bkm wide



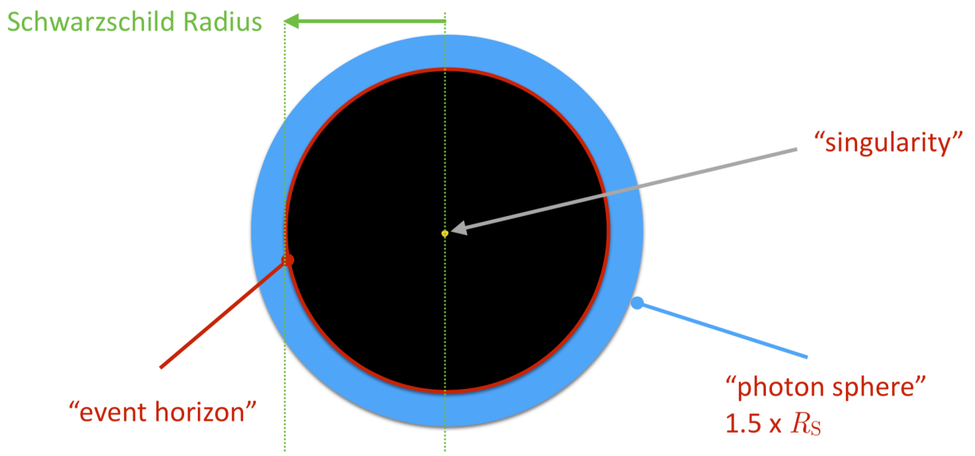
changes in time:



false color represents temperature

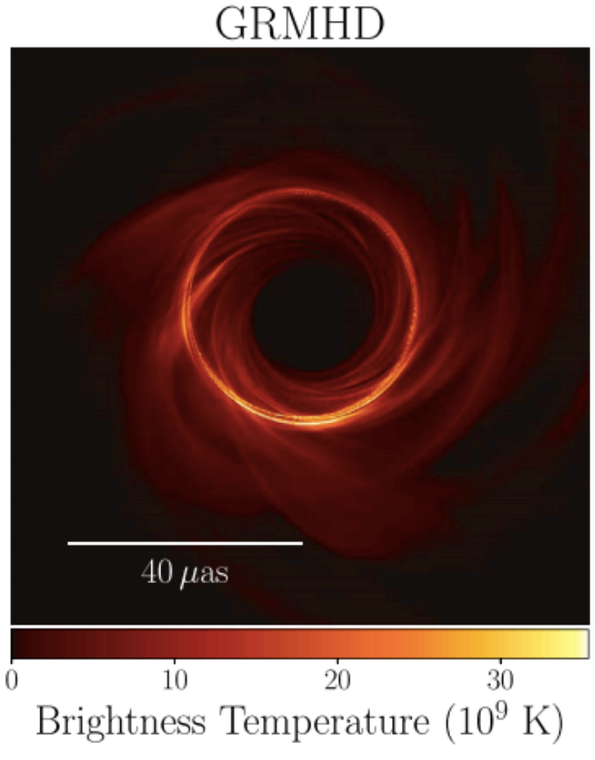
observing wavelength is 1.3 mm - microwaves

black hole anatomy



simplest black hole: not rotating and not charged

realistic black hole: rotating...Kerr Black Holes



April 2019

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
31	1	2 lecture	3	4 lecture	5 HW9 due	6 HW10
7	8	9 lecture	10	11 lecture	12 project day 2 HW10 due	13 HW11
14	15	16 lecture	17	18 lecture	19	20 HW12
21 HW11 due	22	23 lecture	24	25 lecture	26 Honors data upload HW12 due	27
28 2nd Midterm	29	30	1	2	3 FINAL EXAM 07:30	4


KEEP
CALM
AND
LET'S
REVIEW

Here's what we've learned about quantum mechanics

Heisenberg uncertainty principle

says what Nature cannot do

Schroedinger quantum mechanics

says what Nature cannot be

the wavefunction…can't live with it, can't live without it

What's "real" has become confusing

and we don't lose sleep over it

because QM works exquisitely well

But…QM was non-relativistic until 1928

and Dirac figured out how to fix it…

with a welcome surprise

and an unexpected surprise

jargon alert: **fermion**

refers to: any particle with half-integer spin

entomology: from Fermi's theoretical work on the behavior of large numbers of Fermions

example: electron, proton, neutron

jargon alert: **boson**

refers to: any quantum object with integer spin

entomology: from Satyendra Nath Bose, who worked on the effects of multiple boson aggregates

example: photon, pion, Higgs Boson

spin is a defining quality of an electron

electron

symbol:	e
charge:	$-1e$
mass:	$m_e = 9.0 \times 10^{-31}$ kg ~ 0.0005 p
spin:	1/2
category:	fermion, lepton

again, an inherent angular momentum and a defining property of photons

particle: **photon**

symbol: γ

charge: 0

mass: $m_\gamma = 0$

spin: 1

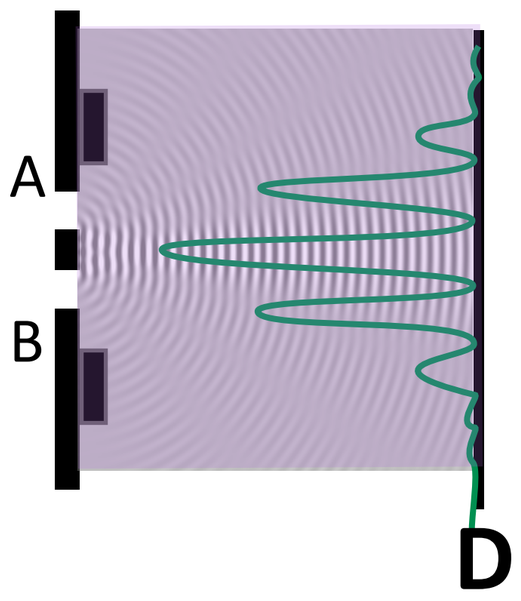
category: boson, aka Intermediate Vector Boson

Rutherford, 1919

particle:	**proton**
symbol:	*p*
charge:	$+1e$
mass:	$m_p = 1.6726\times10^{-27}$ kg = 1 p
spin:	1/2
category:	fermion, hadron

quantum mechanics and GR

mortal enemies at this moment: something's wrong



In that intermediate region, the electron is ... everywhere?

But m(electron) should deform spacetime...where??

look at space

as finely as you can imagine…

what happens to Heisenberg’s Uncertainty Principle?

We lack a theory of “quantum gravity”

shifting gears

antimatter

Dirac’s result

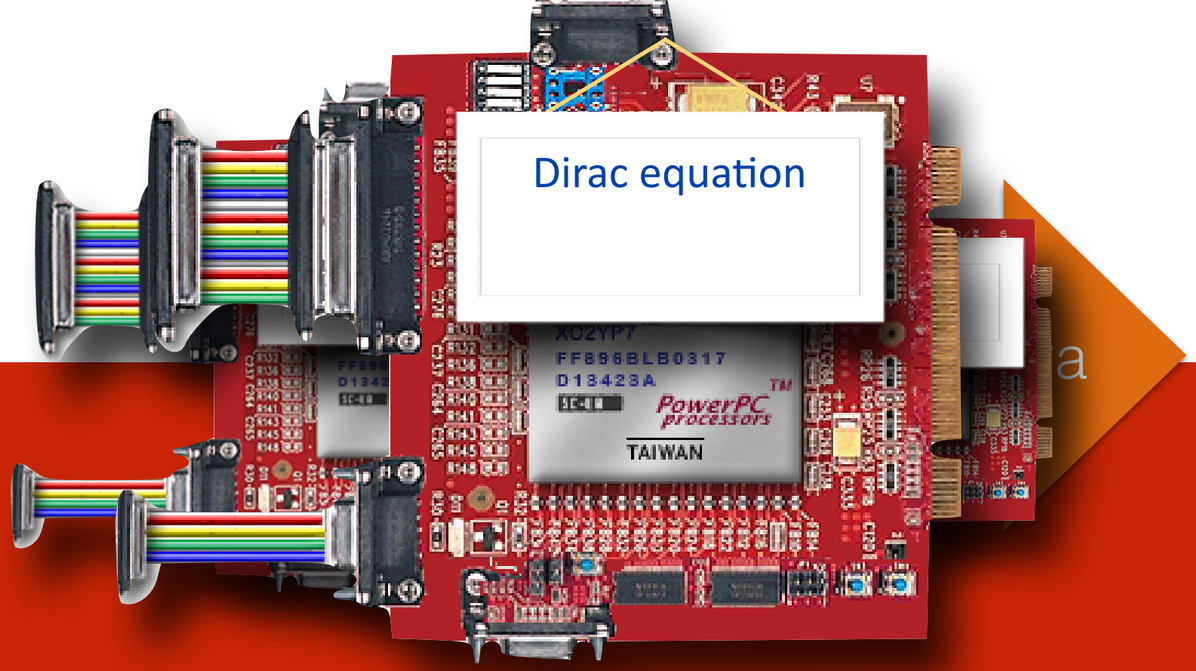
required: 4 quantum fields, rather than 1 $\psi_{up}(+E),\ \psi_{down}(+E)$

2 have positive energy, 2 have negative energy $\psi_{up}(-E),\ \psi_{down}(-E)$

each pair is related precisely to spin

Dirac showed that spin is a wholly relativistic effect

...it just popped out of his equation.



Wolfgang Pauli, 1925:

“Pauli Exclusion Principle”:

No two electrons can be in the same quantum state

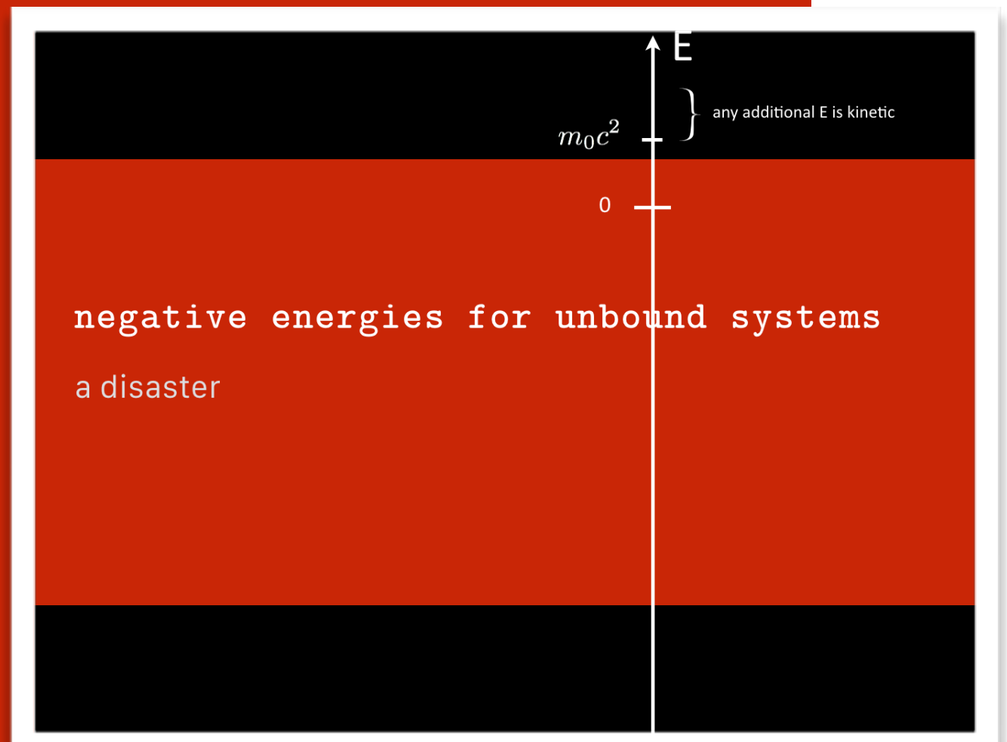
Paul Dirac, 1928

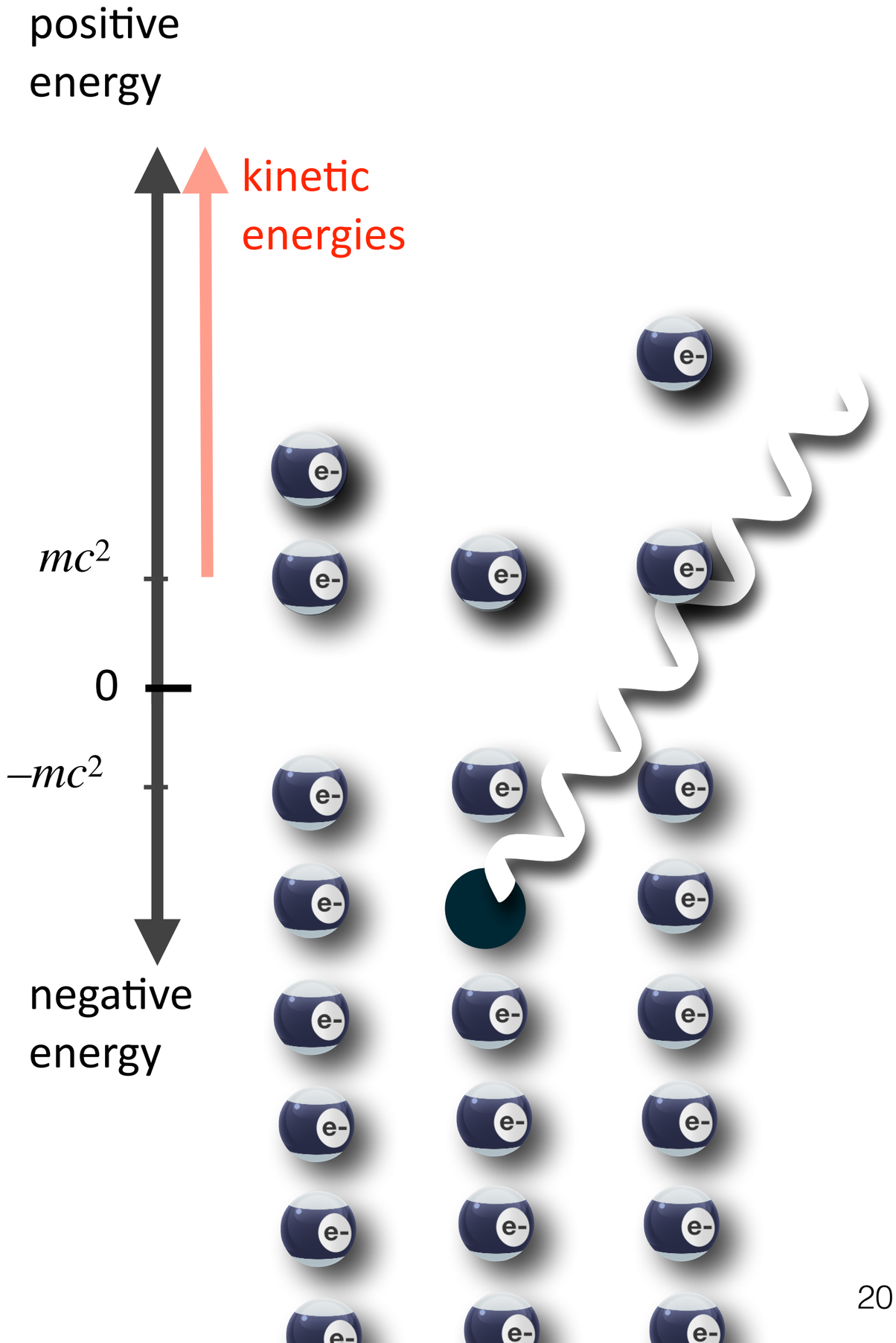
“The Dirac Equation”

still negative energies?

"solved" it with Pauli's Exclusion Principle

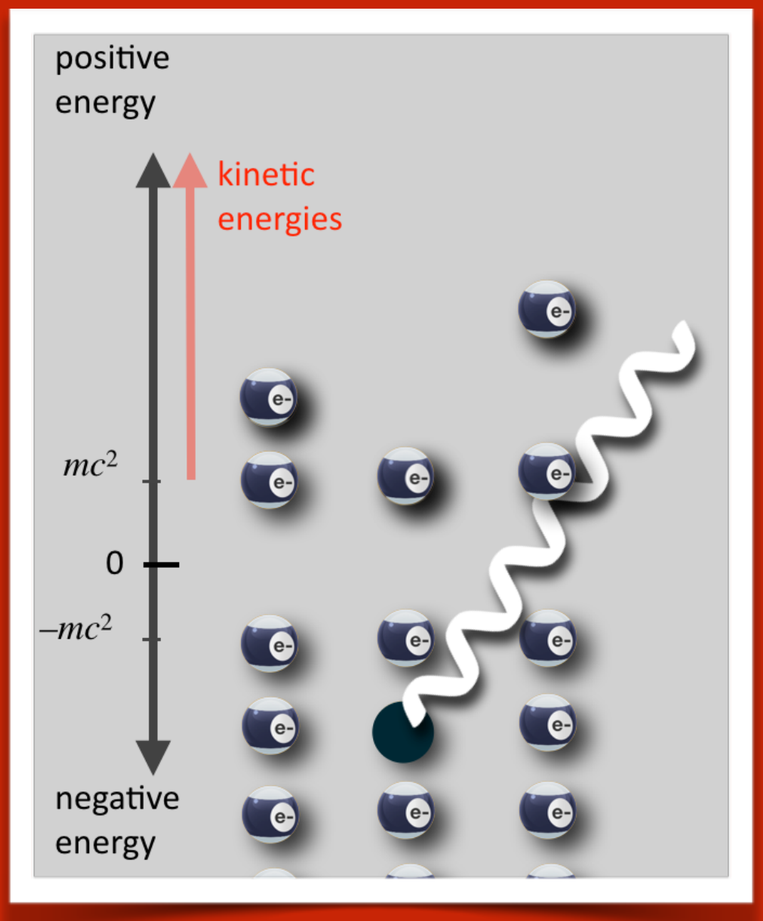
His vacuum is full of negative energy electrons





start with nothing

$$E_\gamma > 2\, m_e\, c^2$$



NOTHING

+ Energy

Let’s talk about Nothing.

Dirac began this discussion

which continues today

in particle physics

and in cosmology

what is this?

$\psi(-\mathrm{E})$ a positively charged object with negative energy?

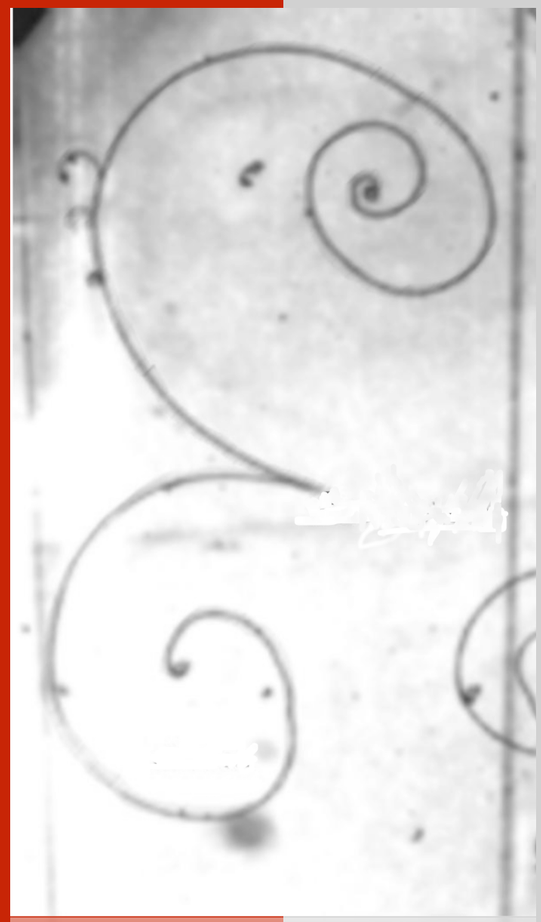
At first, he thought: “proton”

nah. A bolder idea: an anti-electron. The Positron.

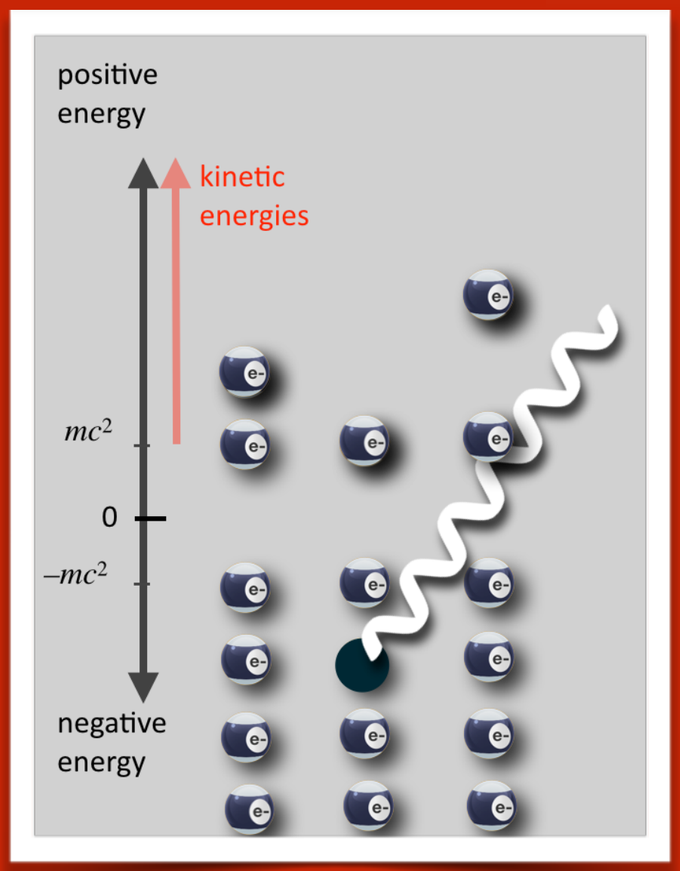
Yes...antimatter.

ANGELS & DEMONS

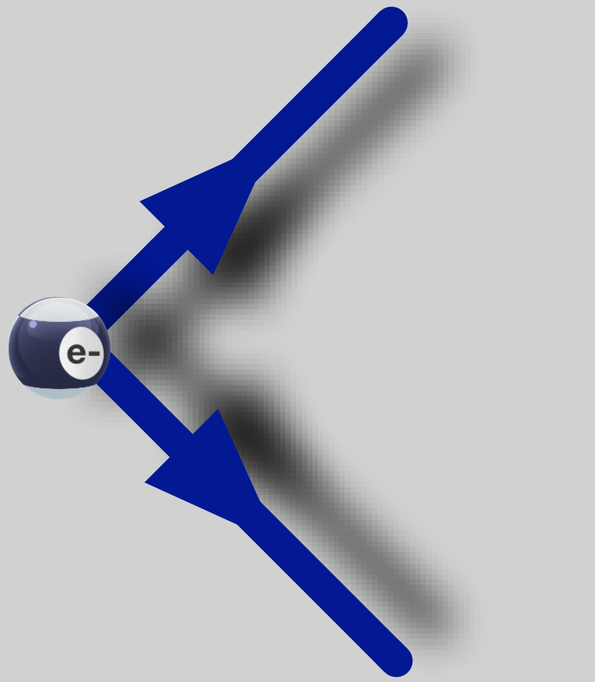
modern intepretat

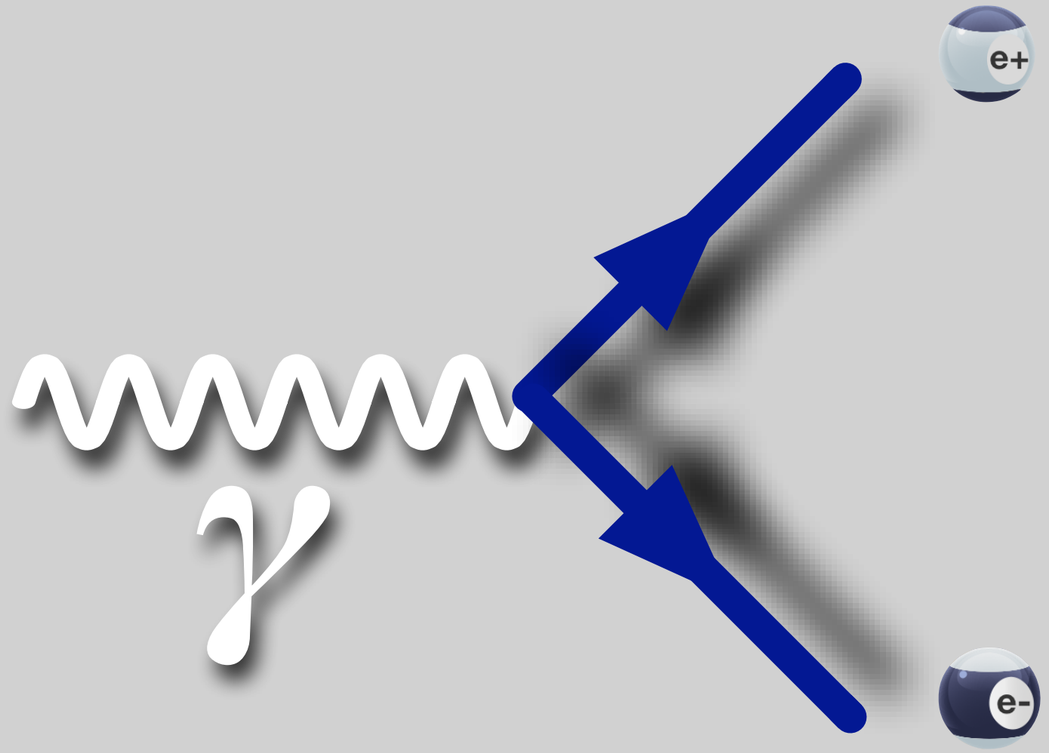


a photon poof-disappears



γ





γ

The antimatter story has a happy ending:

1932

Cosmic Rays

very high energy protons from space

~2 per minute per fingernail

Carl Anderson

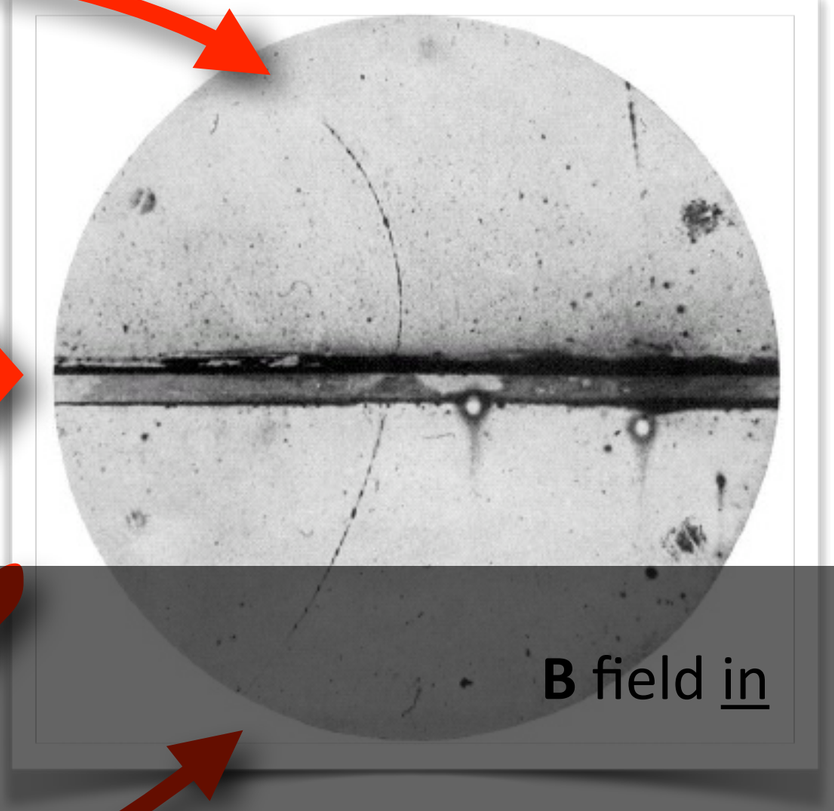
Right on schedule: 1932

B field in

clever...put in a lead plate to cause particles to lose energy

look at this track...

sharper curvature at top

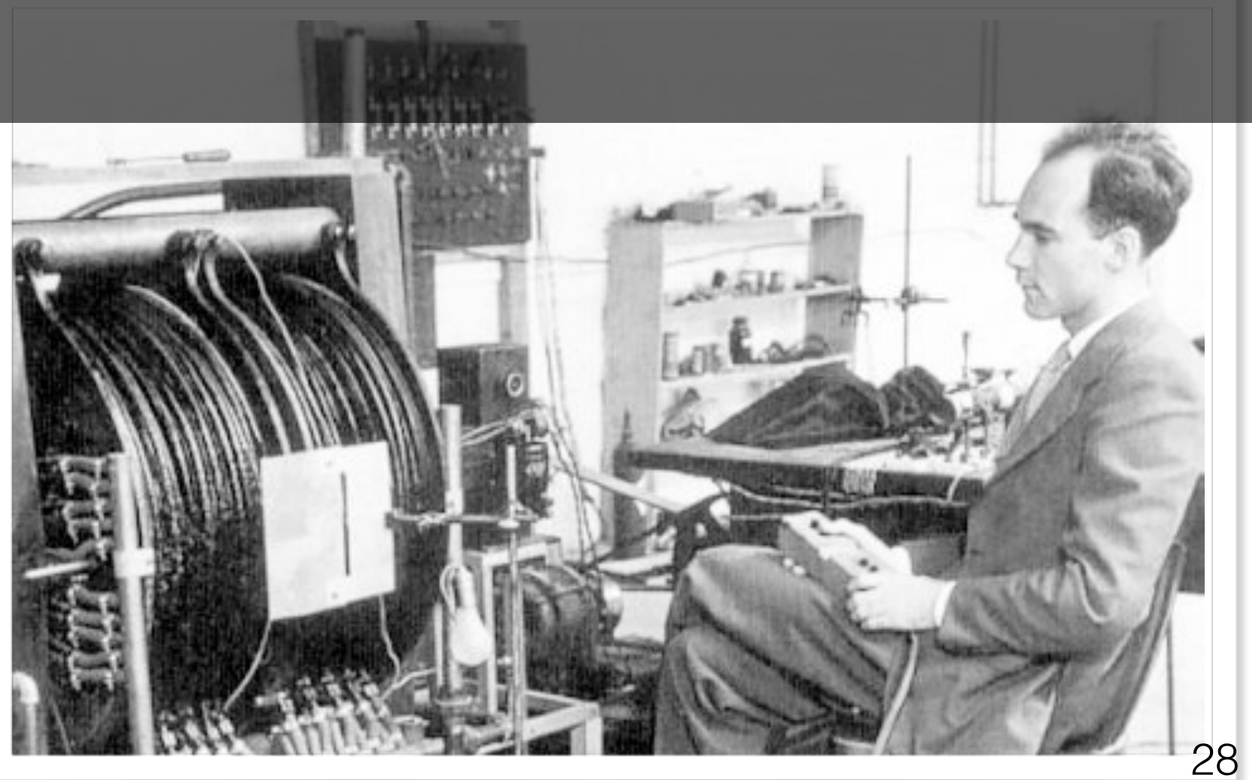


B field in

DOWN and negative?

UP and positive?

Yes...antimatter.



the bar over the top will mean "antiparticle"

anti-electron, aka "positron"

symbol:	$\overline{e}$ or e^+
charge:	$+1e$
mass:	$m_e = 9.0 \times 10^{-31}$ kg ~ 0.0005 p
spin:	*1/2*
category:	anti-fermion, anti-lepton

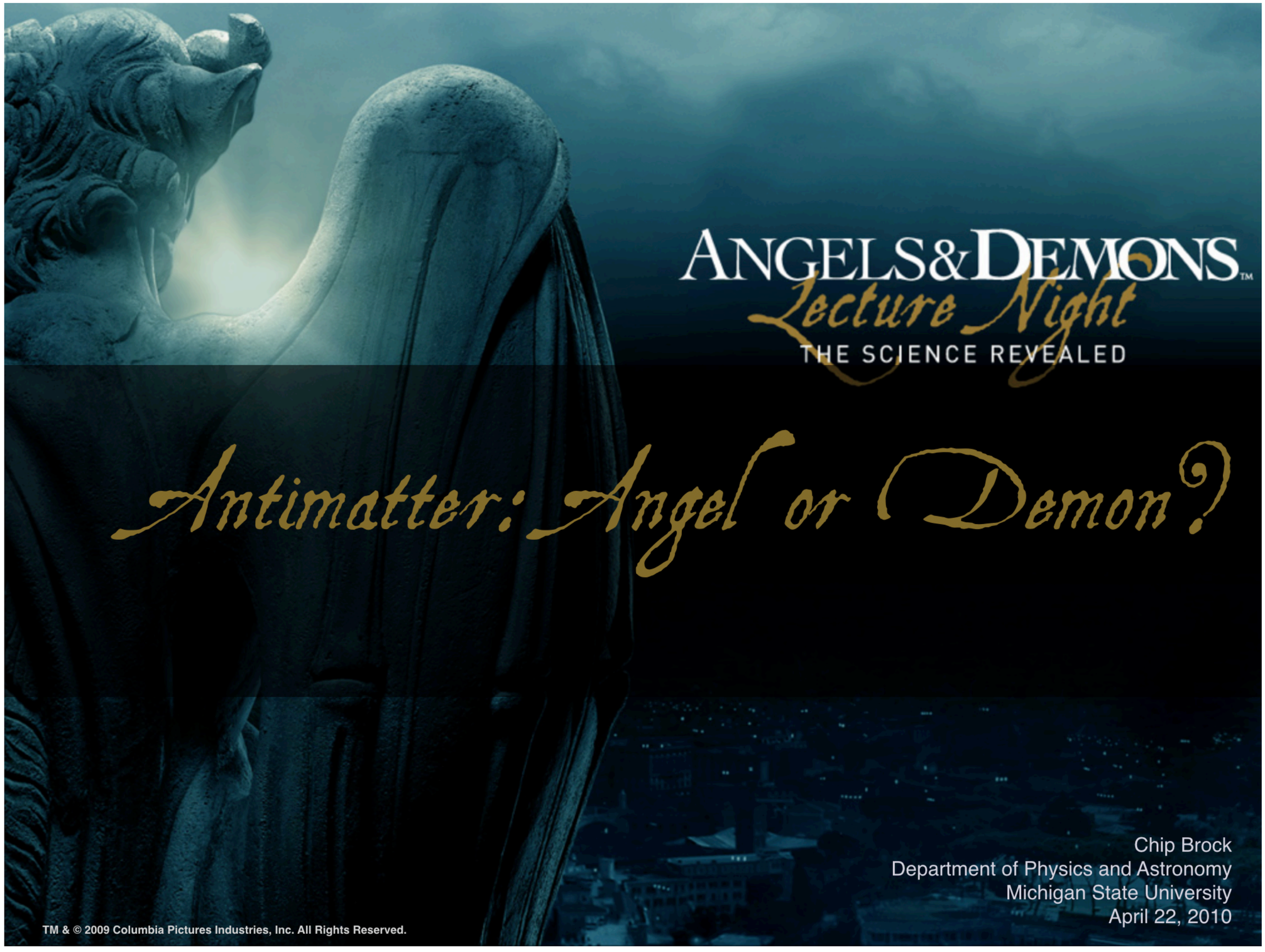
antimatter

is a fact of life

every particle has it’s anti-particle partner

same mass, different electrical charge

short interlude



2

Angel?

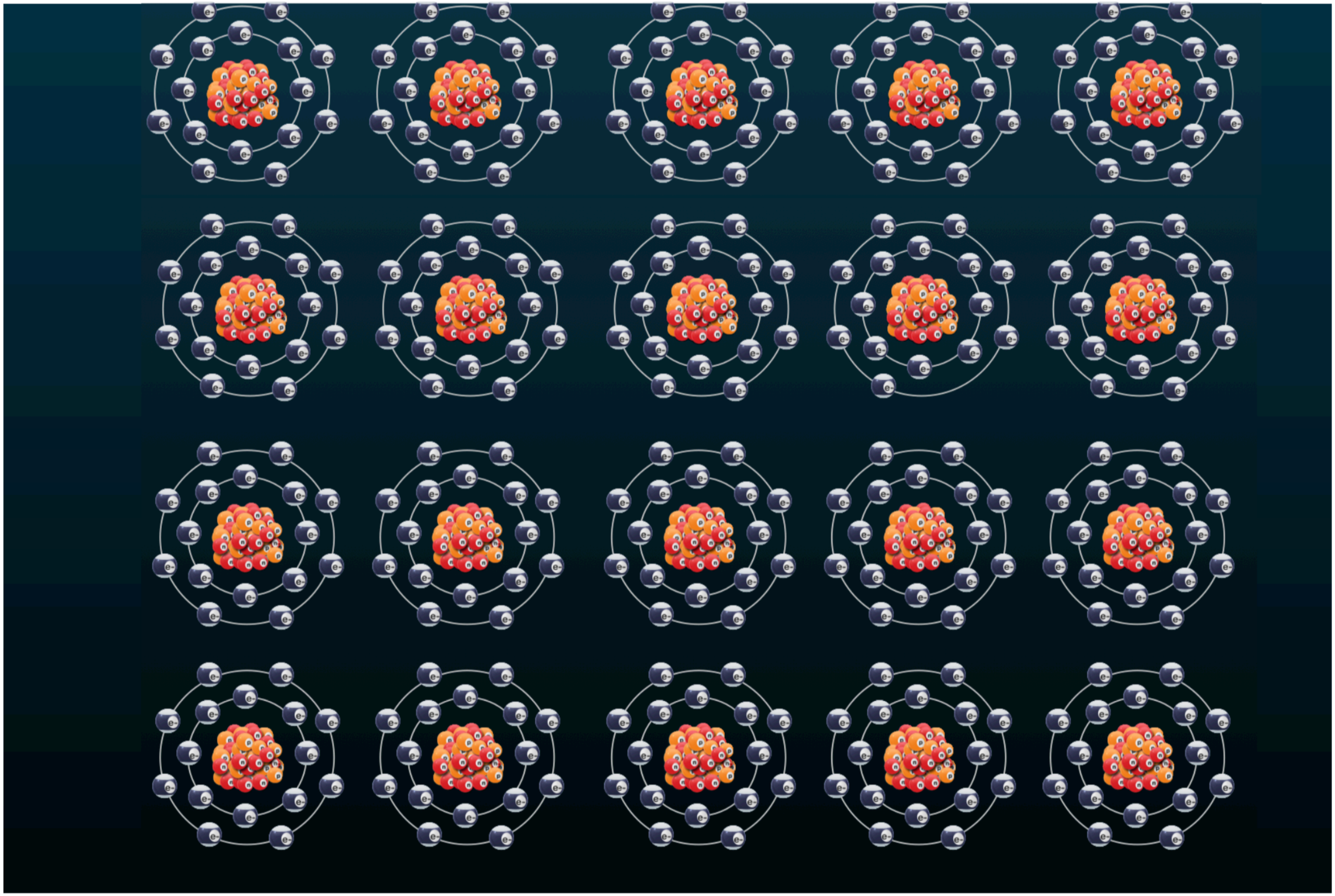
nuts and bolts

timeout.

what happens in matter?

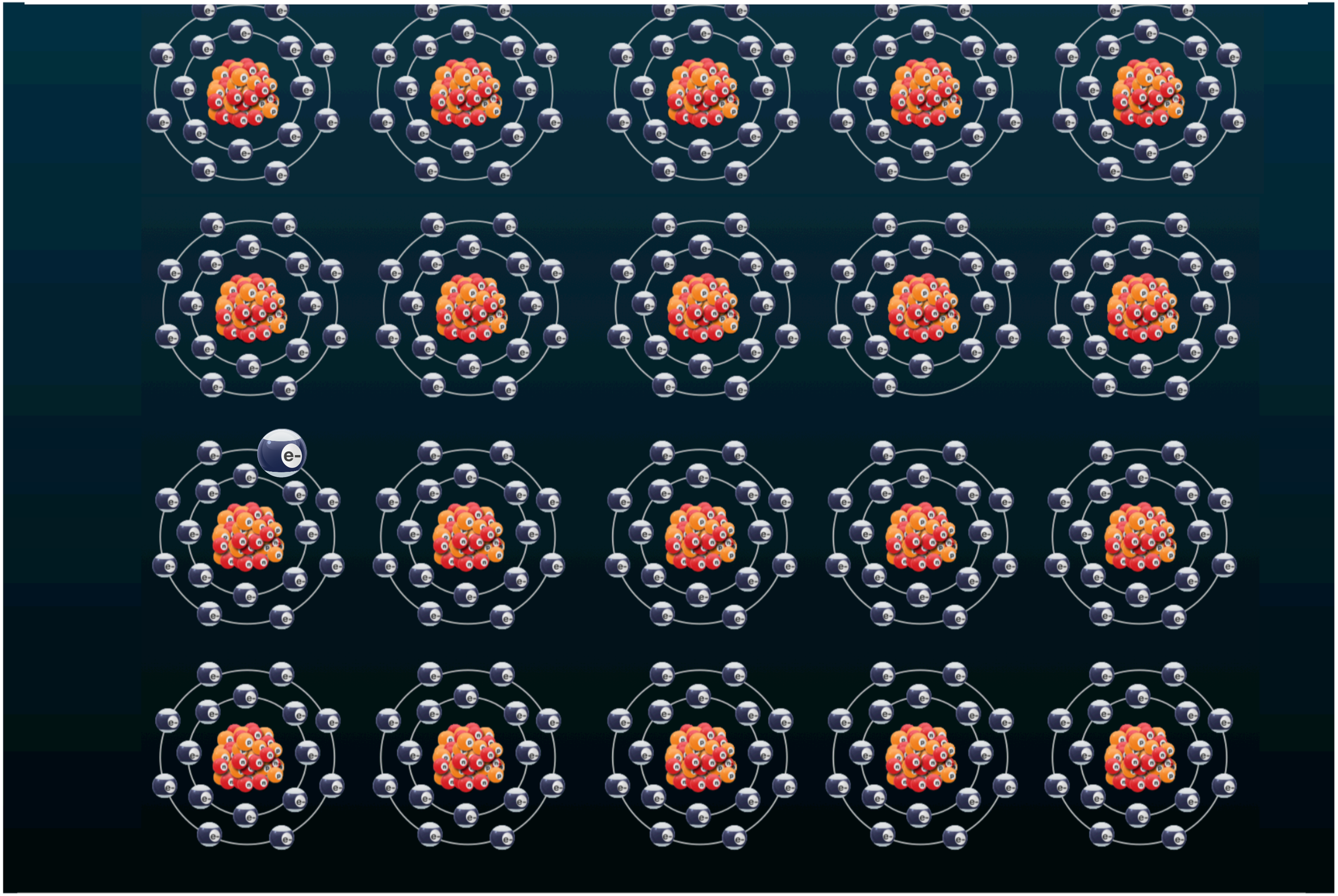
an electron

passing through matter



an positron (anti-electron)

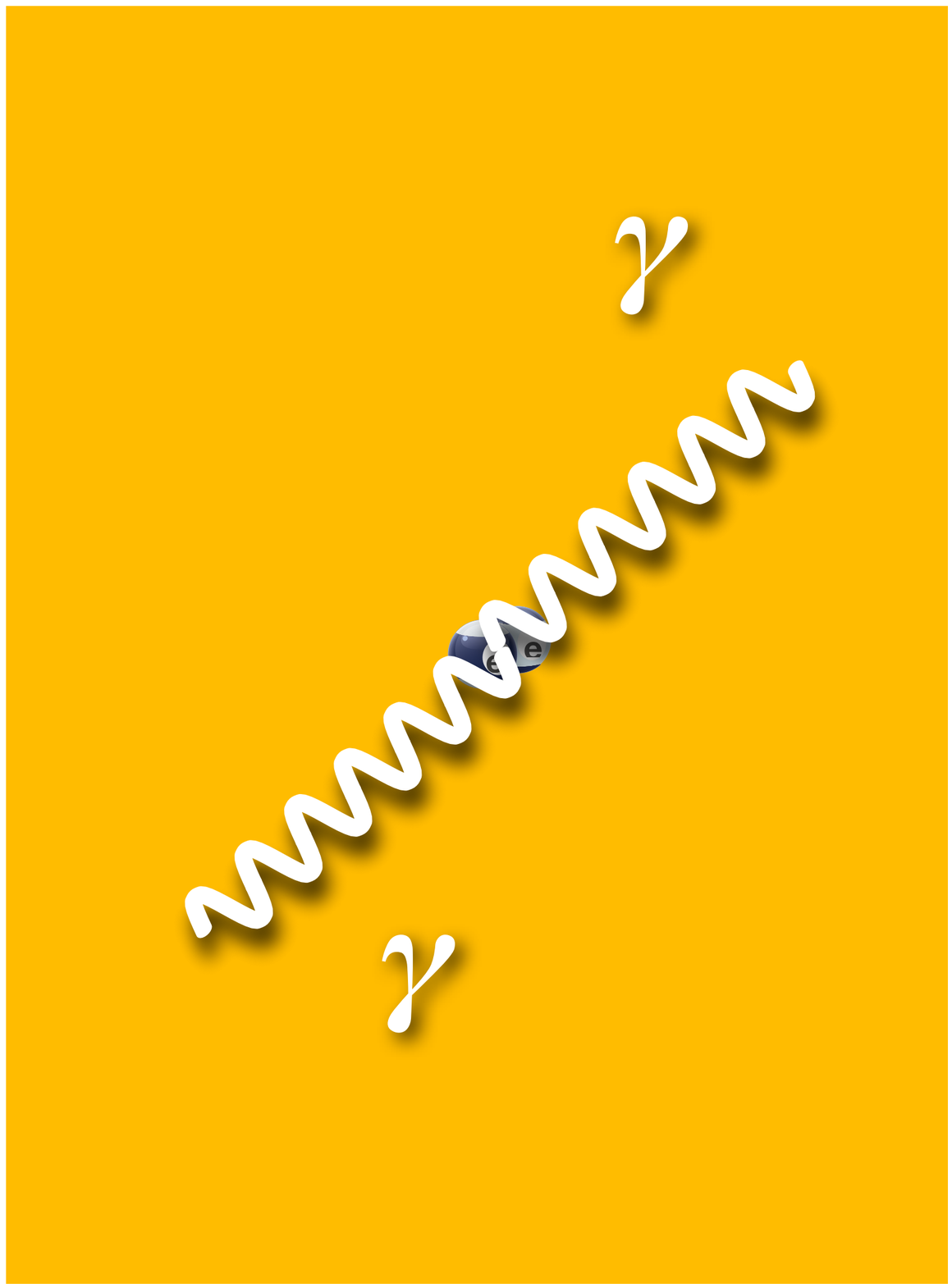
passing through matter


e-
e+

“Positronium”

annihilation:

an atomic dance of death



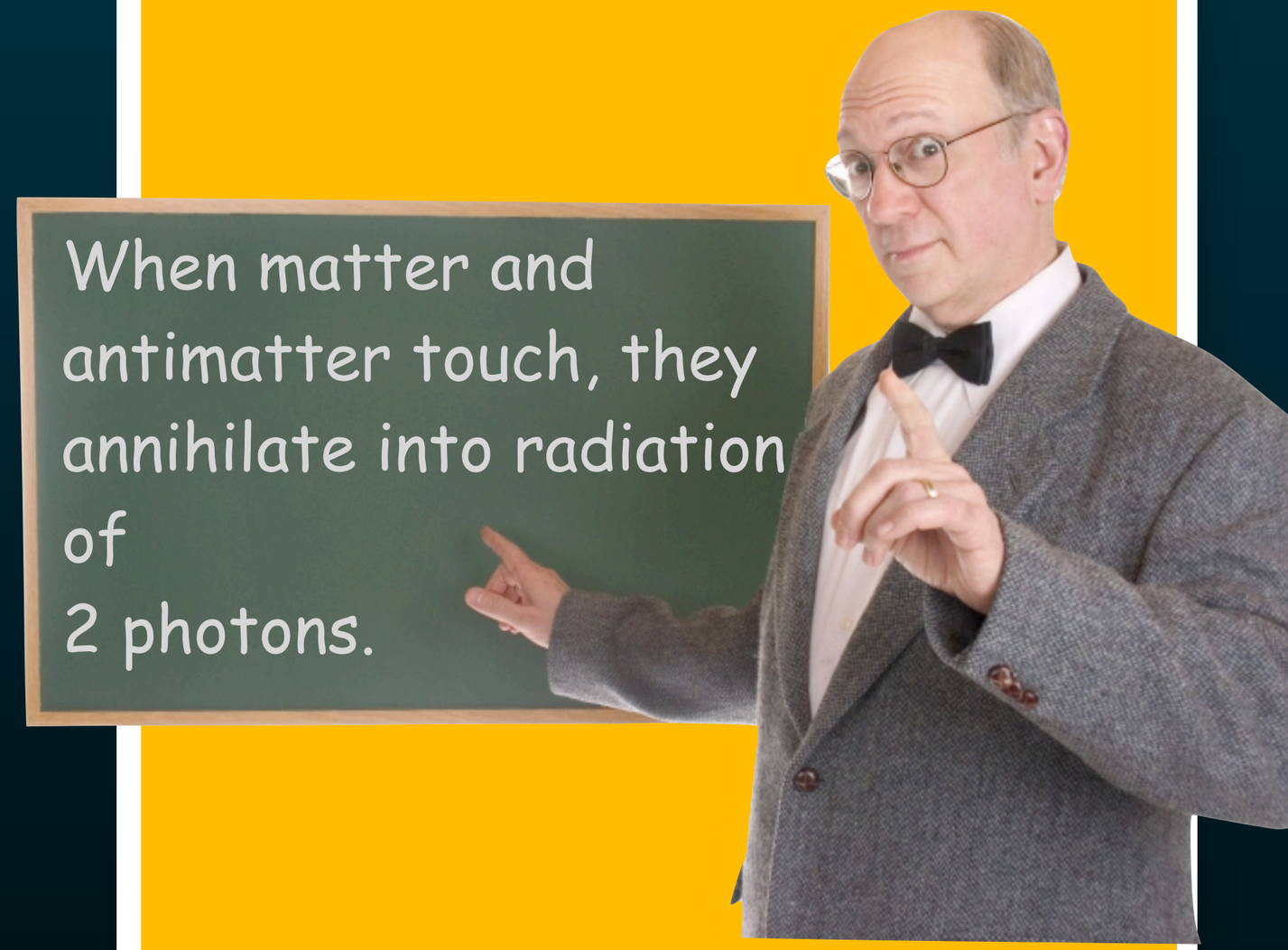
100% efficient

$e^- + e^+ \rightarrow 2\,\gamma$

matter-antimatter **annihilation**

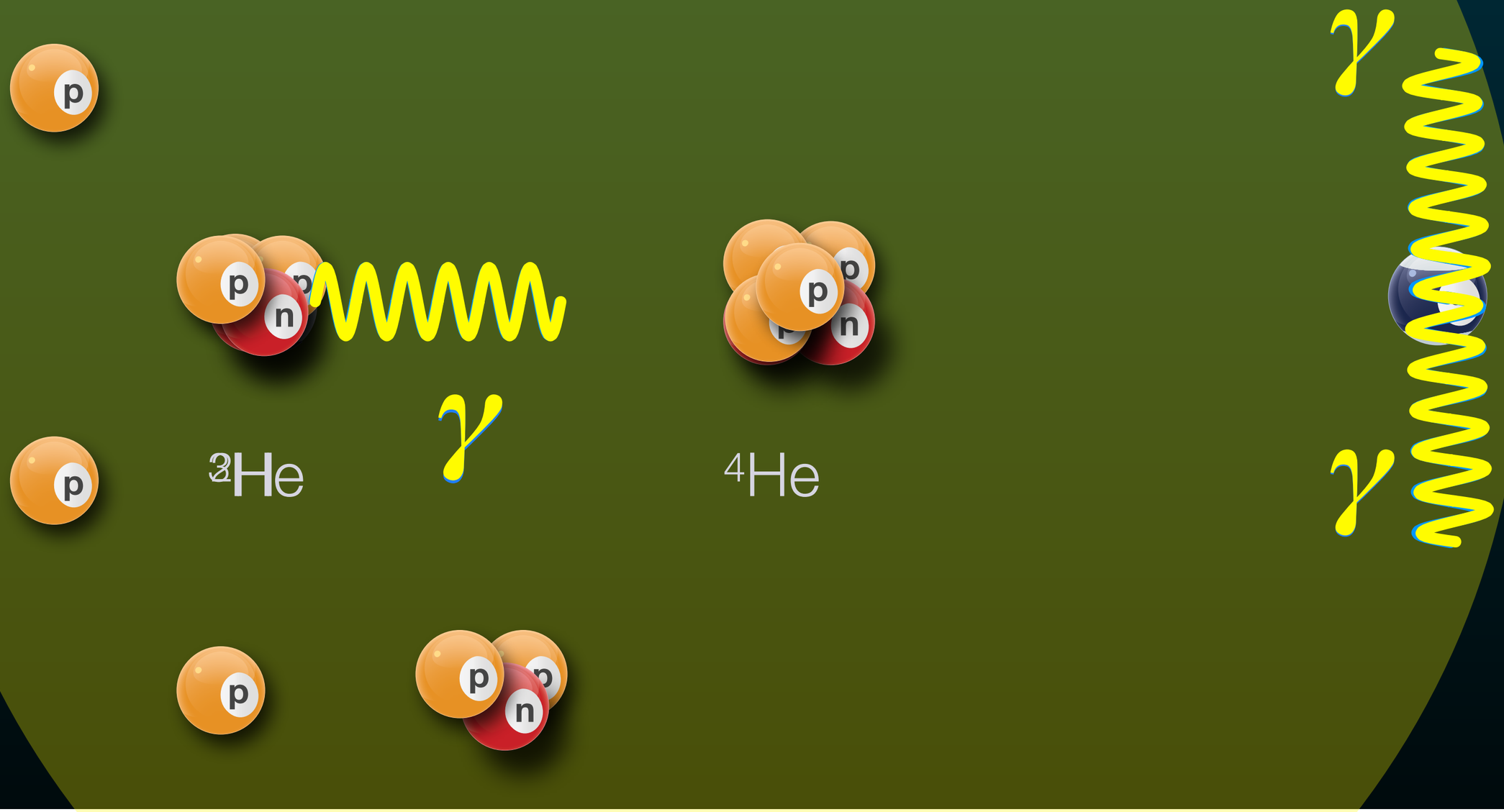
Review:

annihilation



a young sun...
hydrogen: protons and electrons.
lots of them.

the story of sunlight




e+

nuts and bolts

timeout.

nuclear reactions

stuff disappears!

a number:

3

 # ways for nucleus to decay

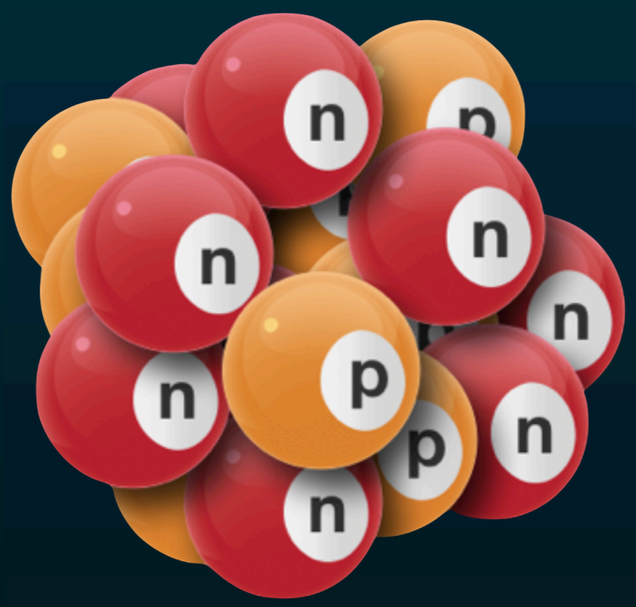
alpha decay

beta decay

gamma decay

“beta decay”

makes a new chemical



Fluorine

^{19}F

9p and 10n

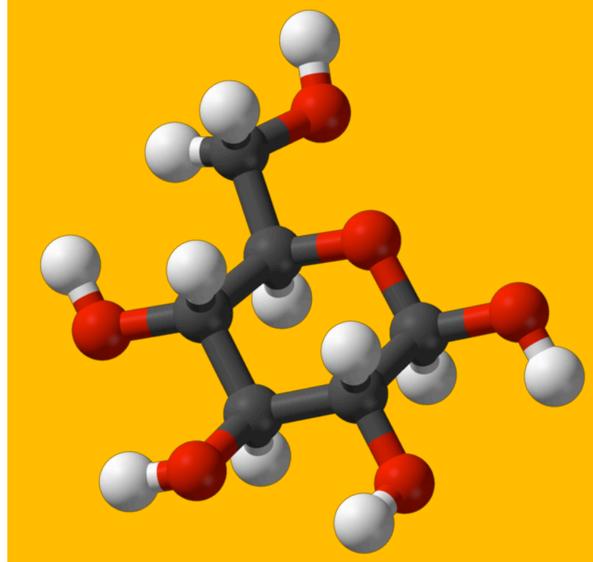
stable

metabolism

requires energy

glucose

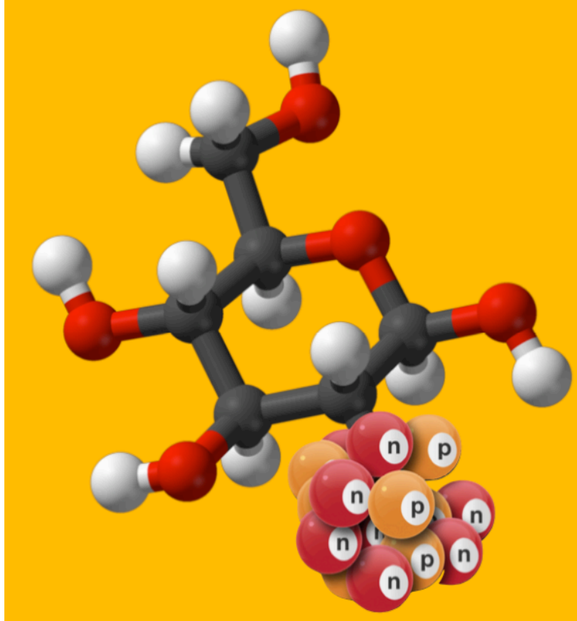
$C_6H_{12}O_6$



metabolism

requires energy

glucose



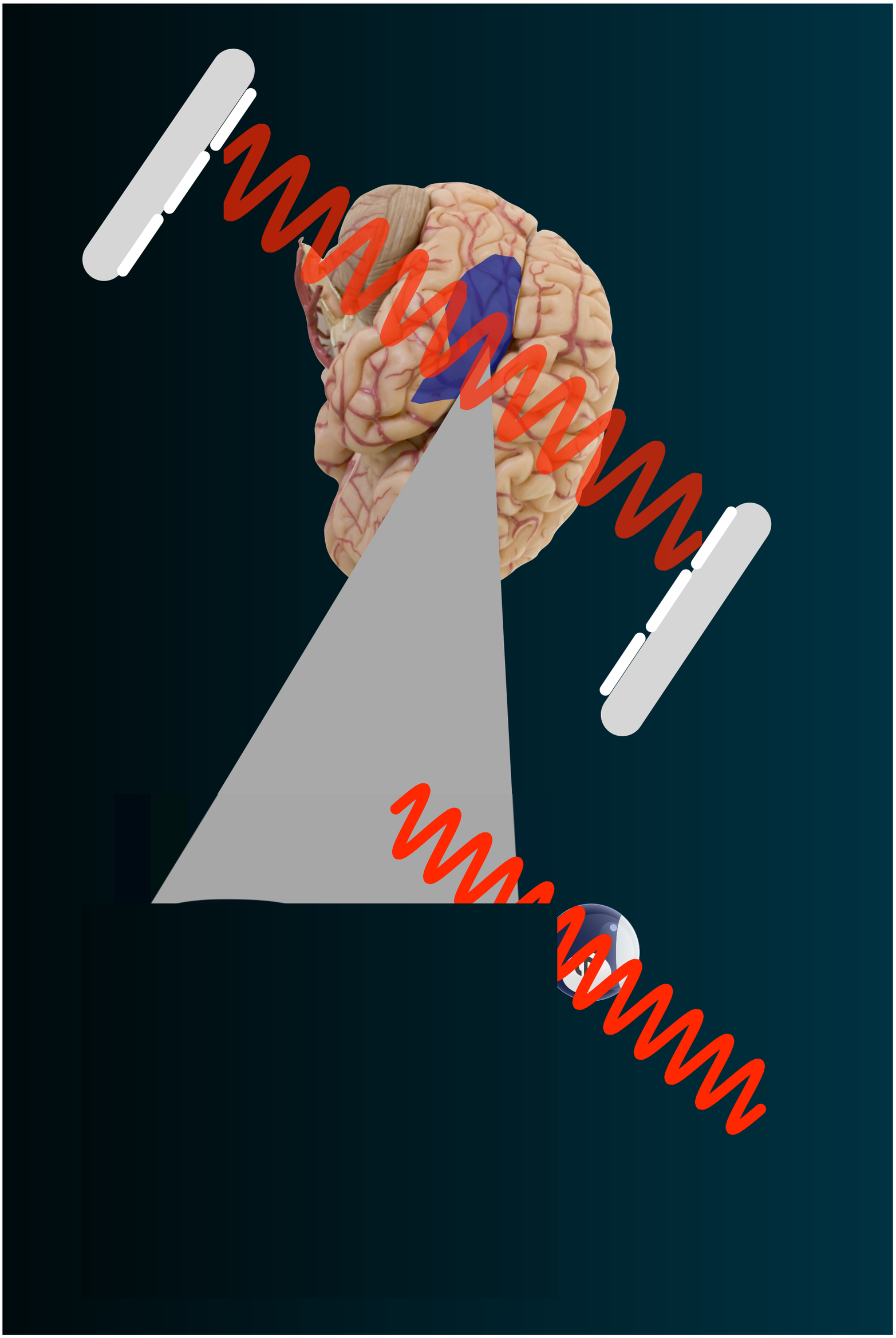
FDG*

Fluorine 18

*2-fluoro-2-deoxy-D-glucose, Fludeoxyglucose

Fluorine 18

to the rescue



PET scanning

Positron Emission Tomography

https://www.clevelandclinic.org/radiology/nuclear-medicine/PET.htm

http://www.radiologyinfo.org/

http://www-dsv.cea.fr/en/la-dsv/toute-l-actualite/presse/premiere-simulation-complete-d-un-examen-d-imagerie-tep-corps-entier-chez-l-homme


e+

3

Demon?

Dirac

Nobel

at the age of 31

Carl Anderson and Victor Hess

Anderson was 31

this is where it gets interesting

we need to establish a language for Dirac-like reactions

“Relativistic Quantum Field Theory”
essentially invented by Paul Dirac

notice a couple of things about what appears in Dirac’s equation

1. it’s about more than one thing: two electrons and a photon

    “regular” Quantum Mechanics is about single objects only

2. stuff appears and stuff disappears

what's

nothing.

what’s

what’s nothing

you’d maybe say:

no objects (particles…quanta)

zero energy

the Heisenberg Uncertainty Principle:

there's no state of Nature that can possess any precise value of, say, energy

and that includes Zero.

the Heisenberg Uncertainty Principle

will not allow a **void**.

but we *still* have a notion of the **vacuum**

it’s the lowest energy state in Nature

where there are no real particles

understanding whatsgoingonhere

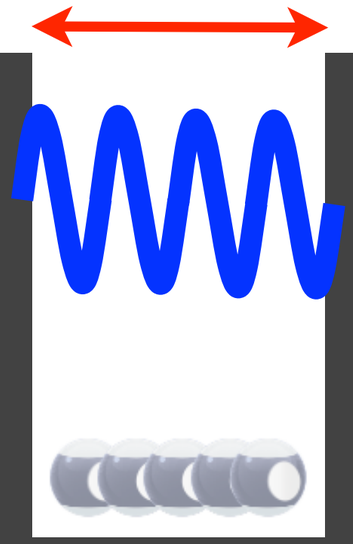
requires some mental fortitude

remember

trying to trap an electron?

let’s make it all about nothing.

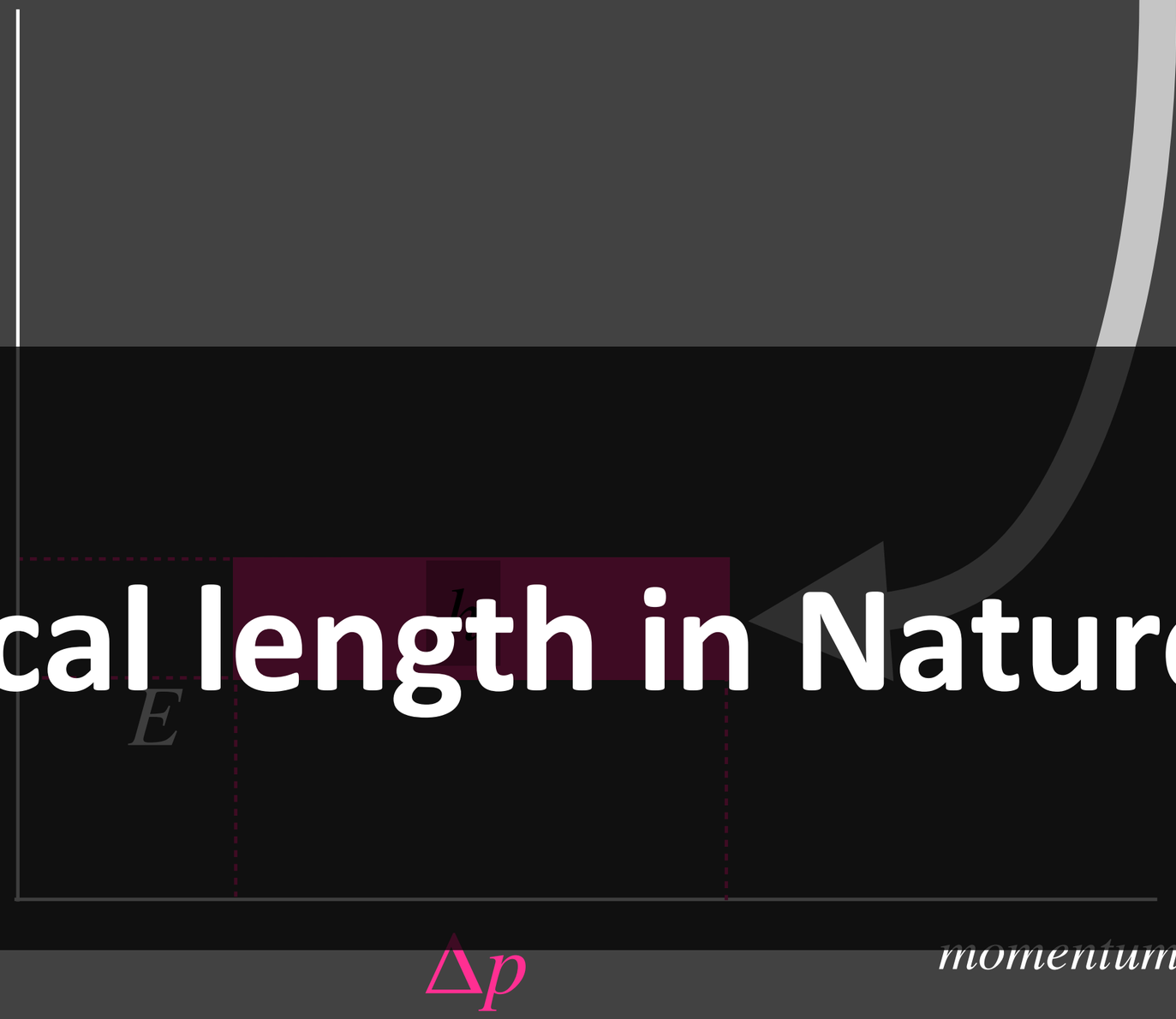
an electron…somewhere here:



make the trap smaller

uncertainty

$$\Delta x \, \Delta p \sim h$$



one. more.
time.

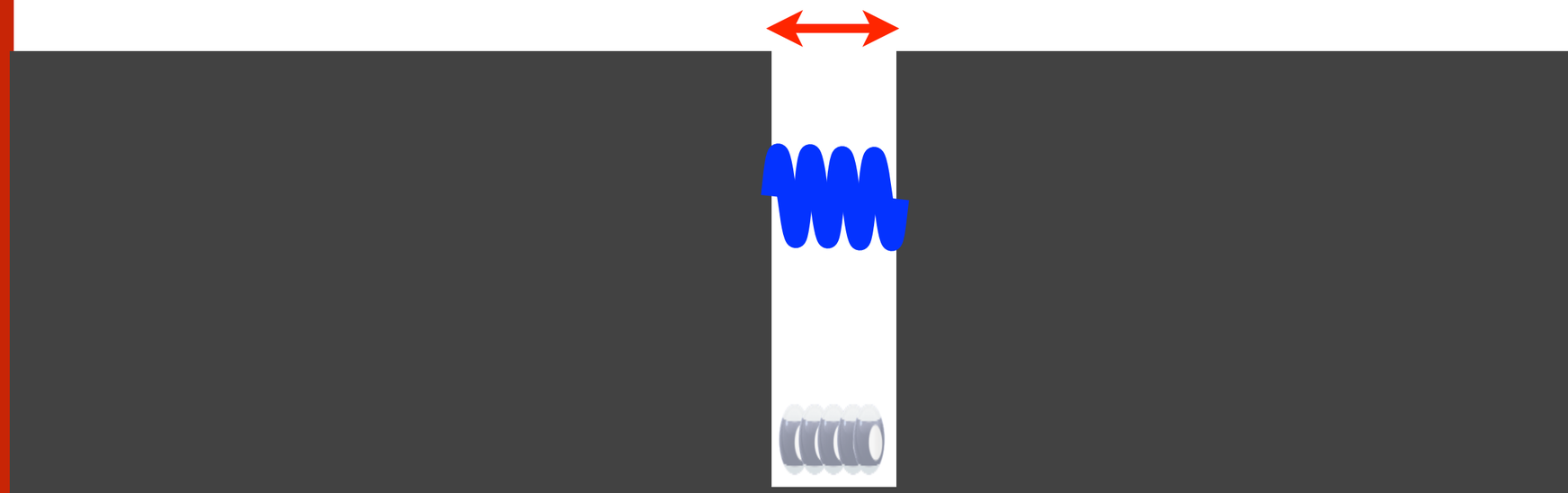
there is a critical length in Nature

remember

trying to trap an electron?

do nothing tighter

or an electron, somewhere here:



make the trap smaller to this value:

$$\Delta x \sim \frac{h}{m_e c}$$

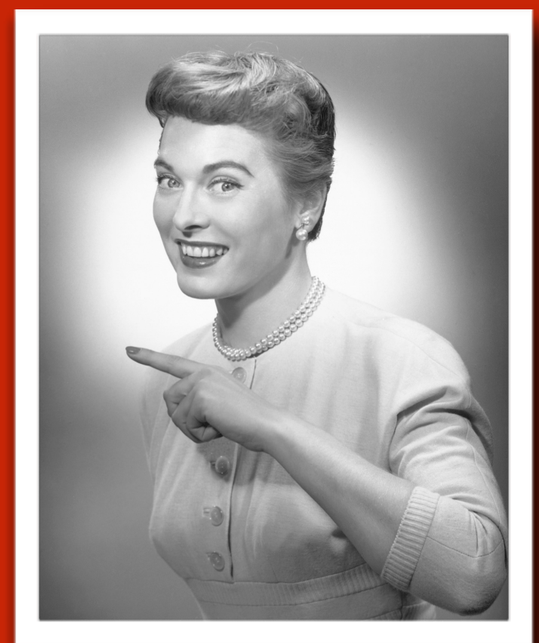
$\sim 2.2 \times 10^{-12}$ m

The size of a Hydrogen atom... 5×10^{-11} m

The size of a proton... $\sim 10^{-15}$ m

an important

but simple calculation about nothing



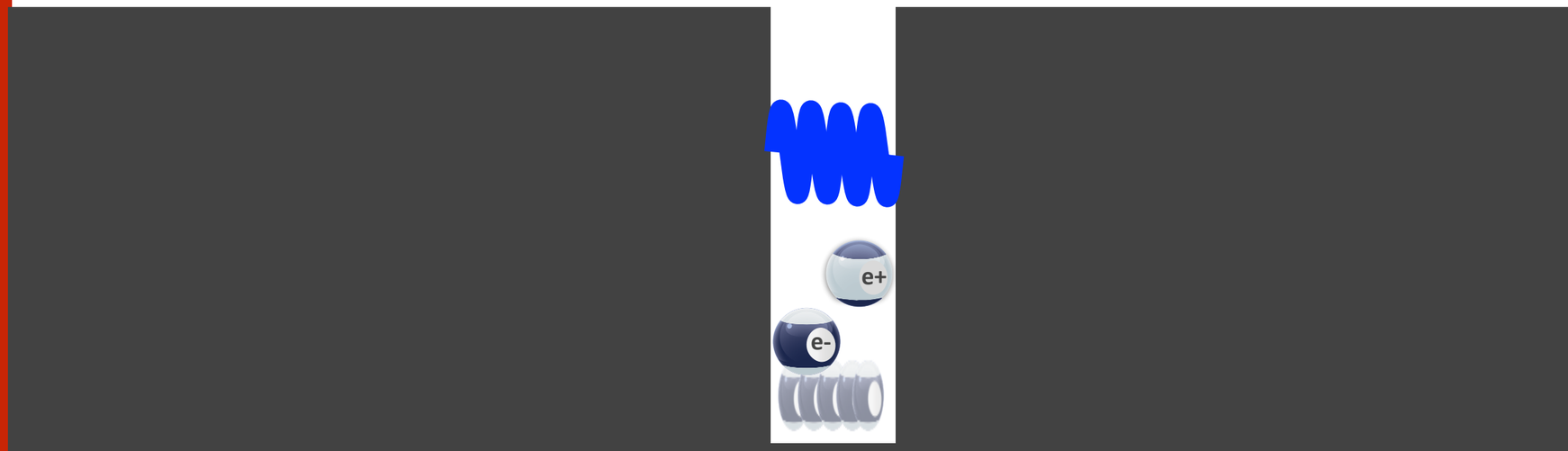
remember

trying to trap an electron?

do nothing tighter

What's in Nothing with an electron?

electron + nothing, somewhere here:



make the trap smaller to this value:

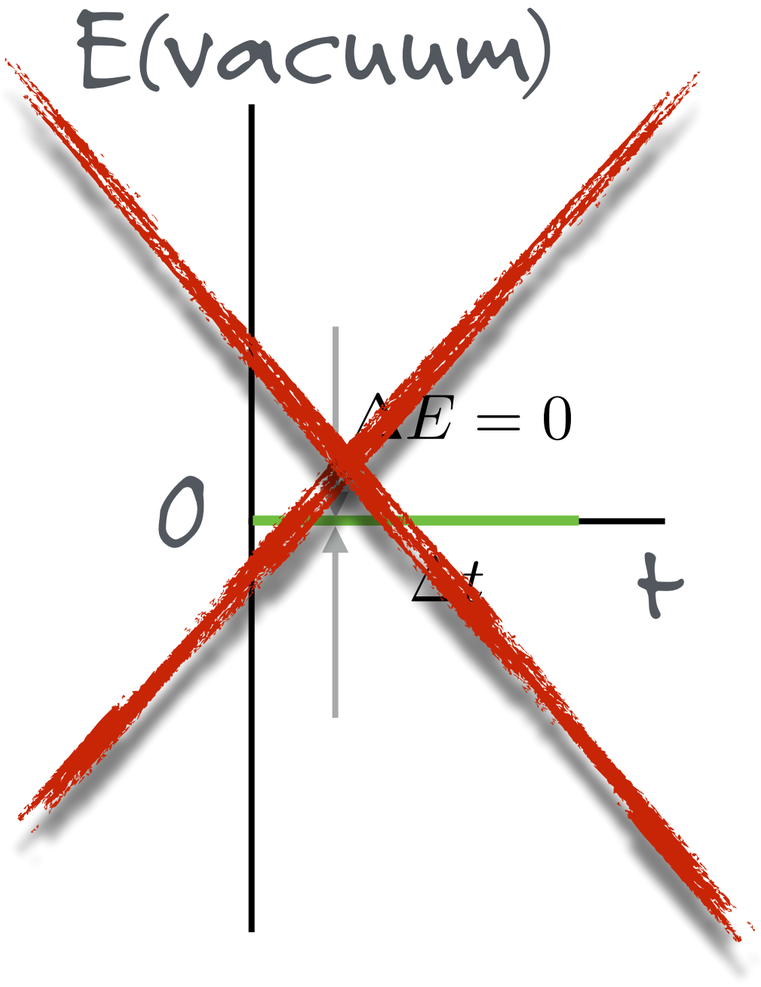
$$\Delta x \sim \frac{h}{m_e c} = \lambda_C$$

~ 1/2 x 2.2 x 10^{-12} m

Heisenberg, again

no precise energy in nature $\Delta E \Delta t \geq h$

that includes E = 0.0

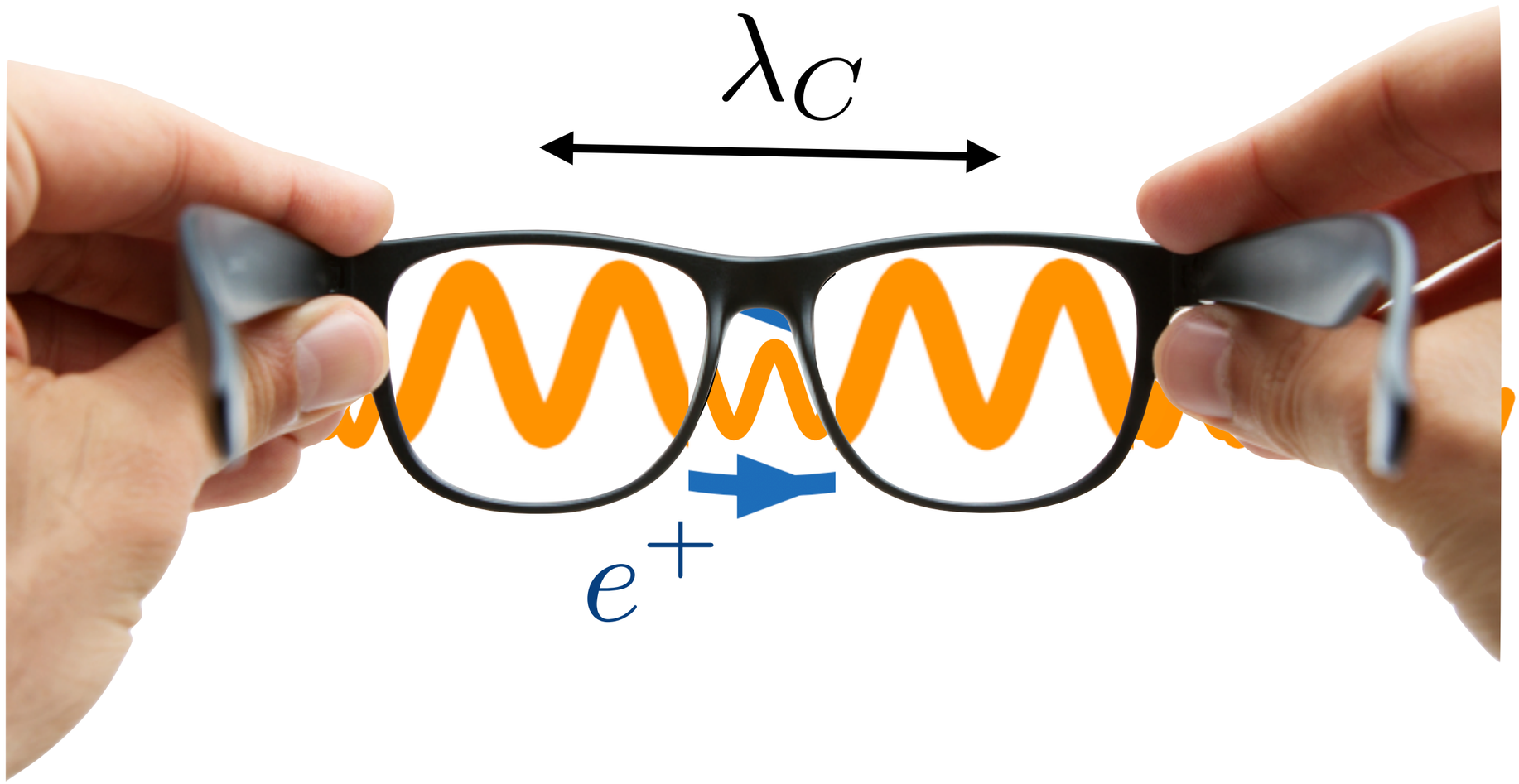


energy means stuff

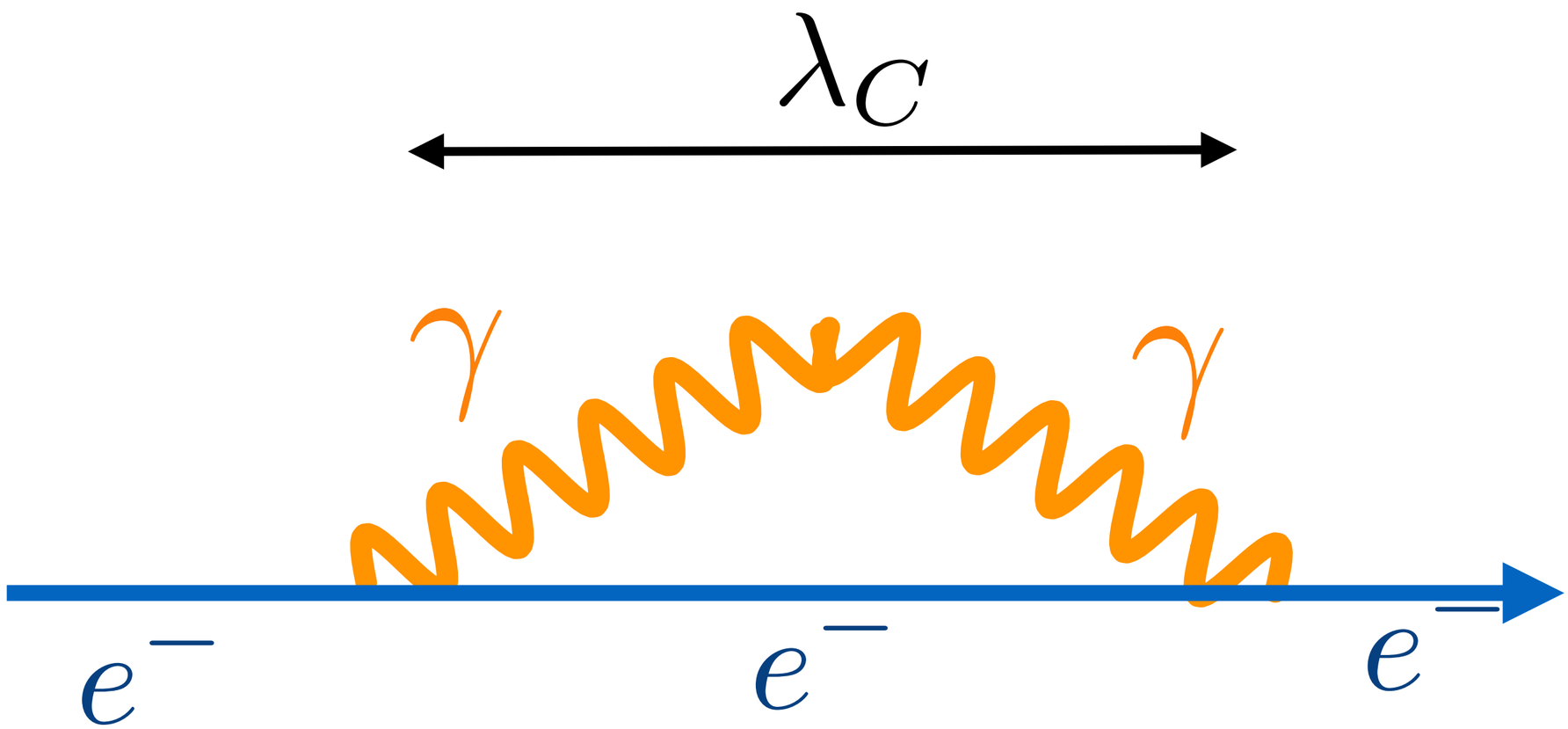
shrink your gaze to this critical size

the same thing happens

trap? How about looking closer and closer



trap? How about looking closer and closer

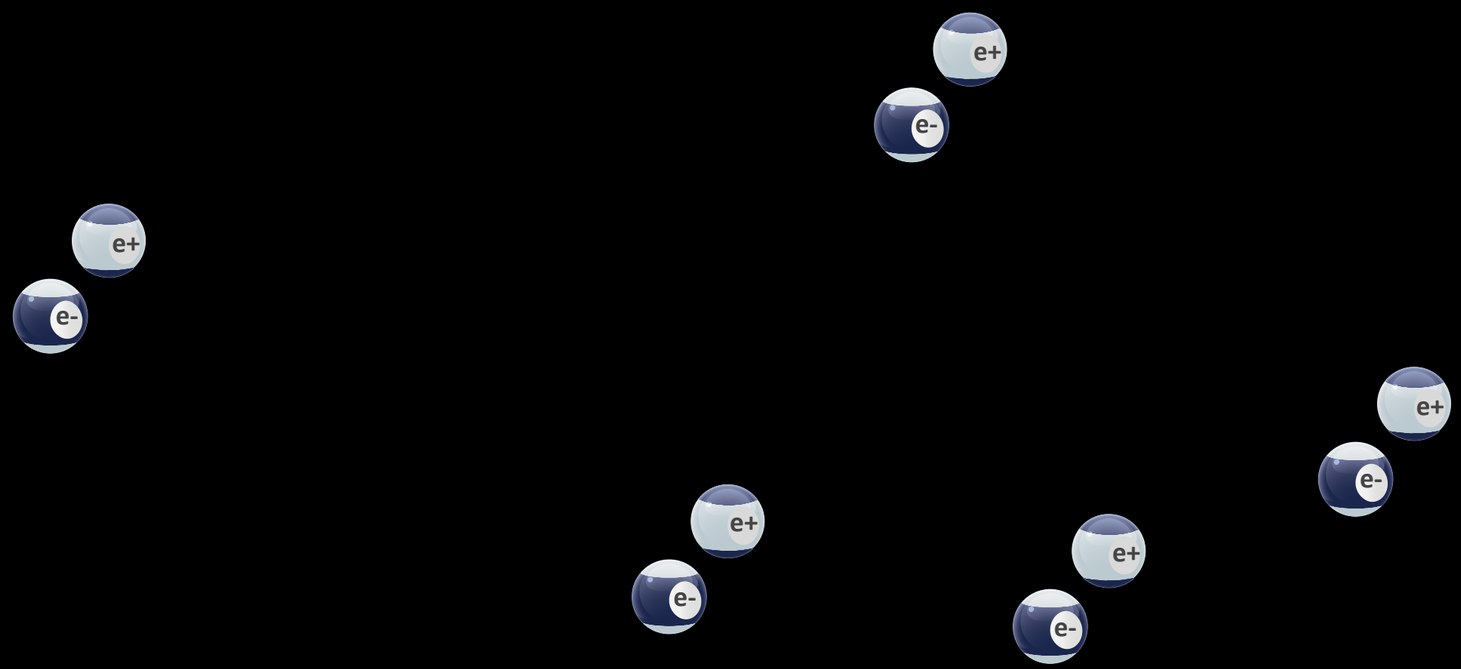


pop

that fluctuation means that

particle-antiparticle pairs pop into and out of existence

all the time



uncertainty principle

+ the particular length of:

$$\lambda_C = \frac{h}{mc}$$

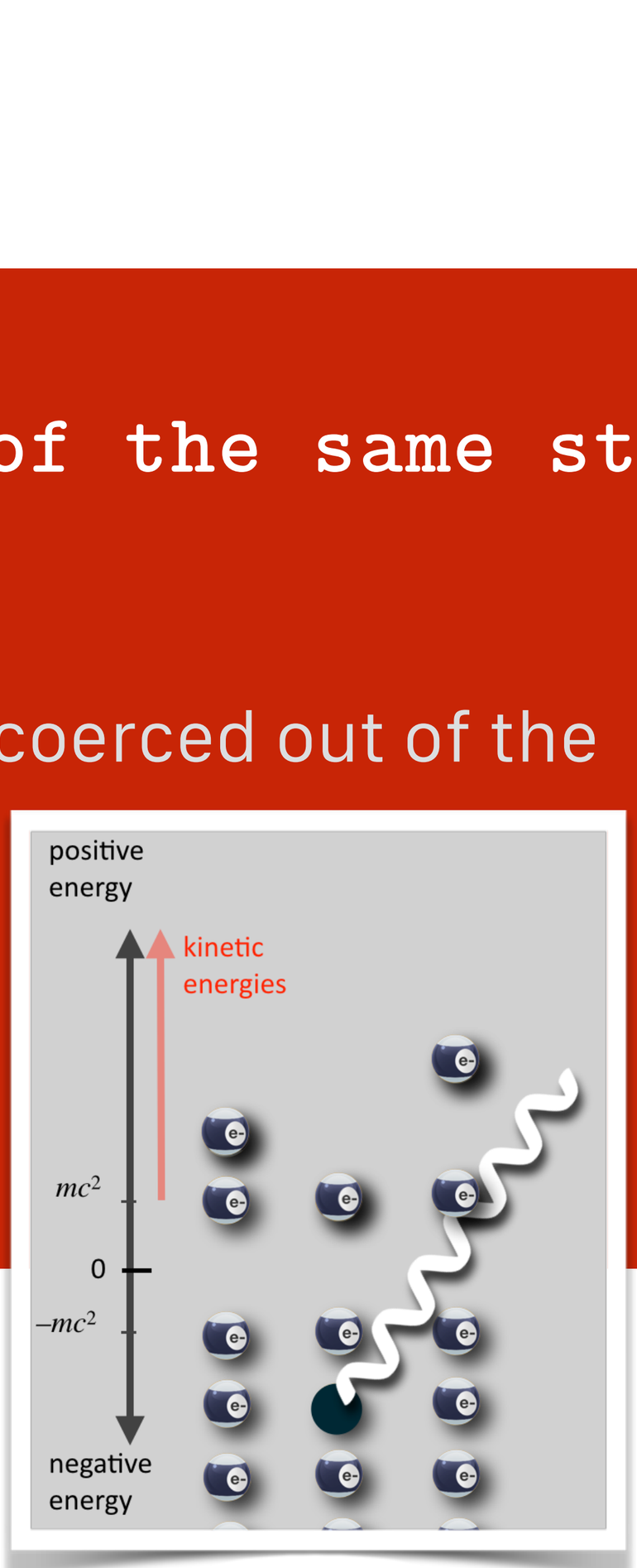
makes the vacuum very active.

they are all popped out of the same stuff

the vacuum Field of the electron

electrons appear because they’re coerced out of the vacuum

like by a photon



the quantum vacuum

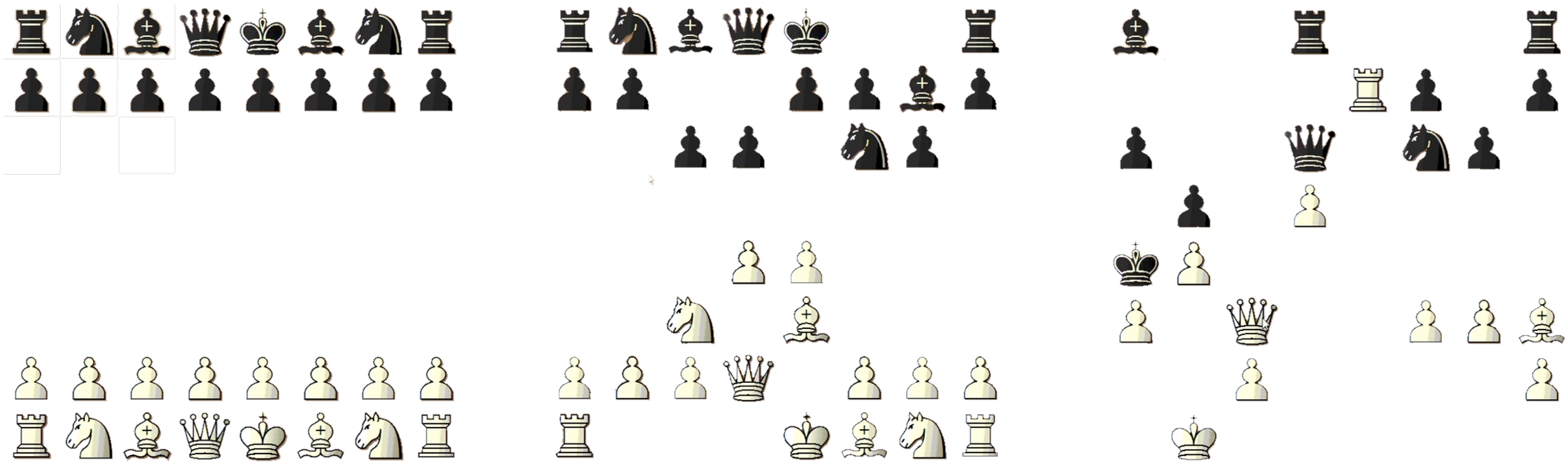
and “Relativistic Quantum Field Theory”

a word about theories

let's play chess...

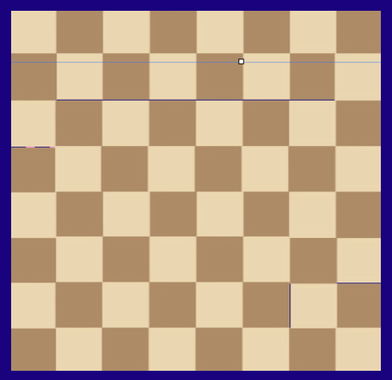
my model of chess

watch tons of matches



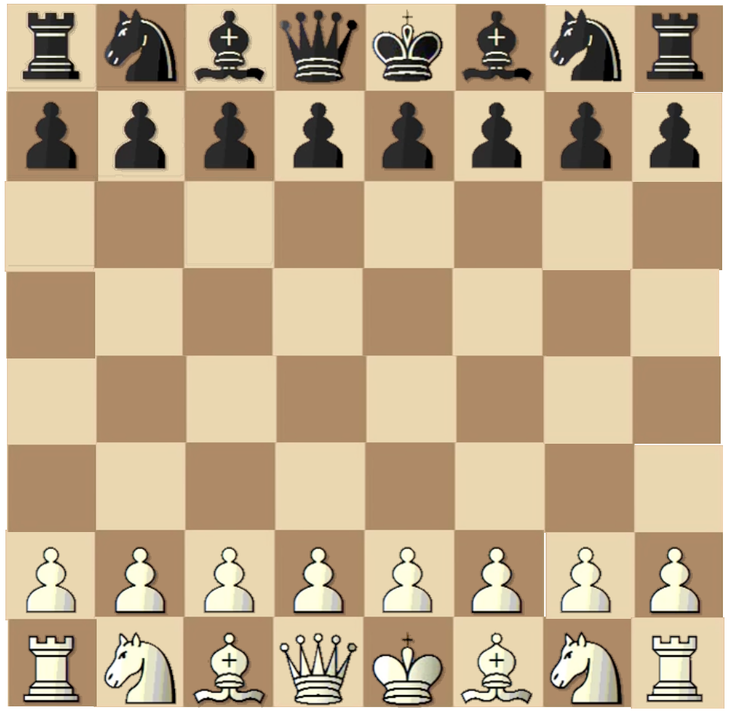
my model requires

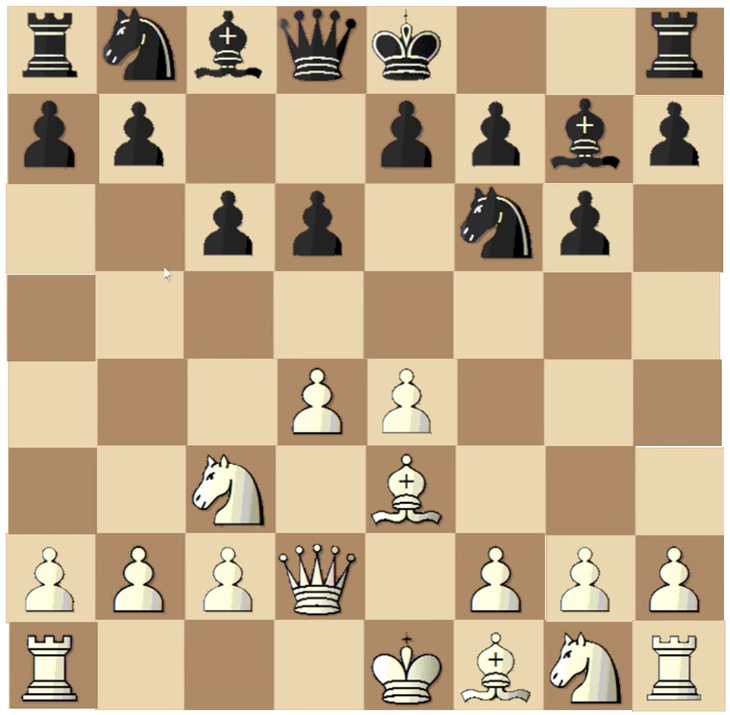
the existence of a new entity

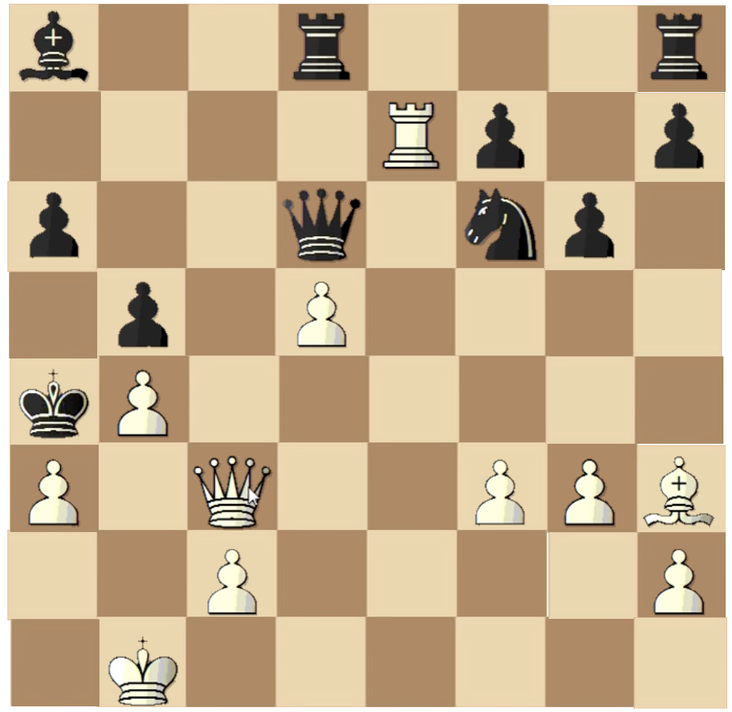


my model of chess

only with the board do the rules make sense

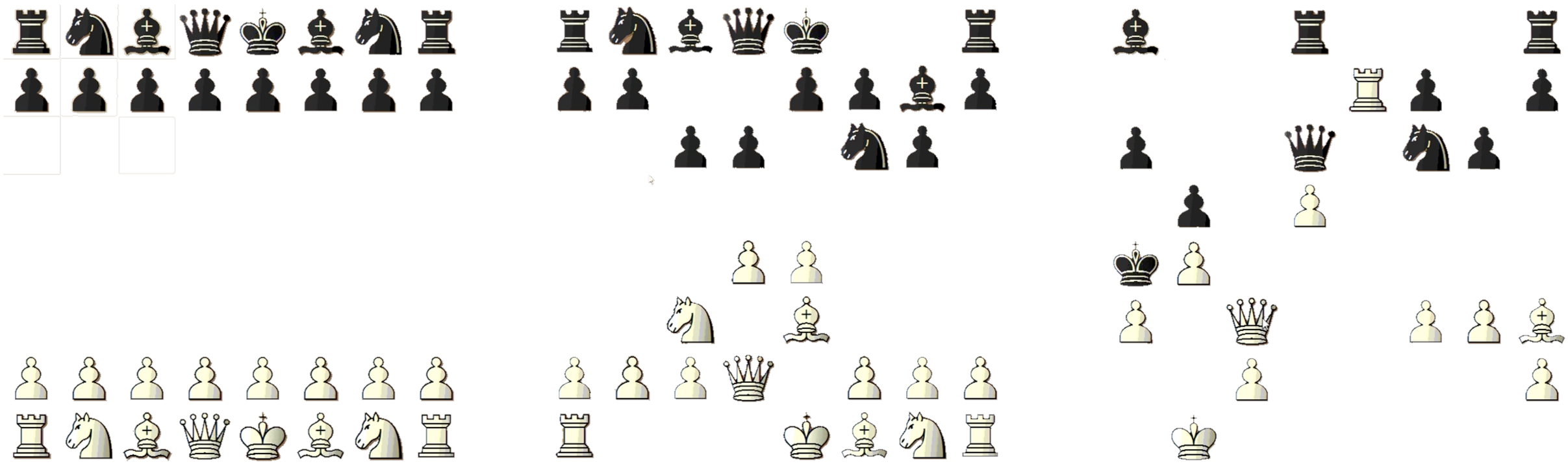






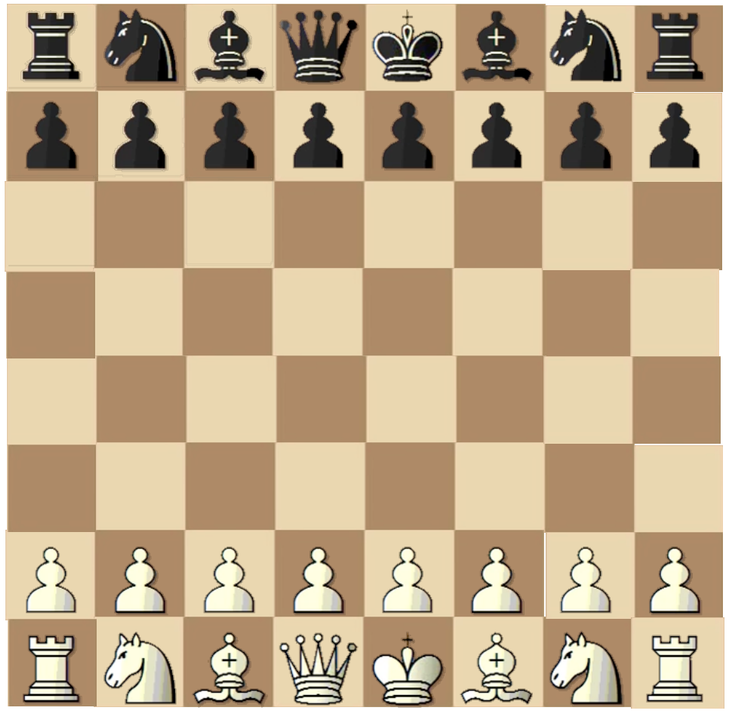
remember

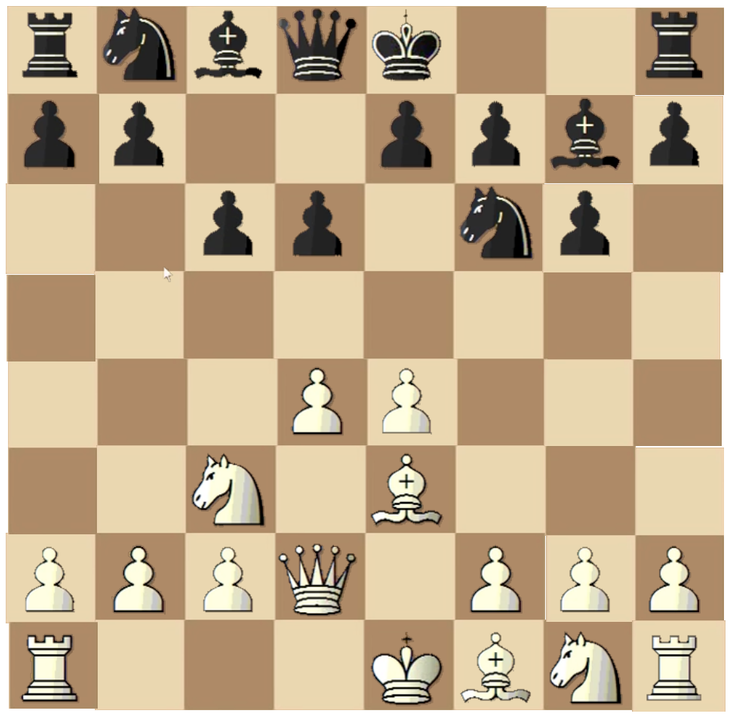
what I see are the pieces

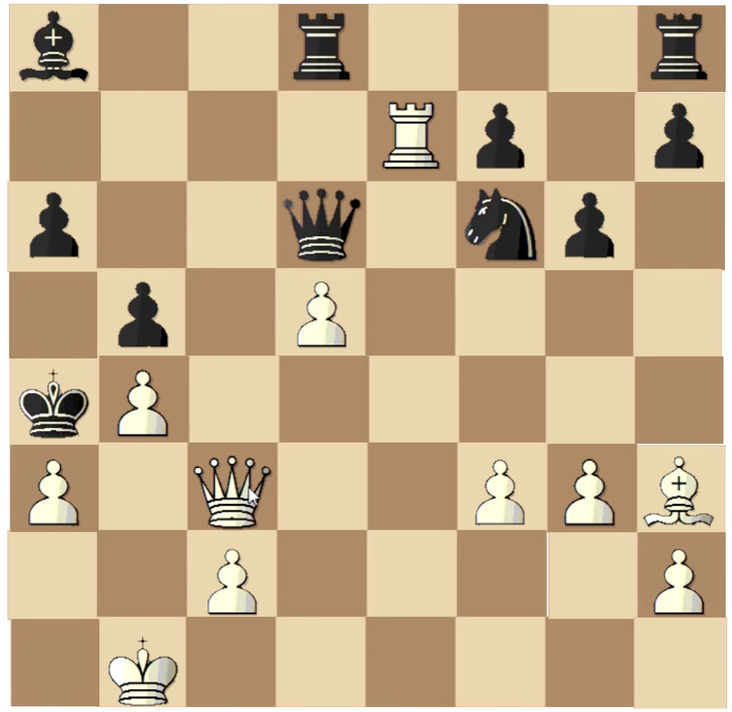


remember

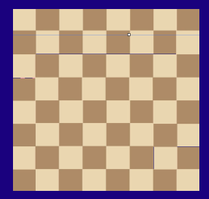
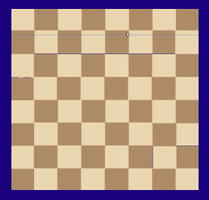
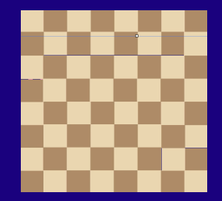
what I need to be the case...is the board







The technical description:

"if it walks like a  and it quacks like a  , then it must be a  "

"  "

a successful physics model that requires an additional commitment!


PHYSICS
OFFICE
COMMON SENSE!

what about

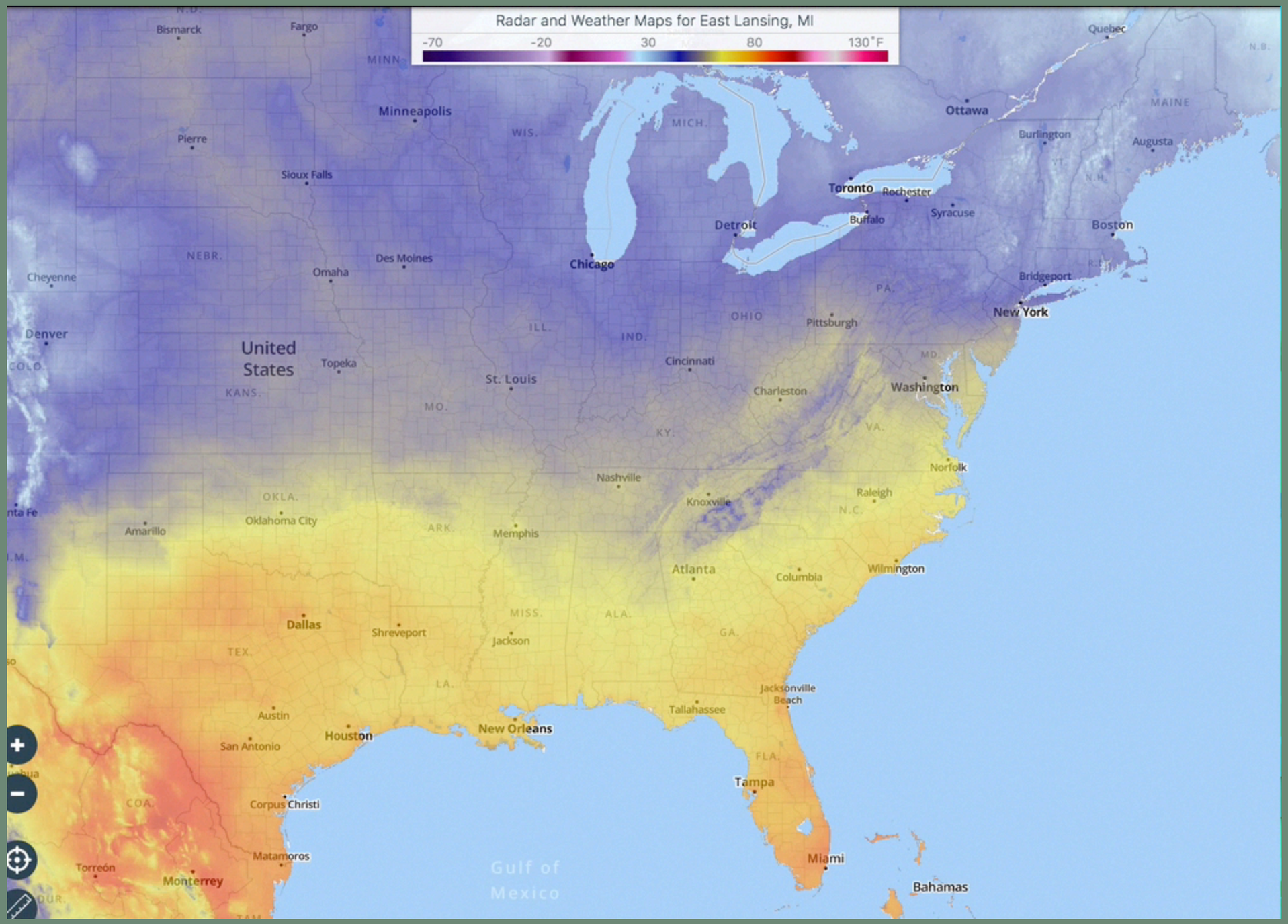
fields?

fields

a number in space

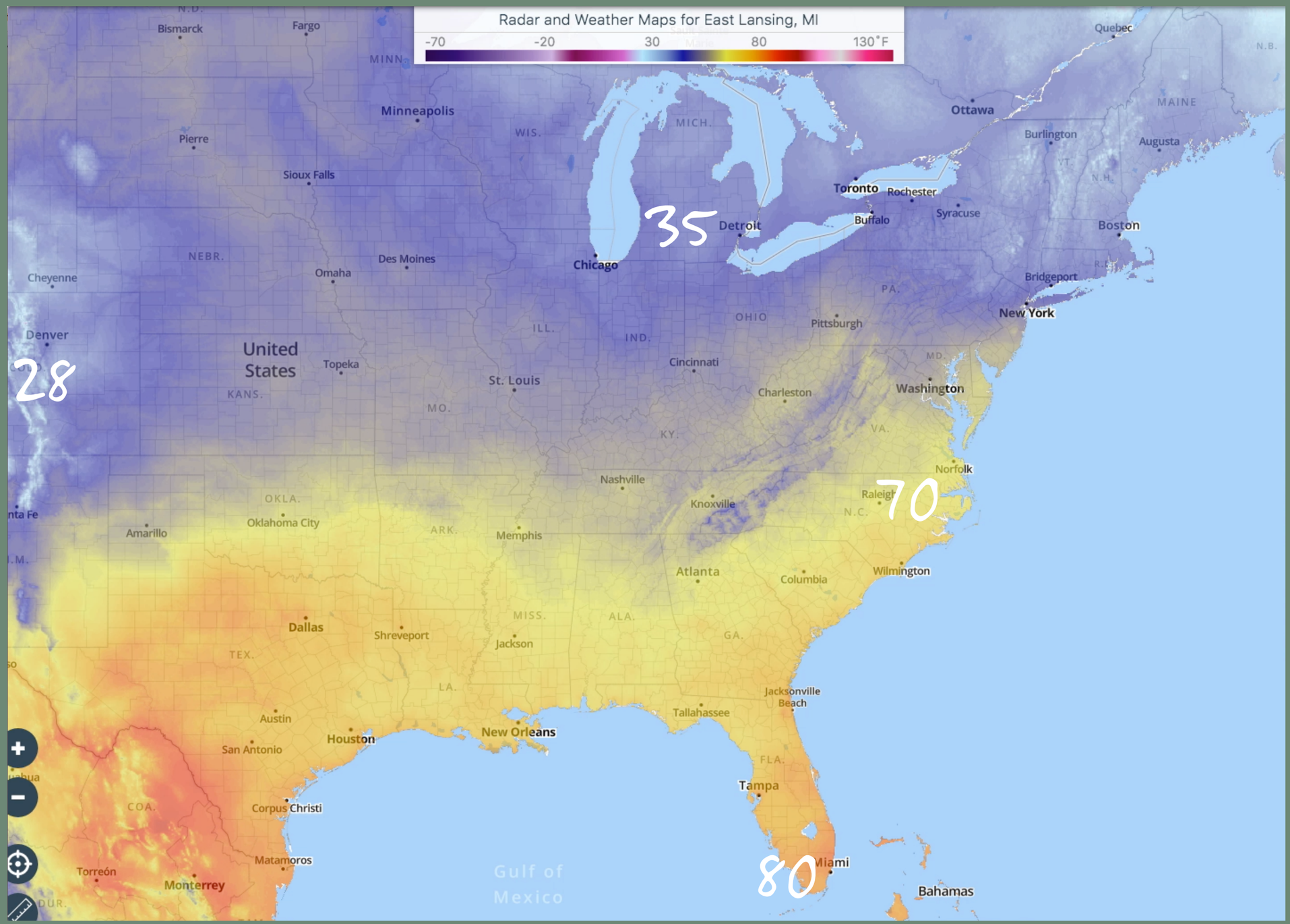
you know one

everywhere...a number



you know one

everywhere...a number



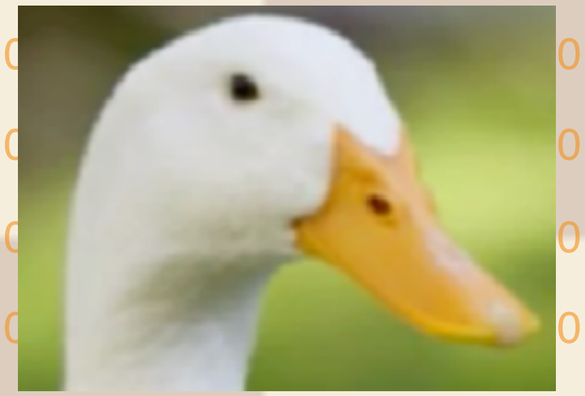
what's a particle?

it's localized wave in a field

PHOTON FIELD

a photon γ

PHOTON FIELD



a photon γ

ELECTRON FIELD

electron

e

0	1	2	0	-1	-2	-1	-1	-2	1	1	1	-1	-2	1	-1	-1	-1	-2	-1	-1	-2	1	-1	0	1	0	0
2	-1	-1	0	-2	0	2	1	2	-1	-1	1	0	-2	-1	-2	-1	-2	2	-2	1	-2	-1	2	1	0	1	2
1	0	2	1	-2	1	-1	0	1	1	2	-2	-2	-2	0	0	-2	0	1	2	-2	-2	0	2	0	1	-2	-2
0	0	1	-2	-1	-1	-2	1	0	0	0	0	1	1	0	2	-1	1	2	0	0	0	1	1	1	-2	-2	2
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2	2	-1	-2	-2	-2	0	2	-1	-2	-1	-2	-1	0	-2	-2	-2	-1	1	1	2	2	1	-2	-1	-2	1	-2
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0	1	-2	-1	2	1	2	0	1	2	1	2	0	2	2	2	-2	1	-2	1	0	0	2	0	-2	-1	-2	0

vacuum fluctuations

here's how

stuff happens

in this particle field theory model

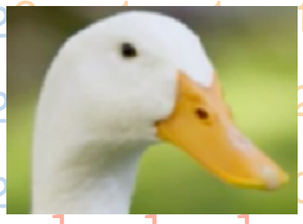
PROTON FIELD

proton

p

electron

photon field "disturbance"

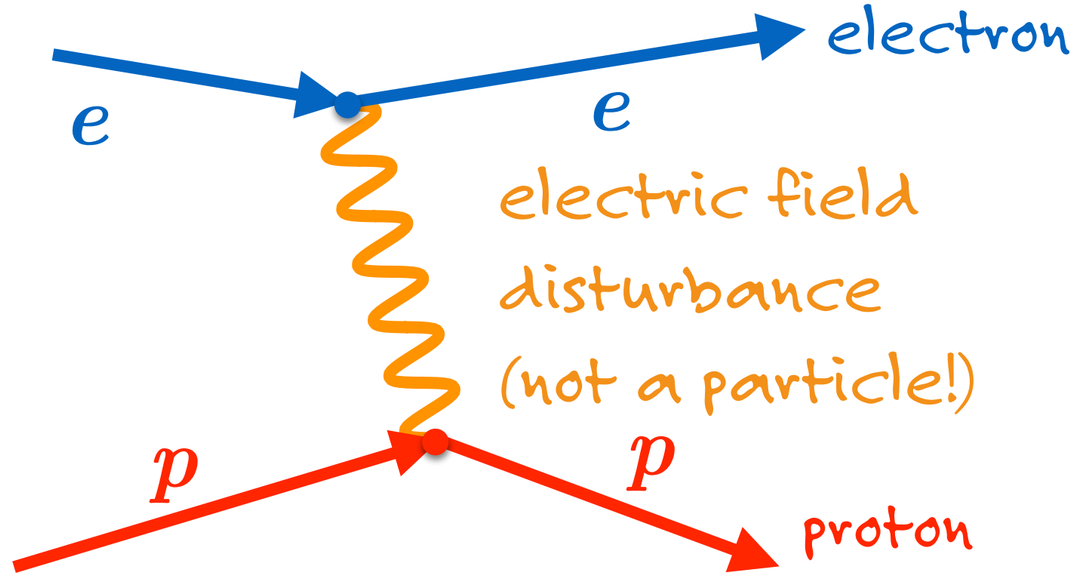


time

proton

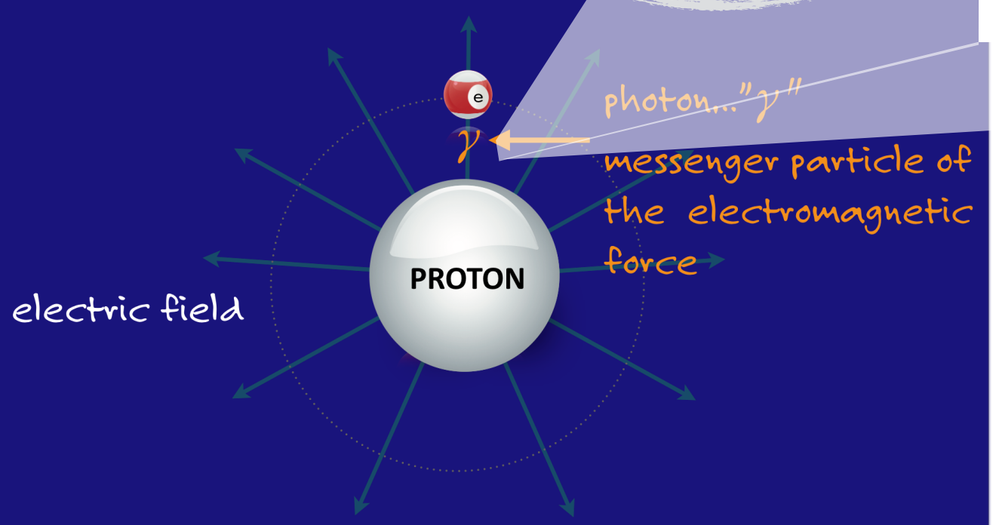
our atom

2nd way



forces?

from particles, 1st way



particle field theory*

the best theory in history

never an incorrect prediction

outrageously precise agreement, prediction and measurement

*Quantum Electrodynamics

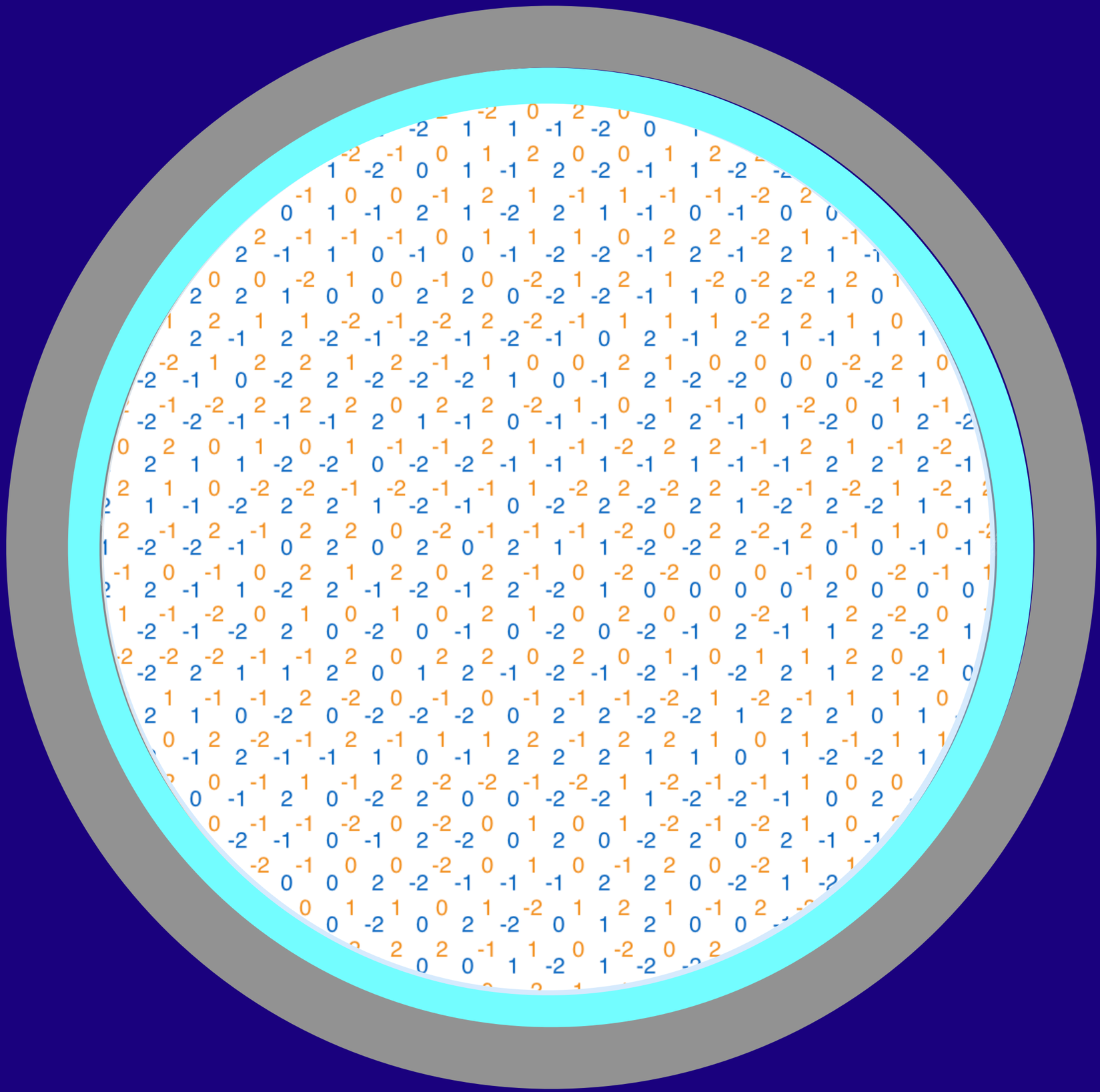
what's more fundamental?

a winner

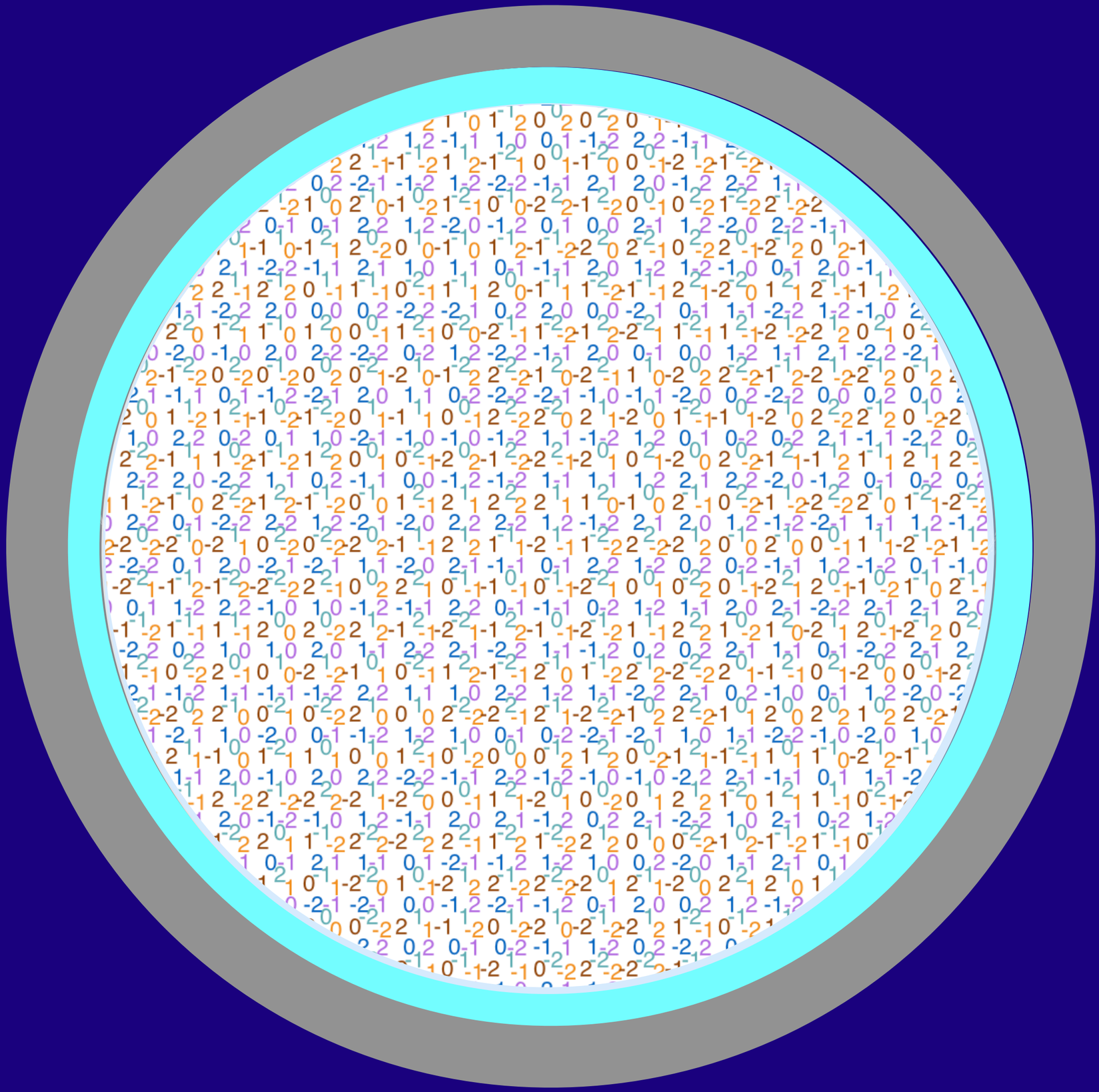
particles

fields

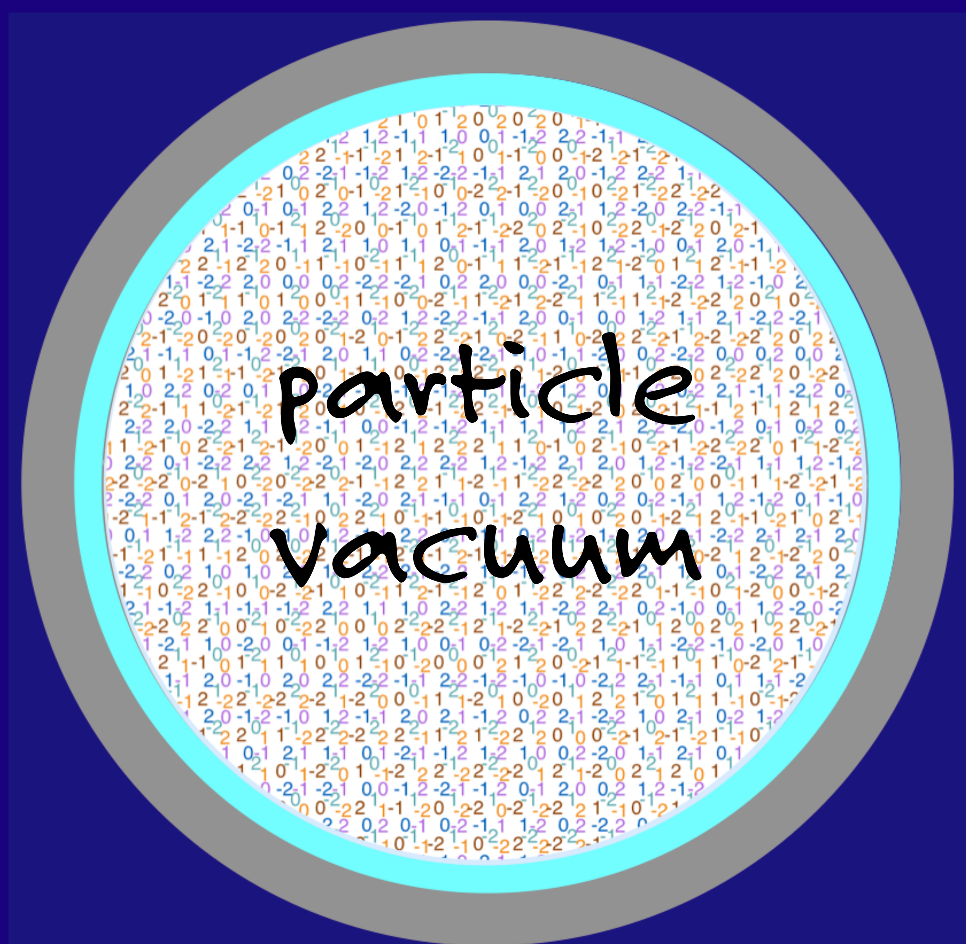
the particle vacuum full of fields:



the particle vacuum full of fields for every "particles"



two predictions for "space"



energy in the particle vacuum is

30,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,0
00,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000

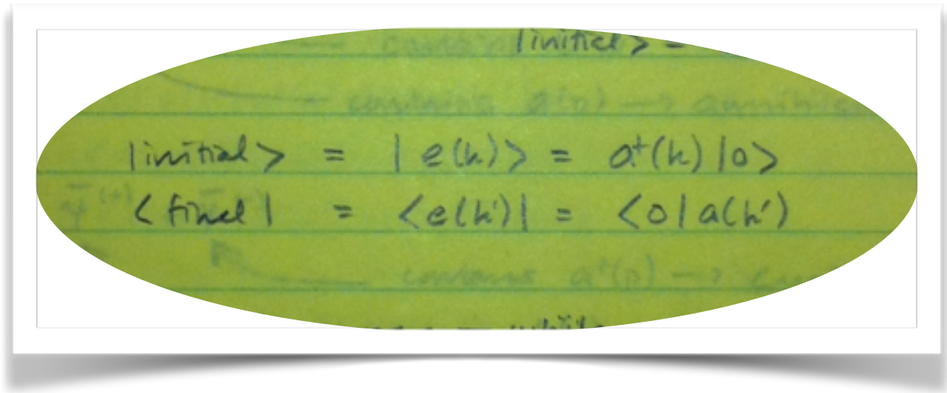
times the energy in the dark energy vacuum

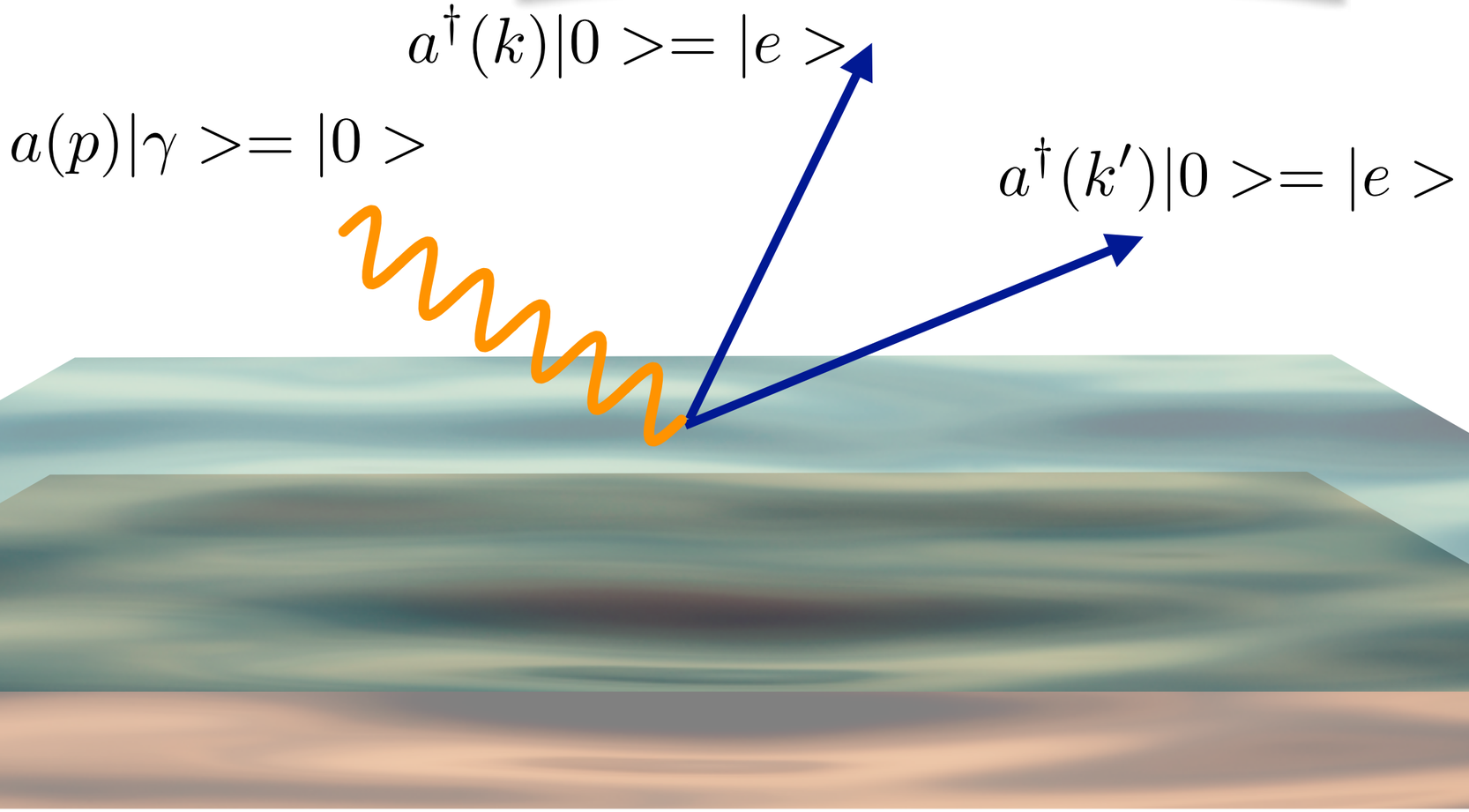
this has a name

"the worst prediction in the history of physics"

a little more specific

what the mathematics tells us





it’s not like the photon is now “in” the electron

the photon pops the electron- positron pair out of the Ur electron field
and itself disappears back into the Ur photon field.

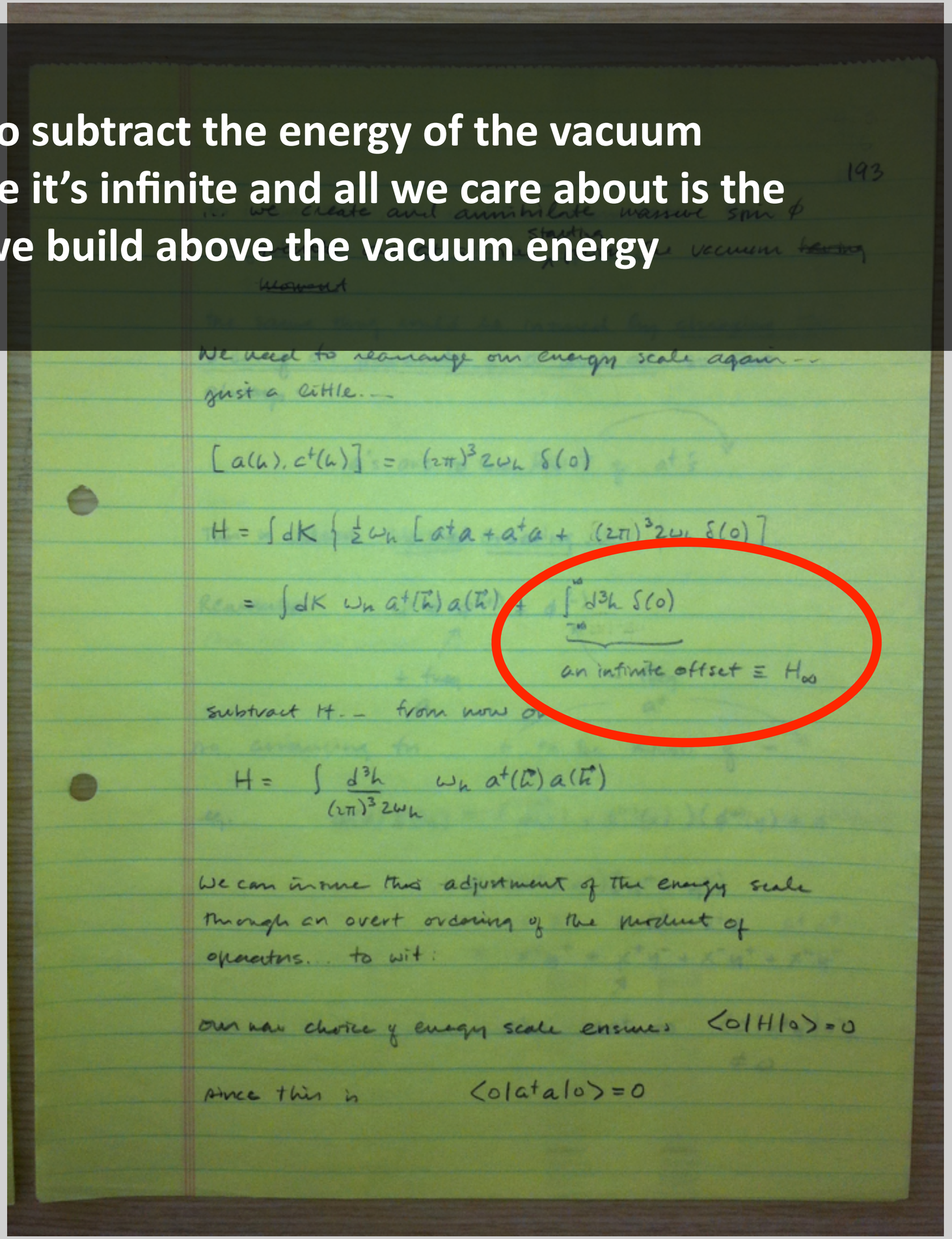
but what does that mean?

it means that the vacuum is full of energy

like a reservoir

particles are created out of the vacuum

we have to subtract the energy of the vacuum away...because it's infinite and all we care about is the states we build above the vacuum energy



Okay. So we don’t like infinity

we subtract it away and worry about the difference between

infinity and finite energies of real particles

Seriously?

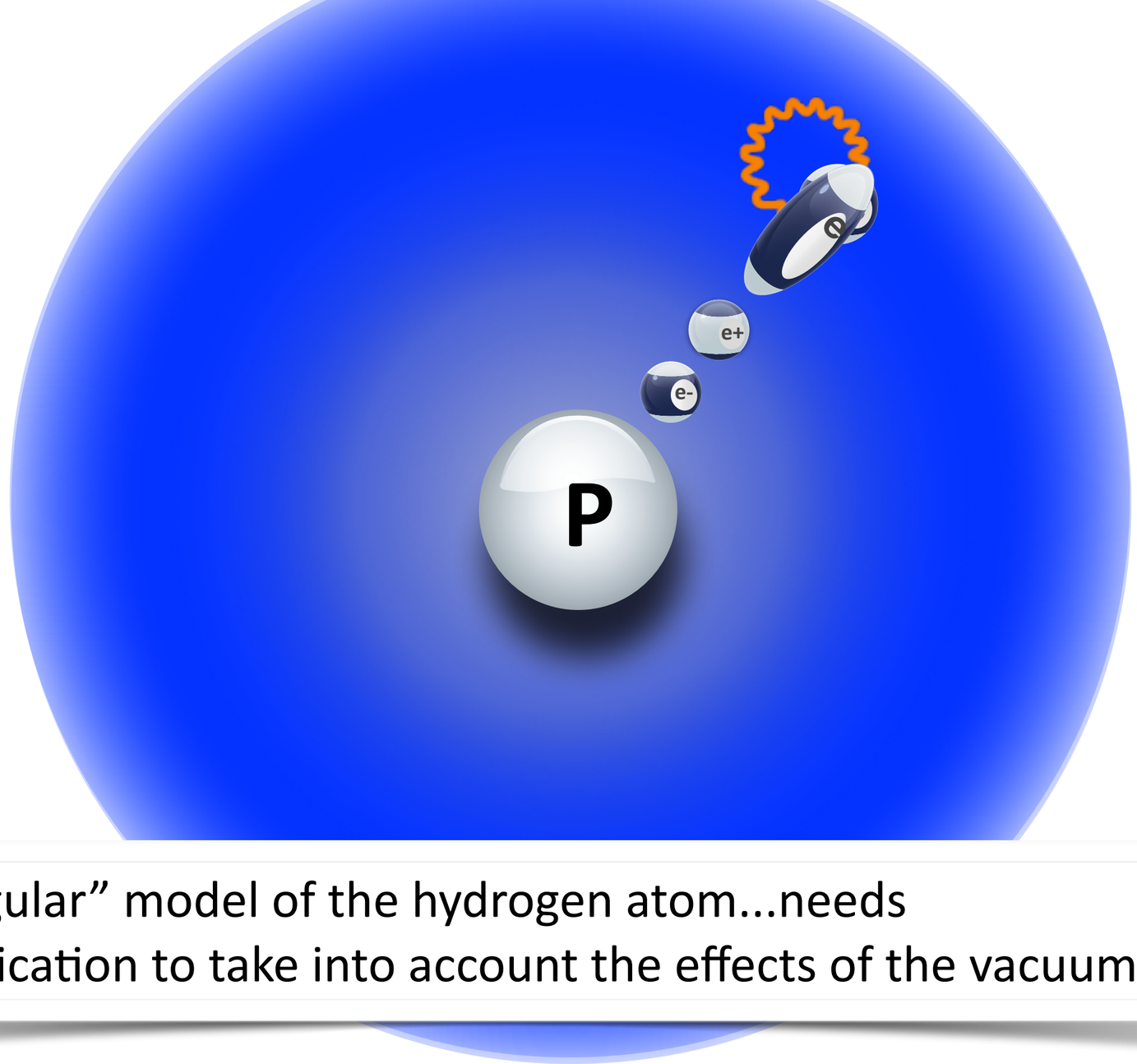
That seems to be the case.

This picture works with exquisite precision and accuracy.

but the vacuum

is roiling with particle-antiparticle "virtual pairs" popping into and out of existence

multiple ways we know this.



A "regular" model of the hydrogen atom...needs modification to take into account the effects of the vacuum

The electron cloud is spread out by the virtual photon and the positron's effects...and that changes the emission spectrum of hydrogen:
The **"Lamb Shift"**...measured after WWII with microwave technologies

1955 Nobel Prize

Willis E. Lamb

died just a few years ago at the University of Arizona

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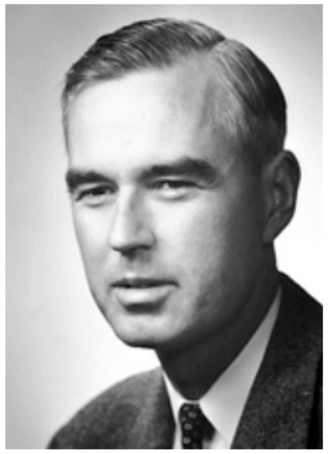
1901 — 2012 — 1955

Sort and list Nobel Prizes and Nob... | Prize category: Physics

The Nobel Prize in Physics 1955

Willis E. Lamb, Polykarp Kusch

- **The Nobel Prize in Physics 1955**
- Nobel Prize Award Ceremony
- Willis E. Lamb
- Polykarp Kusch



Willis Eugene Lamb

Polykarp Kusch

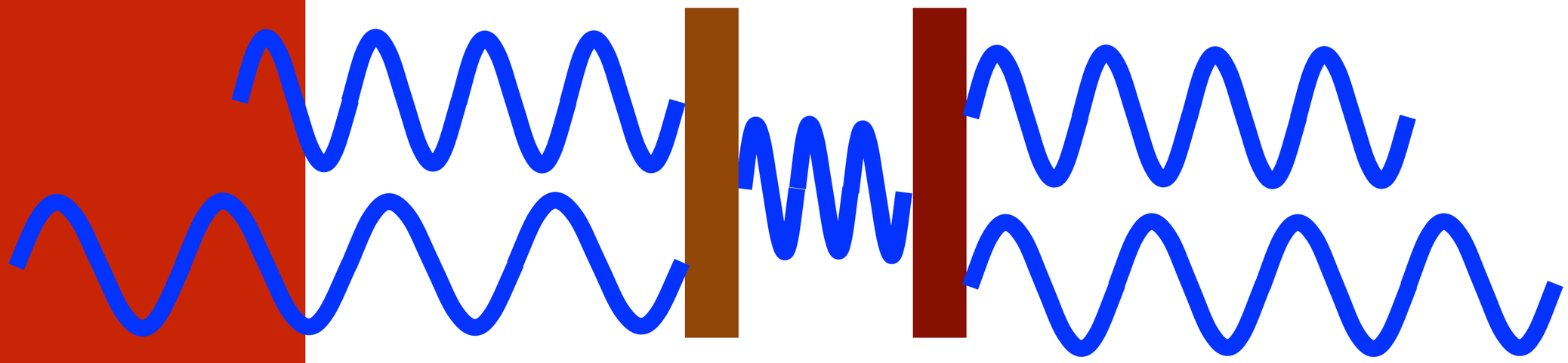
The Nobel Prize in Physics 1955 was divided equally between Willis Eugene Lamb *"for his discoveries concerning the fine structure of the hydrogen spectrum"* and Polykarp Kusch *"for his precision determination of the magnetic moment of the electron"*.

the “Casimir Effect”

two highly polished mirrors isolated from all external effects

The vacuum has all wavelengths of virtual waves from particles and fields...but fewer can fit between the walls

...and the pressure from the outside, moves them closer together



The amount is precisely predicted...and a few years ago the experiments confirmed it convincingly in 2001

the vacuum

is a very complicated thing

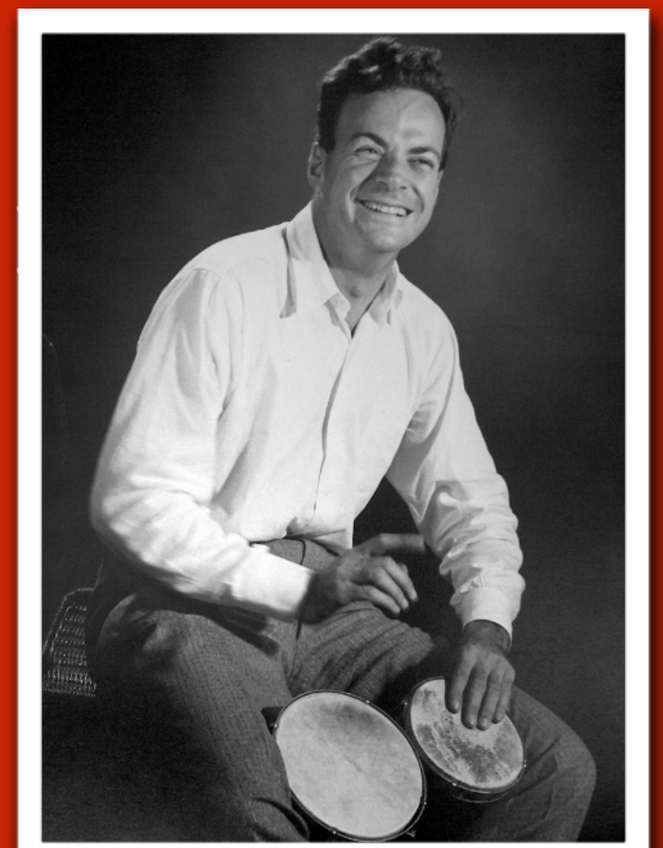
as we'll see when we get back to cosmology

Feynman Diagrams

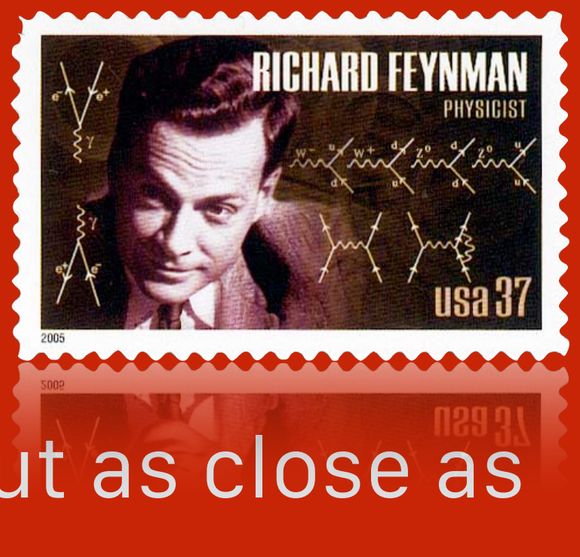
now for real.

creation and annihilation of

can be embodied in Feynman Diagrams



hero worship



about as close as we come