hi

Day 25, 05.12.2018

Quantum Mechanics 4

housekeeping

Gotta come to class

question about anything? I'll make a movie for you:

Quantum Mechanics:

Readings: Oerter, Cosmic Perspective, and Hobson

Hobson_QM1.pdf & Hobson_QM2.pdf are chapters 12 & 13 out of Hobson

Homework #11 is all from MasteringPhysics - ~~due saturday, rather than friday~~

yeah. but I messed up and slipped visibility and due dates by a week... fixed last night, so due Monday, the 16th

honors project began

https://qstbb.pa.msu.edu/storage/Homework_Projects/honors_project_2018/

contains:

- the first instructions: the plan & tutorial
- the second instructions – v2 uploaded, added a missing student
- the data, assigned by name in the second instructions

dates:

- complete first part, March 16
- analyze data by April 24 and hand in complete writeup at the final exam

Here's

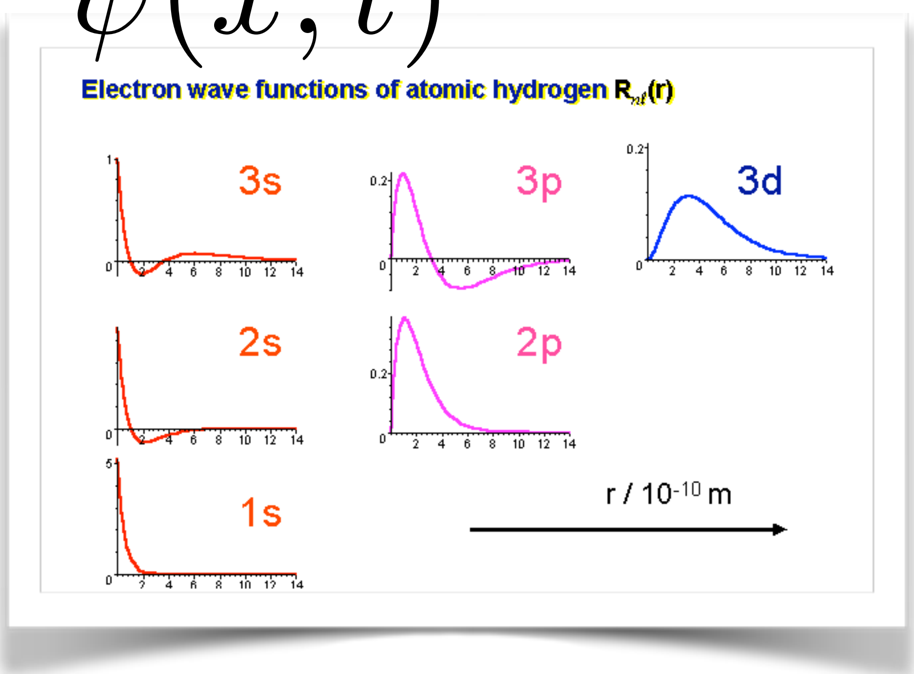
What You Missed About

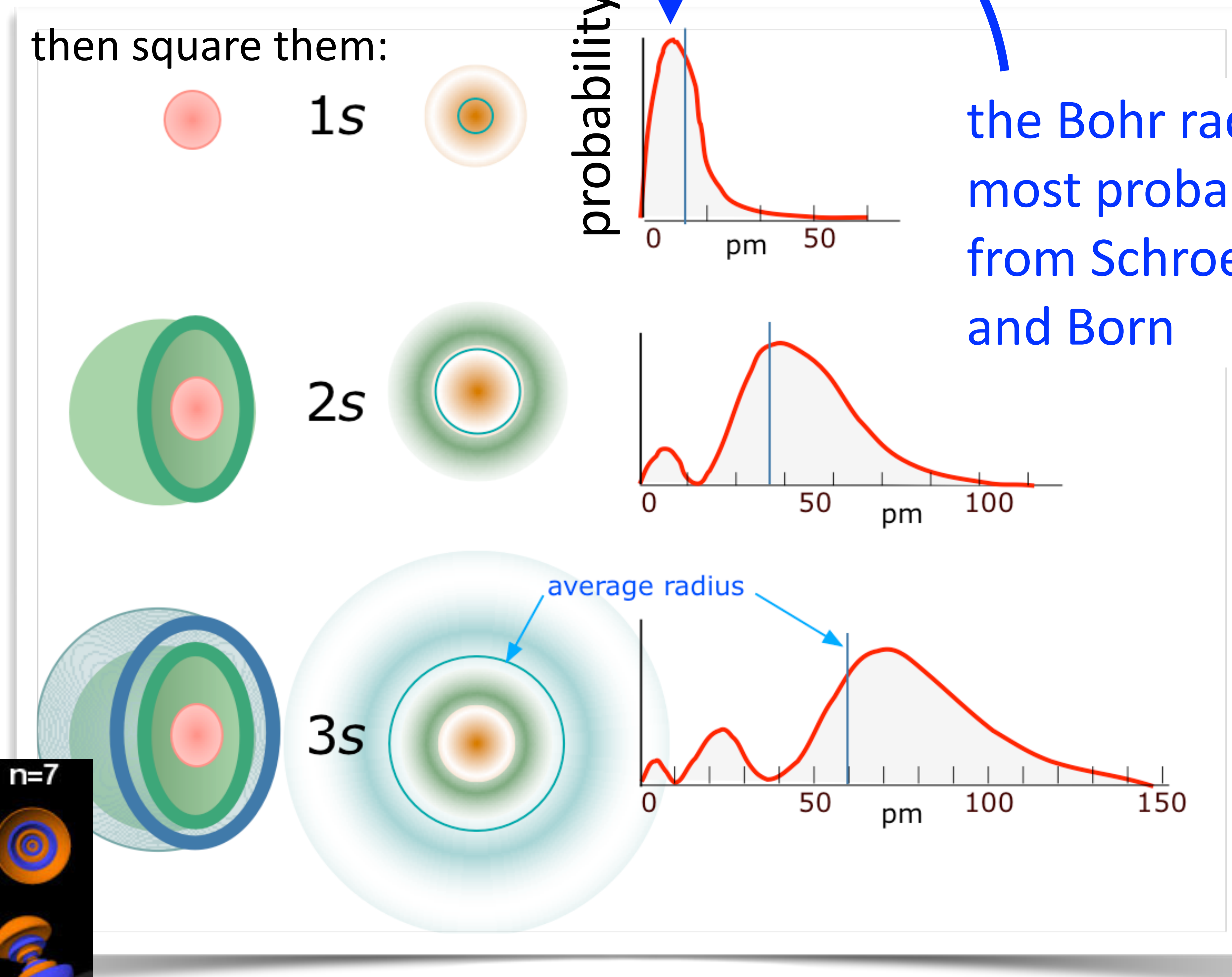
electrons

slice through the wavefunctions of Hydrogen

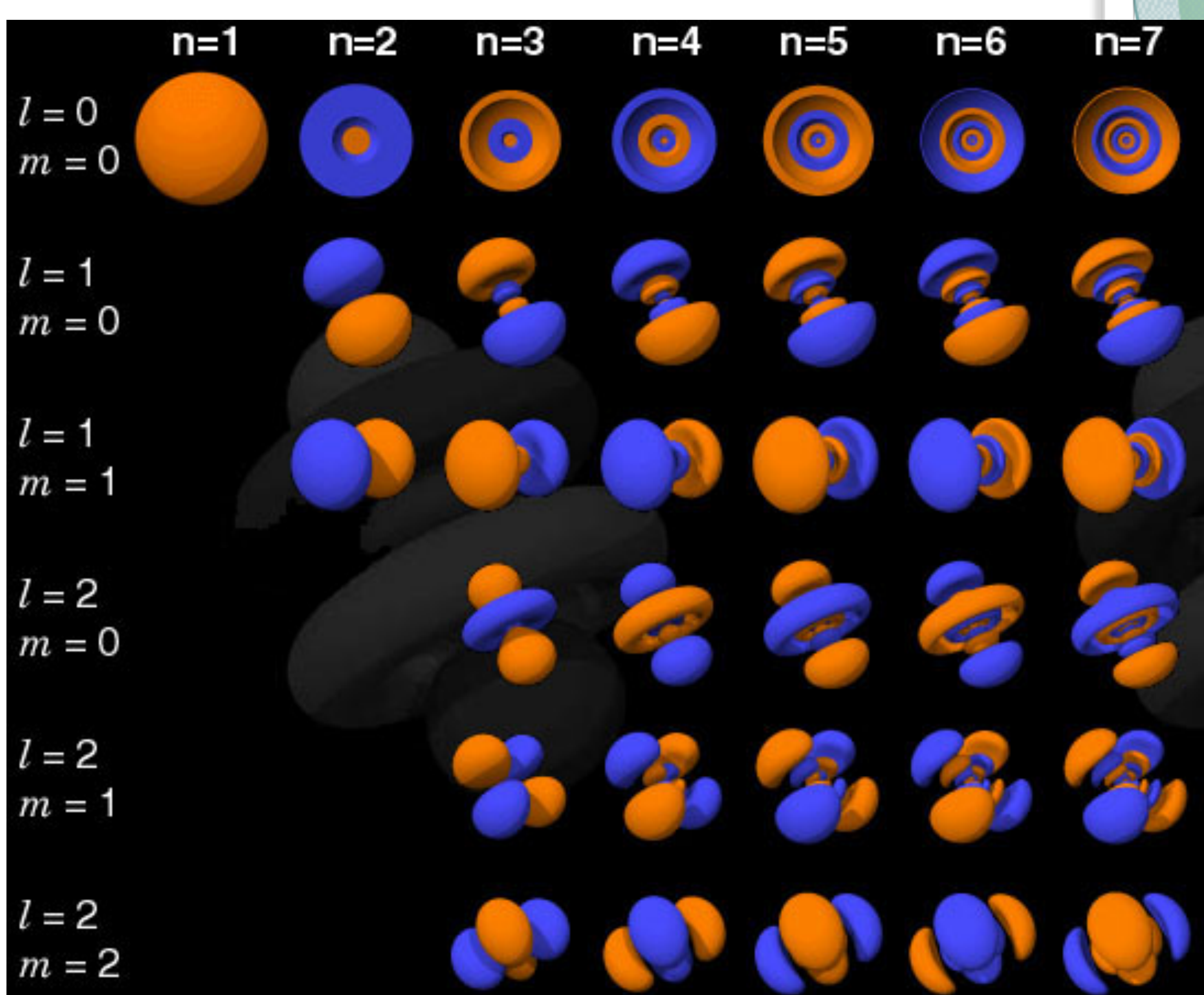
Solve Schroedinger equation and get wavefunctions:

$$\psi(x,t)$$





the Bohr radius - the most probable radius from Schroedinger and Born



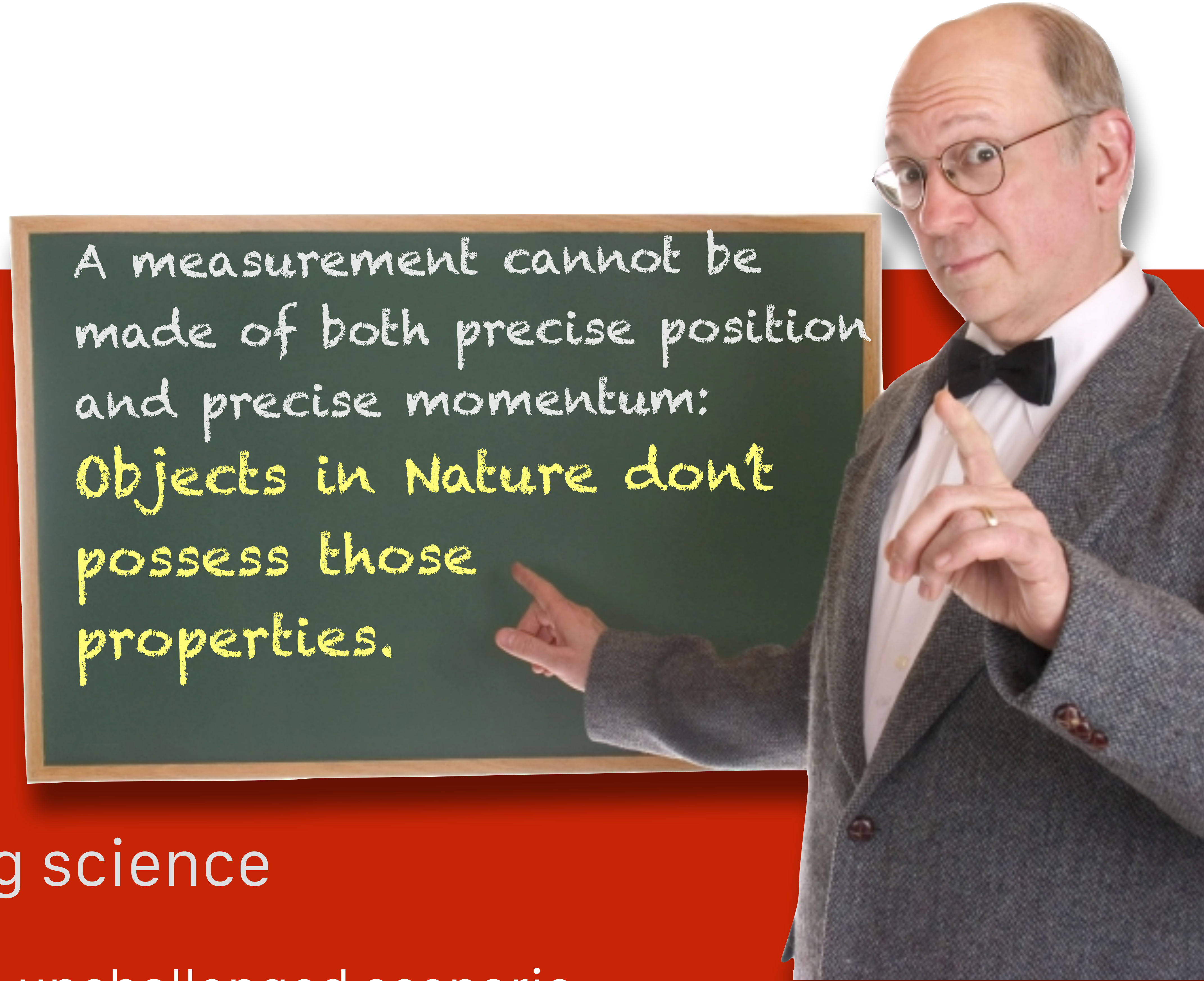
relation alert: **Heisenberg Uncertainty Relation**

refers to: $\Delta x \Delta p \geq h$ & $\Delta t \Delta E \geq h$

an inherent property of Nature

example: lots of things!

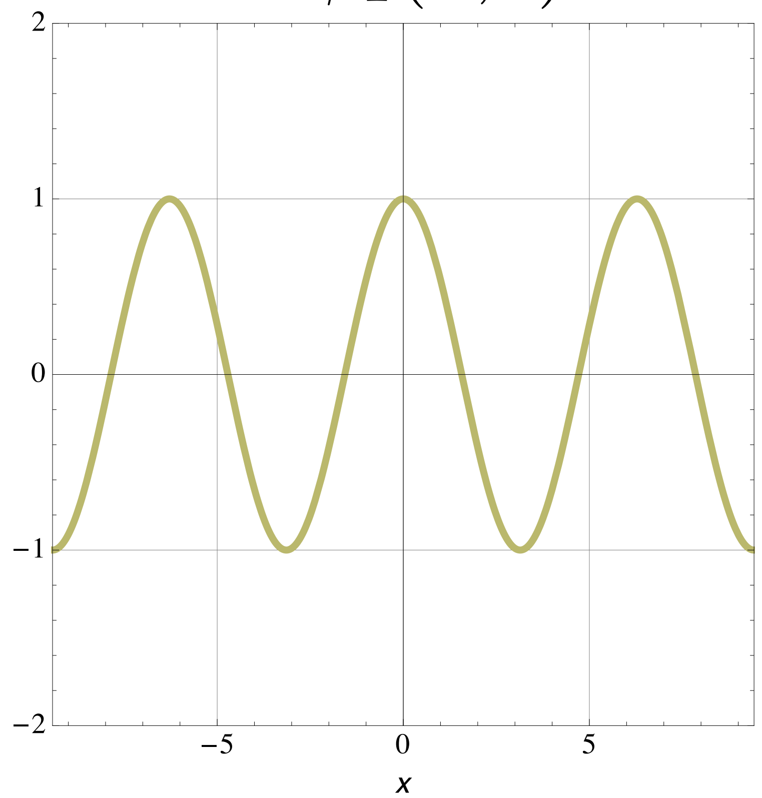
a new way



Of thinking and doing science

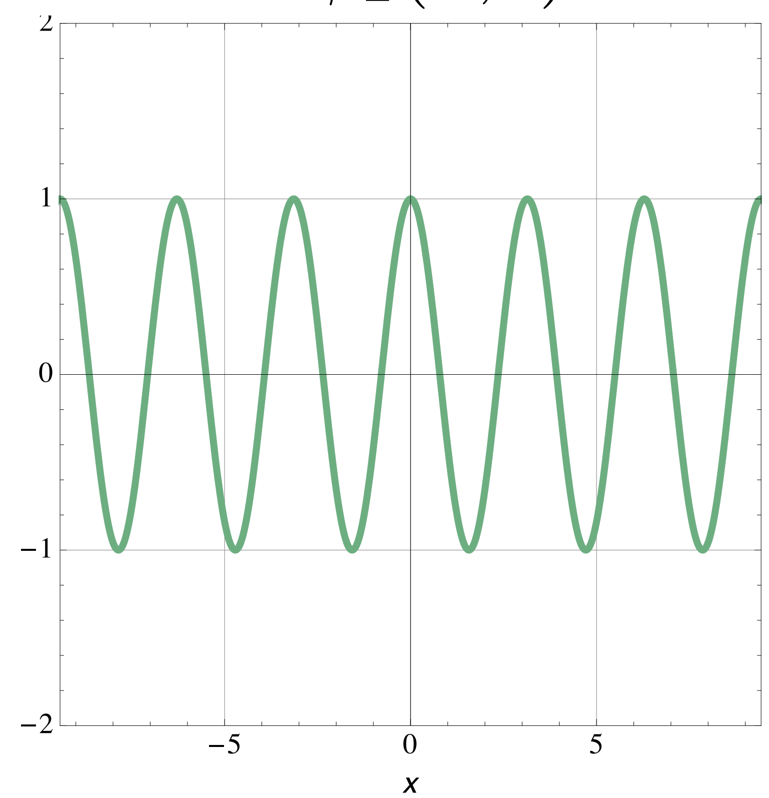
we lose another classical, unchallenged scenario

$\psi_1(x,t)$



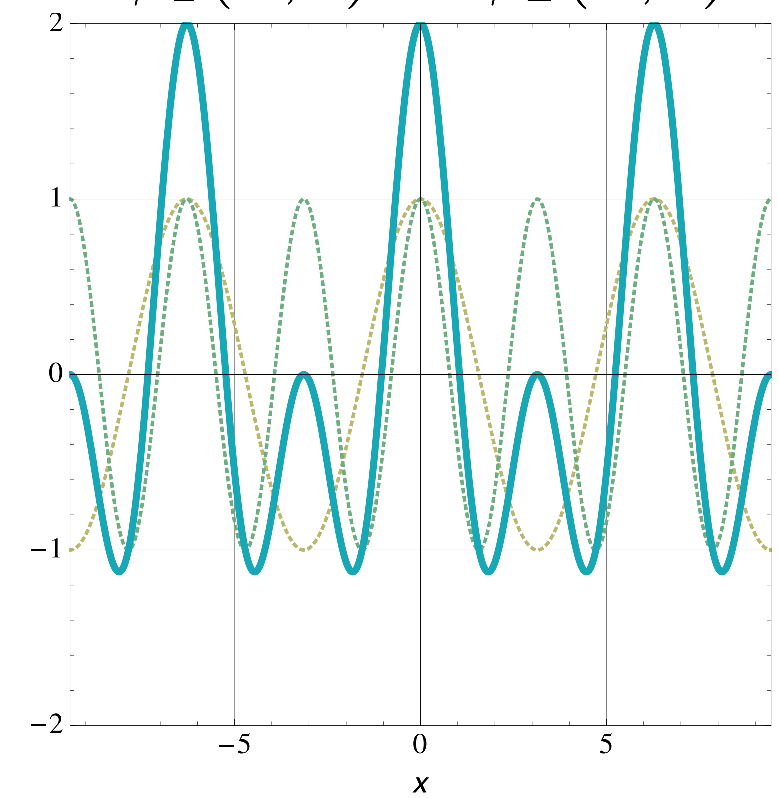
+

$\psi_2(x,t)$



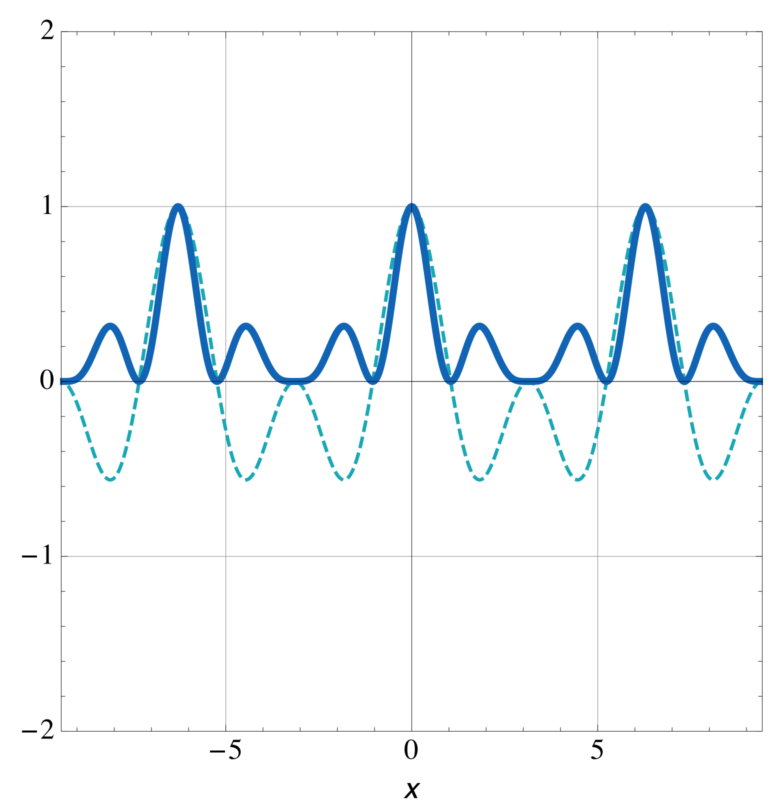
=

$\psi_1(x,t) + \psi_2(x,t)$



But, remember that what's real about the quantum fields is the square: $|\psi(x,t)|^2$

$|\psi_1(x,t) + \psi_2(x,t)|^2$



notice the peaking

(I've changed the heights)

a classical particle (dot) and its wavefunction

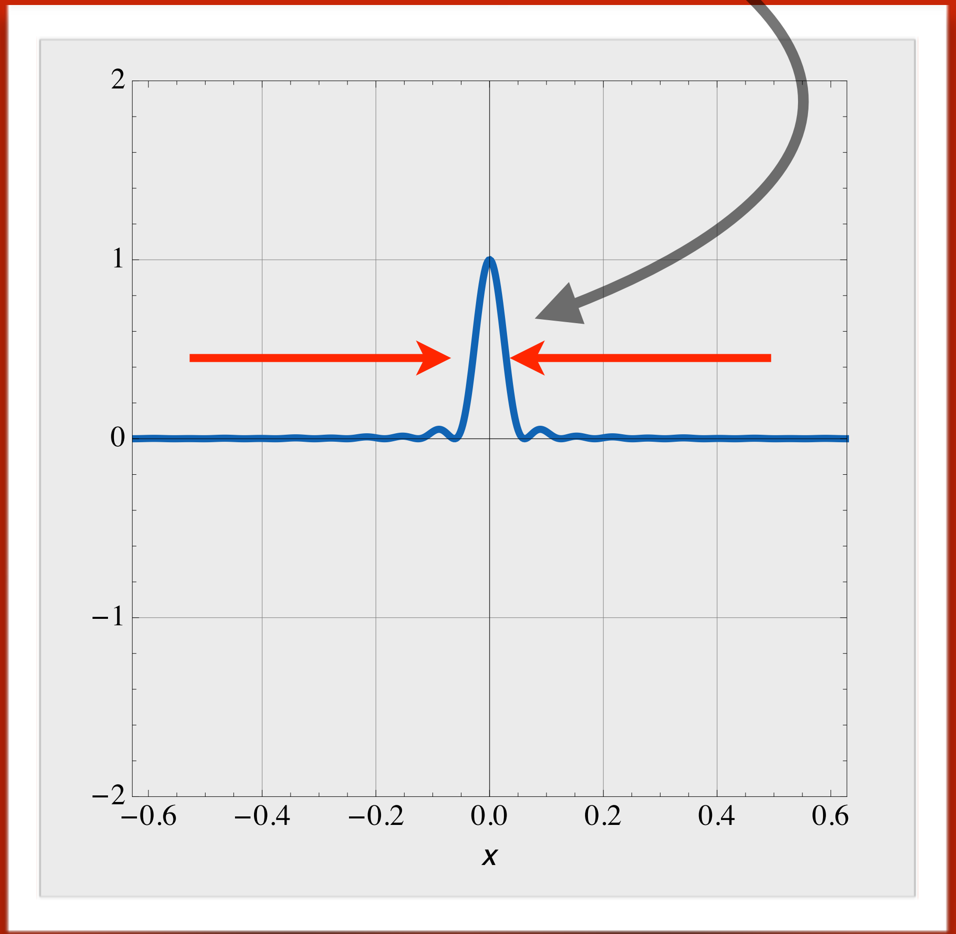
the wave combinations localize the state...with some spread in x

waves of different wavelengths?

$$p = \frac{h}{\lambda}$$

different momenta

Heisenberg Uncertainty Relation at work again



called "wavepackets"

all of the wave combinations means all of the momenta contribute: an spread in p.

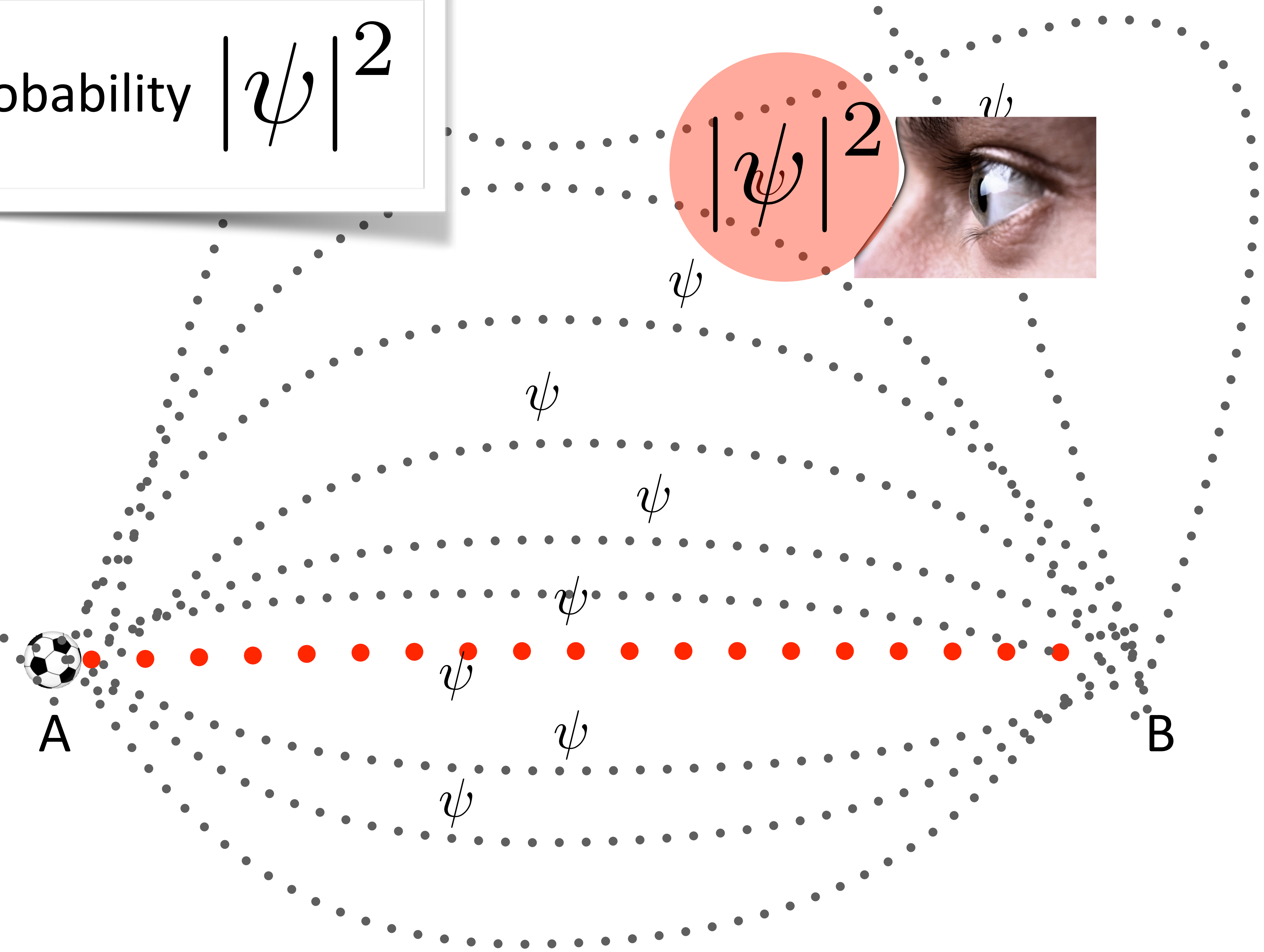
the wavefunctions are everywhere

They're waves, after all.

make a measurement....there

Only then is it real.

the electron is there with probability $|\psi|^2$



Feynman's picture was one of particles: which take all possible paths

We can calculate the wavefunction at any point, very precisely...it's completely deterministic

The trajectory of a big object?

Overwhelmingly probable quantum likelihood: the classical path

so where is a quantum

before it's measured?

anywhere? everywhere?

yeah.

this is how we have to think about it:

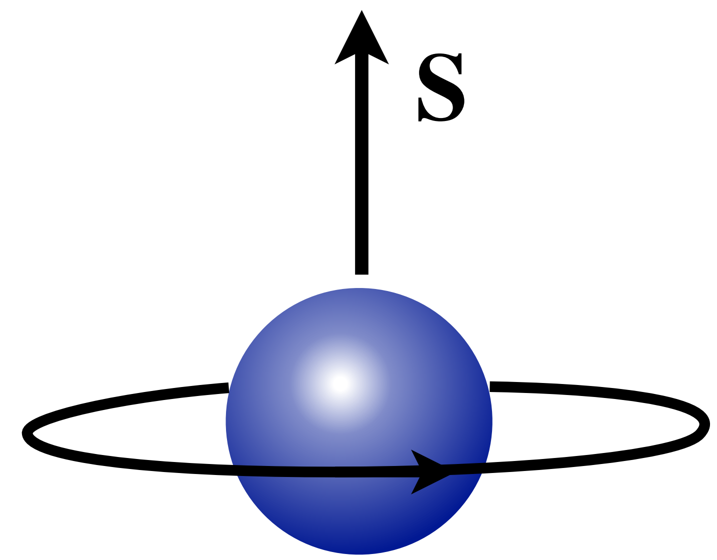
before measurement: alive-dead state -
superposition state of both

after measurement: is **either** alive **or** dead

OBTW: electrons are little magnets

They behave in a magnetic field as if they are little spinning current spheres

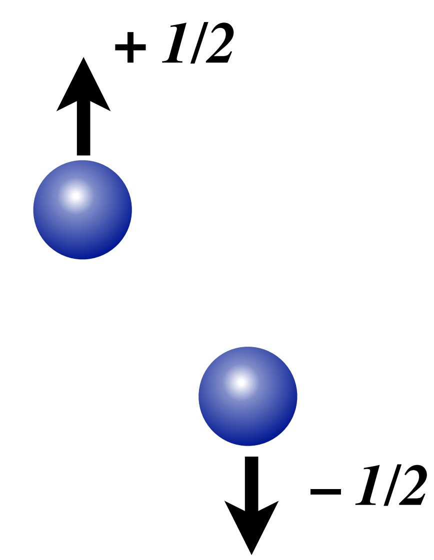
The electron **itself** is *like* a spinning charge...



Electrons have an **intrinsic** angular momentum, "S": "spin"

$$S_z = m_s \frac{h}{2\pi}$$

We say
"spin, plus 1/2" or "spin up"
and
"spin, minus 1/2" or "spin down"



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

particle: **proton**

symbol:	p
charge:	$+1e$
mass:	$m_p = 1.6726 \times 10^{-27}$ kg = 1 p
spin:	1/2
category:	fermion, hadron

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

"

I think I can safely say that nobody understands quantum mechanics.

Richard Feynman

But we can calculate with Quantum Mechanics very, very well.

We're all highly skilled Quantum *Mechanics*

shifting gears

antimatter

here's a number:

0

0

zero

the # of successfully combined models of

Quantum Mechanics and Relativity

prior to 1928

remember the relativistic energy relationship

and compare it to the non-relativistic one

Classical

$$E = \frac{1}{2}mv^2$$

$$p = mv$$

$$v = \frac{p}{m}$$

Relativistic

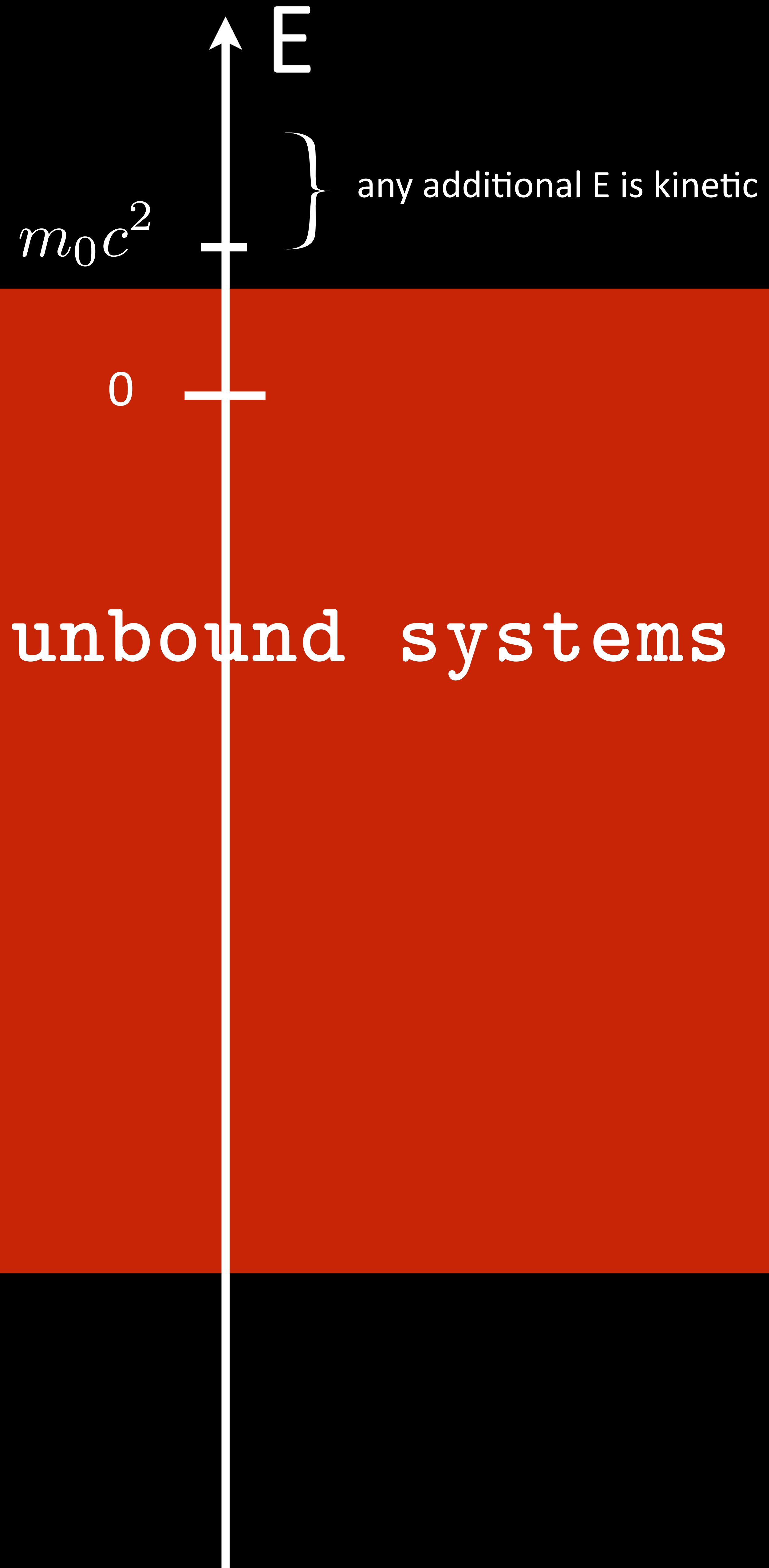
$$E^2 = (m_0c^2)^2 + (pc)^2$$

that square is problematic since it suggests:

$$E = \pm\sqrt{(m_0c^2)^2 + (pc)^2}$$

translated to Schroedinger QM:

negative energies for freely moving electrons



negative energies for unbound systems

a disaster

negative energies for unbound systems

a disaster

negative energies for unbound systems

a disaster

there's no bottom!

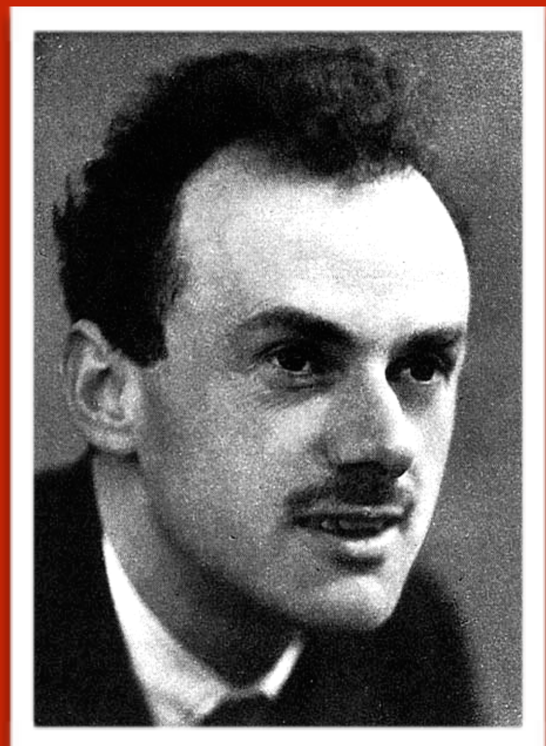
worse!

Quantum Mechanics using Relativity:

required not only negative energies

negative probabilities!

1928



Paul Dirac

1902 – 1984

> At the question period after a Dirac lecture at the University of Toronto, somebody in the audience remarked: "Professor Dirac, I do not understand how you derived the formula on the top left side of the blackboard."
> "This is not a question," snapped Dirac, "it is a statement."

hilarious interview with the Wisconsin State Journal from 1929 on the blog.

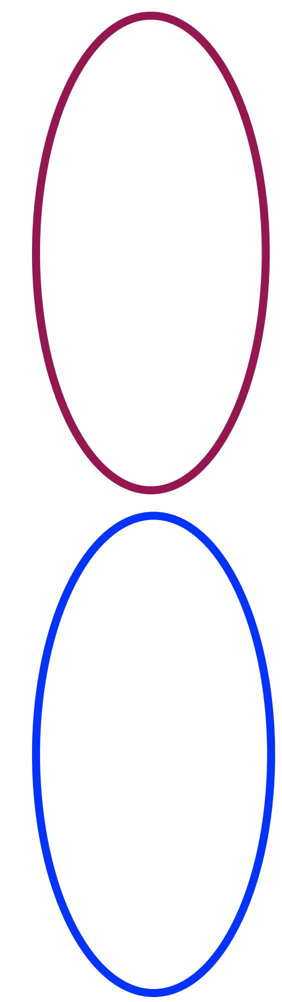
Dirac's Mathematical Imagination

Dirac embraced the negative energy

Solved the negative probability

Dirac set out to find an equation that would solve both problems

Dirac's imagination



negative
electric charge
+ Energy

positive
electric charge
– Energy

The "Dirac Equation" is the correct equation for electrons: Probabilities turn out okay, but required interpretation of negative energies

Dirac's result

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

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

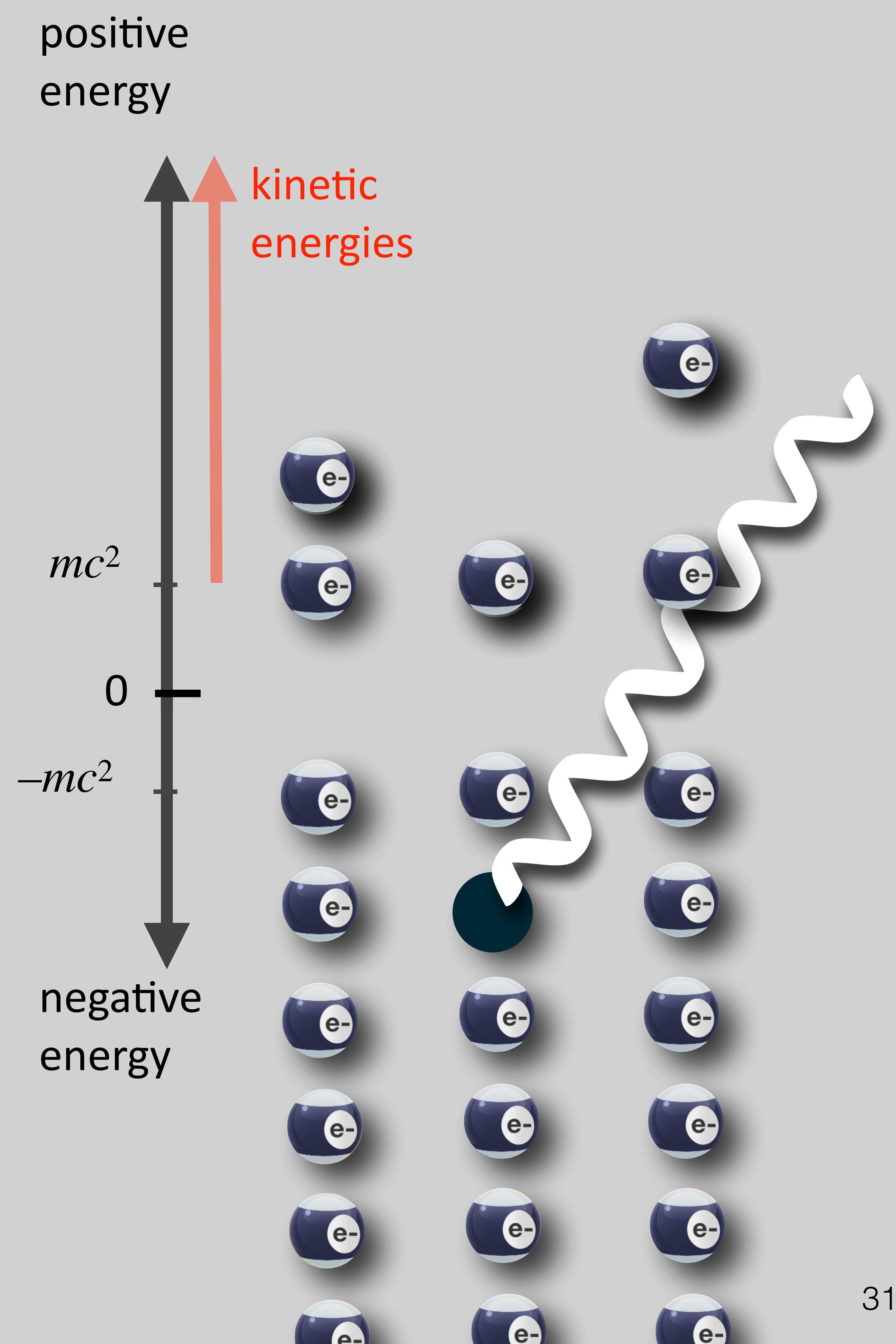
each pair is related precisely to spin

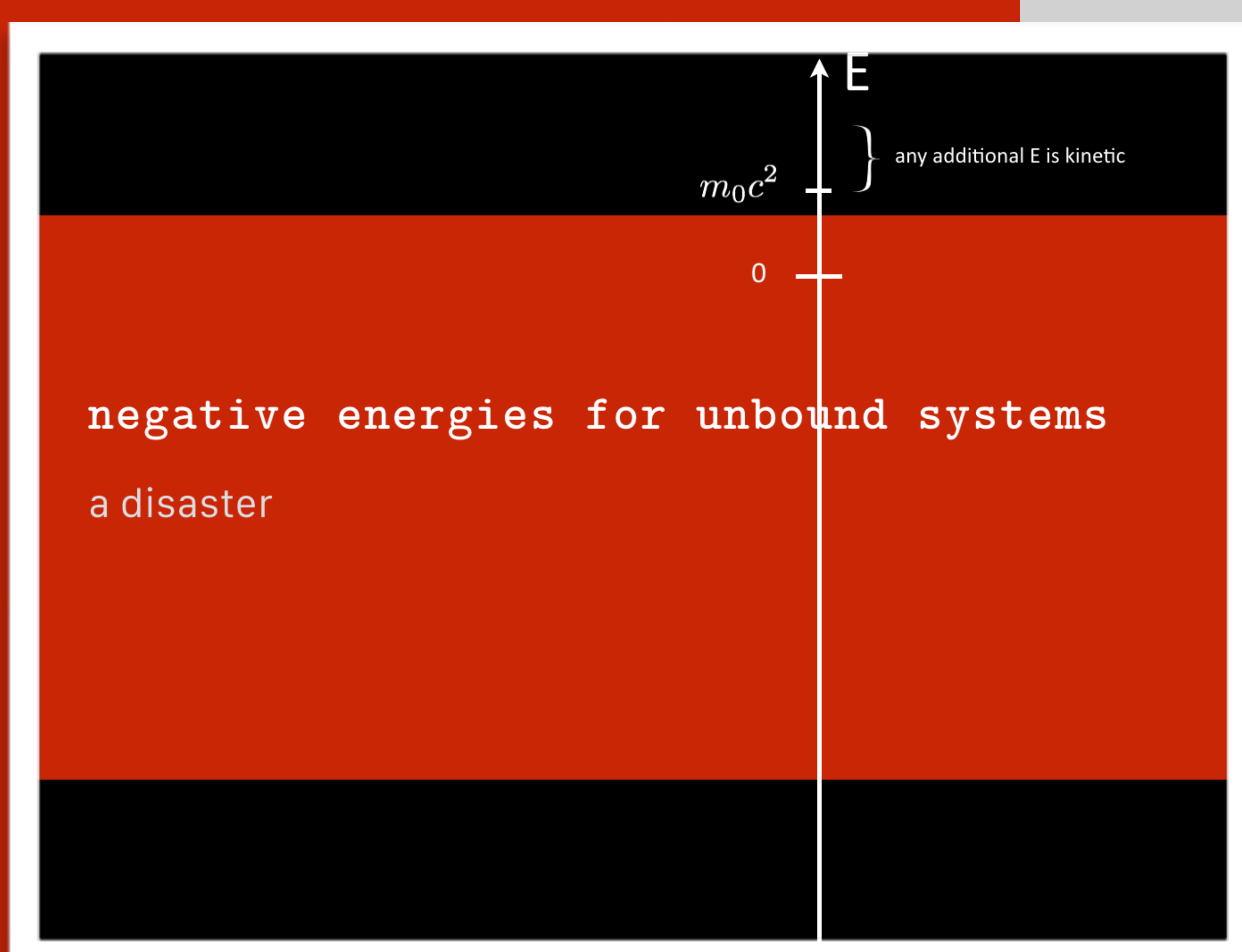
Dirac showed that spin is a wholly relativistic effect
...it just popped out of his equation.

still negative energies?

"solved" it with Pauli's Exclusion Principle

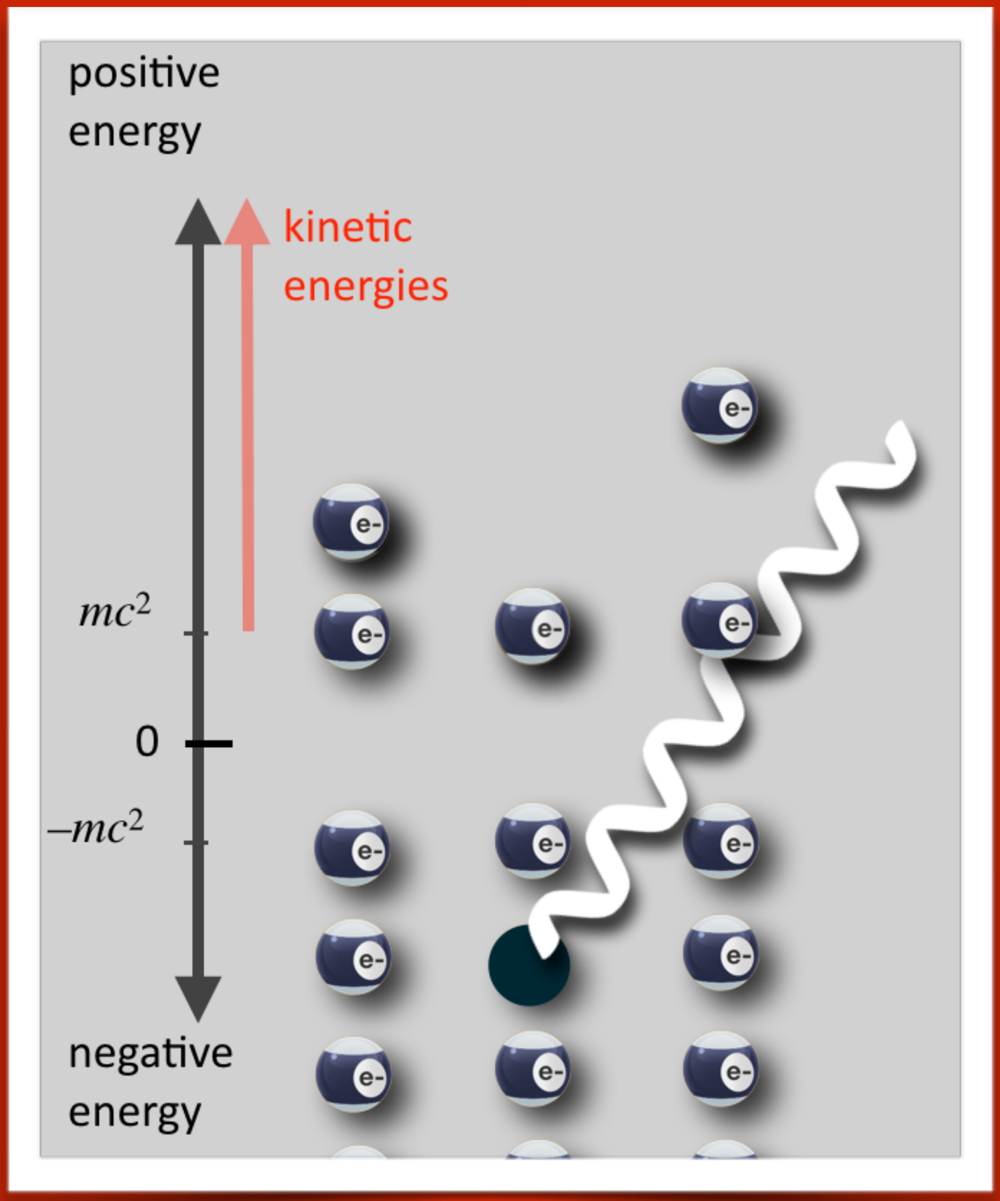
His vacuum is full of negative energy electrons





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 particular physics

and in cosmology

what is this?

$\psi(-E)$ **a positively charged object with negative energy?**

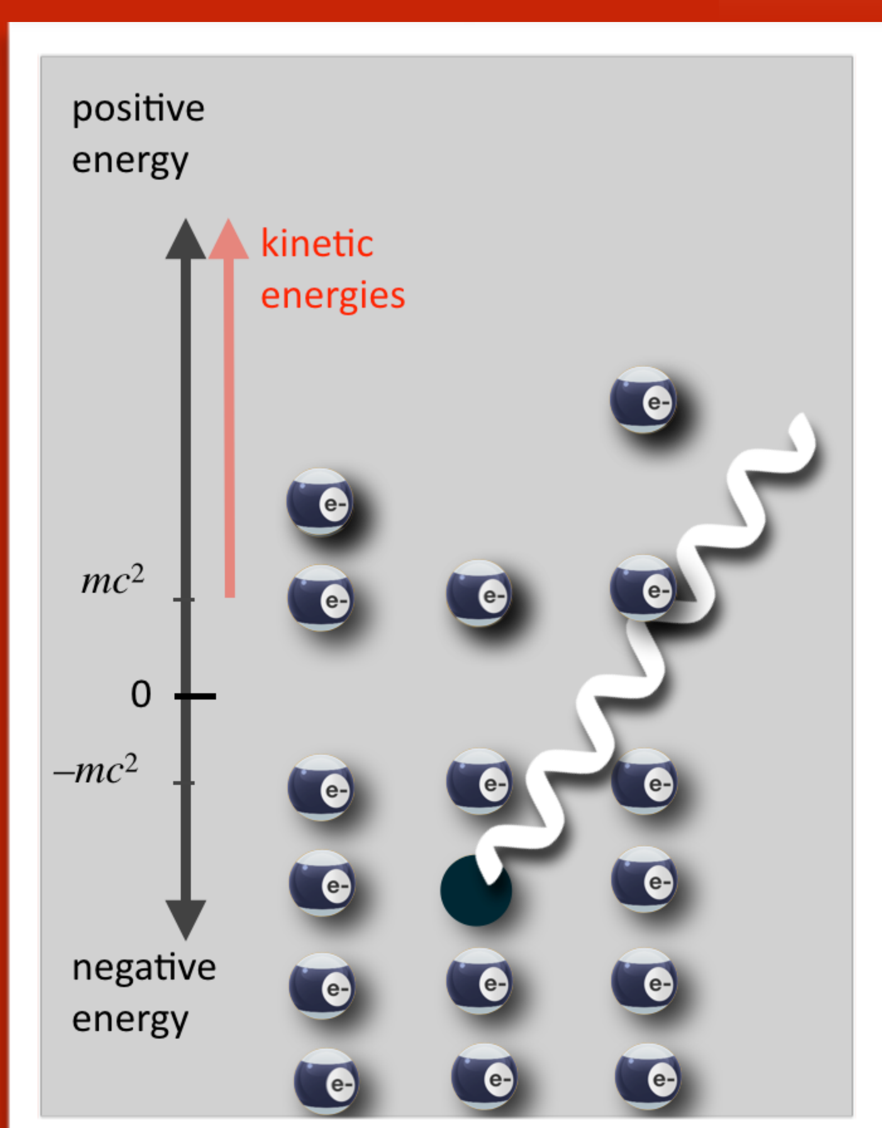
At first, he thought: “proton”

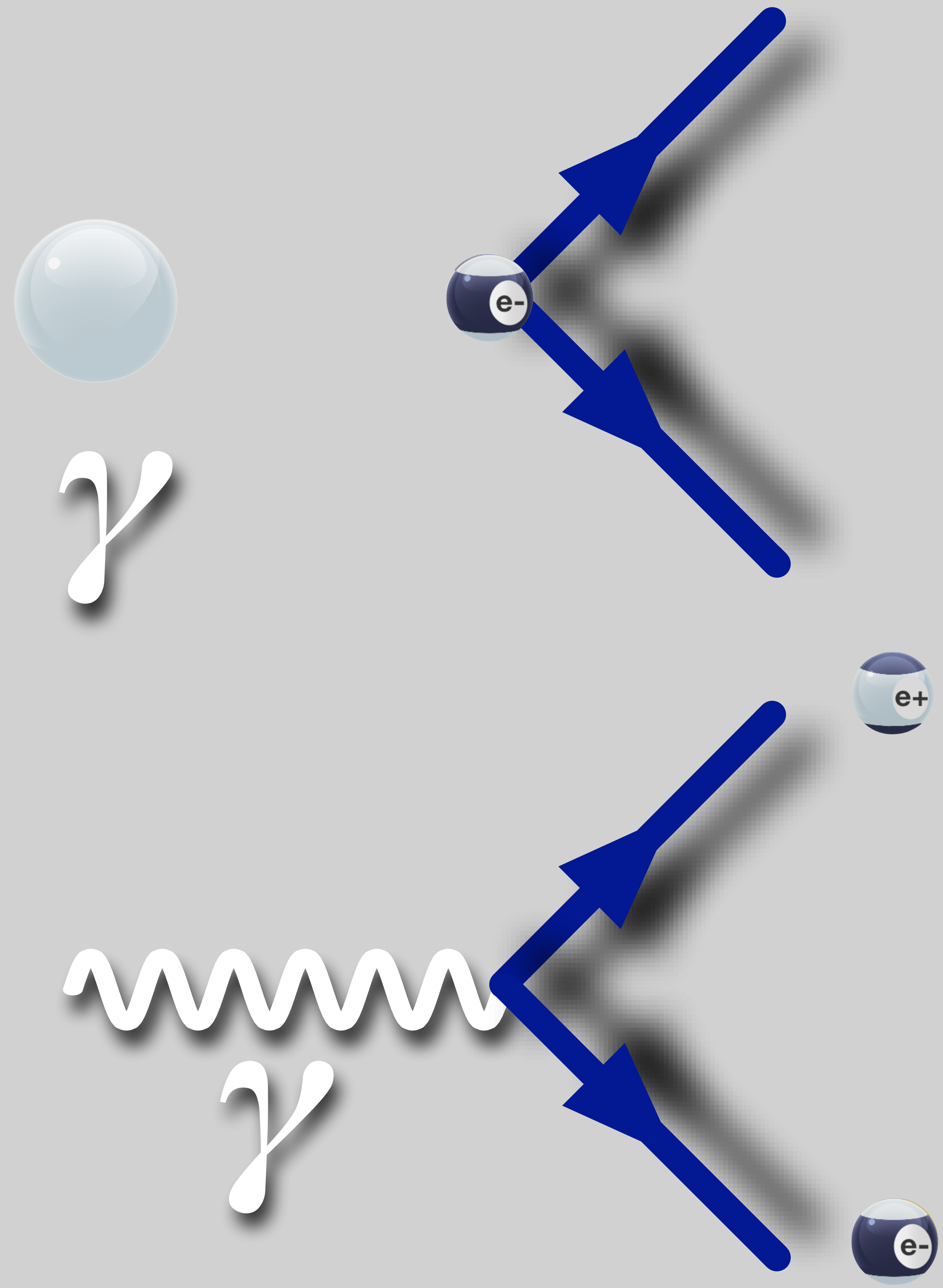
nah. A bolder idea: an anti-electron. The Positron.


Yes...antimatter.
ANGELS&DEMONS
WWW.ENTERTAINMENTWALLPAPER.COM

modern intepretat

a photon poof-disappears





The antimatter story has a happy ending:

1932

Cosmic Rays

very high energy protons from space

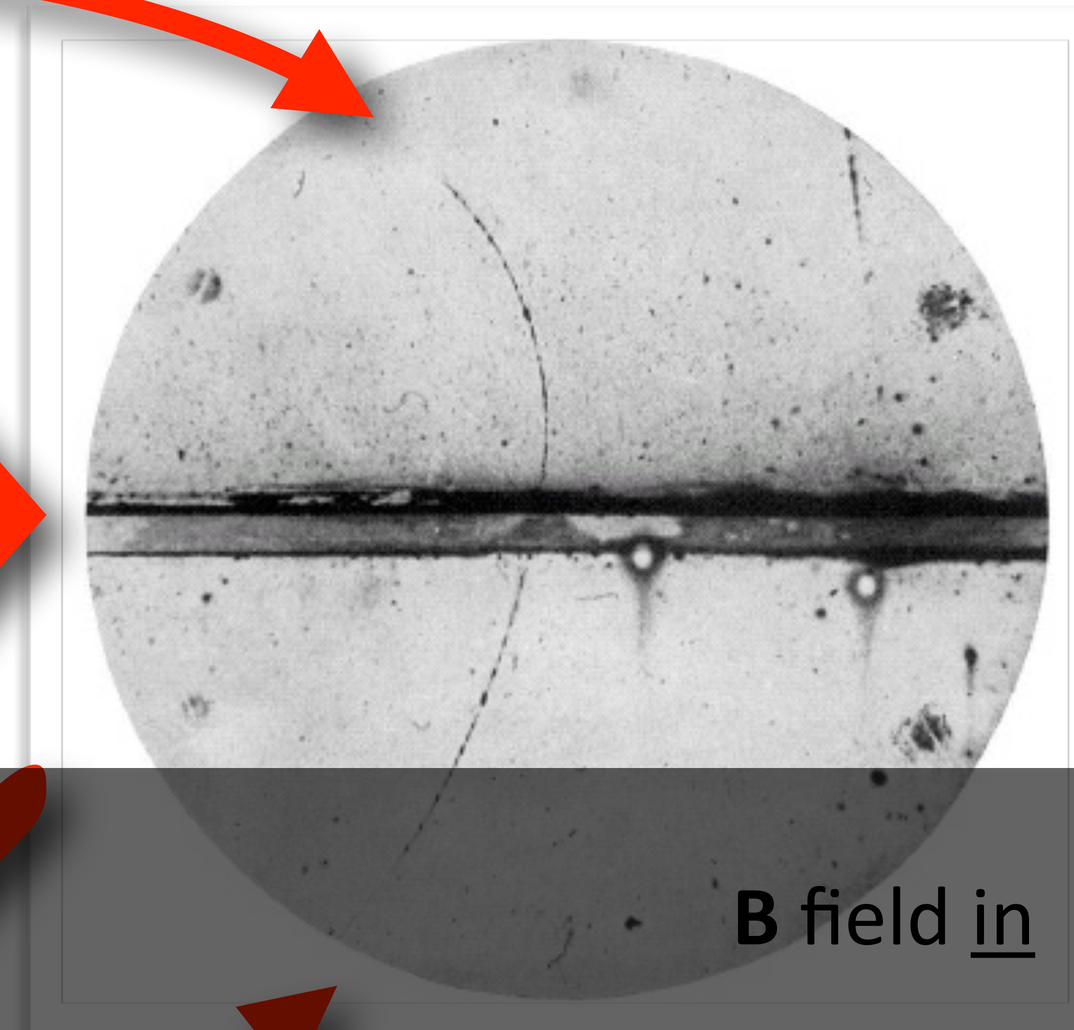
~2 per minute per fingernail

Carl Anderson

look at this track...

sharper curvature at top

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



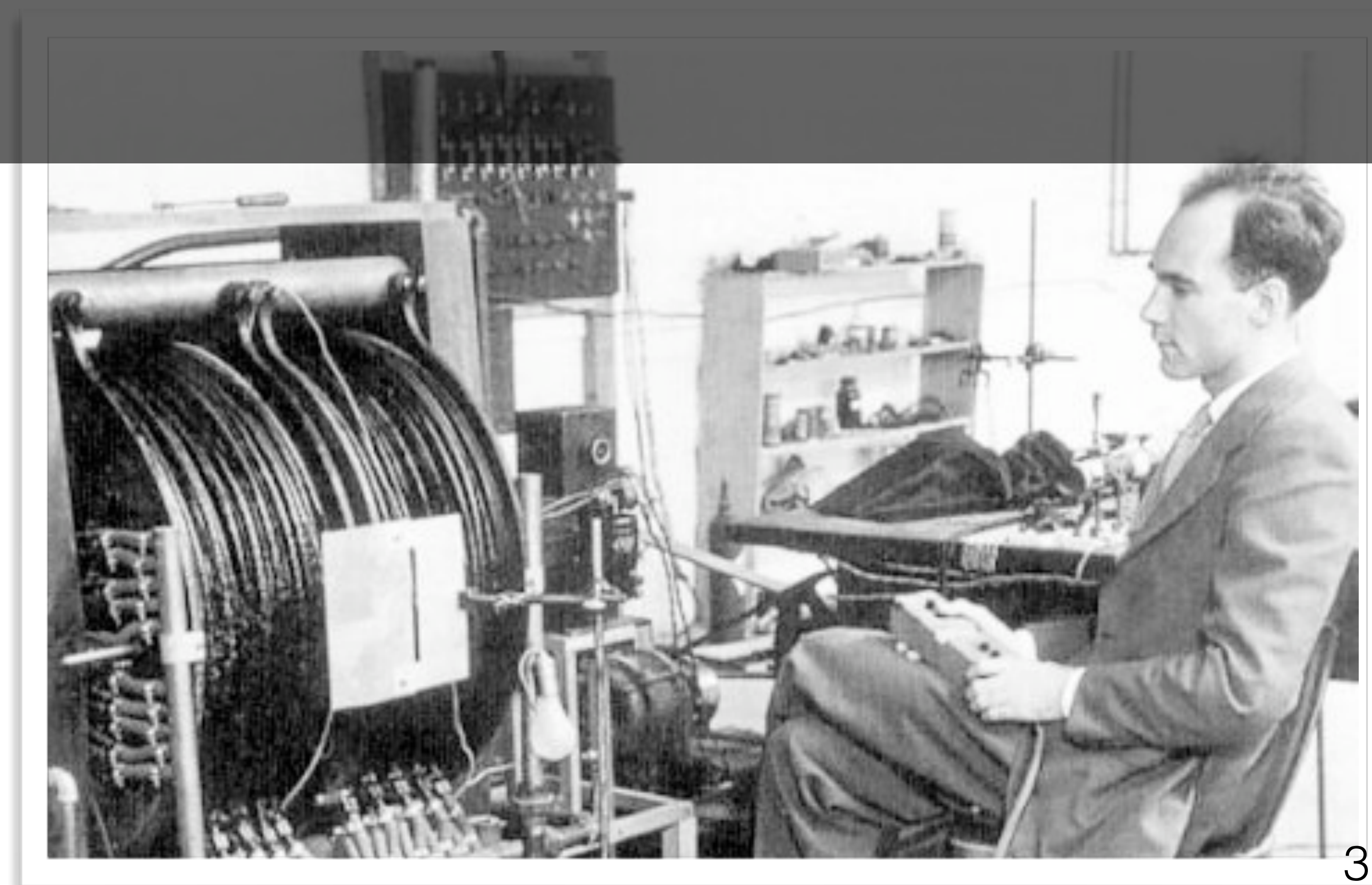
DOWN and negative?

UP and positive?

Right on schedule: 1932

Yes...antimatter.

B field in



the bar over the top will mean "antiparticle"

anti-electron, aka "positron"

symbol: $\overline{e}$ or e^+

charge: +1*e*

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

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 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`

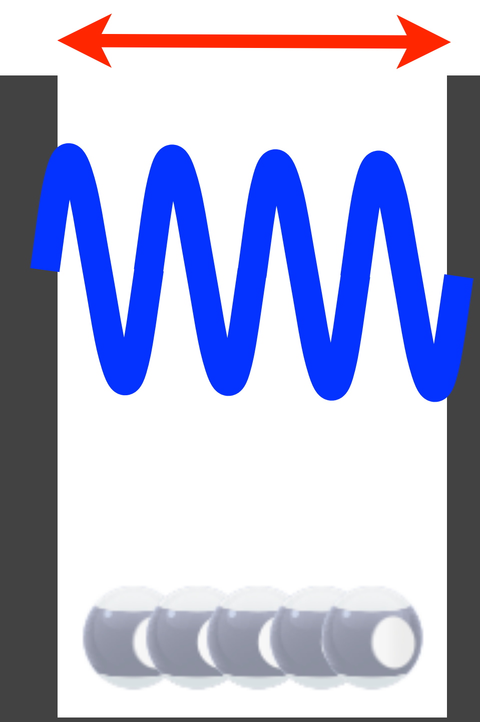
requires some mental fortitude

remember

trying to trap an electron?

let’s make it all about nothing.

an electron…somewhere here:



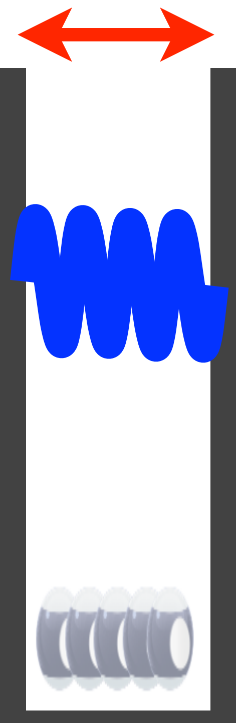
make the trap smaller

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

a very important "length"

Compton Wavelength

we consider this to be "the size of a particle"

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

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

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

$$\frac{1}{m_e c^2} \Delta pc \sim 1$$

$$\Delta pc \sim m_e c^2$$

Remember: $E_T^2 = (mc^2)^2 + (pc)^2$

An energy equivalent to the mass energy...all by looking closely at 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:

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

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

but wait.

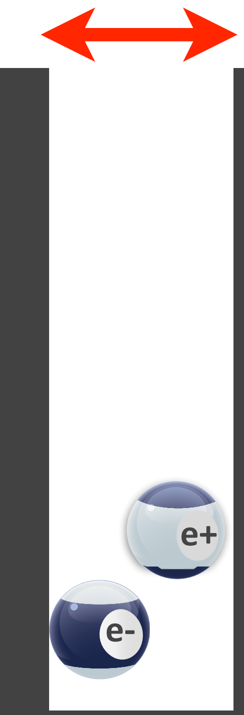
let’s just do this in space…shrink to this critical size

the same thing happens

remember

What's in Nothing?

or **NOTHING**, somewhere here:



trying to trap an electron?

do nothing tighter

make the trap smaller to this value:

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

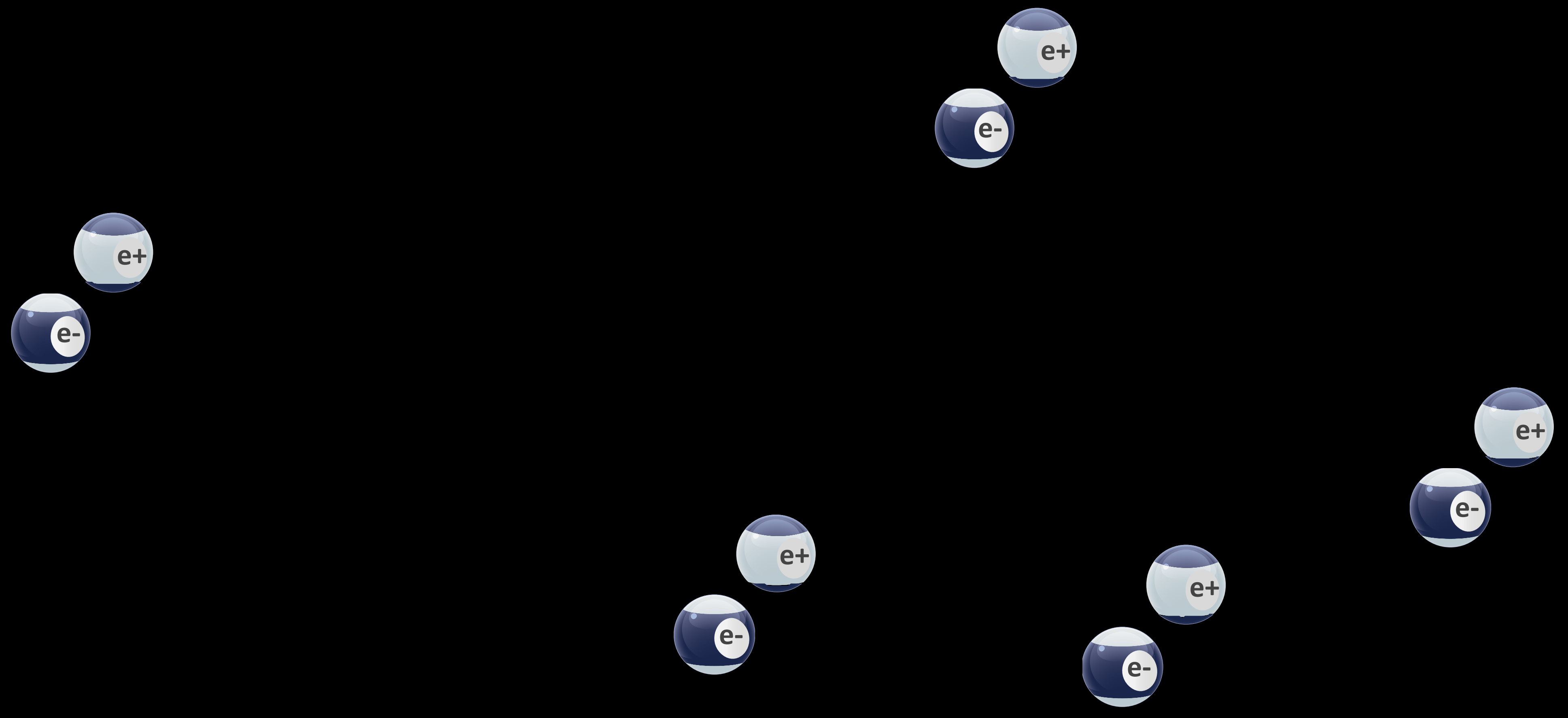
$\sim 2.2 \times 10^{-12}$ m

pop

the Uncertainty Principle requires

that particle-antiparticle pairs pop into and out of existence

all the time



uncertainty principle

+ the particular length of:

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

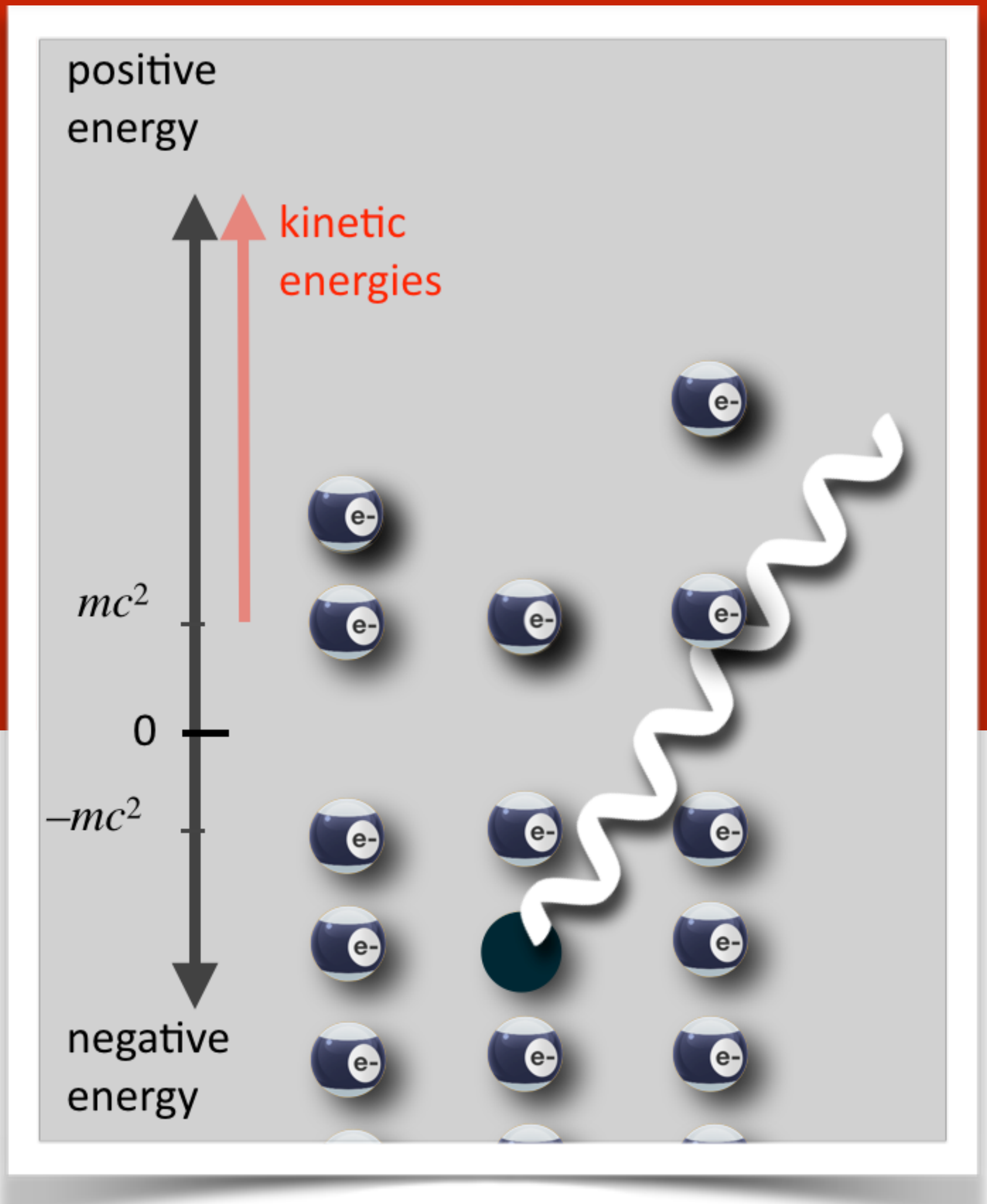
makes the vacuum very active.

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



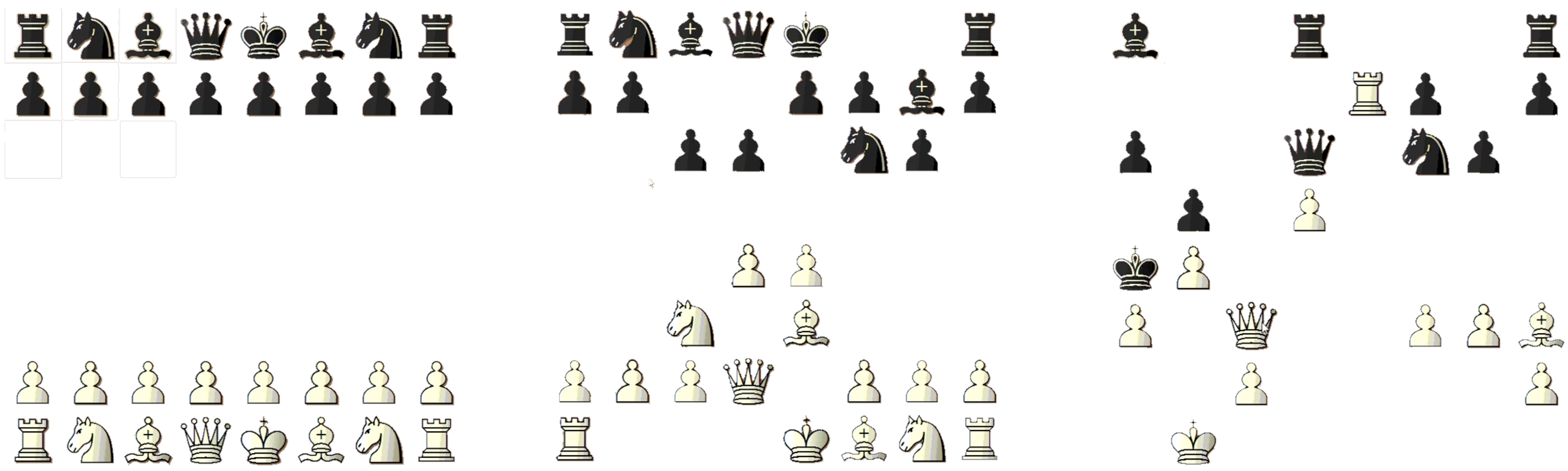
the quantum vacuum

a word about theories

let's play chess...

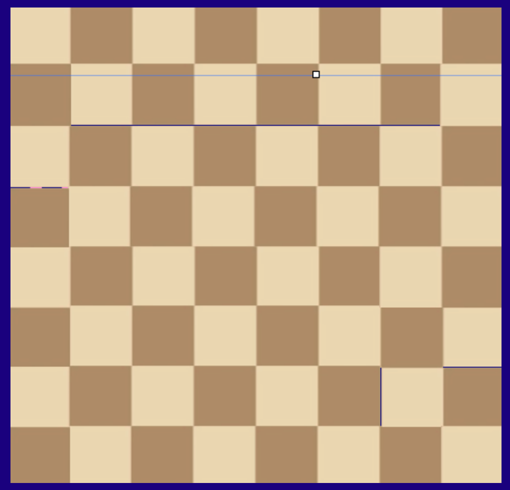
my model of chess

watch tons of matches



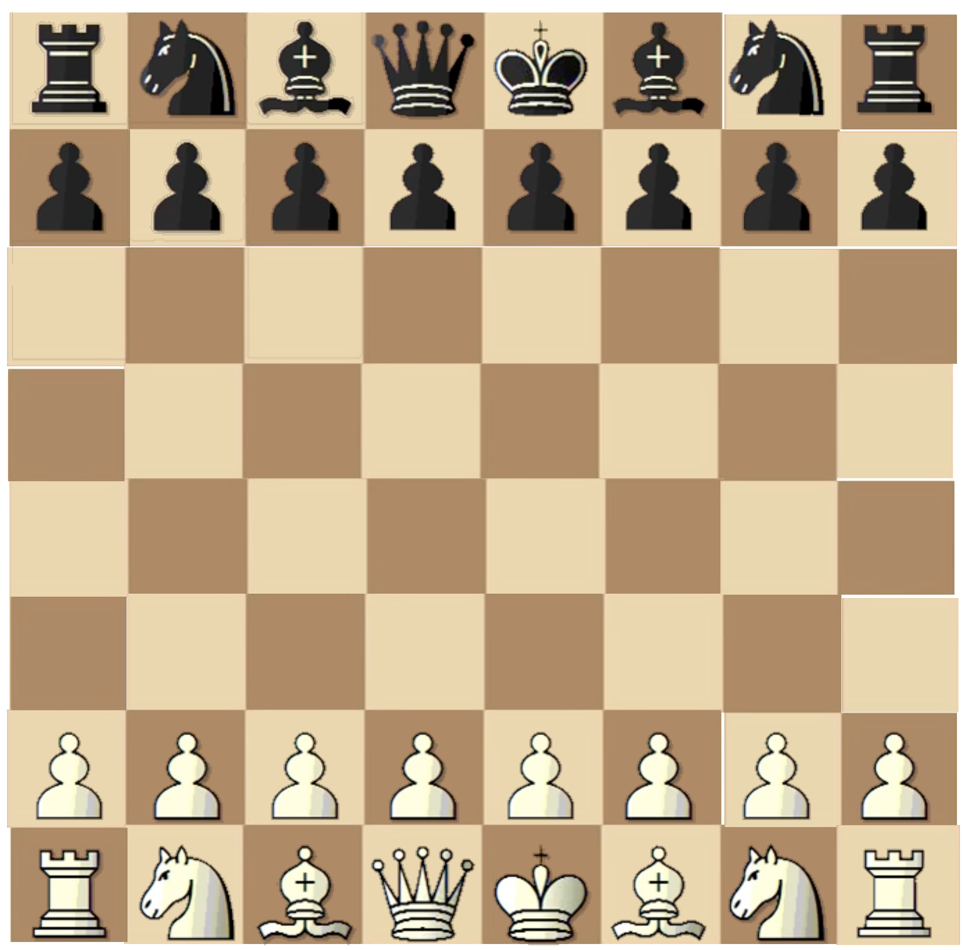
my model requires

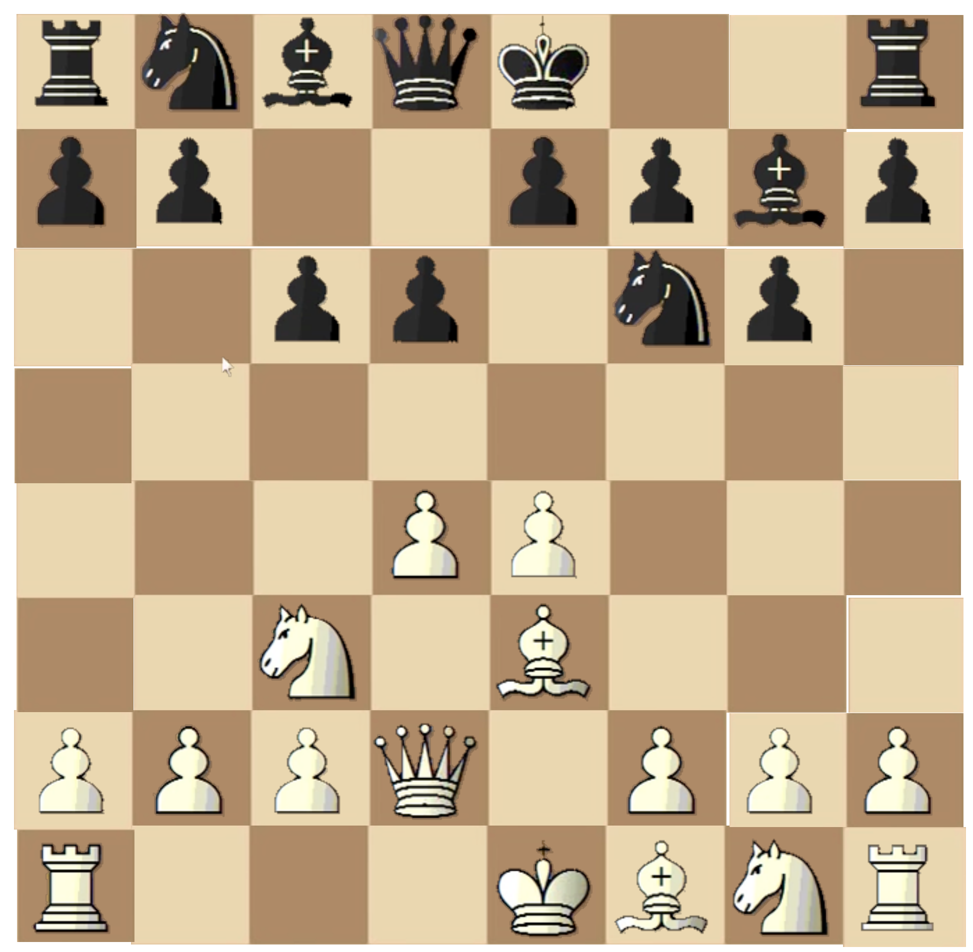
the existence of a new entity

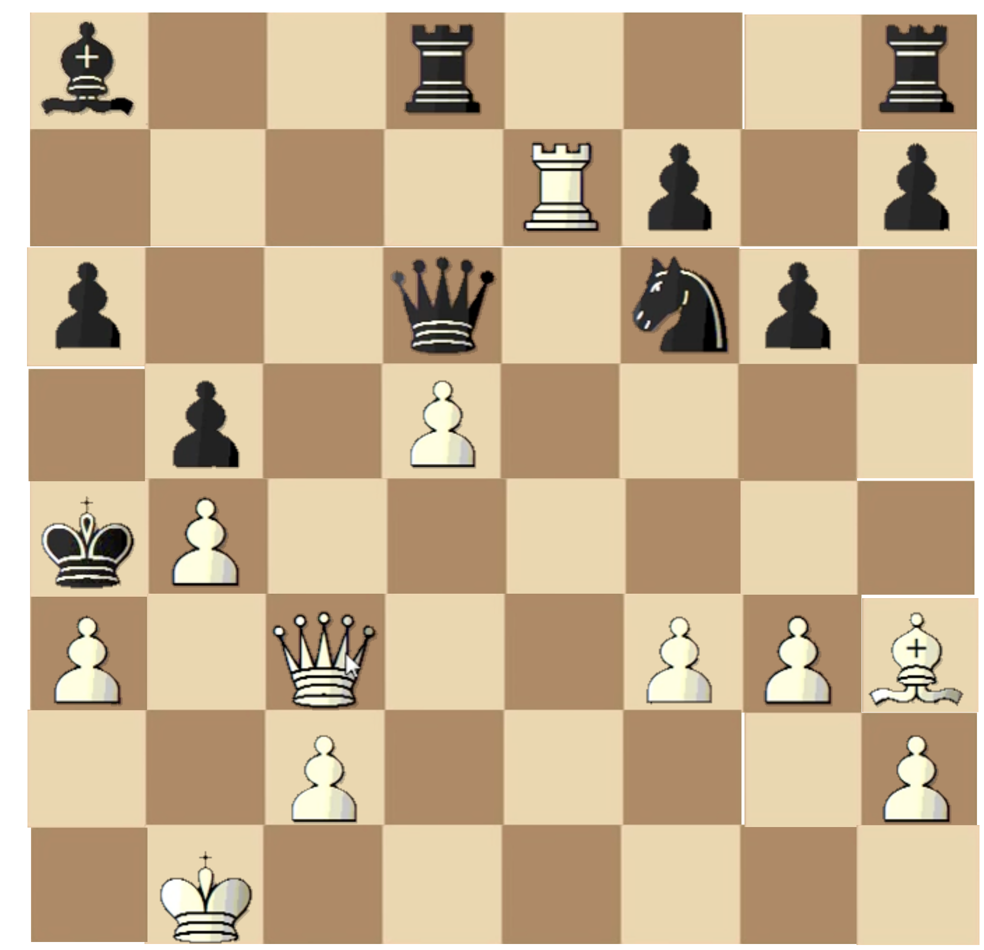


my model of chess

only with the board do the rules make sense

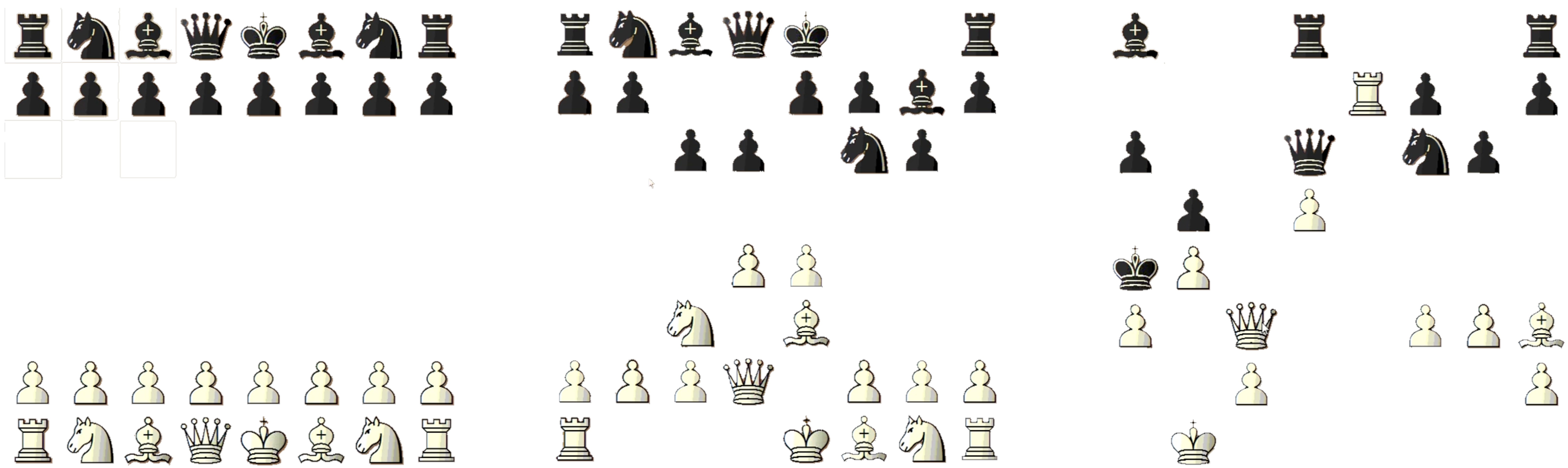






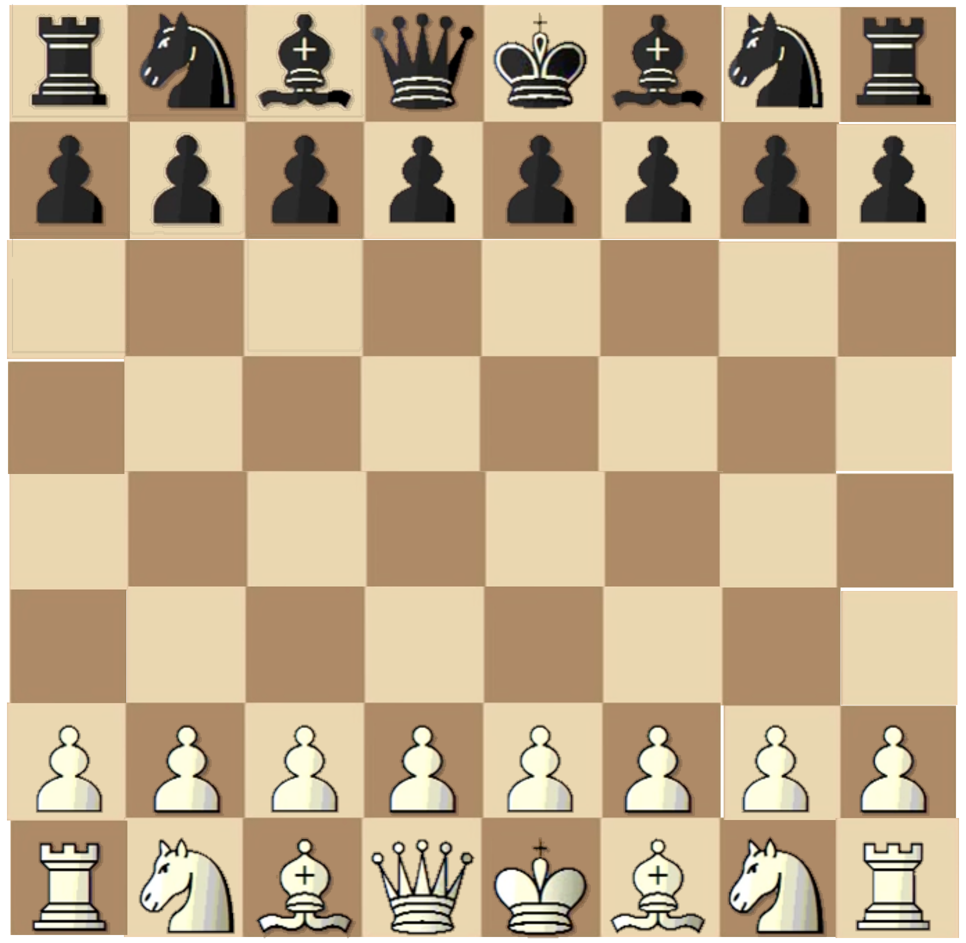
remember

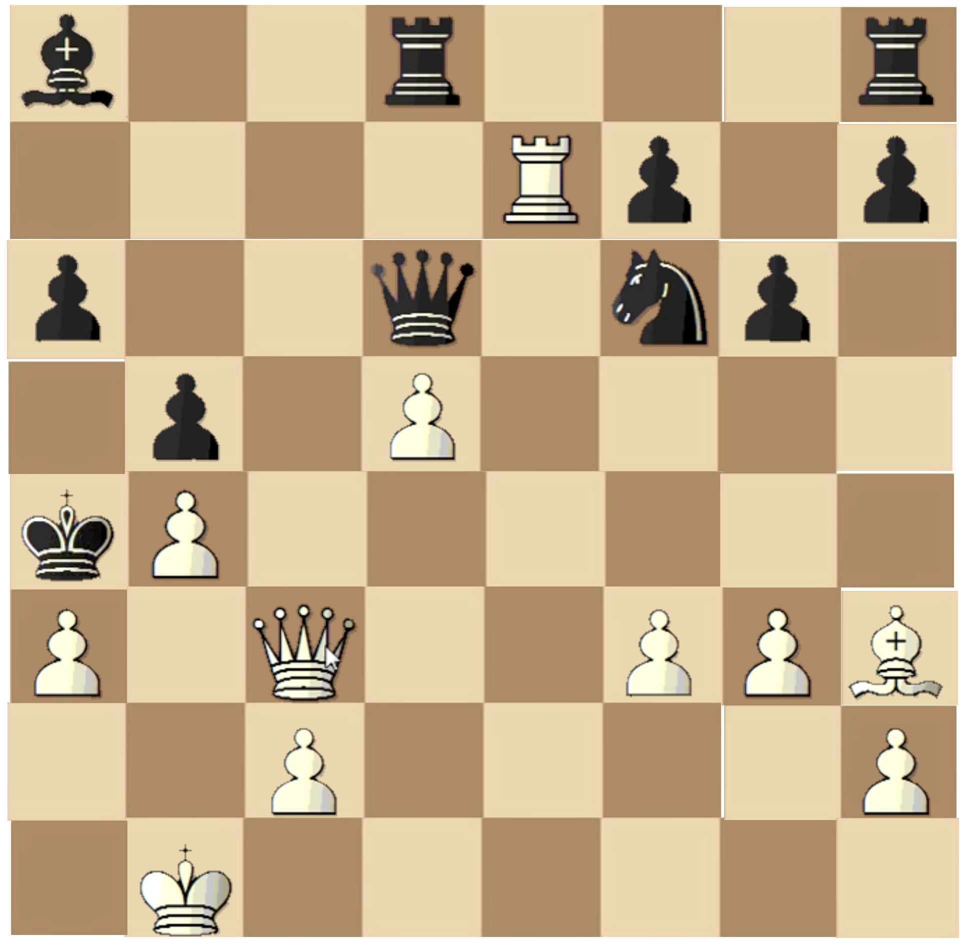
what I see are the pieces



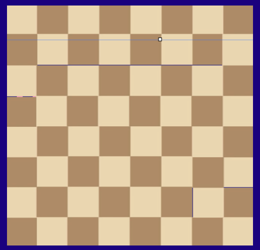
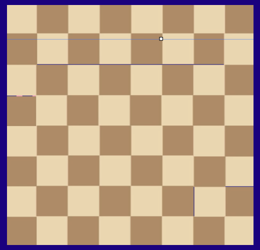
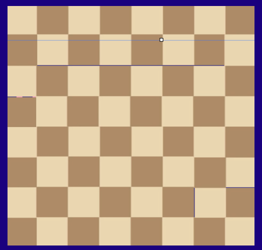
remember

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!

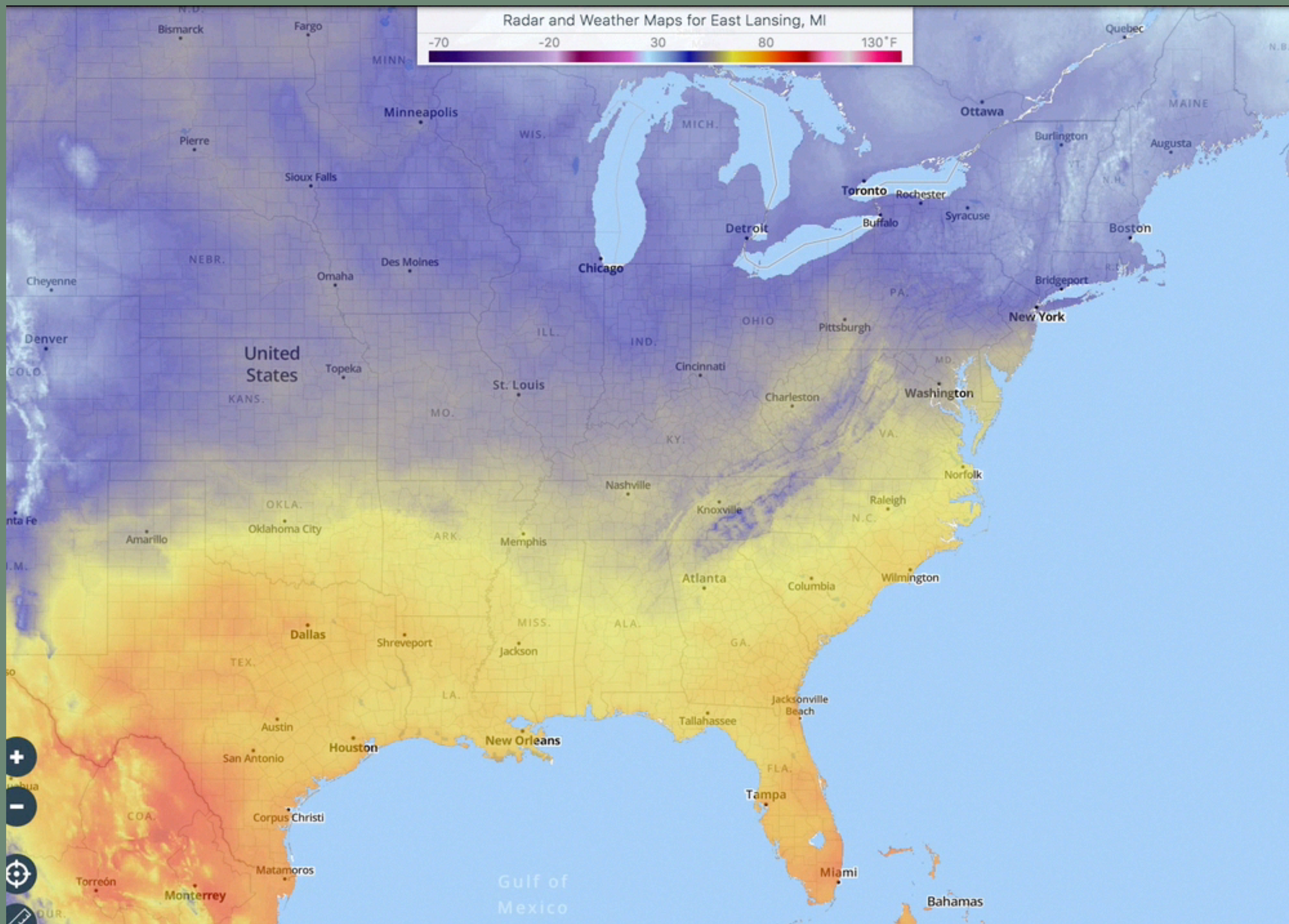
what about

fields?

fields

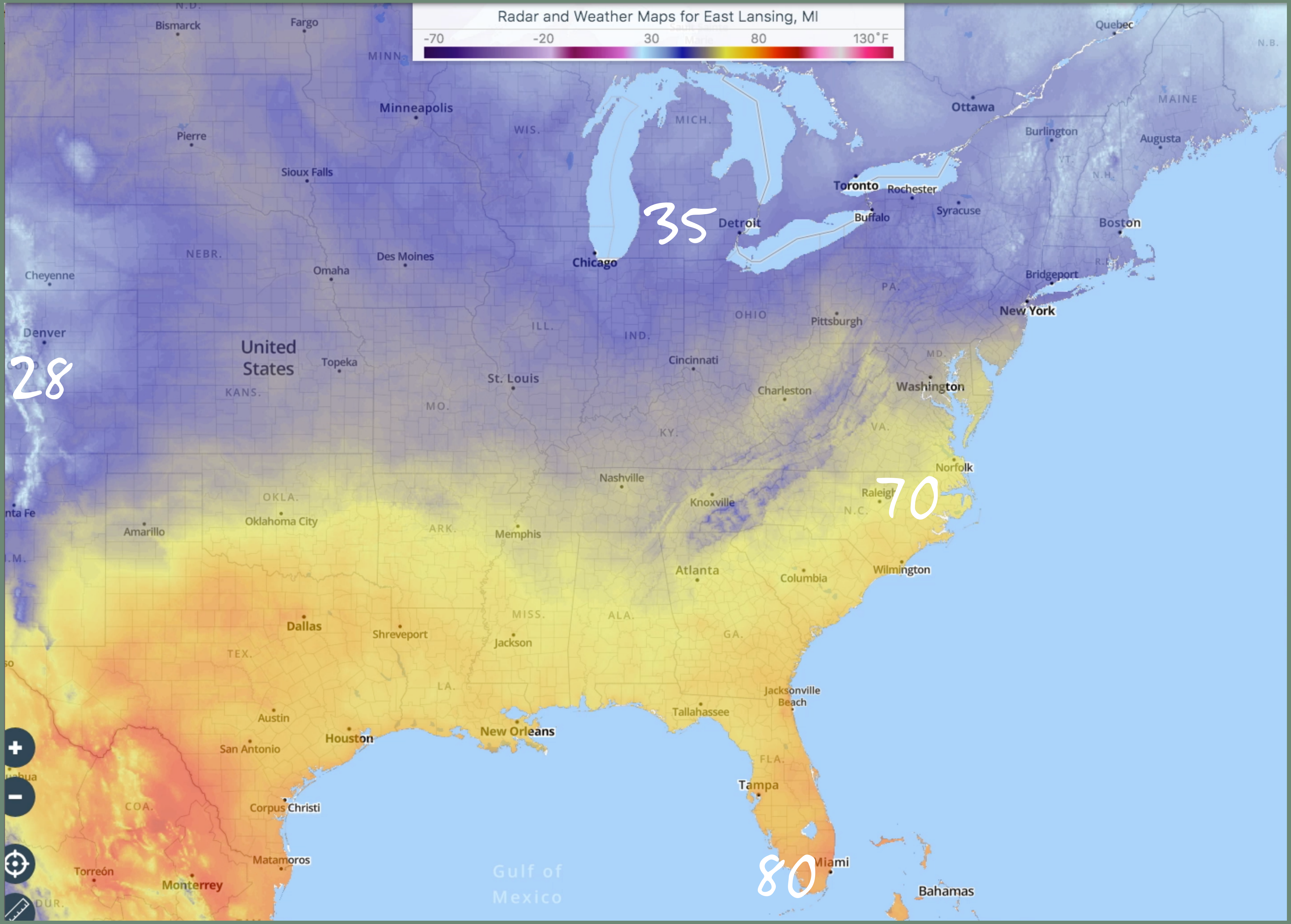
a number in space

you know one everywhere...a number



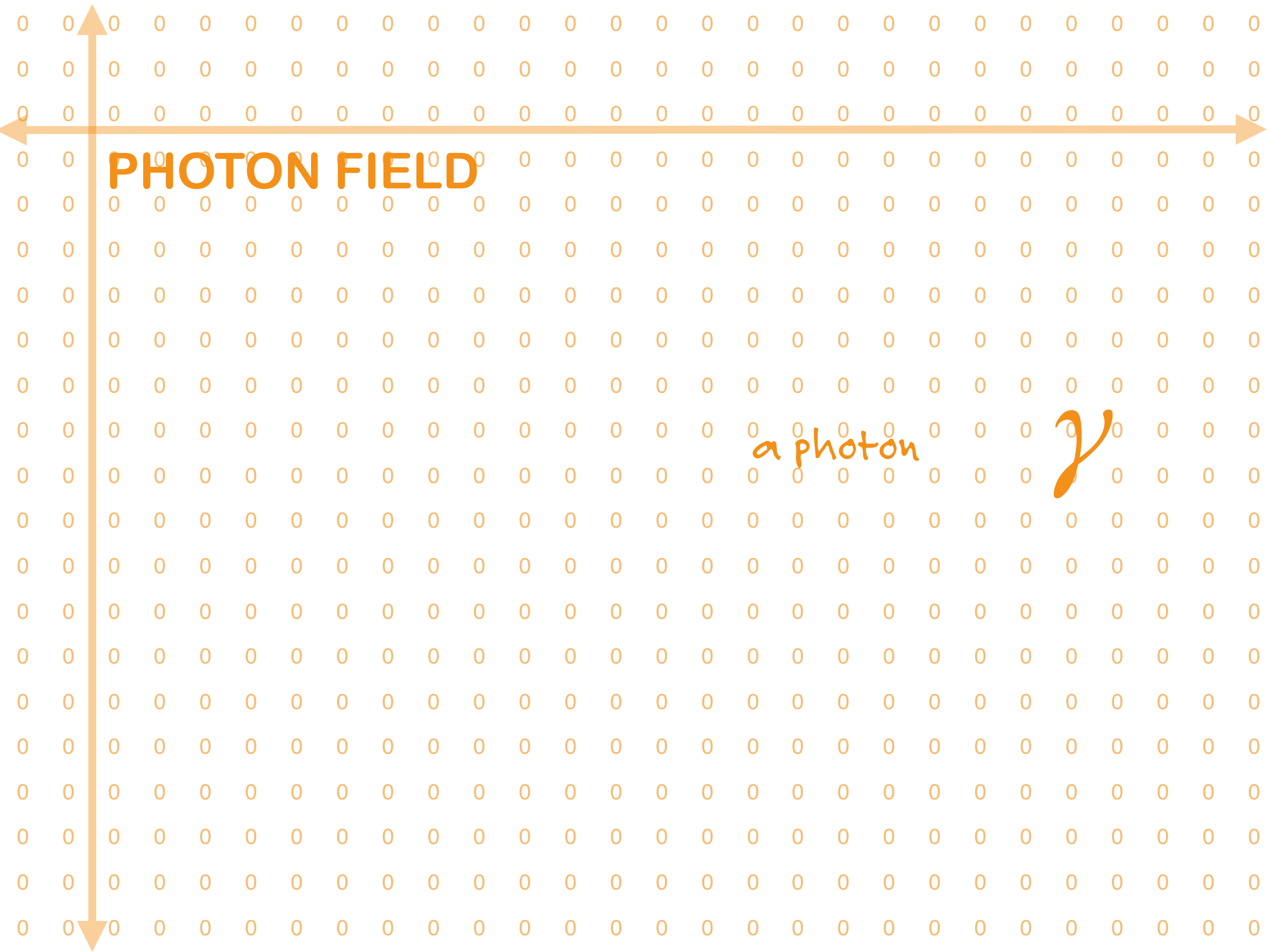
you know one

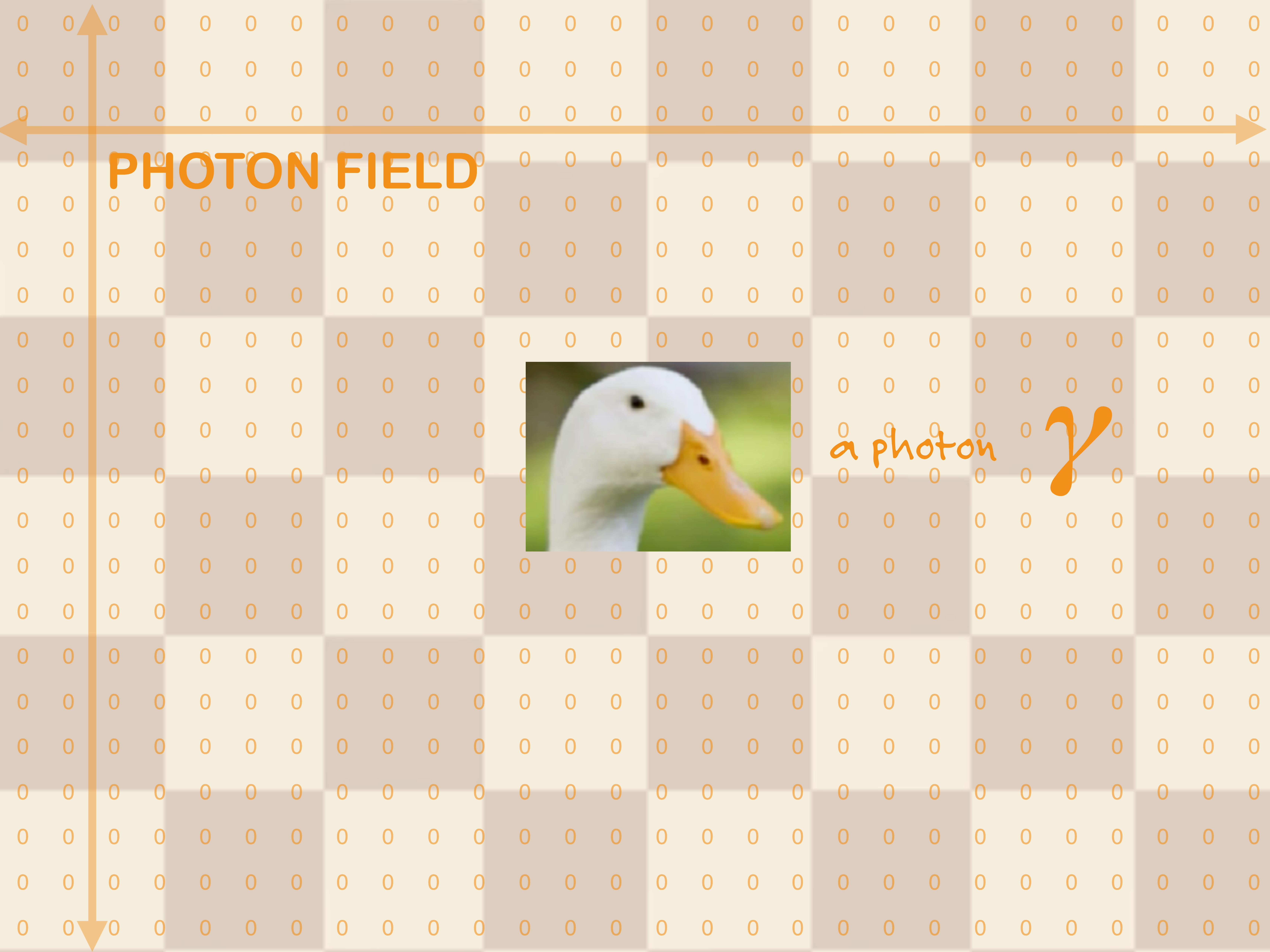
everywhere...a number

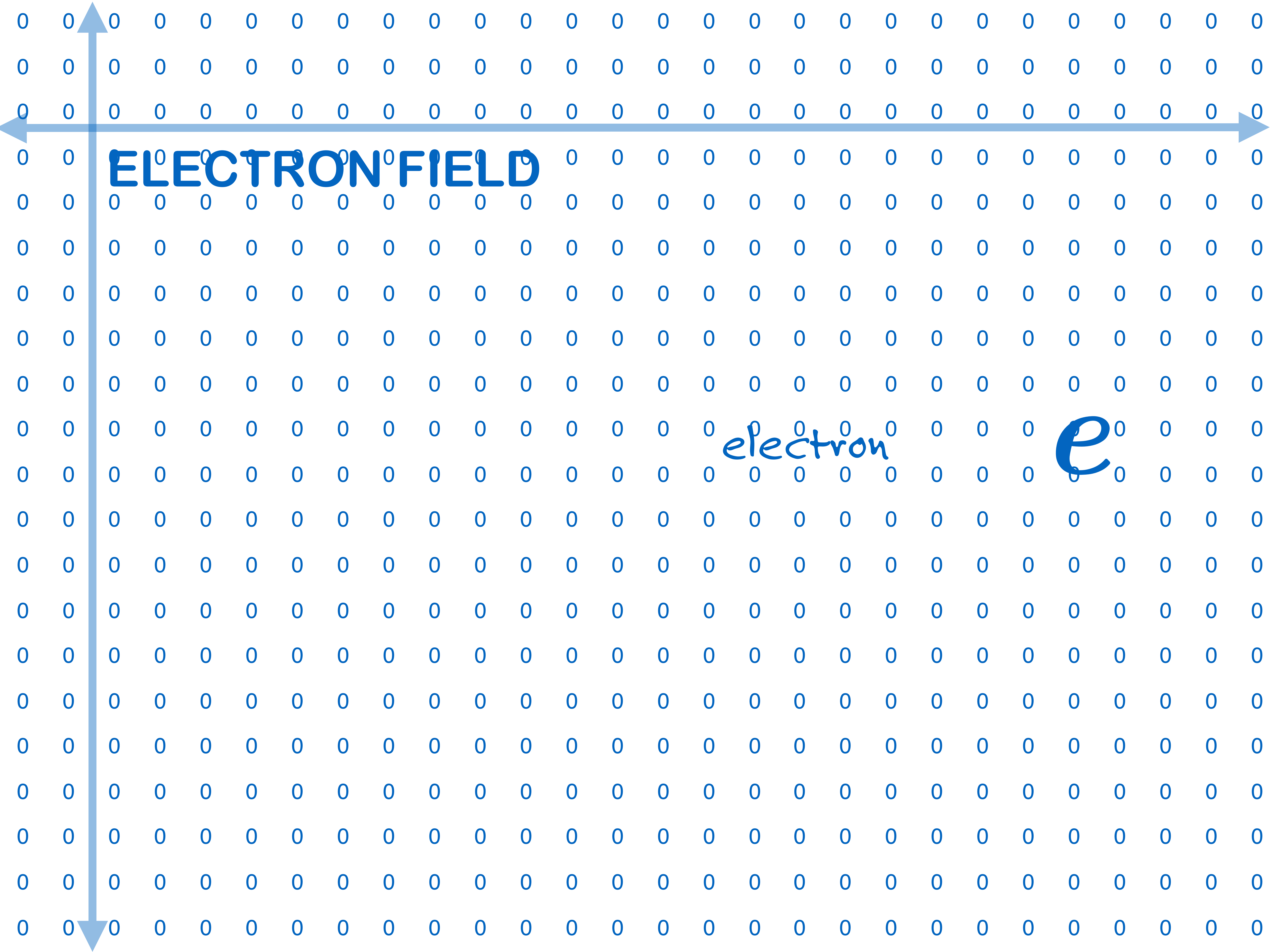


what's a particle?

it's localized wave in a field


PHOTON FIELD
a photon
γ


PHOTON FIELD
a photon γ


ELECTRON FIELD
electron
e

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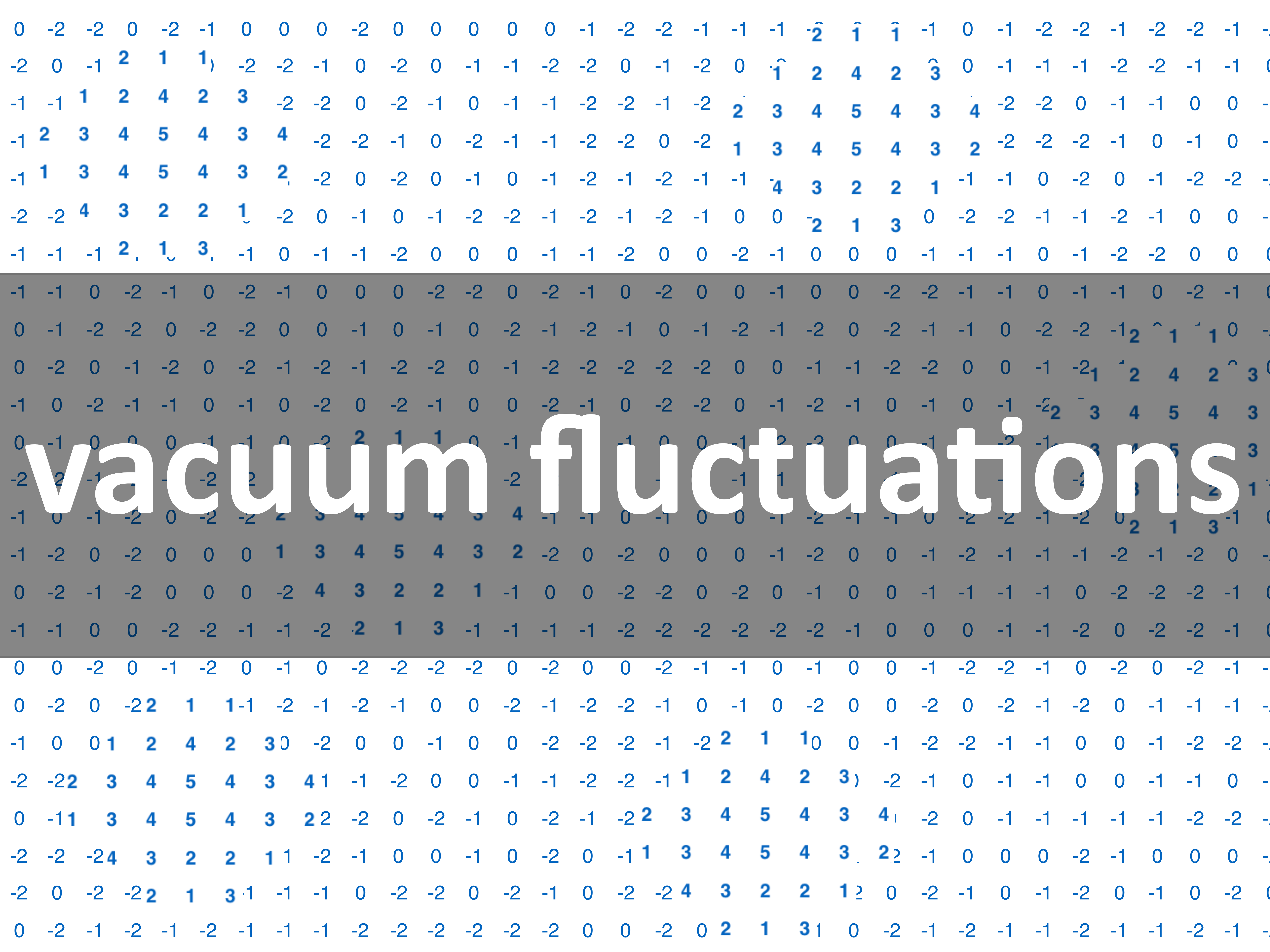
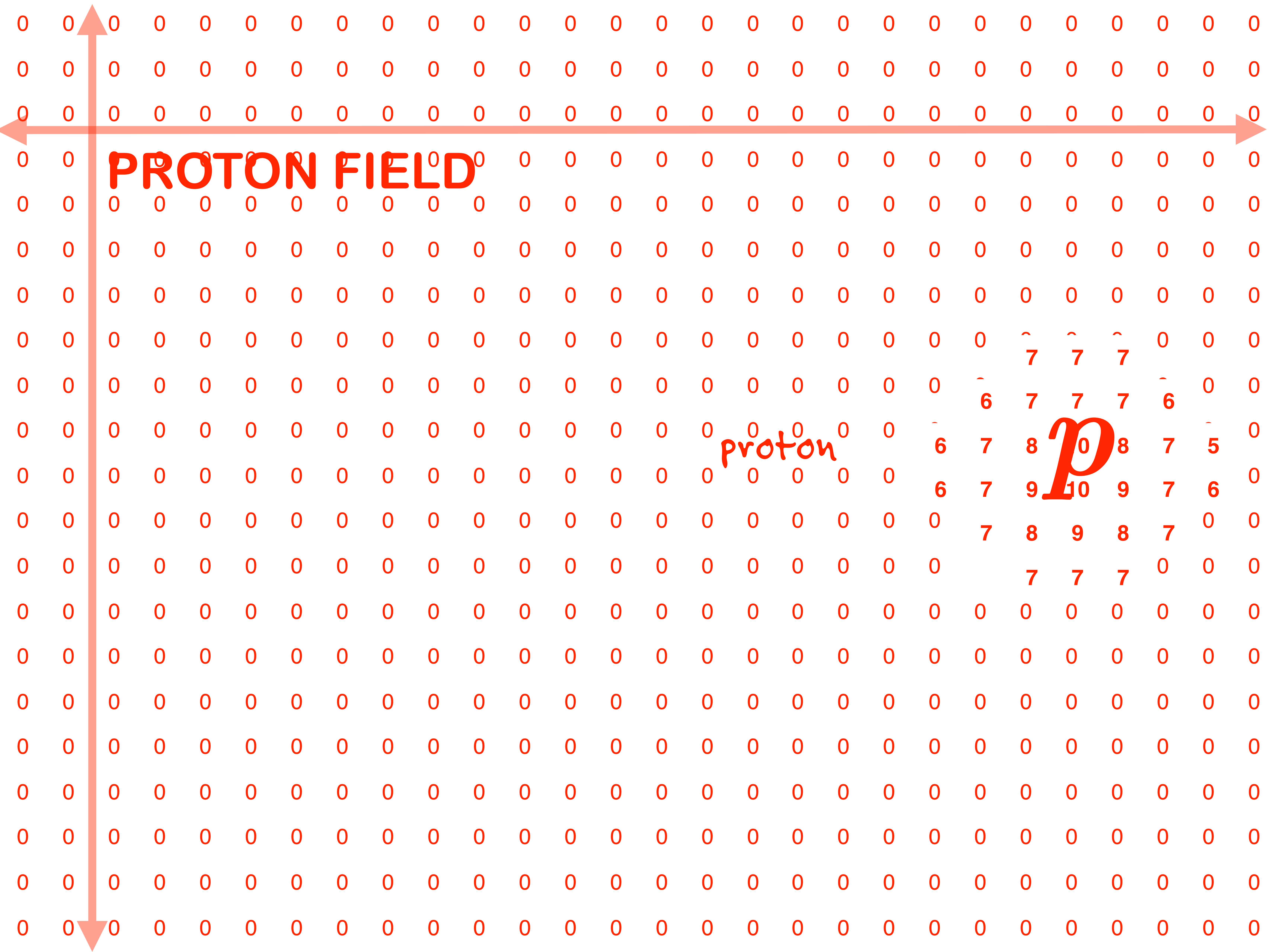

vacuum fluctuations

here's how

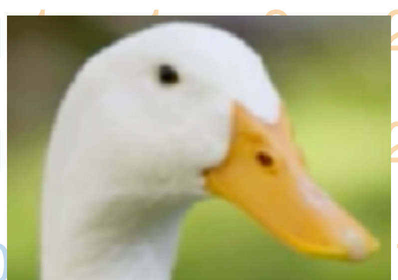
stuff happens

in this particle field theory model


PROTON FIELD
proton
p

electron

photon field “disturbance”

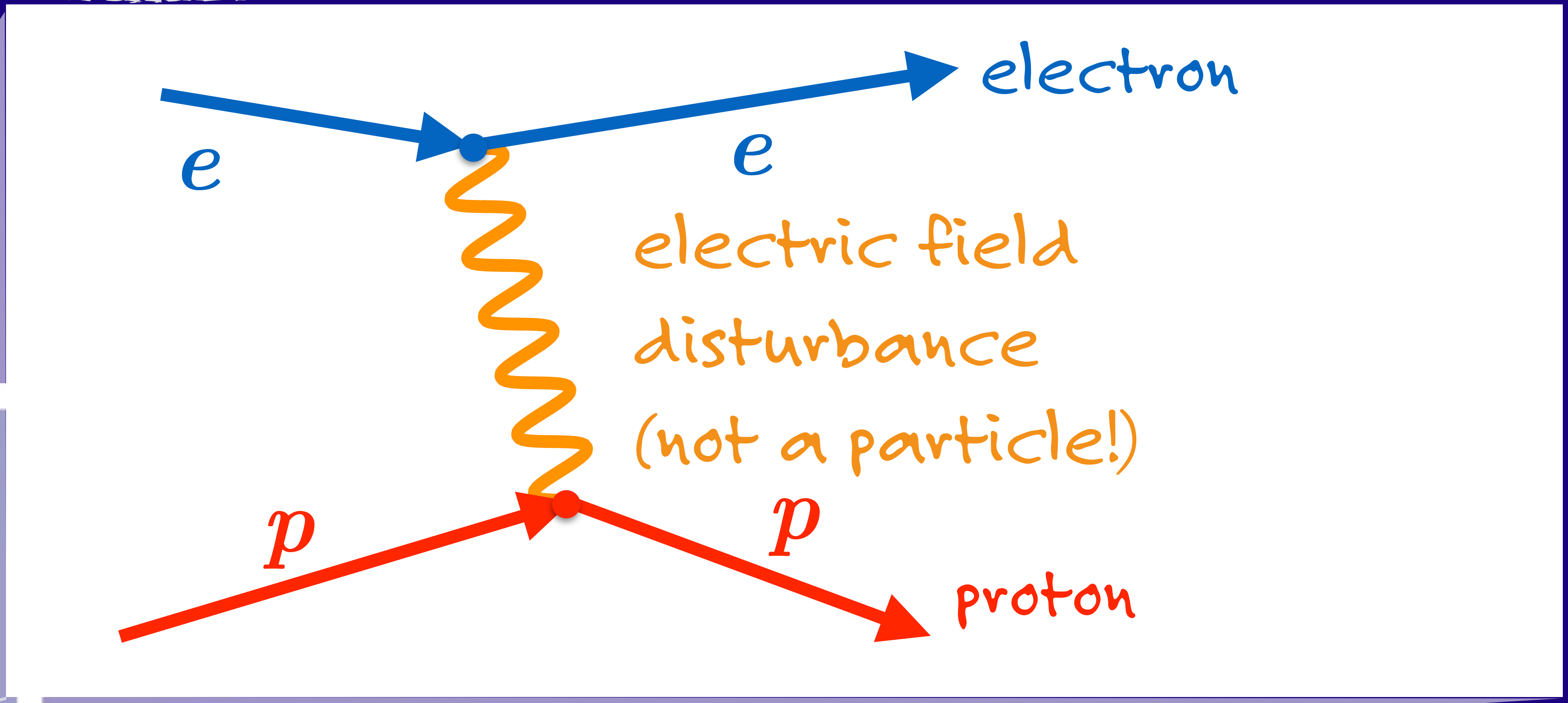


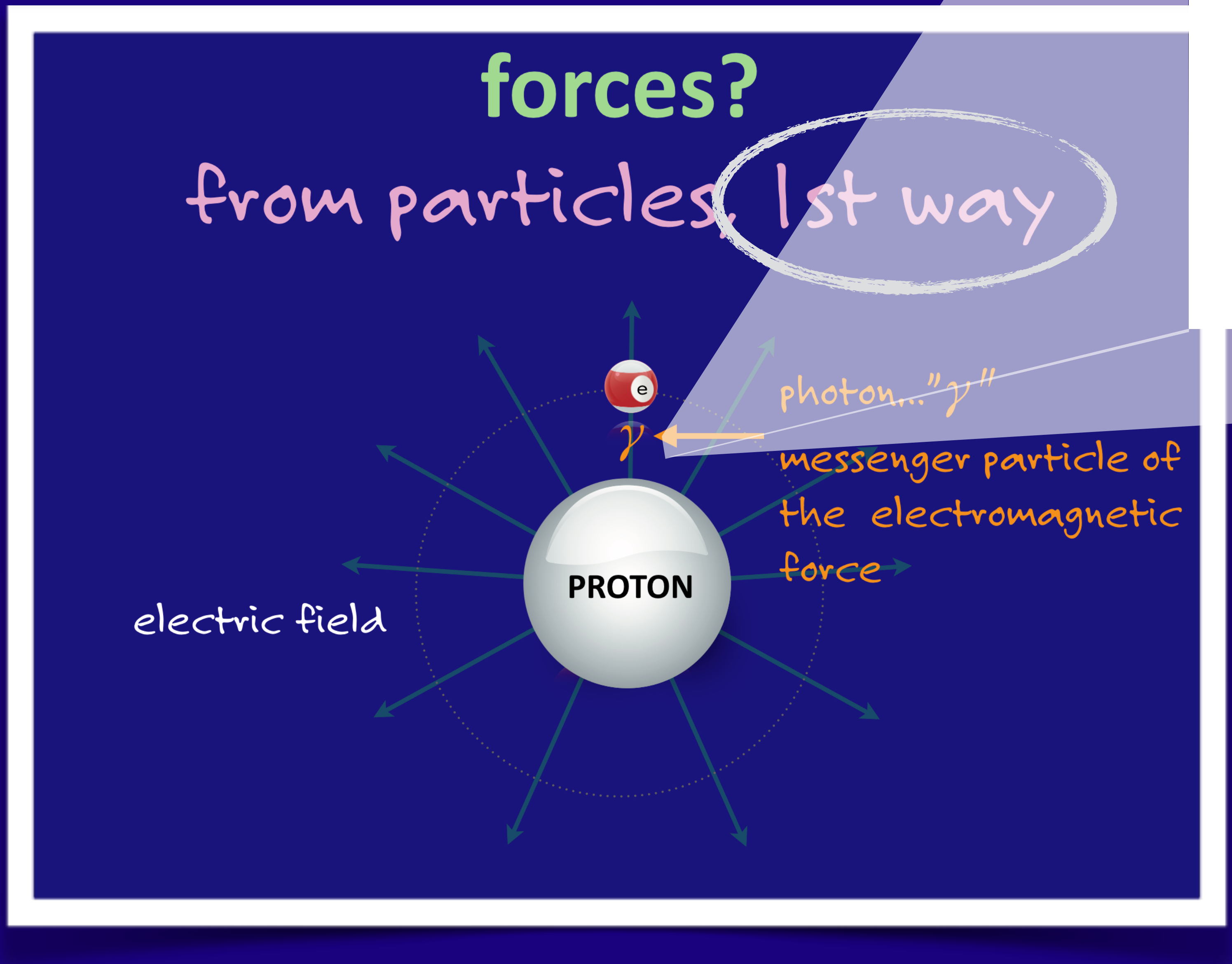
time

proton

our atom

2nd way





particle field theory*

the best theory in history

never an incorrect prediction

outrageously precise agreement, prediction and measurement

*Quantum Electrodynamics

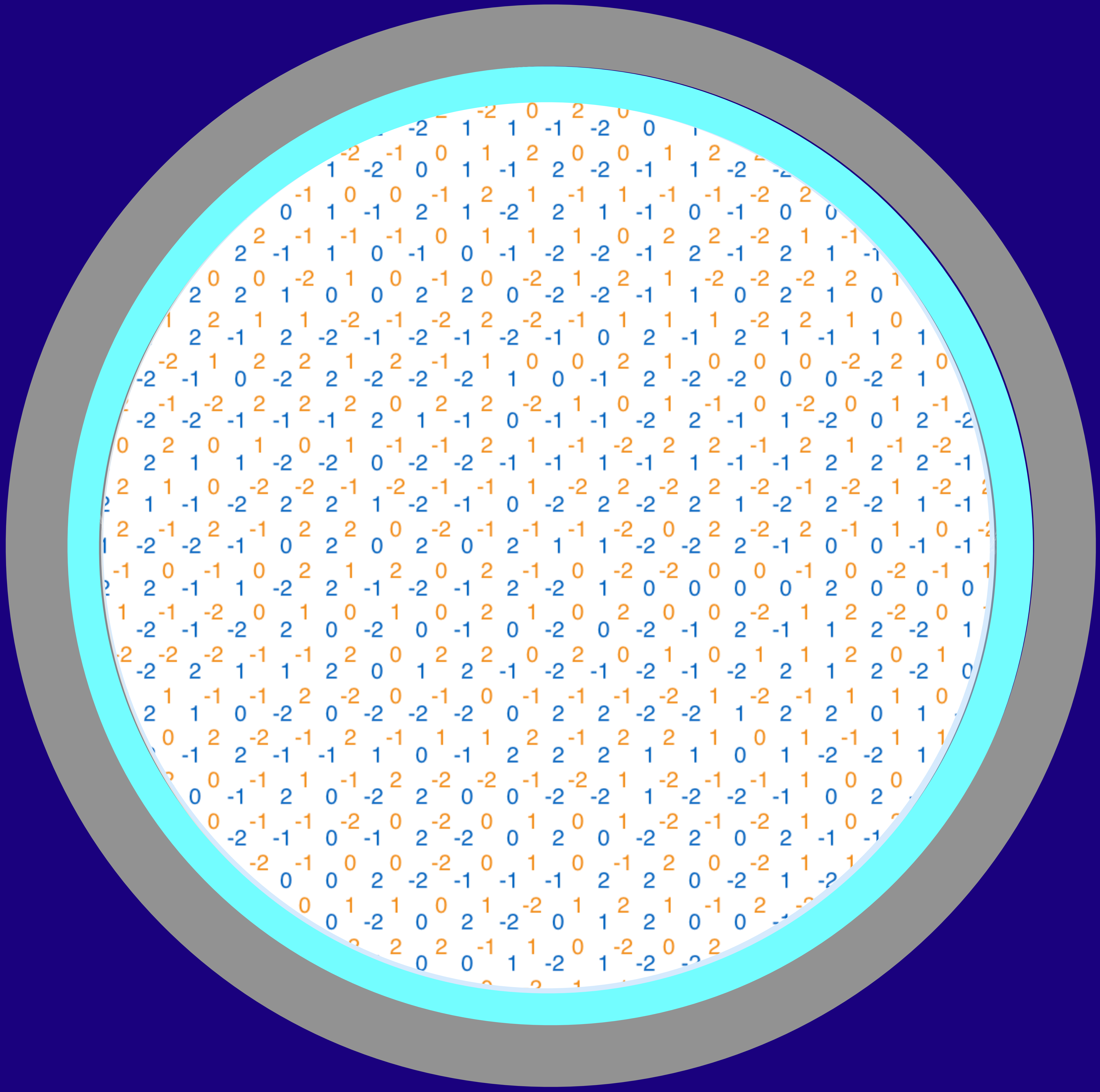
what's more fundamental?

a winner

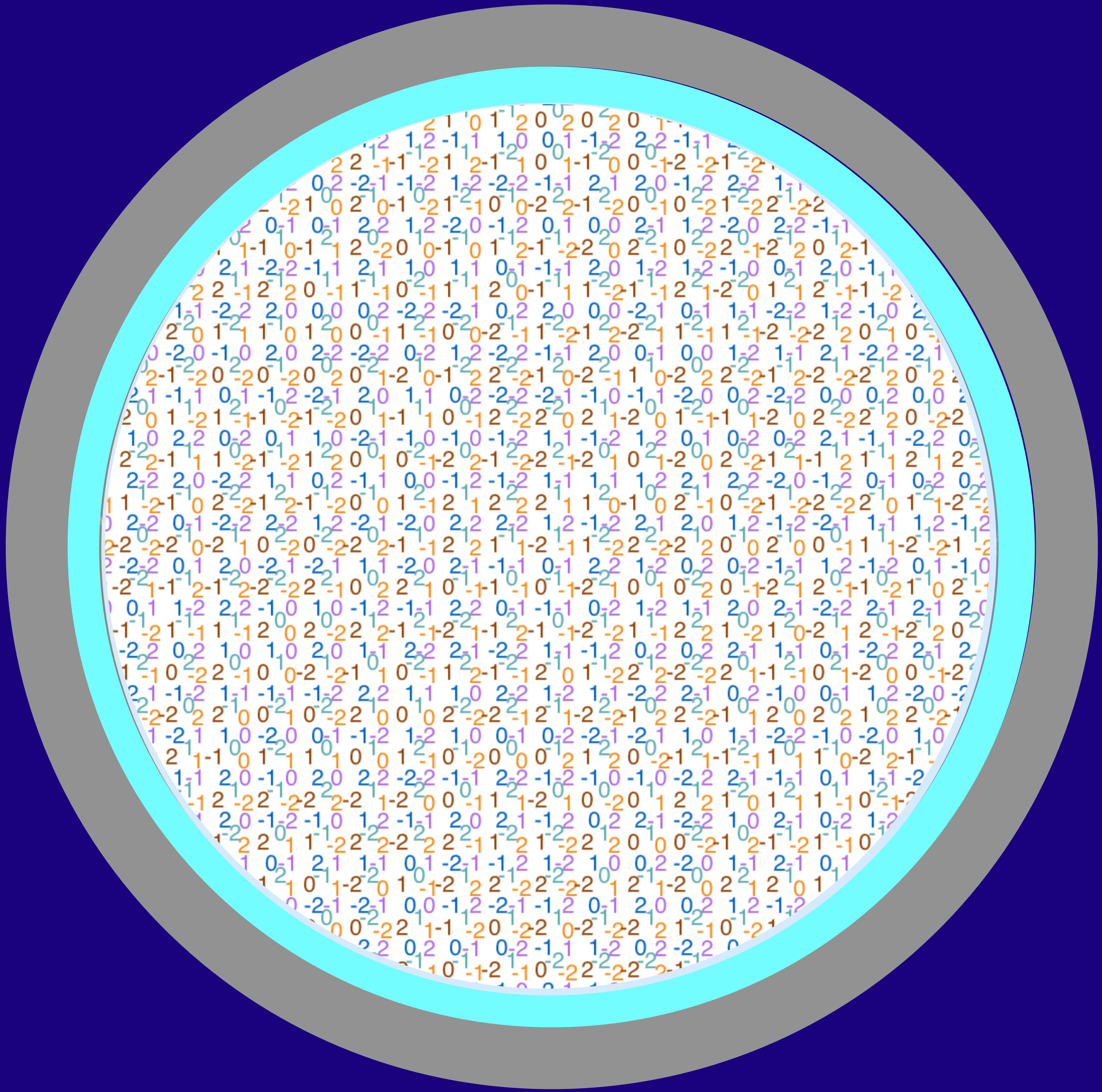
particles

fields

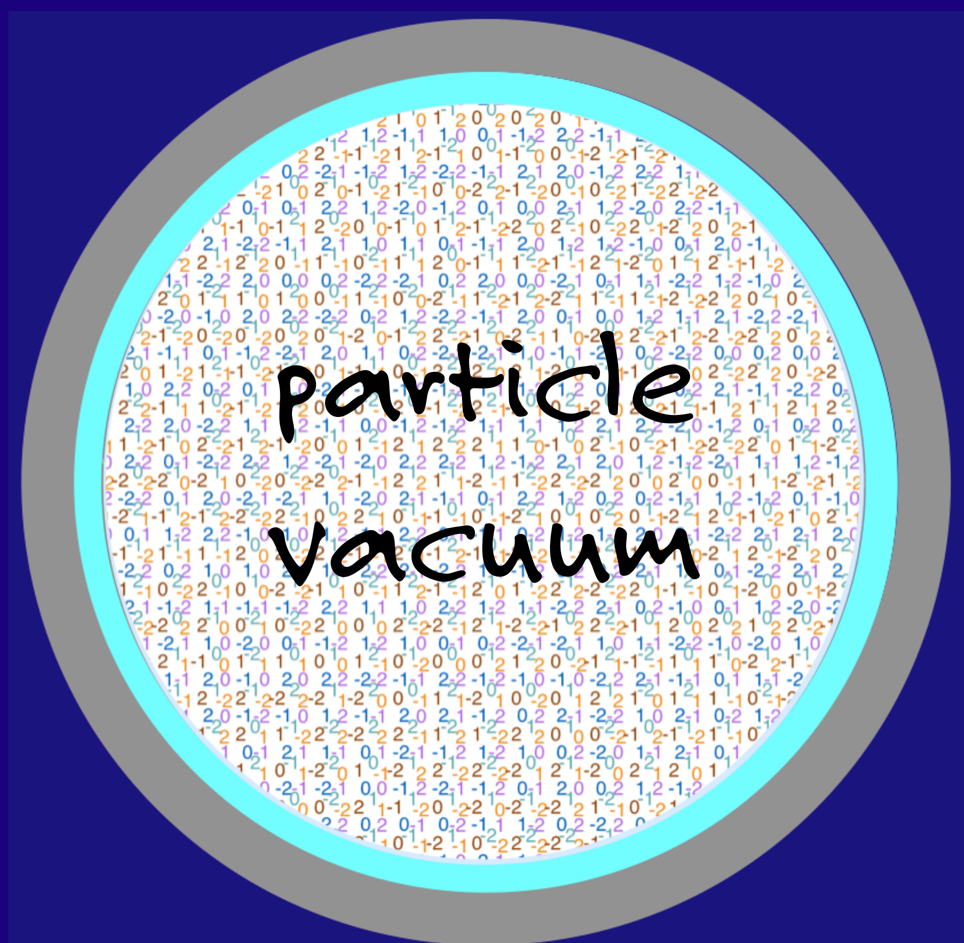
the particle vacuum full of fields:



the particle vacuum full of fields for every "particles"



two predictions for “space”



energy in the particle vacuum is

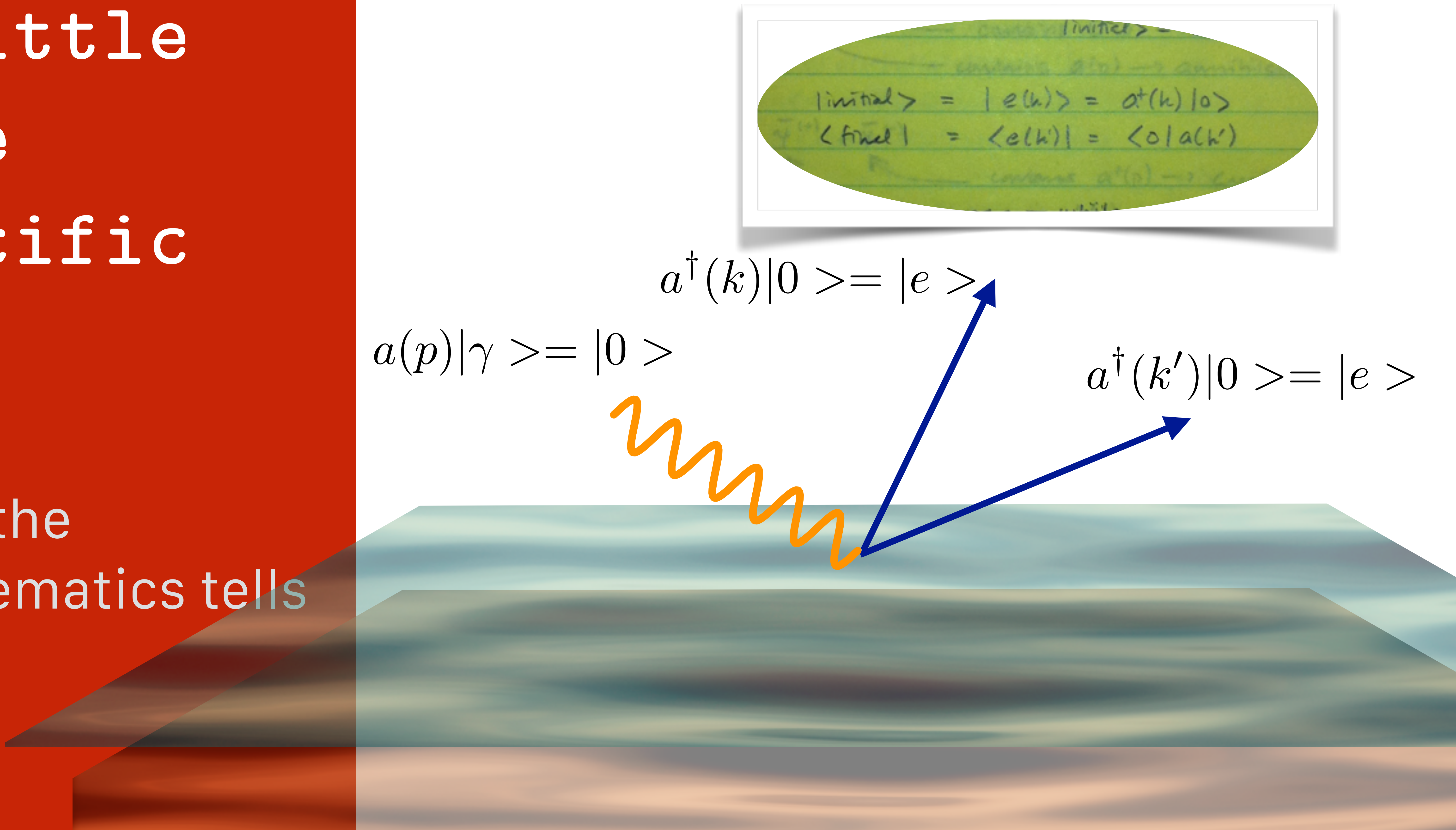
30,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,0
00,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000

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.

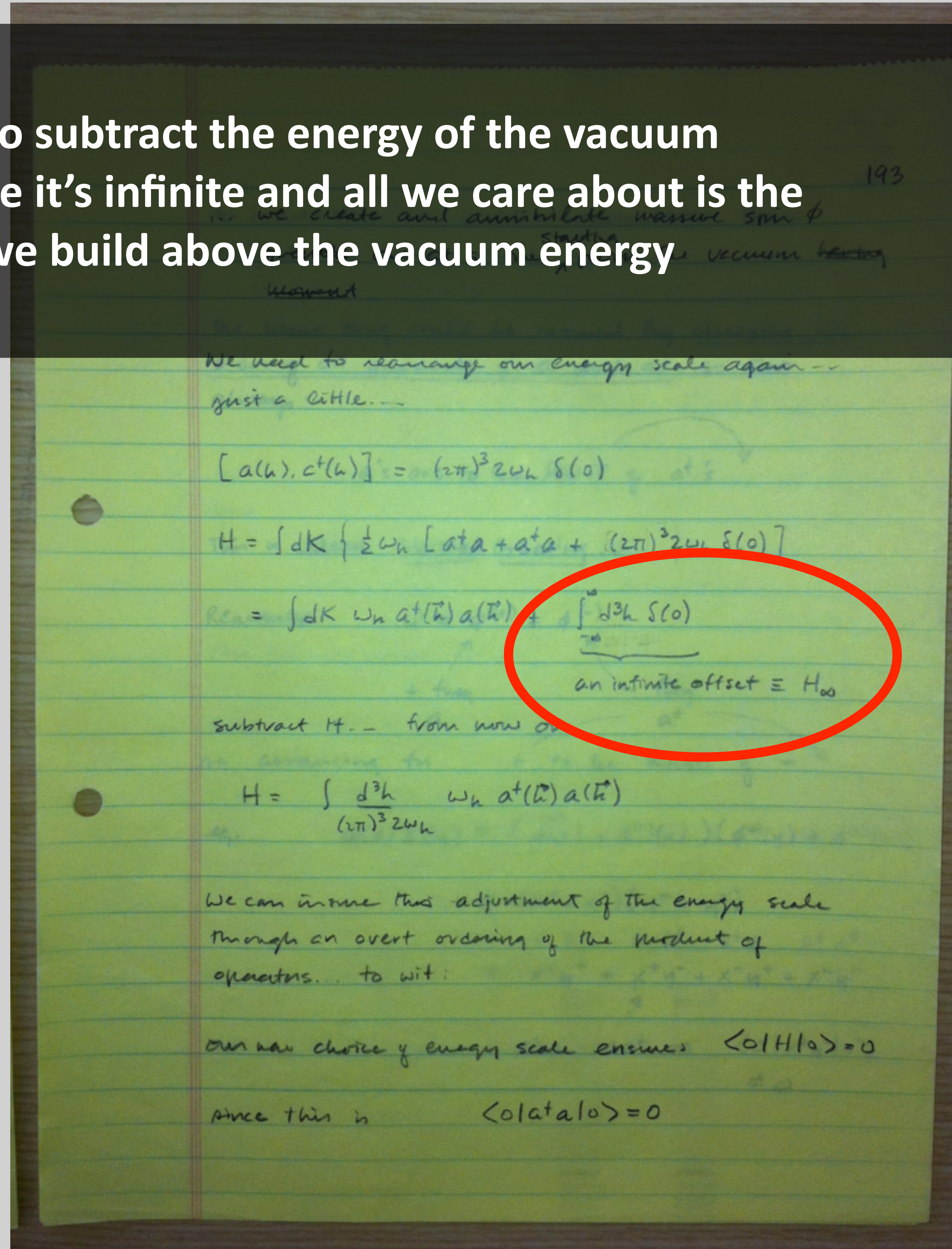
but what does that mean?

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

it means that the vacuum is full of energy

like a reservoir

particles are created out of the vacuum



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?

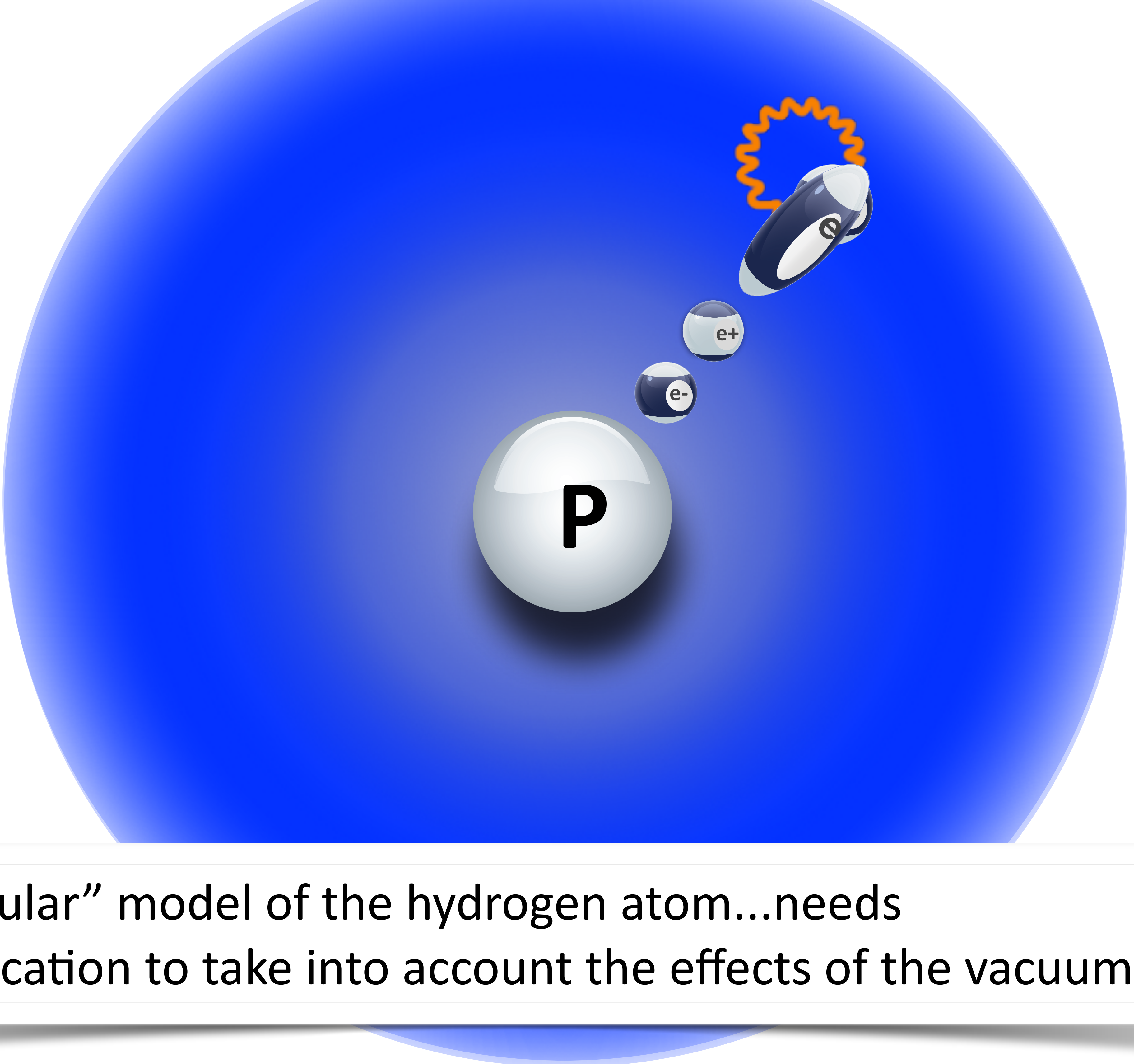
That seems to be the case.

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.



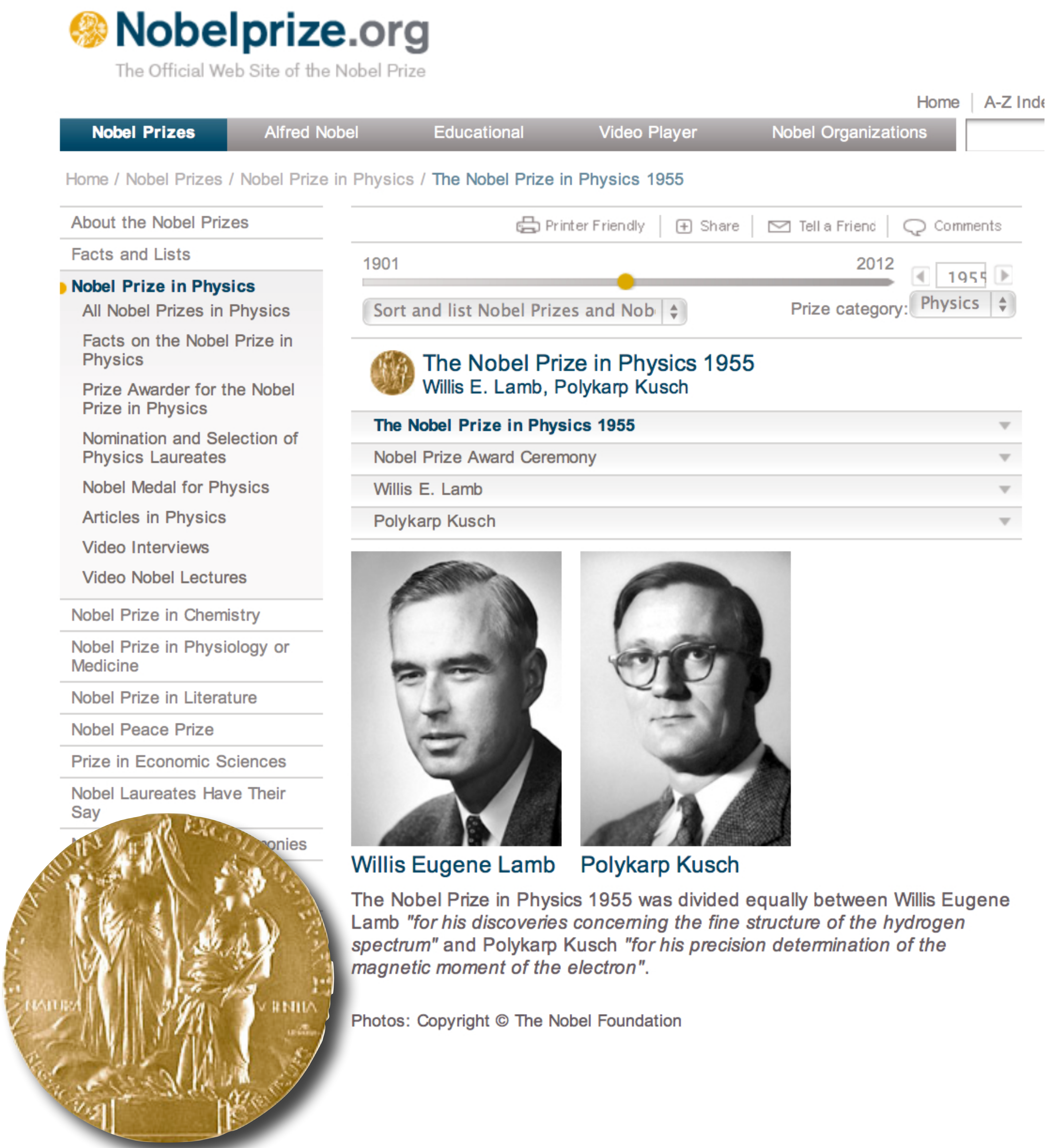
A "regular" model of the hydrogen atom...needs modification to take into account the effects of the vacuum

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

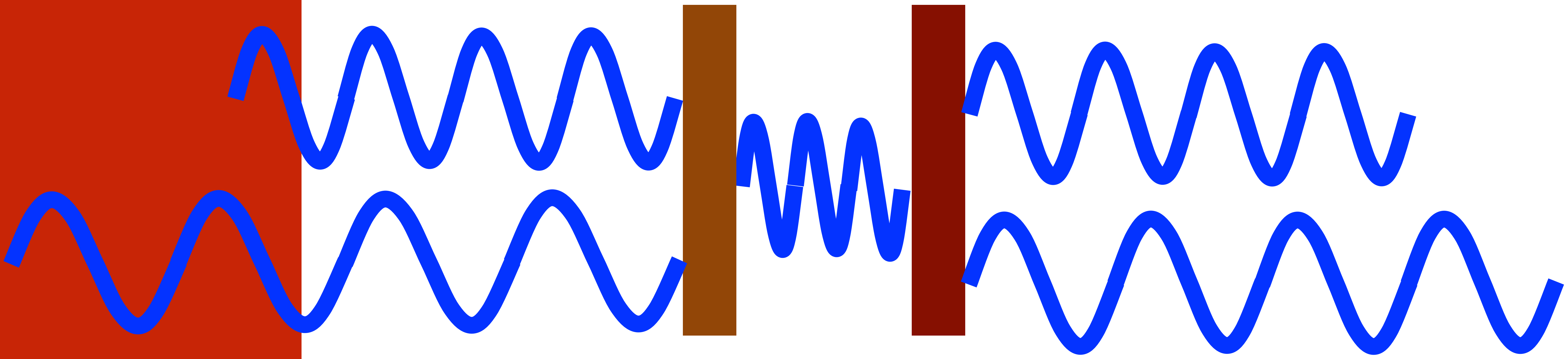


the "Casimir Effect"

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

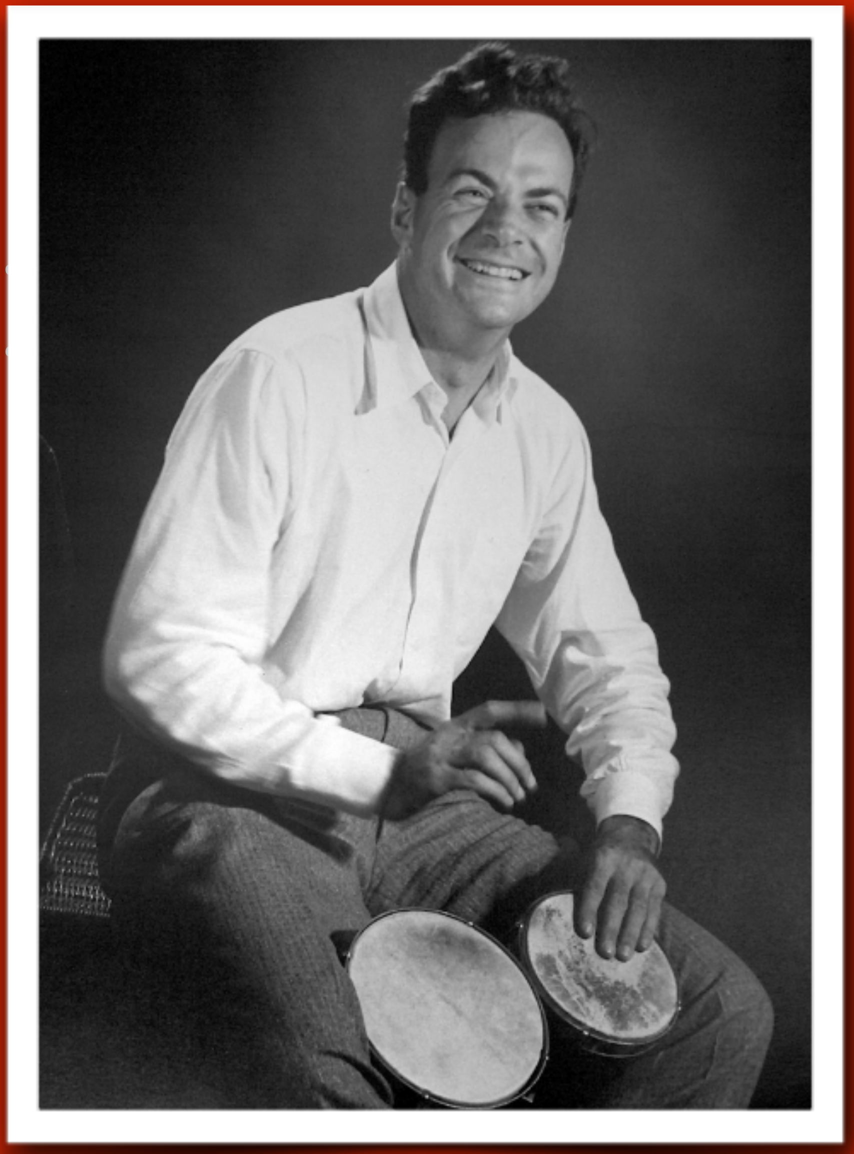
as we'll see when we get back to cosmology

Feynman Diagrams

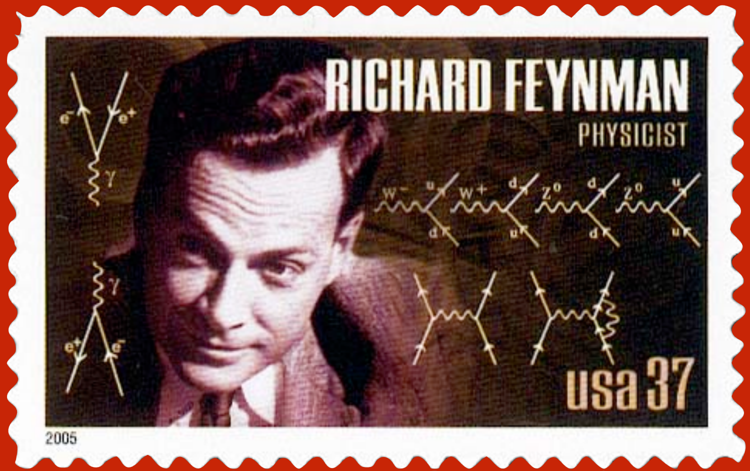
now for real.

creation and annihilation of

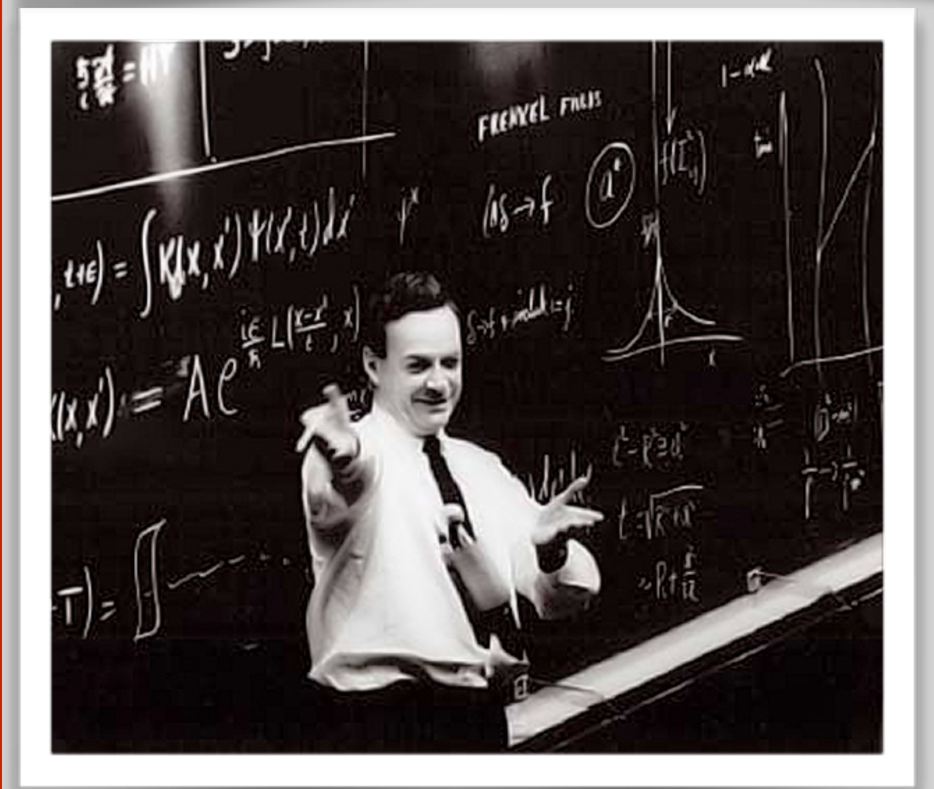
can be embodied in Feynman Diagrams

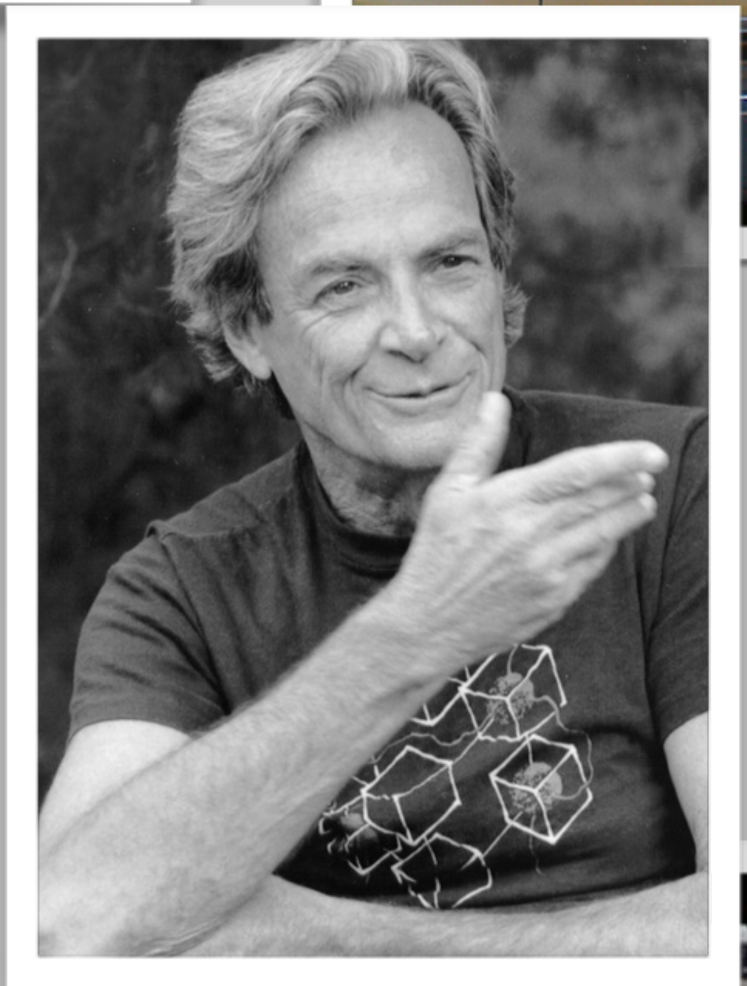


hero worship



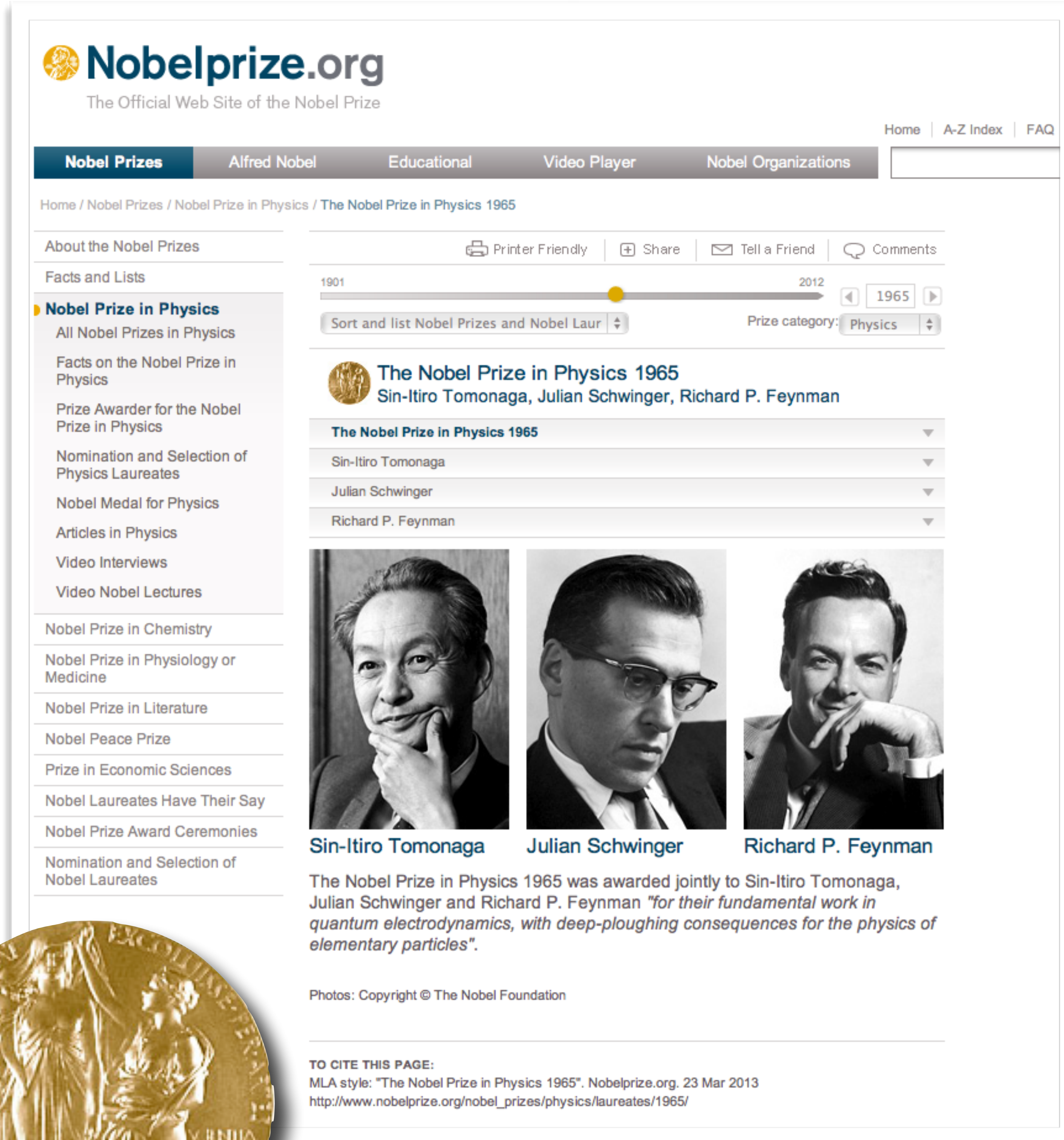
about as close as we come





Richard Feynman, Sin-Itiro Tomonaga, Julian Schwinger

1965 Nobel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Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

The Nobel Prize in Physics 1965
Sin-Itiro Tomonaga
Julian Schwinger
Richard P. Feynman

Sin-Itiro Tomonaga | Julian Schwinger | Richard P. Feynman

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"*.

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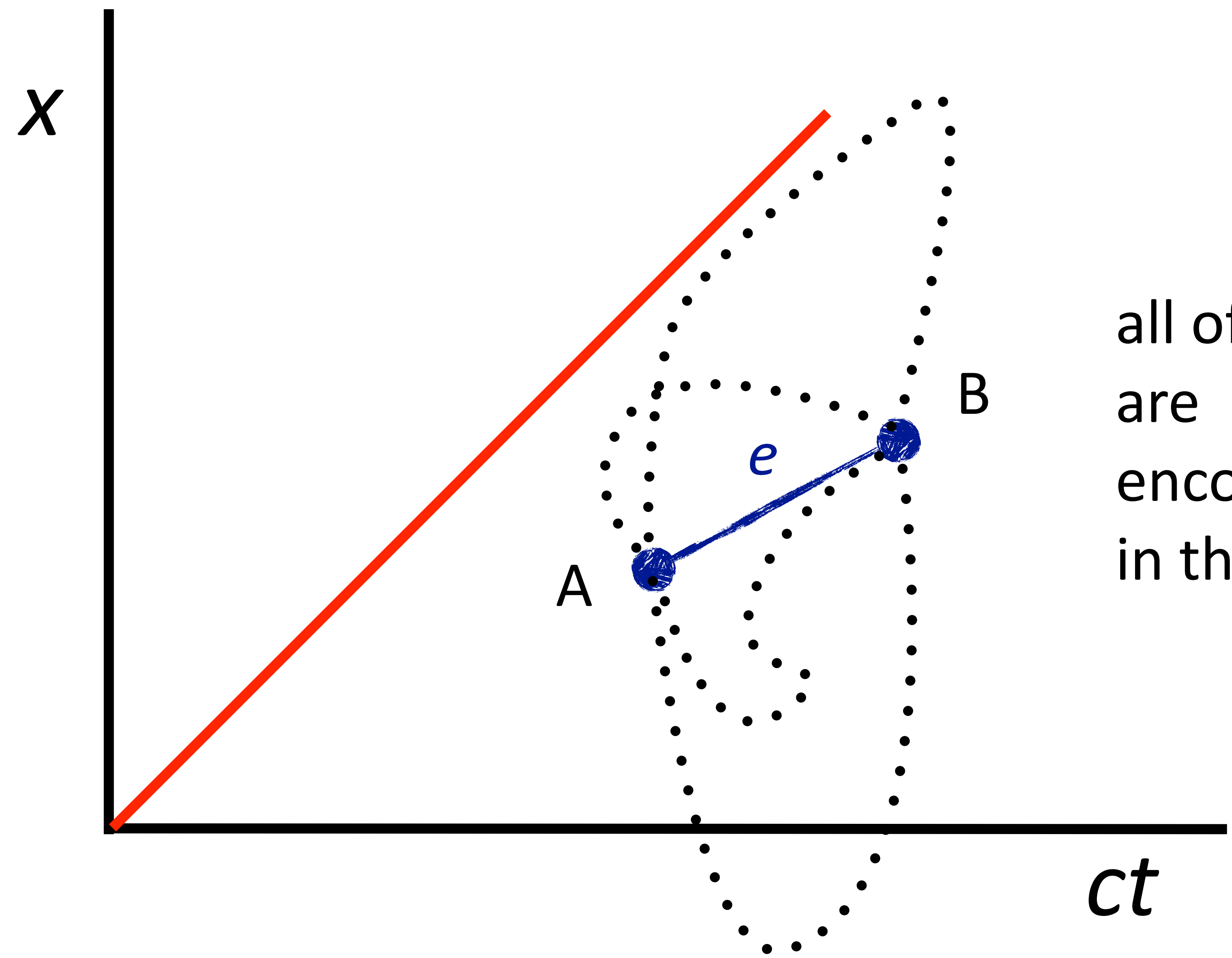
the symbols of Feynman Diagrams

each line represents an entire “history” of trajectories

to go from A to B, represent all histories with a single line.



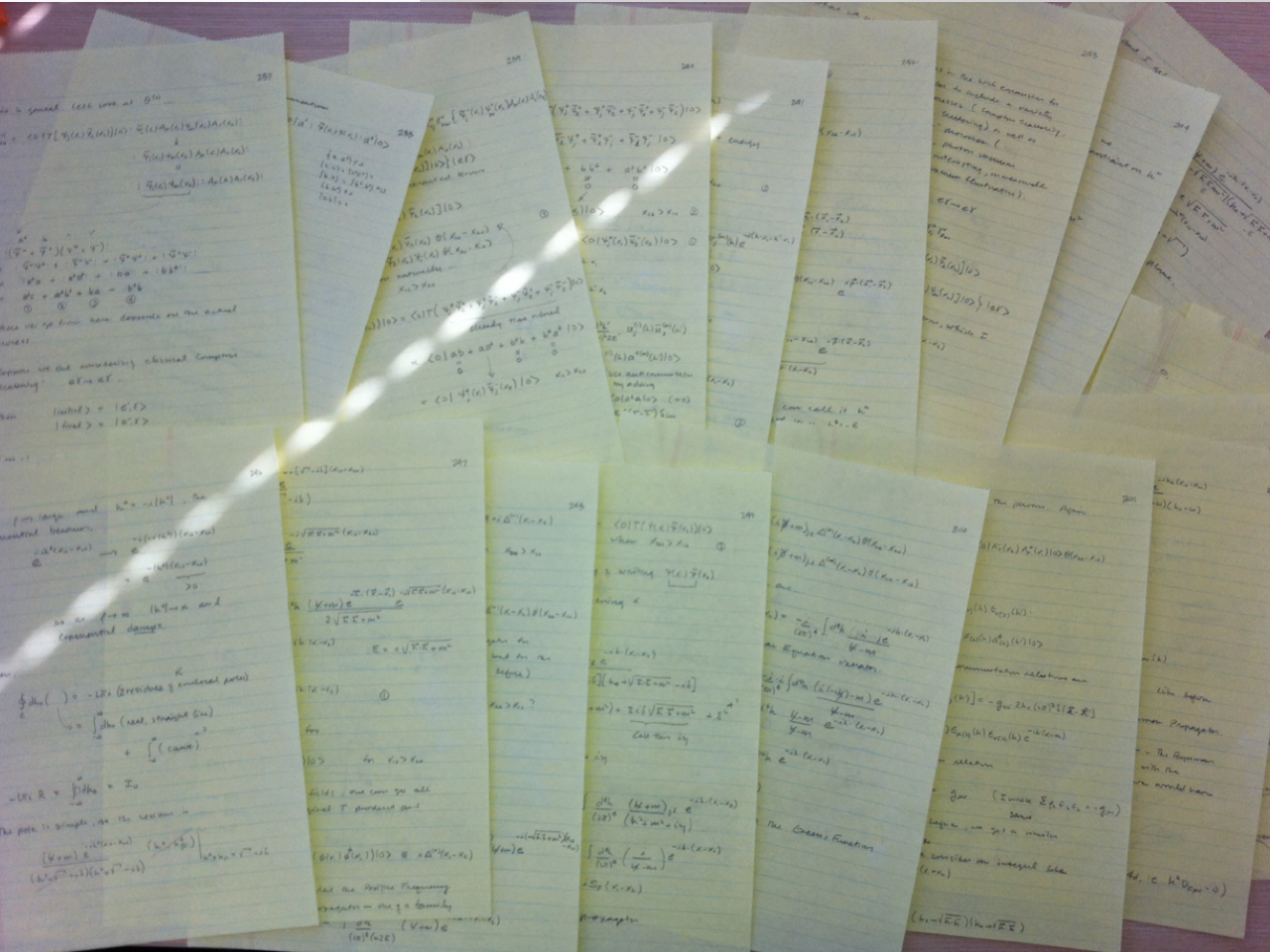
all of the paths are encompassed in the one line

Feynman’s lines include rules on how to calculate the possibilities in a relativistically consistent way.

very efficient

avoids lots of technicalities.

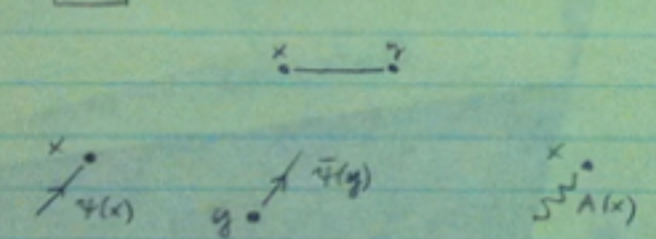
When I teach these techniques to second year graduate students, I first do the calculation of Compton Scattering and do it without Feynman's tools.



311

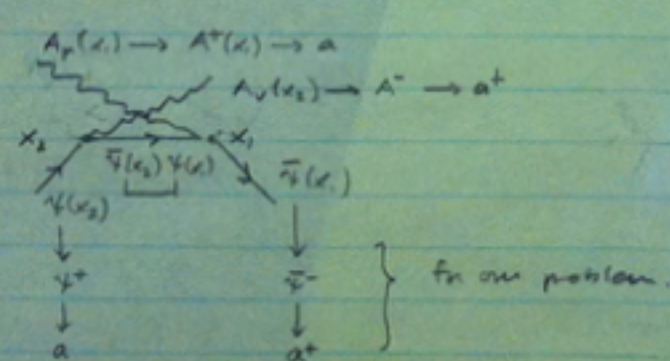
Earlier, I attached a graphical meaning to the Wick expansion terms. Let's recap that according to what we've calculated.

$$\underbrace{\bar{\Psi}(x)\Psi(y)} = \langle 0 | T[\bar{\Psi}(x)\Psi(y)] | 0 \rangle$$



So, the first (① or ②) graph would be

Generally:



and ③ or ④

$A(x_1) \to A^+ \to a$ $A(x_1) \to A^- \to a^+$

312

Remember the Feynman interpretation

↑ time

Ψ — Ψ^+ both annihilates electrons (a) Ψ^- and creates positrons (b^+)

(e^- in, u, Ψ^+ and e^+ out, v, Ψ^-)

$\bar{\Psi}$ annihilates positrons (b) & creates electrons (a^+)

(e^- out, $\bar{u}$, $\bar{\Psi}^-$ and e^+ in, $\bar{v}$, $\bar{\Psi}^+$)

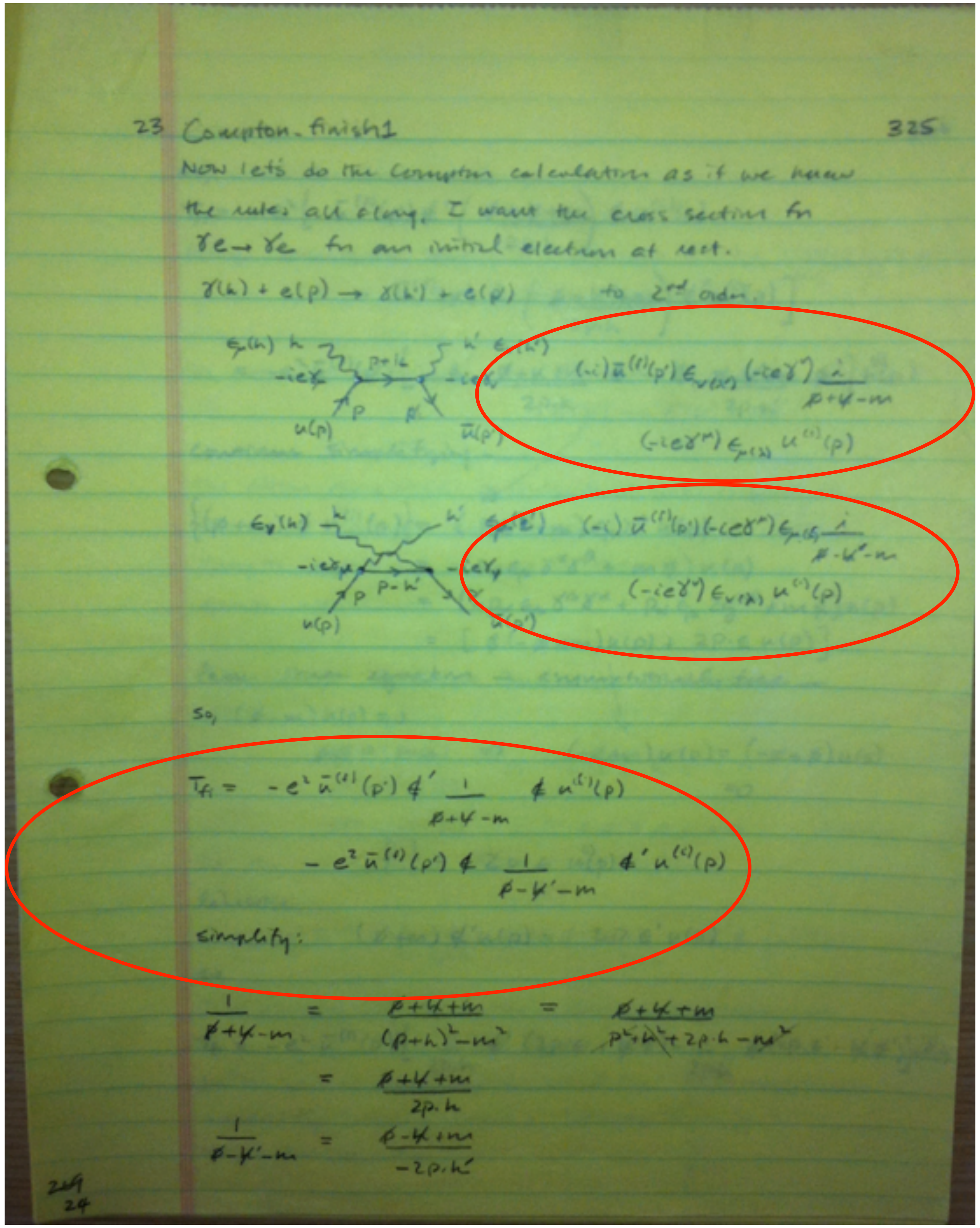
... can be relabeled with the frequency ... indicated.

... Feynman rules eliminate all ... ulation and go directly to ...

his rules eliminate all of that

and I can just write down the "answer"

appropriately labeled, each line tells us what to put into a long equation for further solving



`but the pictures themselves are visually...informative`

and I'm going to try to tell you how to do this

without the geeky mathematics

theoretical papers

each diagram is a complicated calculation

m_{π_T} smaller than 260 GeV. The parameter ϵ refers to the proportion of the top quark mass generated by the extended technicolor which is taken in the range of $\epsilon \sim (0.01, 0.1)$.

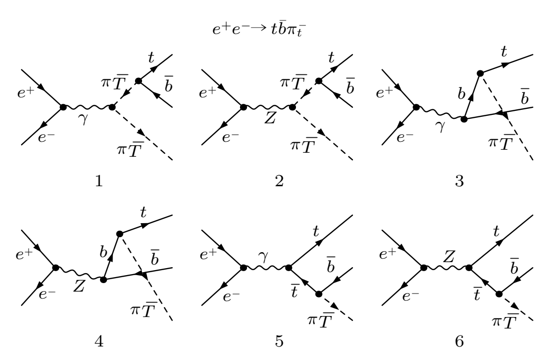


Fig. 1. Diagrams for $e^+e^- \to t\bar{b}\pi_t^-$.

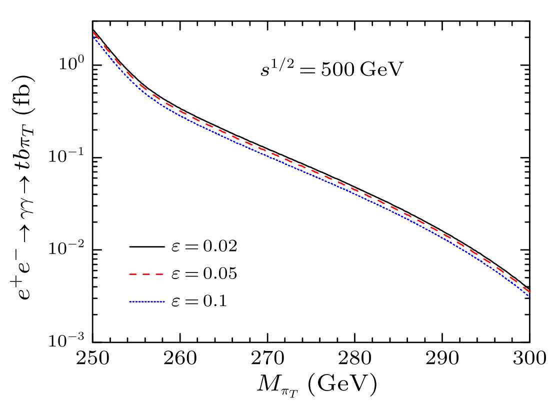


Fig. 2. Dependence of the cross section for $e^+e^- \to t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ on the top-pion mass m_{π_t} at the ILC with energy of 500 GeV.

By using the laser back-scattering technique on electron beam, an e^+e^- LC which has the c.m. energy of hundreds of GeV to several TeV can be transformed to be a photon collider.[19–21] By integrating over the photon luminosity in an e^+e^- linear collider, the total cross section for the process $e^+e^- \to t\bar{b}\pi_t^-$ can be obtained in the form

$$\sigma(s) = \int_{\frac{E_0}{\sqrt{s}}}^{x_{\max}} dz \frac{d\mathcal{L}_{\gamma\gamma}}{dz} \hat{\sigma}(\gamma\gamma \to t\bar{b}\pi_t^-, \text{ at } \hat{s} = z^2 s), \tag{12}$$

where $E_0 = m_t + m_b + m_{\pi_T}$, $\sqrt{s}(\sqrt{\hat{s}})$ is the $e^+e^-(\gamma\gamma)$ c.m. energy, and $\frac{d\mathcal{L}_{\gamma\gamma}}{dz}$ is the distribution function of photon luminosity, which is defined as

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dz} = 2z \int_{z^2/x_{\max}}^{x_{\max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}\Big(\frac{z^2}{x}\Big). \tag{13}$$

For the initial unpolarized electrons and laser photon beams, the energy spectrum of the back scattered photon is given by[22]

$$F_{\frac{\gamma}{e}} = \frac{1}{D(\xi)}\Big[1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}\Big], \tag{14}$$

where $x = 2\omega/\sqrt{s}$ is the fraction of the energy of the incident electron carried by the back-scattered photon, the maximum fraction of energy carried by the back-scattered photon is $x_{\max} = 2\omega_{\max}/\sqrt{s} = \xi/(1+\xi)$, and

$$D(\xi) = \Big(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\Big)\ln(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2}, \tag{15}$$

$$\xi = \frac{2\sqrt{s}\omega_0}{{m_e}^2}, \tag{16}$$

where m_e and $\sqrt{s}/2$ are the mass and energy of the electron, ω_0 is the laser photon energy. In our evaluation, we choose ω_0 such that it maximizes the backscattered photon energy without spoiling the luminosity through e^+e^- pair creation. Then we have $\xi = 2(1+\sqrt{2})$, $x_{\max} \simeq 0.83$, and $D(\xi) \approx 1.84$, as used in Ref. [23].

The processes $\gamma\gamma \to t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ occurs through the u- and t-channel involving charged top-pion bremsstrahlungs originated from different positions on quark lines. The Feynman diagrams are drawn in Fig. 3, but the corresponding diagrams with interchange of the two incoming photons are not shown.

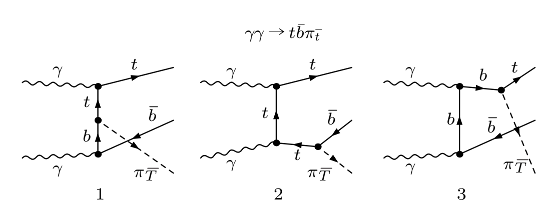


Fig. 3. Diagrams for $\gamma\gamma \to t\bar{b}\pi_t^-$.

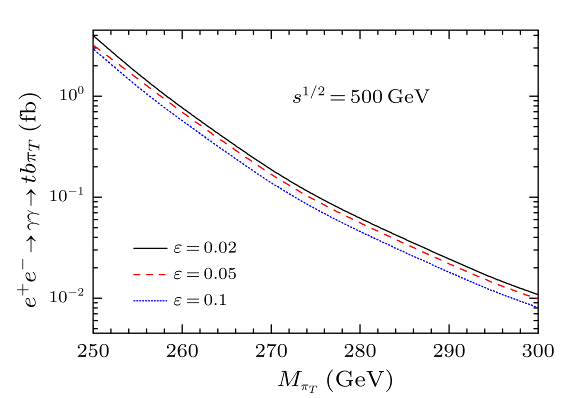


Fig. 4. Dependence of the cross section for $e^+e^- \to \gamma\gamma \to t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ on the top-pion mass m_{π_t} at the ILC with energy of 500 GeV.

We show the cross section for $e^+e^- \to \gamma\gamma \to t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ at the ILC with energy of 500 GeV as a

2.1.1 Lepton and heavy quark pair decays of the SM Higgs particle

In lowest order the leptonic decay width of the SM Higgs boson is given by [10, 37]

$$\Gamma[H \to l^+l^-] = \frac{G_F M_H}{4\sqrt{2}\pi}\, m_l^2 \beta^3 \tag{6}$$

with $\beta = (1 - 4m_l^2/M_H^2)^{1/2}$ being the velocity of the leptons. The branching ratio of decays into τ leptons amounts to about 10% in the intermediate mass range. Muonic decays can reach a level of a few 10^{-4}, and all other leptonic decay modes are phenomenologically unimportant.

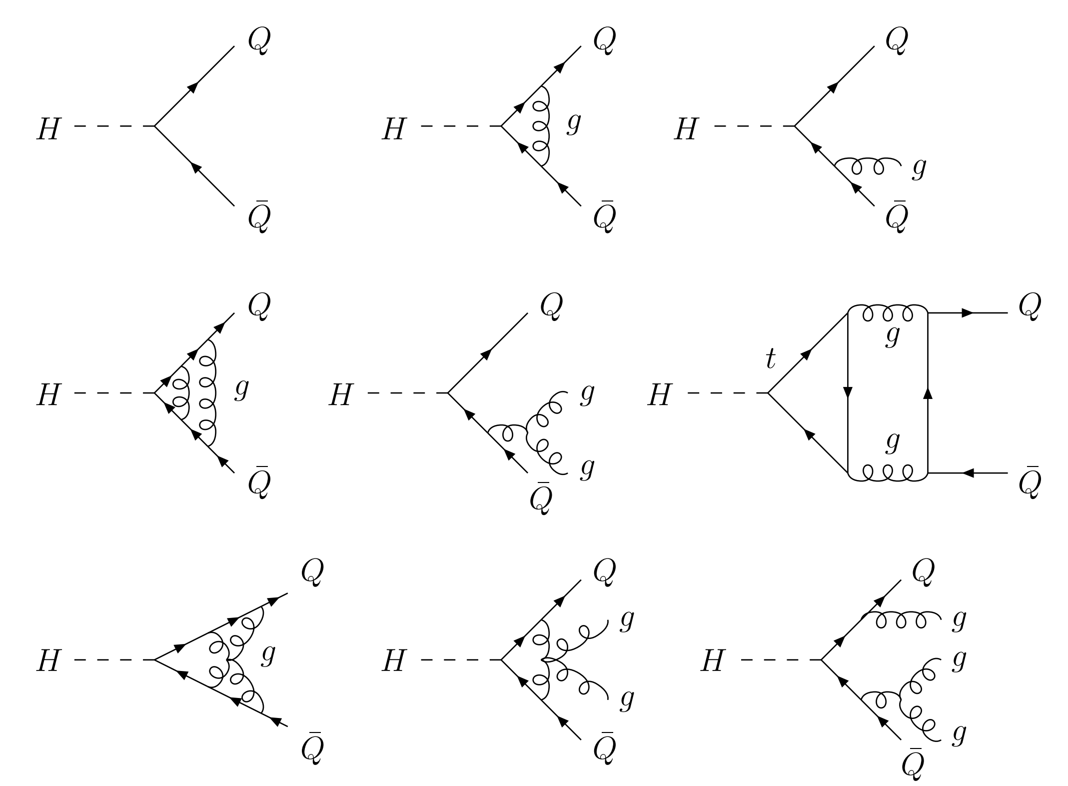
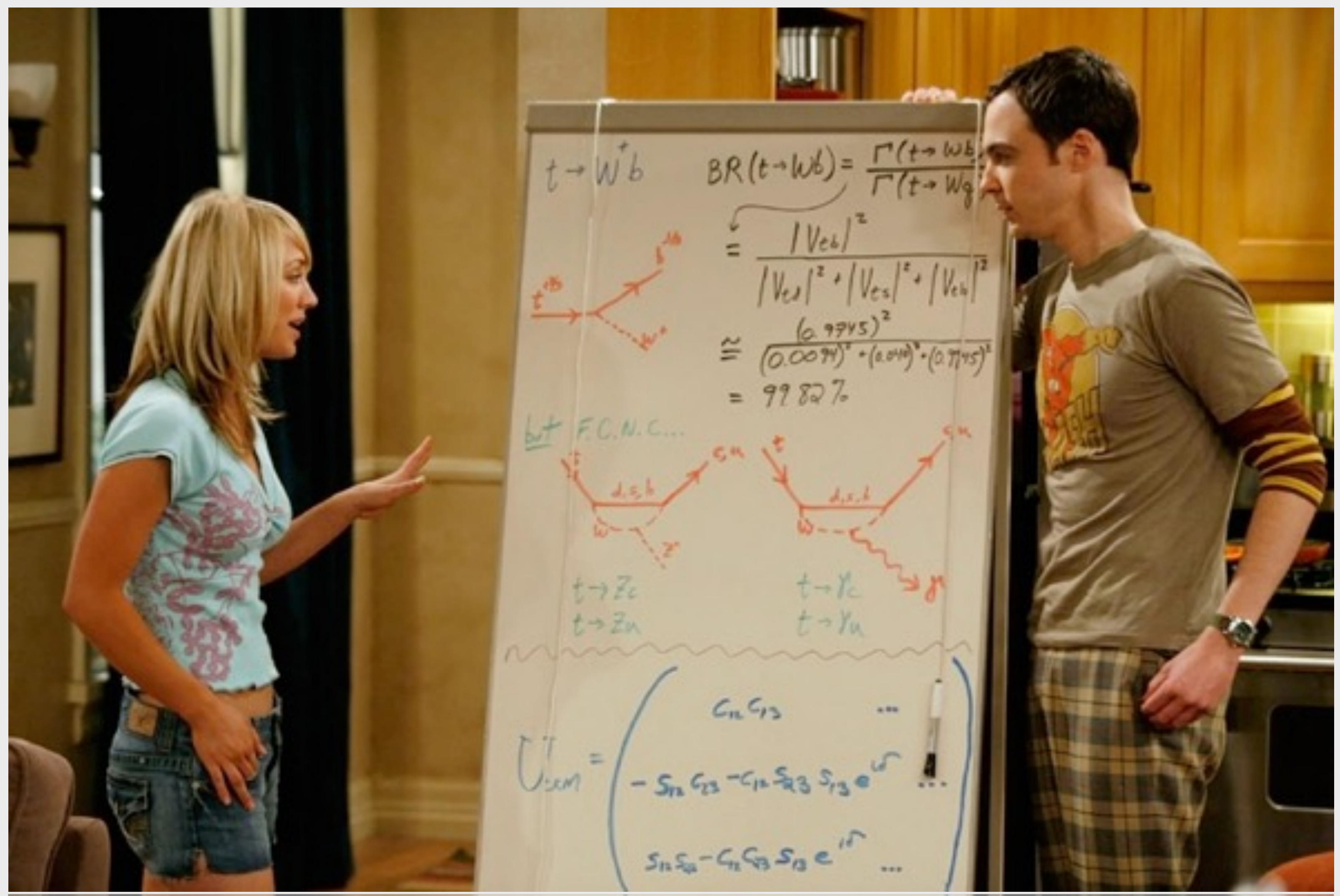


Figure 3: *Typical diagrams contributing to $H \to Q\bar{Q}$ at lowest order and one-, two- and three-loop QCD.*

For large Higgs masses the particle width for decays to b, c quarks [directly coupling to the SM Higgs particle] is given up to three-loop QCD corrections [typical diagrams are depicted in Fig. 3] by the well-known expression [38–40]

$$\Gamma[H \to Q\overline{Q}] = \frac{3G_F M_H}{4\sqrt{2}\pi}\, \overline{m}_Q^2(M_H)\, [\Delta_{\rm QCD} + \Delta_t] \tag{7}$$

we really do use Feynman Diagrams



Feynman's approach is really sneaky and really cute

energy and time appear together in the equations:

In essence, this:

either energy solution: $(\pm E)(t)$

just the -E solution: $(-E)(t)$

move the – sign: $(E)(-t)$

Get a whole new interpretation of antimatter