FEW NOTIONS ON PARTICLE PHYSICS

AD POLOSA (SAPIENZA UNIVERSITY)

QUANTUM MECHANICS

$$\boxed{\hbar = 1.05459\ldots \times 10^{-27}\ \mathrm{erg}\cdot\mathrm{sec}}$$

THE PLANCK CONSTANT!

QUANTUM MECHANICS

$$\boxed{\hbar = 1.05459\ldots \times 10^{-27}\ \mathrm{erg \cdot sec}}$$

THE PLANCK CONSTANT!

IN THE CLASSICAL MECHANICS WORLD

$$\hbar \approx 0$$

WRT TYPICAL ACTIONS

ELECTRON CHARGE

$$F = K \frac{e_1 e_2}{r^2}$$

THE COULOMB LAW

(compare to

$$F = G \frac{m_1 m_2}{r^2}$$)

ELECTRON CHARGE

$$F = K \frac{e_1 e_2}{r^2} \rightarrow \frac{e_1 e_2}{r^2}$$

Two charges <u>1cm</u> apart are of <u>1esu</u> each if the force between them is <u>1 dyne</u>

$$1\,\text{esu} = 1\,\text{cm}\sqrt{1\,\text{dyne}}$$
$$= 1\,\text{cm} \cdot \text{gr}^{1/2} \cdot \text{cm}^{1/2} \cdot \text{sec}^{-1}$$

THE CHARGE OF ELECTRON

$$\boxed{e = 4.8 \times 10^{-10}\,\text{esu}}$$

QUANTUM MECHANICS

$$\hbar = 1.05459\ldots \times 10^{-27}\ \mathrm{erg \cdot sec}$$

$$c = 2.99 \times 10^{10}\ \mathrm{cm/sec}$$

THE VELOCITY OF LIGHT

$$\boxed{\alpha = \frac{e^2}{\hbar c} = \frac{1}{137}}$$

THE FINE STRUCTURE CONSTANT.

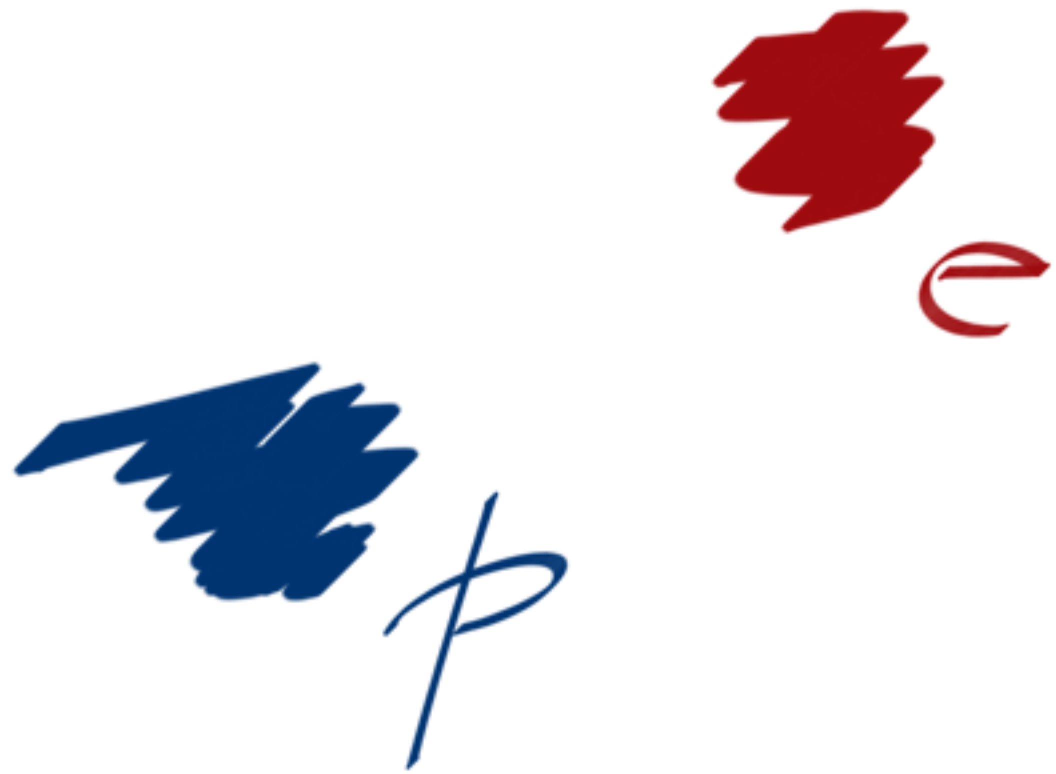
let's check it...

$$\frac{e^2}{\hbar c} = \frac{(4.8\times 10^{-10}\,\mathrm{esu})^2}{(1.05\times 10^{-27}\,\mathrm{erg\cdot sec})(2.99\times 10^{10}\,\mathrm{cm/sec})}$$

$$\simeq \frac{23\times 10^{-20}\,\mathrm{cm^2\,dyne}}{3.13\times 10^{-17}\,\underbrace{\mathrm{erg}}_{\mathrm{dyne\cdot cm}}\cdot\mathrm{cm}}$$

$$\simeq 7.32\times 10^{-3} \simeq \frac{1}{137}$$

THE HYDROGEN ATOM



$\hbar, e, m_e$

The reduced mass. $\mu = \frac{m_e m_p}{m_e + m_p} \simeq m_e$

THE BOHR RADIUS

Make a length out of $\hbar$, m_e, e

$$\boxed{\frac{\hbar^2}{m_e e^2}} =$$

$$= \frac{\text{erg}^2 \cdot \text{sec}^2}{\text{gr} \cdot \text{cm}^2\, \text{dyne}}$$

$$= \frac{\text{erg}^2}{\underbrace{\left(\text{gr}\,\frac{\text{cm}}{\text{sec}^2}\right)}_{\text{dyne}}\text{dyne} \cdot \text{cm}} = \frac{\cancel{\text{dyne}^2} \cdot \text{cm}^2}{\cancel{\text{dyne}^2} \cdot \text{cm}}$$

$$= \text{cm}.$$

06/02/2018

THE BOHR RADIUS

Make a length out of $\hbar$, m_e, e

$$\boxed{\frac{\hbar^2}{m_e e^2}} =$$

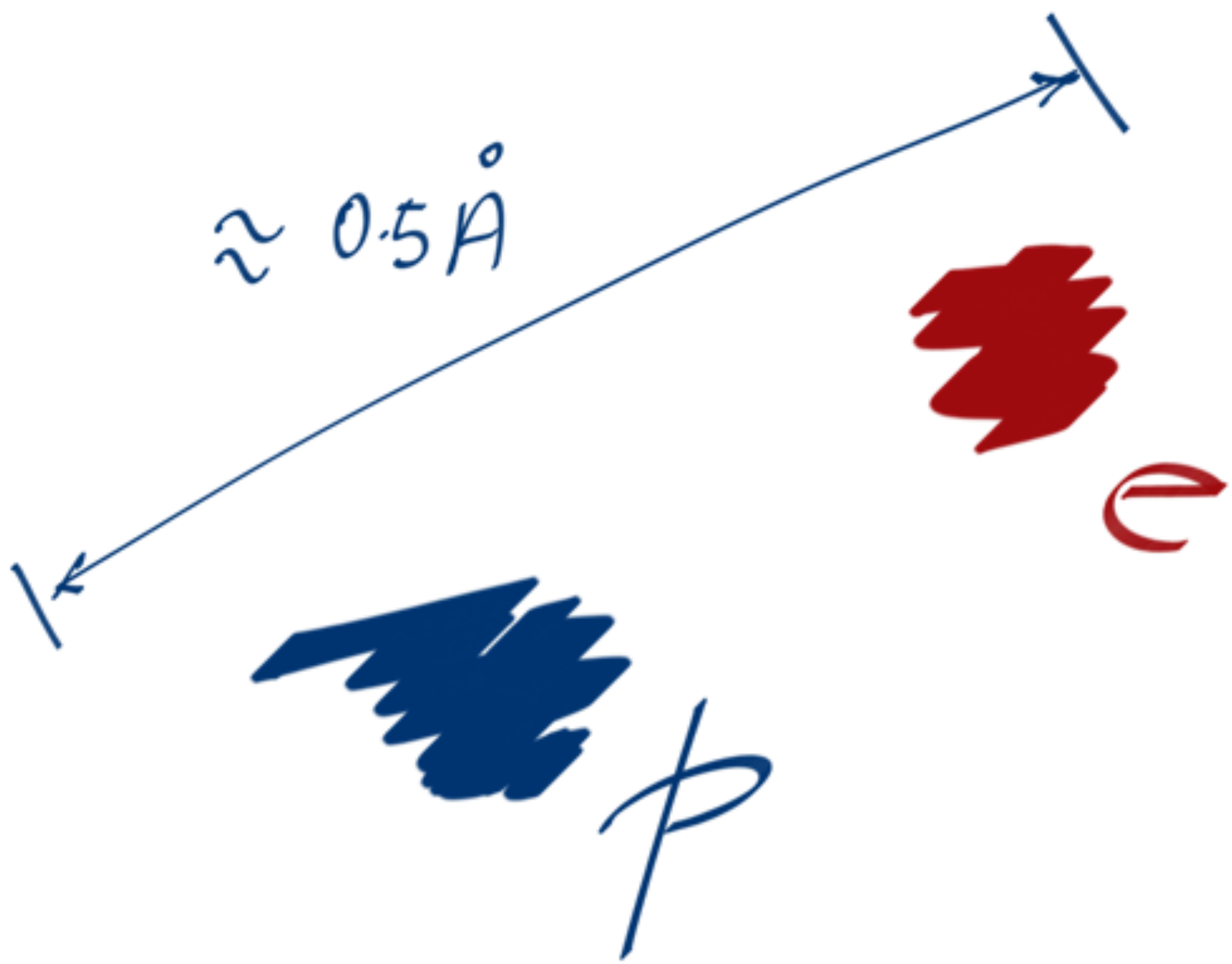
$$= \frac{(1.05 \times 10^{-27})^2}{(9.1 \times 10^{-28})(4.8 \times 10^{-10})^2} = 0.005 \frac{10^{-54}}{10^{-28} \cdot 10^{-20}}$$

$$= 0.005 \; 10^{48-54} = 0.5 \; 10^{-2} 10^{-6} \text{ cm}$$

$$= 0.5 \times 10^{-8} \text{ cm} = 0.5 \; \mathring{A}$$

ANGSTROM

THE BOHR RADIUS

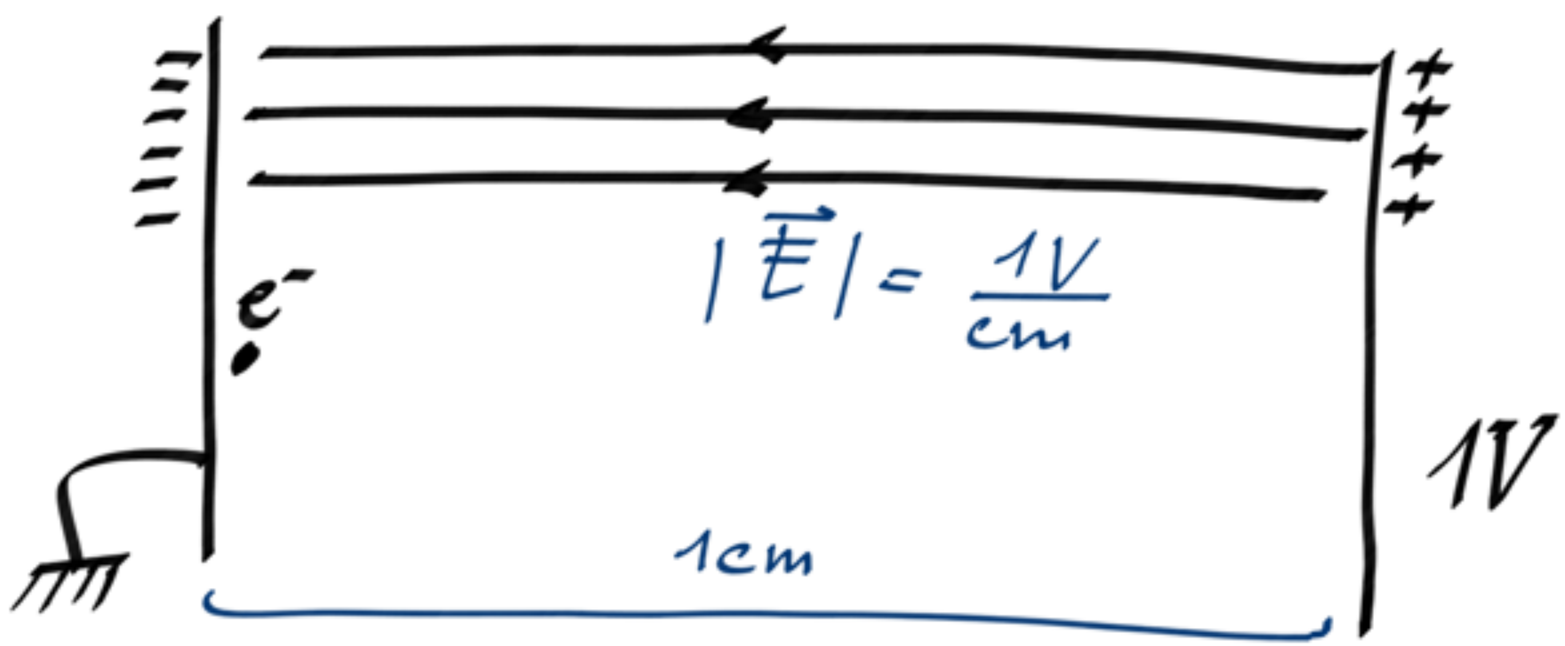


THE SIZE OF HYDROGEN

THE BOHR RADIUS

IN PARTICLE PHYSICS ENERGY/MASS IS USUALLY MEASURED IN eV

$$m_e c^2 = 0.5\ MeV = 0.5\ 10^6\ eV$$



$$W = F \cdot S = e|\vec{E}| \cdot 1cm$$
$$= e \cdot 1V = eV$$

work done on e^- in accelerating it through 1V.

THE BOHR RADIUS

IN PARTICLE PHYSICS ENERGY/MASS IS USUALLY MEASURED IN eV

$$m_e c^2 = 0.5\ MeV = 0.5\ 10^6\ eV$$

$$\frac{1}{2} m_e v^2 = 1 eV$$

$$\frac{1}{2} m_e c^2 \left(\frac{v}{c}\right)^2 = 1 eV$$

$$\frac{v}{c} = \sqrt{\frac{2 eV}{0.5\ 10^6 eV}} = 2 \cdot 10^{-3}$$

or $v = 2 \cdot 10^{-3} c$

$$\cong 6\ 10^7\ cm/sec.$$

this is how fast the e^- is at the end of the run ...

THE BOHR RADIUS

IN PARTICLE PHYSICS ENERGY/MASS IS USUALLY MEASURED IN eV

$$m_e c^2 = 0.5\ \mathrm{MeV} = 0.5\ 10^6\ \mathrm{eV}$$

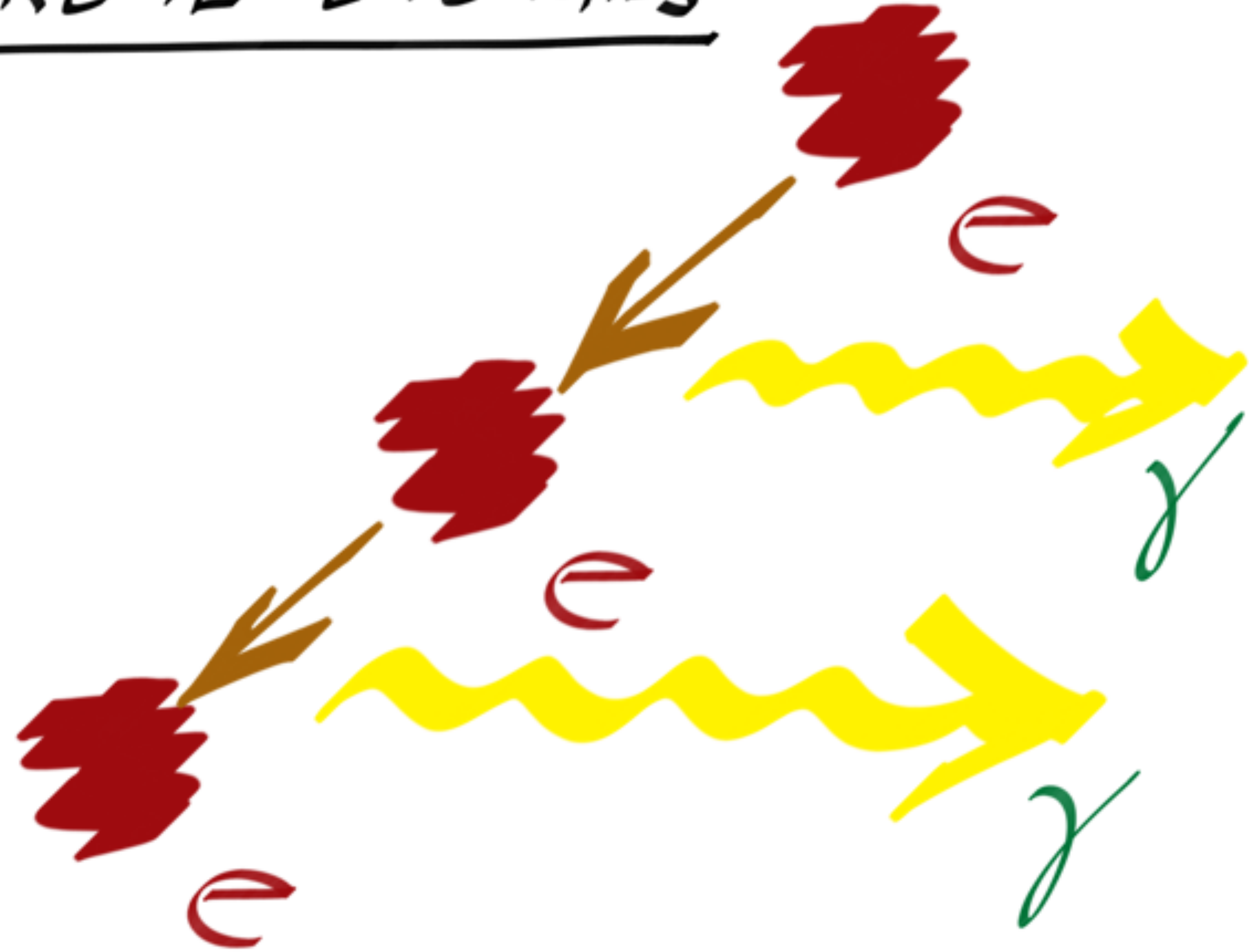
Bohr radius $= \dfrac{\hbar^2}{m_e e^2} = \dfrac{\hbar c}{m_e c^2 \dfrac{e^2}{\hbar c}} =$

$$= \frac{\hbar c}{m_e c^2 \alpha} = \frac{\hbar c}{(0.5\ \mathrm{MeV}) \frac{1}{137}} = 0.5\ \mathring{A}$$

$$\boxed{\hbar c = 197\ \mathrm{MeV} \cdot \mathrm{fm}}$$

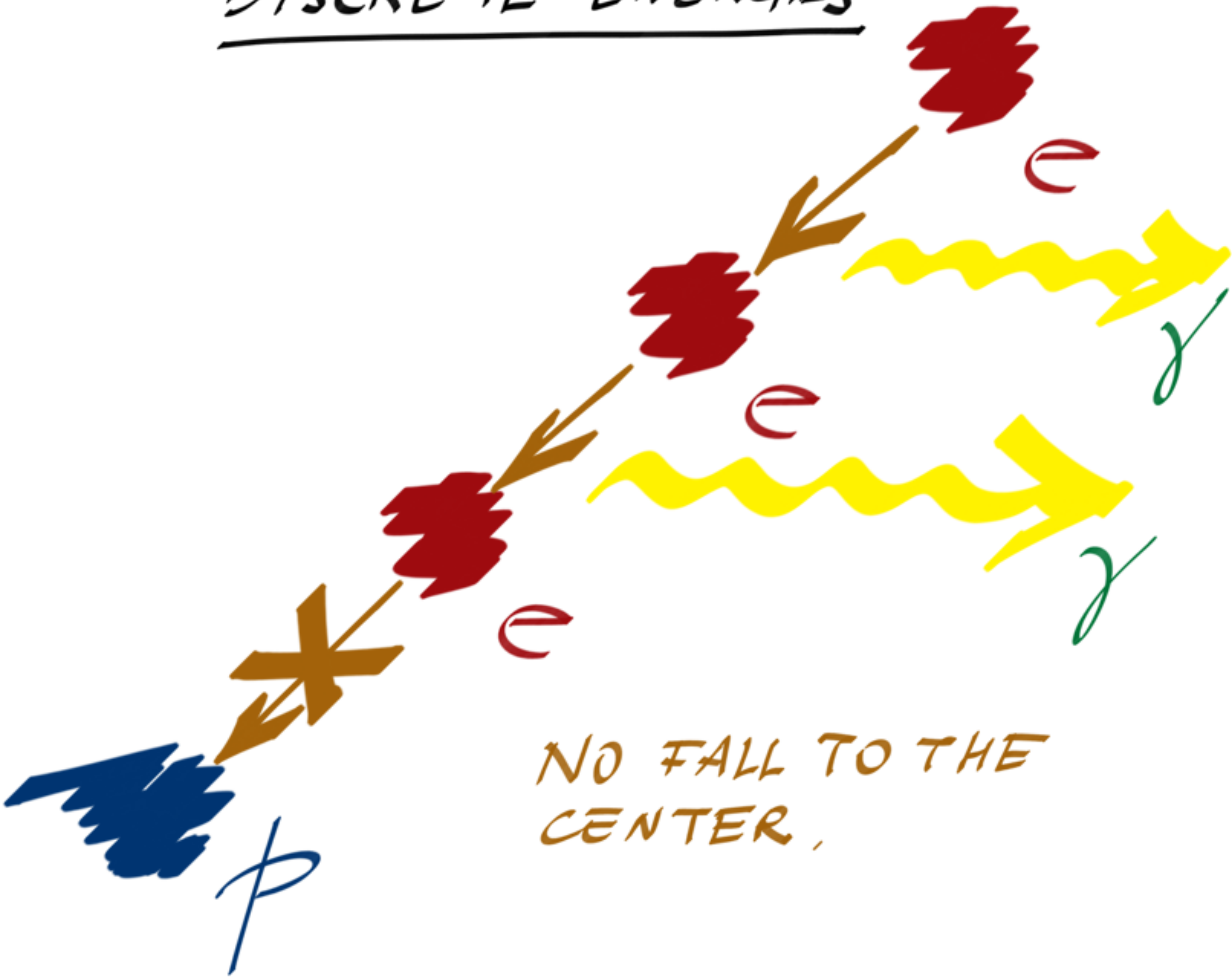
$$\underbrace{1\ \mathrm{fm} = 10^{-13}\ \mathrm{cm}}_{1\ \mathrm{FERMI}}$$

DISCRETE ENERGIES



$$\nu = \frac{E_i - E_f}{h}$$

DISCRETE ENERGIES



NO FALL TO THE CENTER.

DISCRETE ENERGIES

NO FALL TO THE CENTER

IF e^- IS WITHIN A DISTANCE r_0 TO p, WE CAN SAY THAT WE KNOW ITS POSITION WITH **UNCERTAINTY**

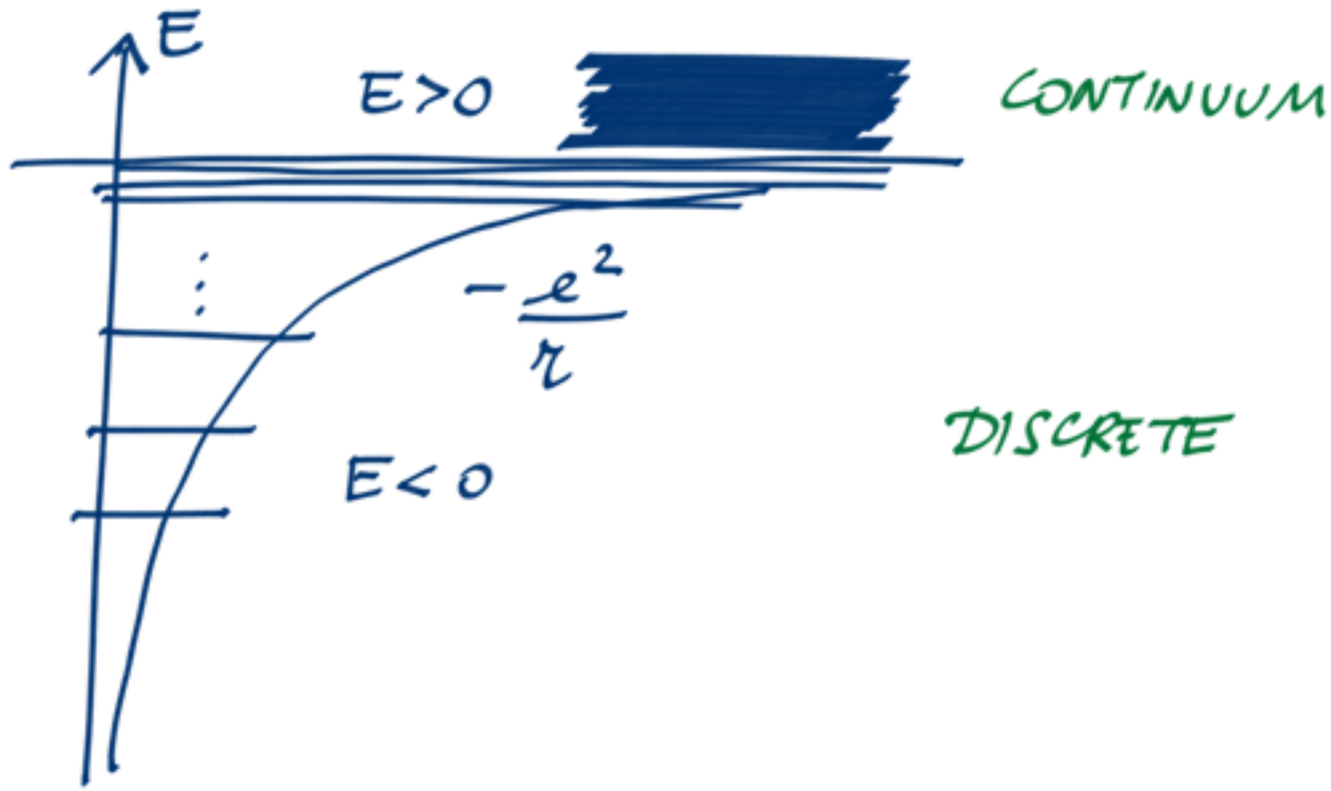
$$\Delta r \sim r_0$$

ANOTHER PILLAR OF QUANTUM MECHANICS ARE HEISENBERG **UNCERTAINTY RELATIONS**

$$\Delta r \Delta p \sim \hbar$$

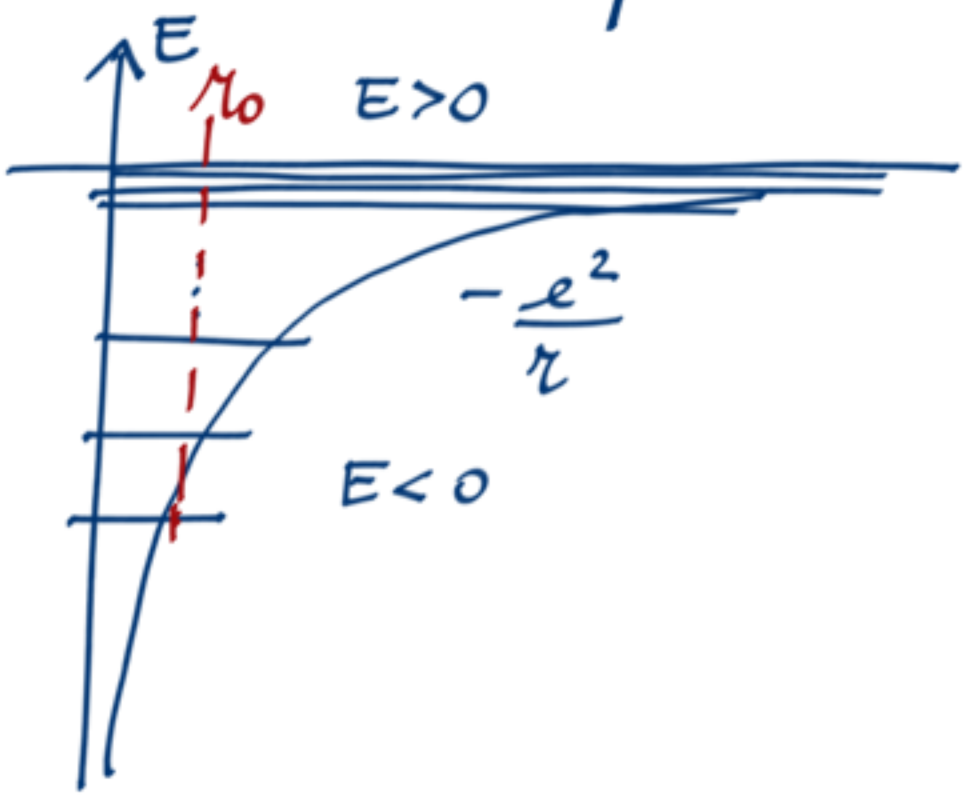
DISCRETE ENERGIES

NO FALL TO THE CENTER



DISCRETE ENERGIES

NO FALL TO THE CENTER



$$E = \frac{p^2}{2\mu} - \frac{e^2}{r_0}$$

$$= \frac{\hbar^2}{2\mu r_0^2} - \frac{e^2}{r_0}$$

wins over the potential energy as $r_0 \to 0 \Rightarrow E > 0$

DISCRETE ENERGIES

$$\frac{\hbar^3}{m e^4} = \frac{\hbar^3 c^2}{m c^2 \alpha^2 (\hbar c)^2} = \frac{\hbar}{m c^2 \alpha} = \text{seconds.}$$

$$v = \frac{\hbar^2/me^2}{\hbar^3/me^4} = \frac{e^2}{\hbar} = \alpha c \quad \left(\equiv 10^{-2} \text{ the velocity of light!} \right)$$

$$E = \frac{1}{2} m v^2 \approx \frac{1}{2} m \alpha^2 c^2 = \left(\frac{1}{4} \text{MeV} \right) \frac{1}{(137)^2}$$

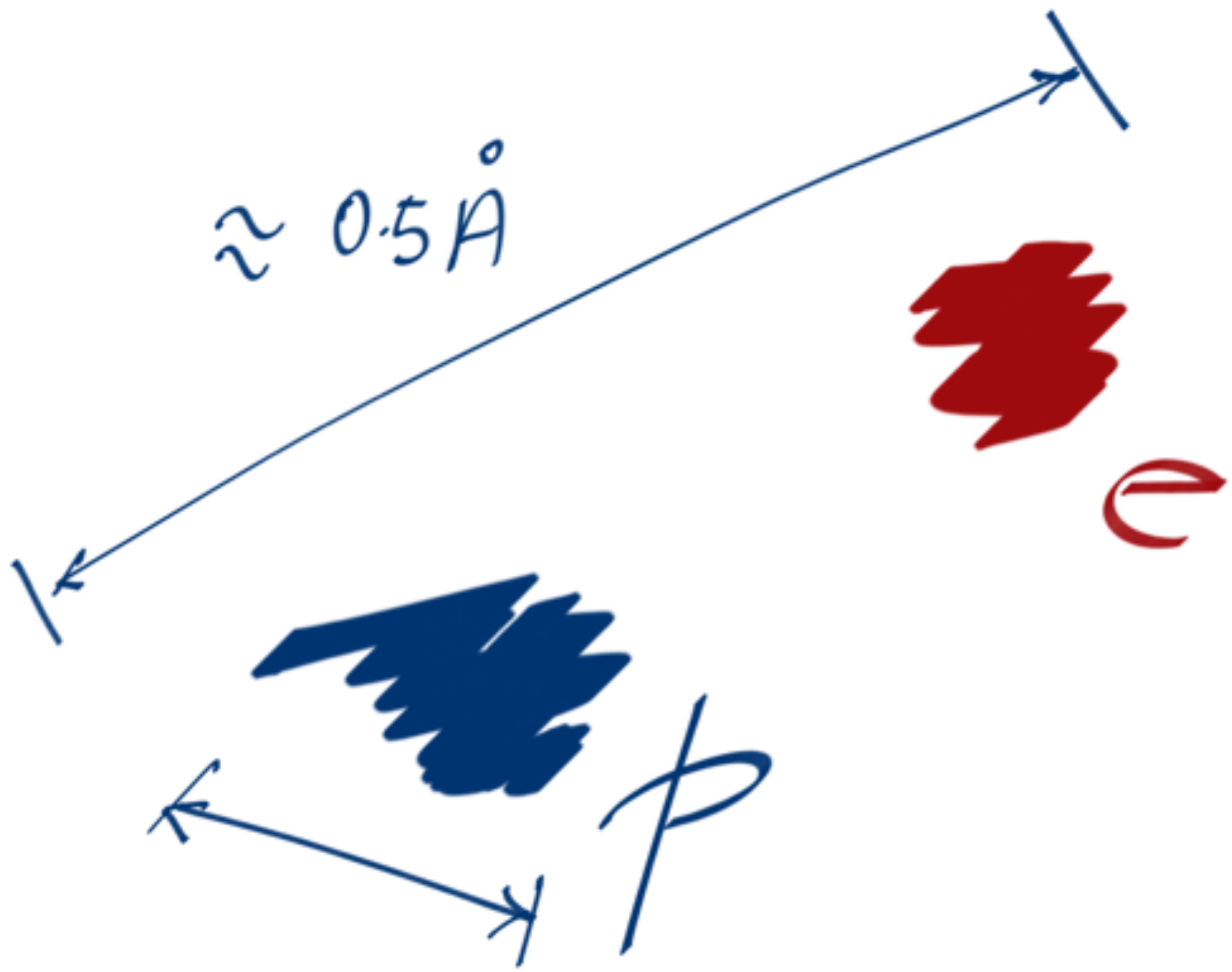
$$= 1.3 \times 10^{-5}\ 10^6 \text{ eV}$$

$$= 13 \text{ eV}$$

THE SCHRÖDINGER EQUATION FOR THE HYDROGEN ATOM GIVES FOR THE GROUND STATE

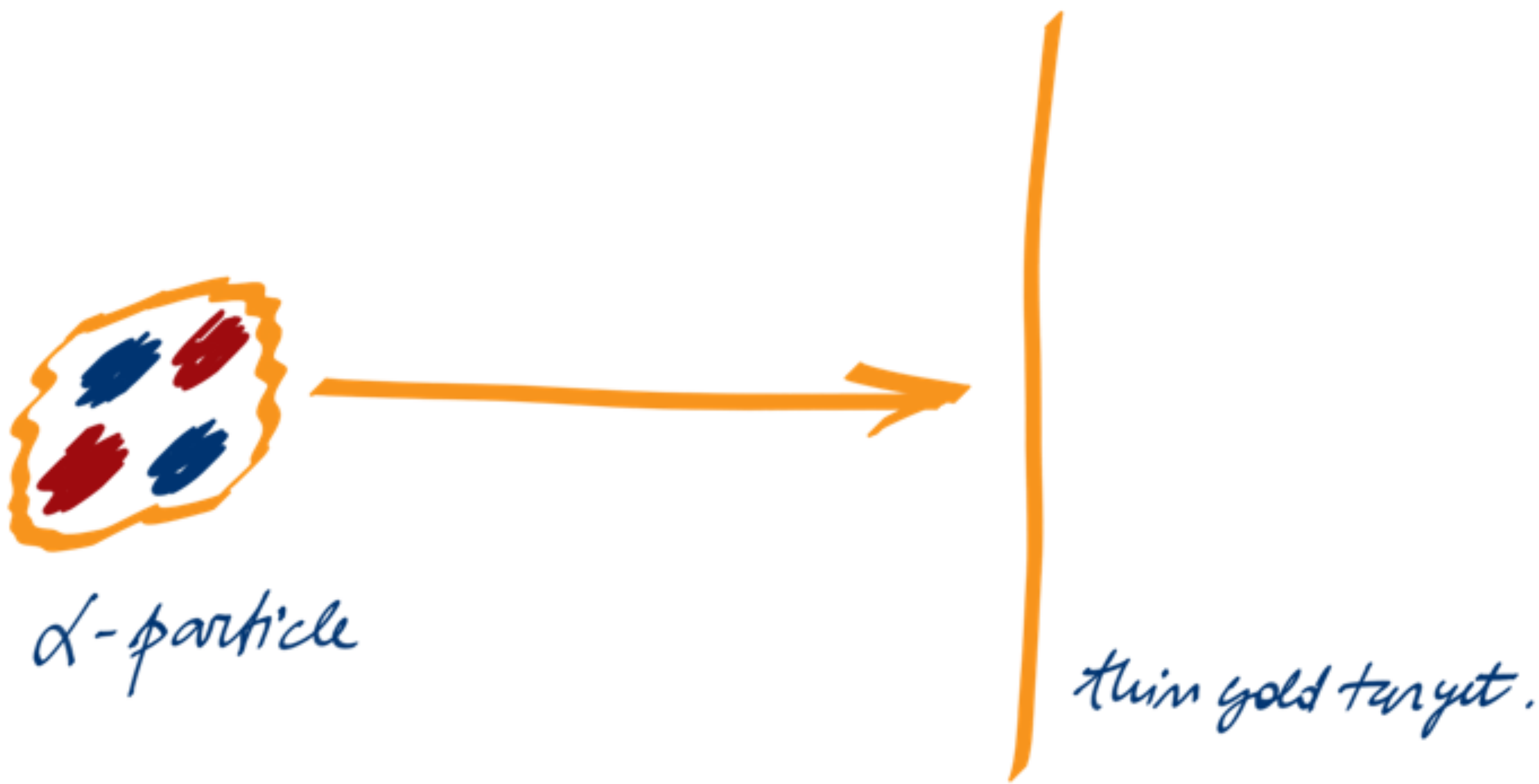
$$E = -13.6 \text{ eV}$$

THE NUCLEAR RADIUS



how large is a proton?
(in the case of hydrogen)

THE NUCLEAR RADIUS



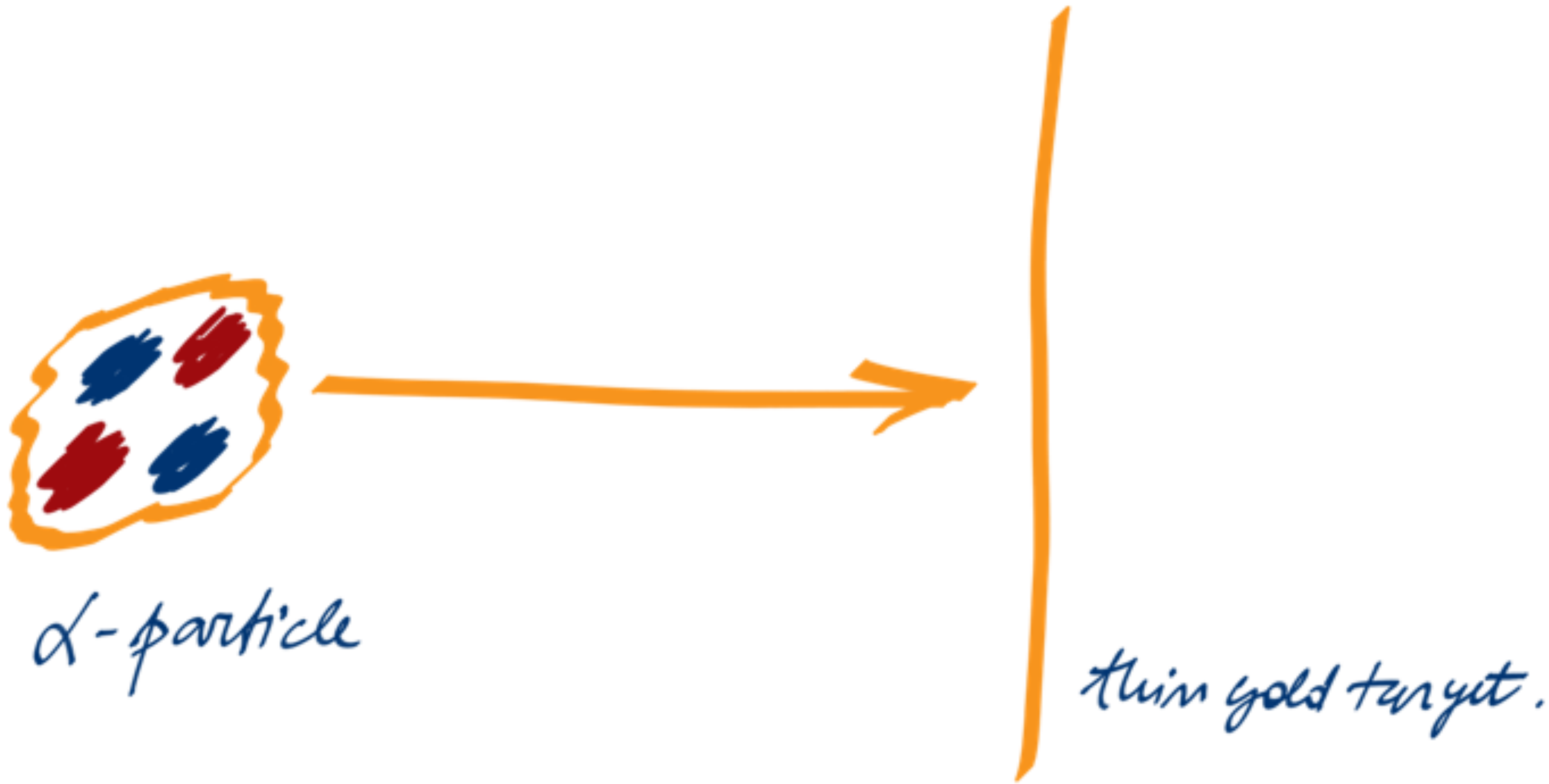
$$m = \frac{m_1 m_2}{m_1 + m_2}$$

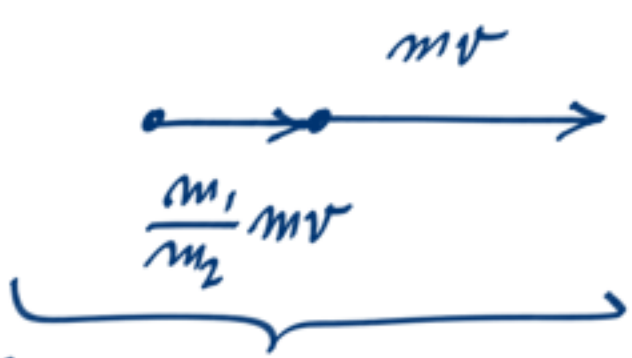
v = relative velocity

$m_1 v$ = momentum of the α impinging on the foil.

(particles of the target almost at rest)

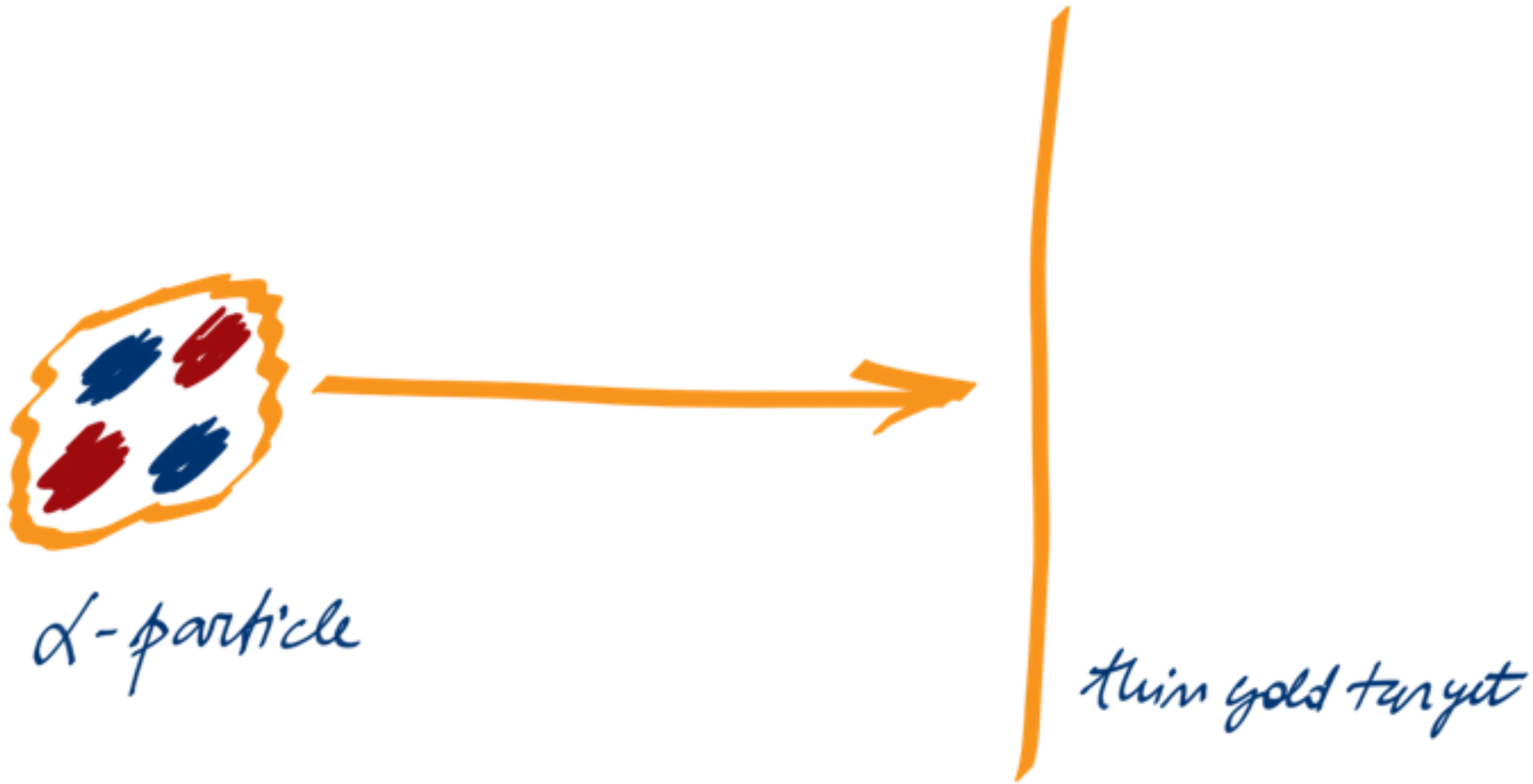
THE NUCLEAR RADIUS

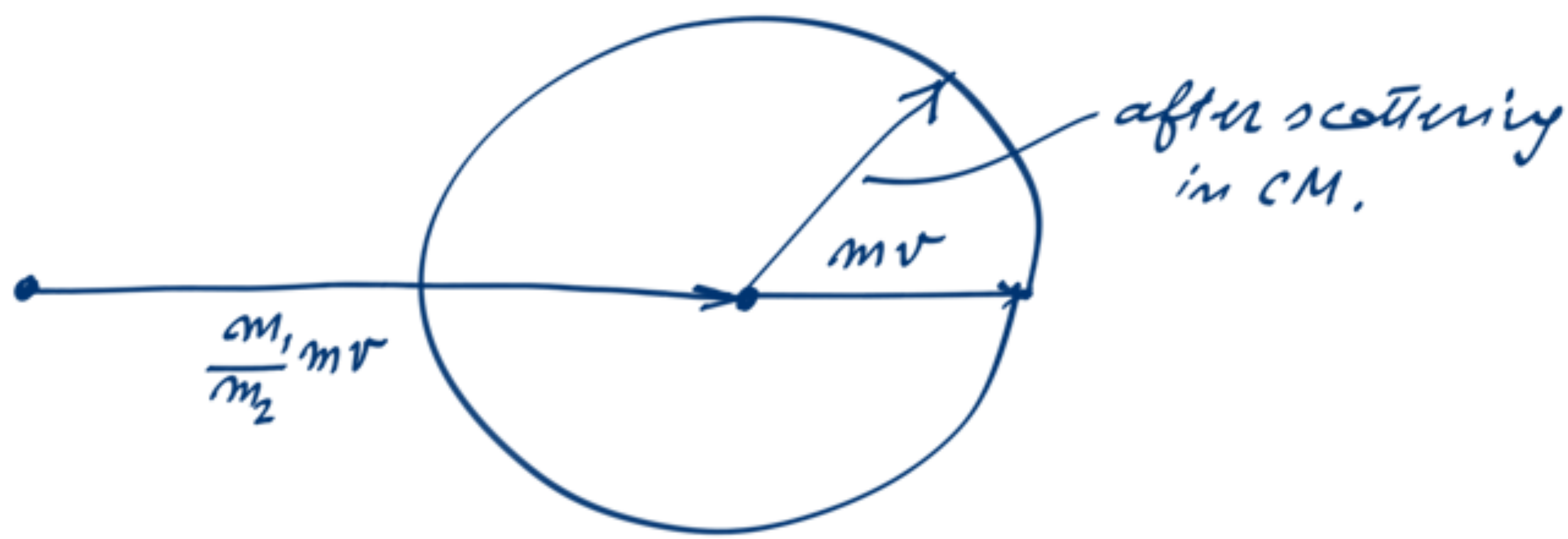




$$\left(\frac{m_1}{m_2} + 1 \right) mv = m_1 v$$

THE NUCLEAR RADIUS





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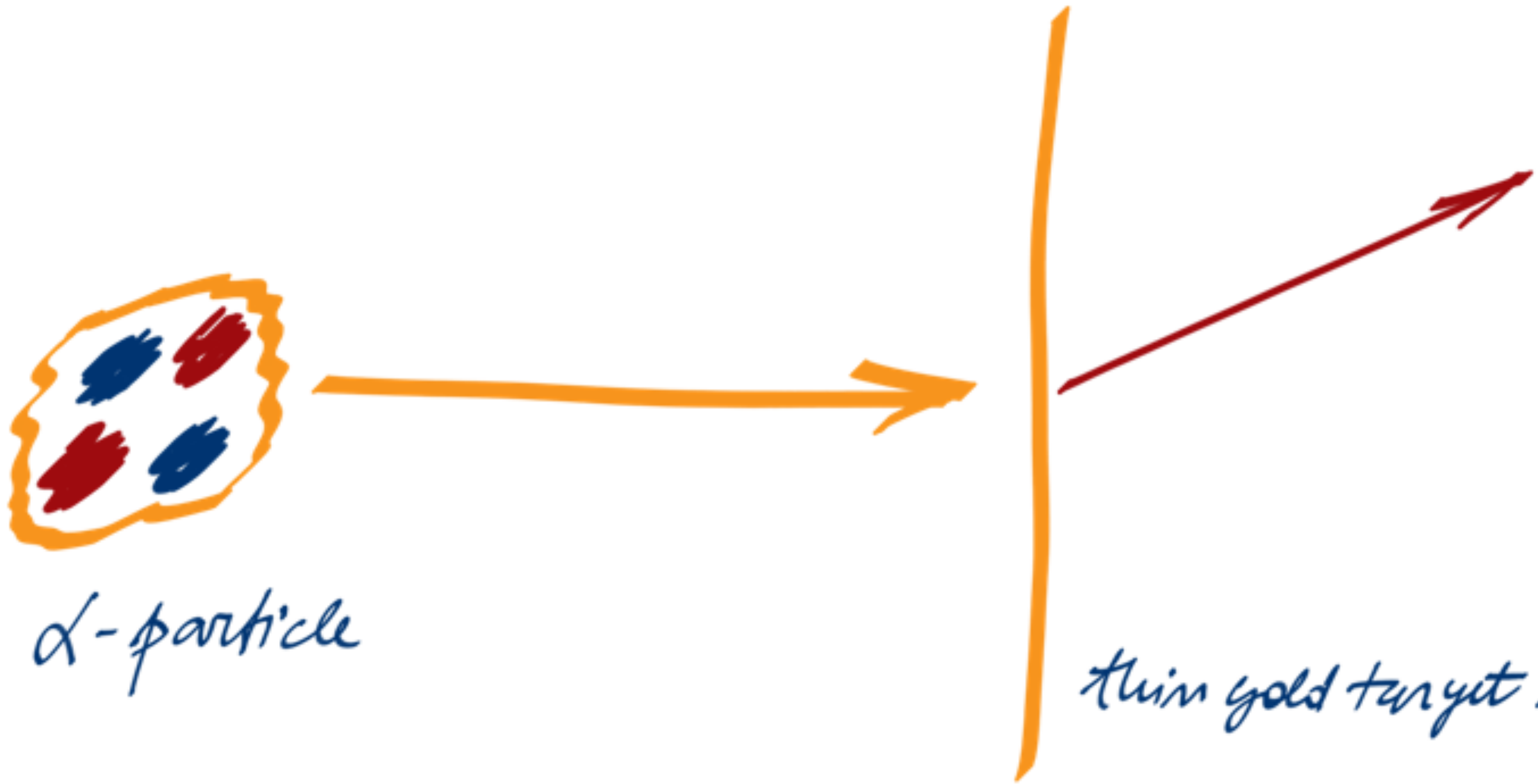
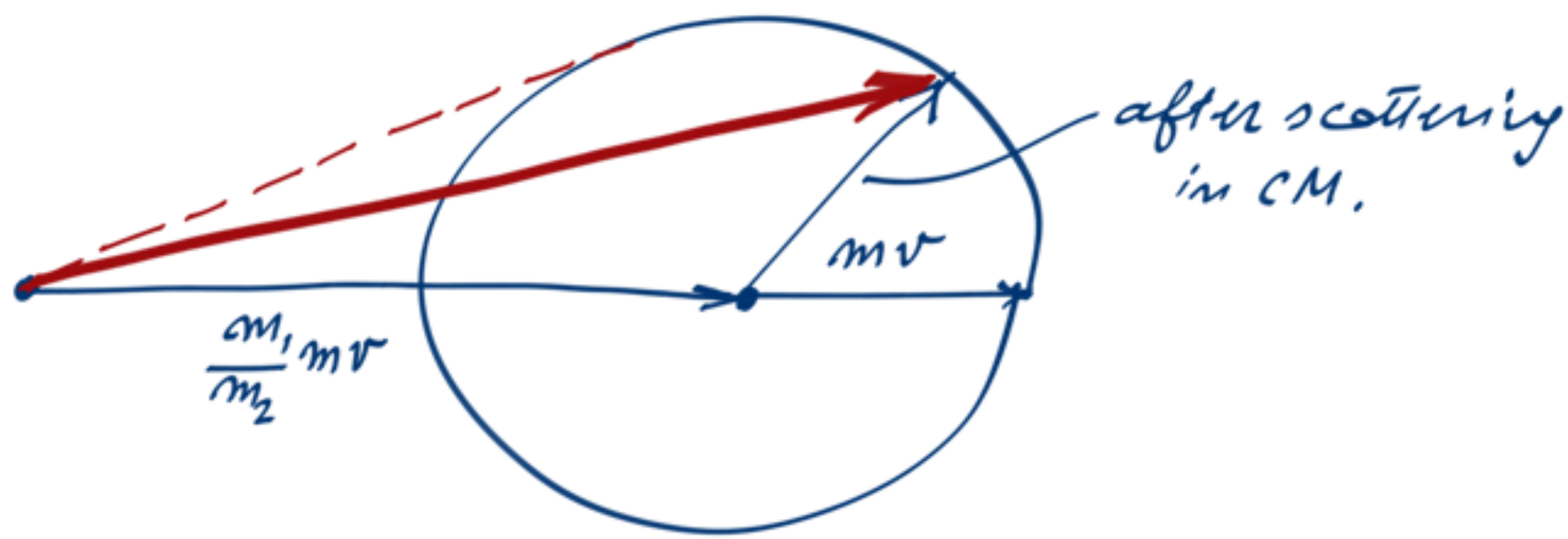
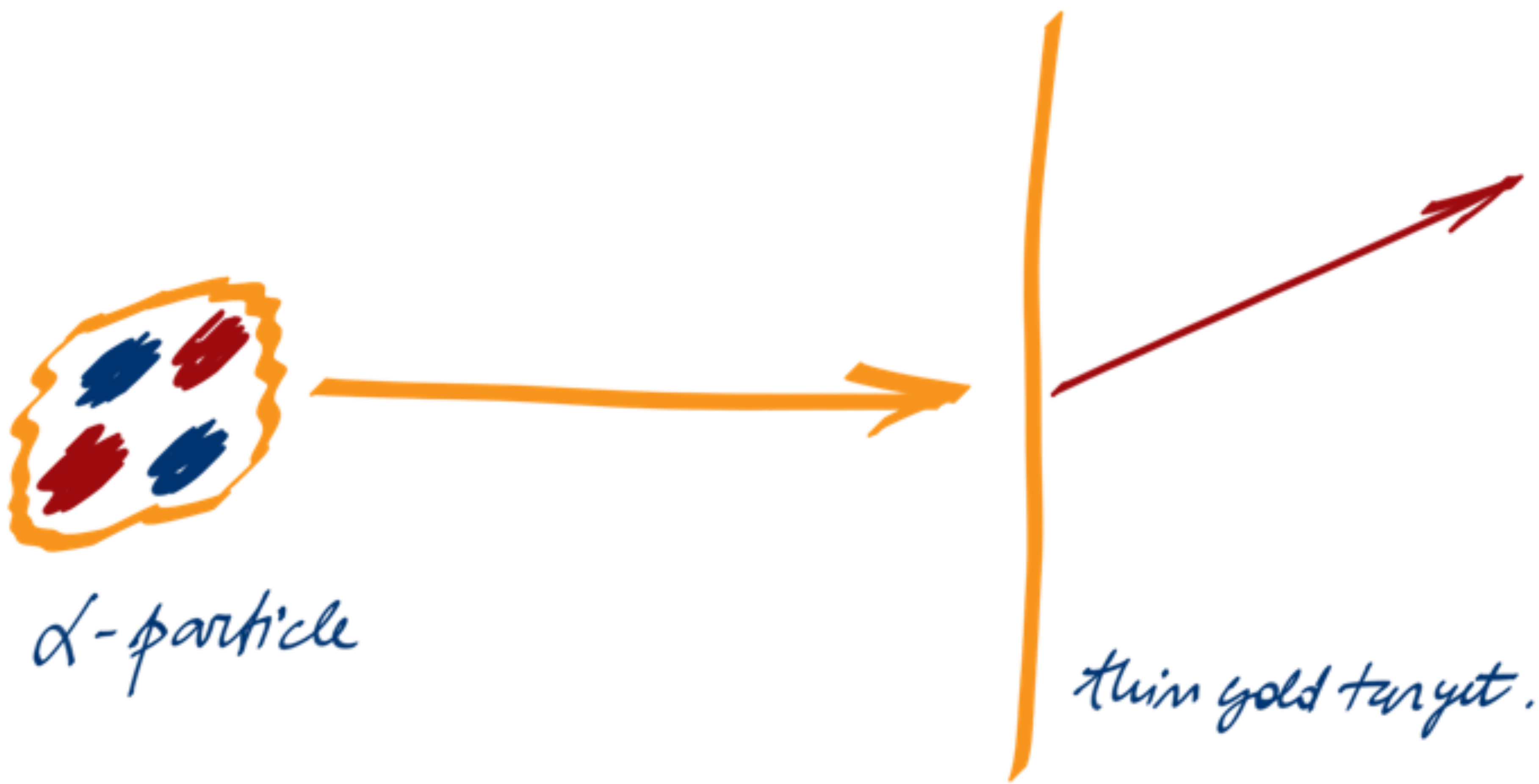
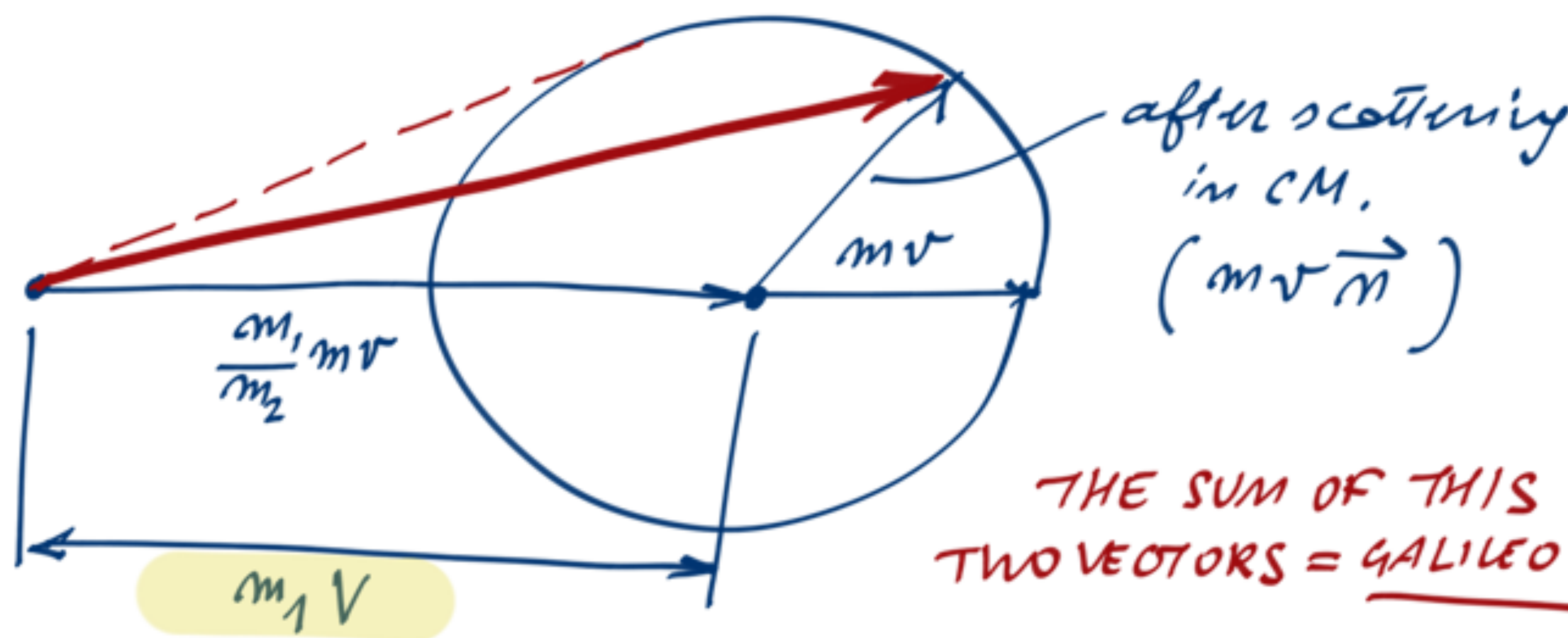




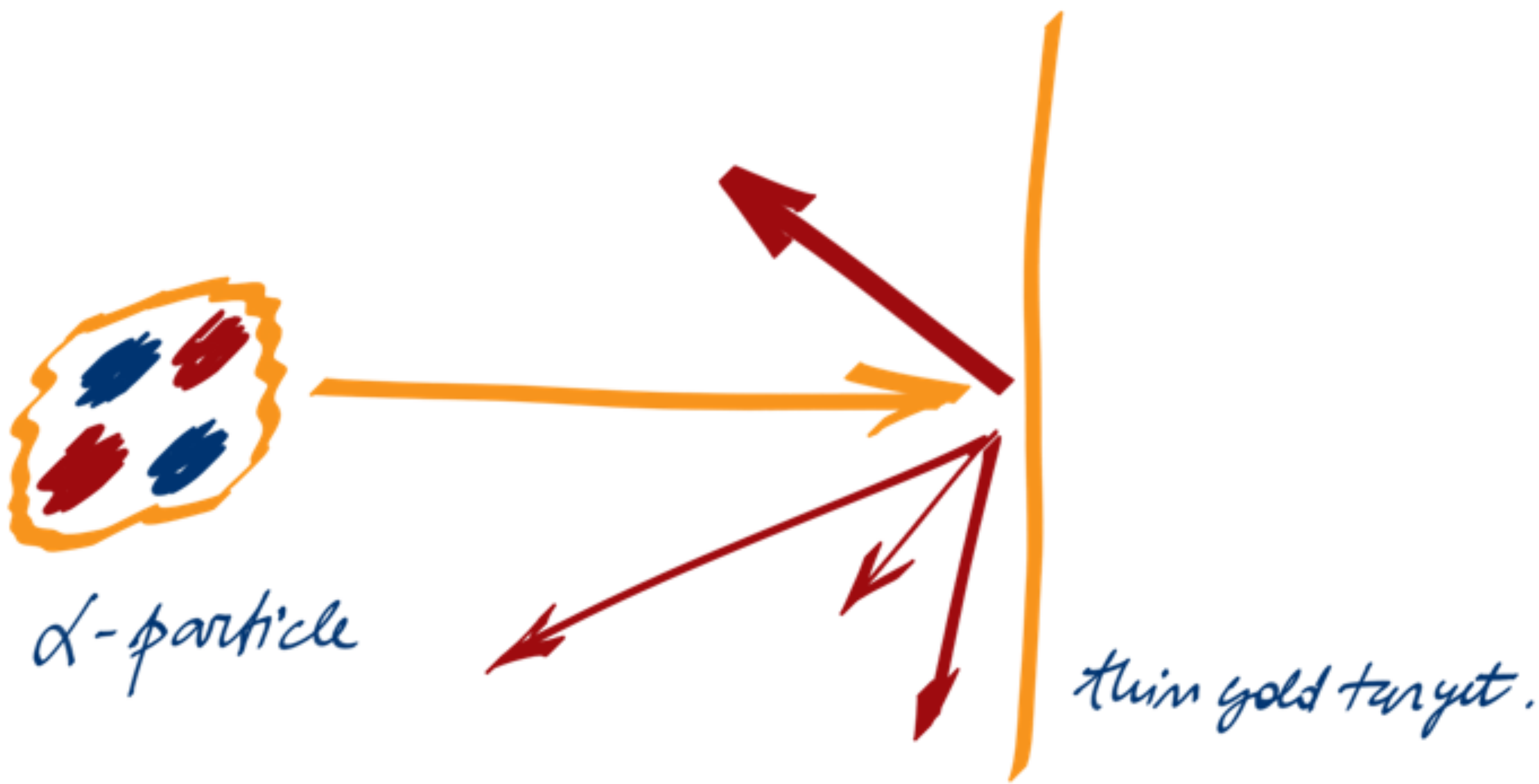
THE NUCLEAR RADIUS



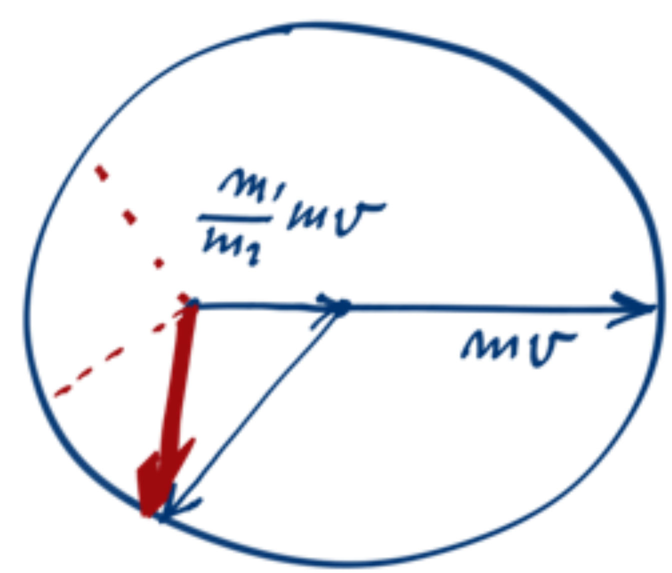


THE SUM OF THIS TWO VECTORS = GALILEO TRANS.

THE NUCLEAR RADIUS



IF $m_1 < m_2$



check that $\vec{p}_1' = \frac{m_1}{m_2} m v \vec{n}_0 + m v \vec{n}$

CM $\quad p_{10} = m v \quad \& \quad p_{20} = - m v$

(in whatever direction)

$$v_{10} = \frac{m_2 v}{m_1 + m_2} \quad \& \quad v_{20} = - \frac{m_1 v}{m_1 + m_2}$$

AFTER THE COLLISION ONLY THE DIRECTIONS GET CHANGED

$$\vec{v}_{10}' = \frac{m_2 v}{m_1 + m_2} \vec{n} \quad \& \quad v_{20}' = - \frac{m_1 v}{m_1 + m_2} \vec{n}$$

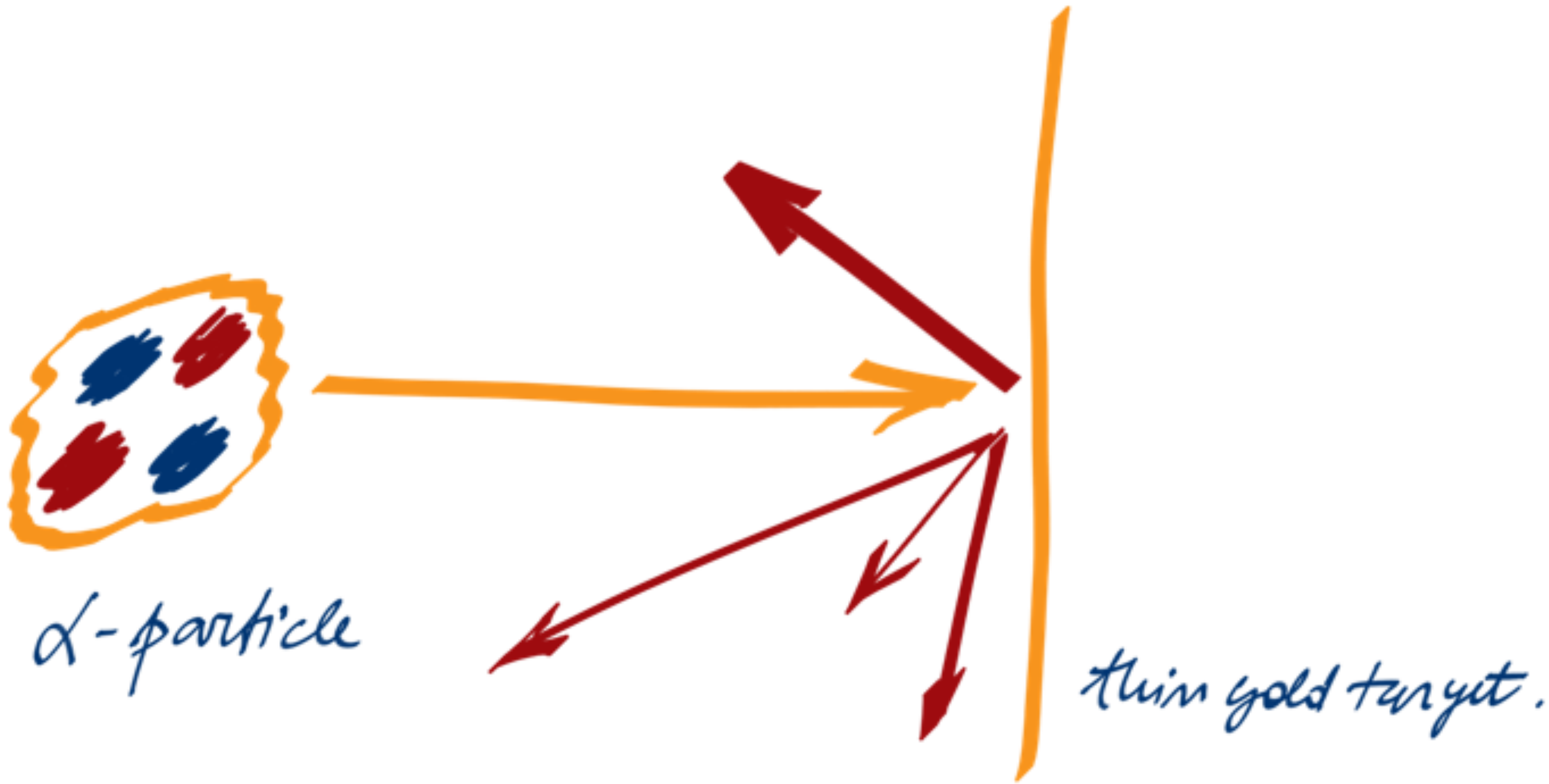
LAB (FROM CM $\to$ LAB use GALILEO TRANSF.)

$$\vec{v}_1' = \vec{v}_{10}' + \vec{V} \quad \text{where} \quad \vec{V} = \frac{m_1 \vec{v}_1 + m_2 \vec{v}_2}{m_1 + m_2}$$

$$\simeq \frac{m_1}{m_1 + m_2} \vec{v}_1 \text{ for us.}$$

$$\boxed{\vec{p}_1' = m v \vec{n} + \frac{m_1}{m_2} m v \vec{n}_0}$$

THE NUCLEAR RADIUS

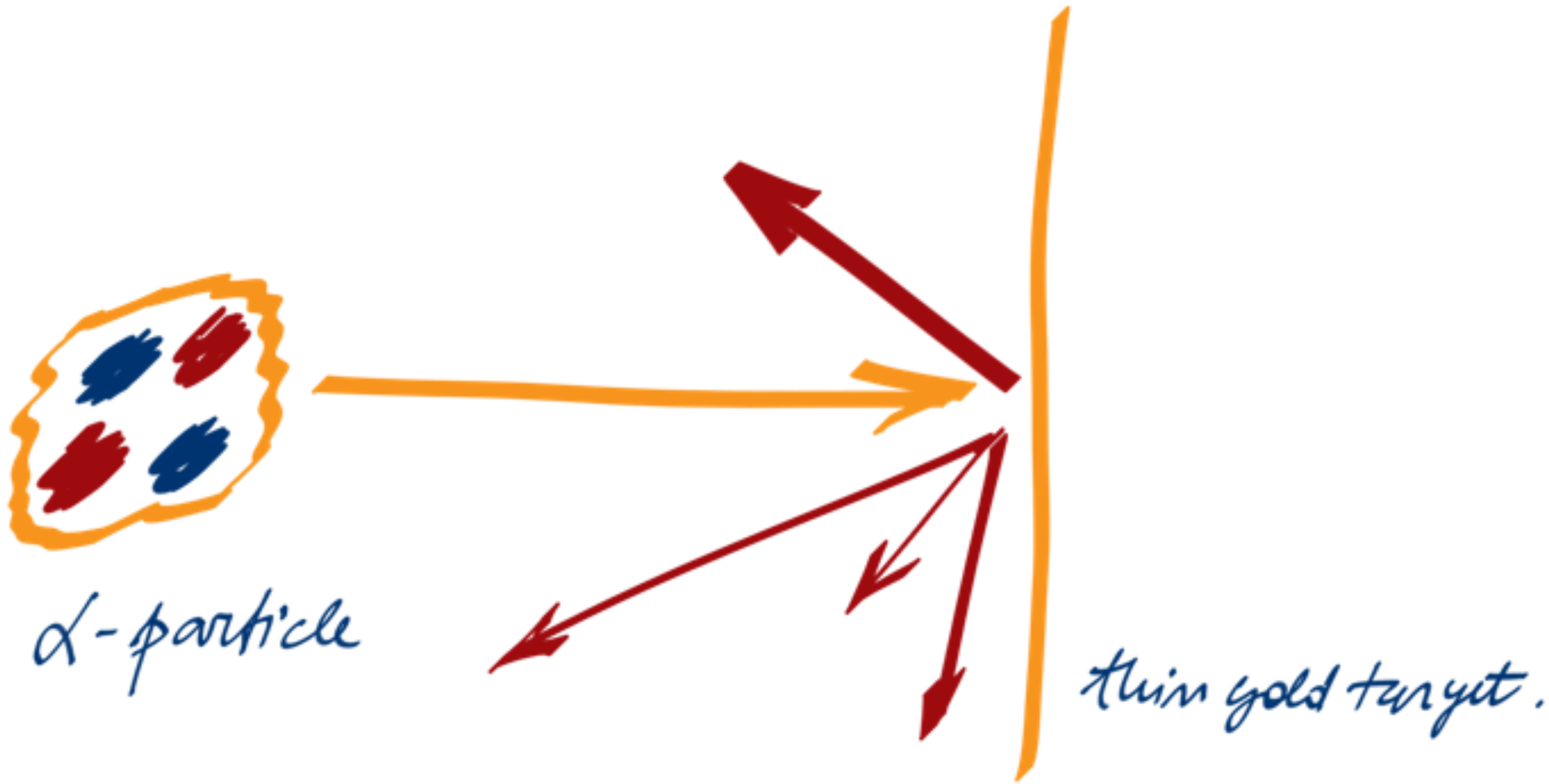


α – PARTICLES WERE FOUND TO RECOIL
BACKWARDS FROM A VERY THIN FOIL!

THEY HAD COLLIDED WITH SOME VERY **HEAVY MASS**

$$m_2 \gg m_1$$

THE NUCLEAR RADIUS



THIS $m_2 \gg 1$ HAS TO BE ALSO CONCENTRATED IN A SMALL REGION

THE NUCLEAR RADIUS

THE CHARGE OF THE PROJECTILE $= 2e$

THE VELOCITY (emitted from radium) $\simeq 2 \cdot 10^9$ cm/sec.

changes sign for large angle scattering

→ goes through zero — thanks to the coulomb repulsion of the heavy target

→ Kinetic energy converted to potential energy within R

$$\frac{1}{2} M v^2 = \frac{2e\,Ze}{R}$$

$$\boxed{R =} \quad \frac{4e^2 Z}{M v^2} \cong \boxed{3Z \times 10^{-14}\,\text{cm}}$$

$$\frac{e^2}{Mv^2} = \frac{e^2}{\hbar c} \cdot \frac{\hbar c}{Mc^2\left(\frac{v^2}{c^2}\right)} \cong \alpha \, \frac{197\,\text{MeV}\cdot\text{fm}}{4\,\text{GeV}\left(\frac{2\cdot 10^9}{3\cdot 10^{10}}\right)^2} = 0.36\cdot 10^{-3} \cdot \frac{9}{4}\, 10^{2} \cdot 10^{-13}\,\text{cm}$$

$$\cong 3 \cdot 10^{-14}\,\text{cm}$$

THE NUCLEAR RADIUS

$$R = \frac{4e^2 Z}{Mv^2} \cong 3Z \times 10^{-14}\ \mathrm{cm}$$

THE NUCLEUS IS MUCH SMALLER THAN THE ATOM

$\sim 0.5 \times 10^{-8}$ cm

even for some value as $Z = 100$.

$$\begin{cases} R \sim a_0 A^{1/3} \\ a_0 \simeq 1\ \mathrm{fm} \end{cases}$$

THE ELECTRON RADIUS

$$\boxed{e \cdot \frac{e}{r} \qquad r \to 0\ ?}$$

ELECTROM. CONTRIBUTION TO THE e^- MASS

$$\frac{e^2}{R} \lesssim mc^2$$

$$R \gtrsim \frac{e^2}{\hbar c} \frac{\hbar c}{mc^2} =$$

$$= \frac{1}{137} \frac{197\ \text{MeV} \cdot \text{fm}}{0.5\ \text{MeV}}$$

$$= 2.8\ \text{fm}\ ??$$

AS LARGE AS A NUCLEUS WITH $A = 27$!

THE ELECTRON RADIUS

$$\boxed{e \cdot \frac{e}{r} \qquad r \to 0\ ?}$$

WHEN YOU LOOK CLOSER AND CLOSER YO NEED SHORTER AND SHORTER λ PHOTONS - AT SOME POINT λ IS SUCH THAT THE PHOTON HAS ENERGY

$$E = h\frac{c}{\lambda} \left(= 2\pi \frac{\hbar c}{\lambda} \right) = mc^2$$

$$\lambda_c = \frac{h}{mc}$$ (COMPTON WAVELENGTH)

$$\left(ƛ_c = \frac{\hbar}{mc} \right)$$

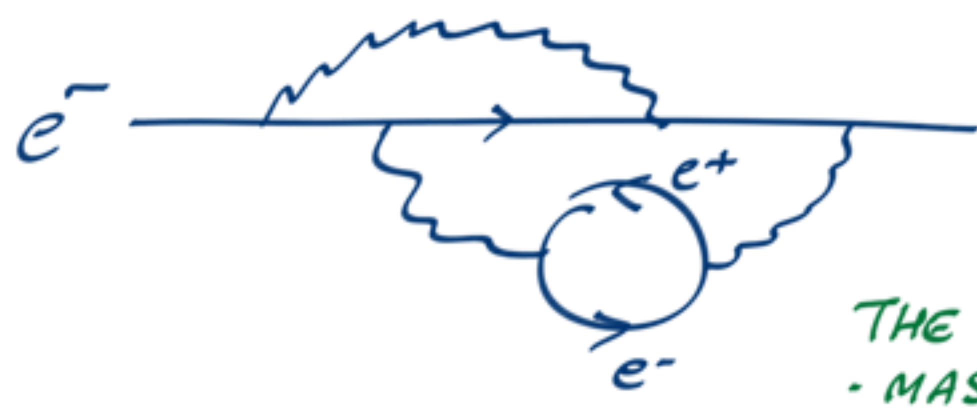
THE ELECTRON RADIUS

$$\boxed{e \cdot \frac{e}{r} \qquad r \to 0 \, ?}$$

$$1\,fm \Rightarrow E = 200\,MeV \gg \underline{2m_e = 1\,MeV}$$

THE ELECTRON RADIUS

$$\boxed{e \cdot \frac{e}{r} \qquad r \to 0 \,?}$$



THE EM CONTRIBUTION TO e-
- MASS IN A THEORY OF e^+ & e^+

$$e\,\frac{e}{r} \longrightarrow \frac{e^2}{\hbar c}\, m_e c^2 \underbrace{\ln\left(\frac{\hbar}{m_e c}\,\frac{1}{r}\right)}_{\text{instead of } 1/r \,-\, \ln r}$$

THE ELECTRON RADIUS

$$\boxed{e \cdot \frac{e}{r} \qquad r \to 0\,?}$$

$$m_{em}c^2 \simeq \alpha m c^2 \ln\left(\bar{\lambda}_c / r\right)$$

$$\bar{\lambda}_c = 2.42 \times 10^{-10}\,\mathrm{cm} = 2.42 \times 10^{3}\,\mathrm{fm}$$

$$R \simeq \bar{\lambda}_c \exp(-137) \quad !$$

THE ELECTRON RADIUS

$$e \cdot \frac{e}{r} \to \alpha m c^2 \ln\left(\frac{r}{\bar{\lambda}_e}\right)$$

A HUGE ELECTRON RADIUS LOOKED AS 'UNNATURAL'

THE SOLUTION TO THE PUZZLE CAME FROM A NEW THEORY DESCRIBING THE INTERACTIONS OF

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

NATURALNESS: NEED OF NEW PHYSICS WHENEVER UNNATURAL (...) SITUATIONS ARE FACED

THE NEUTRON

ELECTRONS & PROTONS ARE **STABLE** PARTICLES

$$\left(\tau_p \gtrsim 6 \times 10^{39} \text{ yrs} \right)$$

WHEREAS THE NEUTRON IS **UNSTABLE**

$$\tau_n \sim 10.2 \text{ minutes}$$

$$n \longrightarrow p\, e^- \bar{\nu}_e$$

EVEN THOUGH IT GETS STABILIZED IN MOST NUCLEI

α-particle (HELIUM NUCLEUS)

UNSTABLE NUCLEUS WITH $E_b \ll E_b^{(\alpha)}$

THE FERMI THEORY

PARTICLES IN GENERAL ARE NOT PERMANENT ENTITIES: THEY CAN DECAY OR BE CREATED.

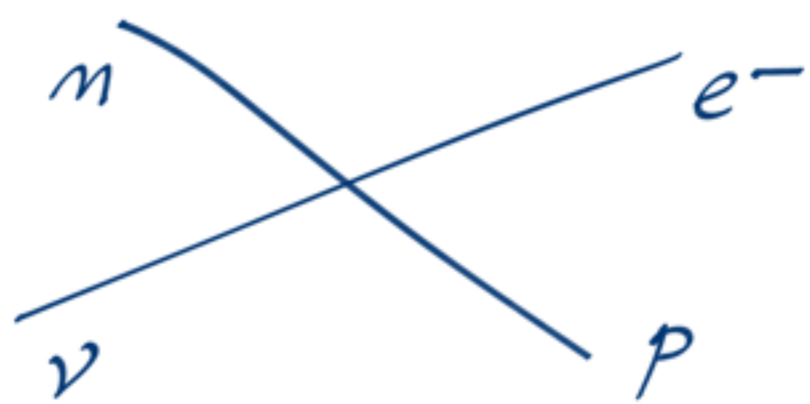
FIELDS ARE PERMANENT ENTITIES.

PARTICLES ARE LOCALIZED EXCITATIONS ON FIELDS.

THE FACT THAT FIELDS MAY INTERACT LEADS TO THE VARIETY OF PARTICLE REACTIONS OBSERVED (neutron decay is one of them).

$$G_F \cdot \bar{\Psi}_p \gamma^\mu \Psi_n \bar{\Psi}_e \gamma_\mu \Psi_\nu$$

"interaction density"



PARTICLES & INTERACTIONS

BUILDING BRICKS OF ATOMS : e^-, p, n

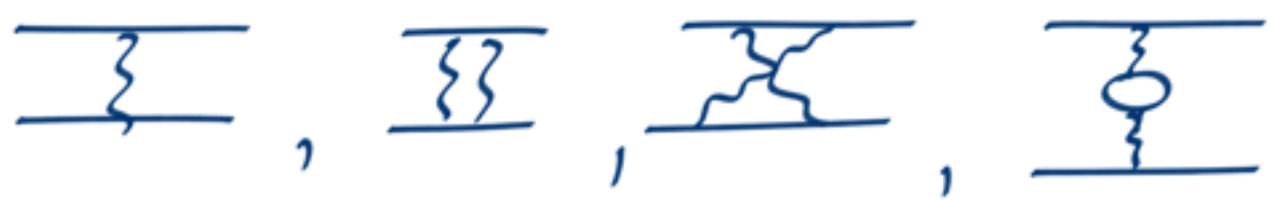
EM. FORCE MEDIATOR : γ

THERE IS NOT REALLY A PARTICLE SHOOTED FROM ONE e^- TO THE e^- (OR e^+), OTHERWISE ONLY REPULSIONS WOULD BE POSSIBLE _ THESE DIAGRAMS ARE BOOKKEEPING GRAPHICAL TOOLS ___ THEY ARE DEFORMABLE IN ANY WAY

PARTICLES & INTERACTIONS

BUILDING BRICKS OF ATOMS : e^-, p, n

EM. FORCE MEDIATOR : γ



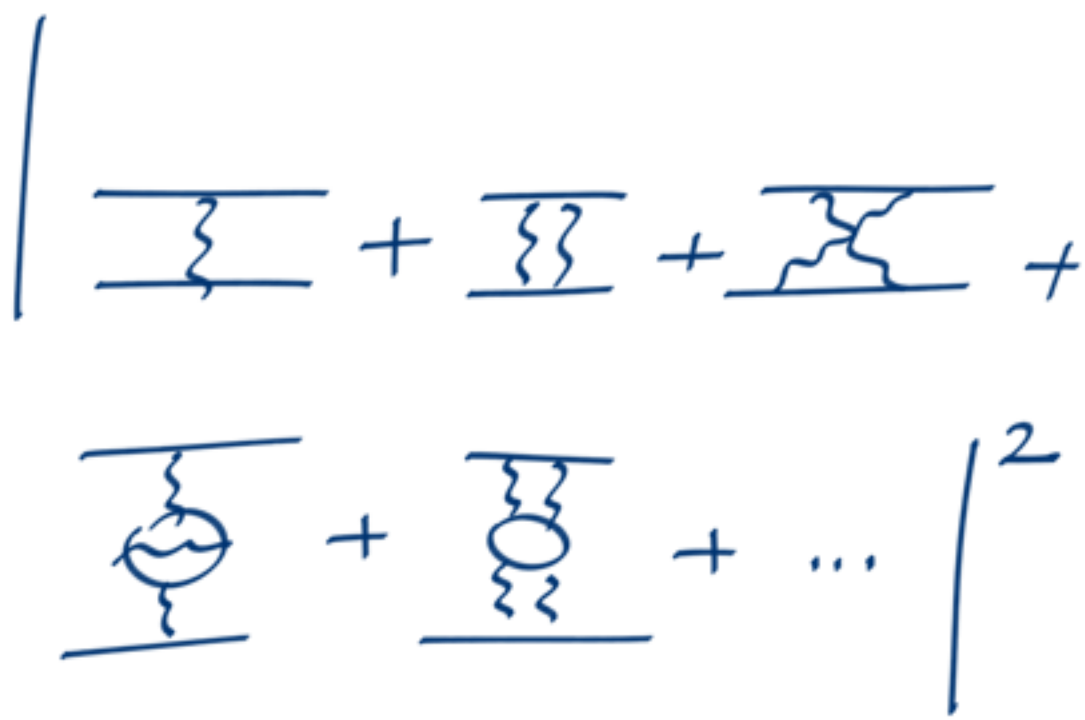
... an infinite # of ALTERNATIVES

PARTICLES & INTERACTIONS

BUILDING BRICKS OF ATOMS : e^-, p, n

EM. FORCE MEDIATOR : γ

IF THE ALTERNATIVES CANNOT BE DISTINGUISHED



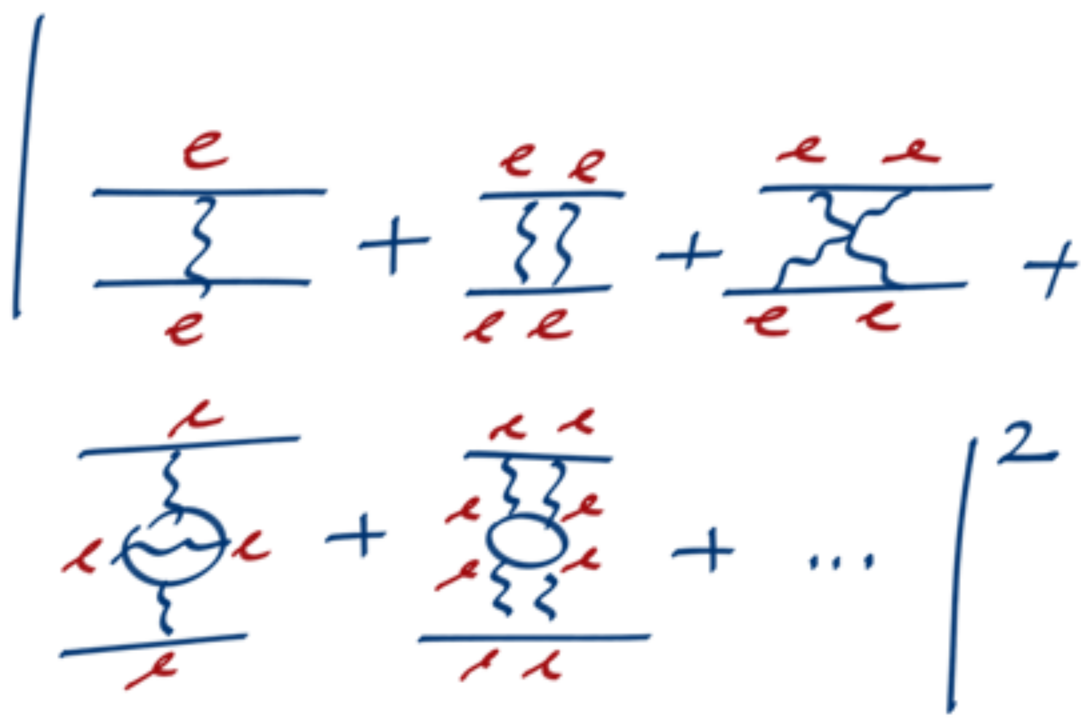
$\propto$ PROBABILITY OF THE PROCESS

PARTICLES & INTERACTIONS

BUILDING BRICKS OF ATOMS : e^-, p, n

EM. FORCE MEDIATOR : γ

IF THE ALTERNATIVES CANNOT BE DISTINGUISHED



$\propto$ PROBABILITY OF THE PROCESS

SINCE $\alpha = \frac{1}{137}$ IT IS LIKE THE INTERACTION WERE ESSENTIALLY

.

QUARKS

IS THE p OR n ELEMENTARY AS THE e^- ?

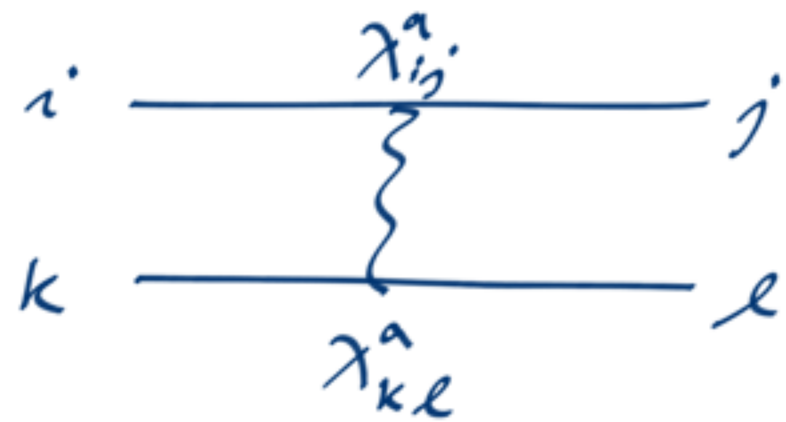
TURNS OUT THAT

	up	down	strange	charm	beauty	top
	u	d	s	c	b	t
charges	$2/3$	$-1/3$	$-1/3$	$2/3$	$-1/3$	$2/3$

STANDARD MATTER

COLOR

QUARKS HAVE A DIFFERENT KIND OF CHARGE, CALLED COLOR — three types.



λ's ARE 3X3 MATRICES AND IN THE ABOVE DIAGRAM IT IS MEANT

$$\sum_{a=1}^{8} \lambda^a_{ij}\, \lambda^a_{kl}$$

WHICH SUBSTITUTES THE PRODUCT OF CHARGES e^2

THERE ARE 8 DIFFERENT **GLUONS** IN PLACE OF THE PHOTON OF ELECTROMAGNETISM.

THESE ARE STRONG FORCES

RECAP (PARTICLES)

quarks:

$$\underbrace{u, d}_{\text{few MeV}}, \underbrace{s}_{100\,\text{MeV}}, \underbrace{c}_{1.5\,\text{GeV}}, \underbrace{b}_{4.5\,\text{GeV}}, \underbrace{t}_{170\,\text{GeV}}$$

leptons:

$$\underbrace{e^-}_{0.5\,\text{MeV}}, \underbrace{\mu^-}_{105\,\text{MeV}}, \underbrace{\tau^-}_{1777\,\text{MeV}}$$

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

≤ 0.12 eV (sum of three flavors)

mediators: (gauge fields)

$$\underbrace{\gamma, \; g^1, g^2, \ldots, g^8}_{\text{massless}}$$

$$\underset{80\,\text{GeV}}{W^\pm}, \; \underset{90\,\text{GeV}}{Z^0}$$

INTERACTION STRENGTHS

GRAVITY: $G_N = 6.67 \times 10^{-8}\ cm^3 g^{-1} sec^{-2}$

use that $1\,cm = 10^{13}\,fm$

$1\,erg = 6.2 \times 10^5\,MeV$

$g^{-2} = 3.2 \times 10^{-48} \left(\frac{GeV}{c^2}\right)^{-2}$

$$\boxed{G_N \simeq 6.7 \times 10^{-39} (\hbar c) \left(\frac{GeV}{c^2}\right)^{-2}}$$

WEAK INTERACTION:

$$\boxed{\frac{G_F}{(\hbar c)^3} = 1.16 \times 10^{-5}\,GeV^{-2}}$$

INTERACTION STRENGTHS

$$\frac{G_N}{G_F} = \frac{6.7 \times 10^{-39}}{1.16 \times 10^{-5}} \frac{(\hbar c)(GeV/c^2)^{-2}}{(\hbar c)^3 \, (GeV)^{-2}}$$

$$= 5.7 \times 10^{-34} \; \frac{\hbar c^5}{\hbar^3 c^3}$$

Thus

$$\boxed{\frac{G_N \hbar^2}{G_F \, c^2} = 5.7 \times 10^{-34}}$$

THE GRAVITY FORCE IS IMMENSLY WEAKER THAN THE WEAK FORCE

INTERACTION STRENGTHS

SIMILARLY WE SEE THAT

$$\frac{G_N m_e^2}{K e^2} = \frac{6.7 \times 10^{-39} (\hbar c) \left(\frac{GeV}{c^2}\right)^{-2} m_e}{\alpha (\hbar c)}$$

$$= 2.3 \times 10^{-43}$$

COMPARING NEWTON FORCE TO COULOMB FORCE GIVES AN EVEN SMALLER RATIO

GRAVITY $\ll$ WEAK $\ll$ ELECTROMAGNETIC $\ll$ STRONG

DESPITE OF THIS IT IS THOUGHT THAT THE FOUR FORCES HAD THE SAME STRENGTH BACK TO THE BIG BANG. CALLED **UNIFICATION.**

SPIN

AN ELEMENTARY PARTICLE, e.g. THE ELECTRON, CAN HAVE AN ORBITAL ANGULAR MOMENTUM ℓ IN AN EXTERNAL <u>CENTRAL FIELD</u>, e.g. THE COULOMB FIELD GENERATED BY THE PROTON NUCLEUS IN HYDROGEN ATOM.

THE ELECTRON WILL BE DESCRIBED BY A MATHEMATICAL FUNCTION $\psi_\ell(\vec{x})$ CALLED THE <u>WAVEFUNCTION</u>

THE TRANSFORMATION LAW OF $\psi_\ell(\vec{x})$ UNDER ROTATIONS ARE FULLY UNDERSTOOD WHEN

$$\ell \quad \& \quad S$$

ARE **BOTH** SPECIFIED.

S IS SOME SORT OF INTRINSIC ANGULAR MOMENTUM OF THE PARTICLE CALLED <u>SPIN</u>.

<u>NOTHING</u> LIKE AN e^- SPINNING 

SPIN

SPIN CAN BE INTEGER : 0, 1, 2, 3...

OR HALF-INTEGER : $1/2$, $3/2$, $5/2$, $7/2$ ...

A PARTICLE WITH SPIN S HAS

$$(2S+1)$$

COMPONENTS

SPIN 1 PARTICLE HAS 3 COMPONENTS

TRANSFORMS LIKE A VECTOR UNDER ROTATIONS

SPIN $1/2$ " " 2 COMPONENTS

HAS SPECIAL TRANSFORMATIONS UNDER ROT.

SPIN 0 " " 1 COMPONENT

INVARIANT UNDER ROTATIONS

SPIN

$e^-, \mu^-, \tau^-, \nu_{e,\mu,\tau}, u, d, s, c, b, t$ SPIN = 1/2

$\gamma, W^\pm, Z^0, g^1, \dots, g^8$ SPIN = 1

graviton $\mathcal{G}$ SPIN = 2

HIGGS SPIN = 0

PARTICLES WITH HALF-INTEGER SPIN ARE CALLED

FERMIONS

PARTICLES WITH INTEGER SPIN ARE

BOSONS

ISOTOPIC SPIN = ISOSPIN

FOR. FORM THE ISOSPIN I DOUBLETS OF **MASSLESS** PARTICLES

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} b \\ t \end{pmatrix}$$

ELECTRON^{+} AN NEUTRINO ARE TWO ISOSPIN COMPONENTS OF THE SAME PARTICLE —— SIMILARLY FOR u & d ... FROM THE HEISENBERG IDEA THAT p & n ARE THE TWO ISOSPIN STATES OF THE **NUCLEON** N

$$N = \begin{pmatrix} p \\ n \end{pmatrix}$$

$^{+}$ THE ELECTRON WITH <u>LEFT "CHIRALITY"</u>

ELECTROWEAK UNIFICATION

Introduce three mediators A_1, A_2, A_3, B

$$W = A_1 + iA_2 \quad (+e)$$

$$W^* = A_1 - iA_2 \quad (-e)$$

(neutral) $$\begin{pmatrix} Z \\ A \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A_3 \\ B \end{pmatrix}$$

NEED A MECHANISM TO GIVE MASS TO

$$W^\pm, Z, e^-$$

NOT TO THE γ.

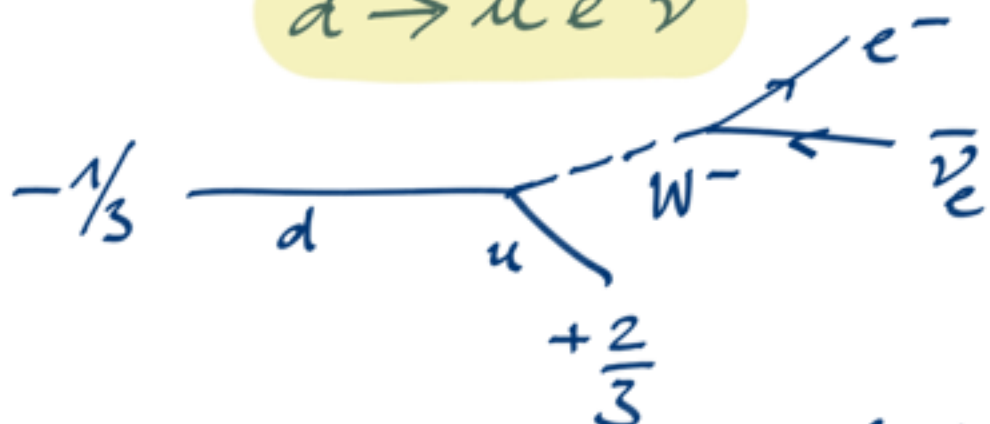
THIS MECHANISM REQUIRES THE EXISTENCE OF A NEW PHYSICAL FIELD (and thus of its particle) NAMED AS THE **HIGGS FIELD**: ϕ^0

WEAK PROCESSES

$$n \to p\, e^- \bar{\nu} \qquad (\beta\text{-decay})$$

$$(udd) \quad (uud)\, e^- \bar{\nu}$$

$$d \to u\, e^- \bar{\nu}$$



$$-\frac{1}{3} - (-1) = +\frac{2}{3}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} W^- \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} W^-$$

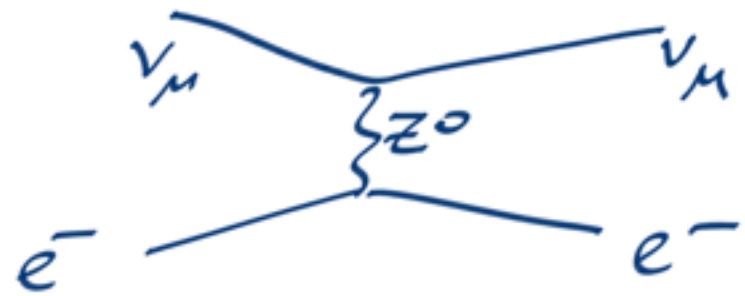
THE RANGE IS TINY

$$V \approx e^{-r/r_0} = e^{-\frac{m_W c}{\hbar} r}$$

$$r_0 = \frac{\hbar}{m_W c} = \frac{\hbar c}{m_W c^2} = \frac{197\,\text{MeV}\cdot\text{fm}}{80\,\text{GeV}} \simeq 2\cdot 10^{-3}\,\text{fm}$$

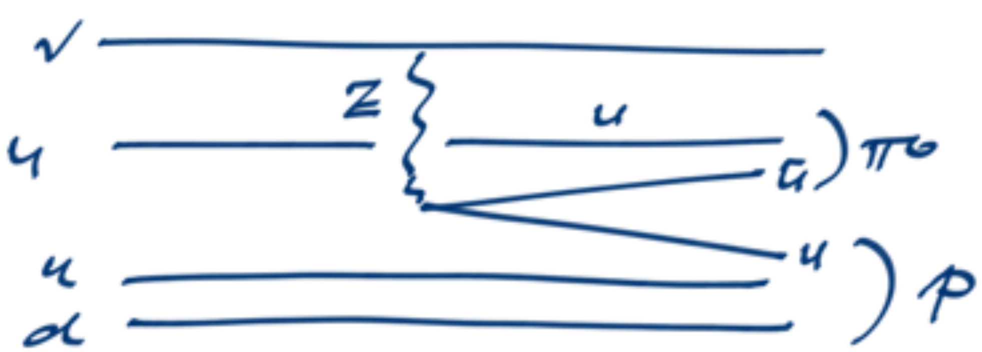
NEUTRAL CURRENTS

$\nu_\mu e^- \longrightarrow \nu_\mu e^-$ (or $\bar{\nu}_e$, $\bar{\nu}_\mu$ ..)



$e^+ e^- \longrightarrow \mu^+ \mu^-$

$\nu p \longrightarrow \nu p + \pi^0$



BIG OPEN ISSUES

The size of G_F is determined by the mass of the Higgs boson

$$G_F \sim m_{\phi^0}^{-2}$$

THE ϕ^0 INTERACTS WITH ANY PARTICLE WITH A STRENGTH PROPORTIONAL TO THE PARTICLE MASS OR THE ENERGY E FOR VIRTUAL PARTICLES

SINCE THE VACUUM (IN WHICH ϕ^0 PROPAGATES) IS FULL OF VIRTUAL PARTICLES, THE m_{ϕ^0} RECEIVES A CONTRIBUTION

$$\delta m_{\phi^0}^2 = k E_{max}^2$$

a sort of thermalization effect at $T = E_{max}$.
Initially
$$m_{\phi^0} = E_{\phi^0} \ll T = E_{max}$$

BIG OPEN ISSUES

THE PROBLEM IS THAT

$$\boxed{G_N \simeq 6.7 \times 10^{-39} (\hbar c) \left(\frac{GeV}{c^2} \right)^{-2}}$$

Planck mass

$$M_p = \sqrt{\frac{\hbar c}{G_N}} \simeq 10^{20} \frac{GeV}{c^2}$$

So M_{ϕ_0} (OR $G_F^{-1/2}$) IS EXPECTED TO BE PROPTO BY k TO E_{max} (OR $G_N^{-1/2}$). But

$$\frac{G_N \hbar^2}{G_F c^2} \sim 10^{-34}$$

Can k do the job? In standard theory $k \simeq 10^{-2}$...

BIG OPEN ISSUES

$$\delta m_{\phi^0}^2 = \underbrace{\frac{3G_F}{4\sqrt{2}\,\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_{\phi^0}^2\right)}_{k}\Lambda^2$$

STANDARD THEORY

THE REQUEST THAT

$$\delta m_{\phi^0} \lesssim 100 \text{ GeV}$$

NEEDS TO REQUIRE THAT k IS THE WRONG FACTOR

BEYOND $\underline{\Lambda \sim 1\,\text{TeV}}$

... THE LHC ERA.

FOR THE TIME BEING NO NEW PARTICLES HAVE BEEN FOUND BELOW THE TeV SCALE_

BIG OPEN ISSUES

DARK MATTER

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