Viaggio al centro del protone

Alessandro Bacchetta
Dipartimento di Fisica, Università di Pavia

Introduzione

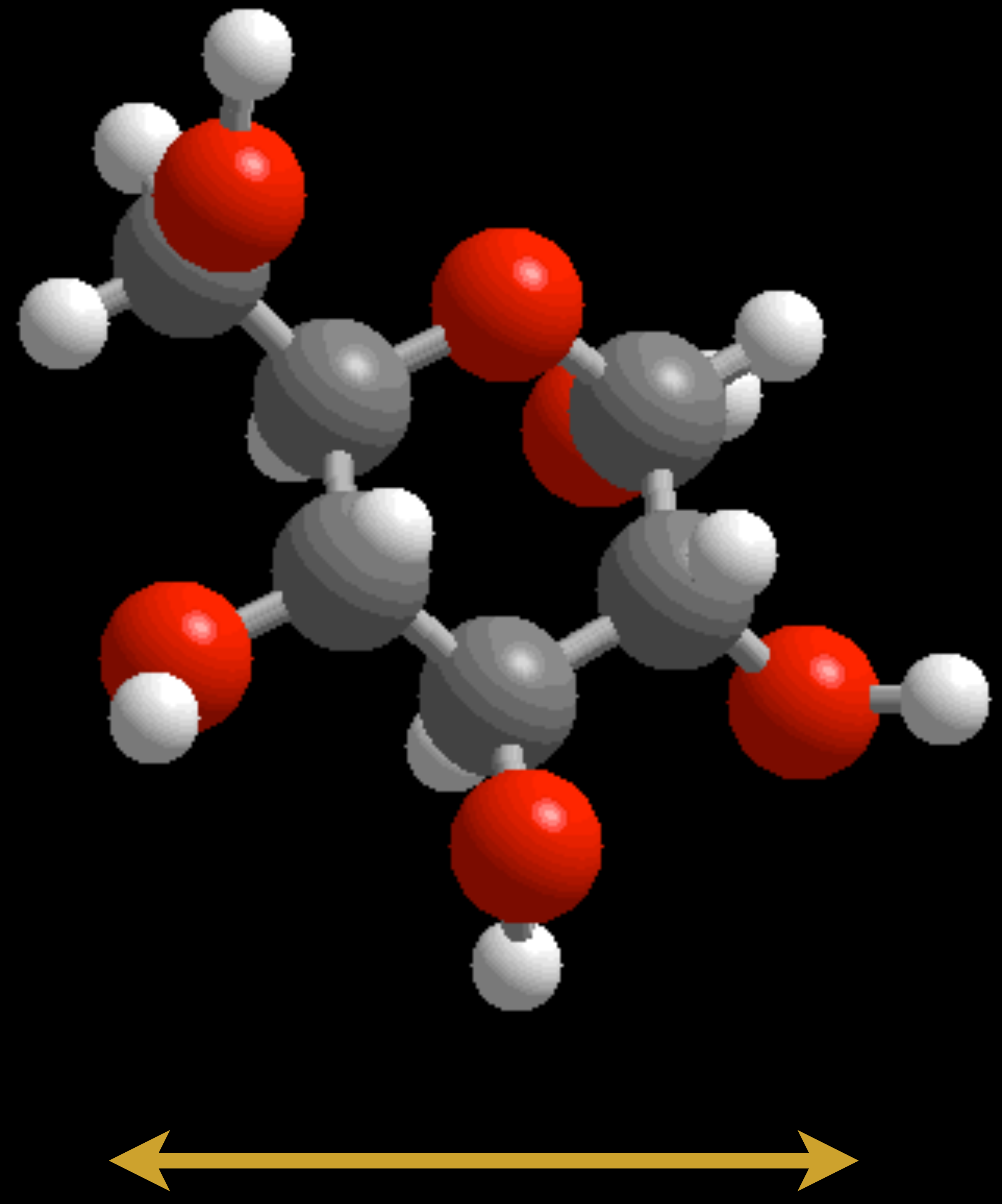
"[...] Esplorare in modo chiaro e comprensibile il mondo della scienza e della ricerca nei suoi vari aspetti.

Il titolo "QUARK" è un po' curioso e l'abbiamo preso in prestito dalla fisica, dove molti studi sono in corso su ipotetiche particelle subnucleari, chiamate appunto "quarks", che sarebbero i più piccoli mattoni della materia finora conosciuti.
È quindi un po' un andare dentro alle cose."

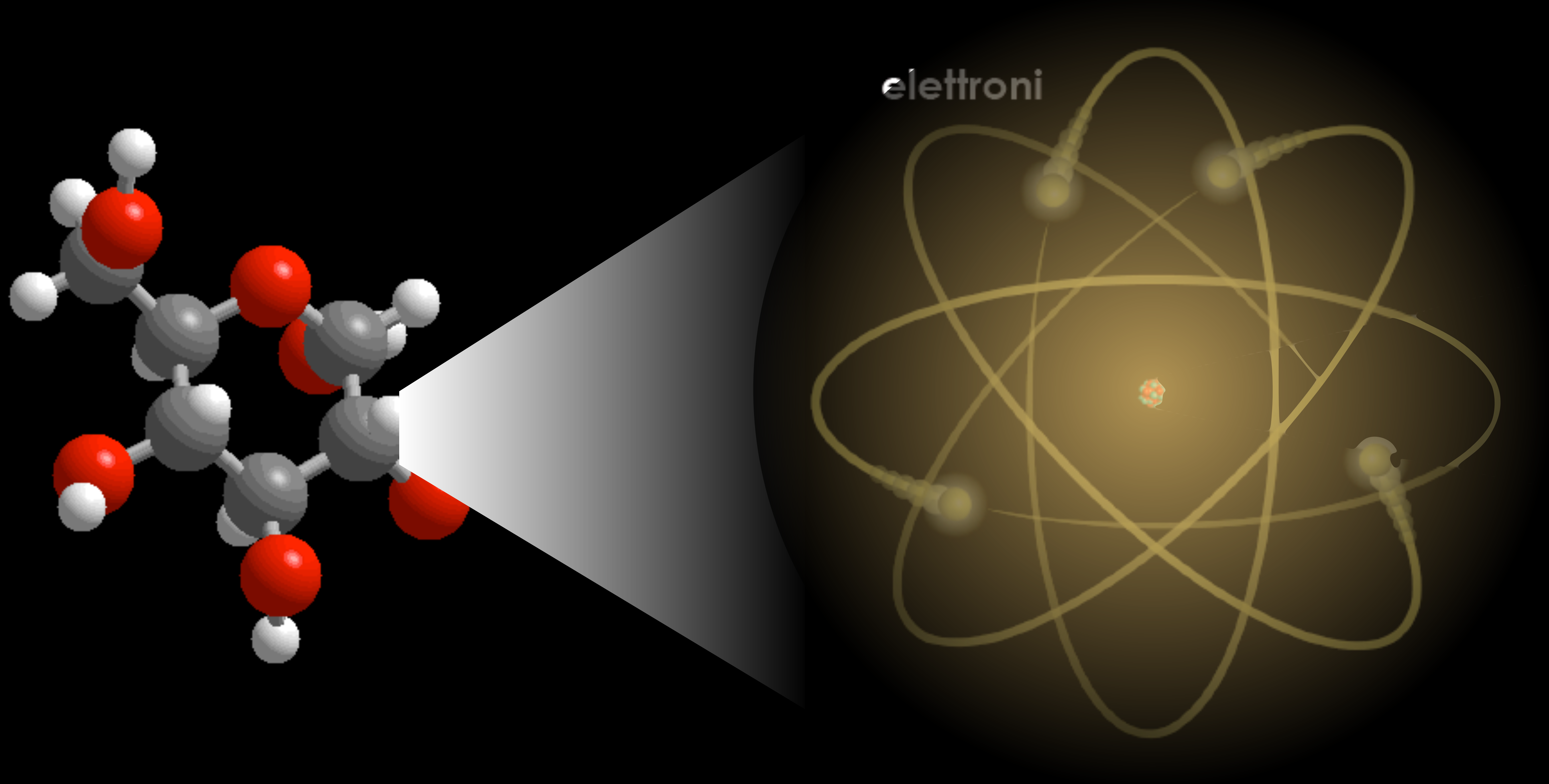
Granello di sabbia (Ministruttura)

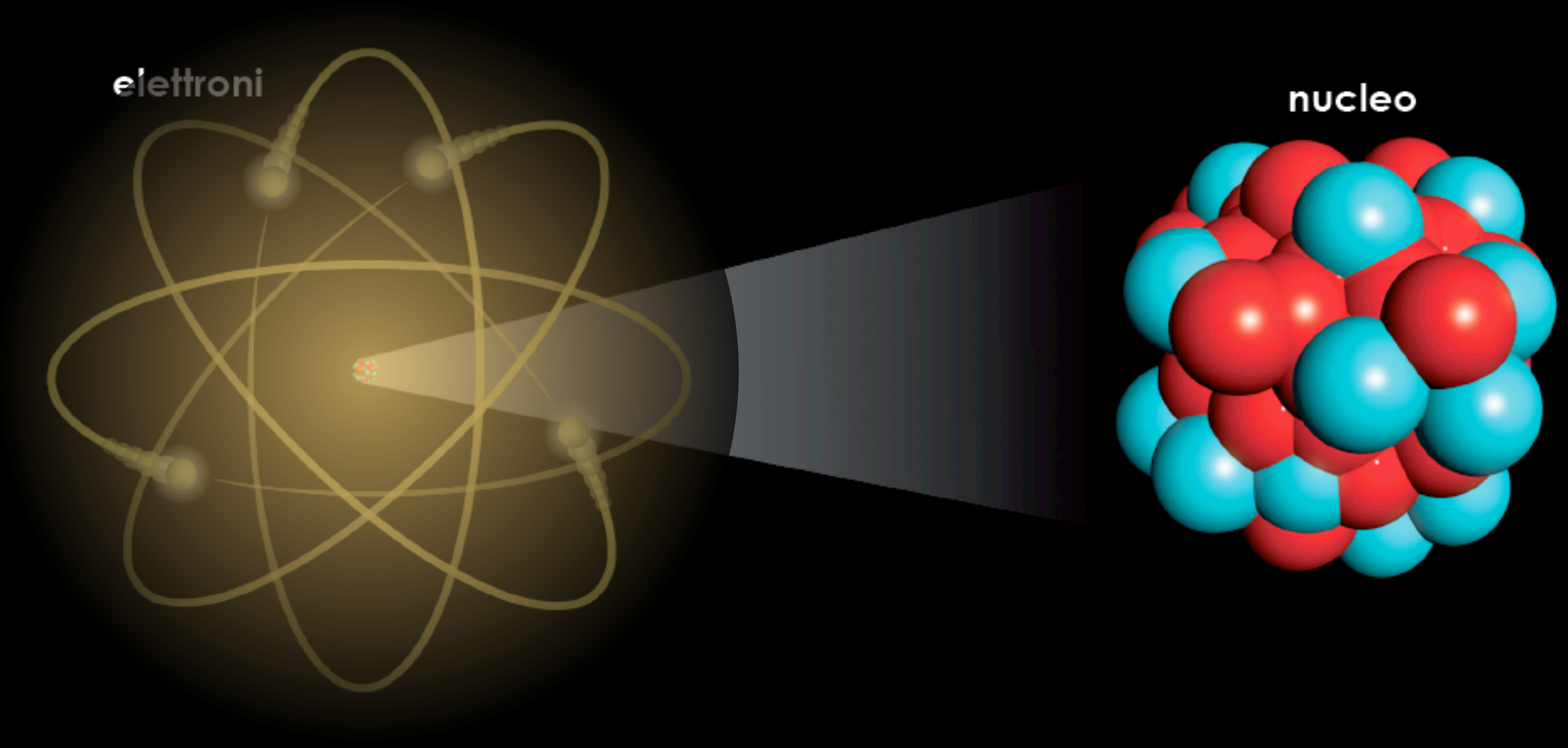
10^{-3} m

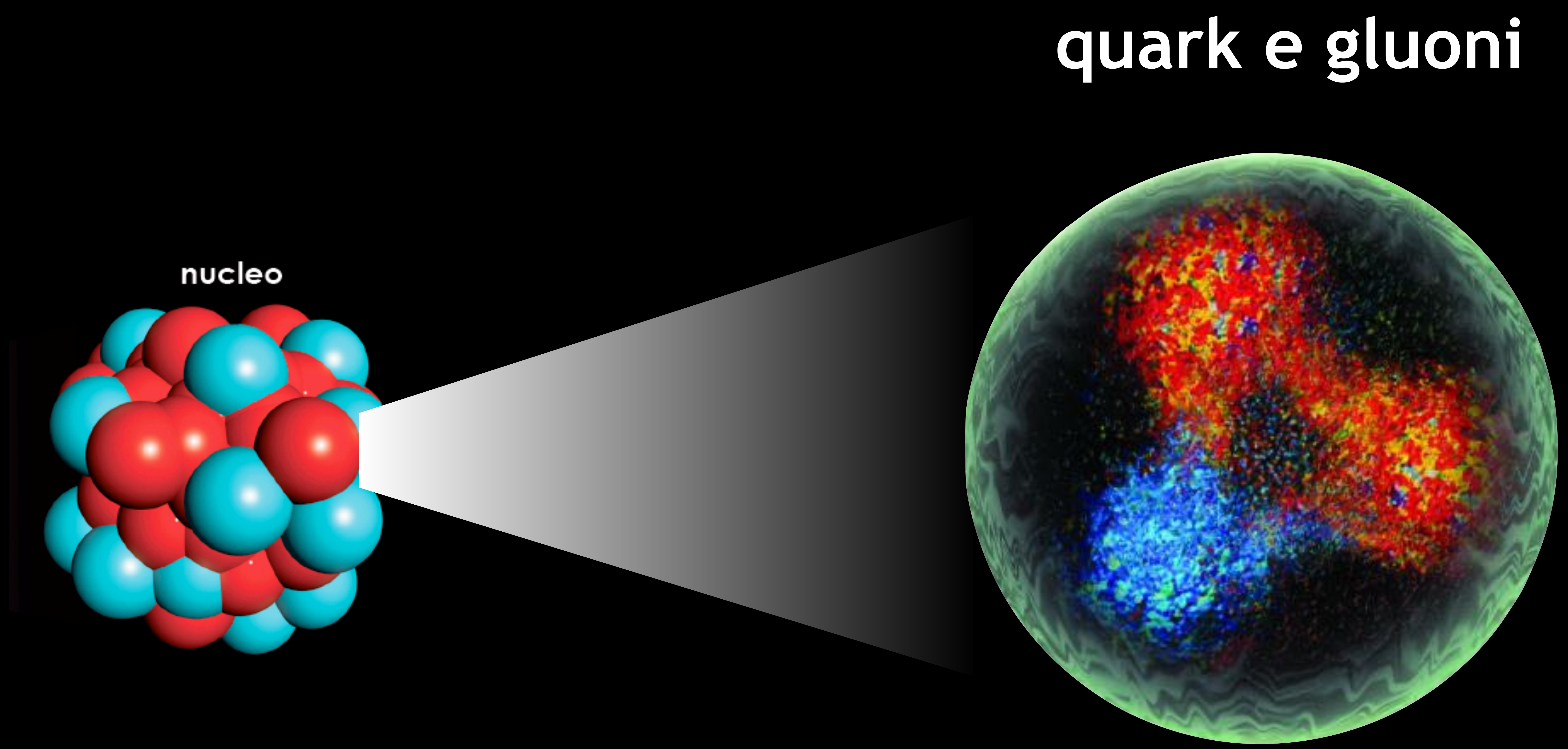
Glucosio (Nanostruttura)



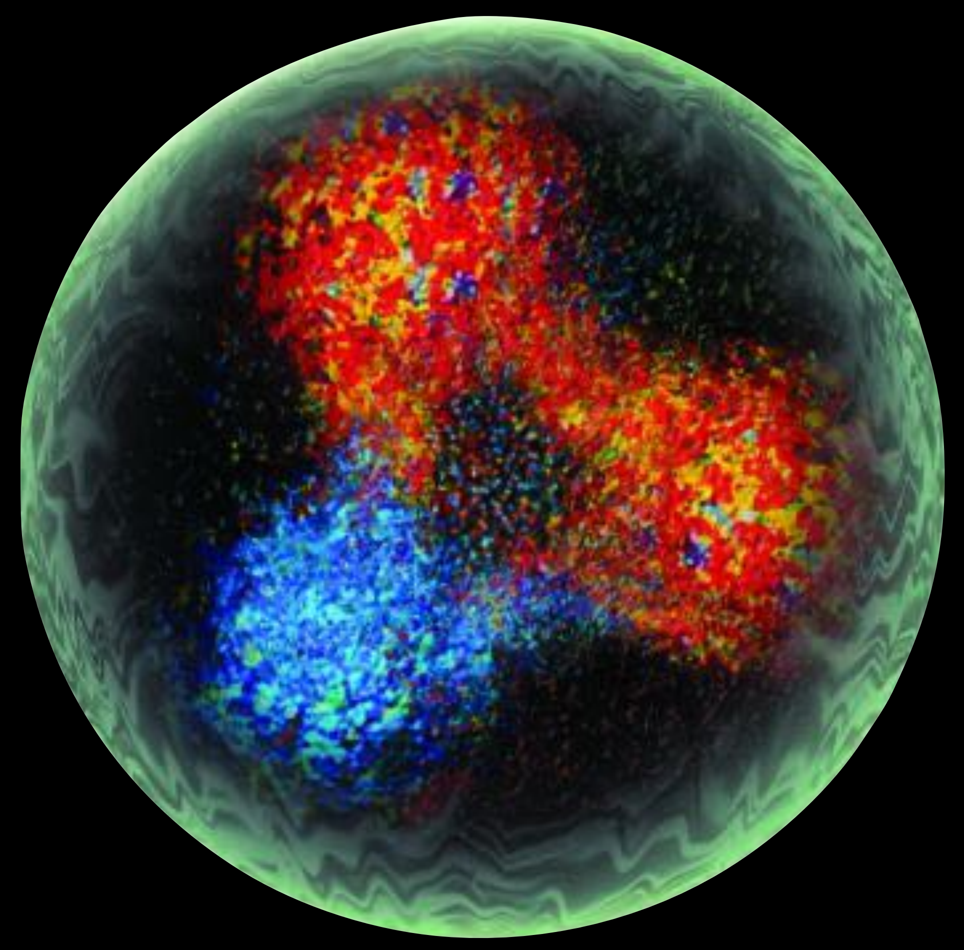
10^{-9} m


elettroni


elettroni
nucleo


quark e gluoni
nucleo

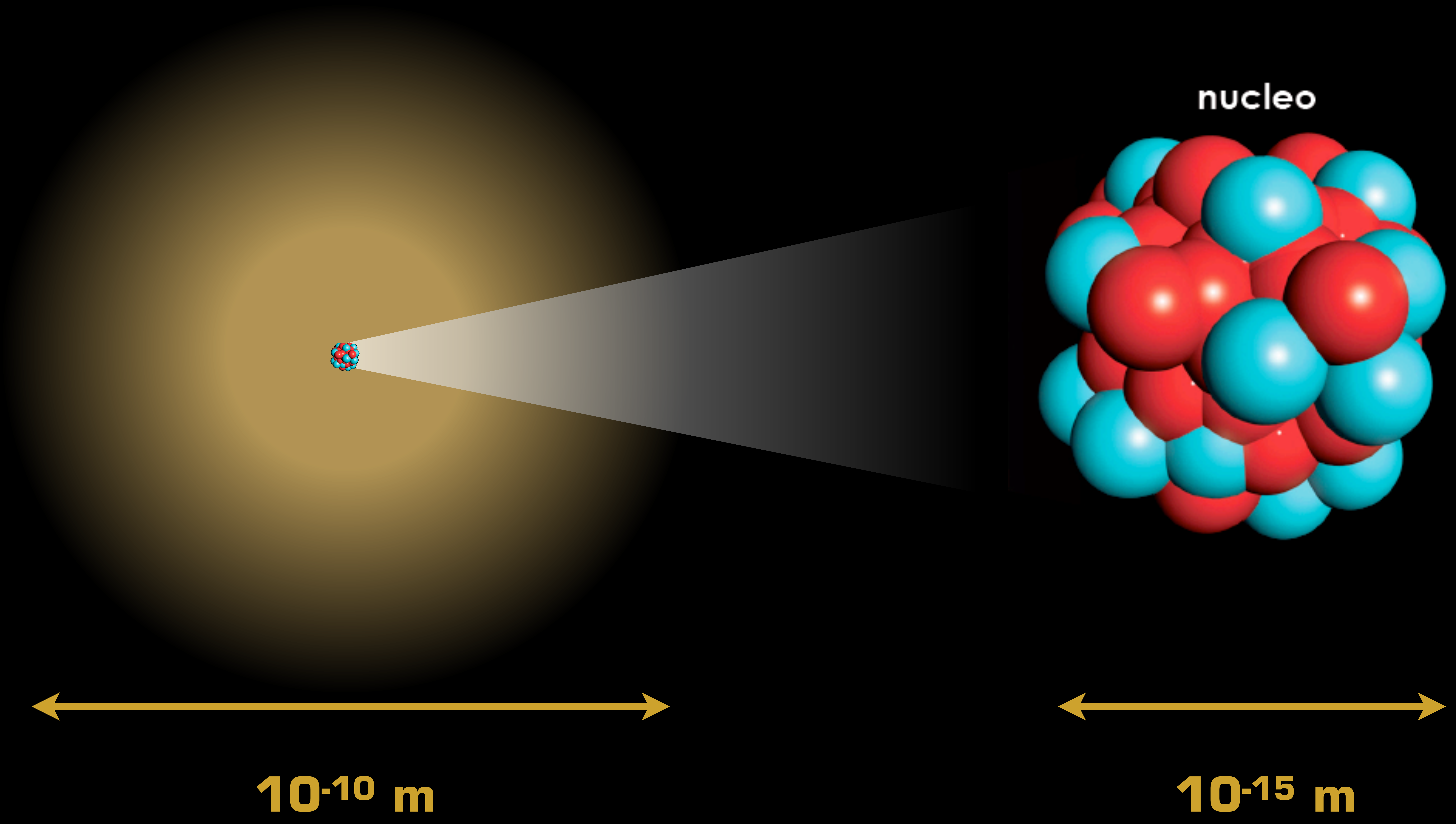
Protone
(Femtostruttura)



10^{-15} m

Elettrone
(Zeptostruttura?)

10^{-21} m

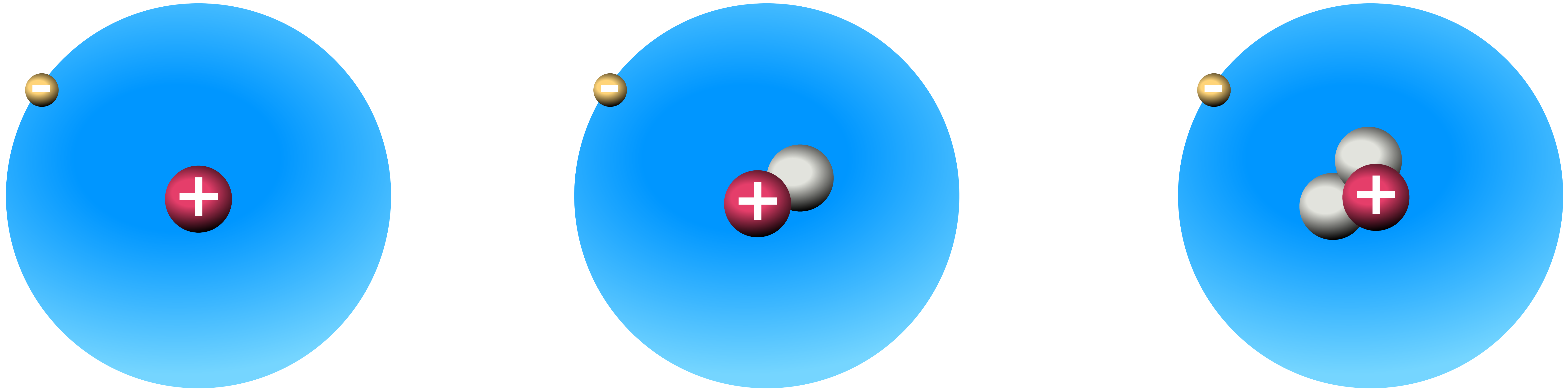

nucleo
10^{-10} m
10^{-15} m

Fisica nucleare

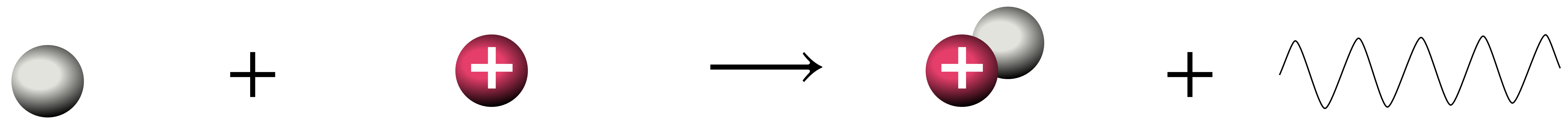
IL NEUTRONE E GLI ISOTOPI

Il neutrone venne scoperto da Chadwick nel 1932

elettrone — protone — neutrone



${}^{1}_{1}H$	${}^{2}_{1}H$	${}^{3}_{1}H$
idrogeno	deuterio	trizio



neutrone idrogeno deuterio gamma

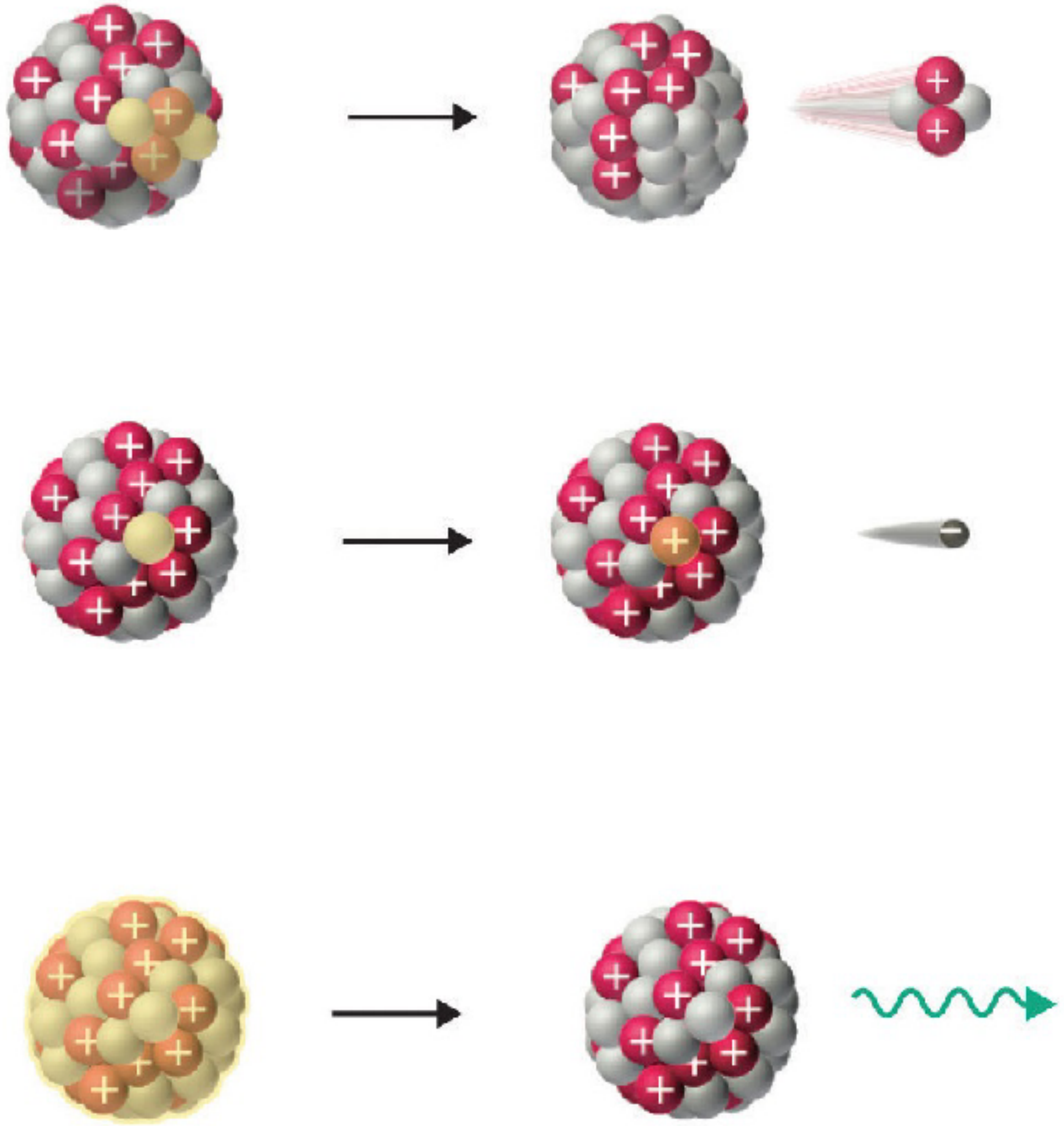
$$^{1}_{0}n + ^{1}_{1}H \longrightarrow ^{2}_{1}H + \gamma$$

$$E = mc^2$$

Massa del neutrone:	939.6 MeV
Massa del protone:	938.3 MeV
Massa del deuterio:	1875.7 MeV
Differenza di massa:	2.2 MeV

LA RADIOATTIVITÀ NATURALE

nucleo padre | nucleo figlio

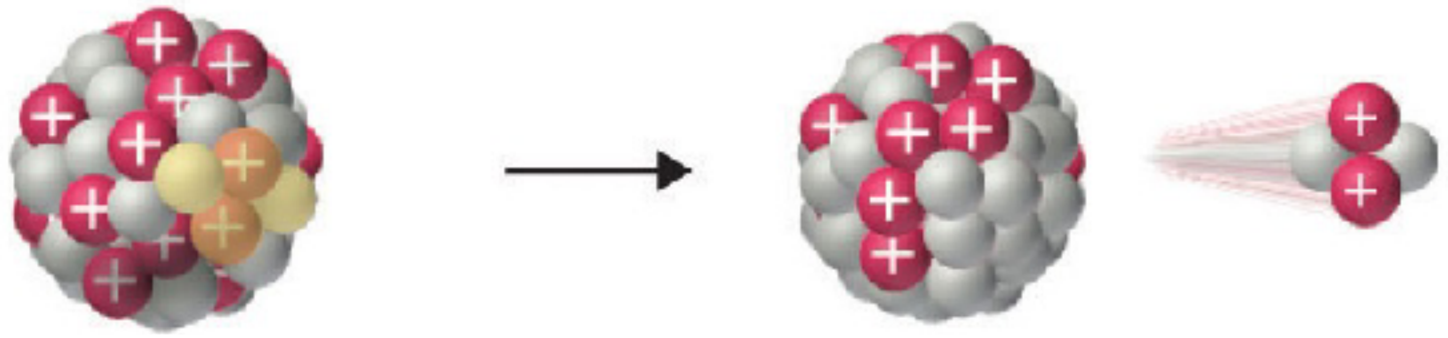


particella alfa

particella beta

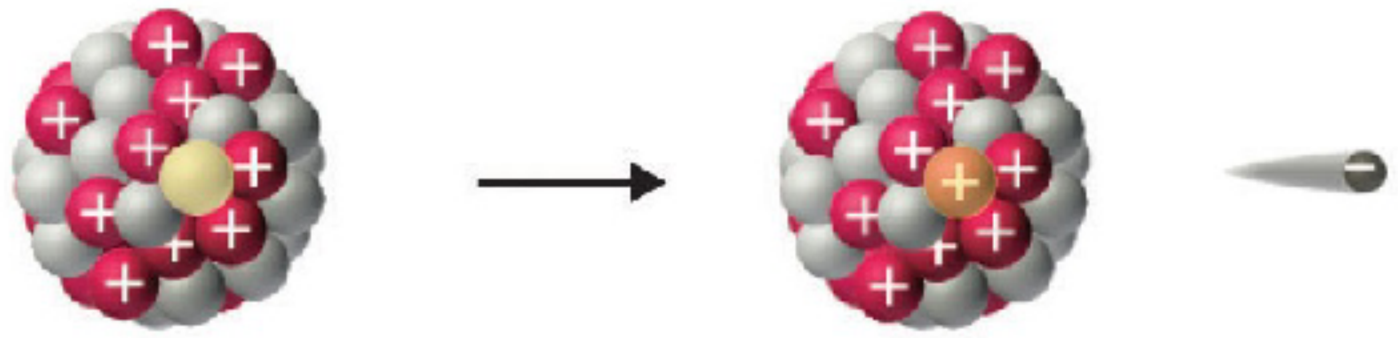
particella gamma

ESEMPI



$$^{238}_{92}U \rightarrow ^{234}_{90}Th$$

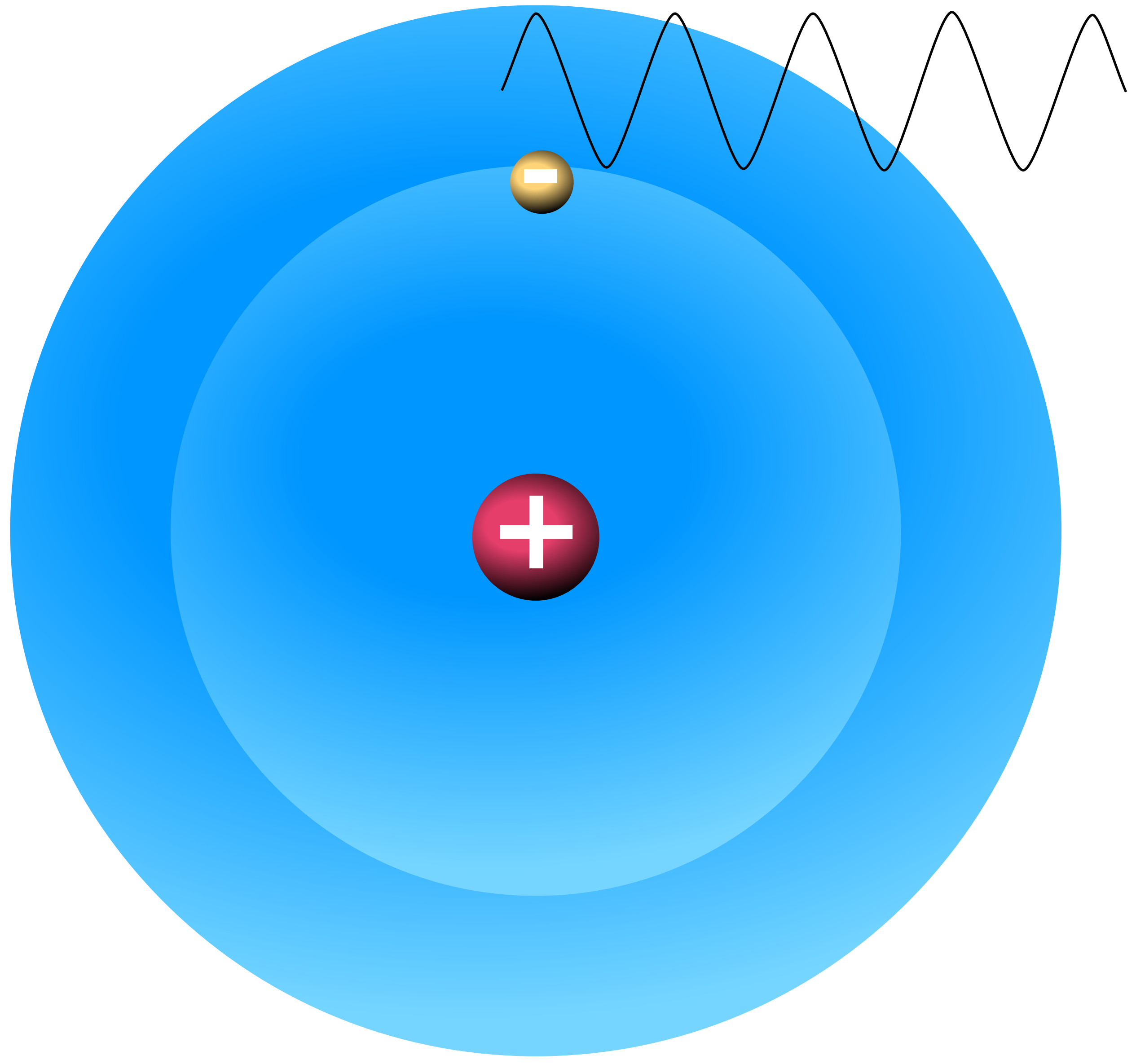
$$^{226}_{88}Ra \rightarrow ^{222}_{86}Rn$$



$$^{40}_{19}K \rightarrow ^{40}_{20}Ca$$

ATOMI E FOTONI

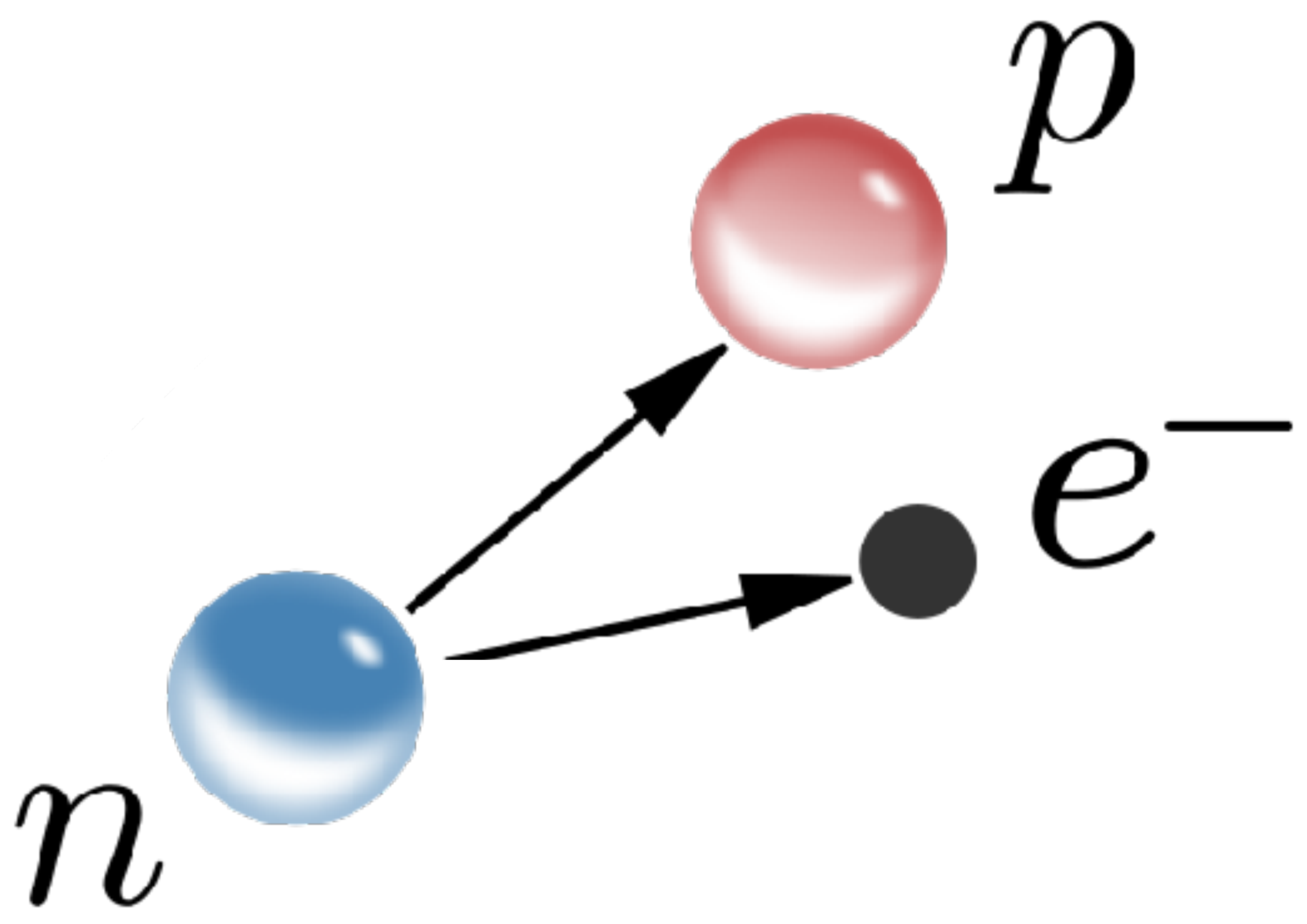
elettrone   protone   fotone



idrogeno

La radiazione gamma nei nuclei si comporta in maniera simile

IL PROBLEMA DEL DECADIMENTO BETA E FERMI



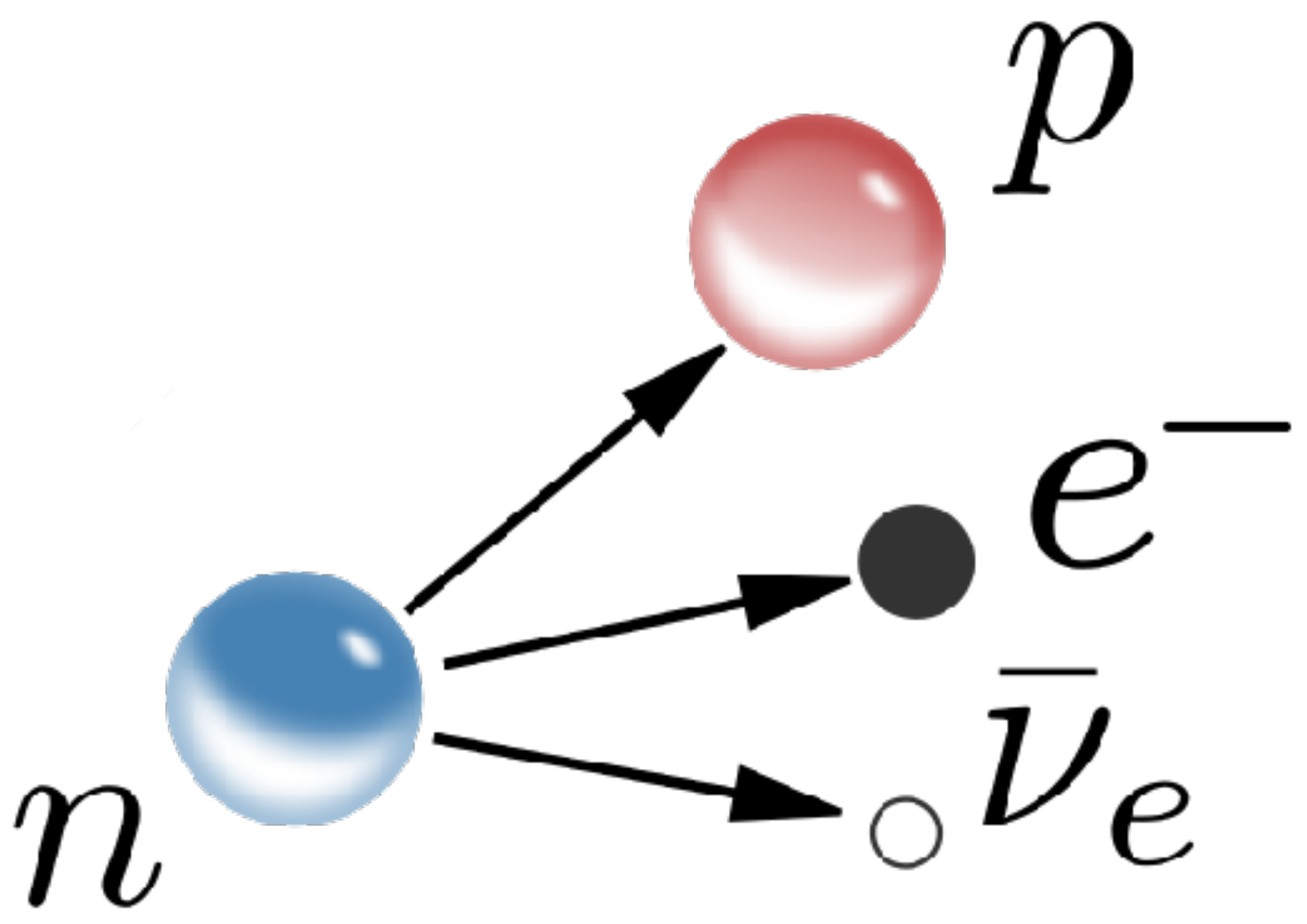
Massa del neutrone:	939.6 MeV
Massa del protone:	938.3 MeV
Massa dell'elettrone:	0.5 MeV
Differenza di massa:	0.8 MeV

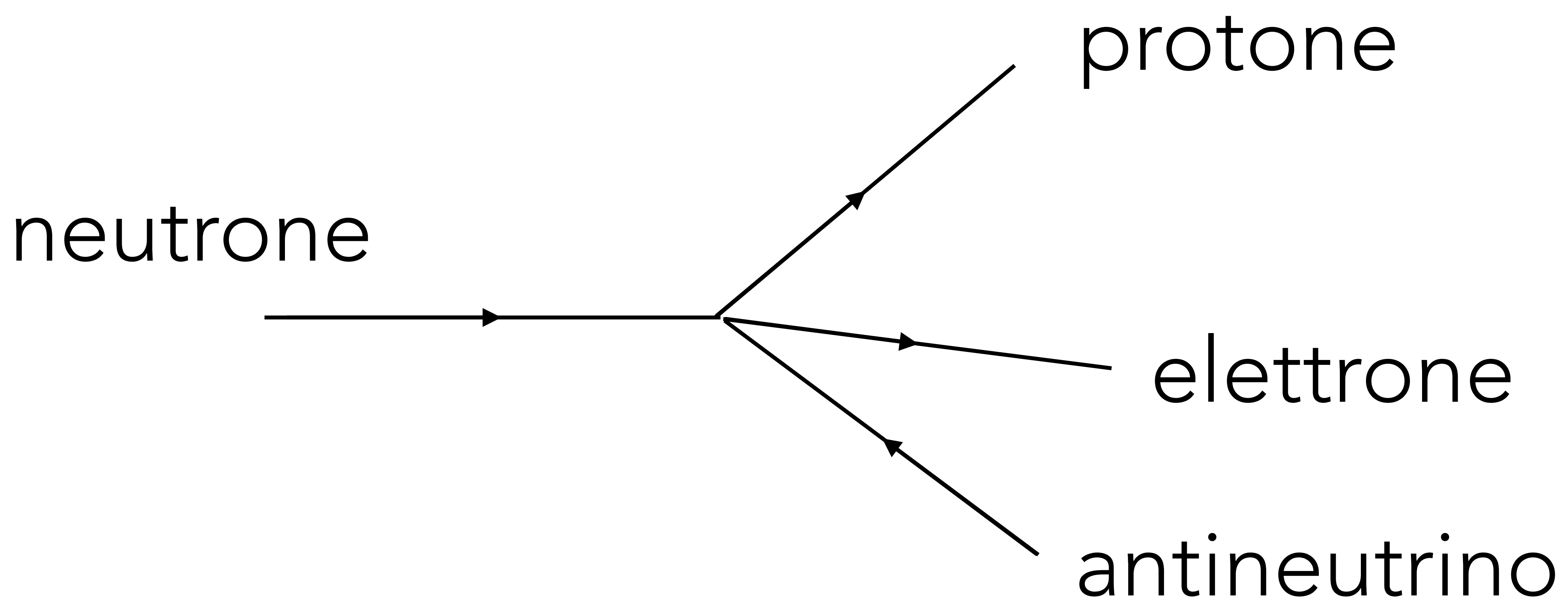
L'energia finale dell'elettrone non tornava con i calcoli!

Pauli postula l'esistenza di una nuova particella, che Amaldi e Fermi battezzarono "neutrino"

LA TEORIA DEL DECADIMENTO BETA

1933

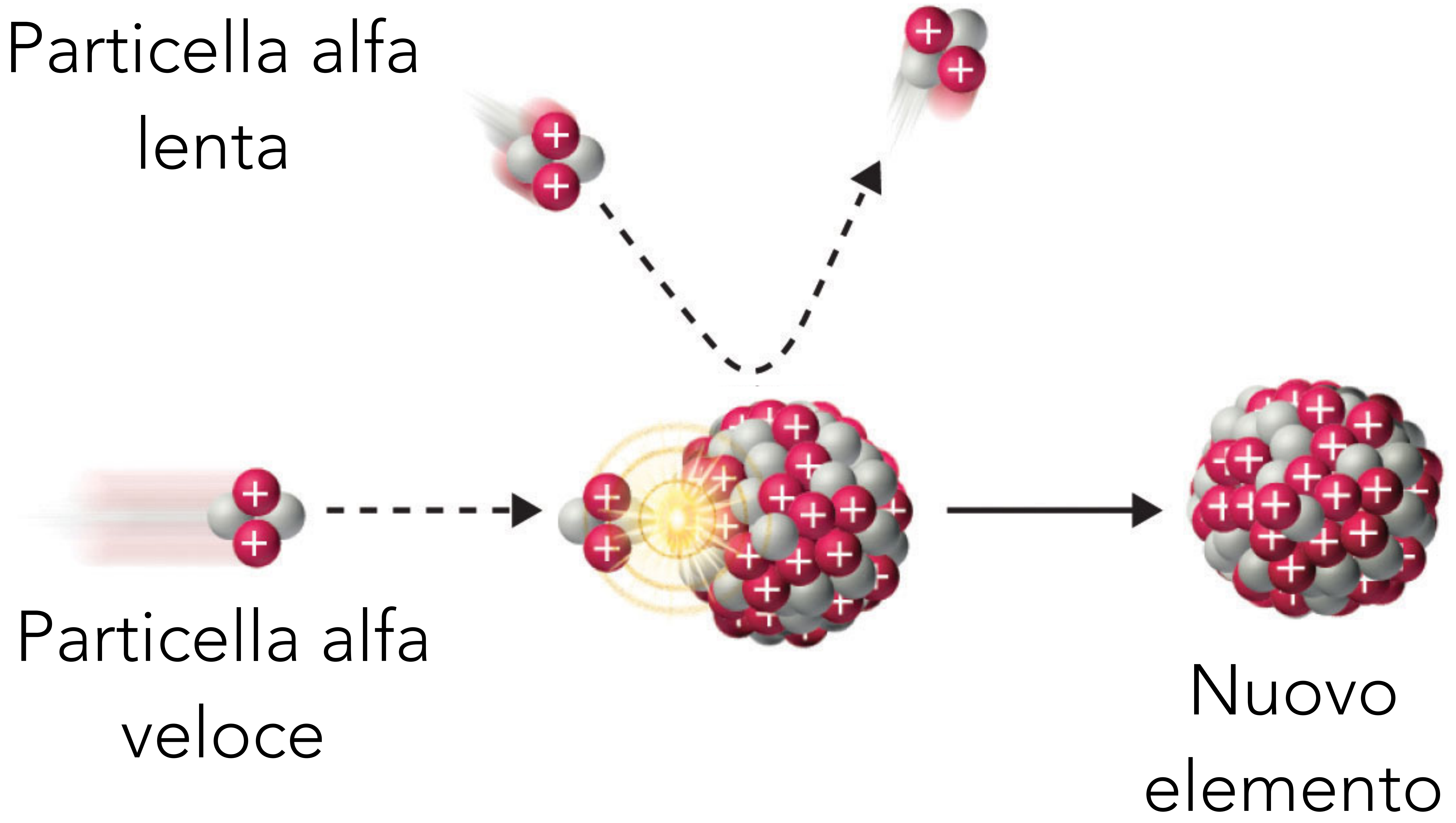




Il decadimento del neutrone è dovuto alla "forza debole", la cui intensità è misurata dalla costante di Fermi.

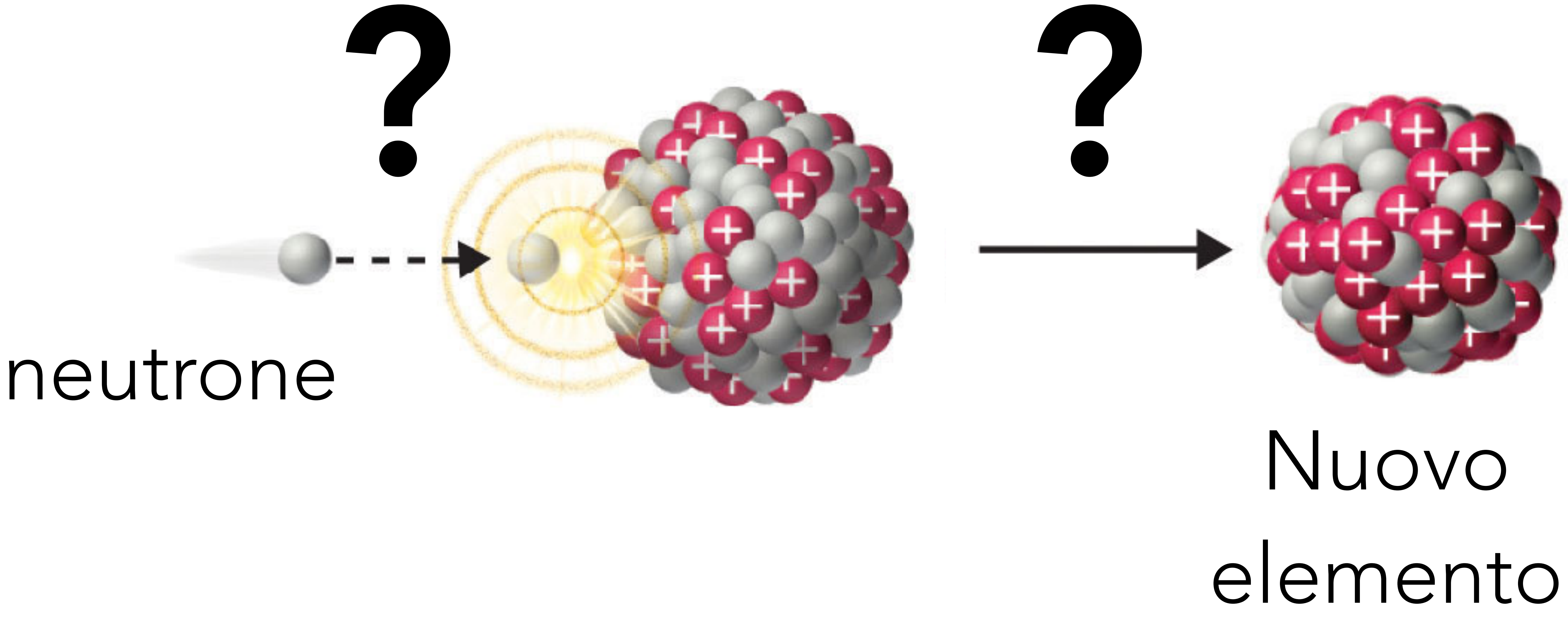
RADIOATTIVITÀ ARTIFICIALE

Nel 1934 Irène Joliot-Curie e suo marito Frédéric avevano reso radioattivi elementi che non lo erano



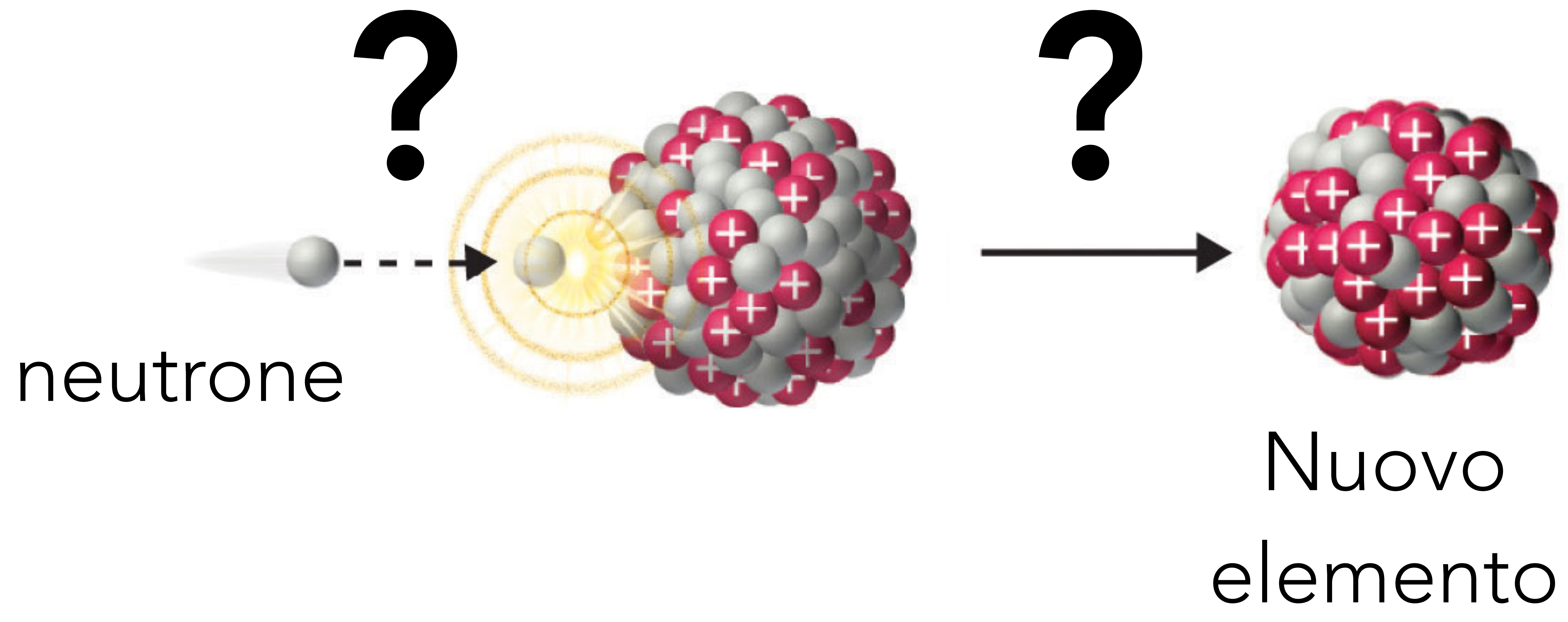
RADIOATTIVITÀ ARTIFICIALE

Fermi pensa di bombardare i nuclei con neutroni,
invece che con particelle alfa



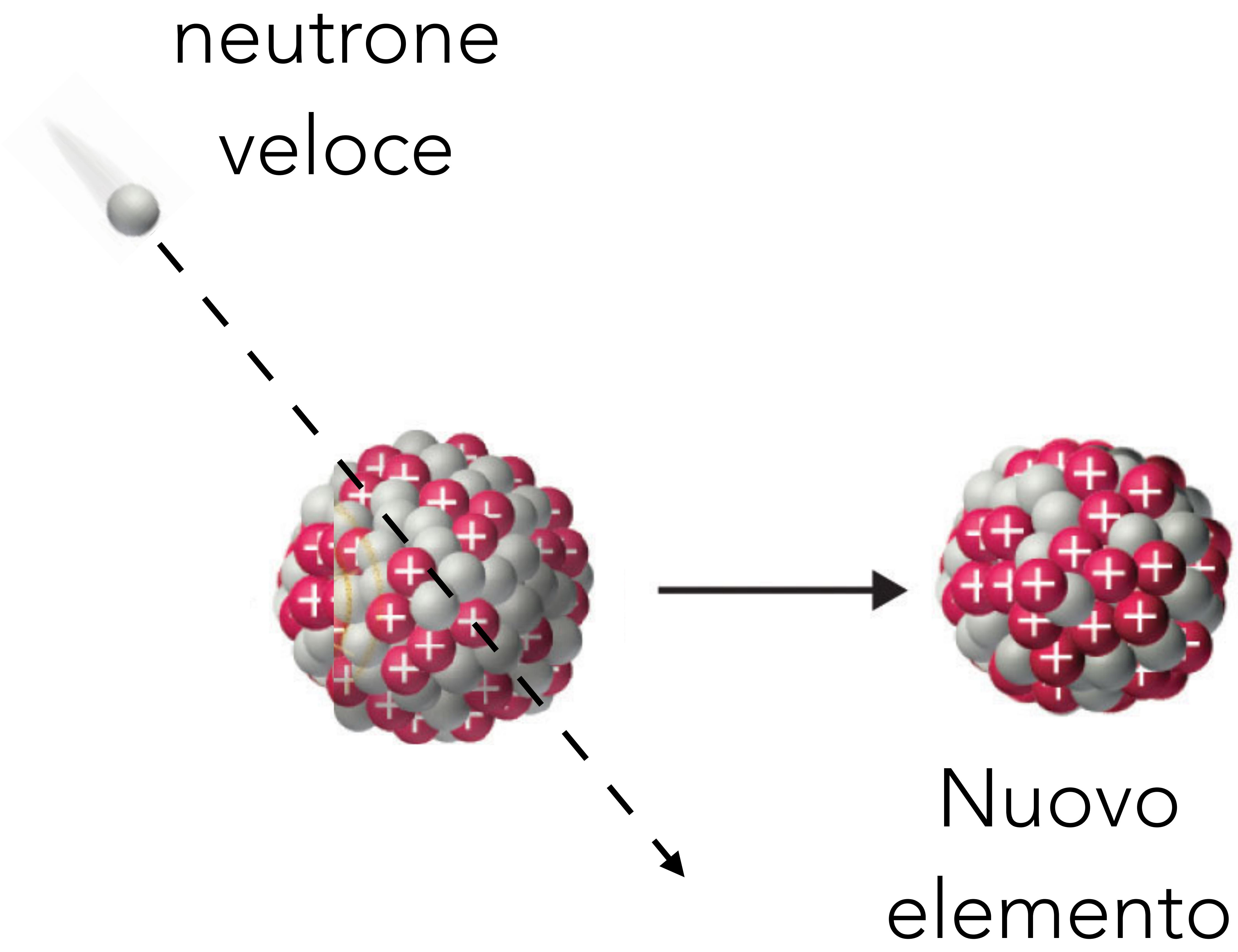
LA SCOPERTA DEI "NEUTRONI LENTI"

L'intensità e il tipo di radioattività indotta sembravano variare da un tentativo all'altro e soprattutto sembravano dipendere dal tavolo dove si svolgeva l'esperimento.



LA SCOPERTA DEI "NEUTRONI LENTI"

«No quello che voglio qui non è un pezzo di piombo, ma uno di paraffina!»



LA SCOPERTA DEI "NEUTRONI LENTI"

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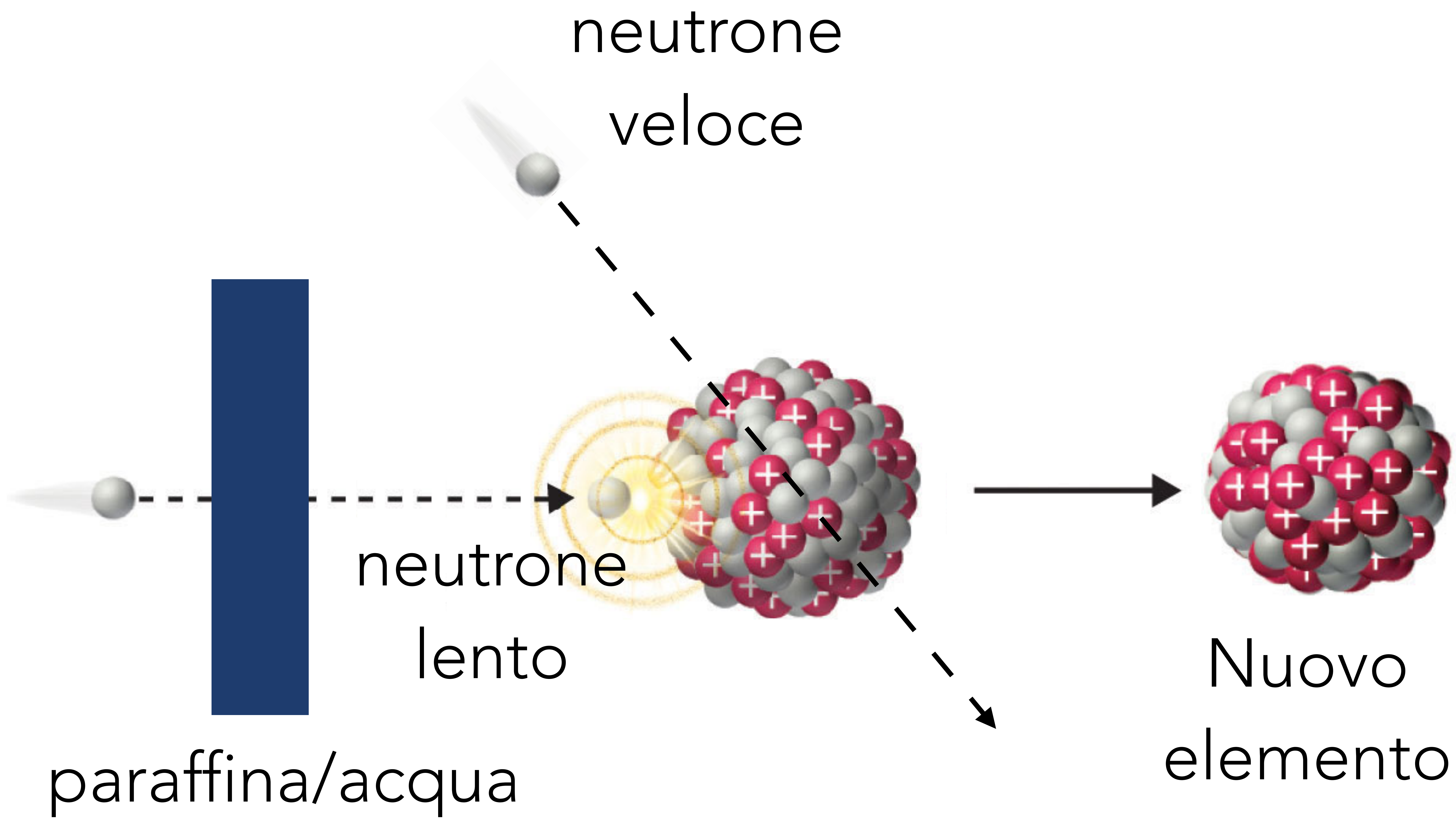
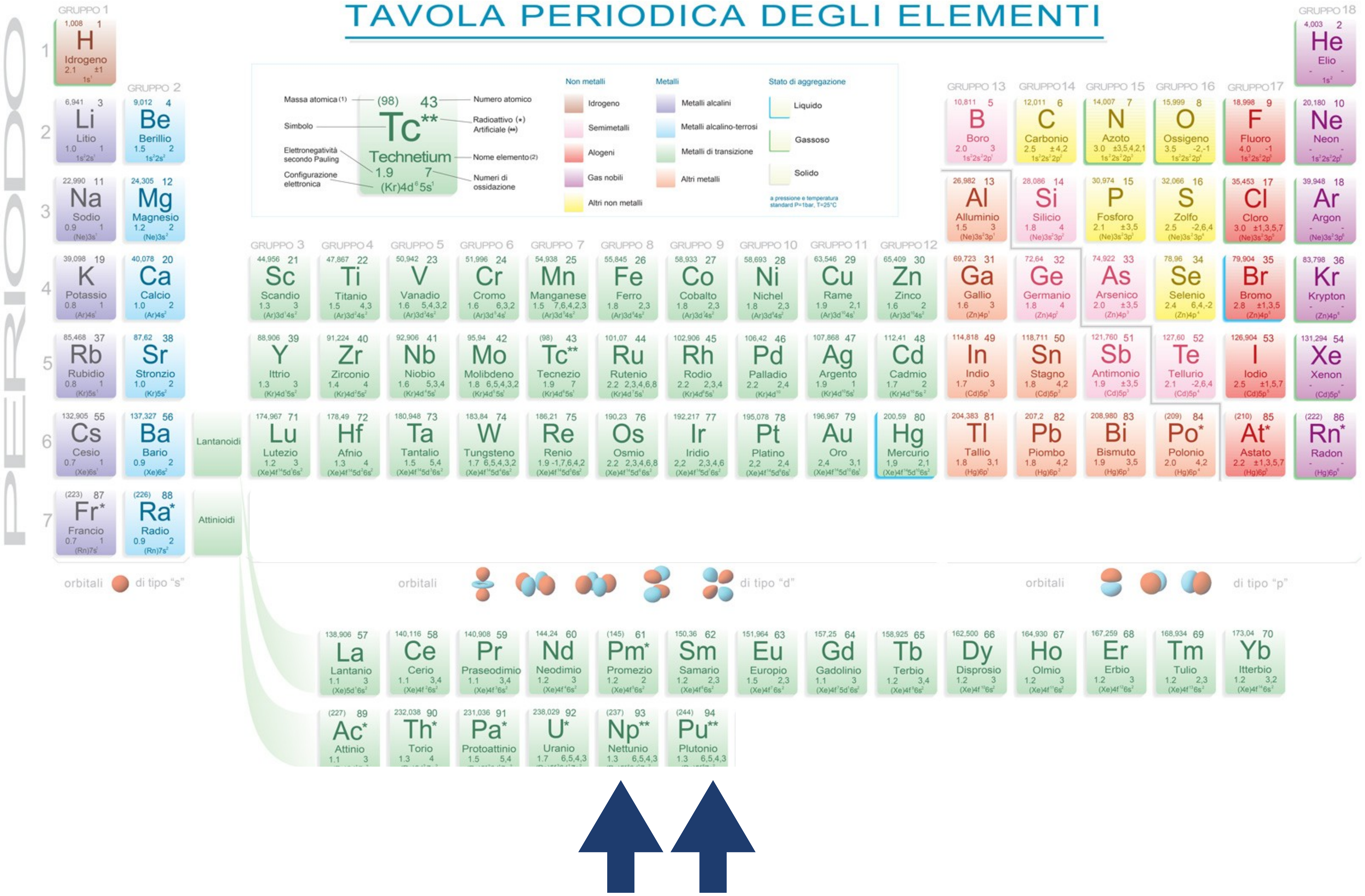
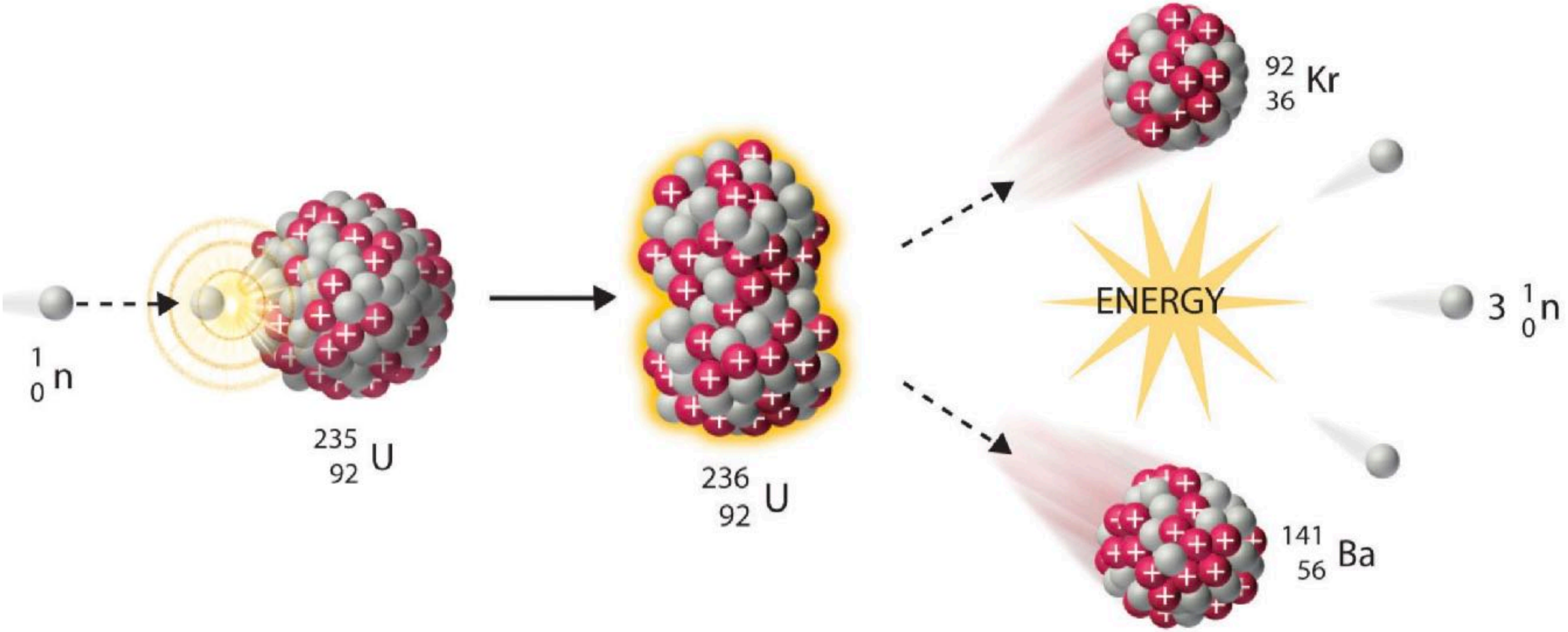


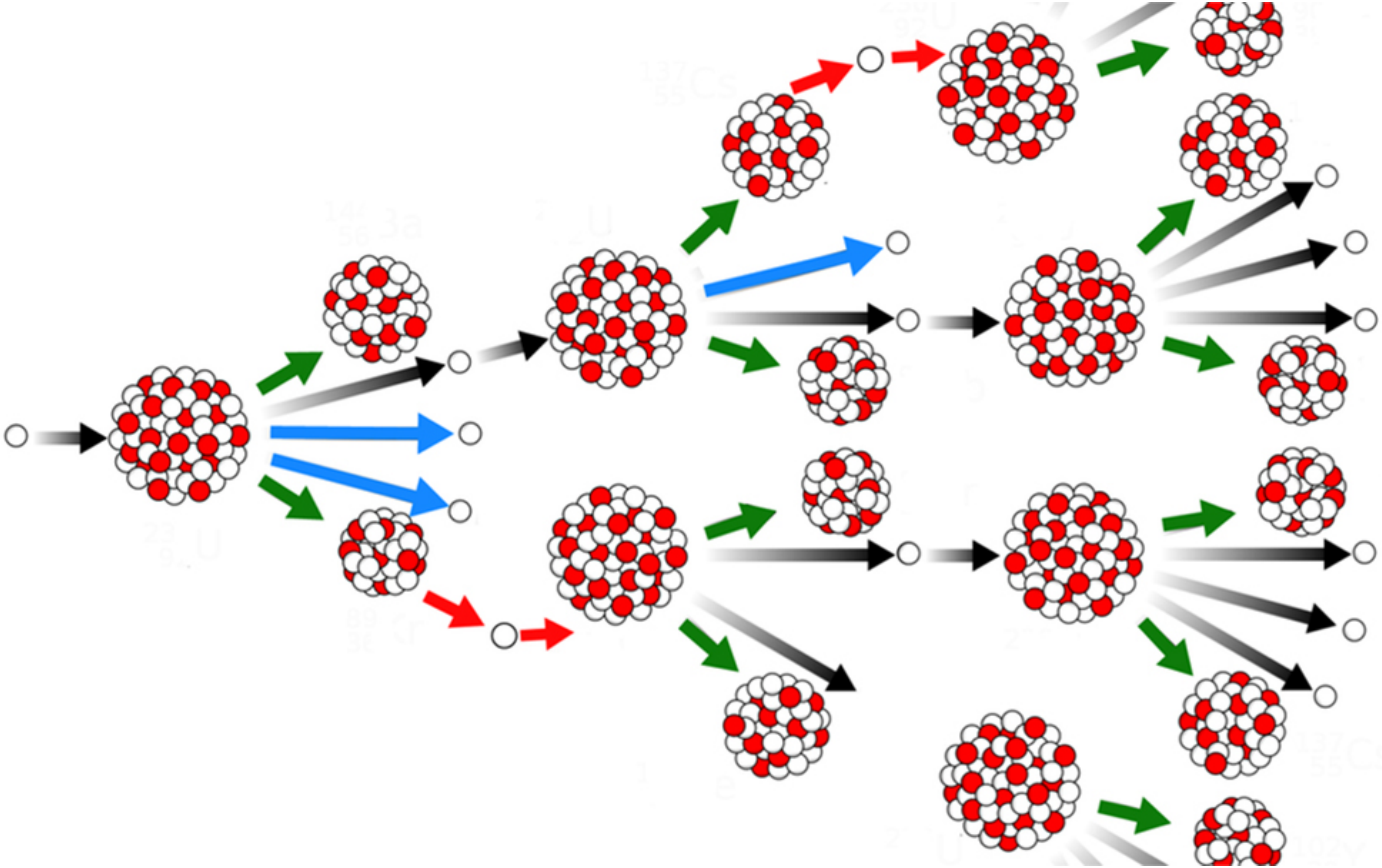
TAVOLA PERIODICA DEGLI ELEMENTI

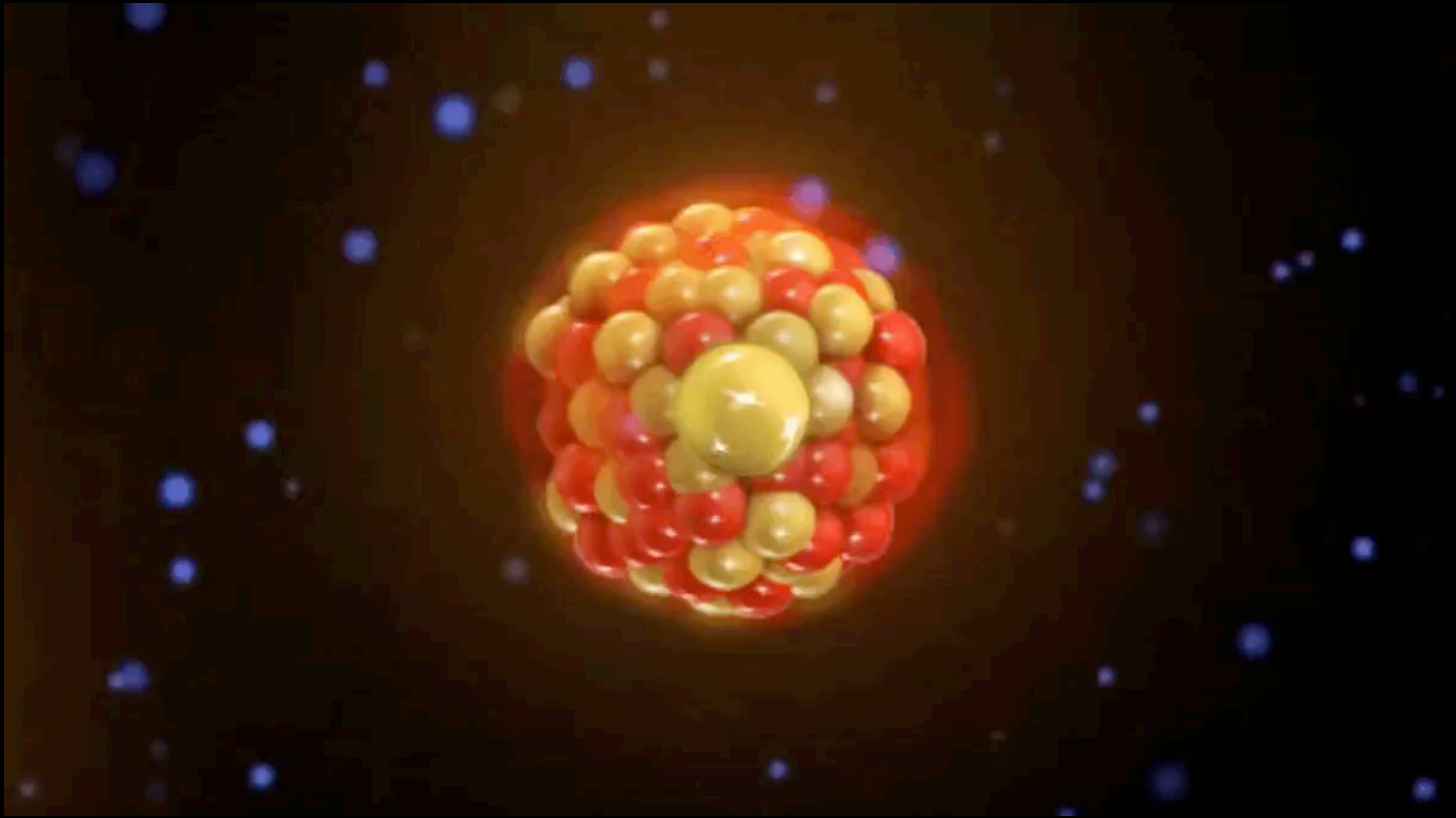


LA FISSIONE NUCLEARE



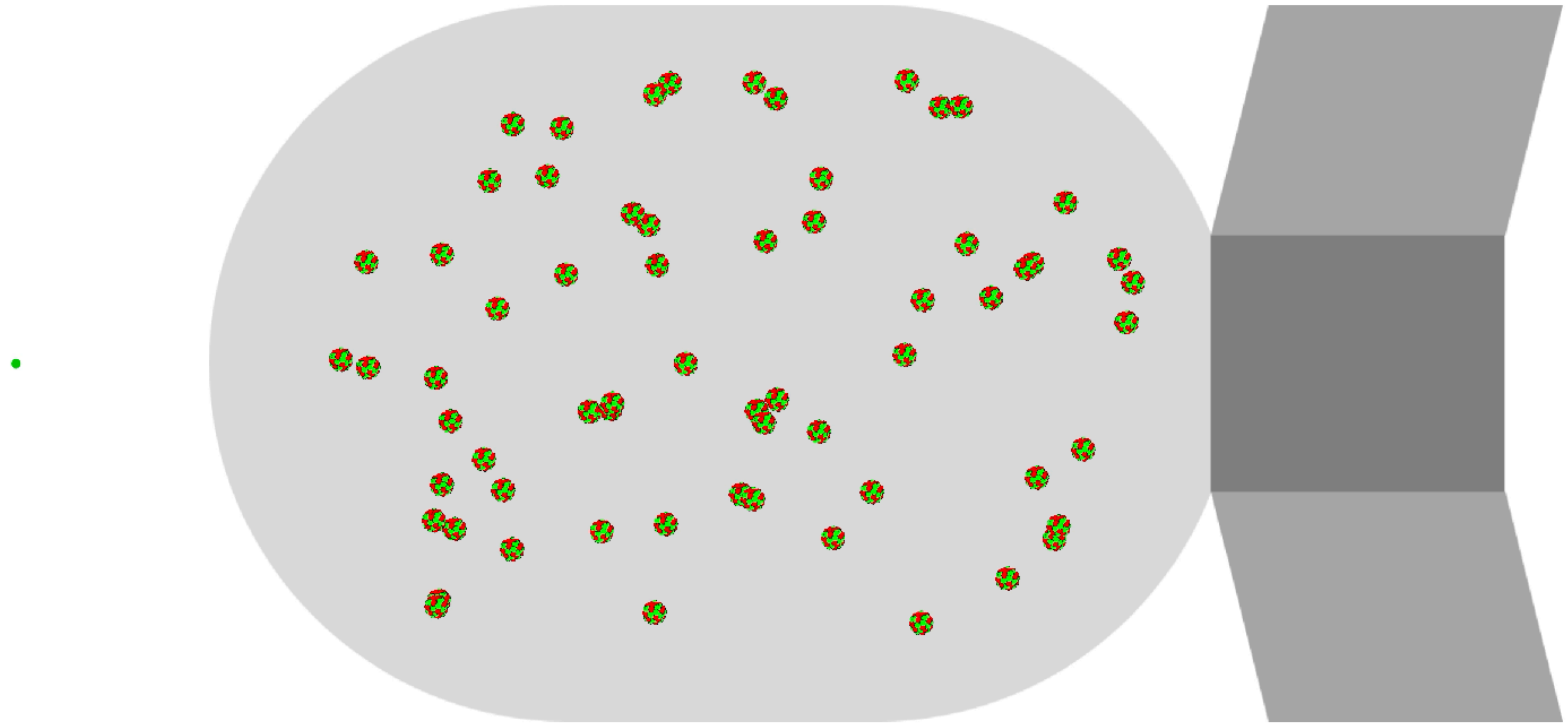
LA REAZIONE A CATENA





NUCLEAR CHAIN REACTION

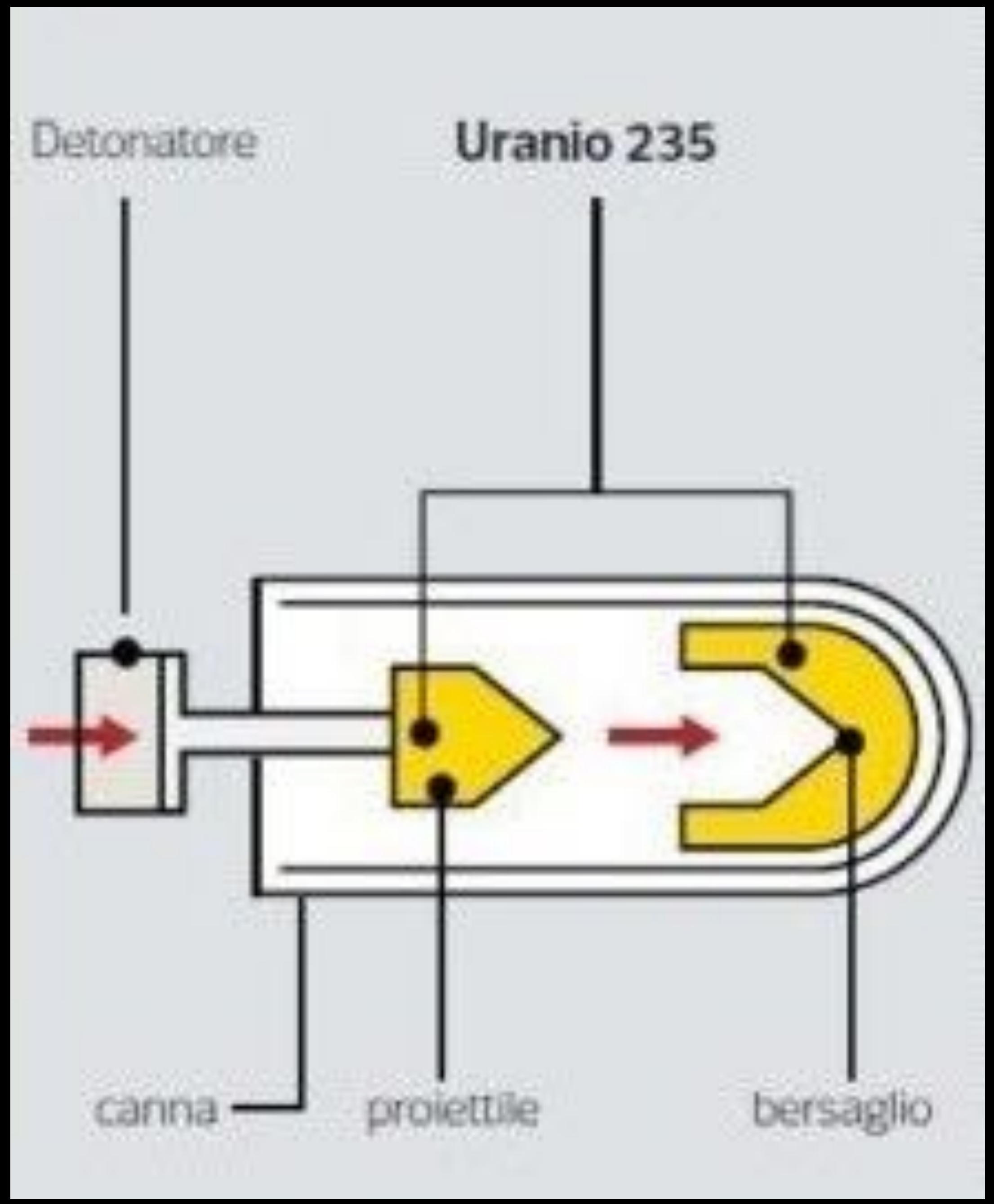
DongJoon | 2018-11-24 | Radioactivity Simulation



Concentration of Uranium-235 Run

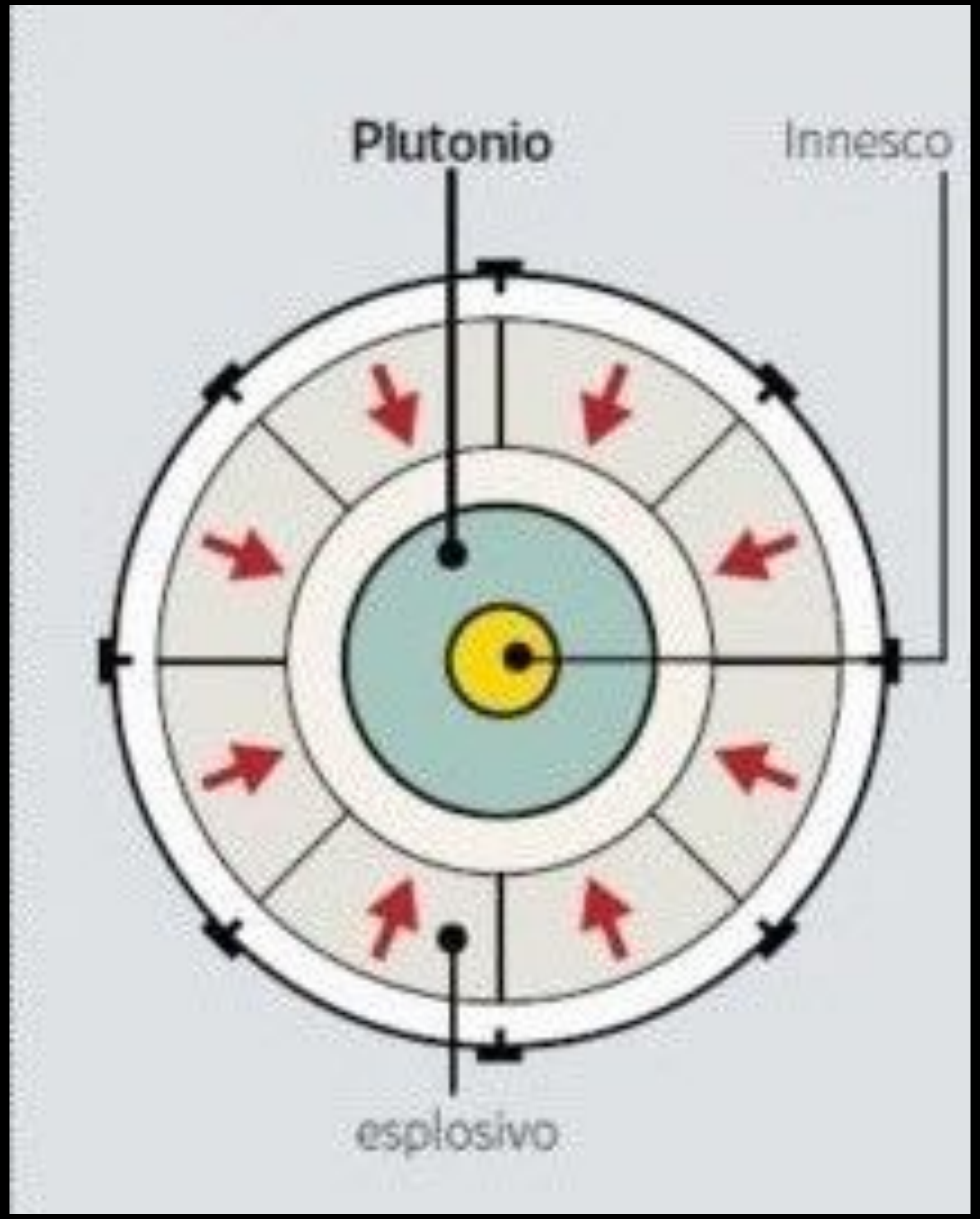
LA BOMBA ATOMICA

Uranio 235



Little Boy
(Hiroshima)

Plutonio



Fat Man
(Nagasaki)

“Trinity Test”, 16 luglio 1945

I quark

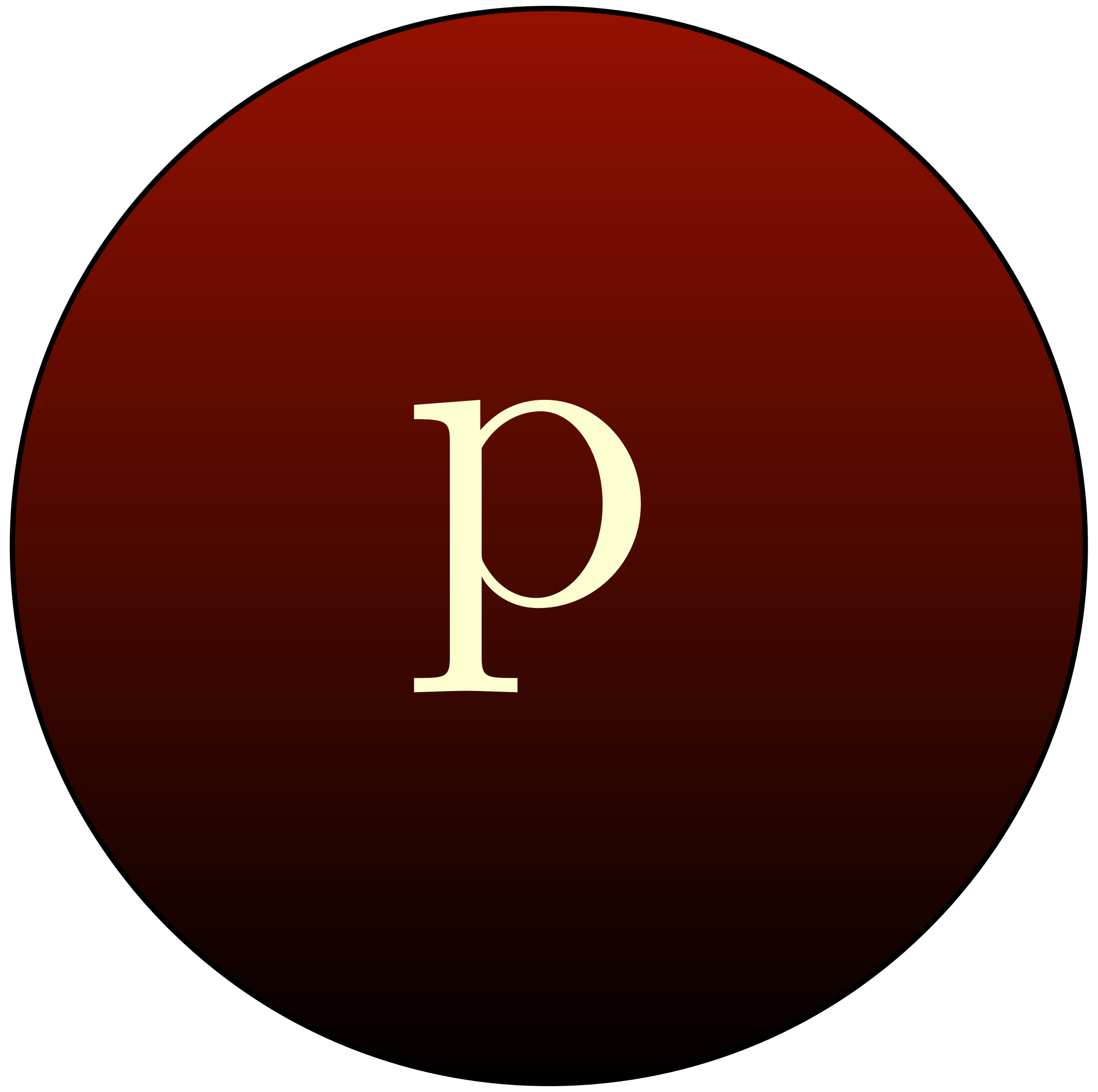
Identikit

Massa: $938.27\ \mathrm{MeV}$ / $1.6726 \times 10^{-27}\,\mathrm{kg}$

$$E = mc^2$$

Carica: $+e$

Spin: $1/2$

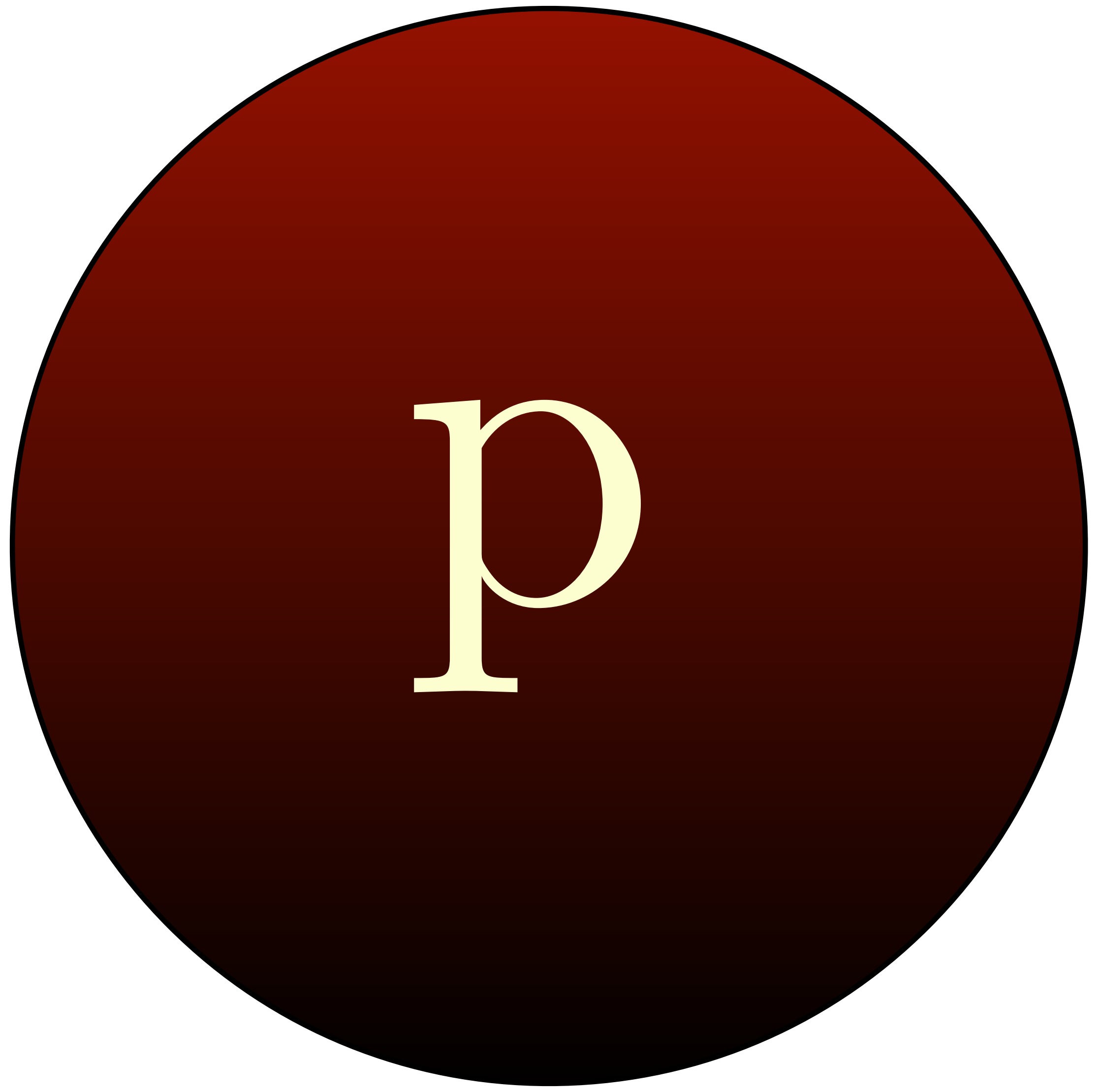


Identikit

Massa: 939.56 / 938.27 MeV

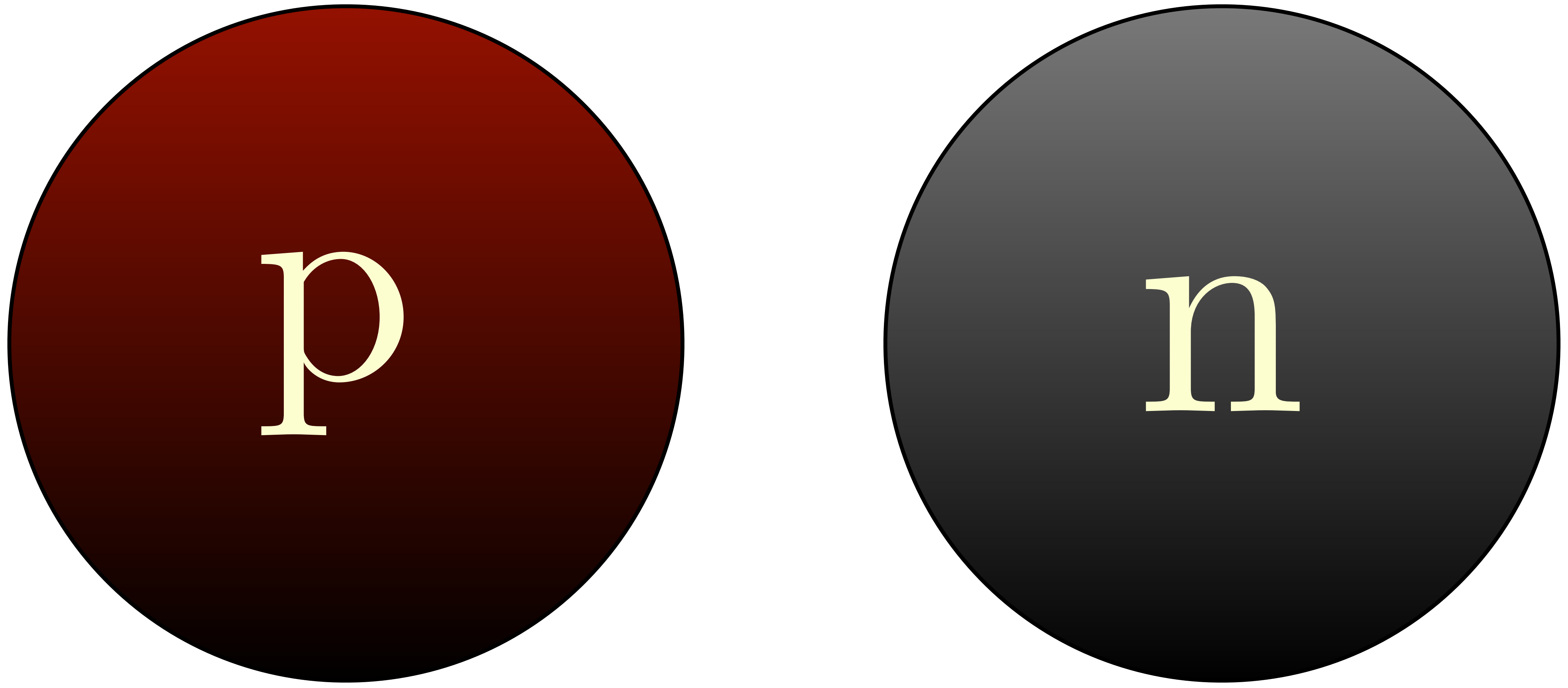
Carica: 0 / $+e$

Spin: $1/2$

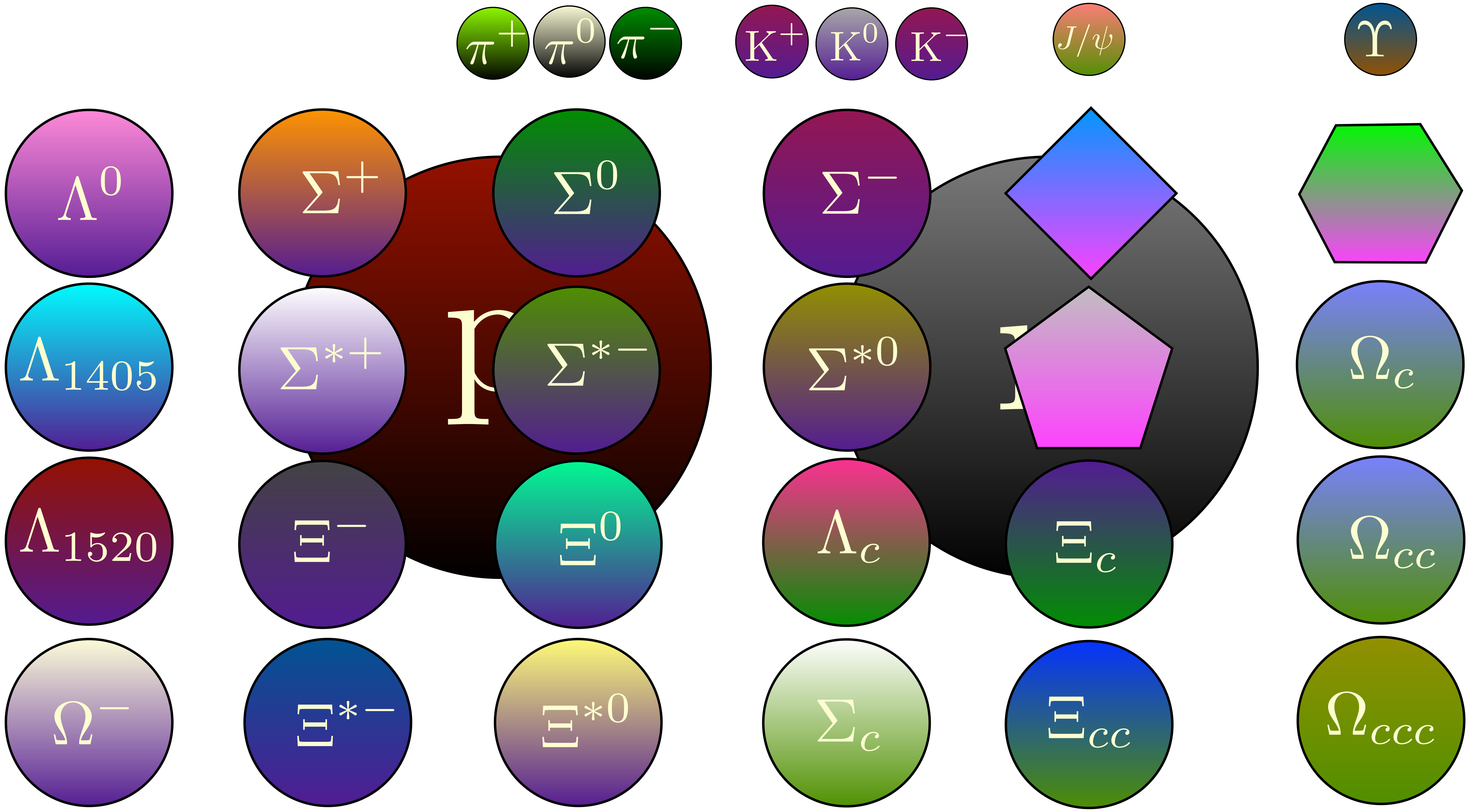


	p	n
Carica:	$+e$	0
Massa:	938.27 MeV	939.56 MeV
Spin:	$1/2$	$1/2$

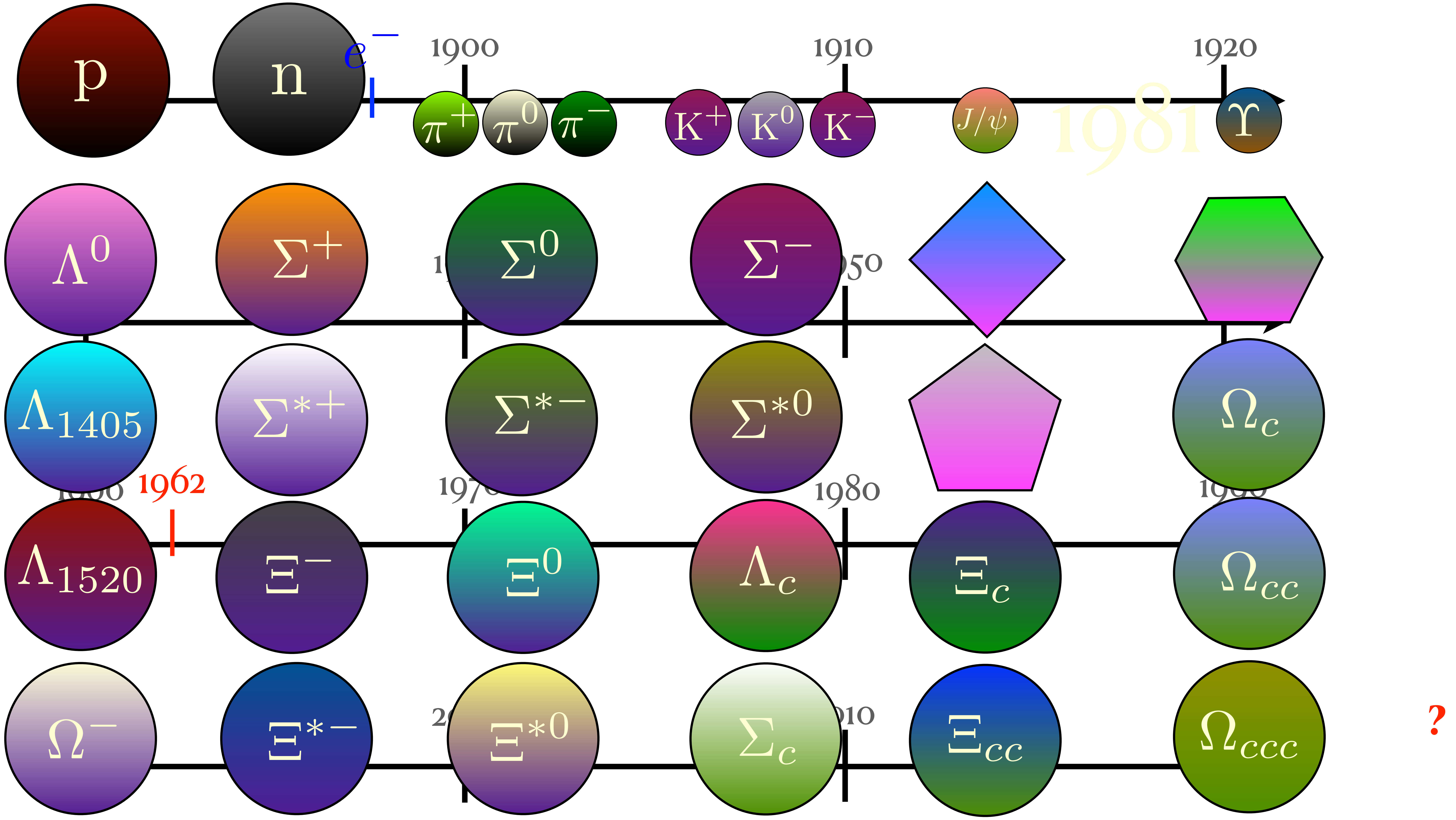
Esistono particelle simili?



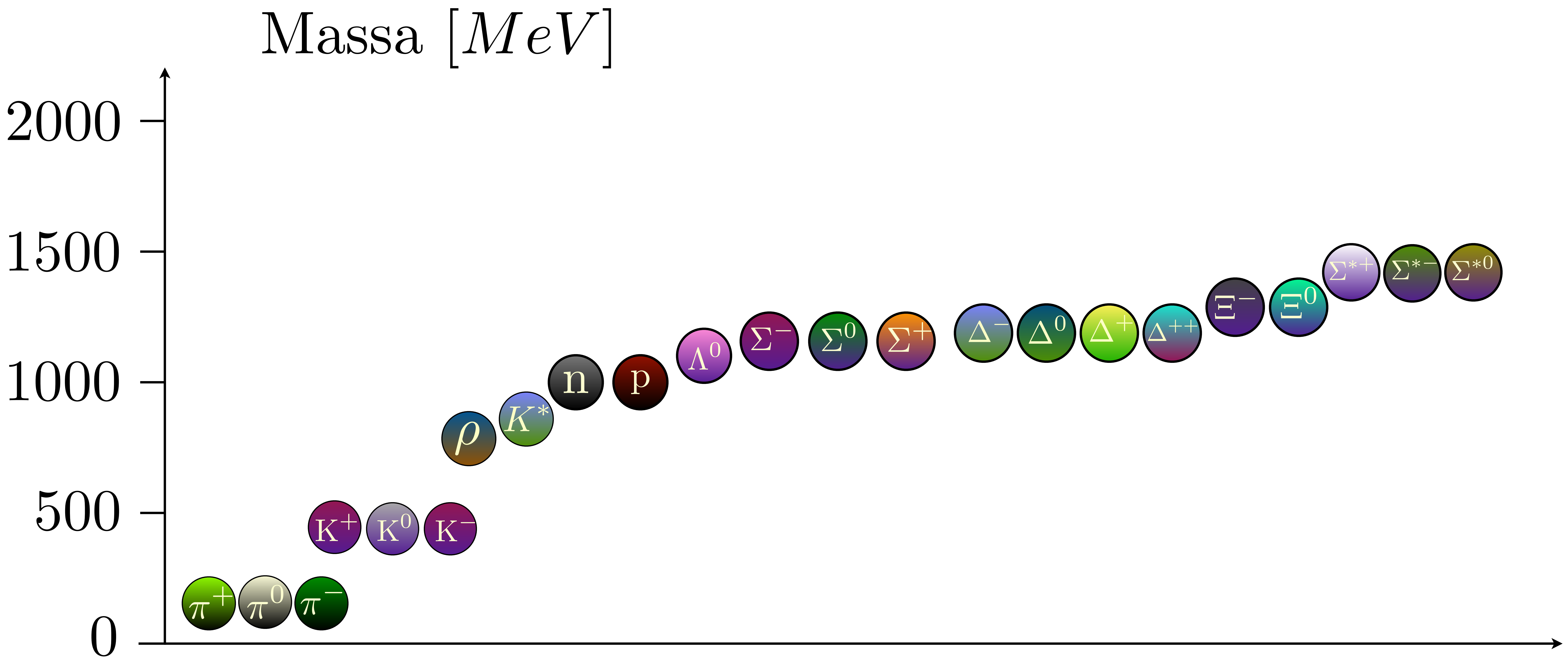
Esistono particelle simili?



Uno “zoo” di particelle



Uno "zoo" di particelle



Modello a quark

1969: “Per i suoi contributi e le sue scoperte riguardo alla classificazione delle particelle elementari e le loro interazioni”

Le particelle elementari che costituiscono gli adroni sono detti quark.

I quark esistono in tre “sapori” diversi: up, down, strange

I quark sono dotati di una carica di “colore”

Ogni quark ha il suo antiquark

I quark

u

$$+\frac{2}{3}e$$

d

$$-\frac{1}{3}e$$

s

$$-\frac{1}{3}e$$

Gli antiquark

$\bar{u}$

$\bar{d}$

$\bar{s}$

$-\frac{2}{3}e$

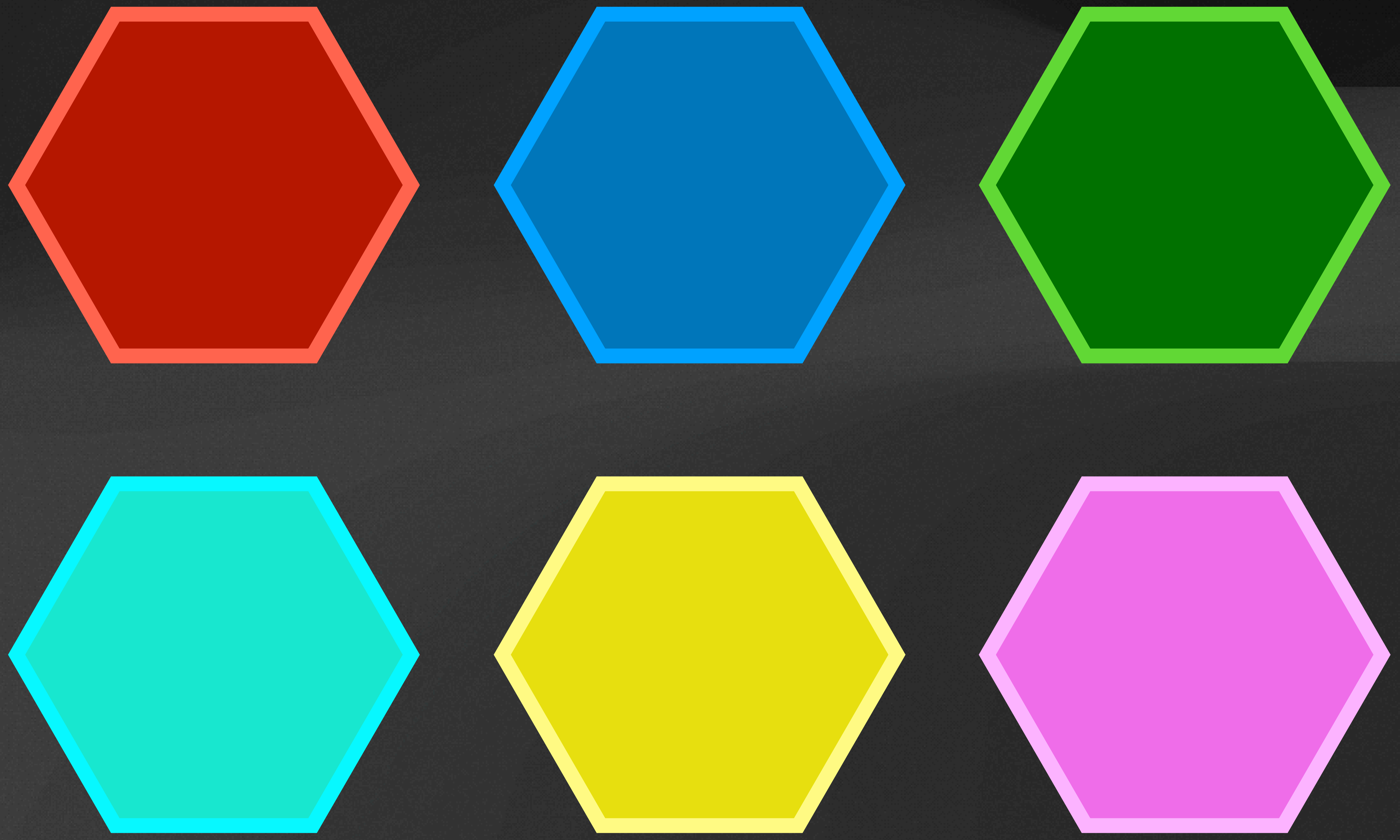
$+\frac{1}{3}e$

$+\frac{1}{3}e$

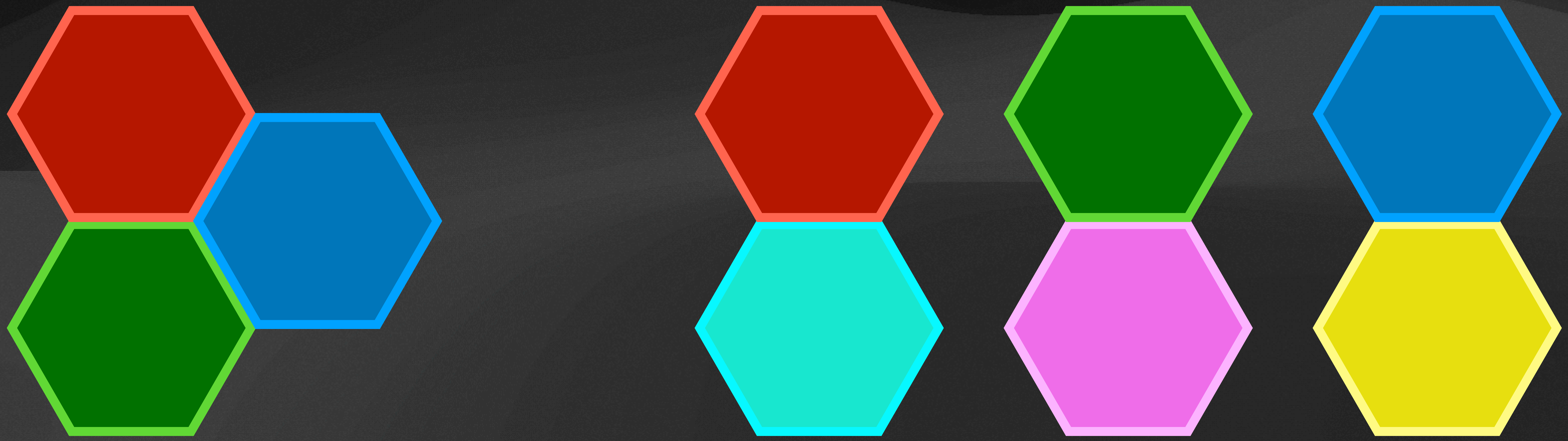
Carica di colore

quark

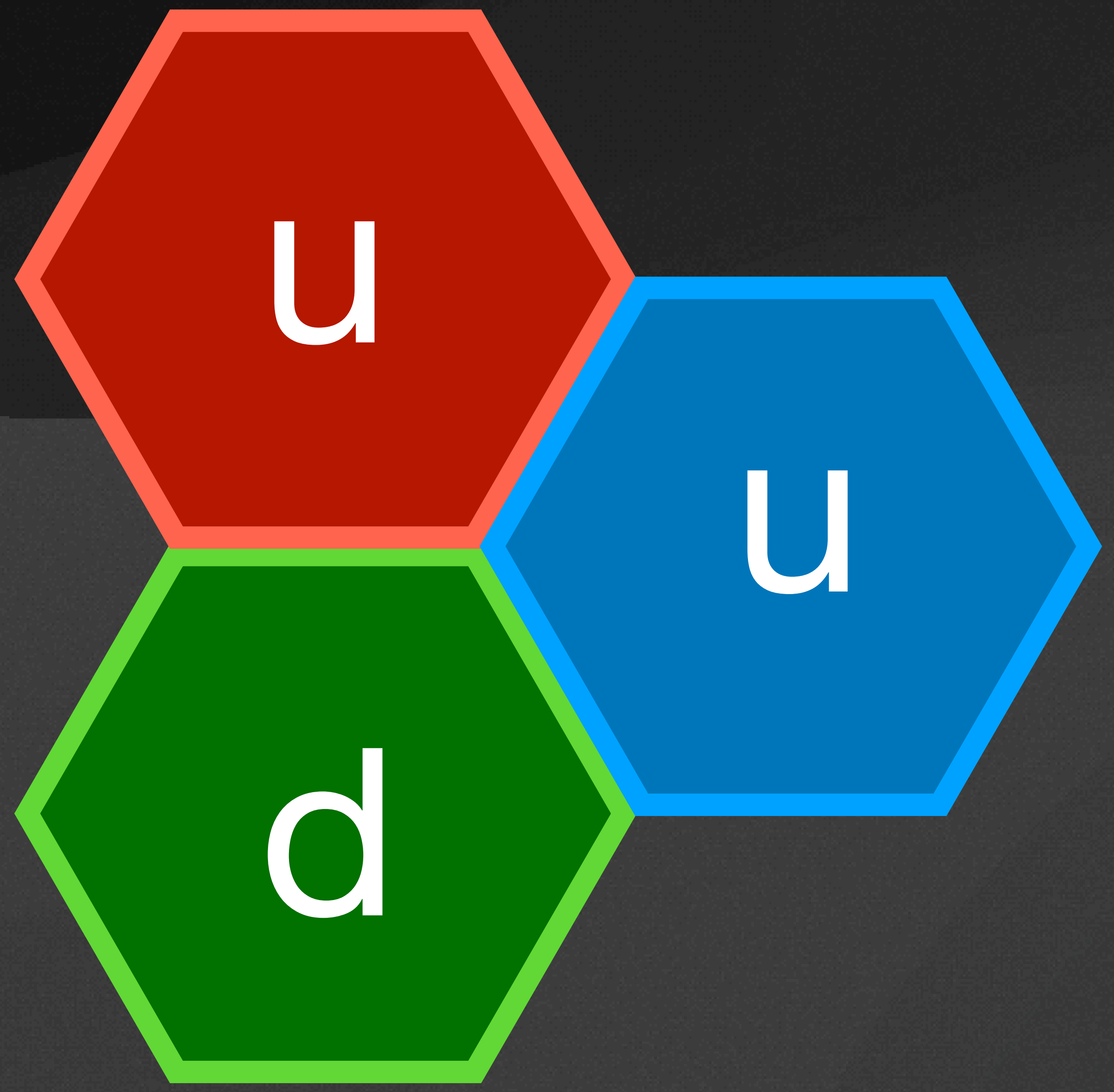
antiquark

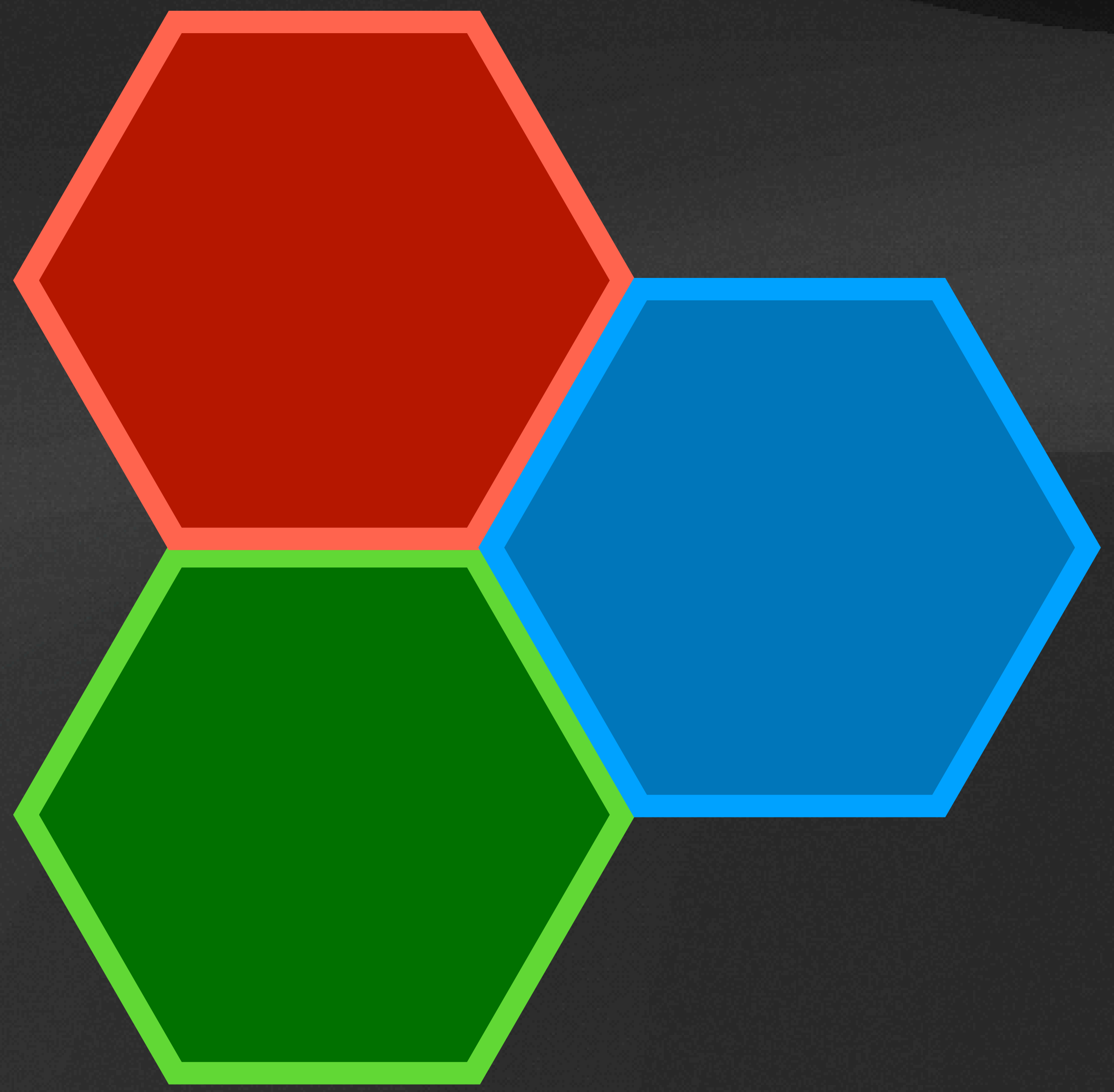


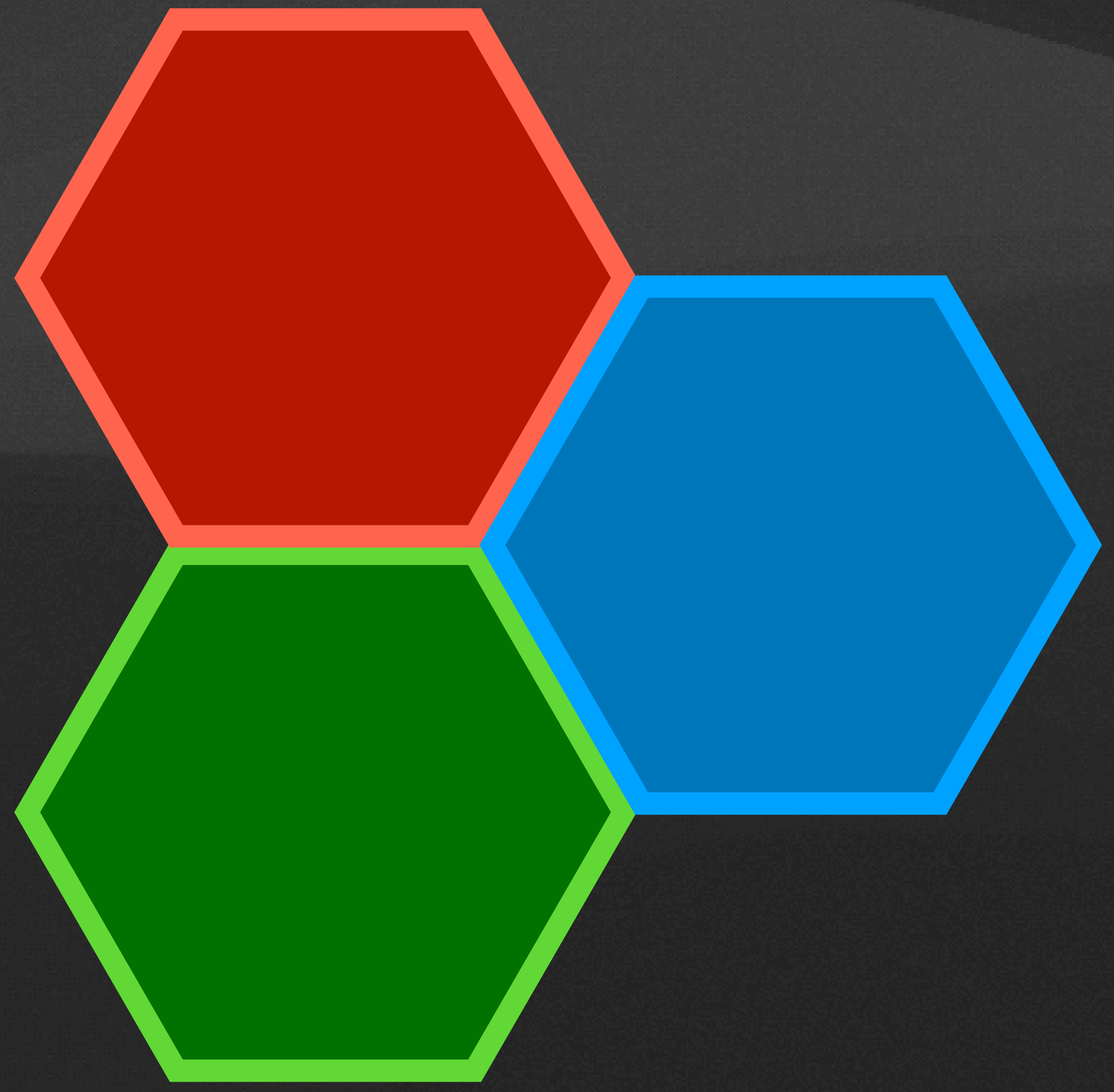
Combinazioni per fare il “bianco”



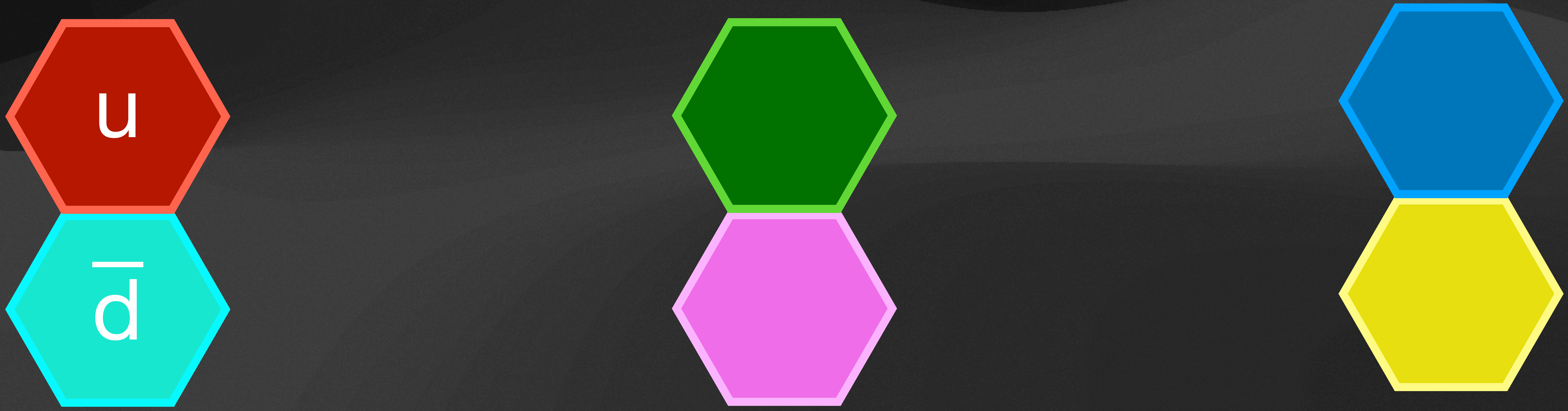
Esempi di “triquark”







Esempi di “biquark”

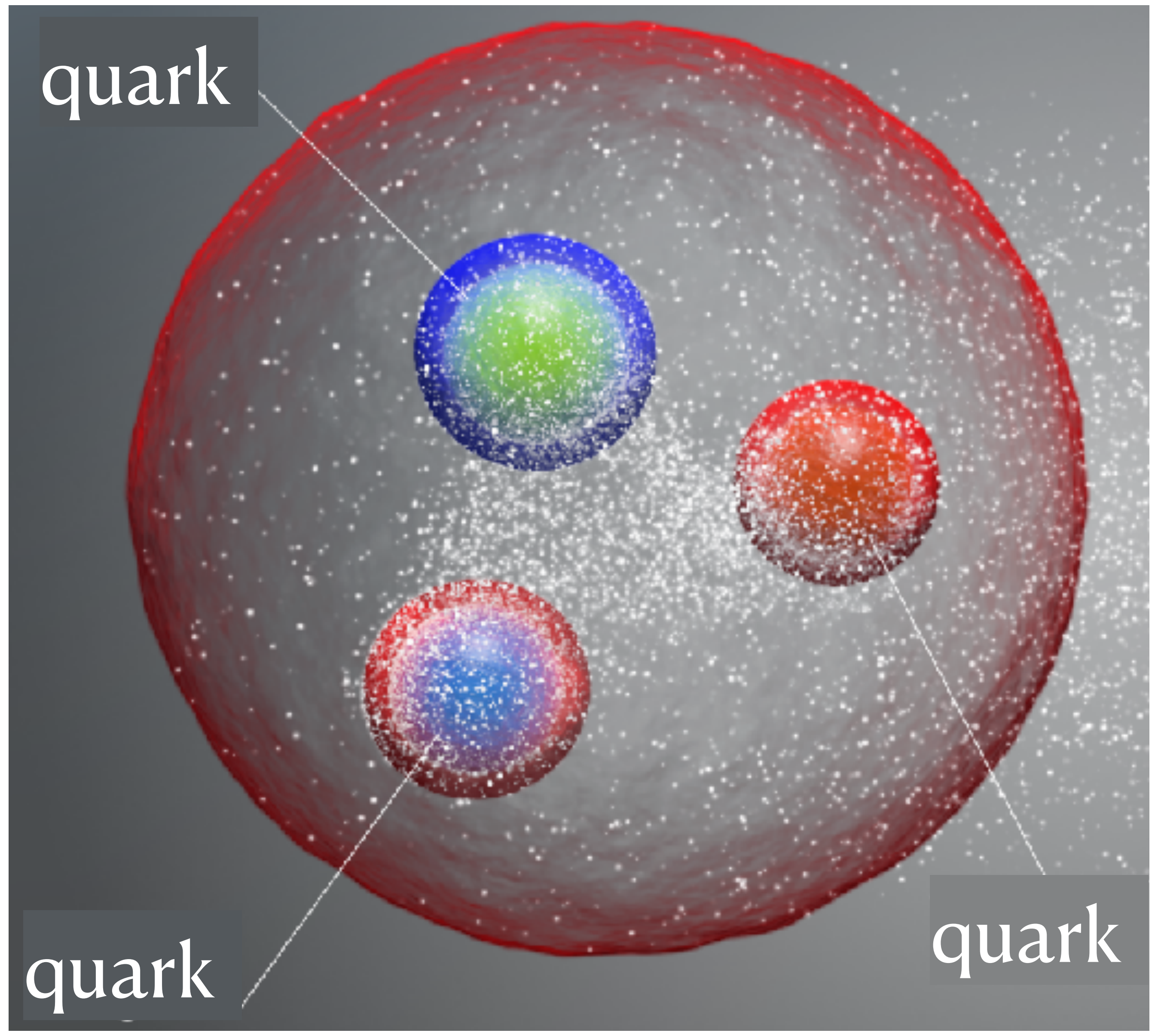


Gli adroni

Sono particelle composte da una certa combinazione di quarks

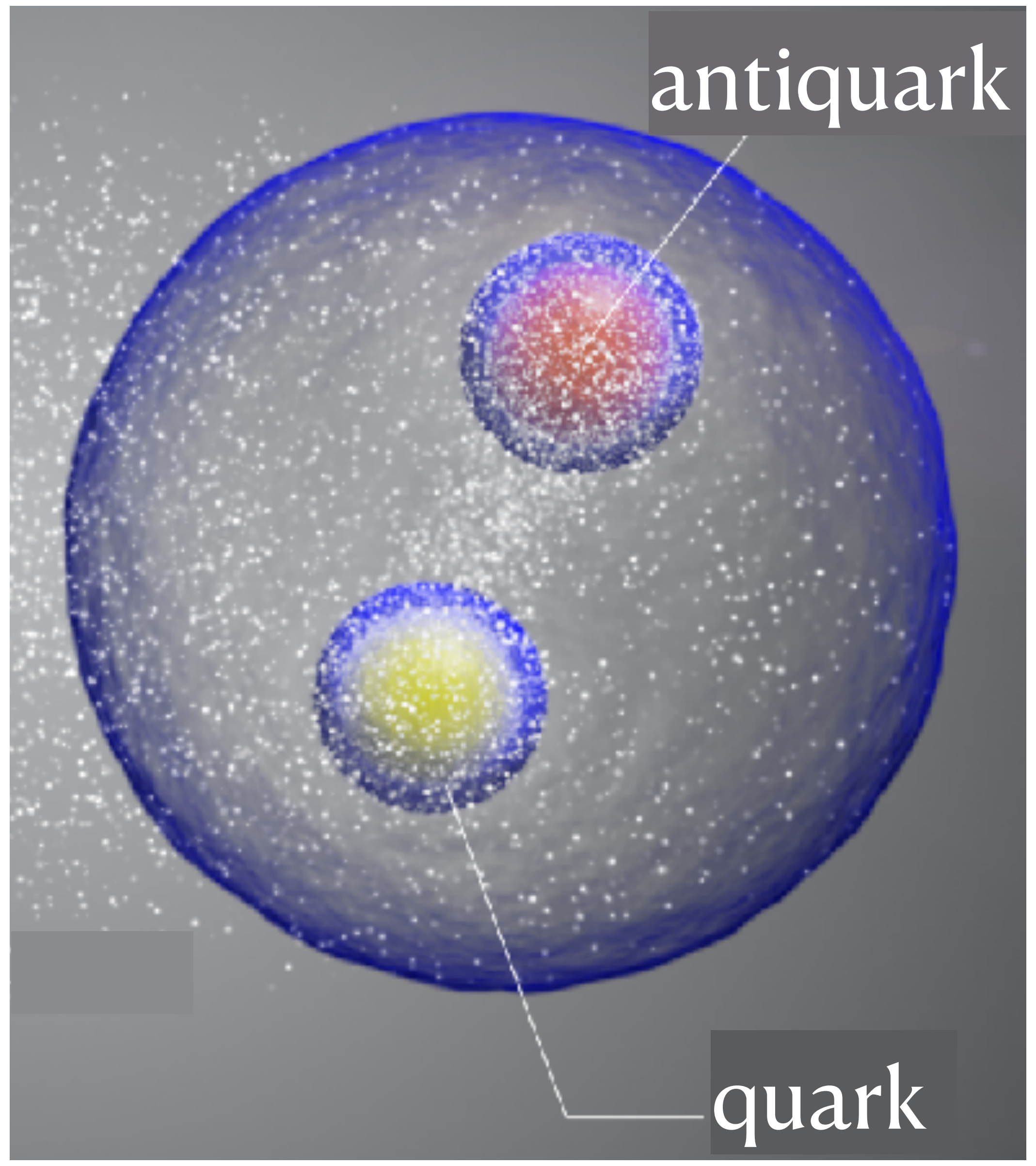
BARIONI

Statistica di Fermi-Dirac

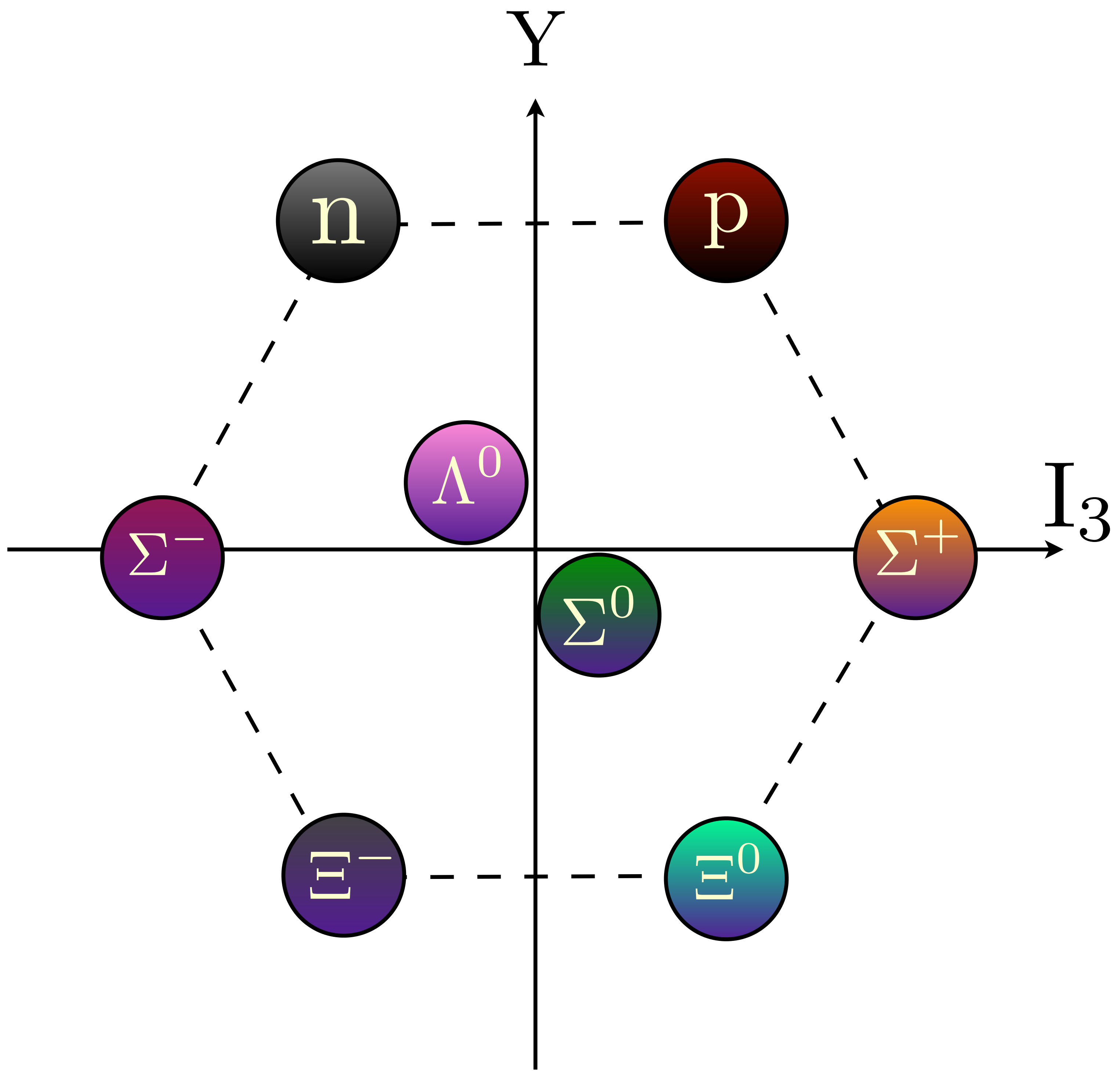


MESONI

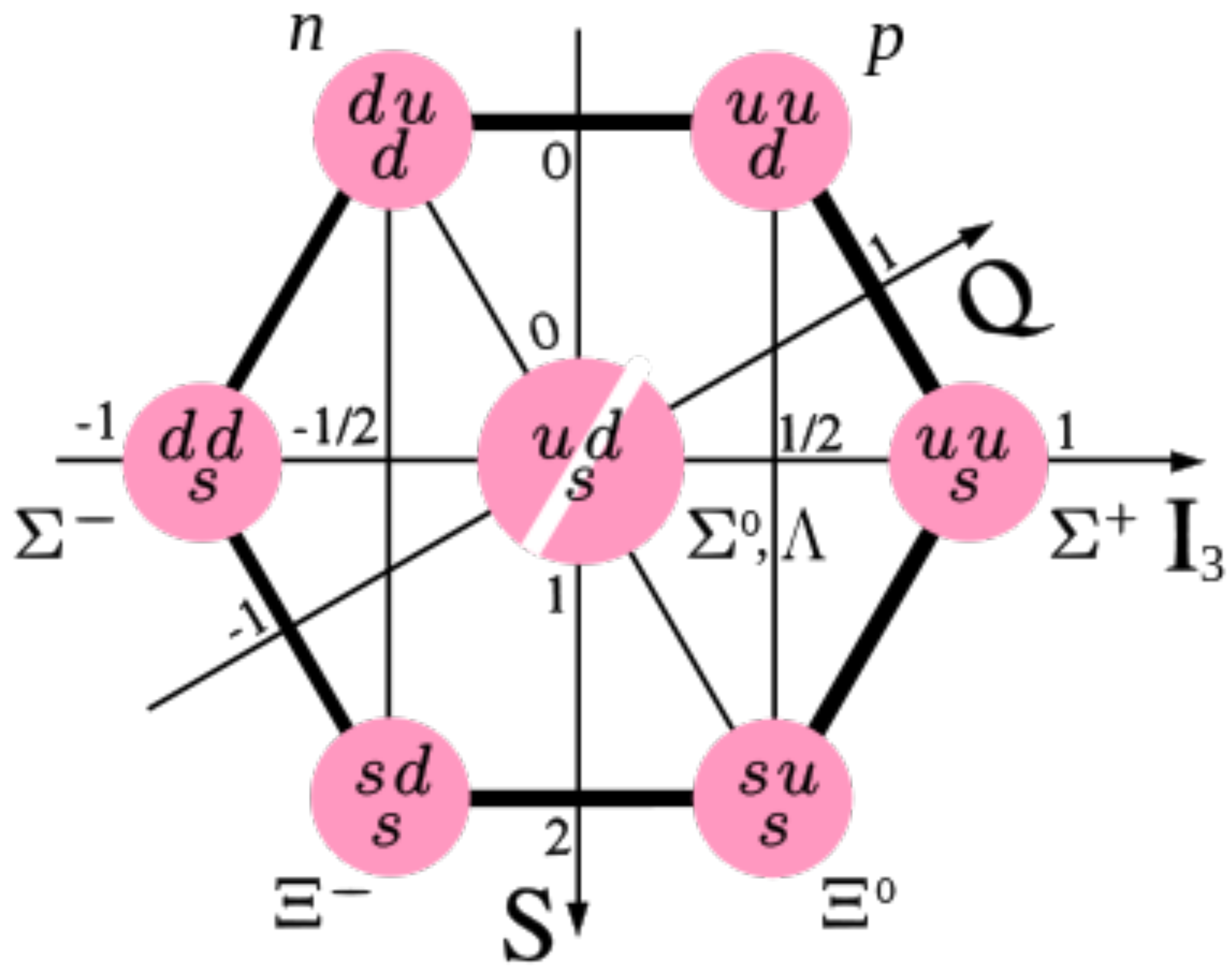
Statistica di Bose-Einstein



BARIONI

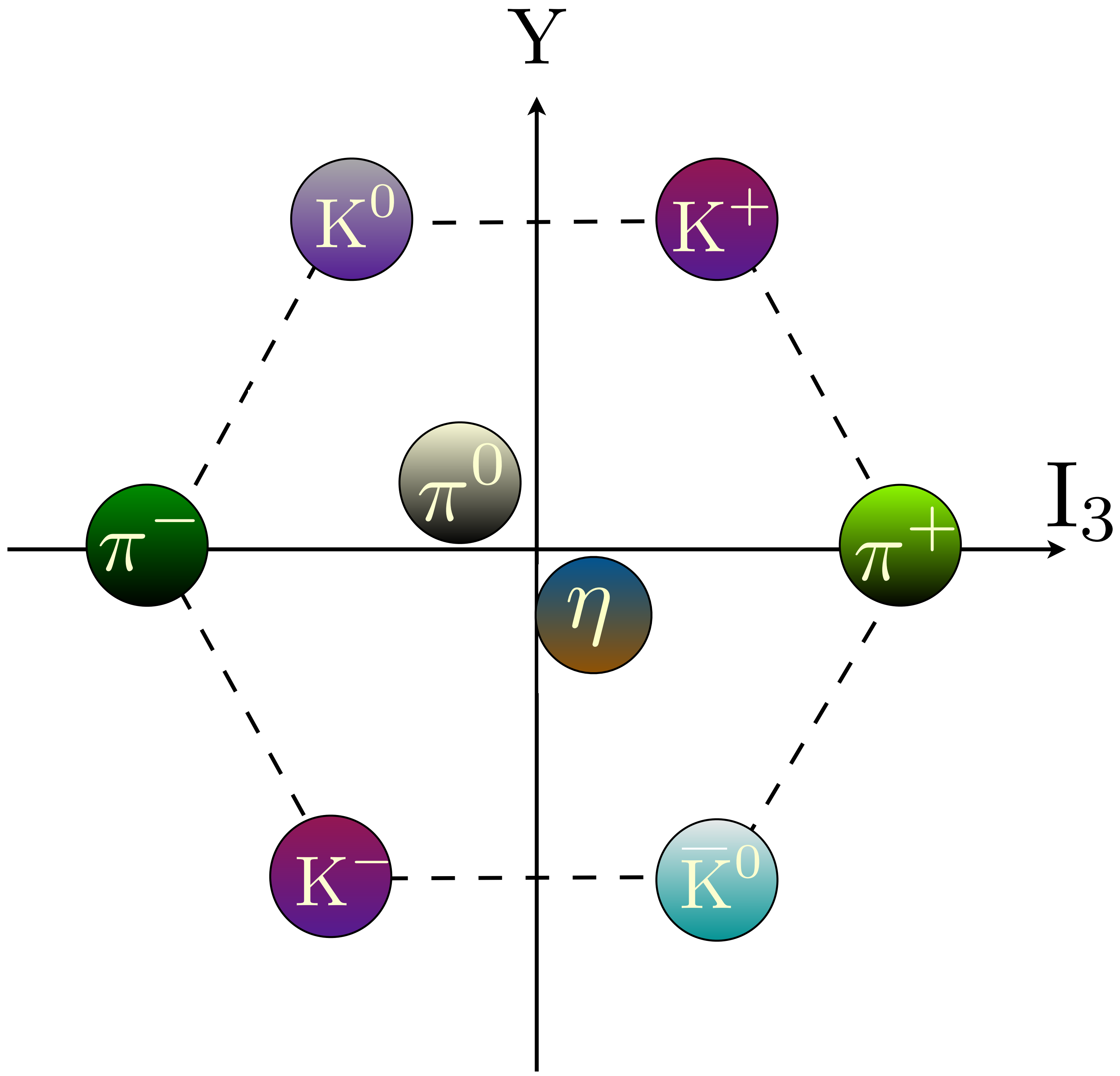


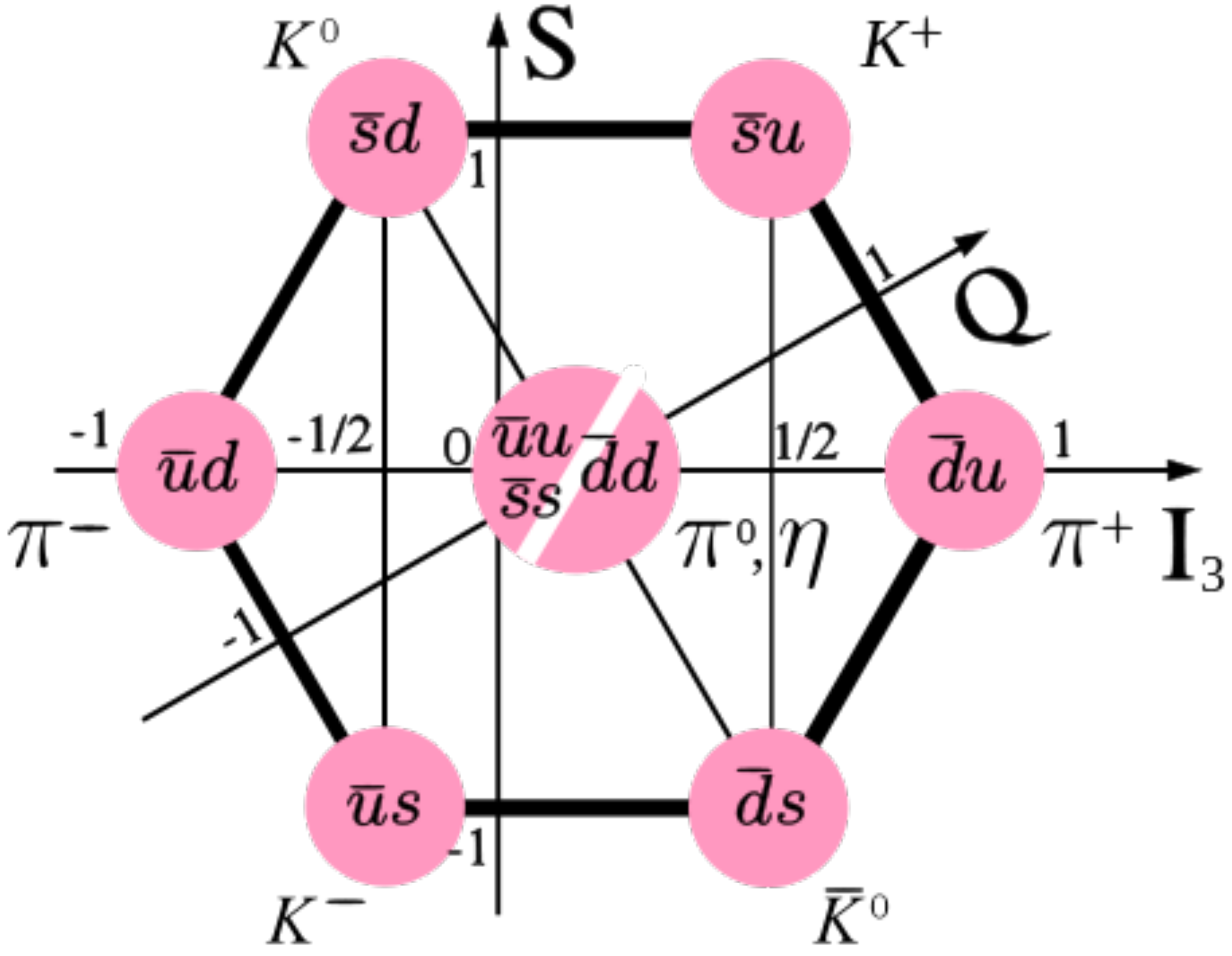
Y
n
p
Λ0
Σ−
Σ+
I3
Σ0
Ξ−
Ξ0



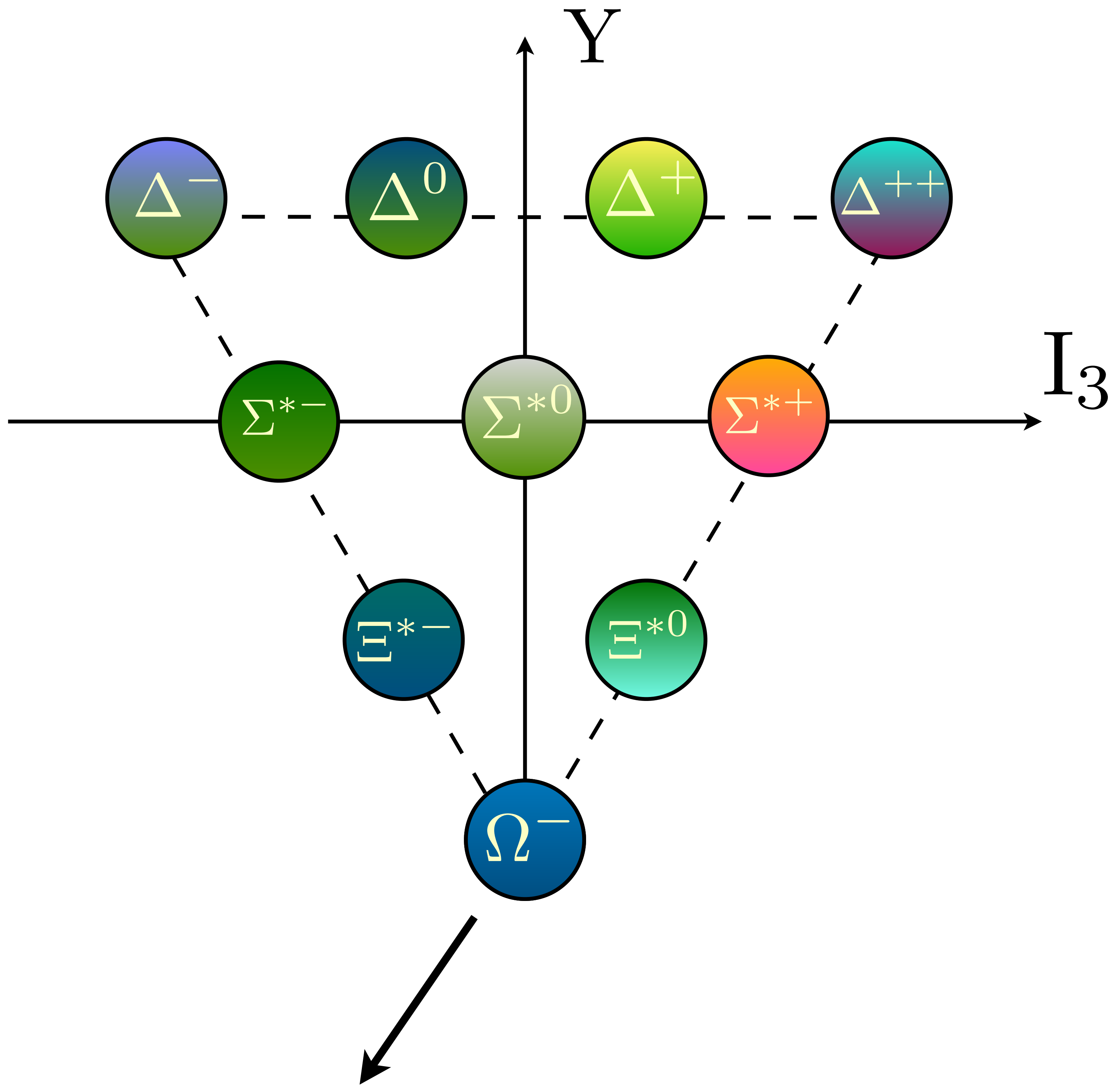
n
p
du d
uu d
0
0
1
Q
-1
dd s
-1/2
ud s
1/2
uu s
1
Σ−
Σ0, Λ
Σ+
I3
1
-1
sd s
su s
2
Ξ−
S
Ξ0

MESONI

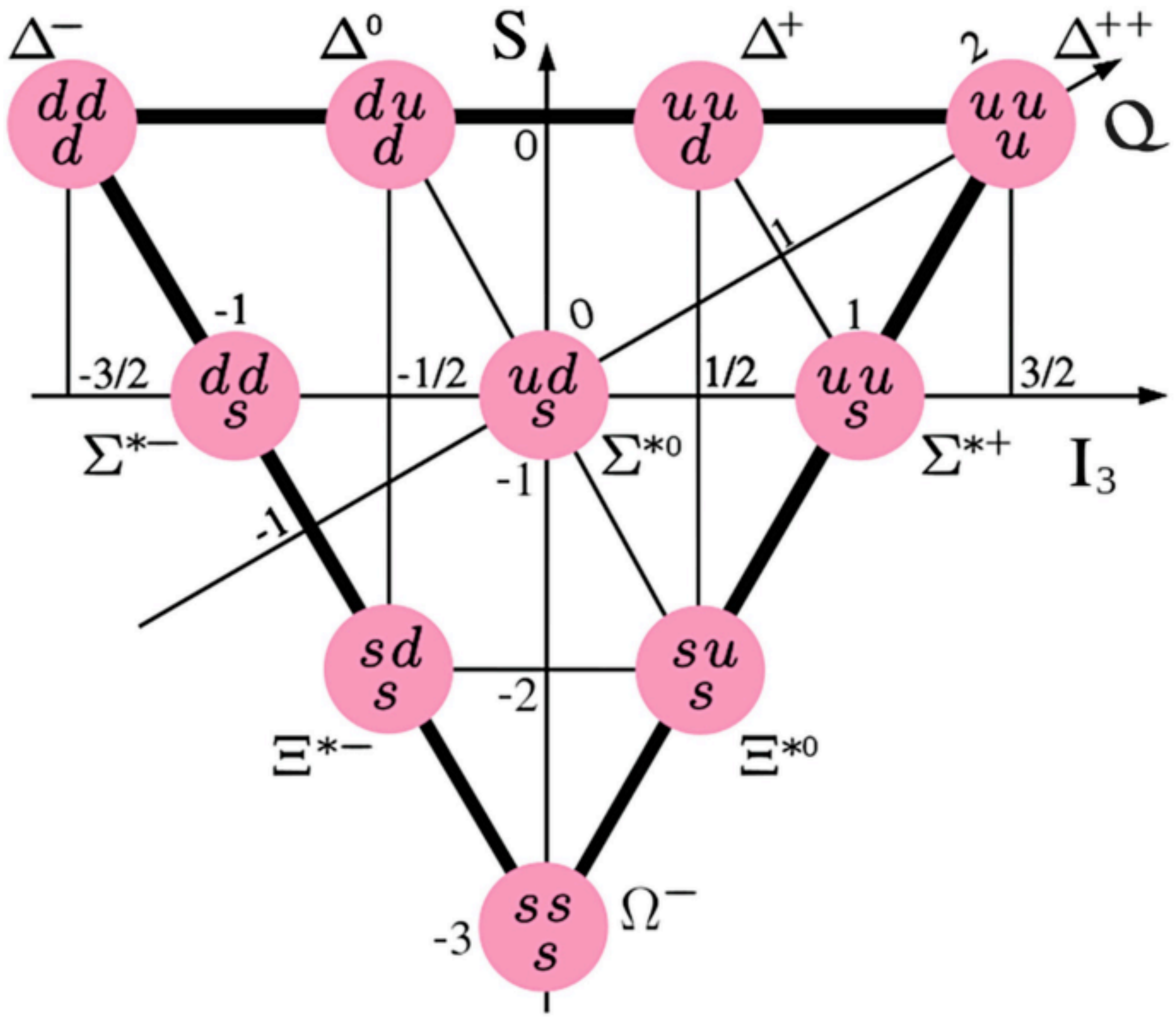

Y
K^0
K^+
π^0
π^-
π^+
I_3
η
K^-
$\bar{K}^0$

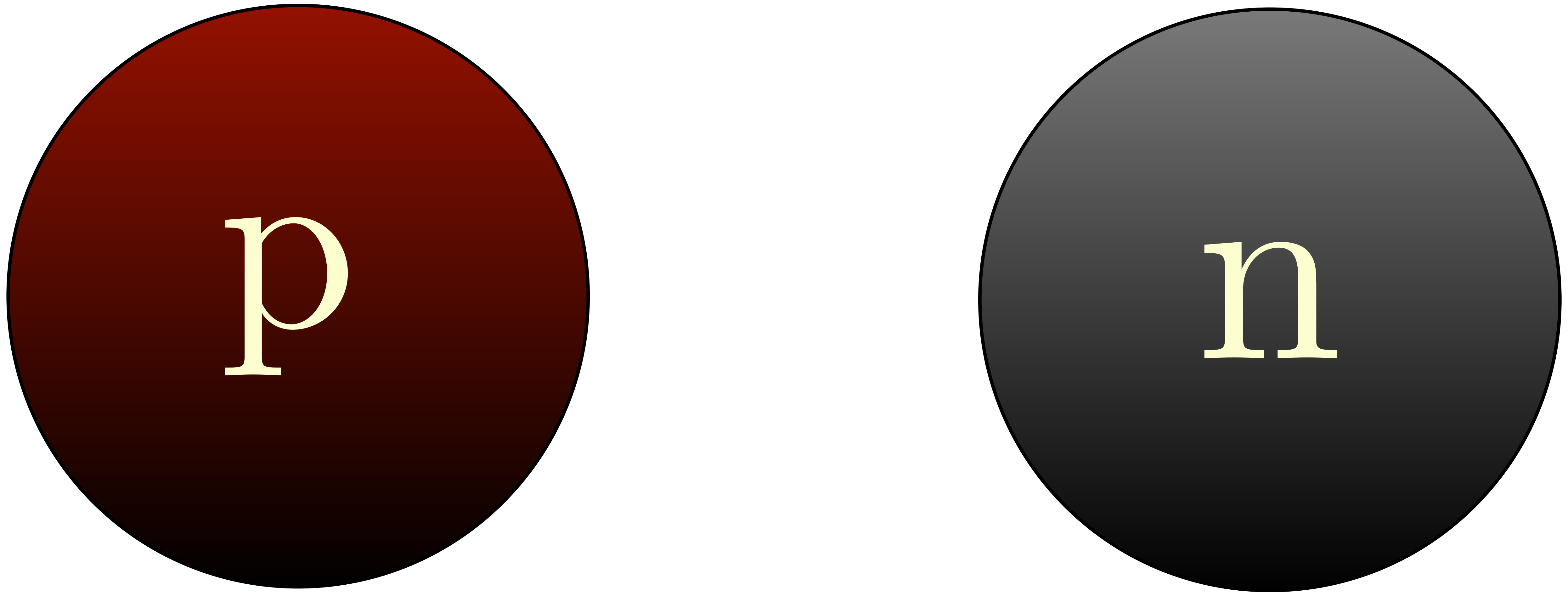

K^0
S
K^+
$\bar{s}d$
$\bar{s}u$
1
Q
-1
-1/2
0
1/2
1
$\bar{u}d$
$\bar{u}u$
$\bar{s}s$
$\bar{d}d$
$\bar{d}u$
π^-
π^0, η
π^+
I_3
-1
$\bar{u}s$
$\bar{d}s$
K^-
$\bar{K}^0$

BARIONI



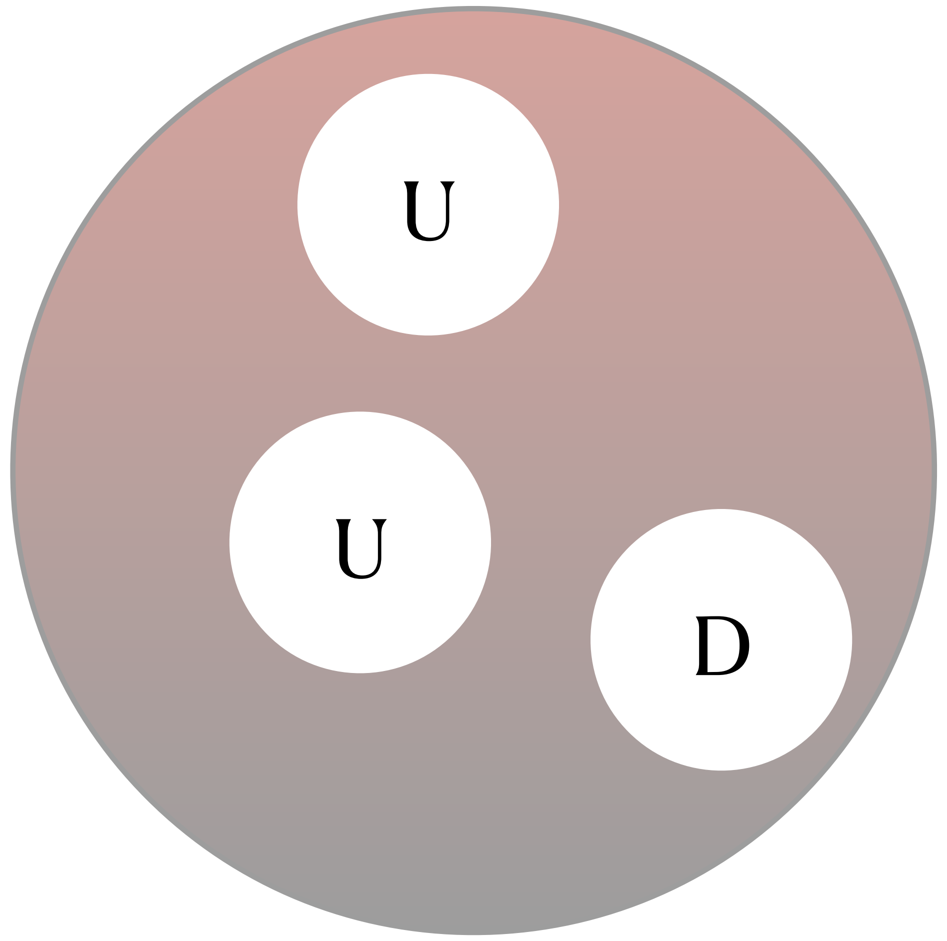
scoperta 2 anni dopo!!

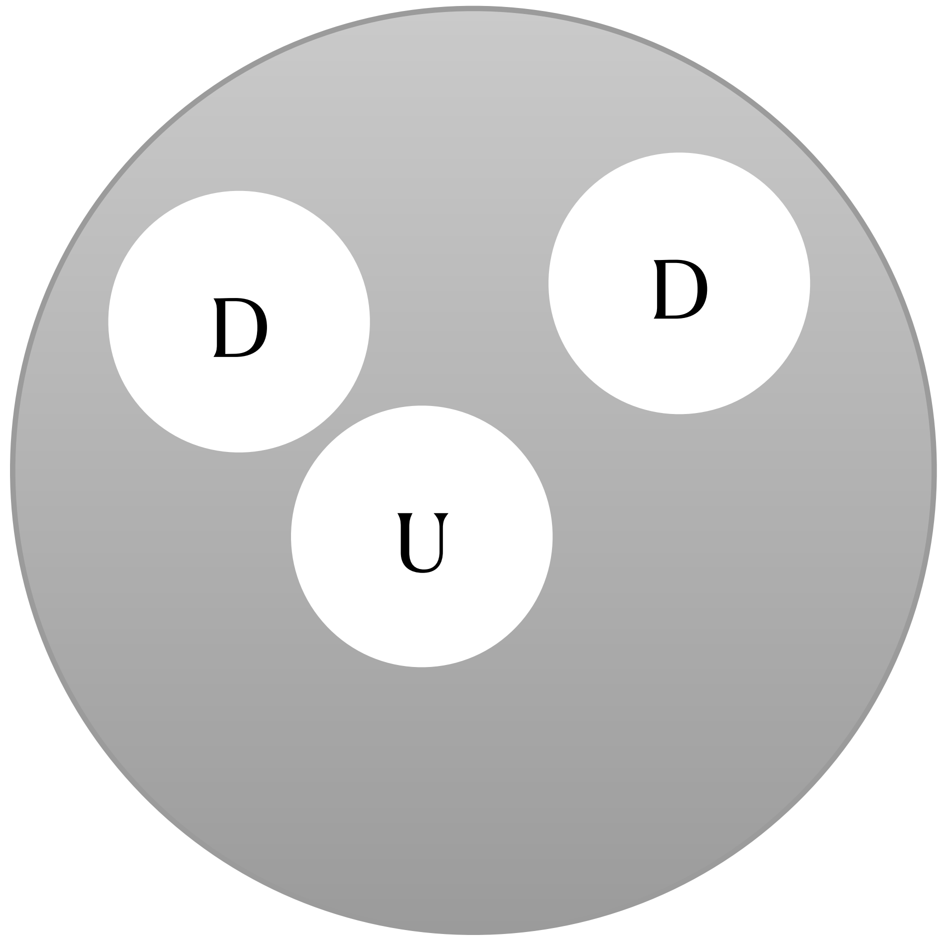




Carica:	$+e$	0
Massa:	938.27 MeV	939.56 MeV
Spin:	$1/2$	$1/2$

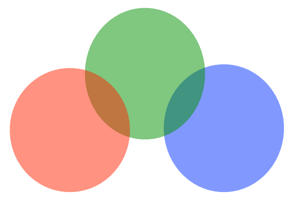
Come spieghiamo questi numeri?





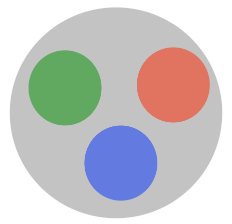
Carica:	$+e$	0
Massa:	938.27 MeV	939.56 MeV
Spin:	$1/2$	$1/2$

Modello a quark



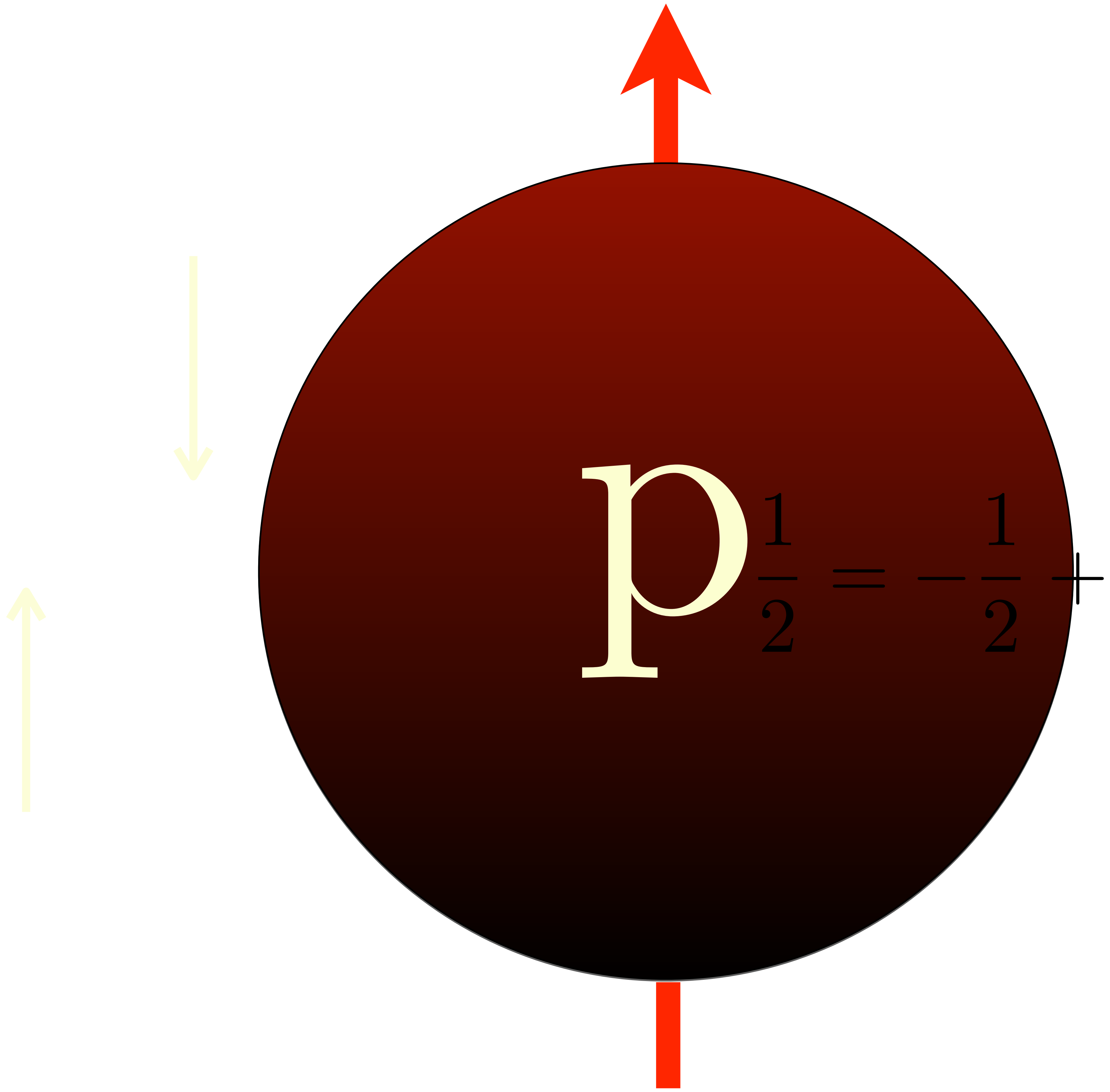
quark **down**
4.8 MeV

quark **up**
2.3 MeV



protone
938.27 MeV

Modello di Gell-Mann

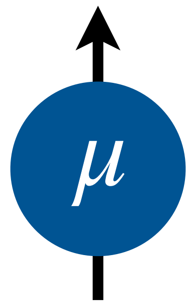


$$\frac{1}{2} = -\frac{1}{2} + \frac{1}{2} + \frac{1}{2}$$

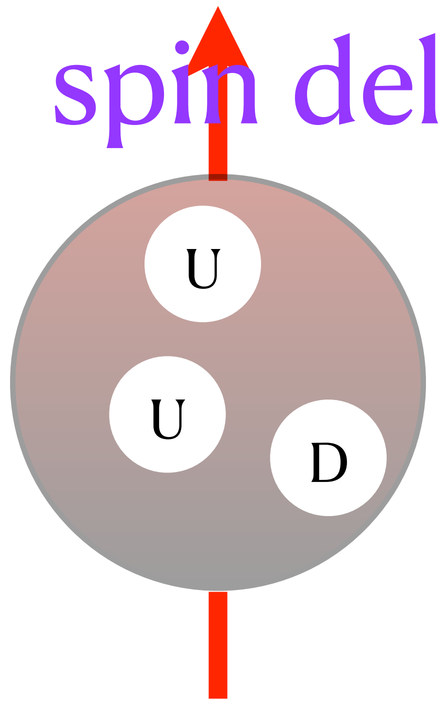
Analisi sperimentale

European Muon Collaboration (EMC, Cern 1987)

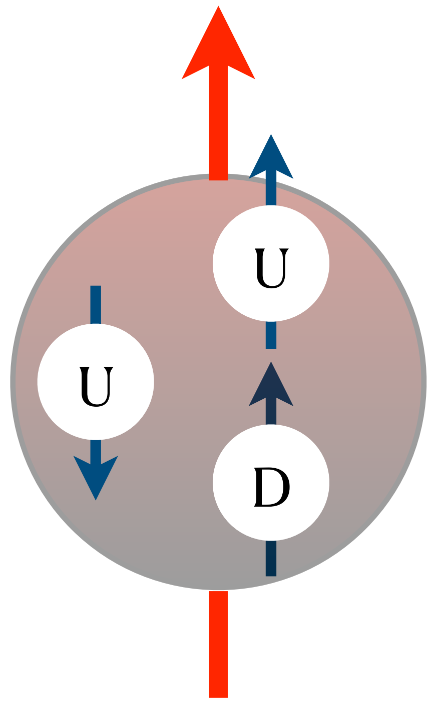
$$\mu^{\uparrow} p^{\uparrow} \rightarrow \mu X$$



Misura del contributo dei quark allo spin del protone



Risultato sperimentale



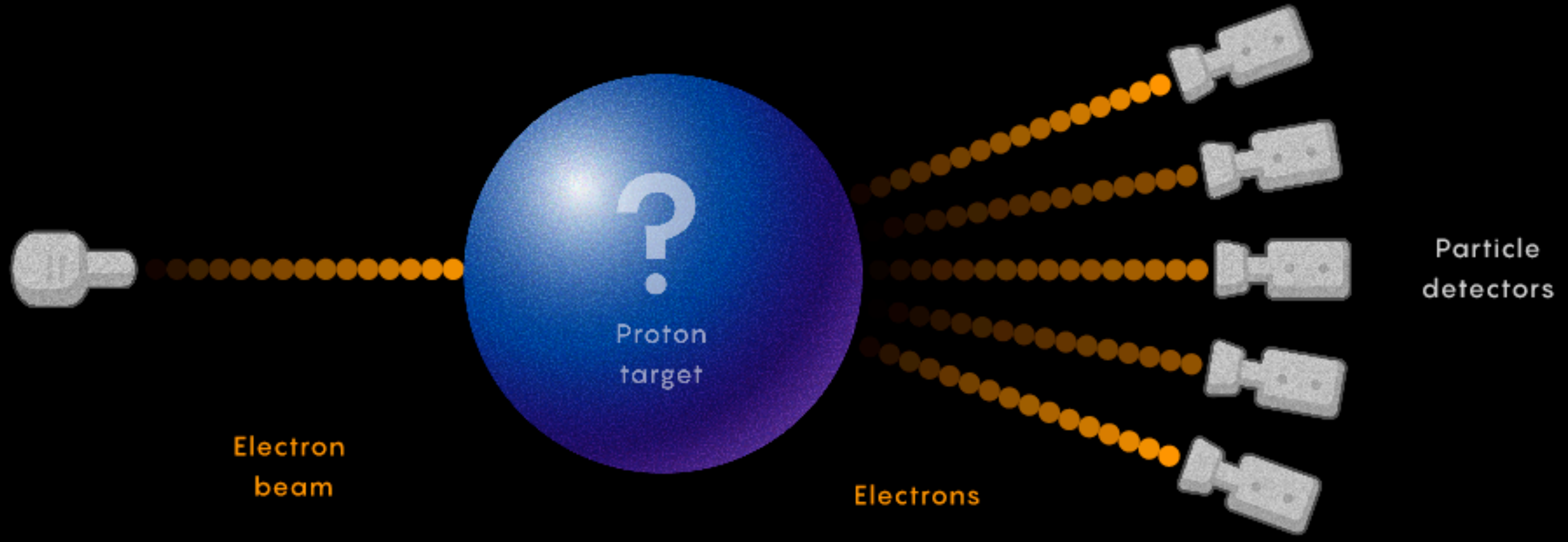
Modello di Gell-Mann $$\frac{1}{2} = -\frac{1}{2} + \frac{1}{2} + \frac{1}{2}$$

$\Rightarrow$ contributo = **100%**

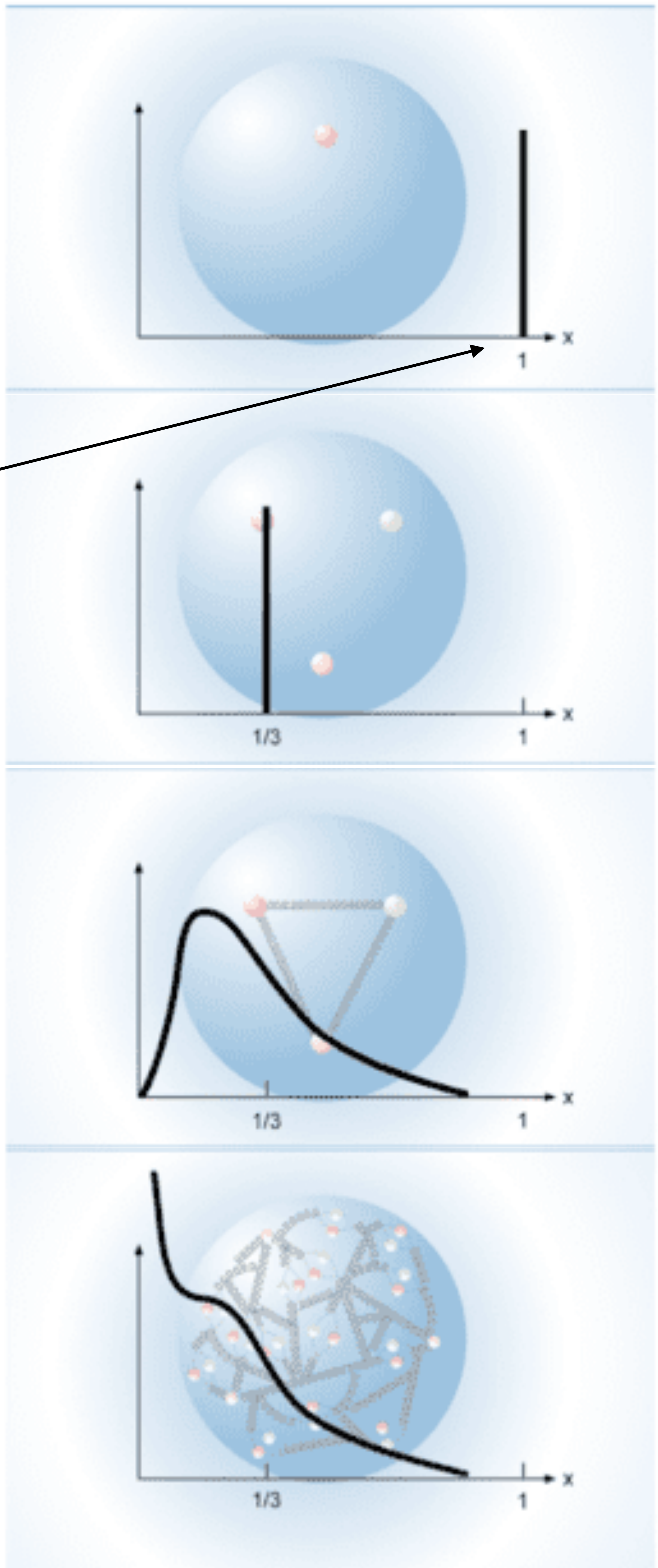
Esperimento EMC

$\Rightarrow$ contributo = 30%

Esperimenti di scattering (diffusione)



Frazione di quantità di moto



Urto contro una particella puntiforme

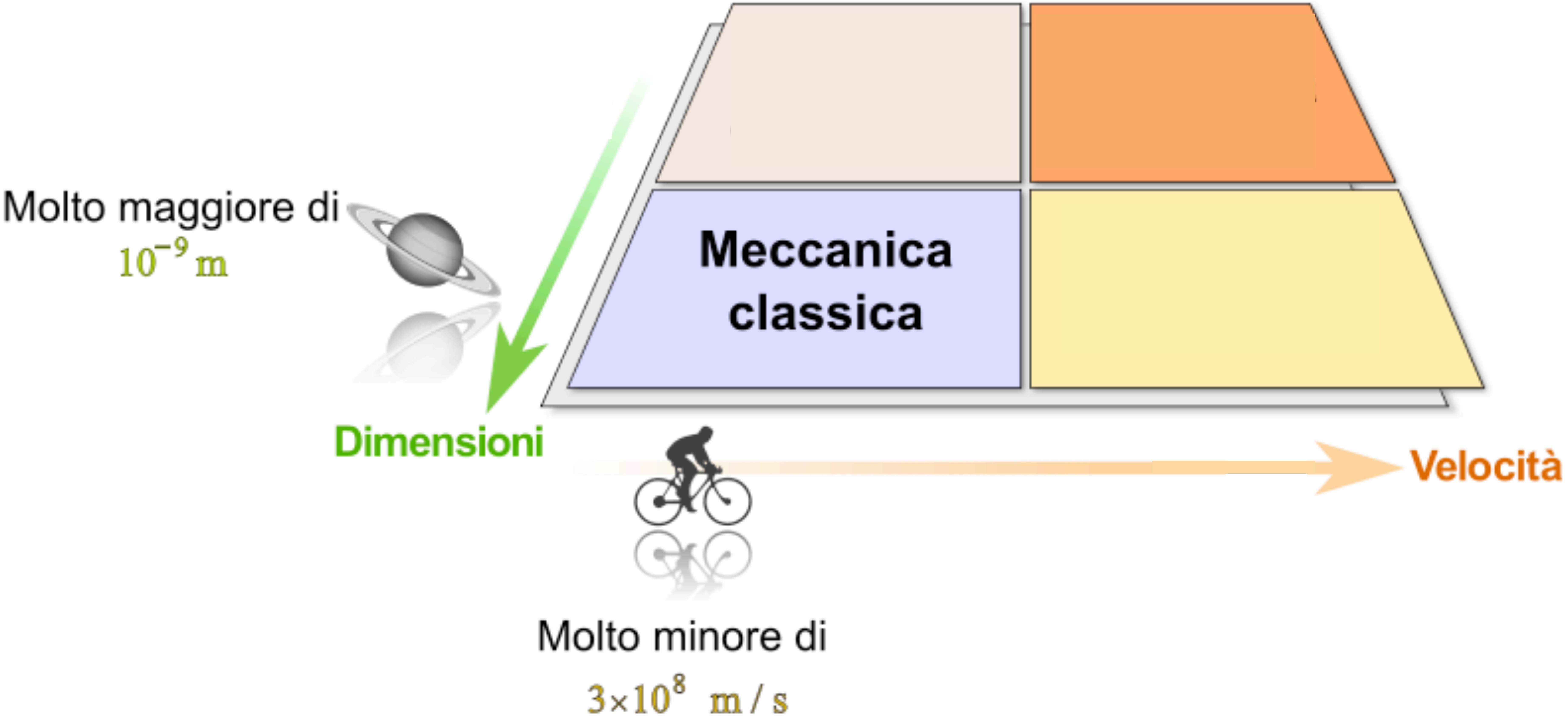
Urto contro tre particelle slegate

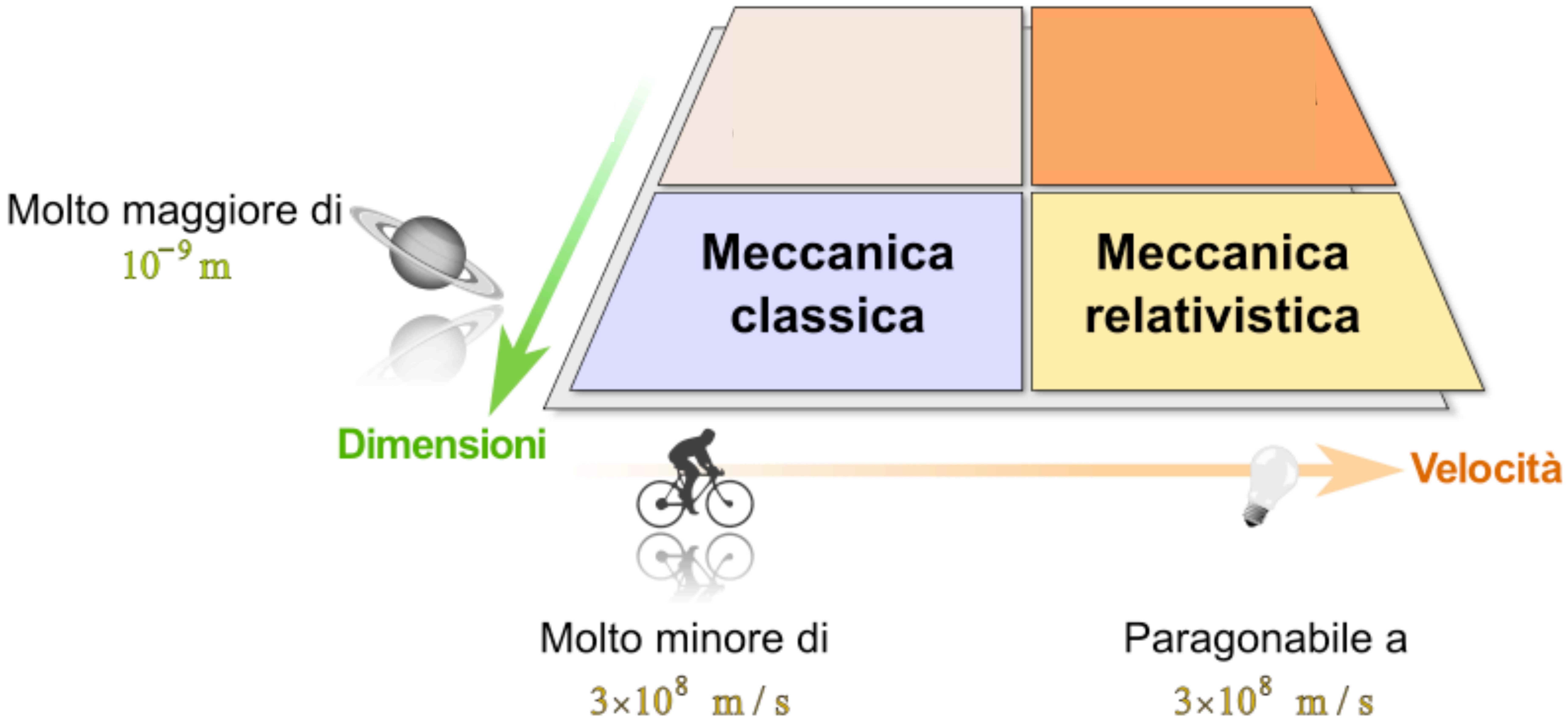
Urto contro tre particelle legate

Urto contro molte particelle legate

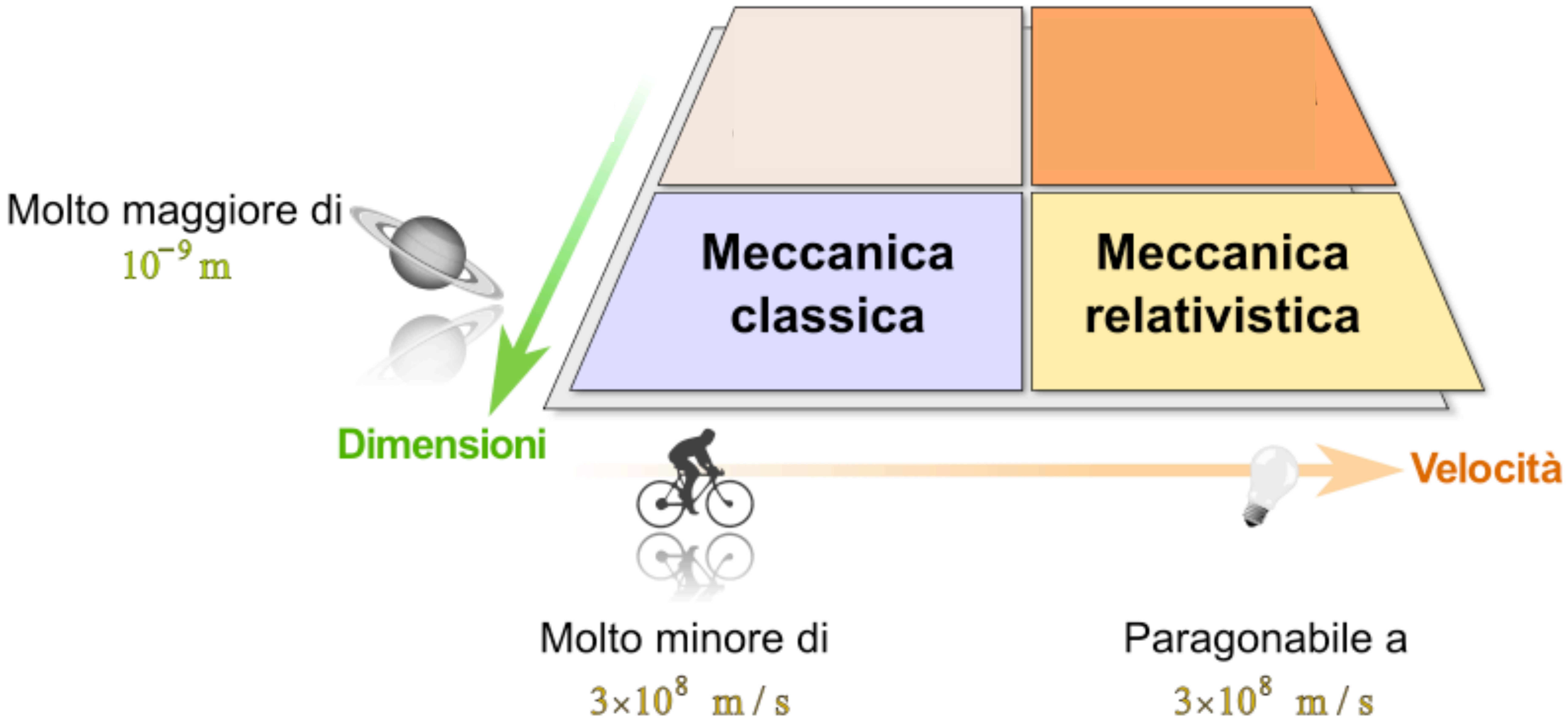
La Cromodinamica Quantistica (QCD)

COME DESCRIVIAMO LE PARTICELLE ELEMENTARI?

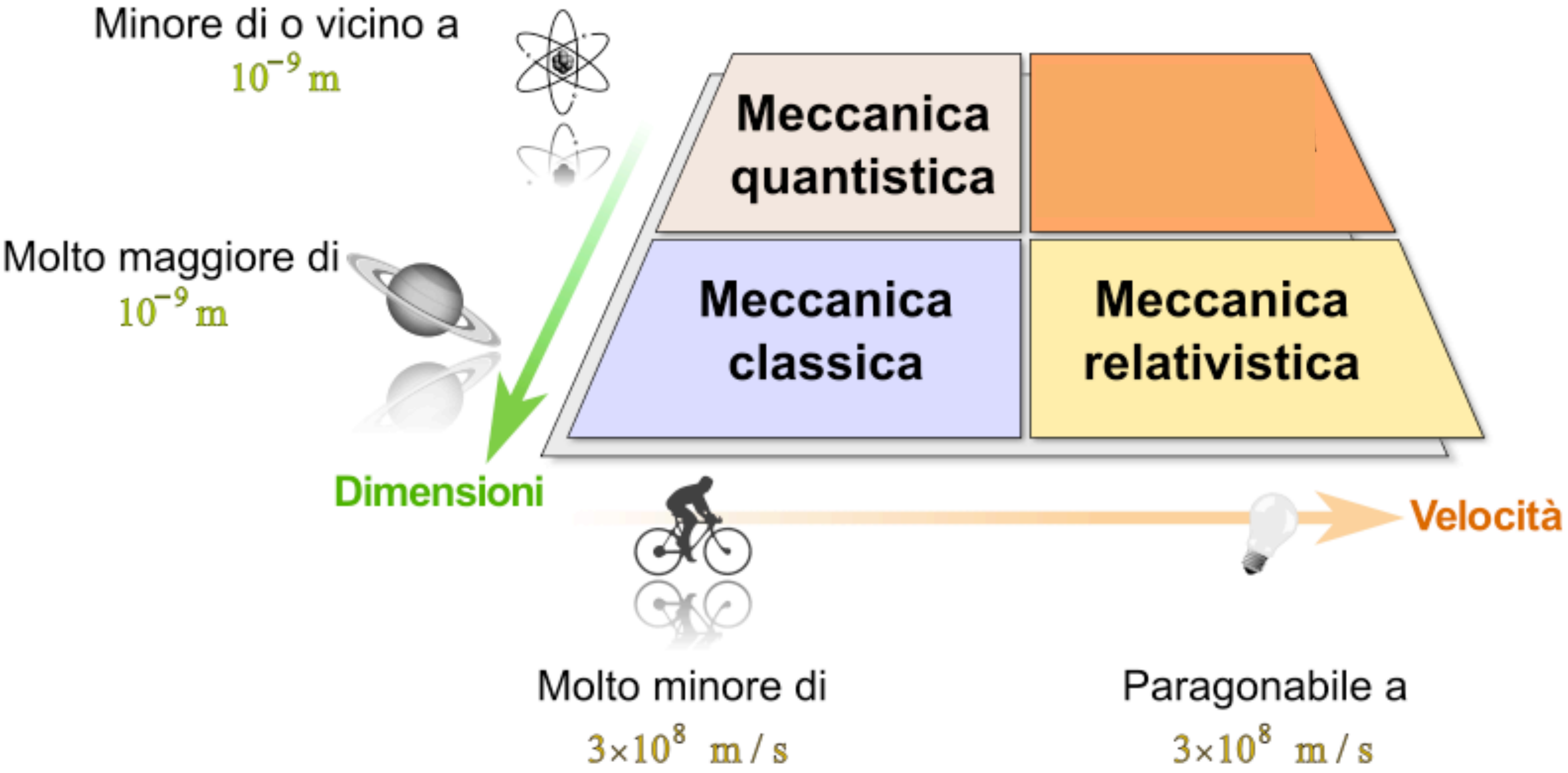

Molto maggiore di
10^{-9} m
Meccanica
classica
Dimensioni
Velocità
Molto minore di
3×10^{8} m / s


Molto maggiore di
10^{-9} m
Meccanica classica
Meccanica relativistica
Dimensioni
Velocità
Molto minore di
3×10^{8} m / s
Paragonabile a
3×10^{8} m / s

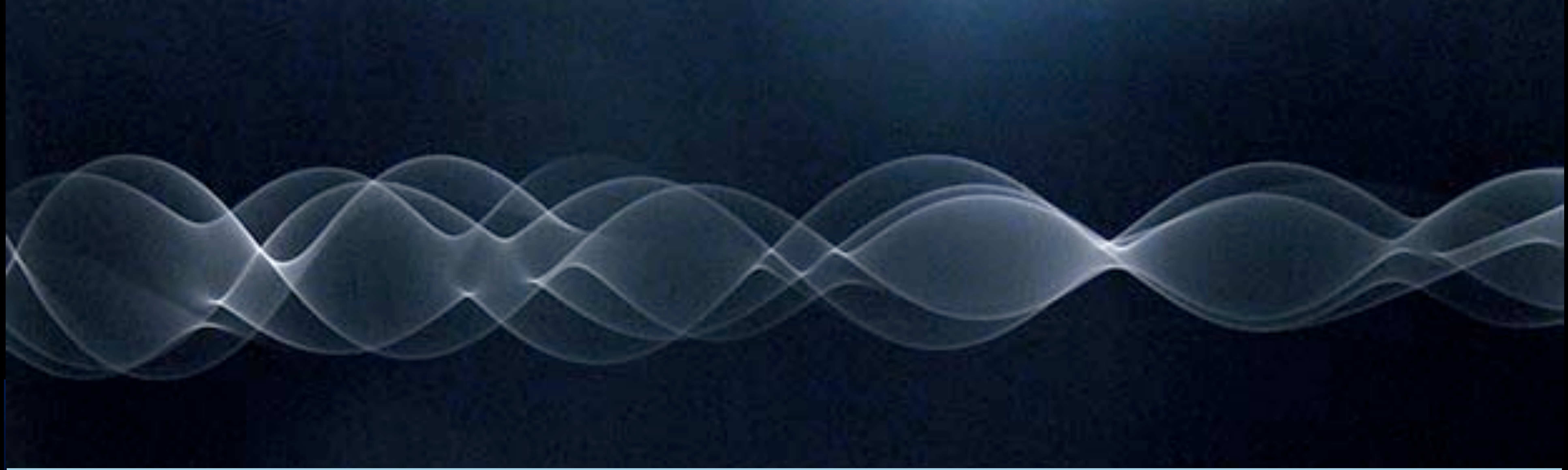
$$E = mc^2$$


Molto maggiore di
10^{-9} m
Meccanica classica
Meccanica relativistica
Dimensioni
Velocità
Molto minore di
3×10^{8} m / s
Paragonabile a
3×10^{8} m / s

$$\Delta x \, \Delta p \geq \hbar/2$$

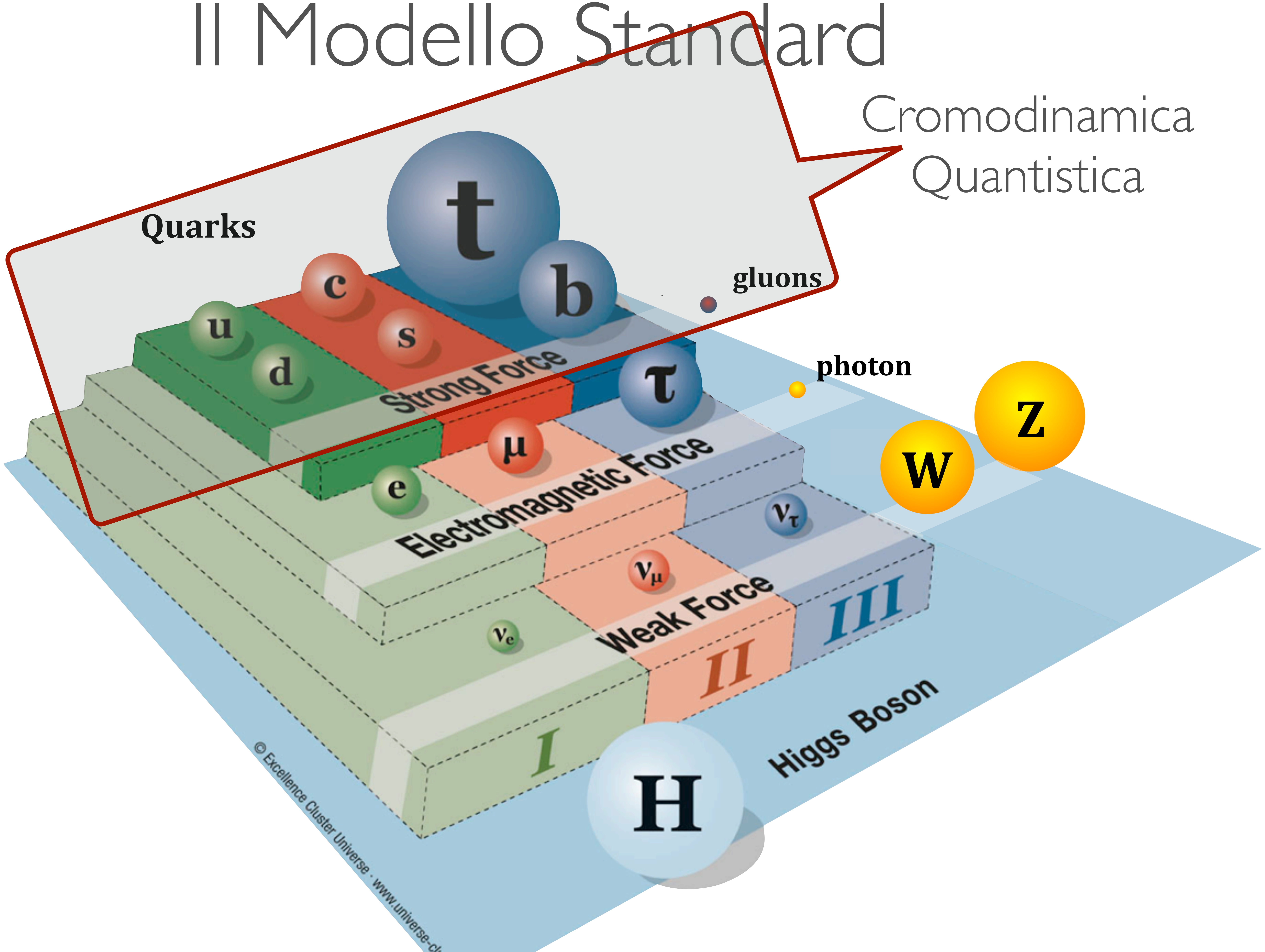


Minore di o vicino a
10^{-9} m
Molto maggiore di
10^{-9} m
Meccanica quantistica
Meccanica classica
Meccanica relativistica
Dimensioni
Velocità
Molto minore di
3×10^{8} m / s
Paragonabile a
3×10^{8} m / s



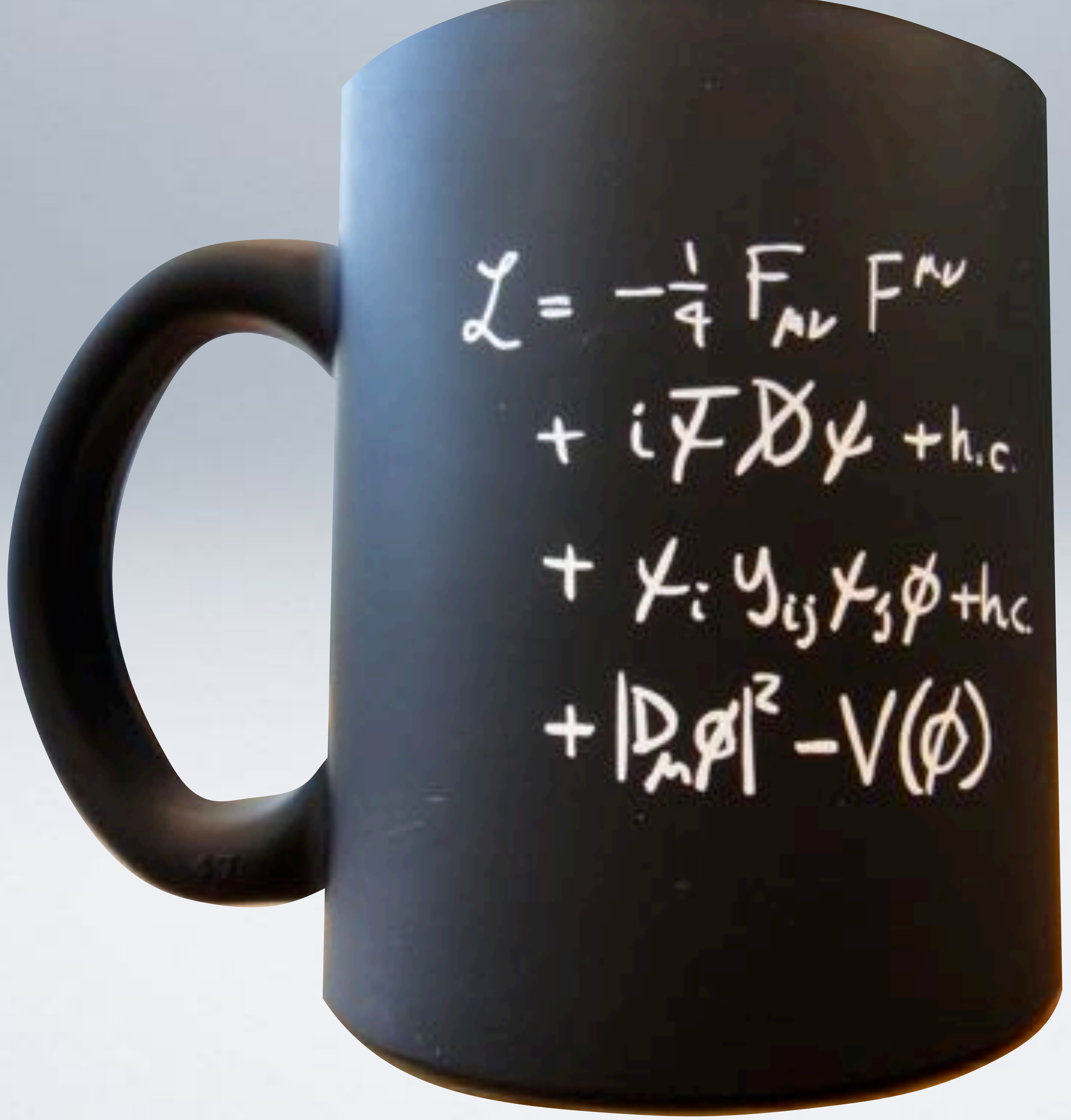
Le “particelle elementari” sono onde di campi quantistici.
Questo è il paradigma con cui attualmente descriviamo la realtà a livello fondamentale

Il Modello Standard



Cromodinamica
Quantistica

LA LAGRANGIANA DEL MODELLO STANDARD



IL MODELLO STANDARD E OLTRE

Beyond the Standard Model

Dark matter

Supersymmetry

Neutrinos

Strings

Quantum Gravity

Elettrodebole

Higgs

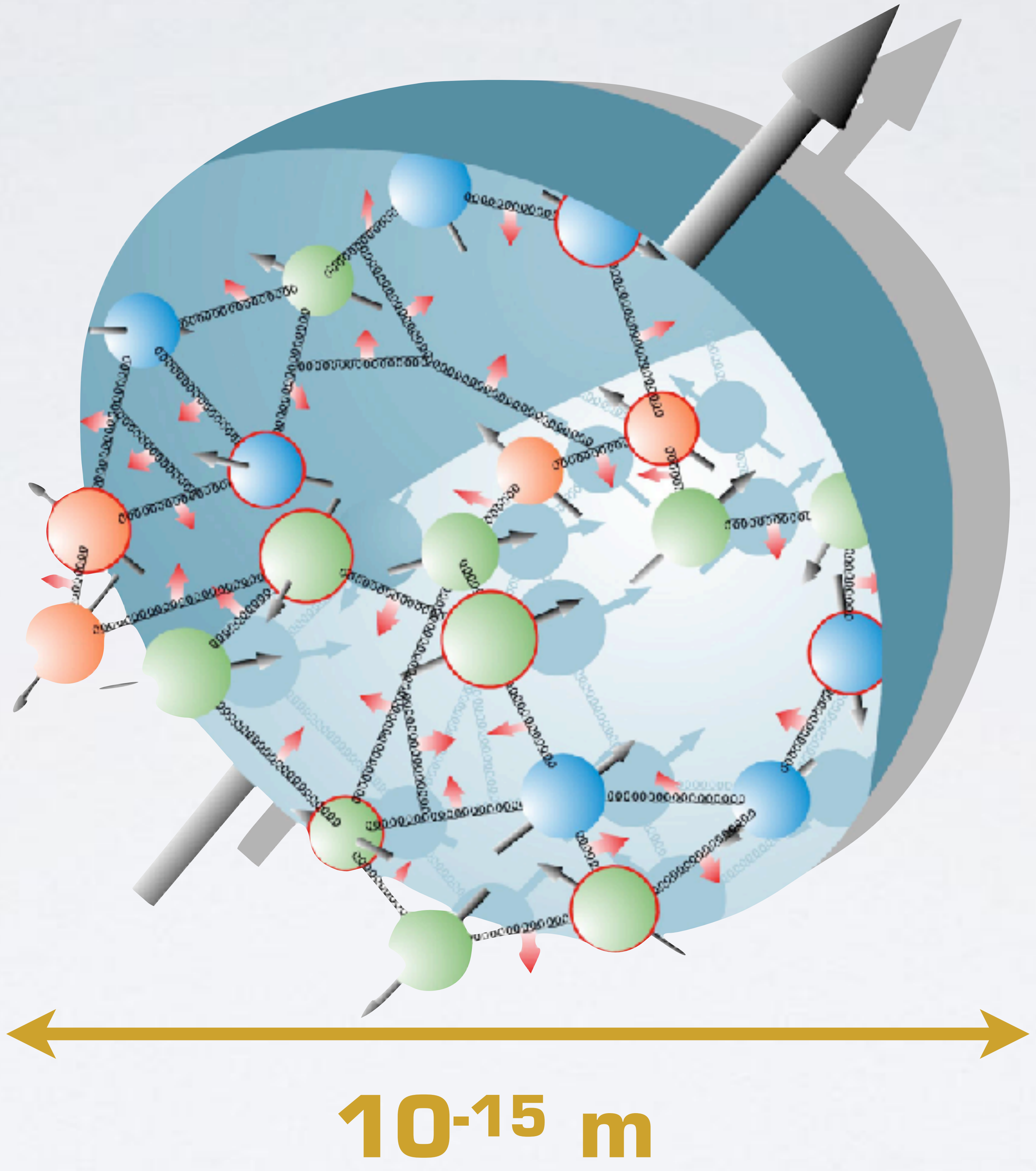
Cromodinamica Quantistica

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not\partial - g \not A + m) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

QCD: il LATO SELVAGGIO del Modello Standard

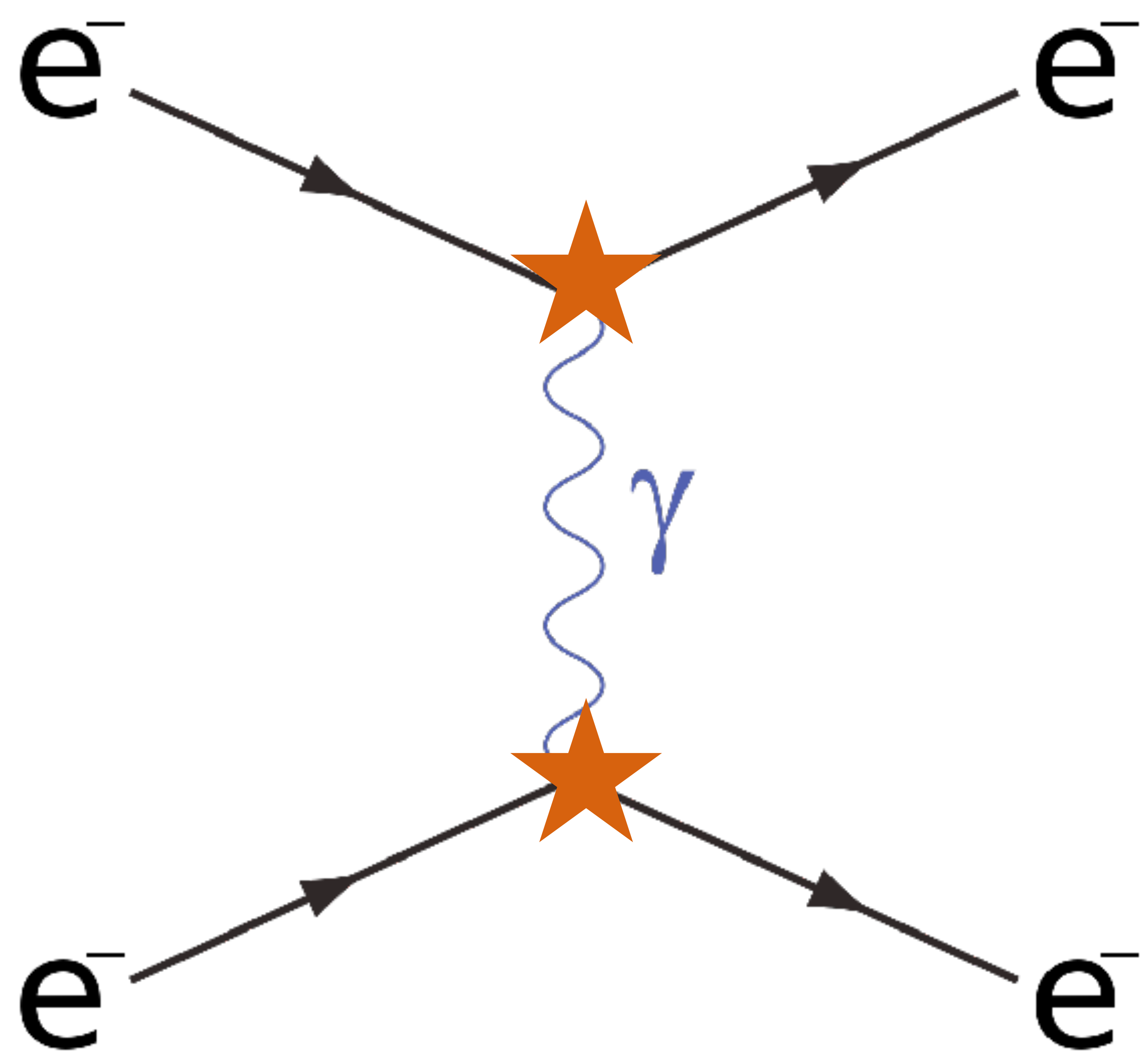
sono più le cose che NON sappiamo ancora spiegare rispetto a quelle che sappiamo spiegare…

L'OBIETTIVO DELLA FISICA ADRONICA



Spiegare le proprietà degli adroni (=particelle formate da quark e gluoni) partendo dalla Lagrangiana di QCD

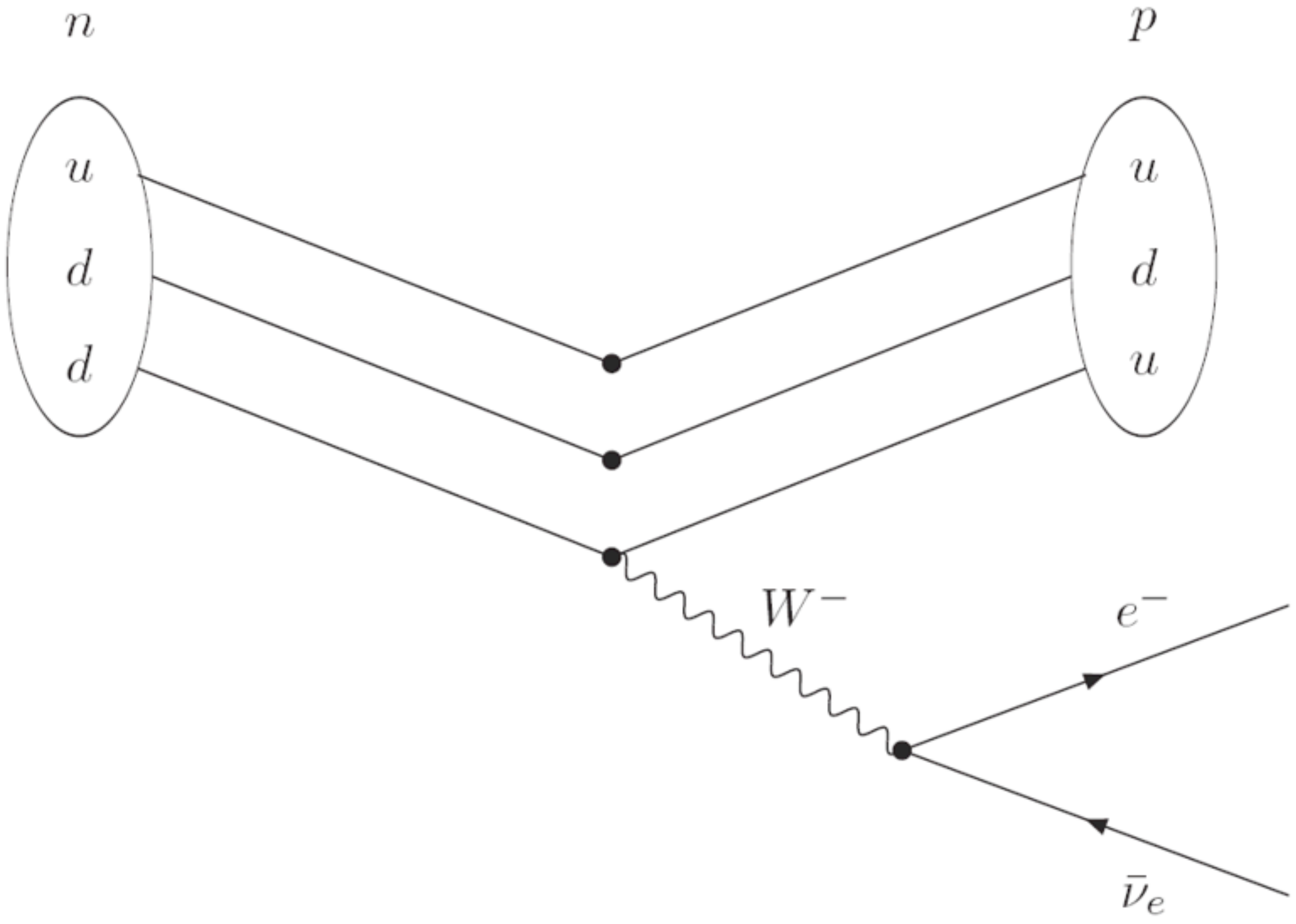
DIAGRAMMI DI FEYNMAN- ELETTRODINAMICA



★ proporzionale a costante di accoppiamento

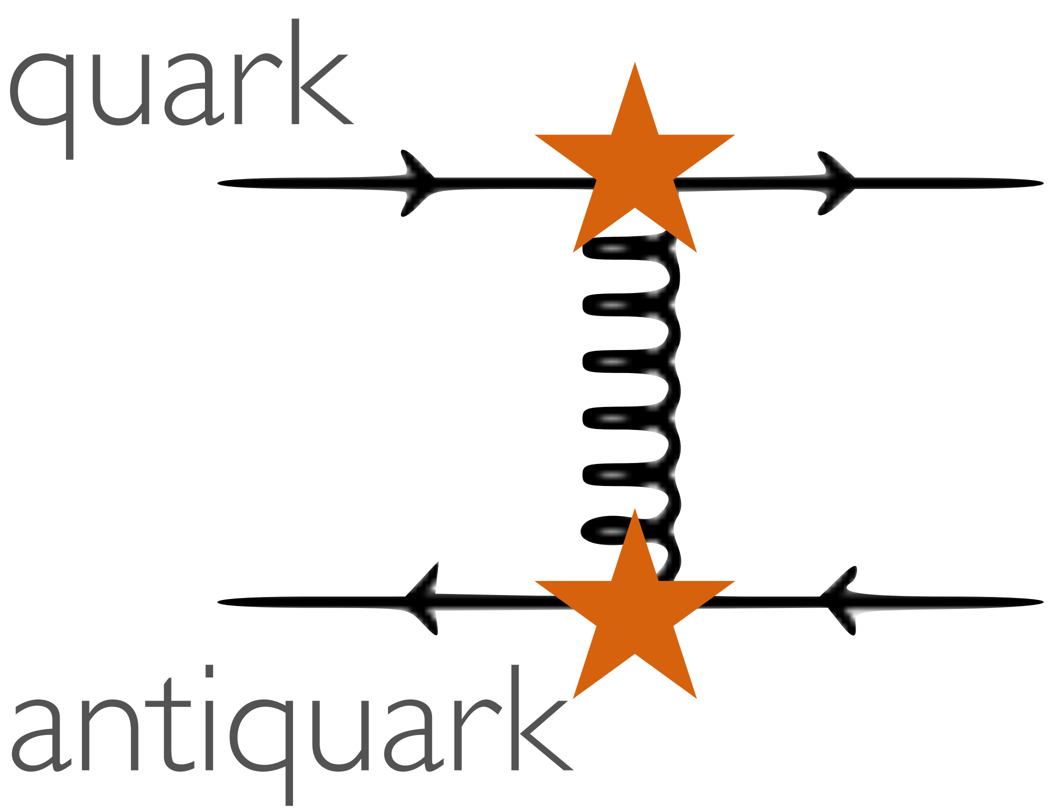
La costante di accoppiamento è piccola
Il fotone è di un solo tipo
Il fotone è neutro

DIAGRAMMI DI FEYNMAN- INTERAZIONE DEBOLE



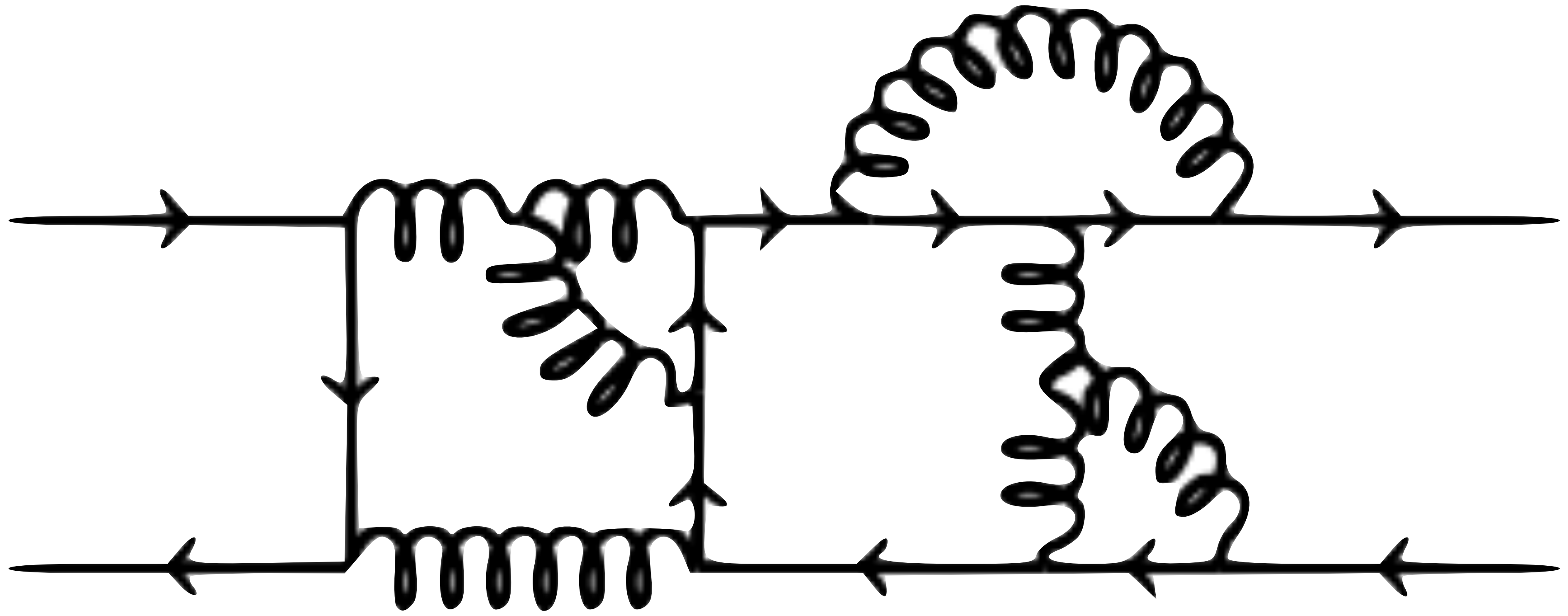
La costante di accoppiamento è piccola
Esistono tre mediatori della forza
Possono avere carica elettrica

DIAGRAMMI DI FEYNMAN- QCD



★ proporzionale a costante di accoppiamento

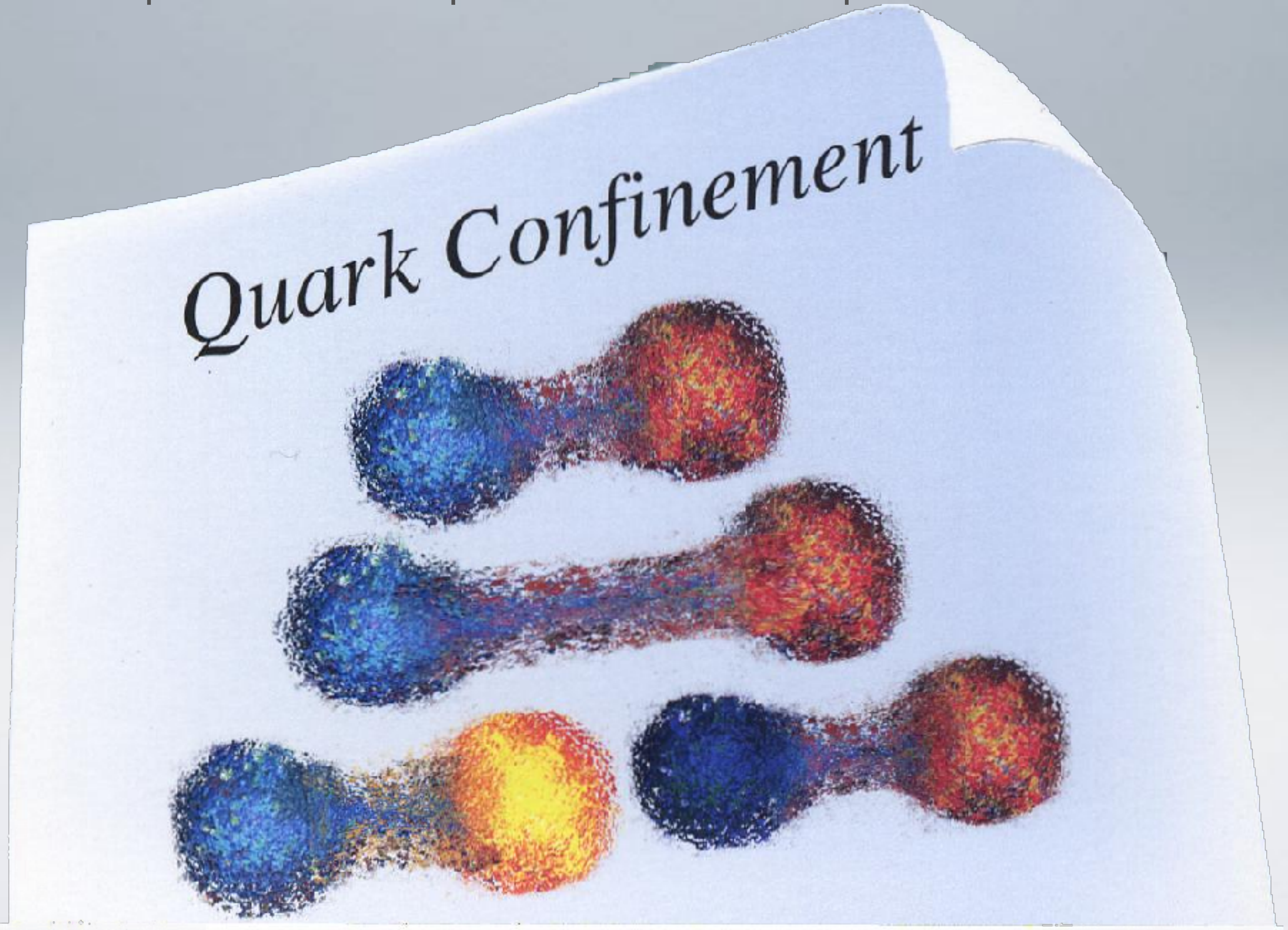
La costante di accoppiamento è grande
Ci sono 8 tipi di gluoni
I gluoni portano carica di colore



Se la costante di accoppiamento è piccola, possiamo fermarci a un certo punto, altrimenti bisogna includere infiniti diagrammi

IL CONFINAMENTO

Se si tenta di separare due quark, l'attrazione tra i due è talmente forte che diventa energeticamente favorevole creare una coppia di quark-antiquark. Non è possibile avere quark isolati.



IL CONFINAMENTO

È uno dei "Millennium Problems"
del Clay Mathematics Institute

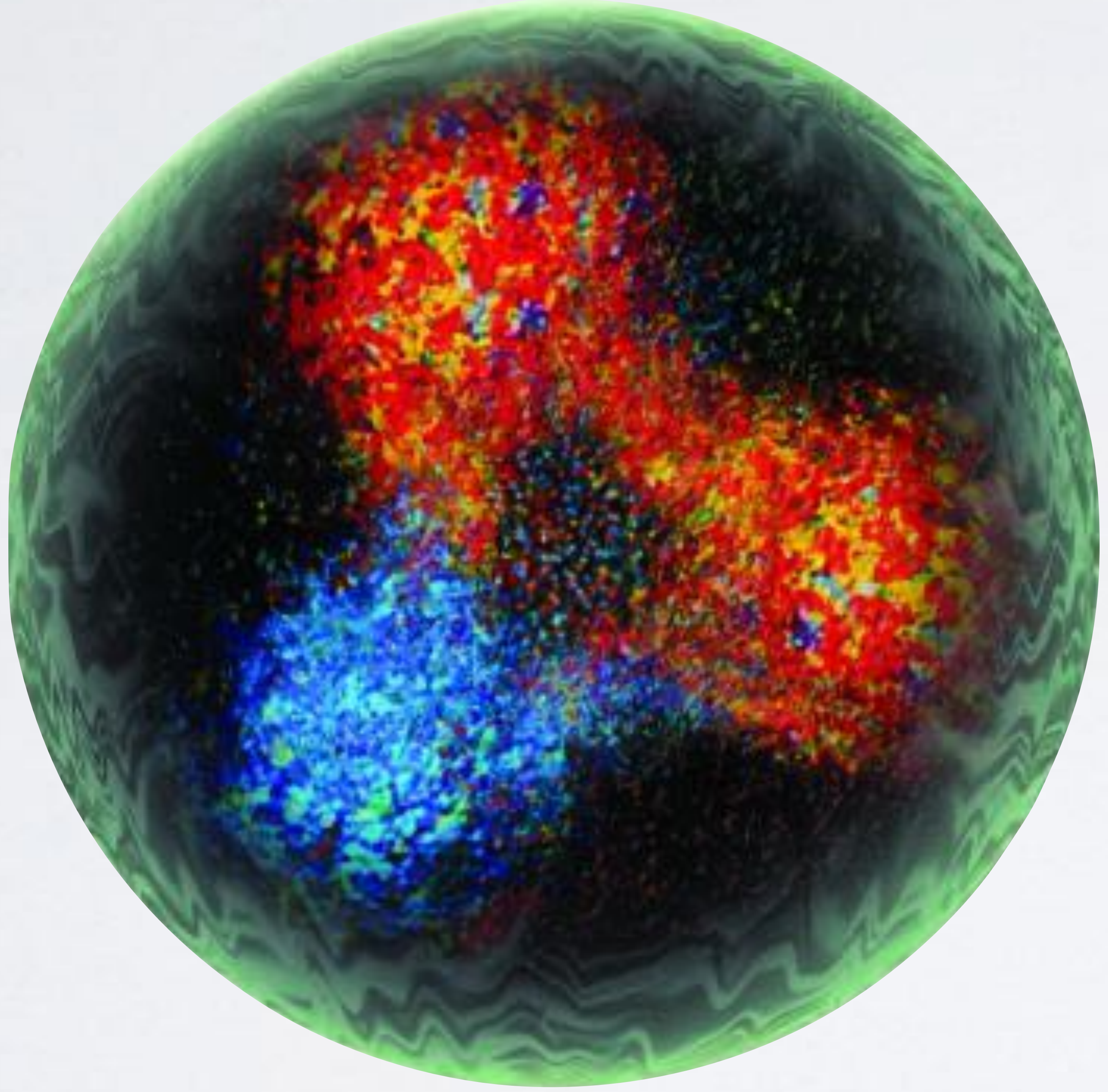
http://www.claymath.org/millennium-problems

Problema aperto

> "Yang-Mills Existence and Mass Gap: Prove that for any compact simple gauge group G, quantum Yang-Mills theory of R^4 exists and has a mass gap $\Delta > 0$."

Per intenderci, sta insieme alla prova che esista una soluzione delle equazioni di Navier-Stokes

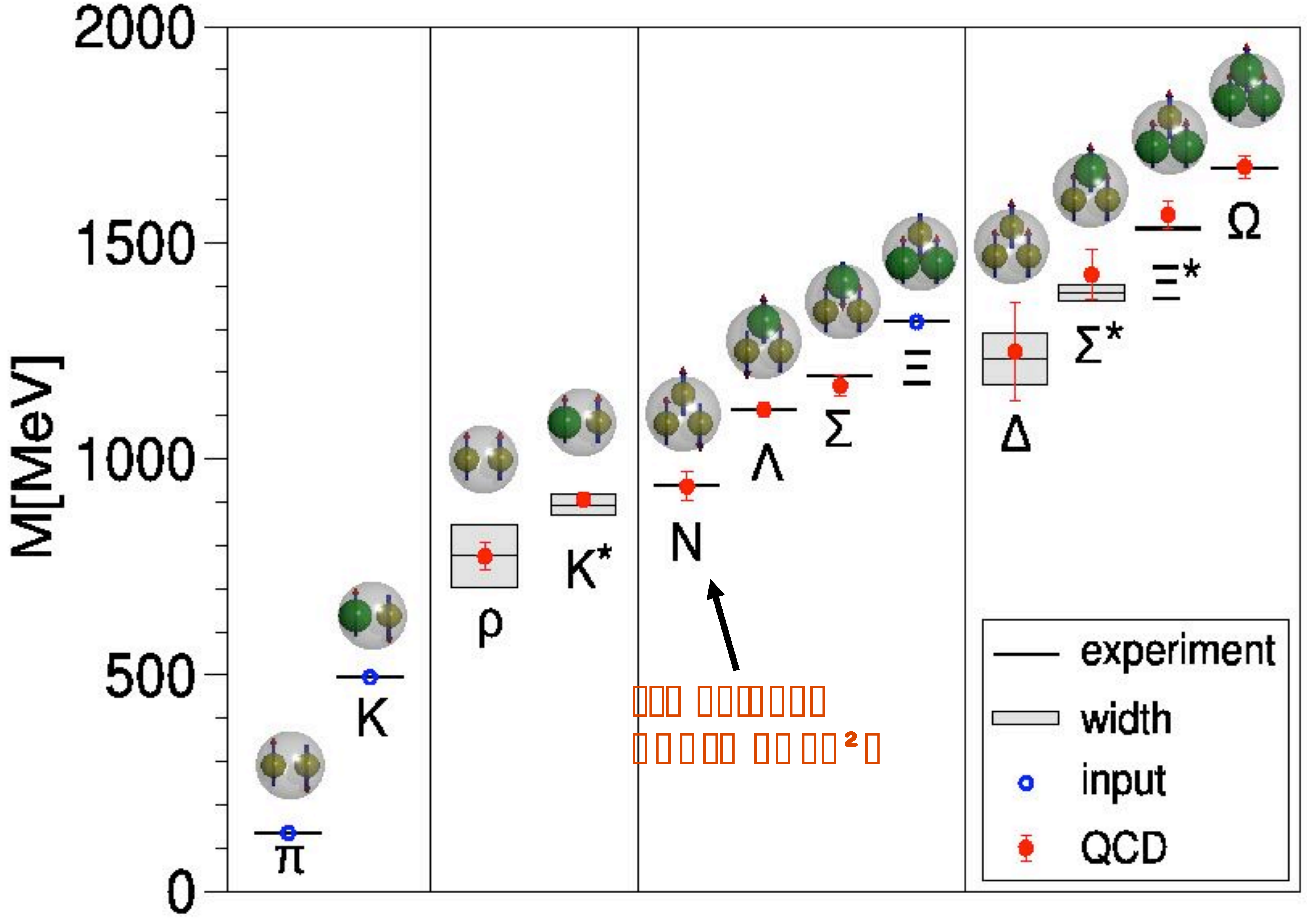
LA MASSA



M_P = 938 MeV

Quasi tutta la massa del protone (e quindi della materia intorno a noi) è dovuta all'energia di legame creata dai gluoni.

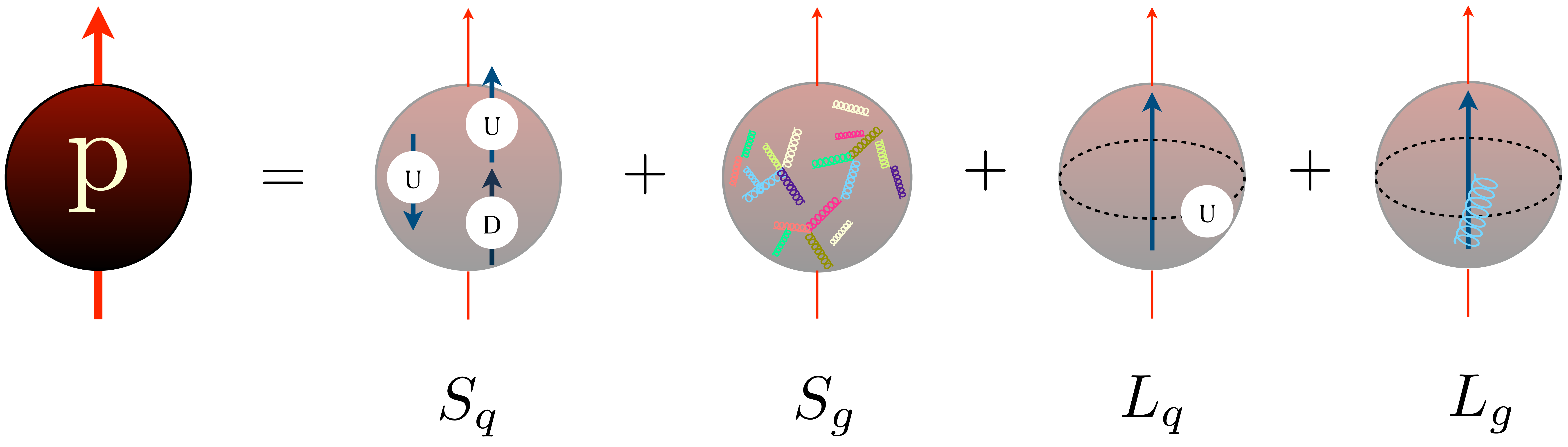
LA MASSA



Durr et al., Science 322 (08)

Calcoli fatti usando la "QCD su reticolo" o "lattice QCD" riproducono correttamente la massa degli adroni

La “crisi dello spin”



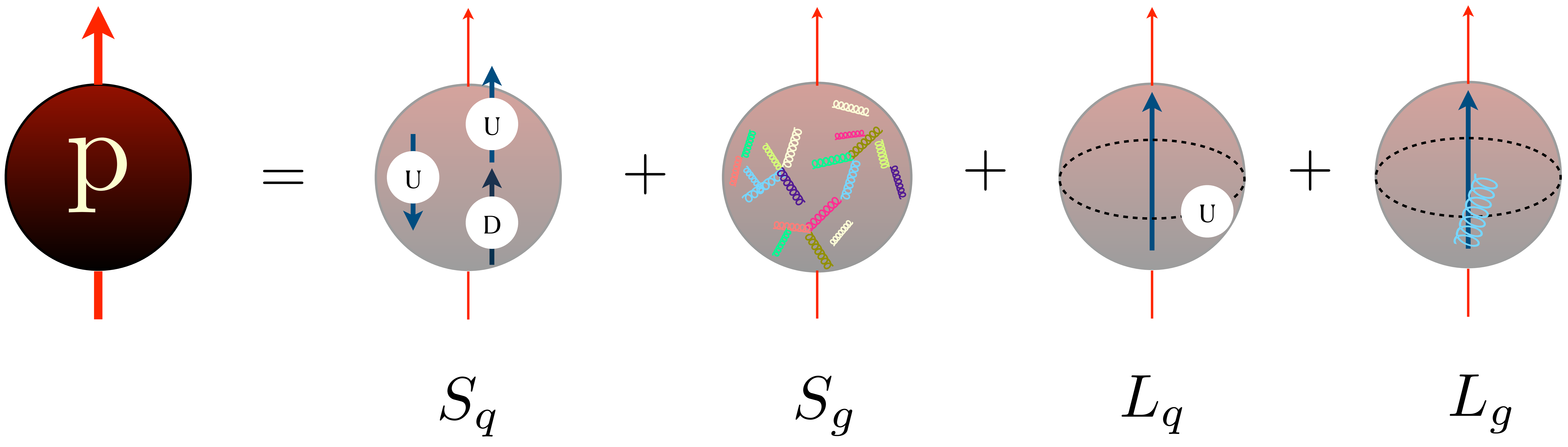
Nuove idee

Contributo del momento angolare L dei quark

Contributo del gluone

Contributo di coppie $q\bar{q}$

La “crisi dello spin”



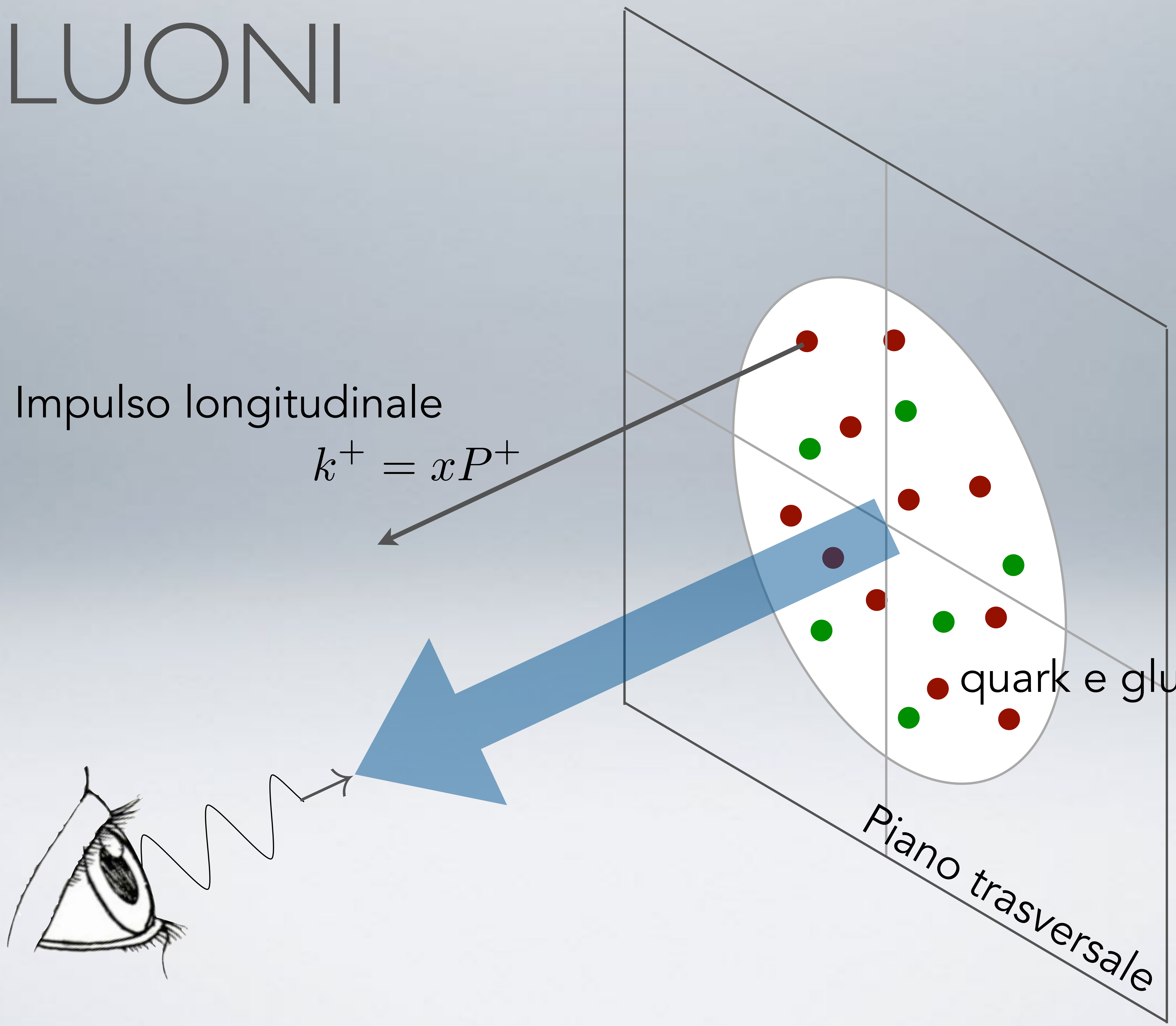
Nuovi metodi

Distribuzioni di momento trasversale dei quark (TMDs)

Distribuzioni partoniche generalizzate (GPDs)

Distribuzioni di Wigner

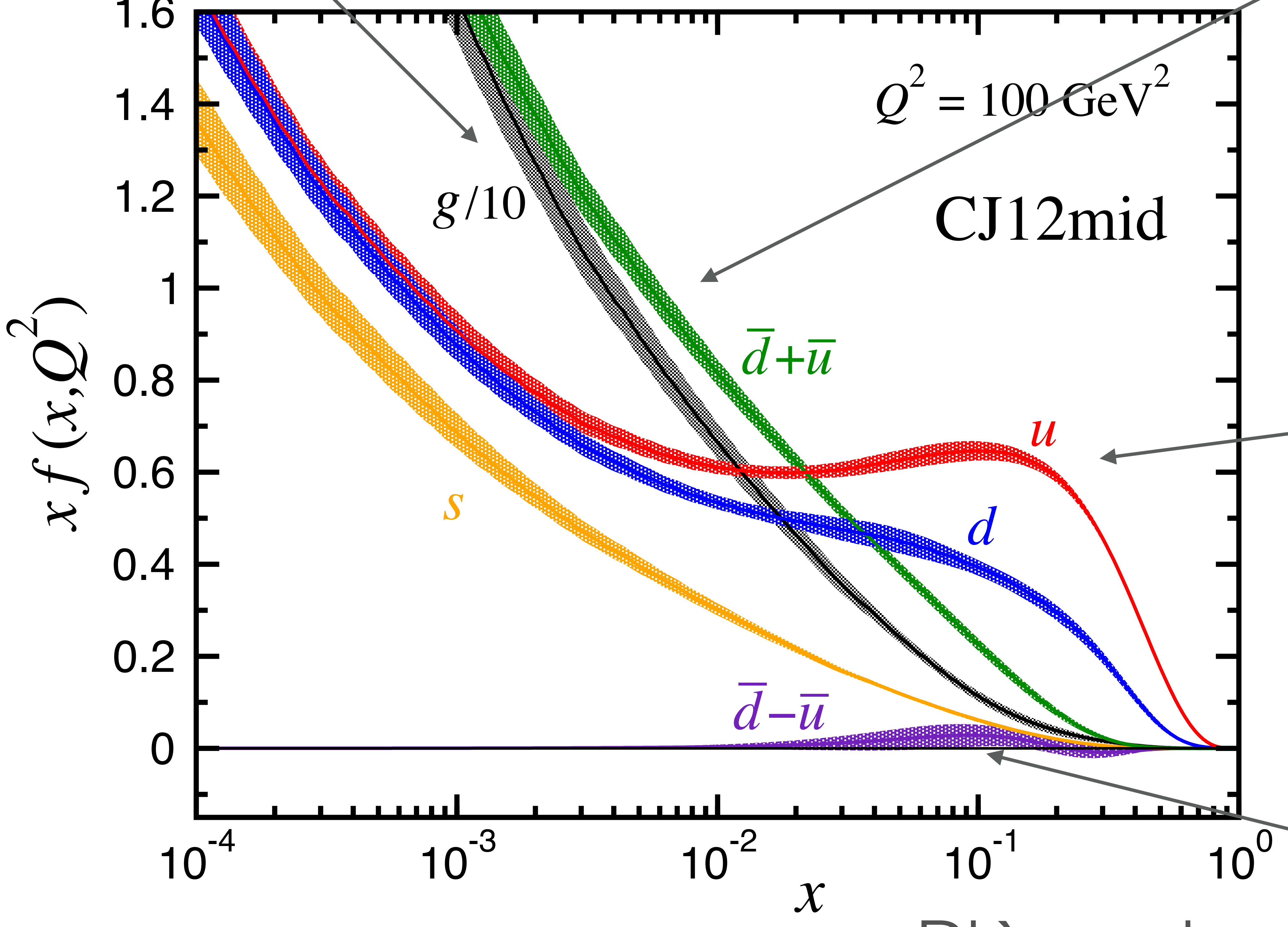
LA DISTRIBUZIONE DI QUARK E GLUONI



FUNZIONI DI DISTRIBUZIONE

Tantissimi gluoni!

Tantissimi antiquark

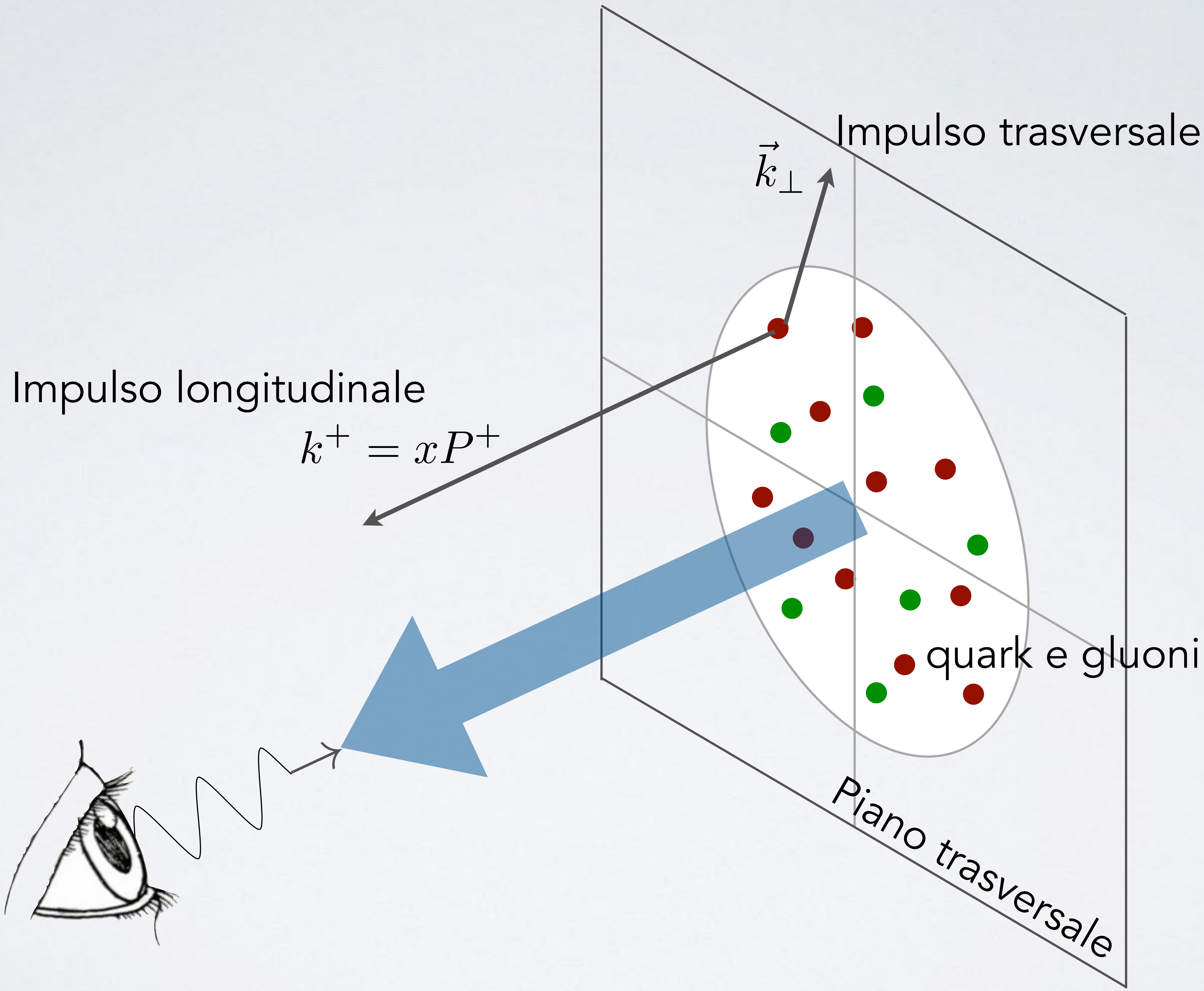


Piccole ma importanti differenze tra quark e antiquark

Più antiquark down che non up

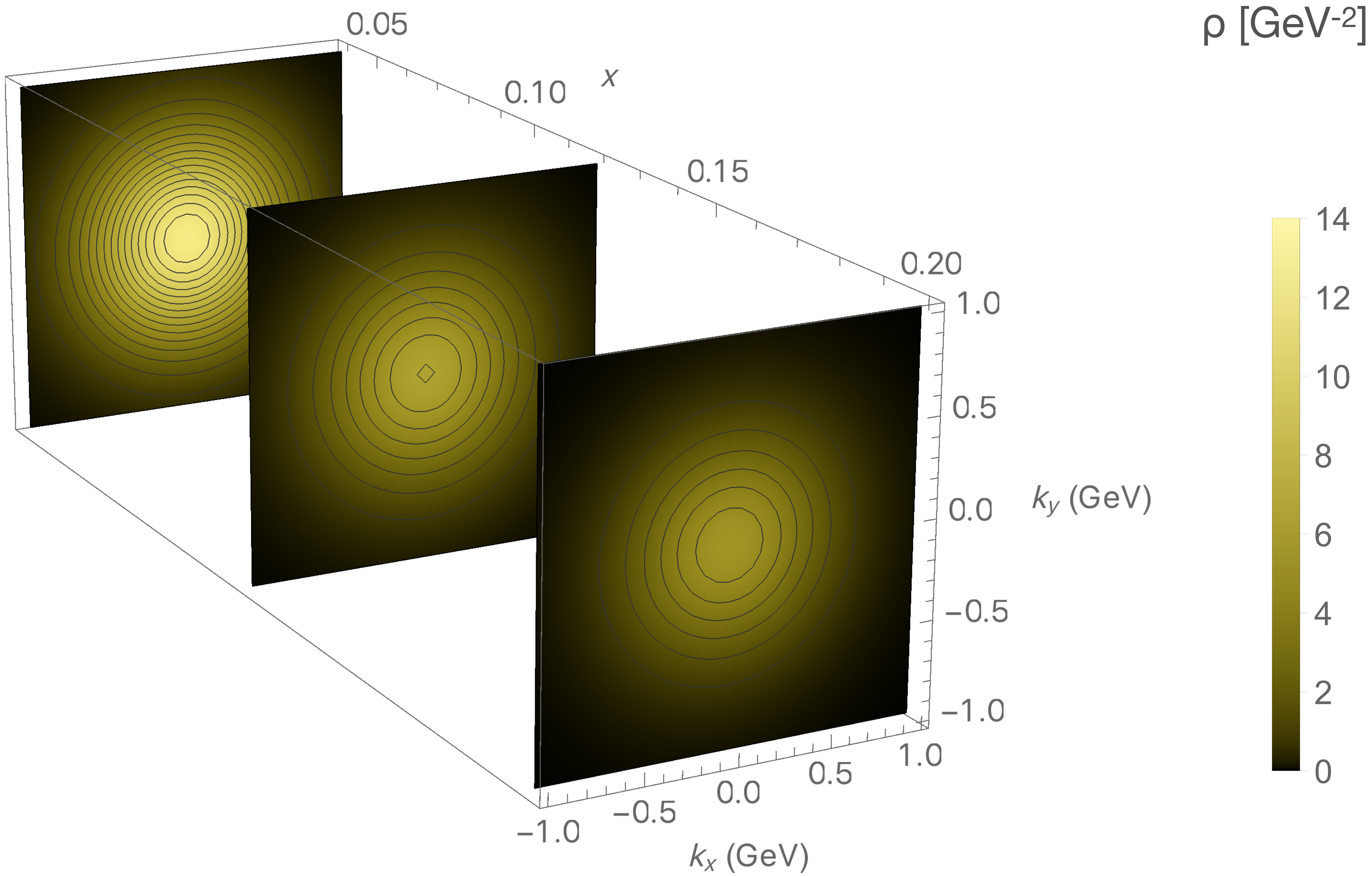
CTEQ - JLAB 12 set, Owens, Accardi, Melnitchouk, PRD87 (13)

DISTRIBUZIONI IN 3D

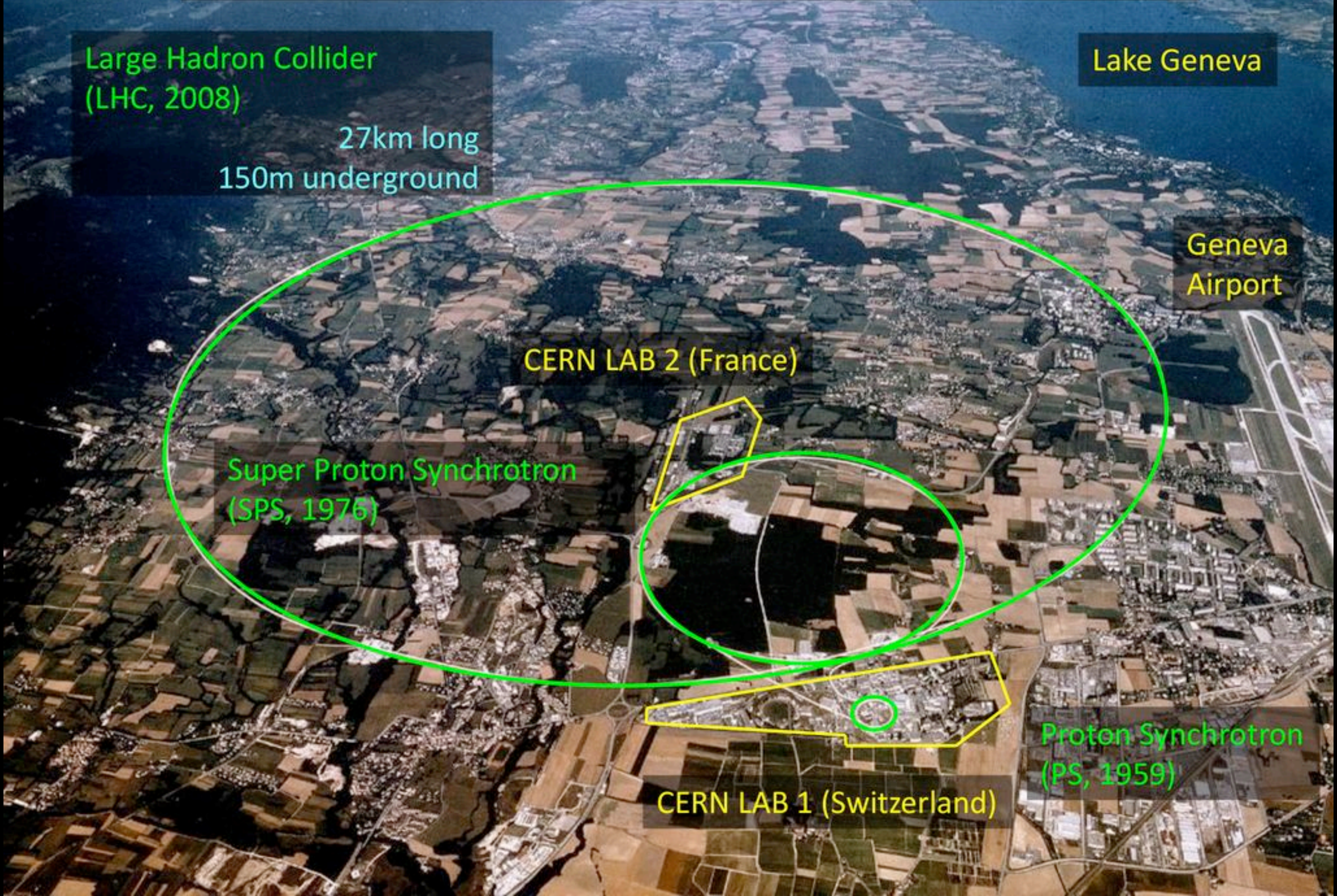


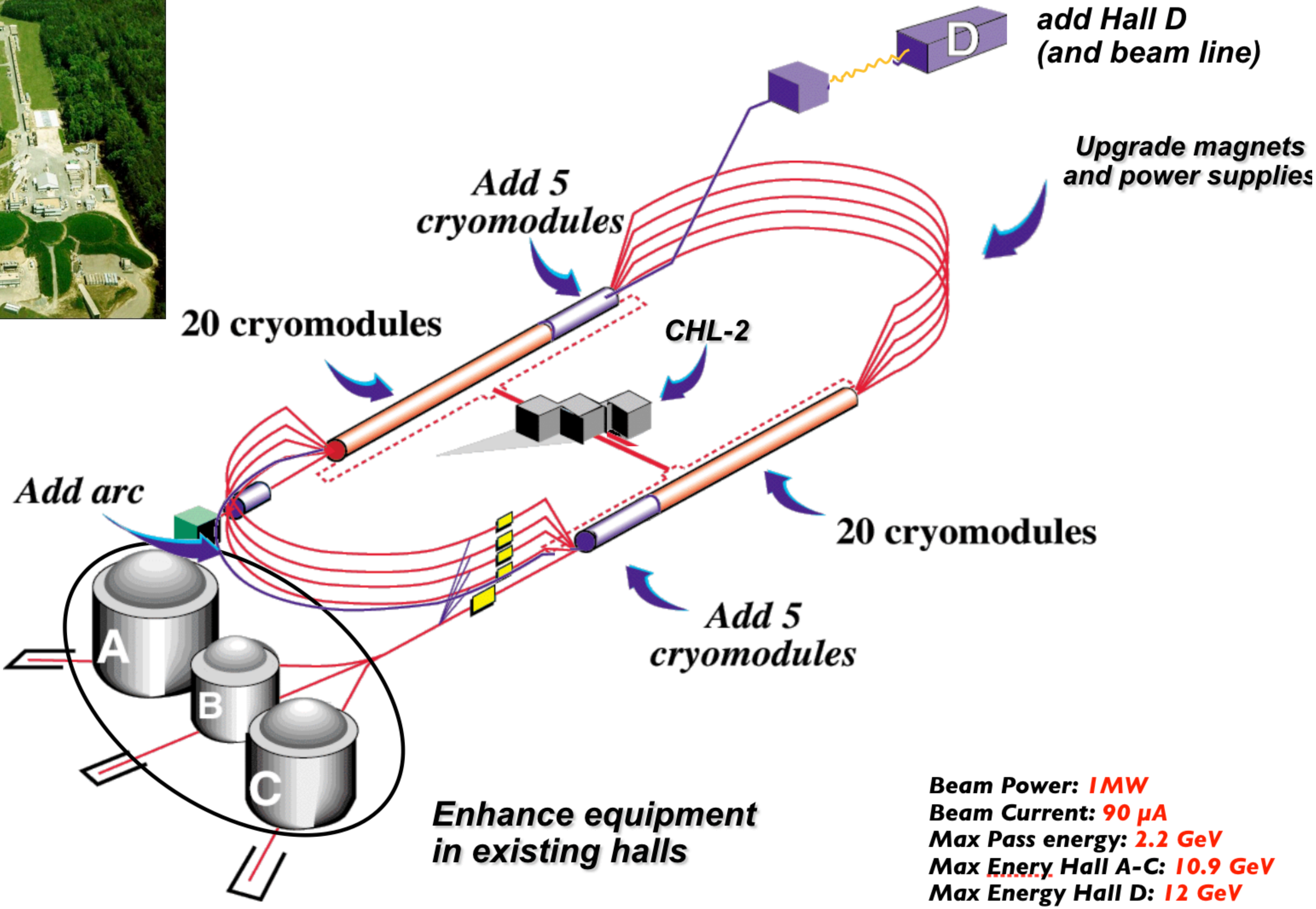
DISTRIBUZIONI IN 3D

Problema aperto



CERN Accelerator Complex

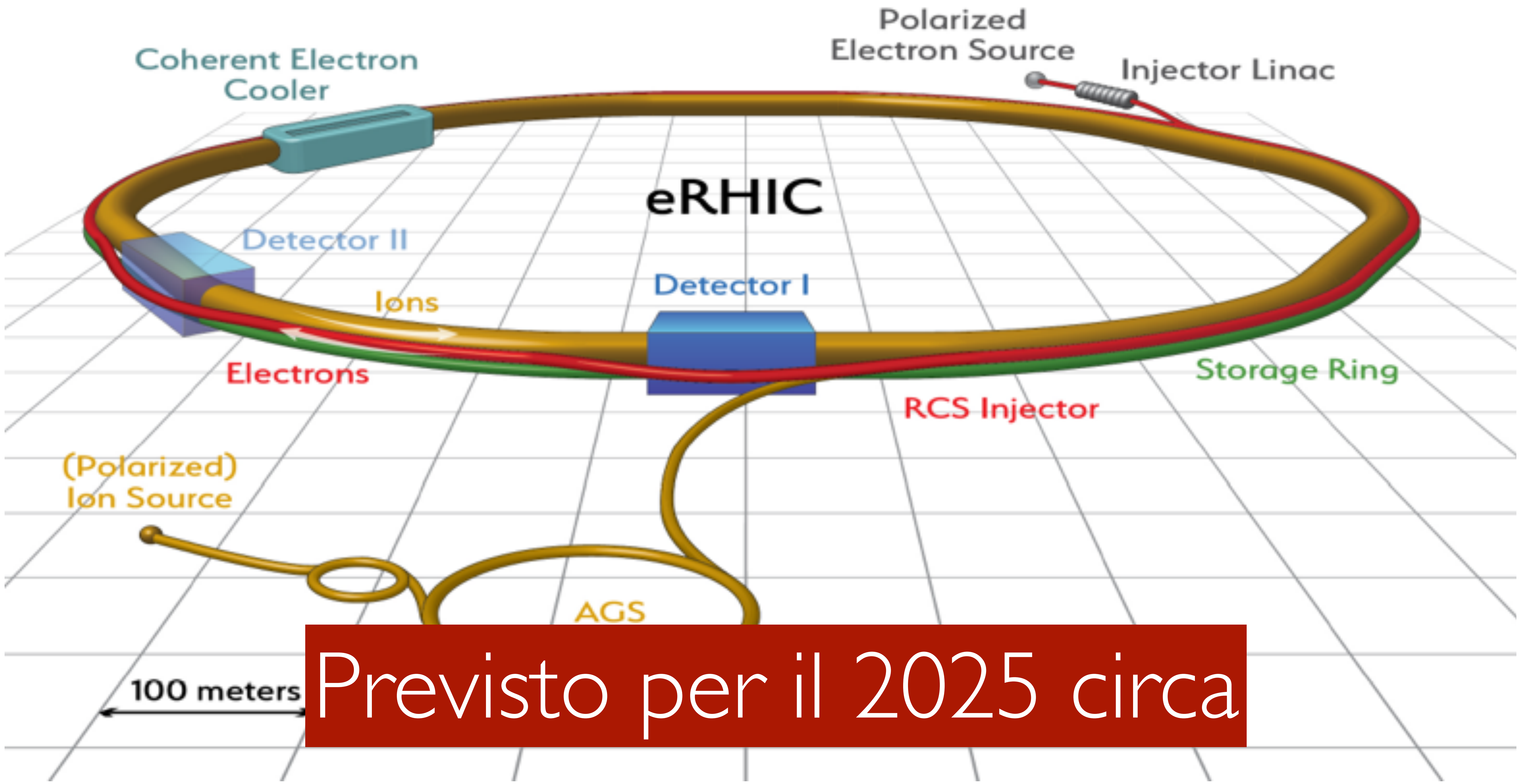




Beam Power: *1MW*
Beam Current: *90 μA*
Max Pass energy: *2.2 GeV*
Max Enery Hall A-C: *10.9 GeV*
Max Energy Hall D: *12 GeV*

ELECTRON ION COLLIDER

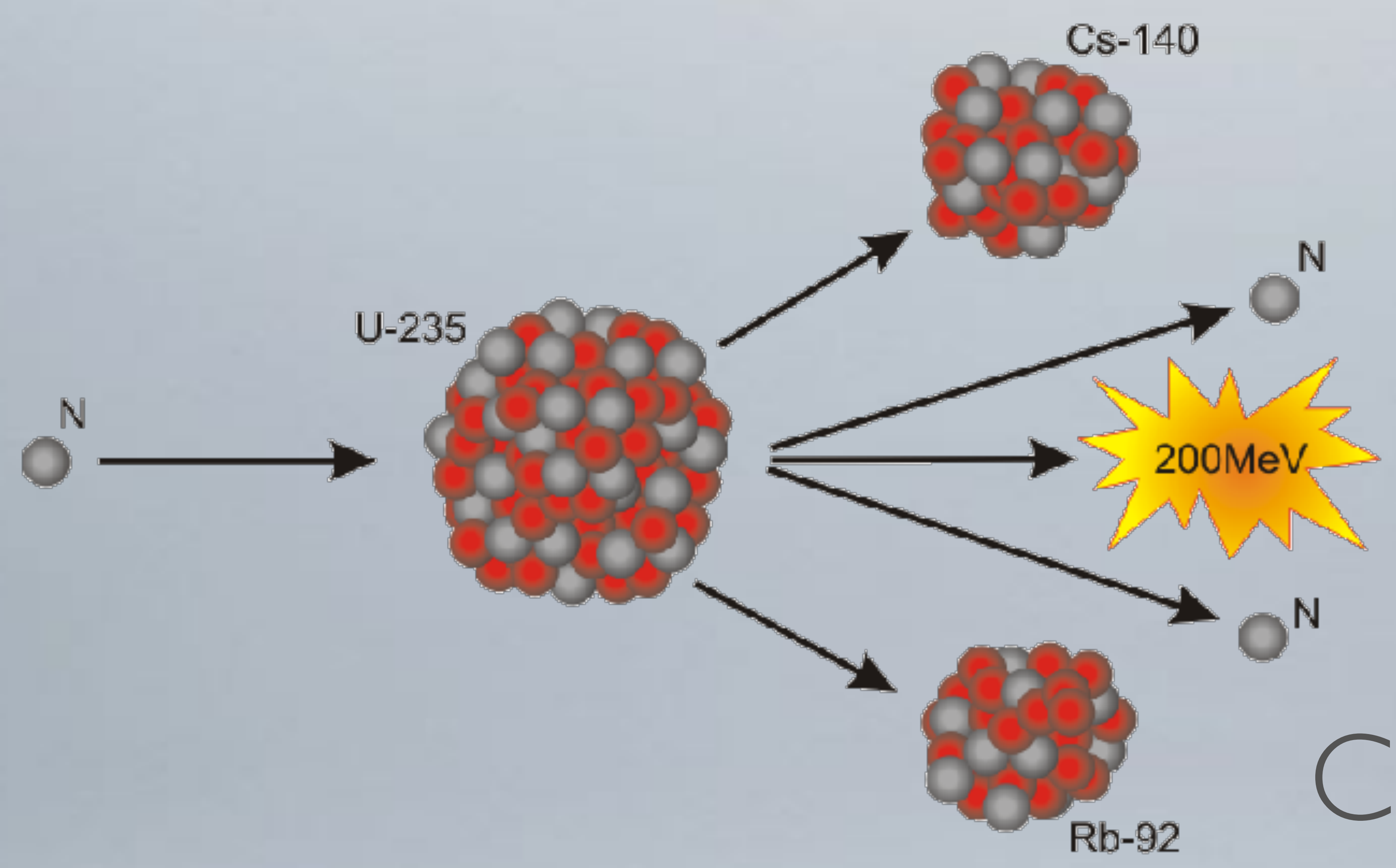
Brookhaven Natl. Lab.



Previsto per il 2025 circa

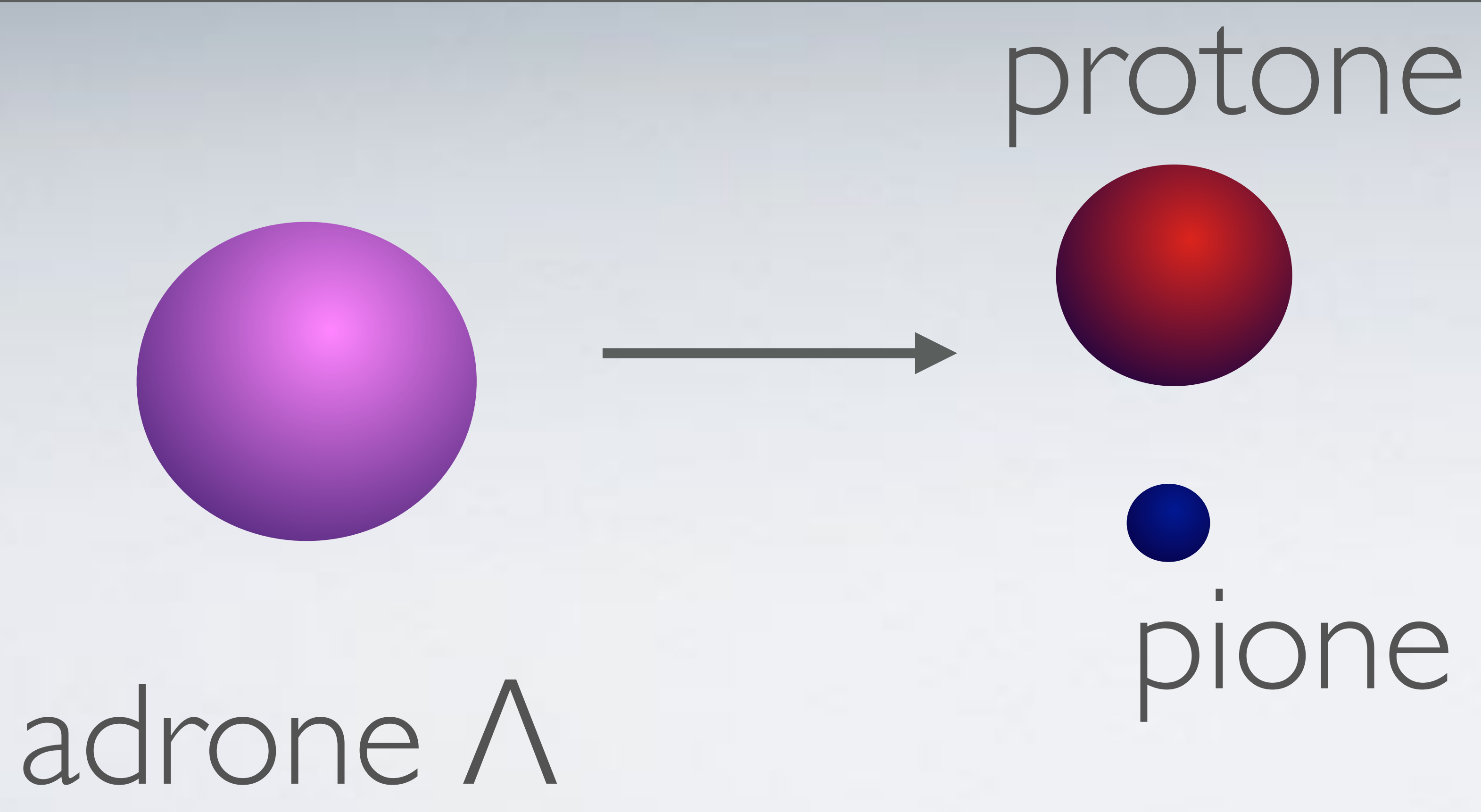
Accardi et al., The Electron Ion Collider: the next QCD Frontier, arXiv:1212.1701

APPLICAZIONI?



Fissione nucleare

Circa 1 MeV per nucleone



Decadimento adronico

Circa 100 MeV per nucleone

DAWN OF THE QUARK AGES

Dopo l'era dell'elettronica e della fotonica

A HOST OF NEW TECHNOLOGIES IS SET TO EXPLODE OUT OF THE ATOMIC NUCLEUS. MICHAEL BROOKS REPORTS

ASK them to name their heart's truest desire, and many a science nut might say the answer to life, the universe and everything – or, failing that, a fully functioning lightsaber.

Odd, then, that one field of scientific enquiry that could conceivably provide both gets so little press. After all the hoopla of the past few years, you could be forgiven for believing that understanding matter's fundamentals is all about the Higgs boson – the "God particle" that explains where mass comes from.

The Higgs is undoubtedly important. But it is actually pretty insignificant for real stuff like you and me, accounting for just 1 or 2 per cent of normal matter's mass. And the huge energy needed to make a Higgs means we're unlikely to see technology exploiting it any time soon.

Two more familiar, though less glamorous, particles might offer more. Get to grips with their complexities, and we can begin to explain how the material universe came to exist and persist, and explore mind-boggling technologies: not just lightsabers, but new sorts of lasers and materials to store energy, too. That's easier said than done, granted – but with a lot of computing muscle, it is what we are starting to do.

Chances are you know about protons and neutrons. Collectively known as nucleons, these two particles make up the nucleus, the meaty heart of the atom. (In terms of mass, the weedy electrons that orbit the nucleus are insignificant contributors to the atom.)

The headline difference between protons and neutrons is that protons have a positive electrical charge, whereas neutrons are neutral. But they also differ ever so slightly in mass: in the units that particle physicists use, the neutron weighs in at 939.6 megaelectronvolts (MeV) and the proton at 938.3 MeV.

That's a difference of just 0.14 per cent, but boy does it matter. The neutrons' extra mass means they decay into protons, not the other way around. Protons team up with negatively charged electrons to form robust, structured, electrically neutral atoms, rather than the world being a featureless neutron gloop.

"The whole universe would be very different if the proton were heavier than the neutron," says particle theorist Chris Sachrajda of the University of Southampton in the UK. "The proton is stable, so atoms are stable and we're stable." Our current best guess is that the proton's half-life, a measure of its stability over time, is at least 10^{32} years. Given that the universe only has 10^{10} or so years behind it, that is a convoluted way of saying no one has ever seen a proton decay.

The exact amount of the neutron's excess

STUDIO TONNE

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hydrogen, wl
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University of
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answer. We'v
protons and
particles, but

overall balance between colours.

Quarks also carry electrical charge – the up quark has a charge of +2/3, the down quark -1/3. But oddly they only ever make up larger particles with zero or whole-number electric charge.

WALT DISNEY STUDIOS/SUPPLIED BY LMK

scale. "I think the possibility of powerful X-ray or gamma-ray sources exploiting sophisticated nuclear physics is speculative, but not outrageously so," says Wilczek.

Gluons, unlike photons, also interact with themselves, and this could conceivably see them confining each other into a writhing pillar of energy – hence Wilczek's tongue-in-cheek suggestion they might make a *Star Wars*-style lightsaber. More immediate, perhaps, is the prospect of better ways to harness and store energy. "Nuclei can pack a lot of energy into a small space," says Wilczek. "If we can do really accurate nuclear chemistry by calculation as opposed to having hit-and-miss experiments, it could very well lead to dense energy storage."

For Fodor, that's still a long way off – but with the accuracy that calculations are now reaching, the road is at last open. "These are mostly dreams today, but now we can accommodate the dreams, at least," he says. "You've reached a level where these technological ideas might be feasible."

Welcome, indeed, to the quark ages. ■

Michael Brooks is a consultant for *New Scientist*