PARTICLE HUNTER: A FIELD GUIDE

POK MAN LO

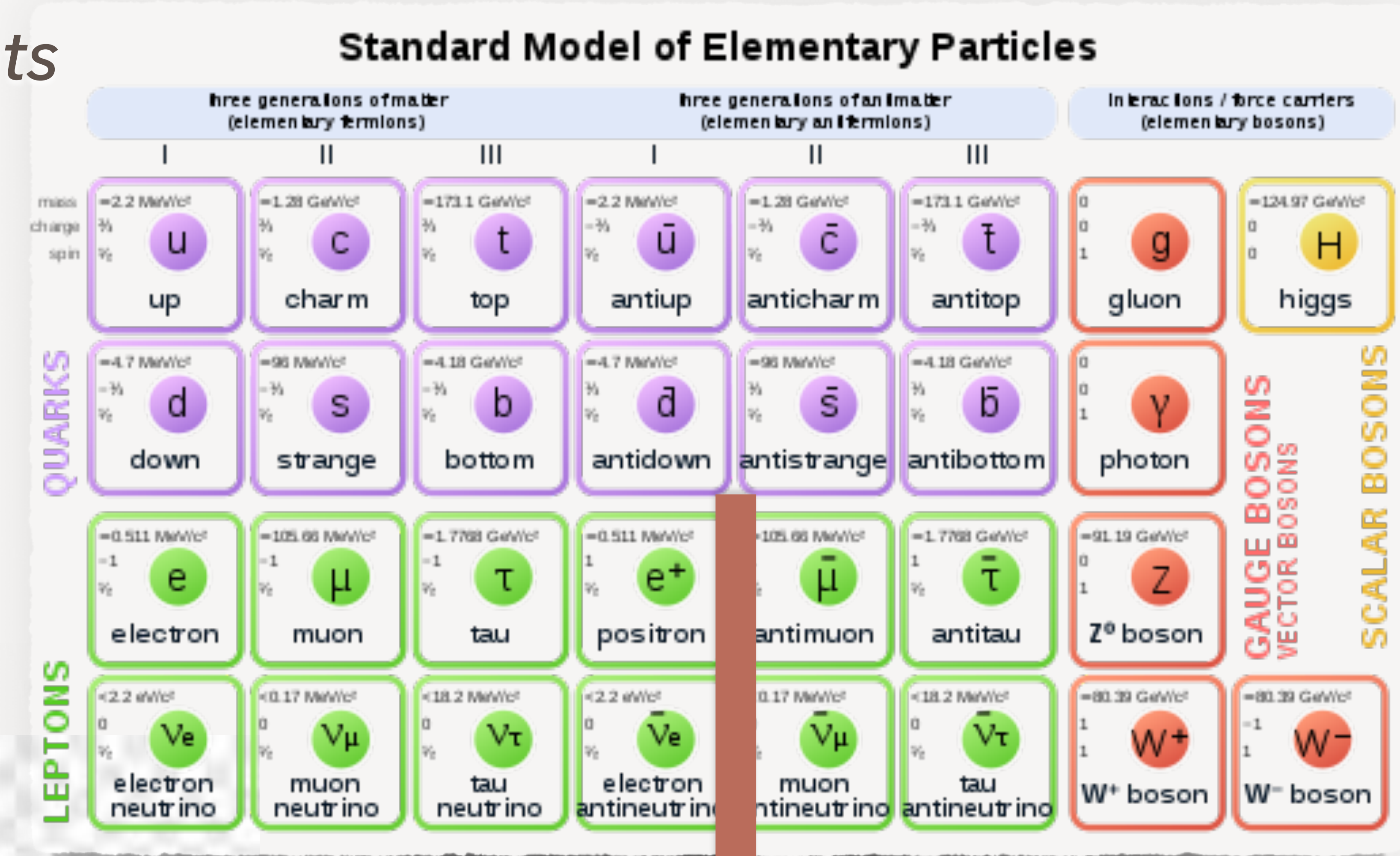
University of Wroclaw

5 OCT, 2021

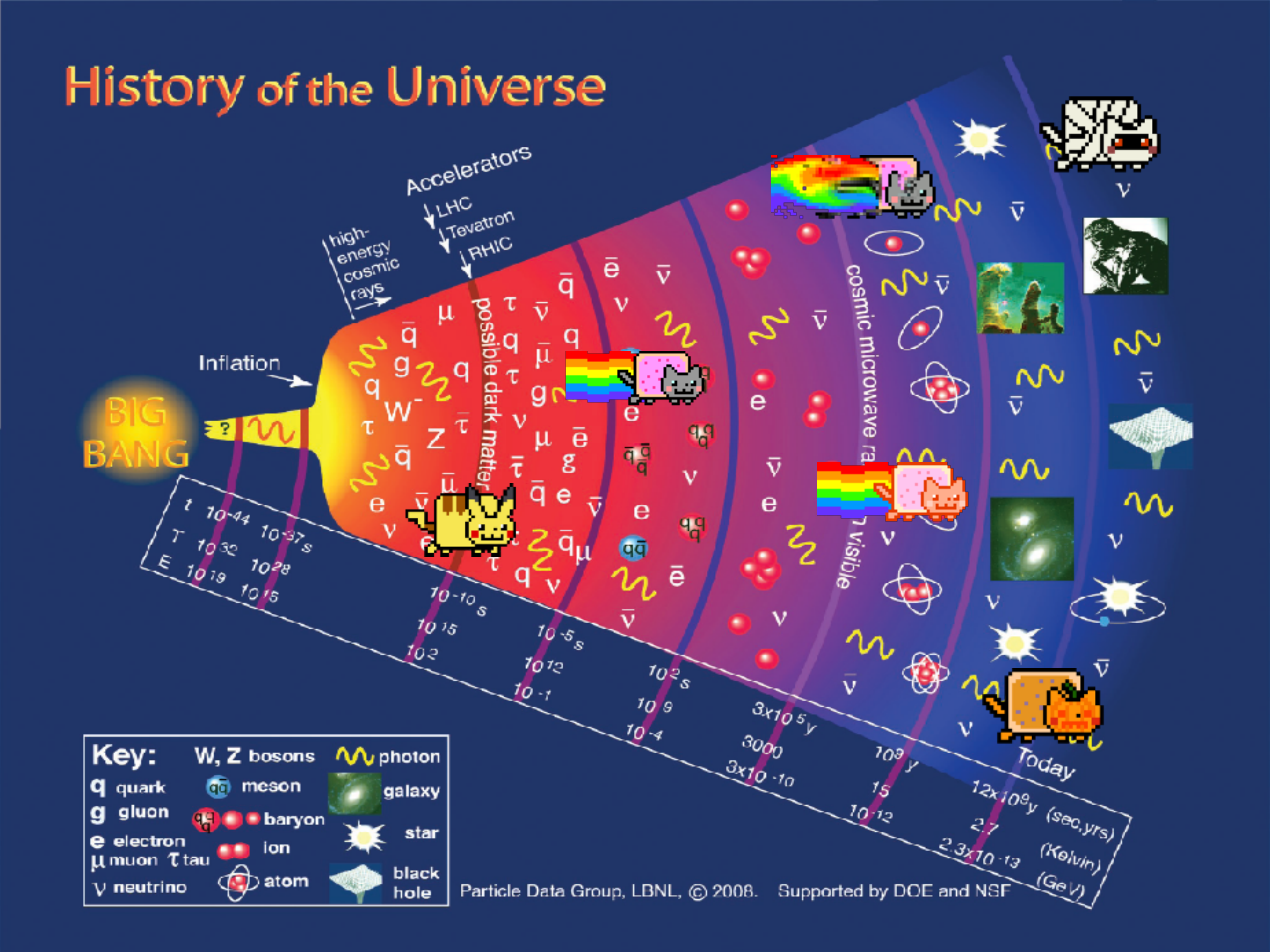
pokman.lo@uni.wroc.pl

PHYSICS FAIRY TALES

ingredients



Com’on kiddos, Grandma’s got some hot stuffs!

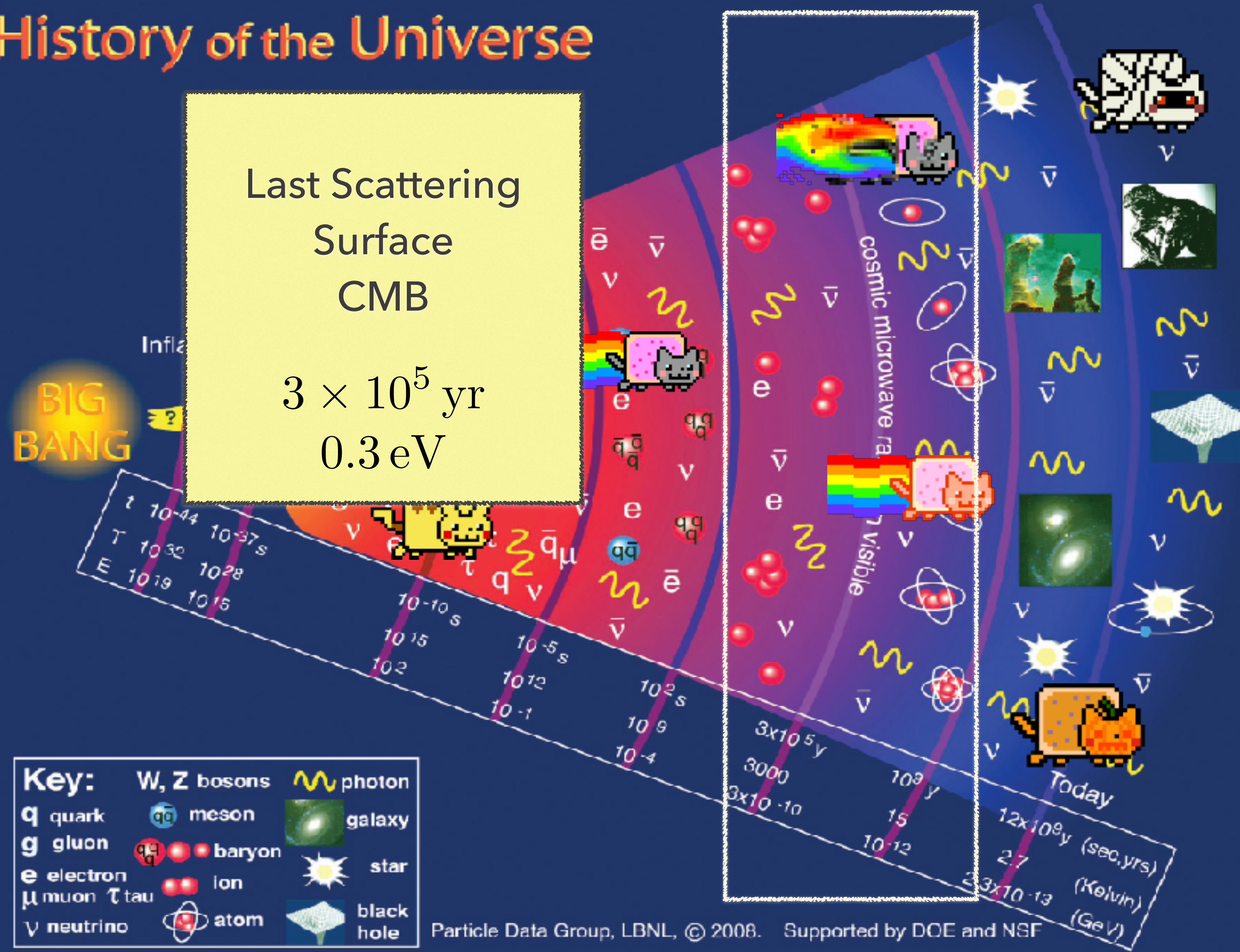


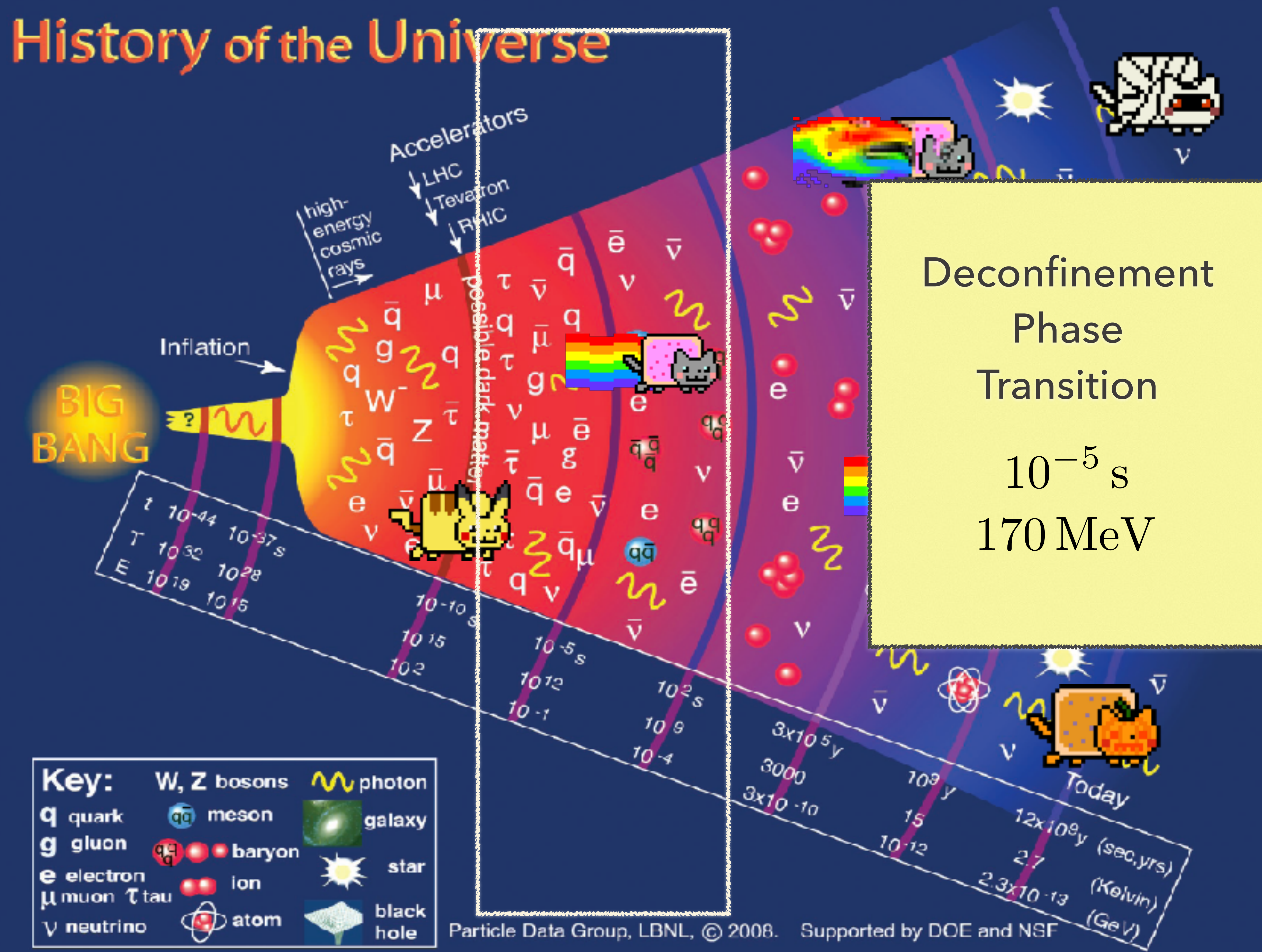
History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter
cosmic microwave ra
visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 16
10-10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

History of the Universe

Last Scattering
Surface
CMB

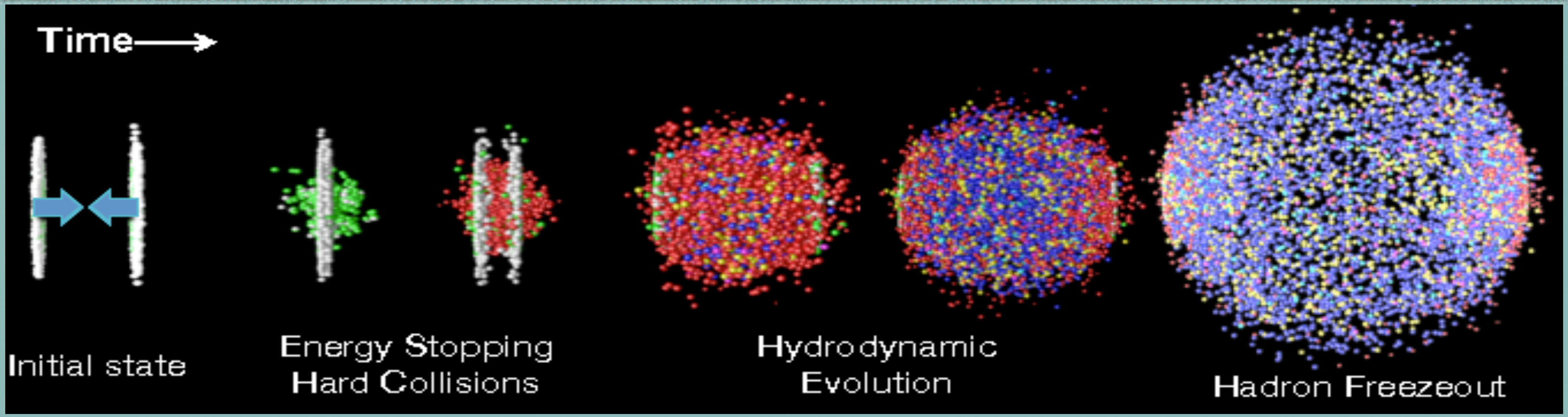
3×10^5 yr
$0.3\,\mathrm{eV}$

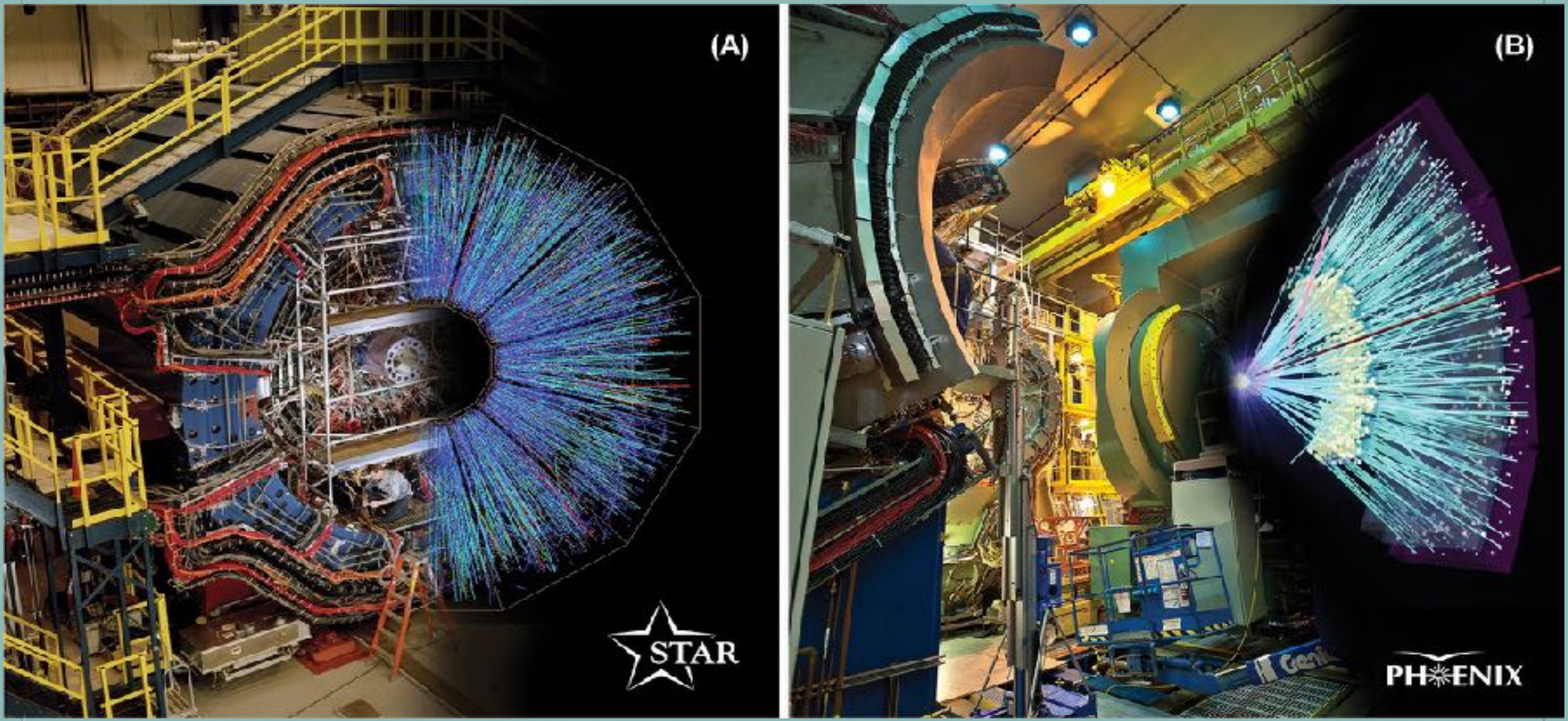



History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter
Deconfinement
Phase
Transition
10^{-5} s
170 MeV
t 10^{-44} 10^{-37}s 10^{-10}s 10^{-5}s 10^{2}s 3×10^{5}y 10^{9}y 12×10^{9}y (sec,yrs)
T 10^{32} 10^{28} 10^{15} 10^{12} 10^{9} 3000 15 2.7 (Kelvin)
E 10^{19} 10^{16} 10^{2} 10^{-1} 10^{-4} 3×10^{-10} 10^{-12} 2.3×10^{-13} (GeV)
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

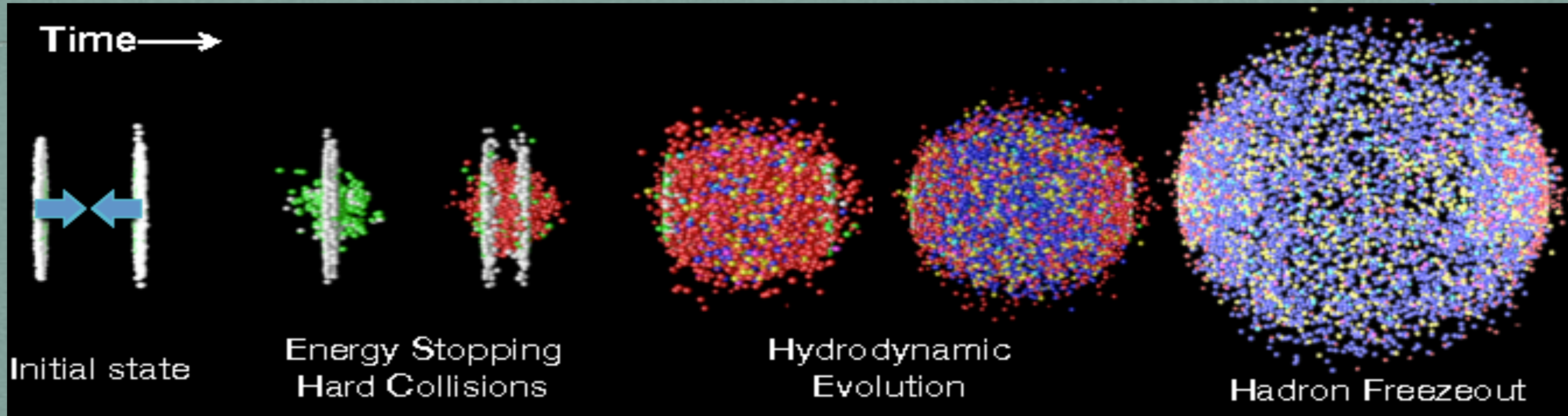
WHERE TO FIND THE PARTICLES??

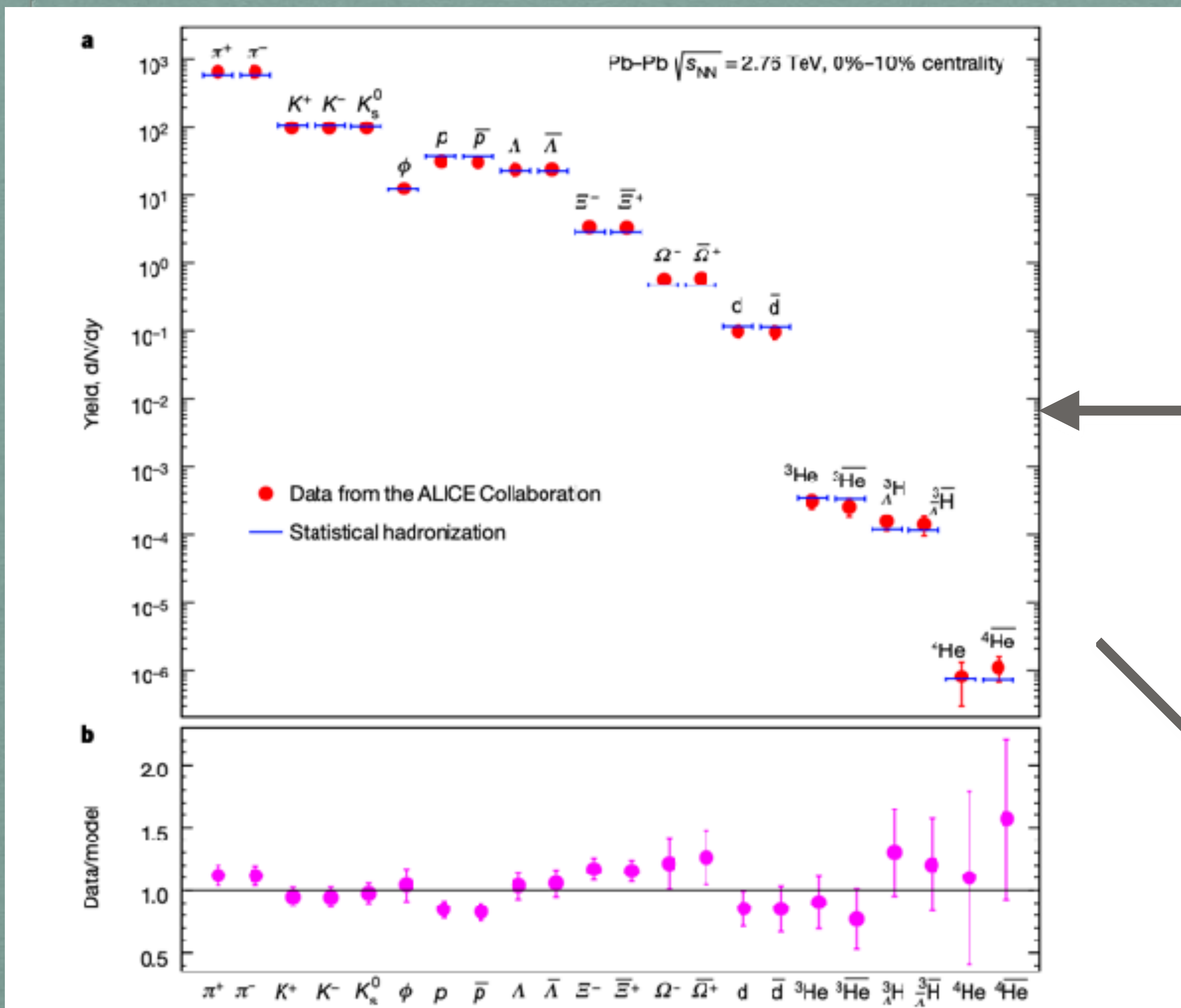
- go back in time, or ask Granny to do it again?
- look at special astronomical objects: neutron stars, black holes
- build an accelerator on earth


Time
Initial state
Energy Stopping
Hard Collisions
Hydrodynamic
Evolution
Hadron Freezeout


(A)
STAR
(B)
PHENIX

Central Au+Au 200 GeV/nucleon
MADAI
Simulation with UrQMD





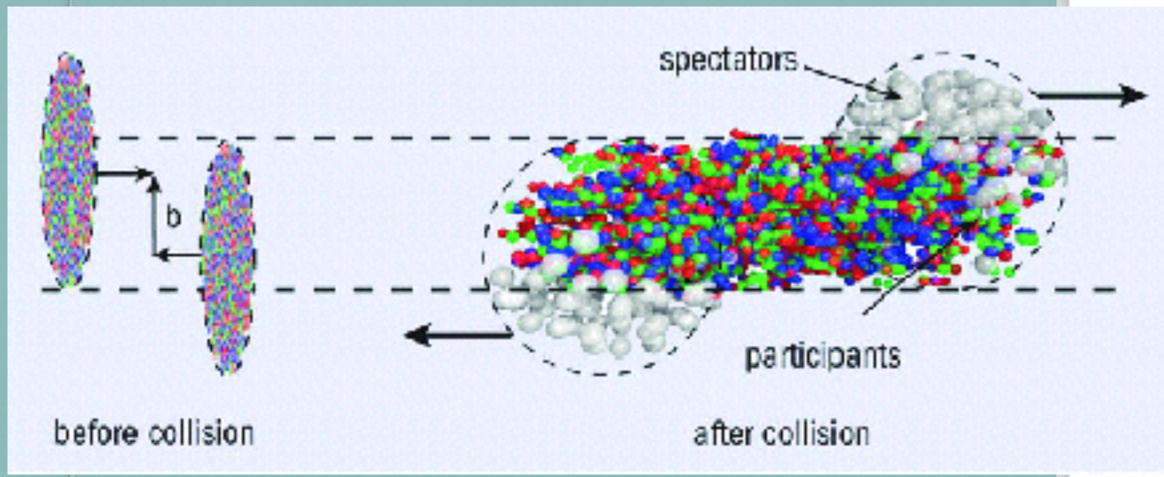
freezeout hadrons yields described by HRG

Freezeout parameters

$$T^f, \mu_B^f, \mu_S^f, \mu_Q^f, \ldots$$

A. Andronic et al 2018 Nature **561,** 321-330 (2018)

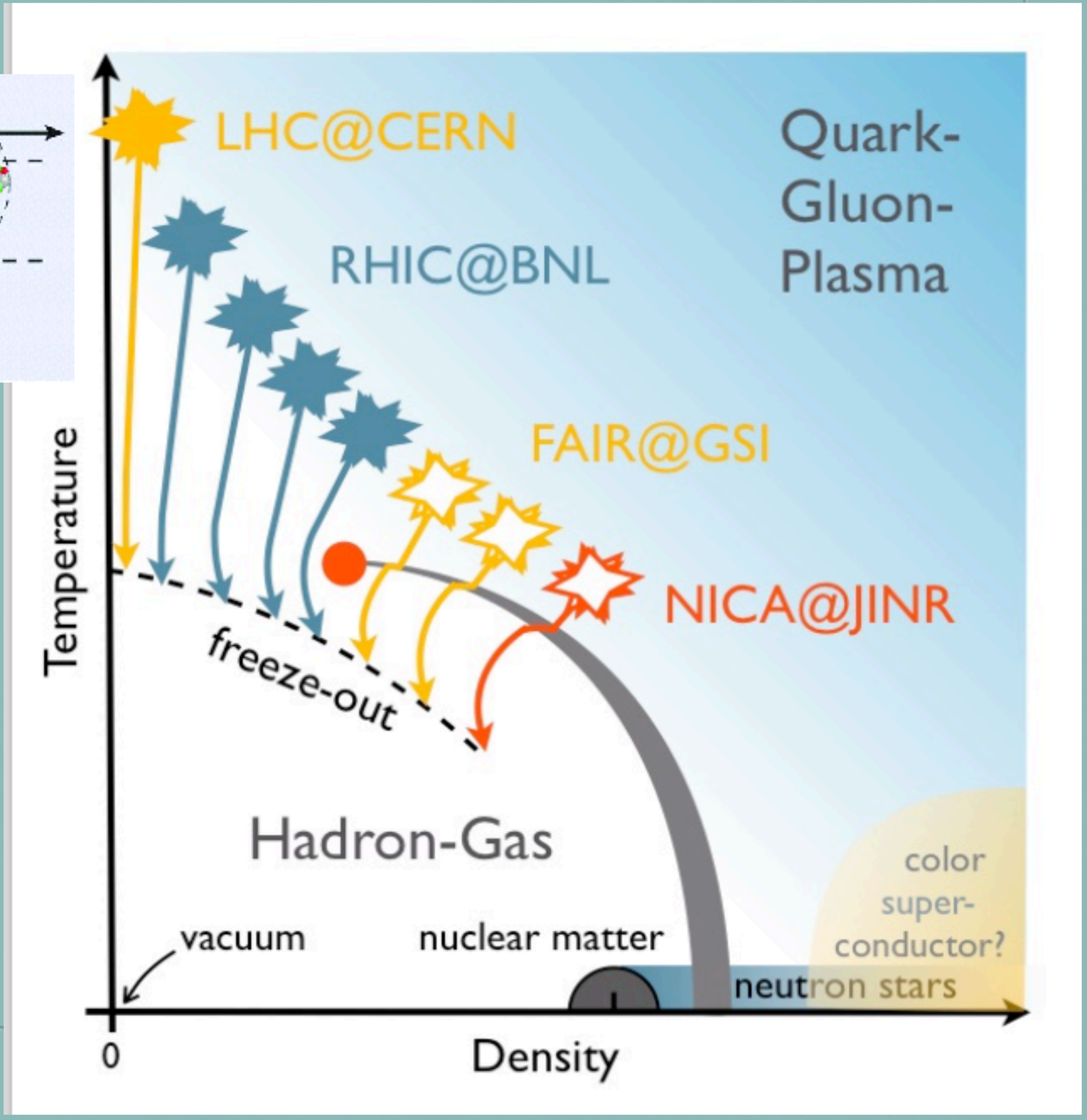
BEAM ENERGY SCAN



$$\sqrt{s}, b, (Z, A), \ldots$$

$$\Updownarrow$$

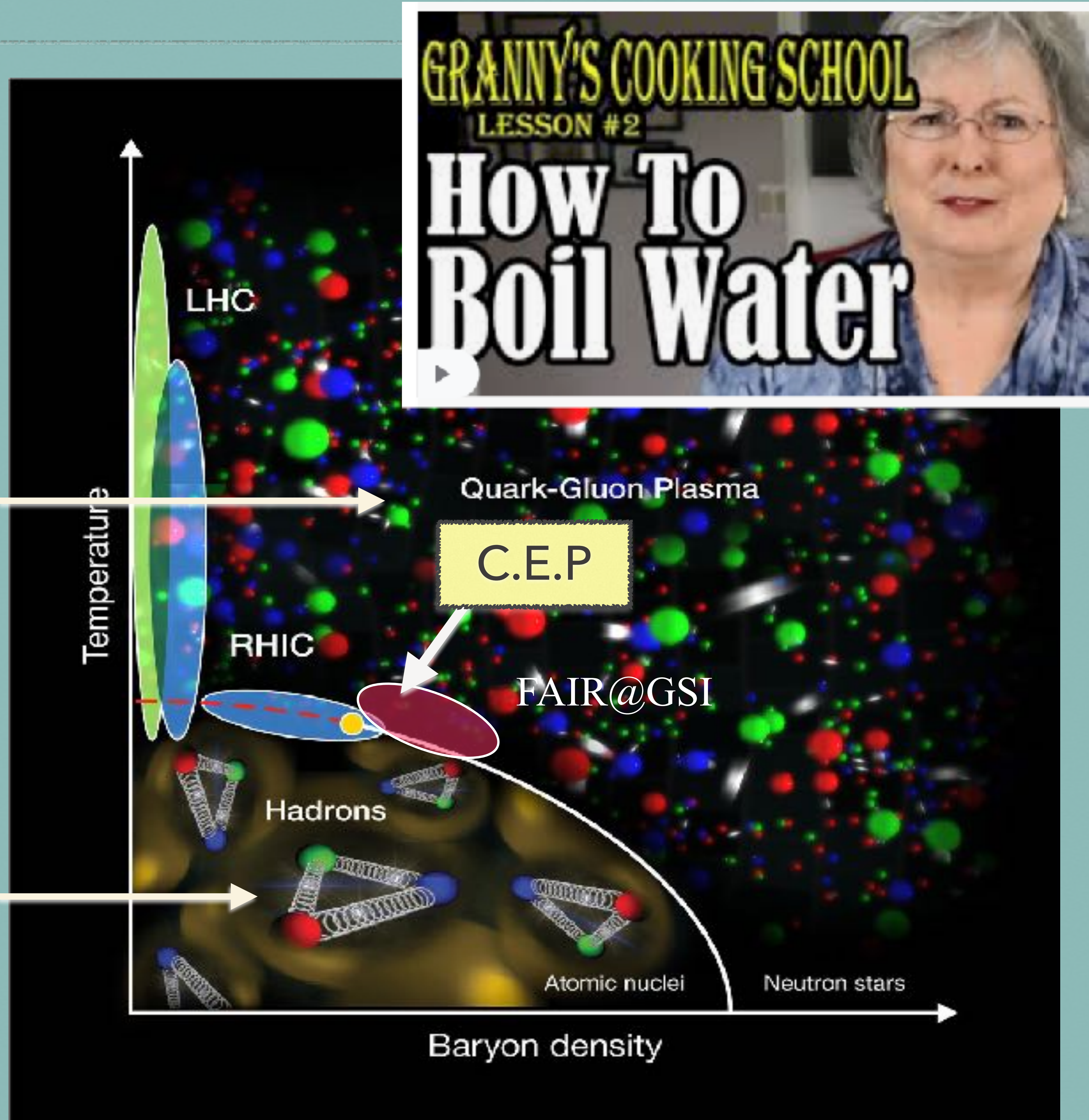
$$T, \mu, B, \ldots$$



QCD Phase Diagram

QGP:
quarks and gluons
are deconfined.

Hadronic phase:
quarks are confined
and massive.



Courtesy of Brookhaven National Laboratory

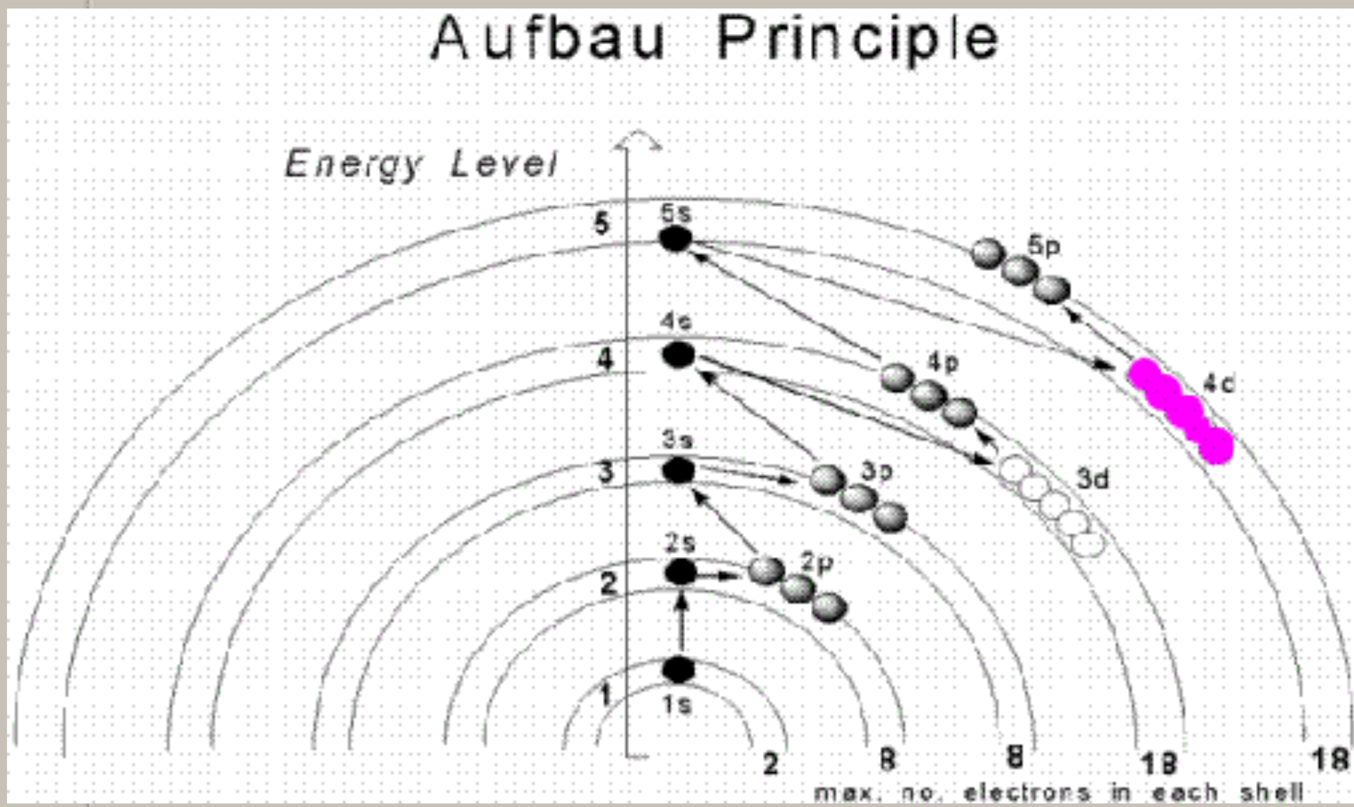
FORCE LAWS

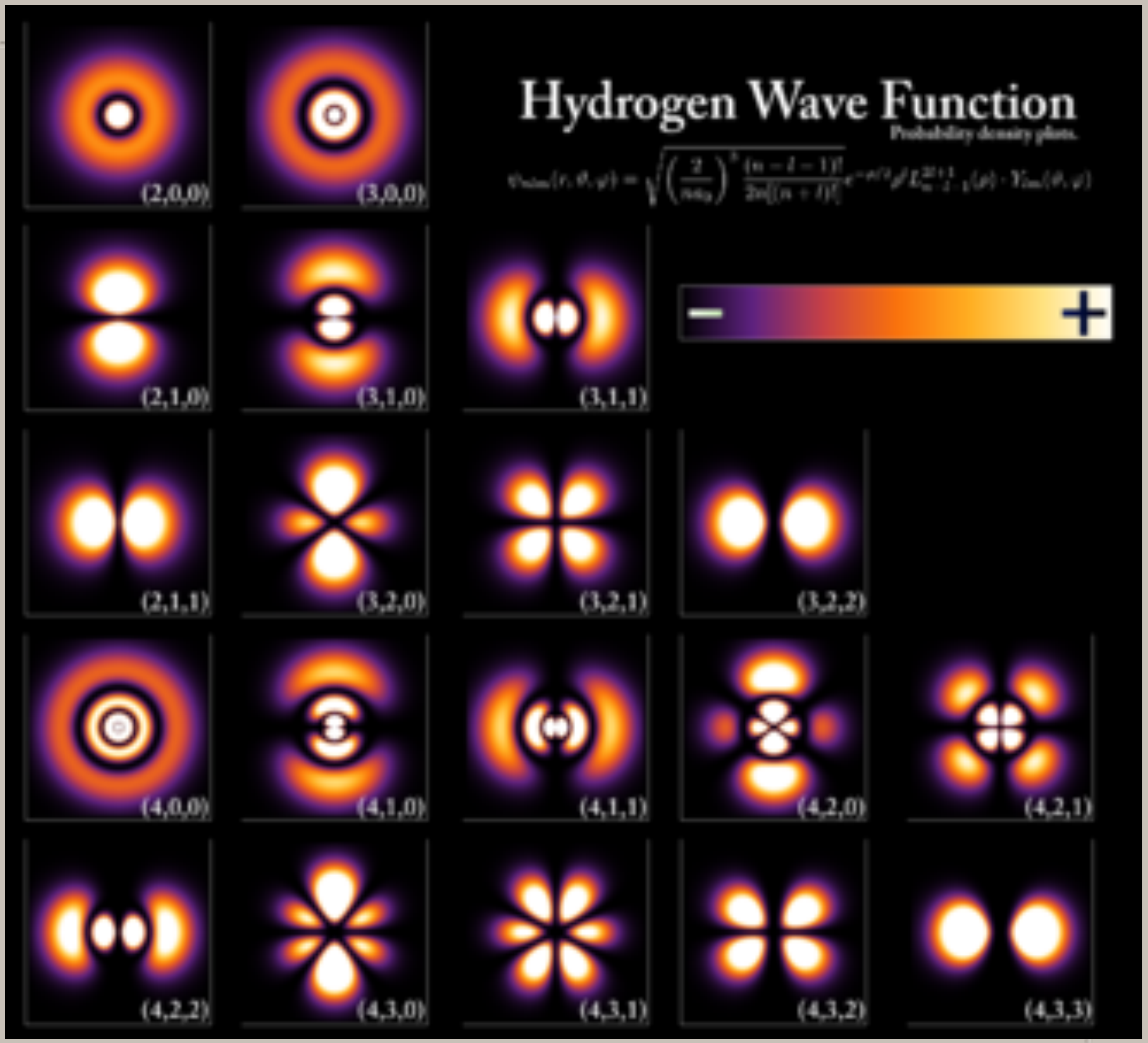
The Periodic Table

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

What is so Periodic?

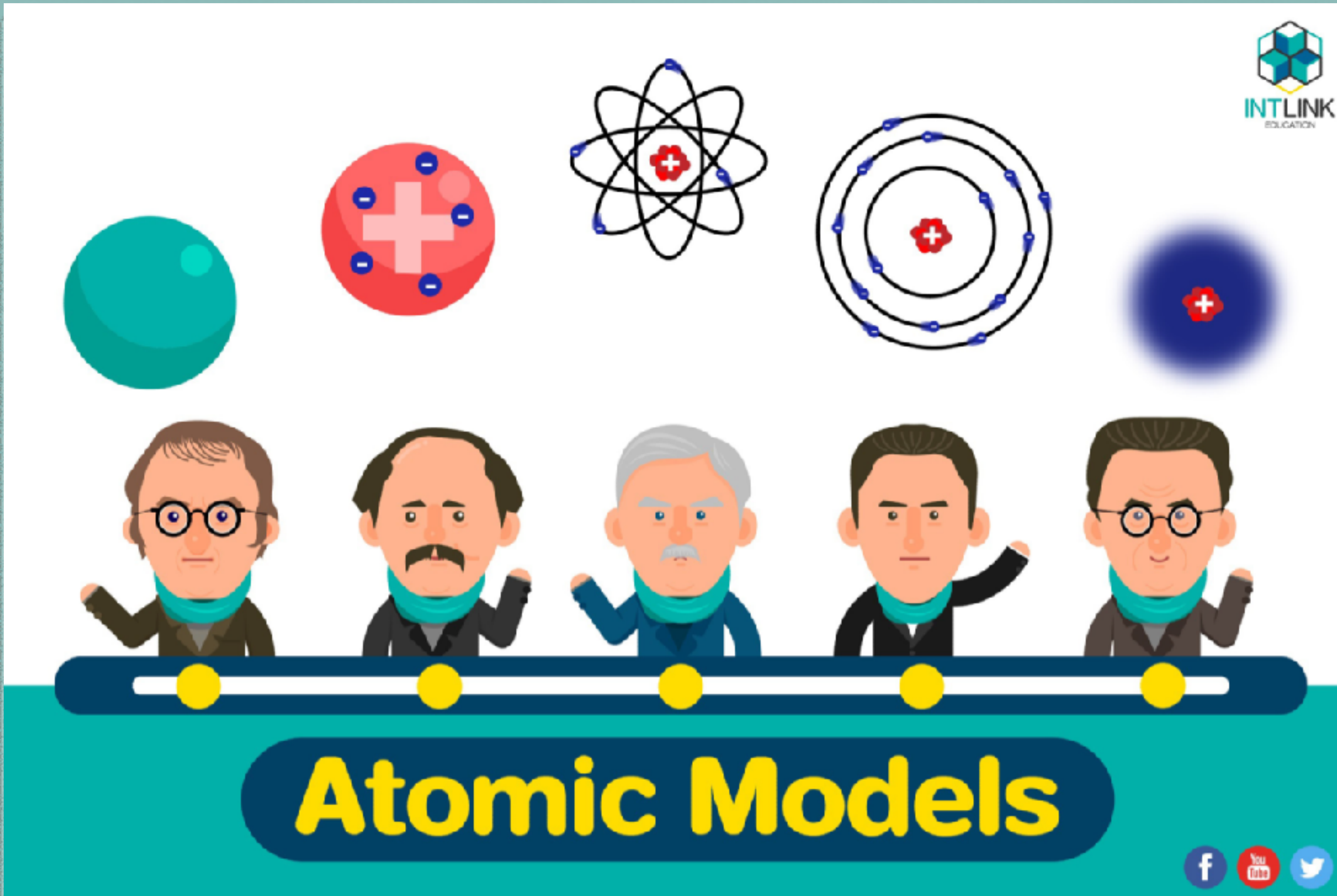
(n, l, m)



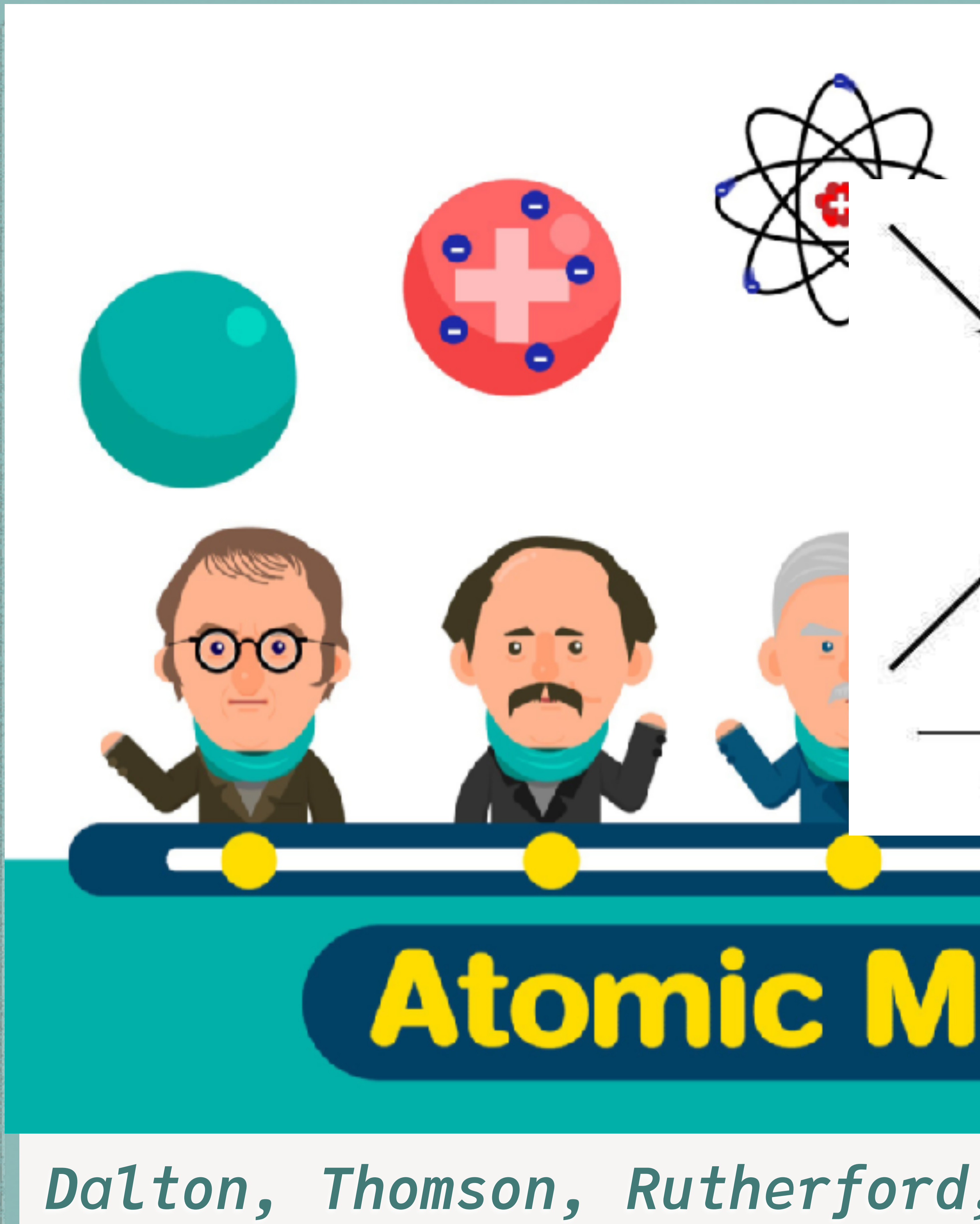


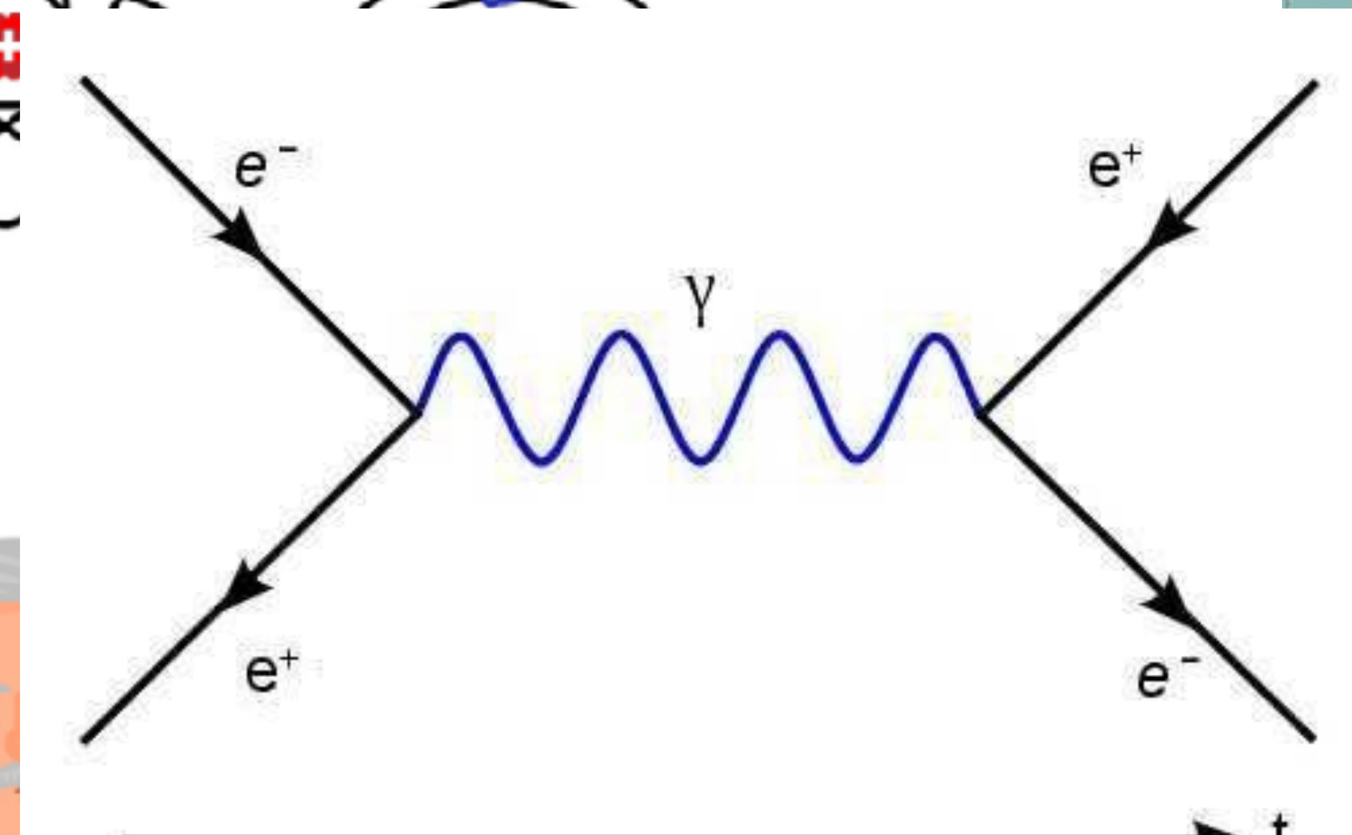

```
1s
2s                                                      2p  2p  2p
3s                                                      3p  3p  3p
4s                                  3d  3d  3d  3d  3d  4p  4p  4p
5s                                  4d  4d  4d  4d  4d  5p  5p  5p
6s  4f  4f  4f  4f  4f  4f  4f  5d  5d  5d  5d  5d  6p  6p  6p
7s  5f  5f  5f  5f  5f  5f  5f  6d  6d  6d  6d  6d  7p  7p  7p
```

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

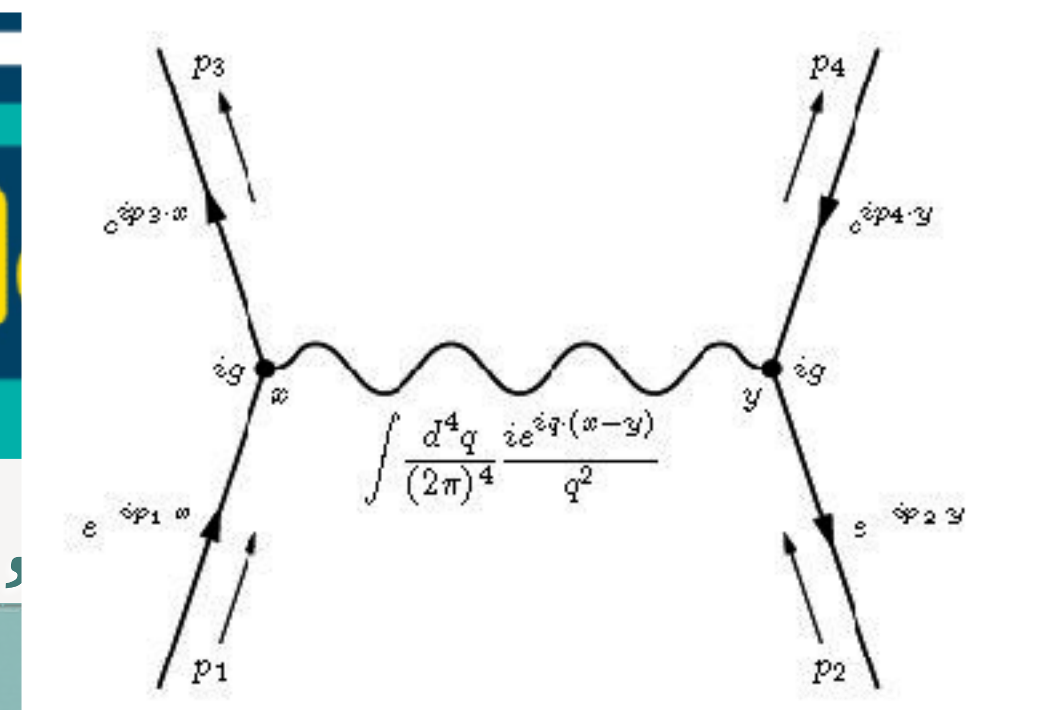


Dalton, Thomson, Rutherford, Bohr, Schroedinger





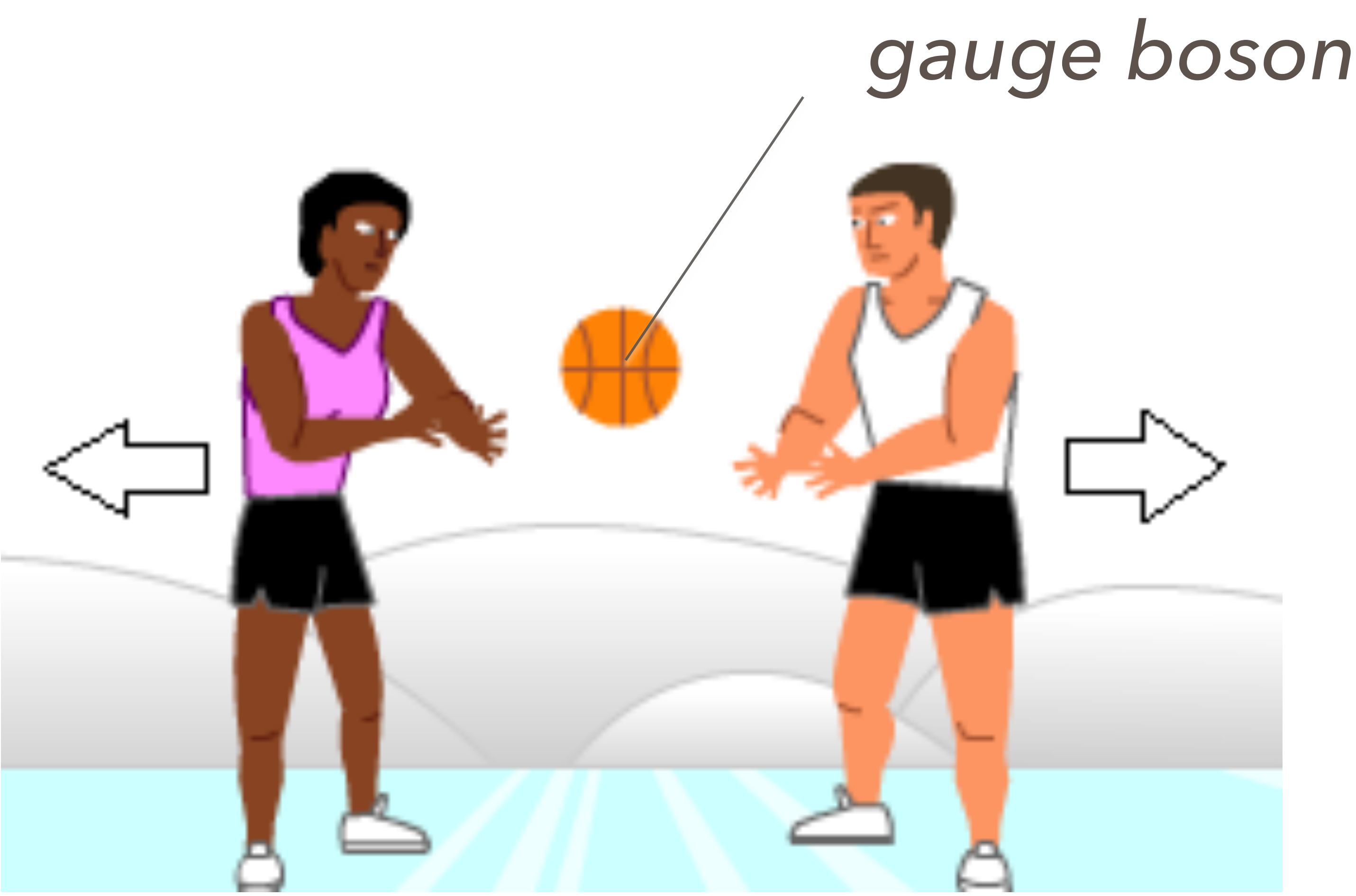
Annihilation of an electron and a positron creating a photon which decays into a new electron positron pair

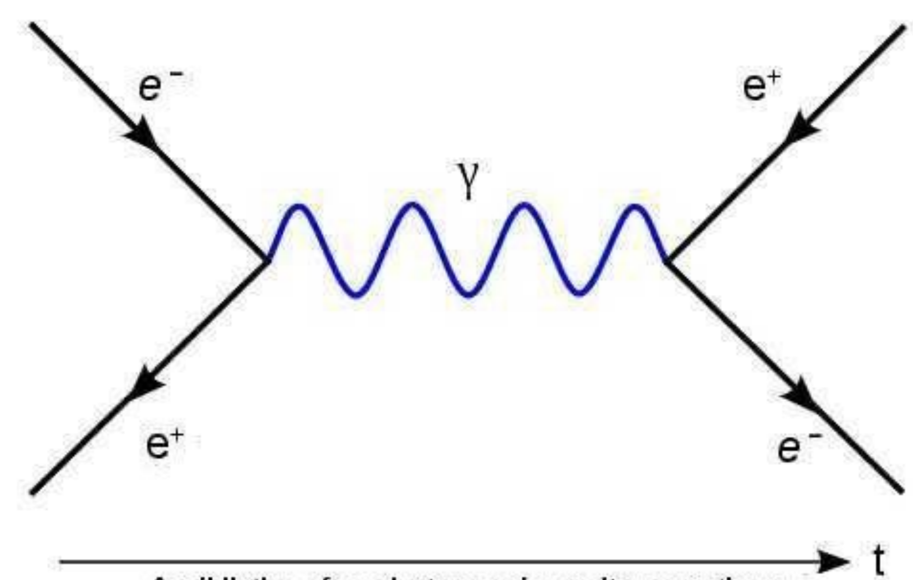


Properties of the Interactions

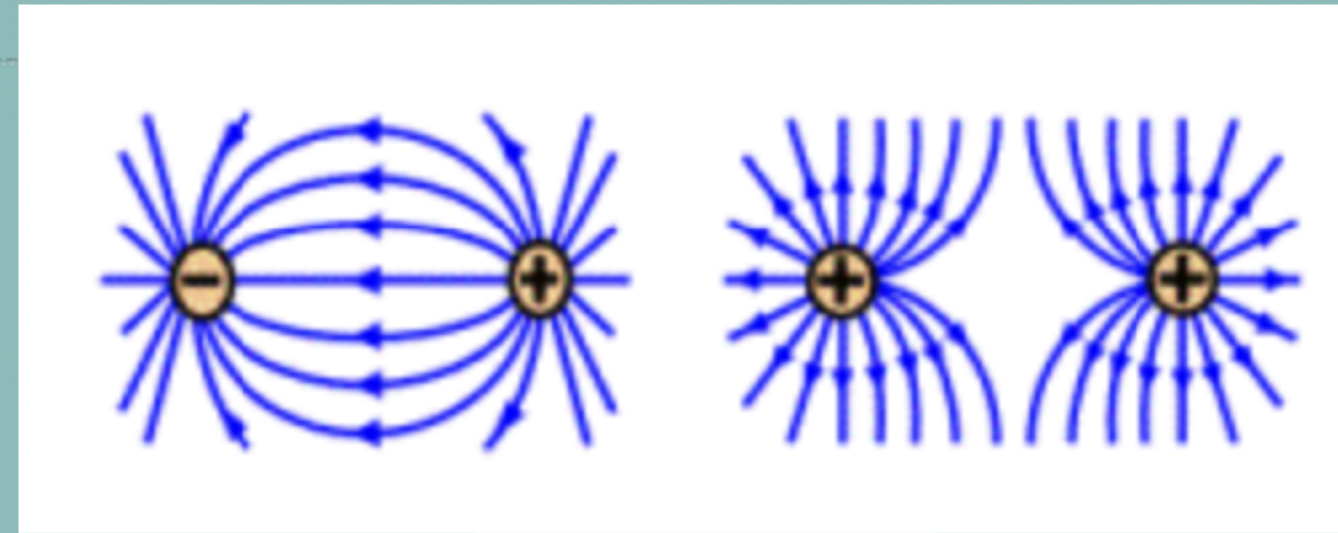
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

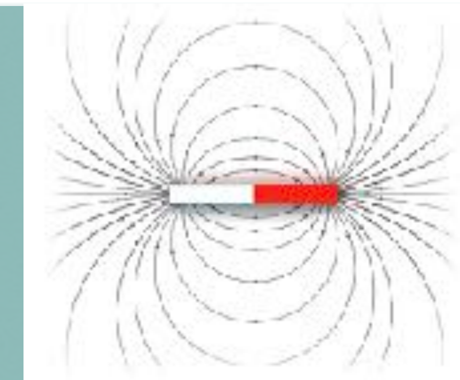
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60



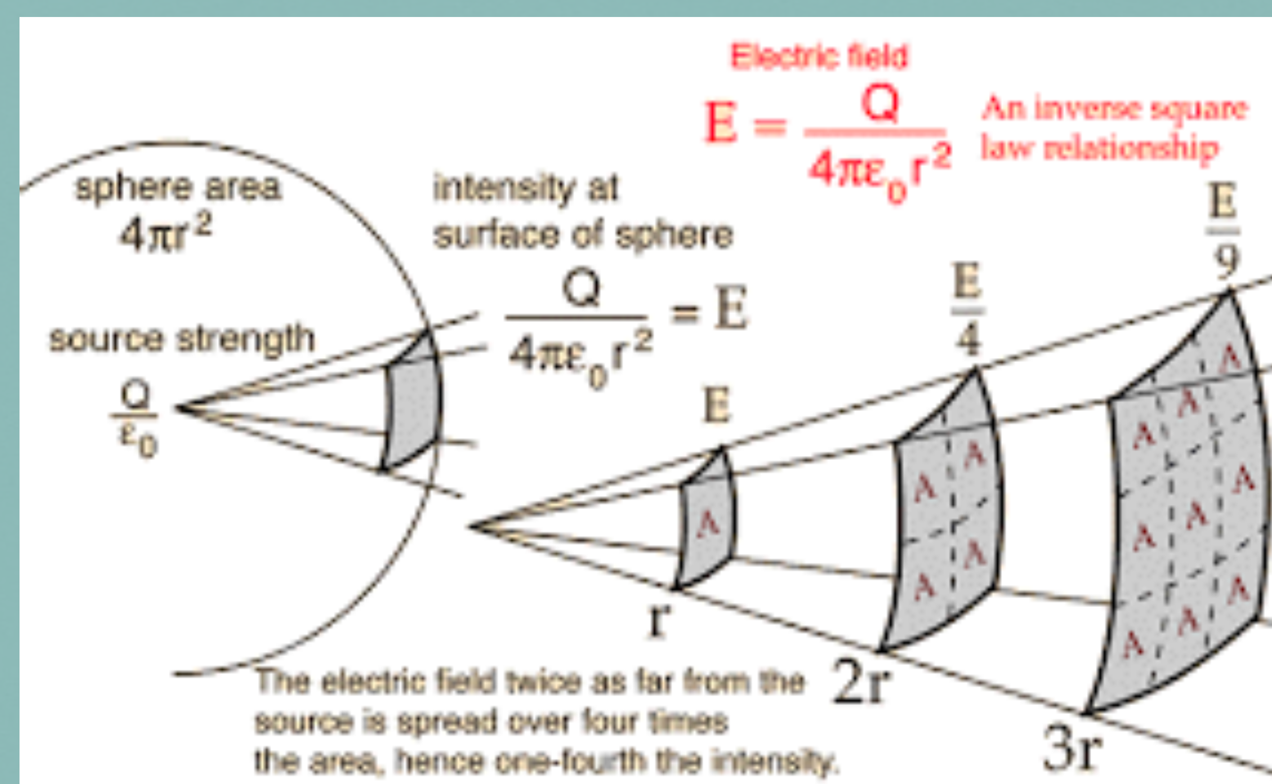


Annihilation of an electron and a positron creating a photon which decays into a new electron positron pair electric charge: +, -





inverse square law



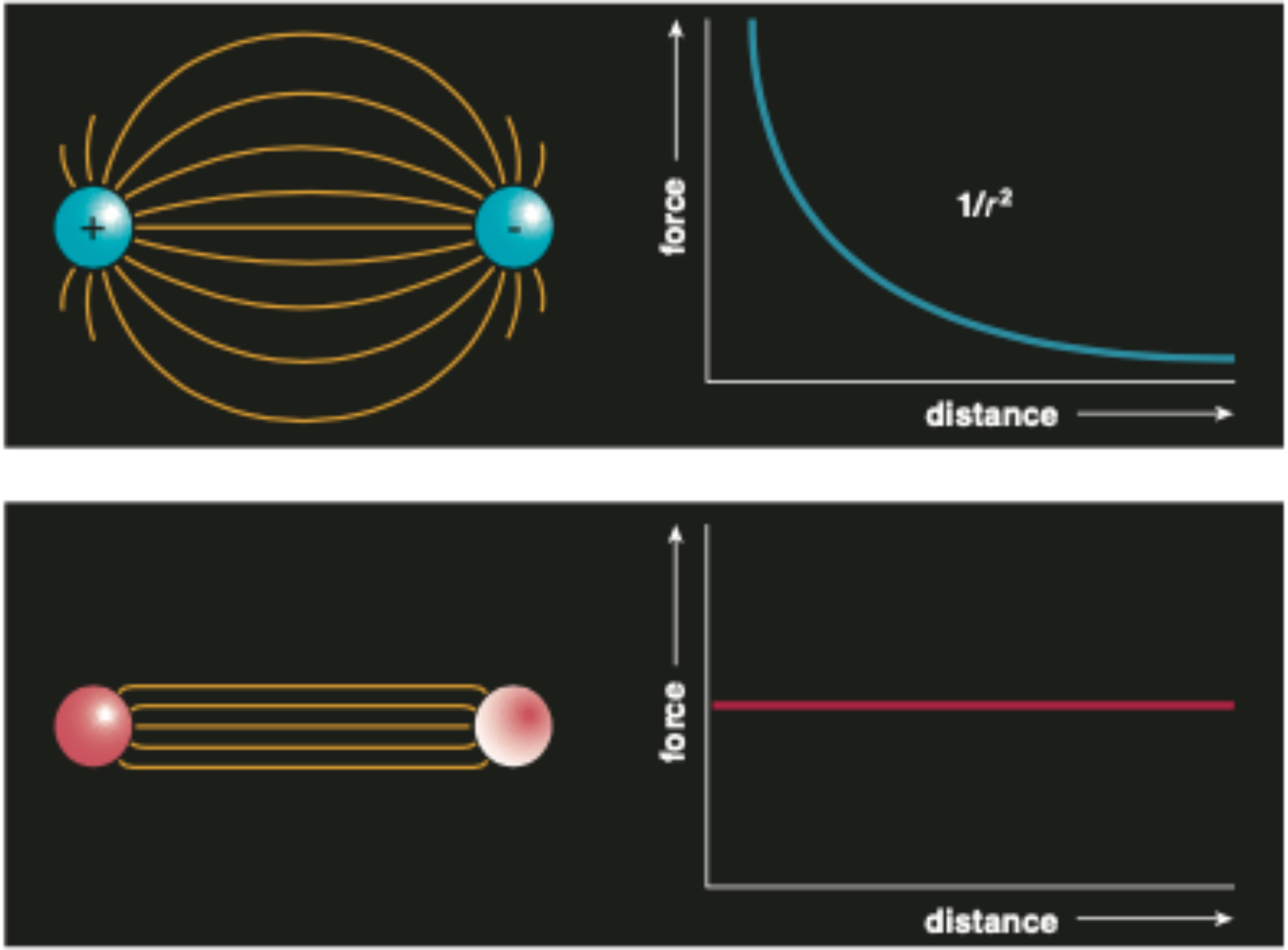
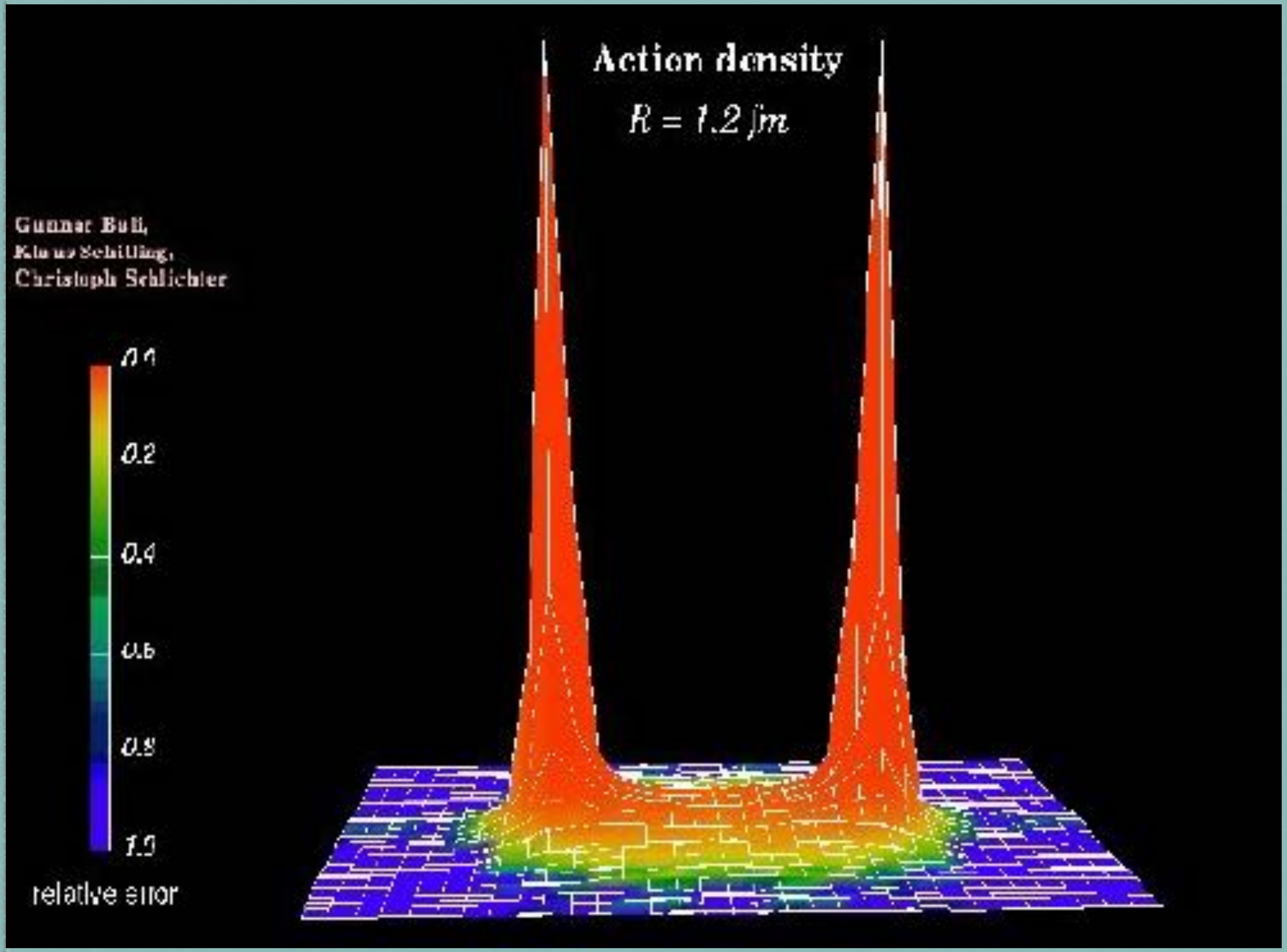
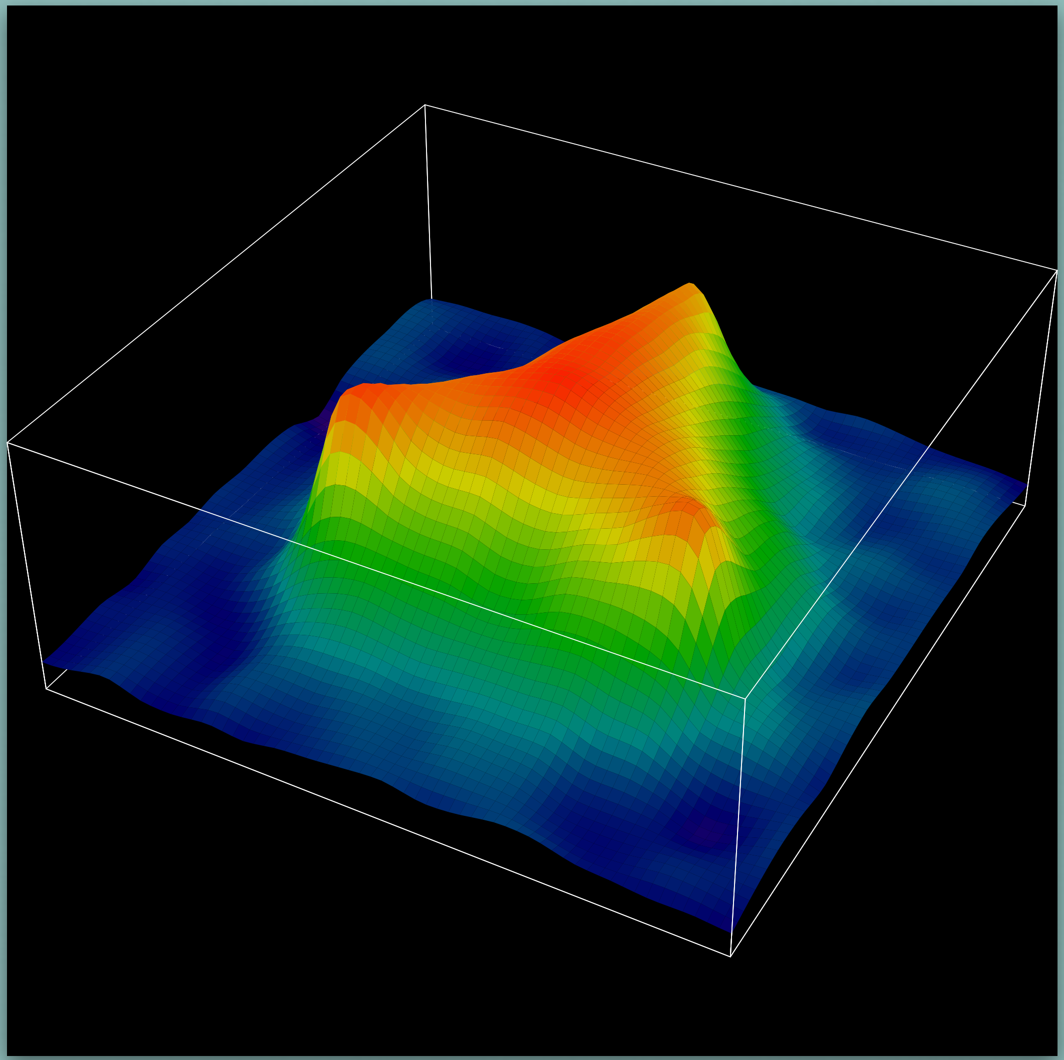


Figure 7. Electric-field lines that connect two oppositely charged particles tend to spread outward, giving rise to a property that is characteristic for the electrostatic (Coulomb) force as well as for gravity: Magnitude of the force diminishes with the square of distance from a charge or mass *(top)*. The quantum chromomagnetic field lines that connect two quarks, however, remain in a tight bundle, which provides a constant force *(bottom)*.

PICTURES OF BARYONS AND MESONS



Bali *et. al.*



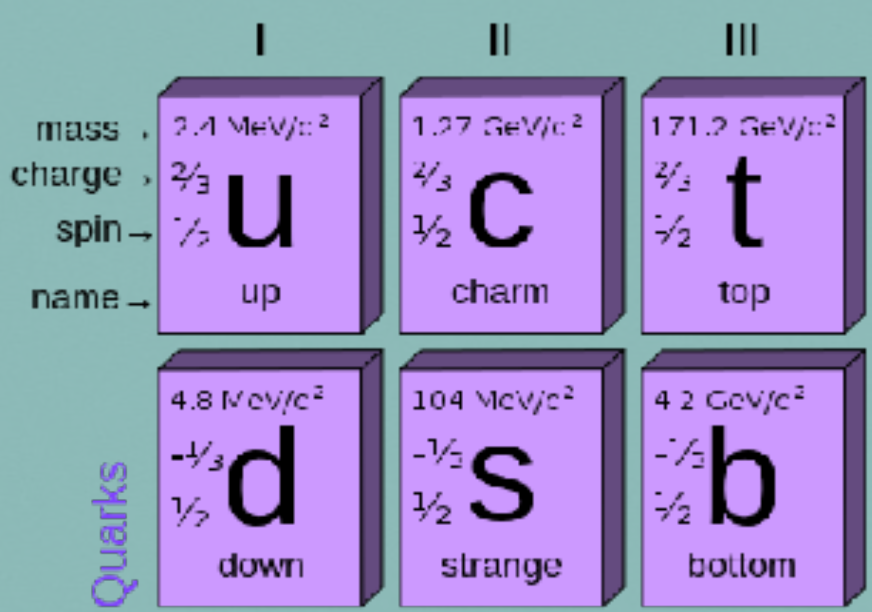
Ichie *et al.*

QCD: THEORY OF HADRONS

INTRODUCTION TO QCD

Quarks

fundamental representation (3) of SU(3)



$+2/3$

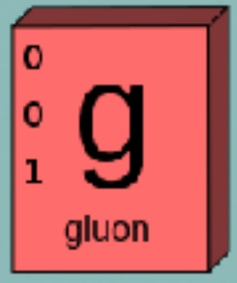
$-1/3$

Gluons

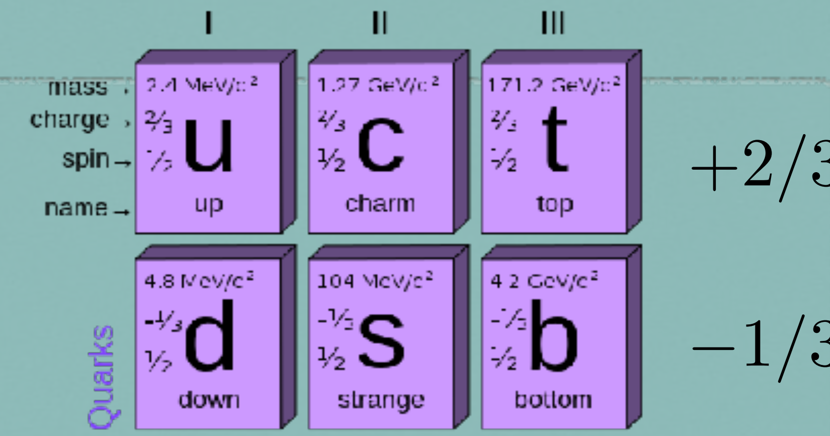
adjoint representation

$$\mathrm{A}_\mu = A_\mu^a T^a$$

$$\mathrm{T}^a = \tfrac{1}{2}(\lambda_{ij})_{3\times 3}$$



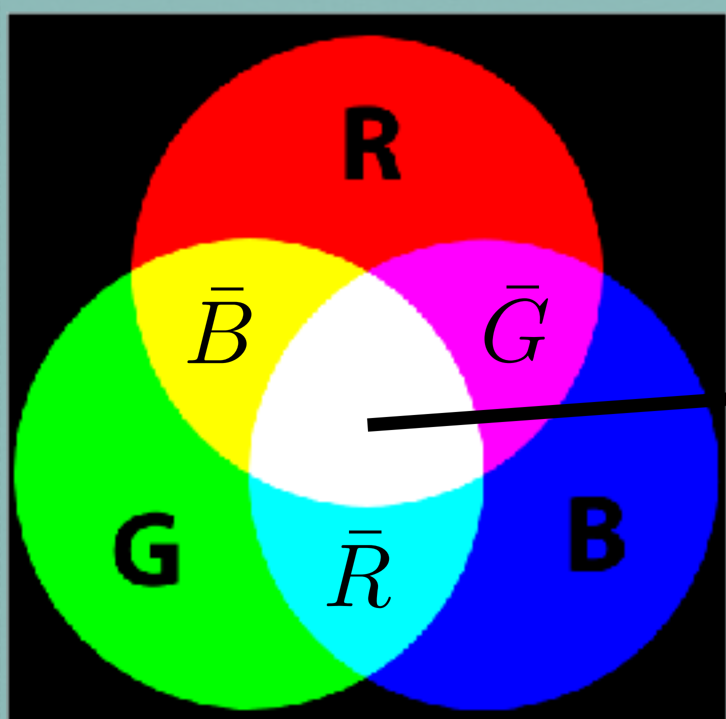
CONFINEMENT

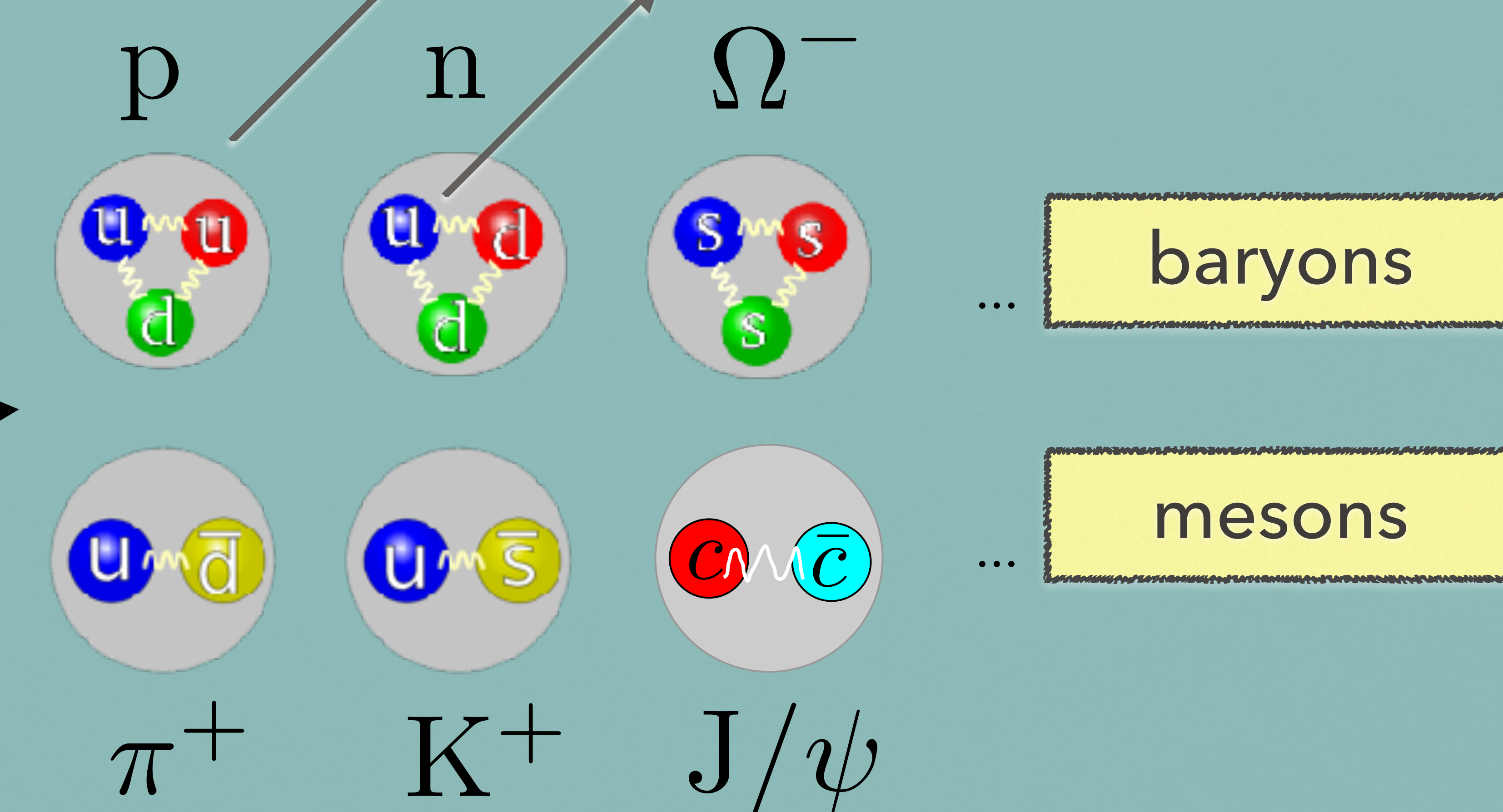


- Only colorless states can exist as free particles
- QCD bound states: hadrons

$$2/3 + 2/3 + -1/3 = 1$$

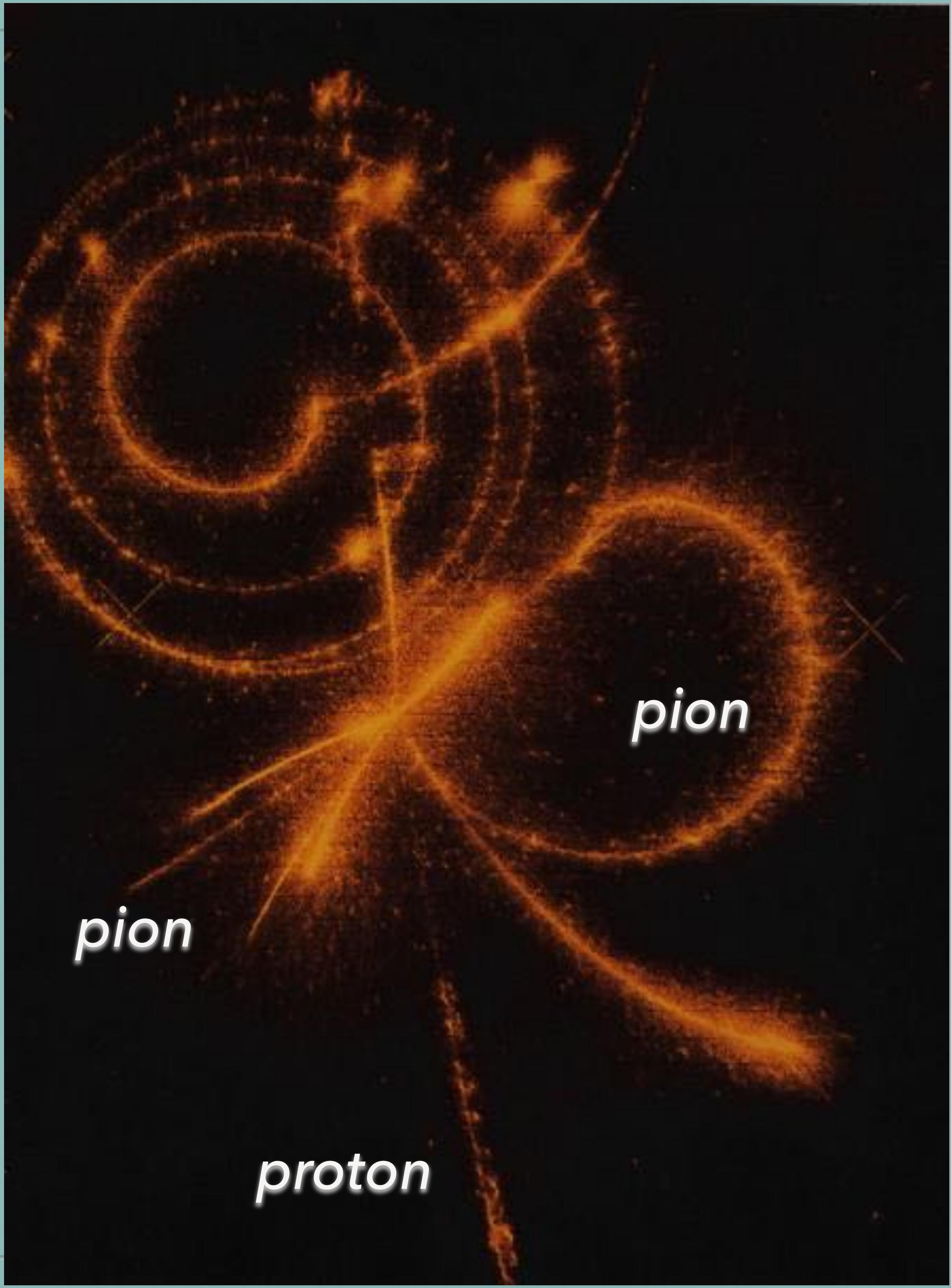
$$-1/3 - 1/3 + 2/3 = 0$$



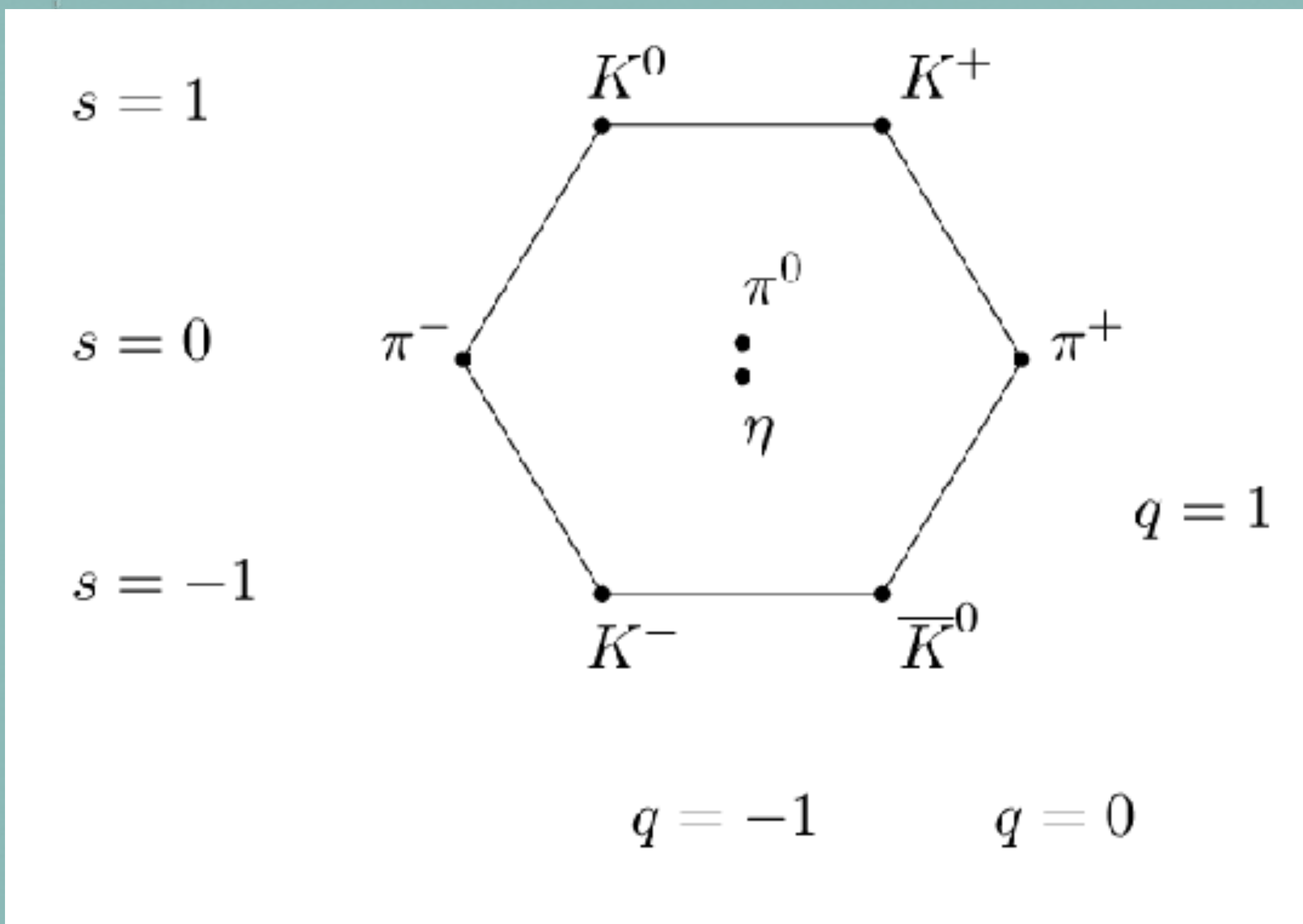


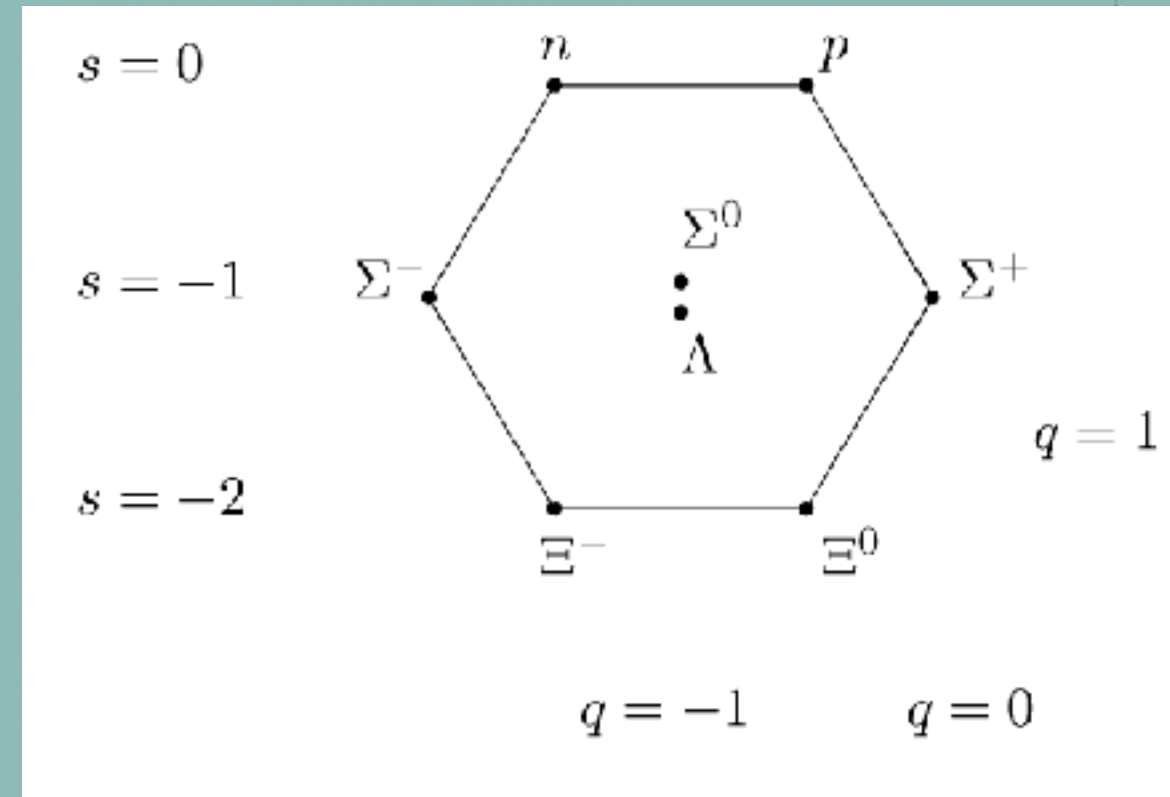
David Parker (Science Source/Photo Researchers, Inc.)

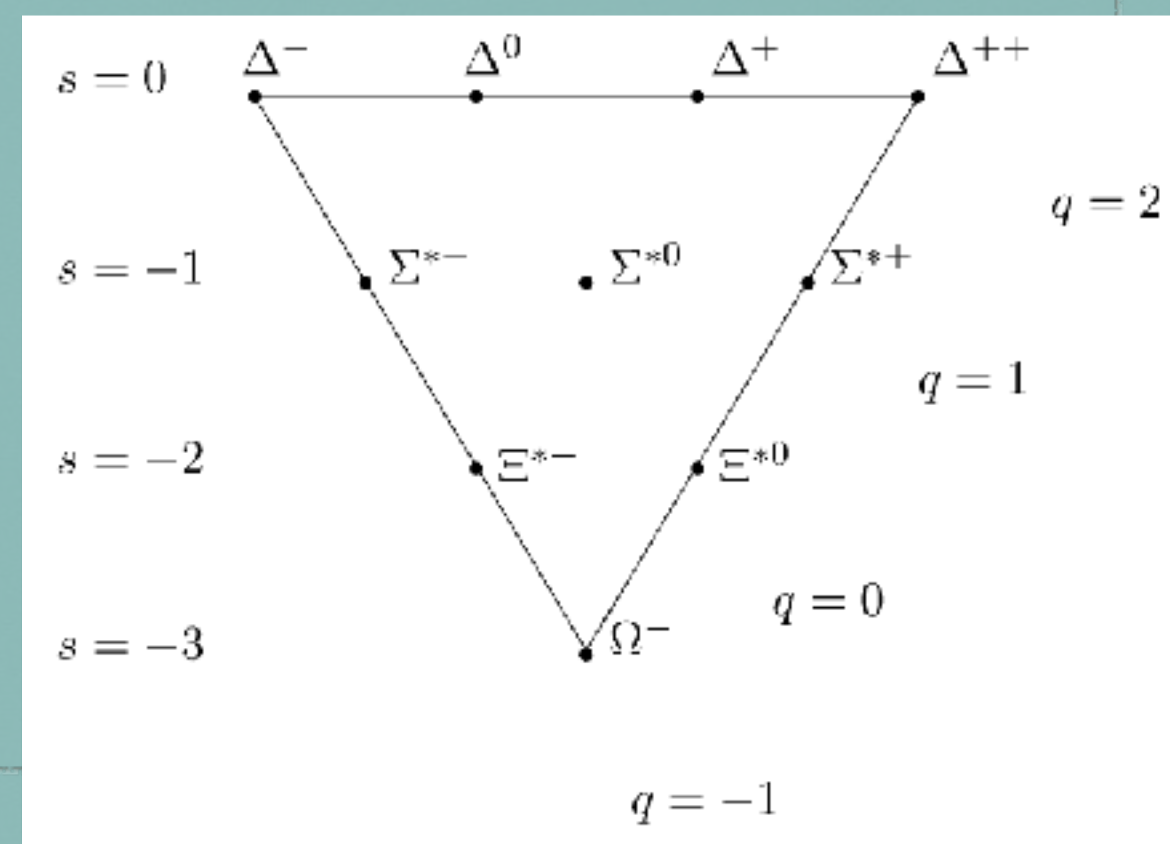
Figure 1. Curving lines in this "bubble chamber" photograph show the trajectories—and thus the identities—of various subatomic particles created by an accelerator. Careful measurement of these tracks (which Renee Jones of Fermi National Accelerator Laboratory is doing here for a 1984 experiment) reveals much about the undetected parent particles that give off such sprays. Like most practitioners now, the authors avoid this labor-intensive step by employing electronic detectors rather than bubble chambers in their current hunt for a special class of exotic particles, ones made (in whole or in part) of the very force that holds matter together.



THE EIGHTFOLD WAY



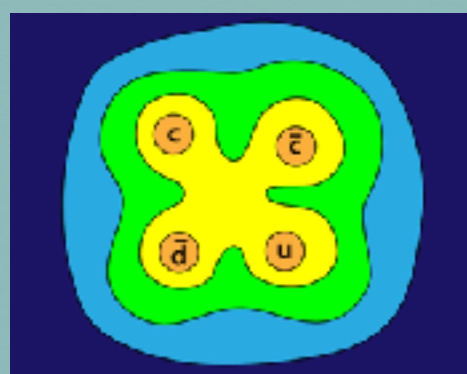




4-QUARK STATE

BESIII and Belle

$$e^+ e^- \longrightarrow \pi^+ \pi^- J/\psi$$



$Z_c(3900)$

$\downarrow$?

$\pi^+ J/\psi$

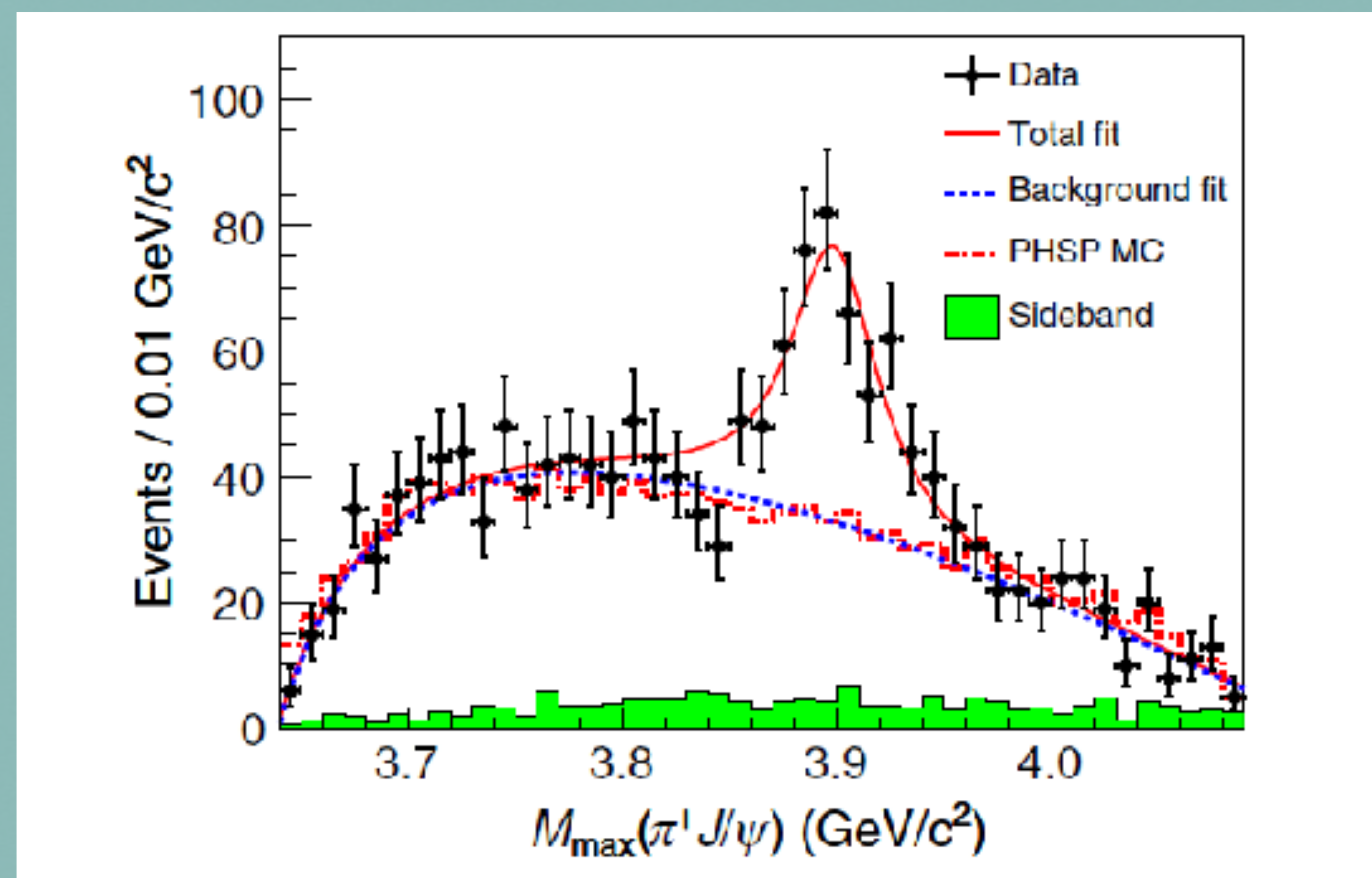
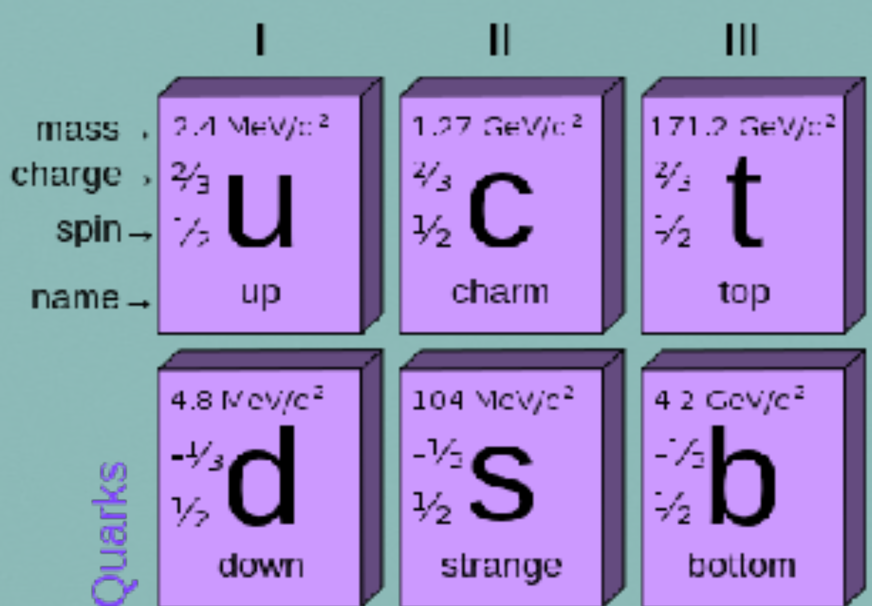


Image by BESIII collaboration

INTRODUCTION TO QCD

Quarks

fundamental representation (3) of SU(3)



$+2/3$

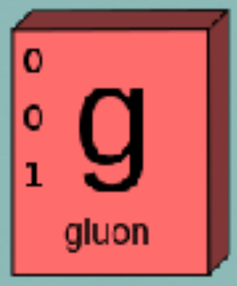
$-1/3$

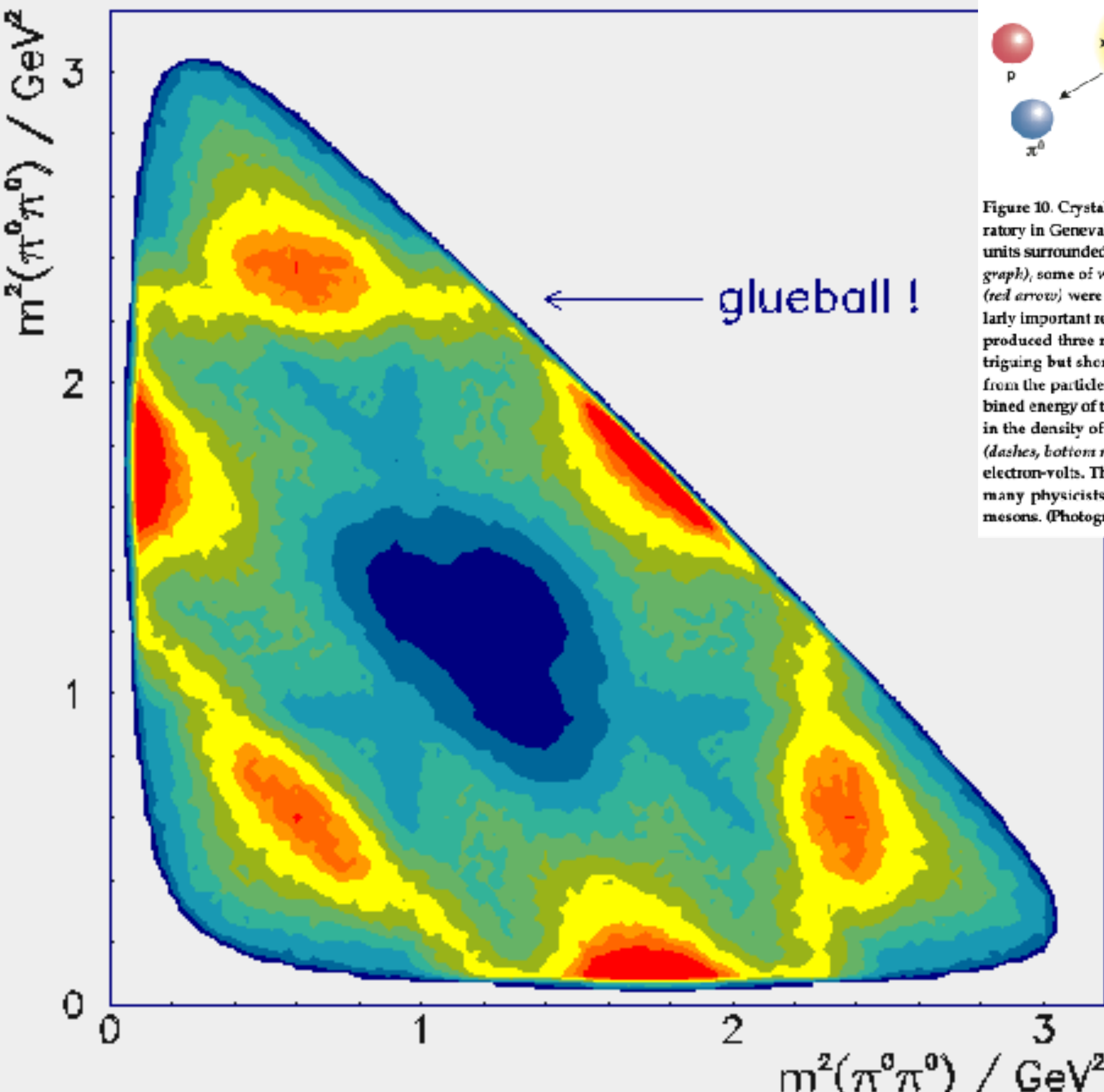
Gluons

adjoint representation

$$\mathrm{A}_\mu = A^a_\mu T^a$$

$$\mathrm{T}^a = \tfrac{1}{2}(\lambda_{ij})_{3\times 3}$$





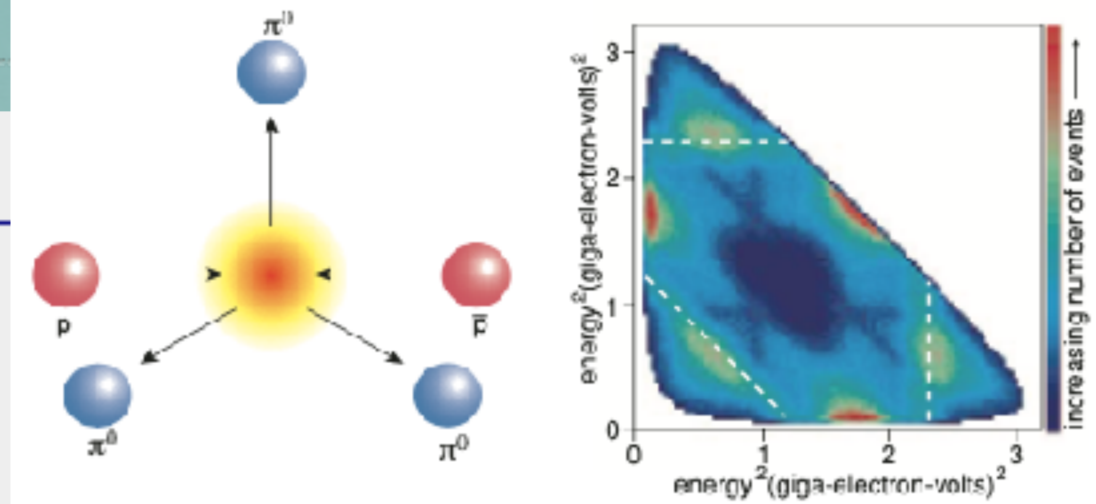
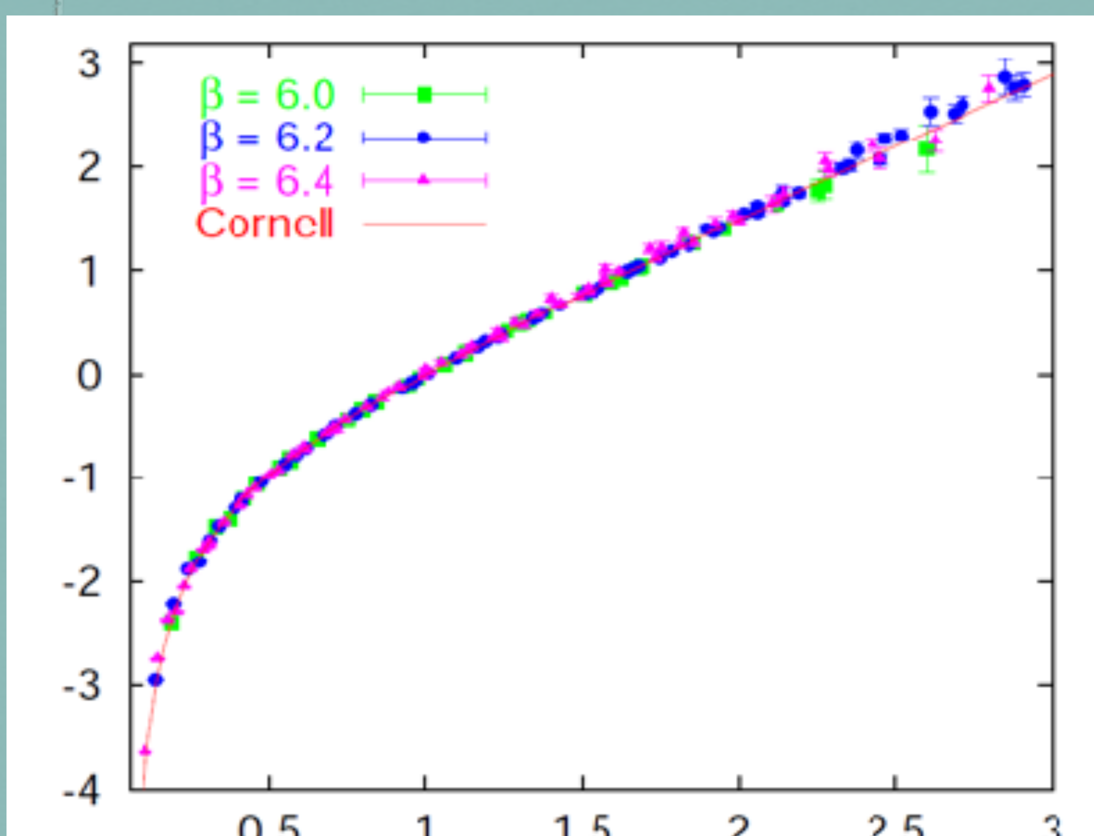
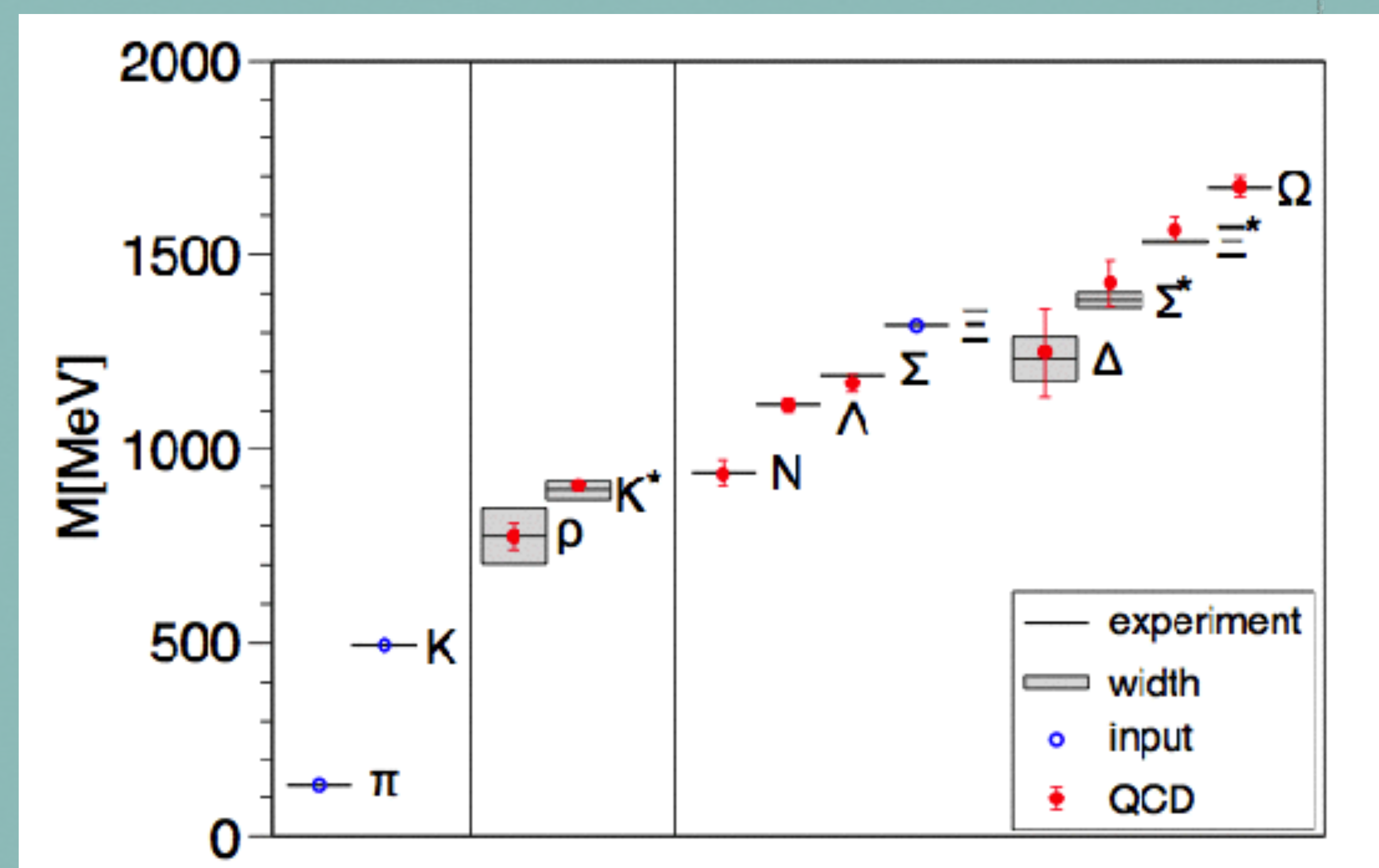


Figure 10. Crystal Barrel apparatus, constructed at CERN (the European particle physics laboratory in Geneva) a decade ago employed 1,380 cesium iodide detectors *(top left; olive)*. These units surrounded a chamber *(red)* containing about 4,000 closely spaced parallel wires *(photograph)*, some of which also registered the charged particles created after energetic antiprotons *(red arrow)* were made to collide with protons in a liquid hydrogen target *(green)*. A particularly important result of the Crystal Barrel experiment came from the analysis of a reaction that produced three neutral pions *(π^0, bottom left)*, two of which came from the decay of an intriguing but short-lived particle. It is impossible in such cases to know which two pions are from the particle of interest. So investigators look at many events and for each plot the combined energy of two pions against the combined energy of a different two, showing variations in the density of points with a range of colors. Lines of high density in such a "Dalitz plot" *(dashes, bottom right)* reveal the mass of a short-lived particle, in this case about 1,500 mega-electron-volts. This particle, called $f_0(1500)$, was considered by some to be a glueball, but now many physicists believe it is a quantum-mechanical combination of a glueball and two mesons. (Photograph courtesy of Curtis A. Meyer.)

how confinement works?

how QCD forces manifest in hadron spectrum?

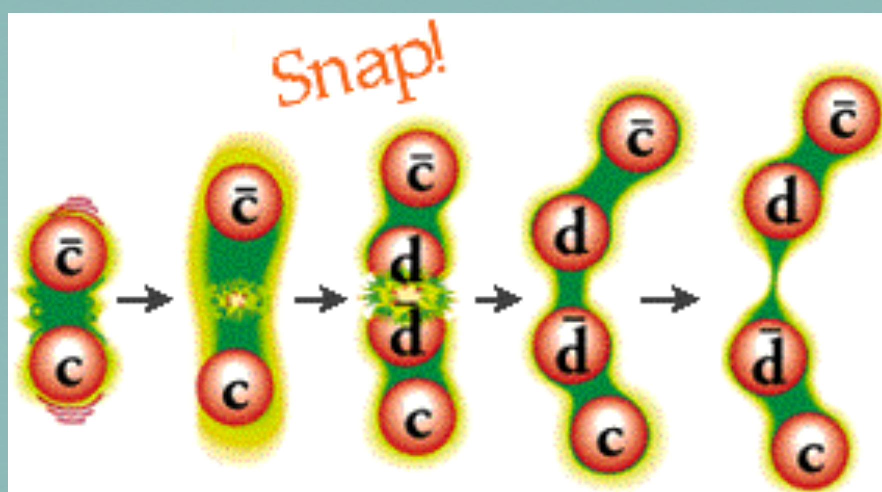


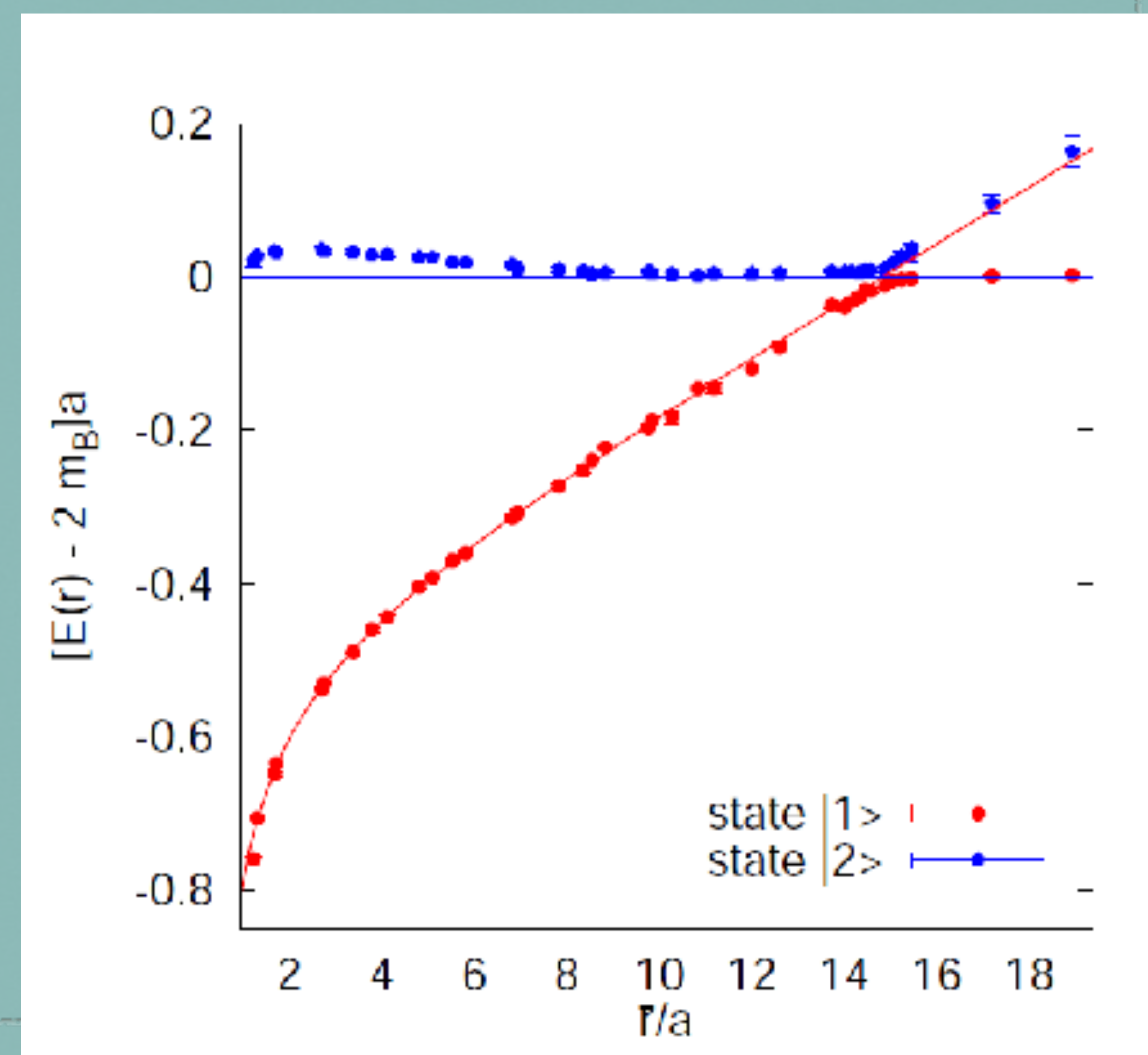


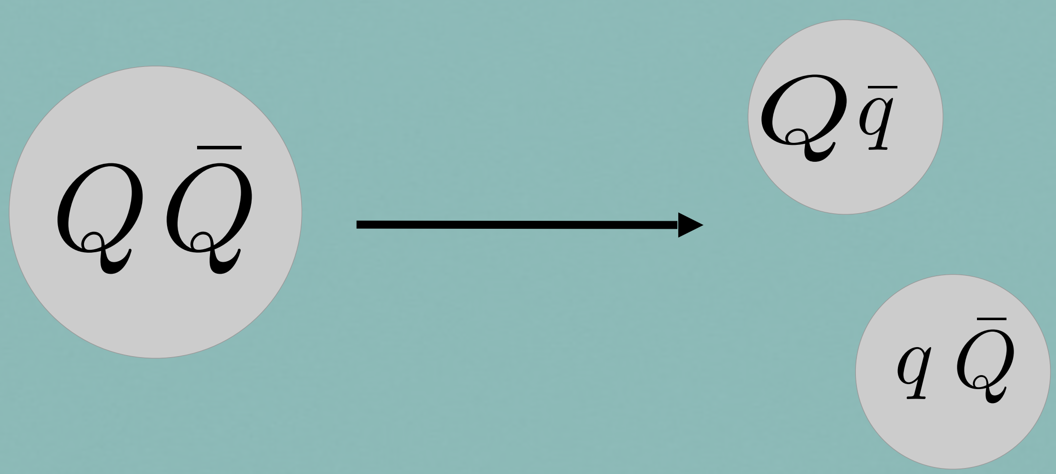
STRING BREAKING

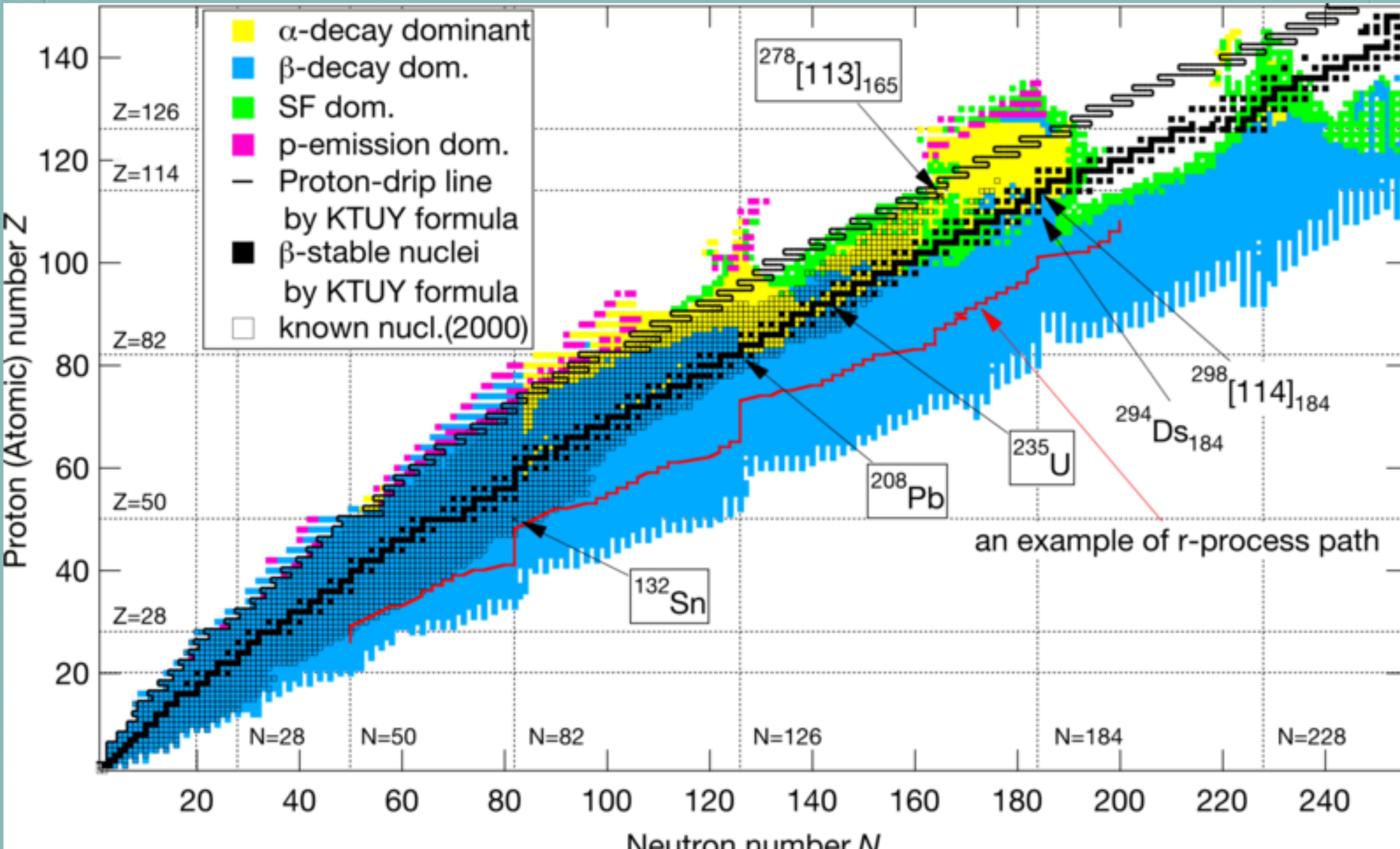
- In the presence of dynamical quarks...

Bali *et. al.*









α-decay dominant
β-decay dom.
SF dom.
p-emission dom.
Proton-drip line by KTUY formula
β-stable nuclei by KTUY formula
known nucl.(2000)
278[113]165
298[114]184
294Ds184
235U
208Pb
132Sn
an example of r-process path
Z=126
Z=114
Z=82
Z=50
Z=28
N=28
N=50
N=82
N=126
N=184
N=228
Proton (Atomic) number Z
Neutron number N
20
40
60
80
100
120
140
160
180
200
220
240

SYMMETRY

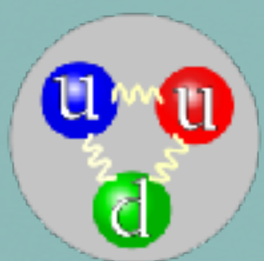
HOW TO LOSE WEIGHT?

move to Mars: gravity is only 38%

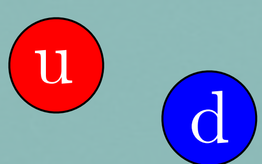
ORIGIN OF MASS

- 99% of the Mass of the visible Universe is **not** explained by Higgs bosons!

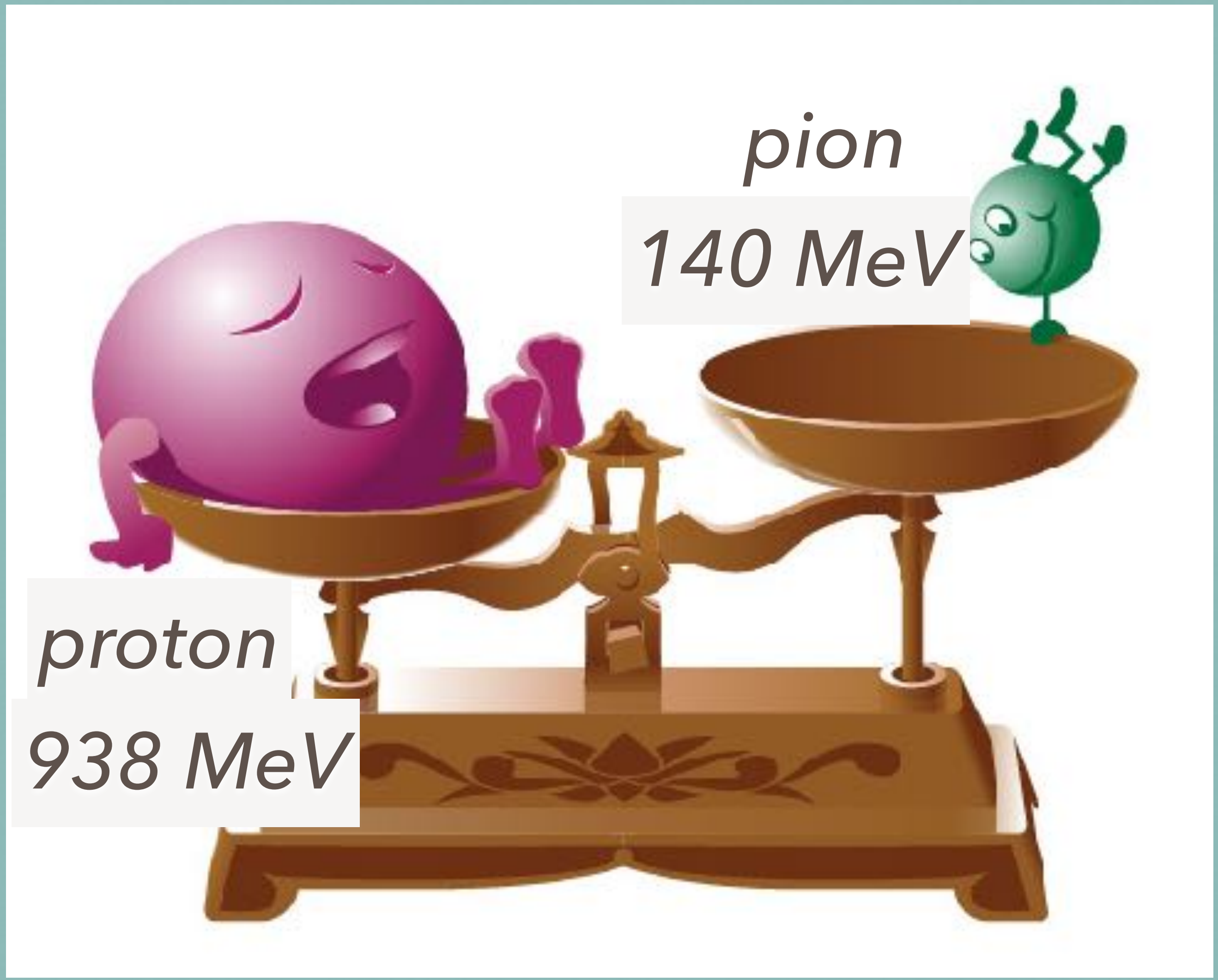
$1000/3 = ?$



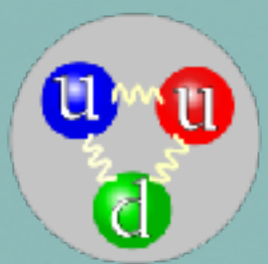
$$M_P = 938\,\mathrm{MeV}$$



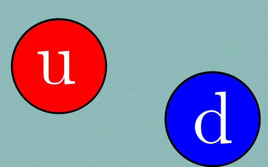
$$m_q \approx \mathrm{few\,MeV}$$



SPONTANEOUS CHIRAL SYMMETRY BREAKING



$$M_P = 938\,\mathrm{MeV}$$



$$m_q \approx \text{few MeV}$$

$m_q \to 0$ → *QCD is chiral symmetric.*

→ **spontaneously** *broken*

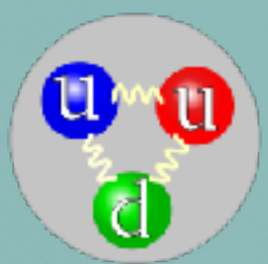
Fermion mass are **dynamically** *generated.*

→ $M_q^{\text{consti.}} \approx 300\mathrm{MeV}$

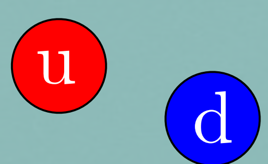
SPONTANEOUS CHIRAL SYMMETRY BREAKING

$\pi \to$ *Goldstone bosons*

$$m_\pi^2 \propto m_q$$



$$M_P = 938\,\mathrm{MeV}$$



$$m_q \approx \text{few MeV}$$

$m_q \to 0$ ⟶ *QCD is chiral symmetric.*

↳ **spontaneously** *broken*

Fermion mass are **dynamically** *generated.*

↳ $M_q^{\mathrm{consti.}} \approx 300\mathrm{MeV}$

SPONT
SYMM

The Nobel Prize in Physics 2008
Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa

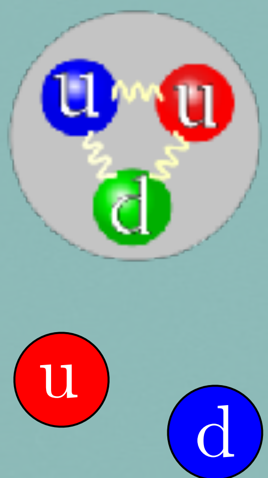
The Nobel Prize in Physics 2008

Photo: University of Chicago
Yoichiro Nambu

© The Nobel Foundation
Photo: U. Montan
Makoto Kobayashi

© The Nobel Foundation
Photo: U. Montan
Toshihide Maskawa

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

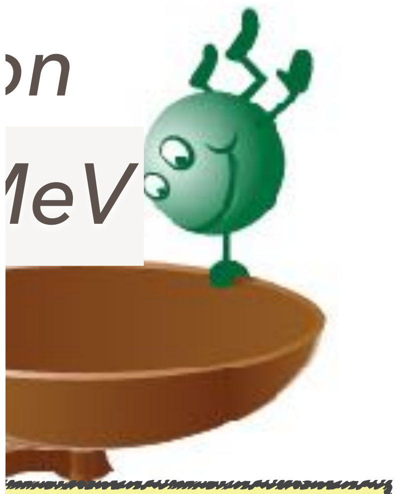


...one bosons

q

...on

...MeV



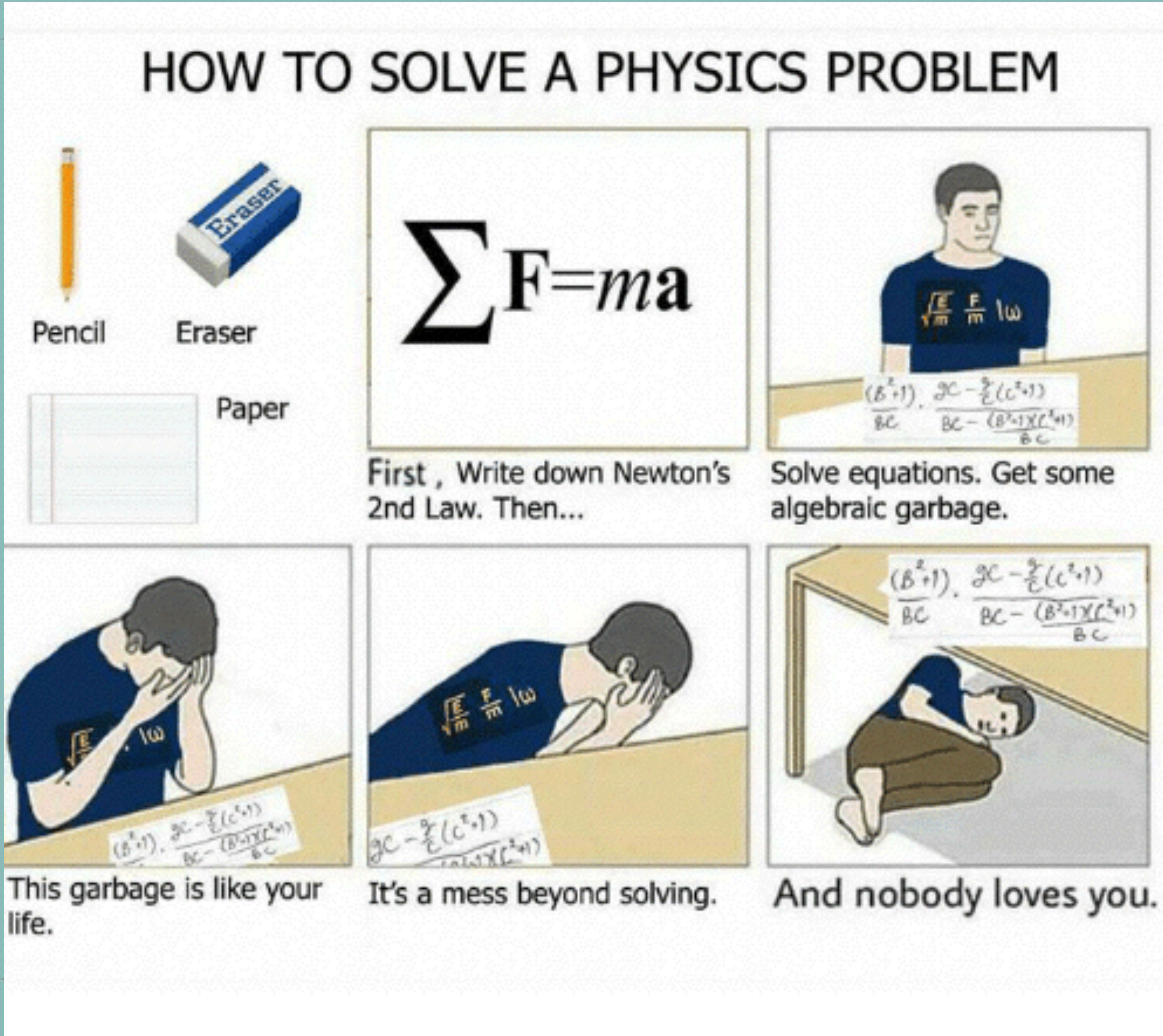
$m_q \to 0$

Fermion m...

...s broken

...00MeV

PHYSICS SKILLS


HOW TO SOLVE A PHYSICS PROBLEM
Pencil
Eraser
Eraser
Paper
ΣF=ma
First , Write down Newton's 2nd Law. Then...
Solve equations. Get some algebraic garbage.
This garbage is like your life.
It's a mess beyond solving.
And nobody loves you.

$$\sqrt{\cdots}$$

scattering

fast

slow

$$\sqrt{9}$$

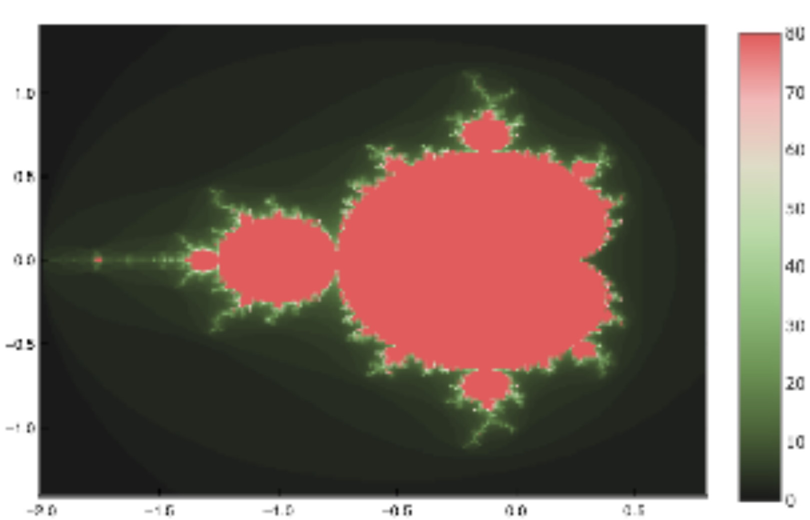
$$\sqrt{-1}$$

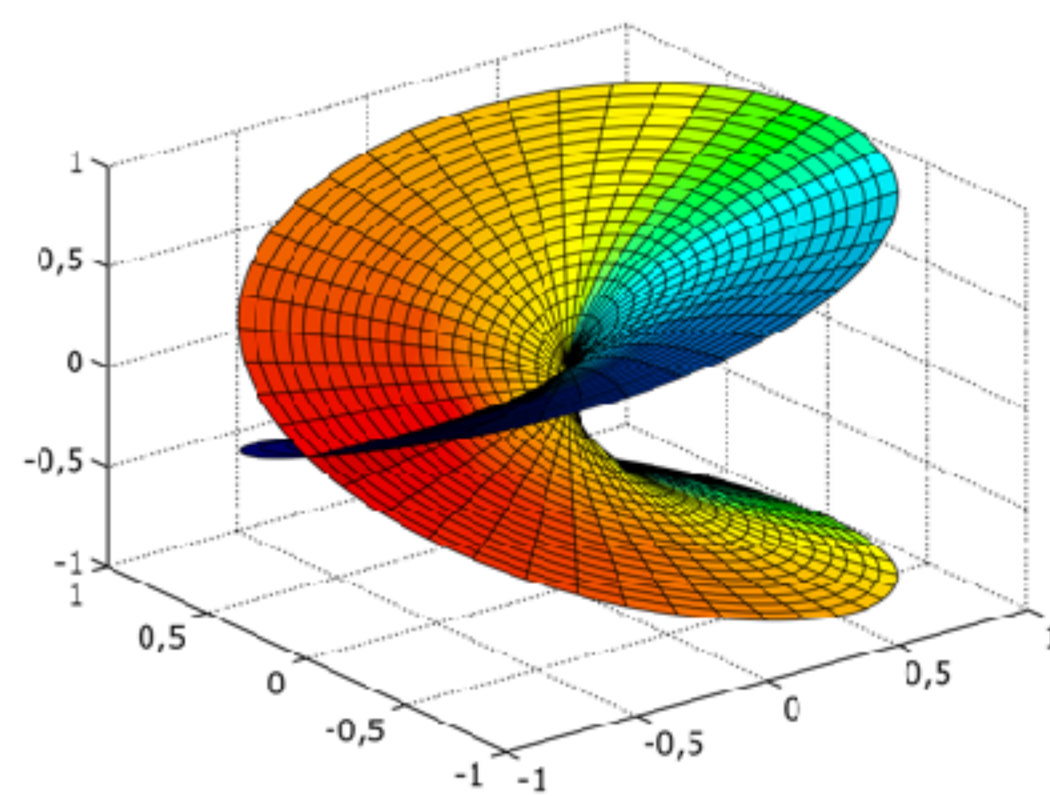
$$\sqrt{i}$$

Babylonian

$$\sqrt{a} \to 1/2 \times (x + a/x)$$

$$z \to z^2 + c$$





some non-sense...

$$\frac{x}{1-x}$$

$$\frac{1}{2}+\frac{1}{2}\times\frac{1}{2}+\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}+\cdots=?$$

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

$$1-2+3-4+\cdots=\frac{1}{4}$$

$$1+2+3+\cdots=-\frac{1}{12}$$

$$\zeta(-1)$$

LAST BUT NOT LEAST… CURIOSITY

THANK YOU

pokman.lo@uwr.edu.pl