THE INTERNAL STRUCTURE OF PARTICLES

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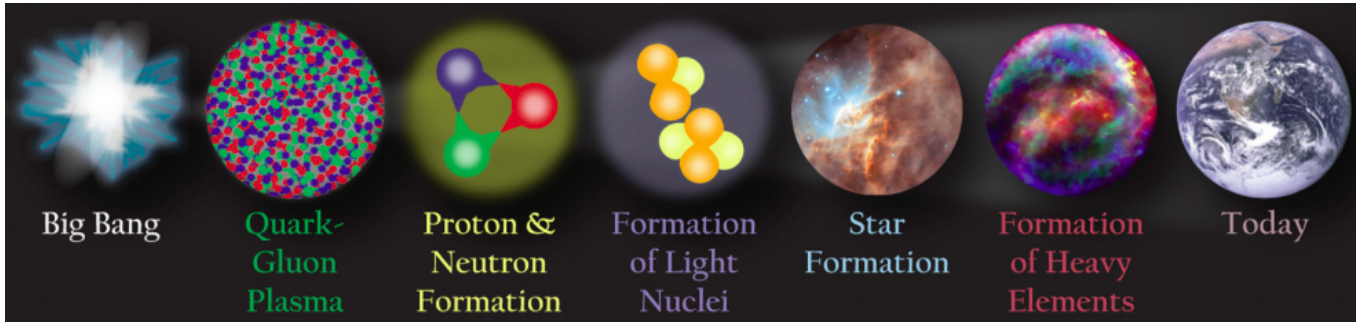
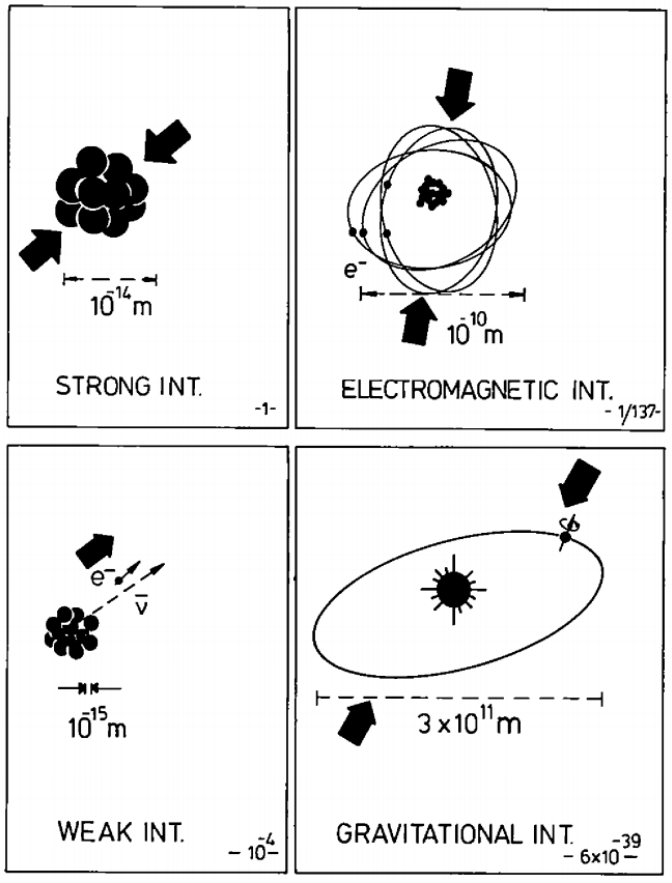
LIP Summer Internship Lecture

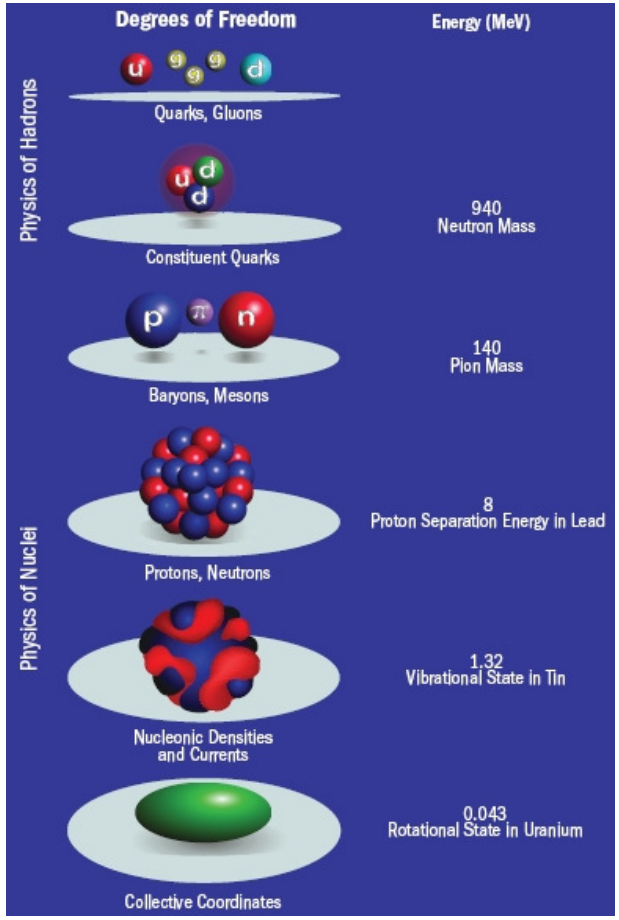
SMALLEST STRUCTURE OF MATTER — QUESTIONS

- What is meant with internal structure of particles?
- What levels of structure exist?
- What kind of experiments probe structure?
- How can structure be described theoretically?

STRONLGY-INTERACTING MATTER MATTERS!

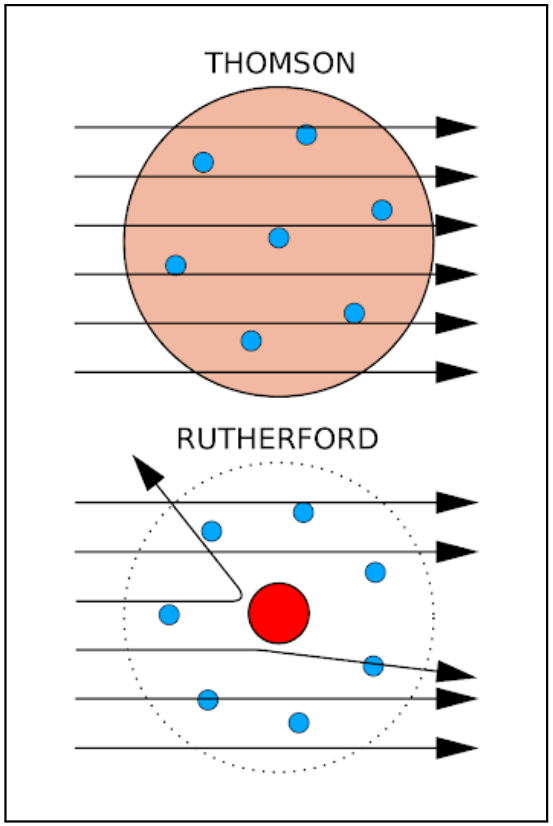


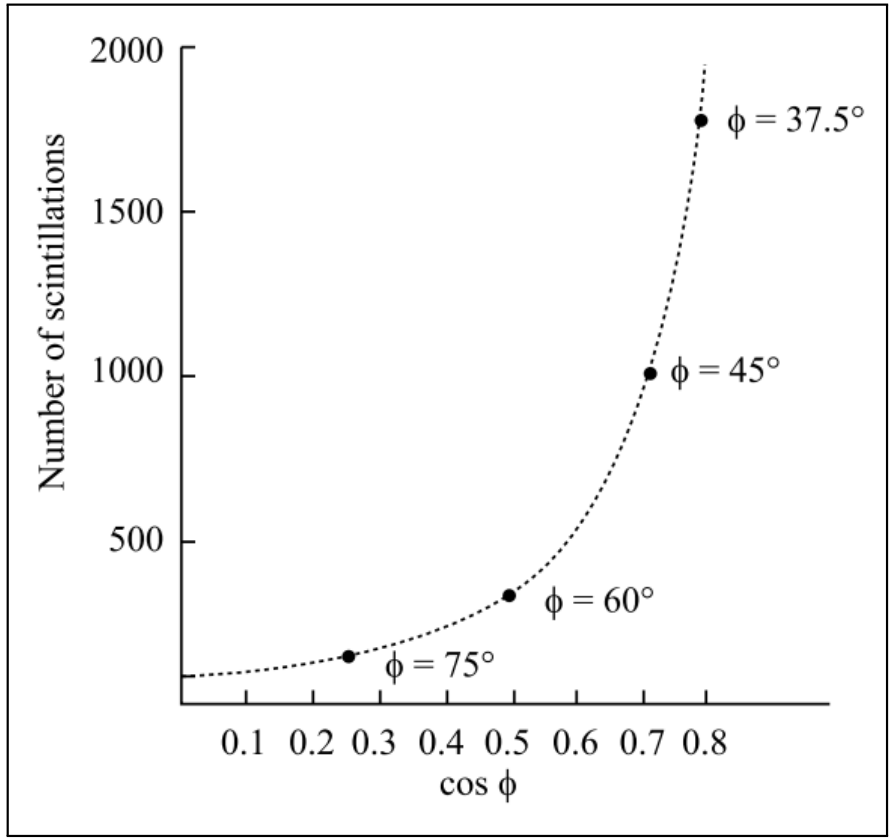




STRUCTURE OF THE ATOM

- Geiger and Marsden 1909 observed in Rutherford scattering:
  α particles reflected by thin gold foil also under **large** scattering angles ϕ

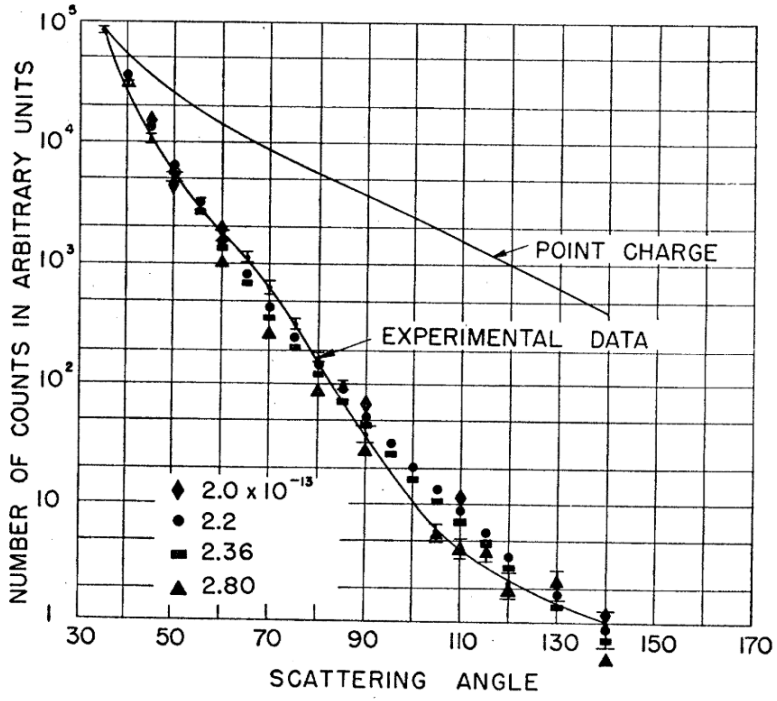


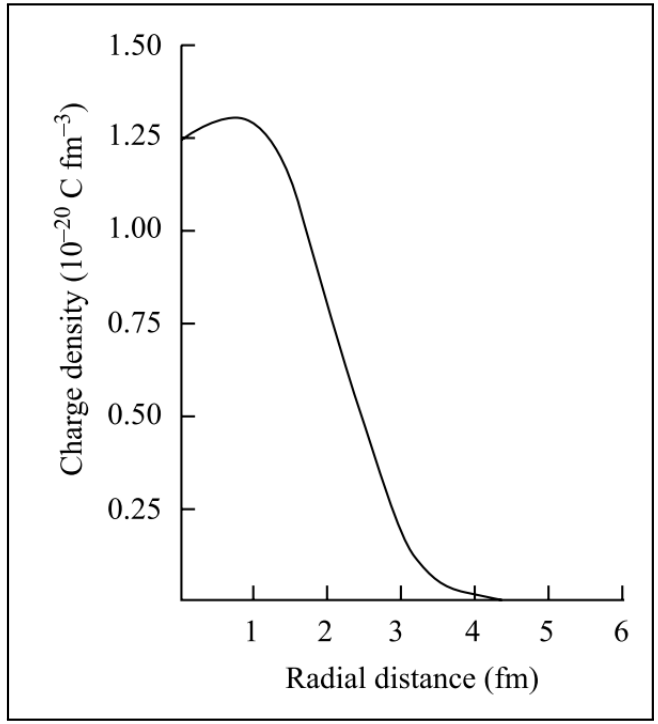


- Rutherford 1911:
  - $\exists$ a 'hard constituent' – a small, massive, positively-charged **nucleus**
  - explains data through famous $\sin^{-4}\phi/2$ **law**
- Question: Is the nucleus pointlike?

STRUCTURE OF THE NUCLEUS

- Hofstadter et al. 1950's: Electron-gold elastic Coulomb scattering
  $\Rightarrow$ **deviations** from Rutherford formula for pointlike nucleus



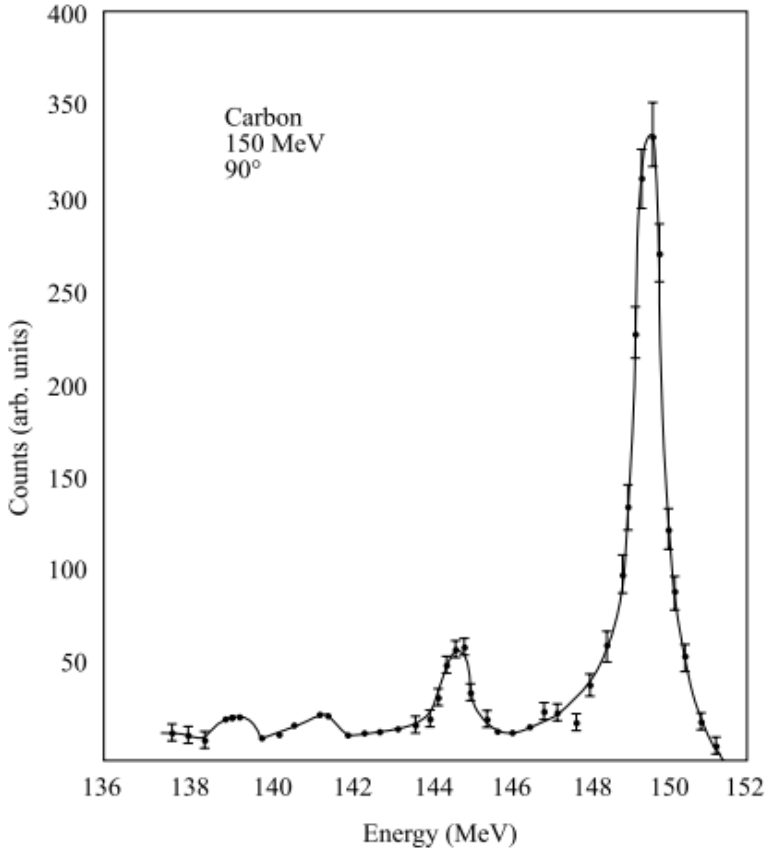


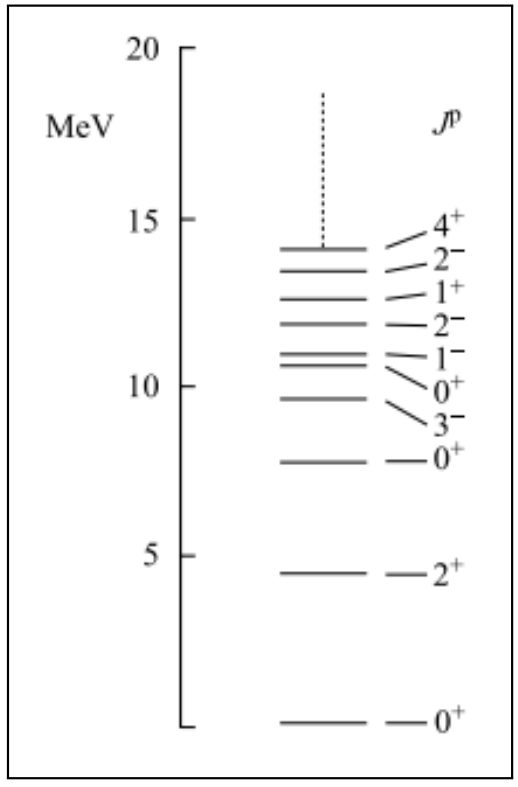
Carbon-12 nucleus

- Spatial extension of nuclear charge density described by **form factor**
  $\Leftrightarrow$ nucleus has **finite size** with radius $\gtrsim 1$ fm $= 10^{-15}$ m
  (for comparison: atomic radius ~ 100 pm $= 10^{-10}$ m)
- Question: Is the nucleus made out of constituents?

ENERGY LEVELS

- **Inelastic** electron-nucleus scattering





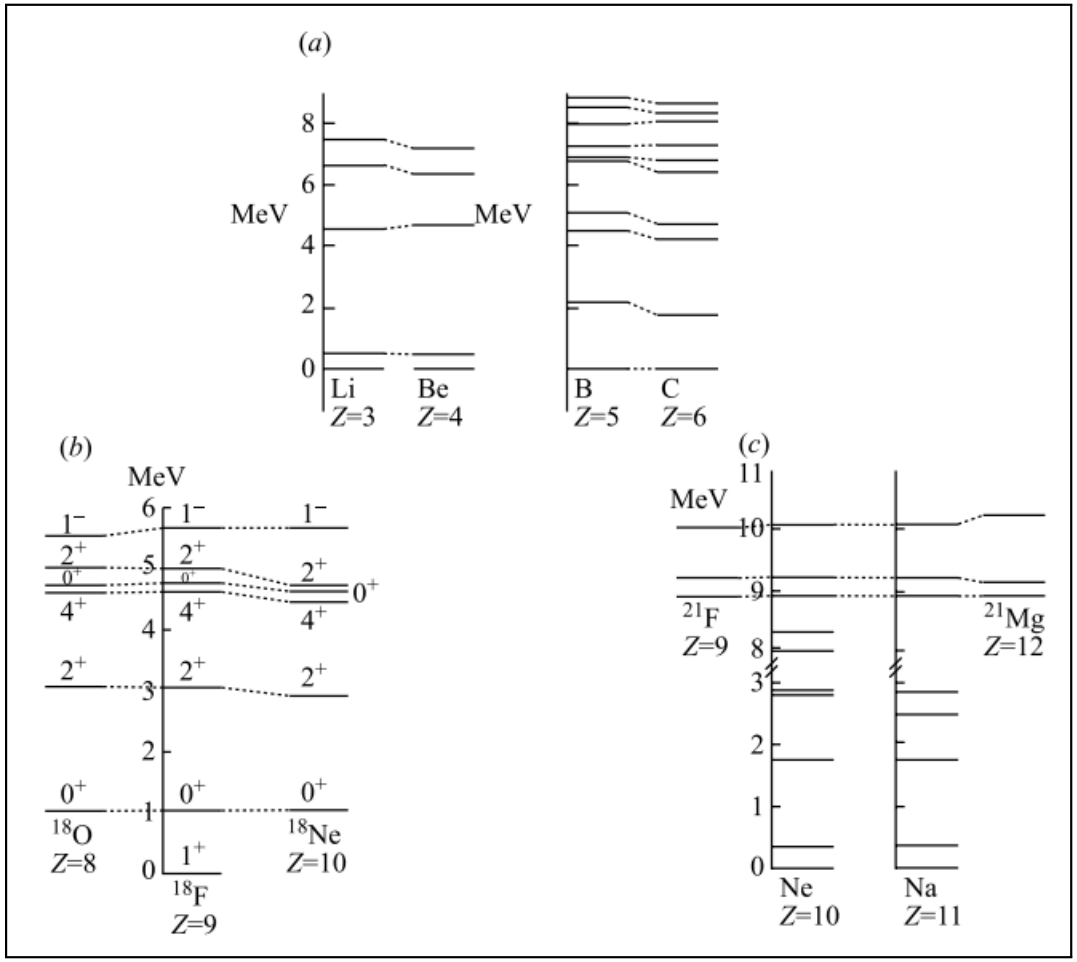
Carbon-12

Fregeau; Hofstadter 1955

- Nucleus excited into **quantized** energy states

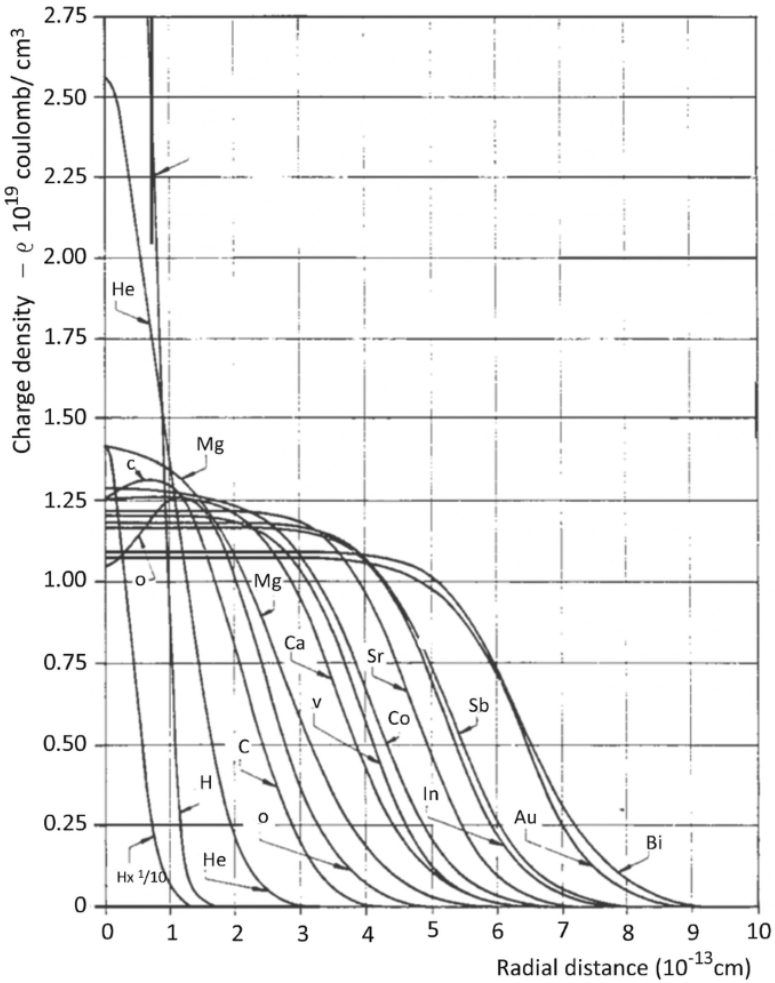
NUCLEONS AND THE STRONG FORCE

- Energy spectra from internal quantized motion of A **nucleons**:
  Z protons and N neutrons (ordinary matter in Universe)
- Question: What is the nature of the strong nuclear force between them?



- Nuclear force
  - almost **charge-independent**
  - **stronger** than electromagnetic force

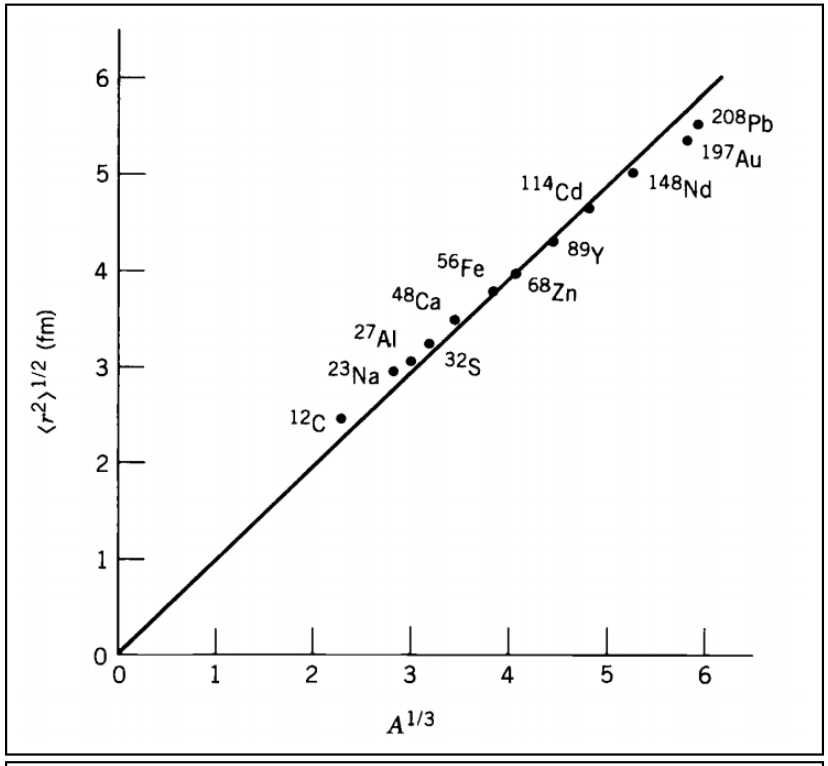
DISTRIBUTION OF NUCLEAR CHARGE

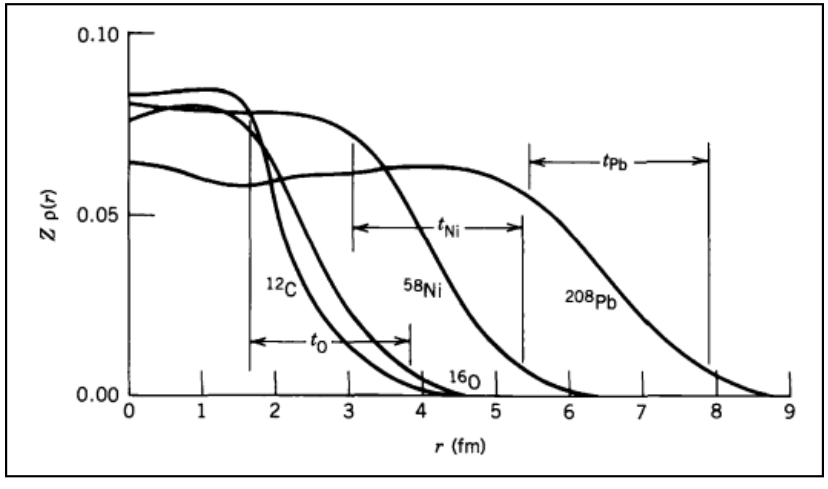


- Charge densities almost same $\forall$ nuclei

  $\frac{A}{4\pi R^3} \sim$ const. $\Rightarrow R = R_0 A^{\frac{1}{3}}$

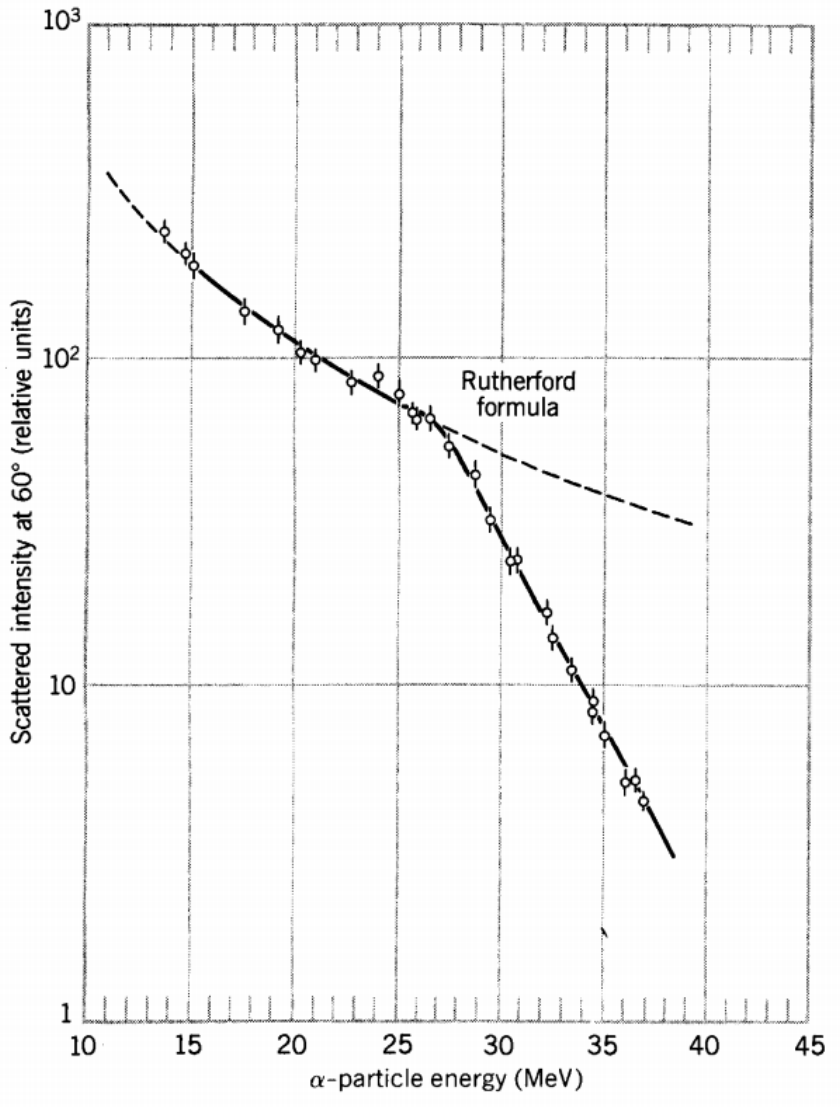
  $R_0 = 1.2 - 1.25$ fm





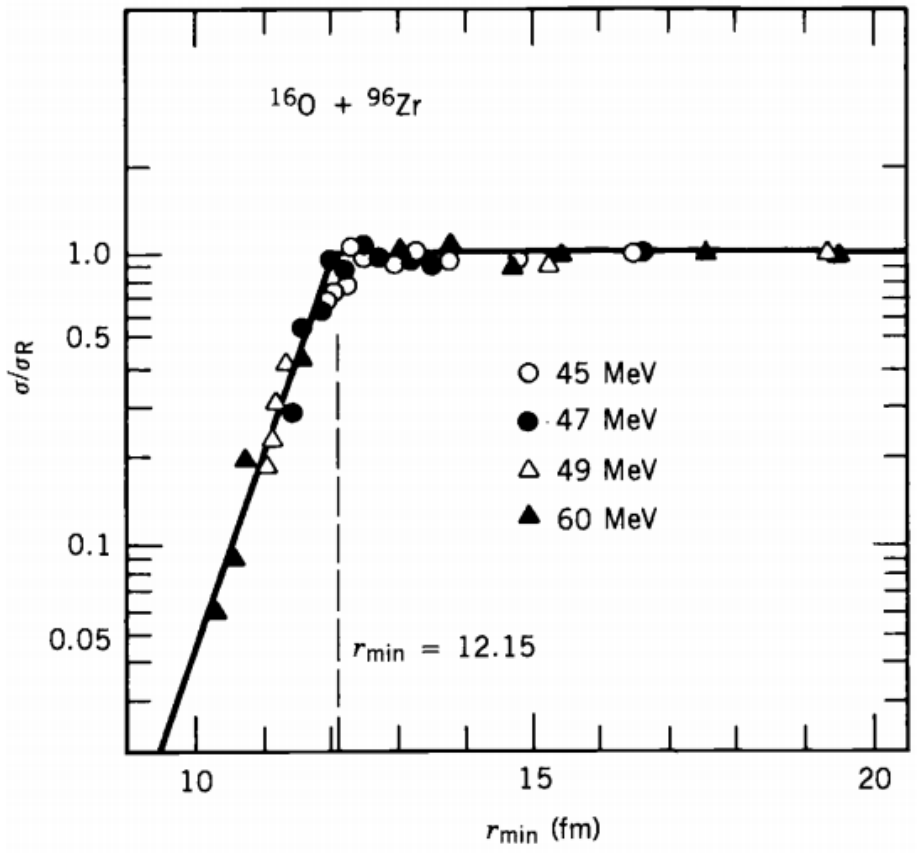
- Skin thickness ≈ 2.3 fm $\forall$ nuclei

DISTRIBUTION OF NUCLEAR MATTER

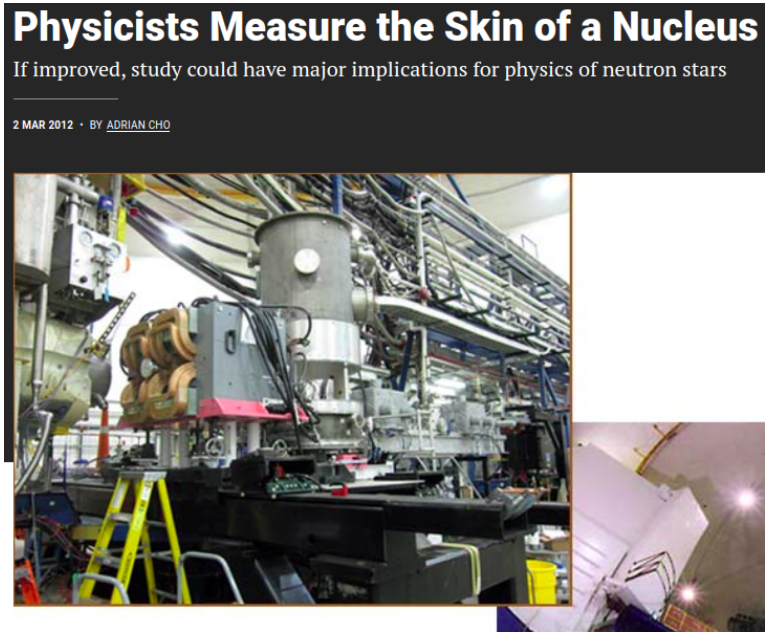


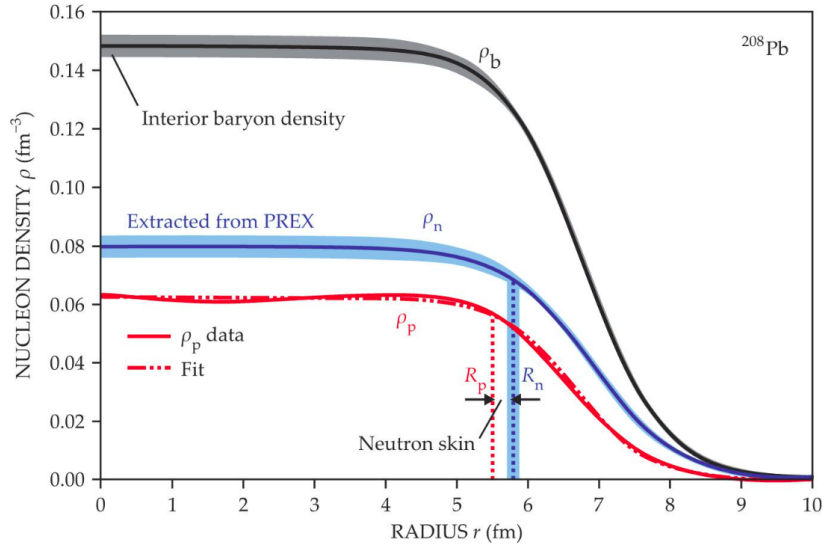
Coulomb-potential scattering: α particles with increasing energy get closer to target nucleus

- start interacting also through **nuclear force**
  $\Rightarrow$ short range
- size of nuclear matter distribution



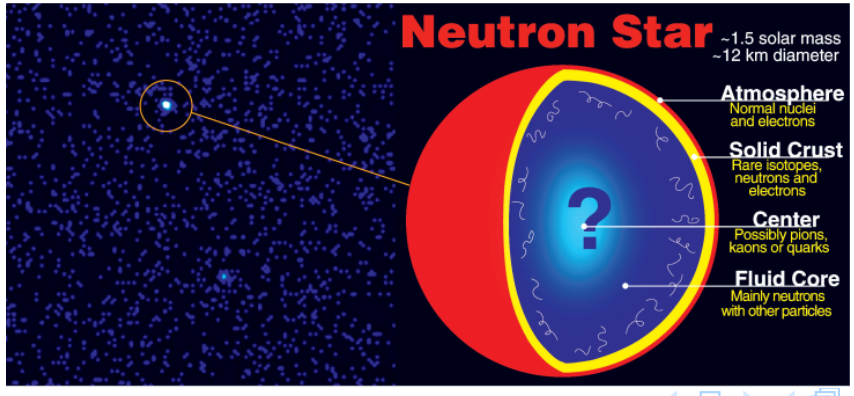
Question: How are the neutrons distributed inside nuclei?





PREX, CREX at Jefferson Lab 2012, 2021

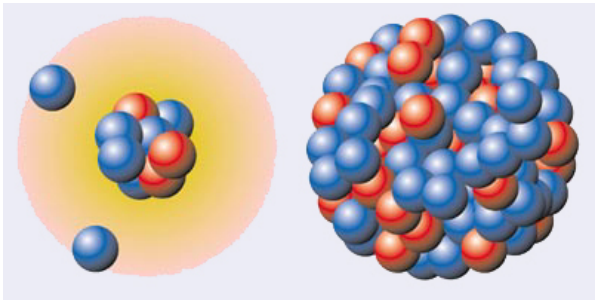
- Polarized electron scattering: interaction of electrons with neutrons via **weak** nuclear force $\Rightarrow$ neutron distribution
- Large nucleus is like a chocolate truffle: filling of protons and neutrons with pure **neutron shell** $R_n - R_p \approx 0.28$ fm
- Astrophysical implications:
  - *r*-**process**: production of heavy elements inside exploding stars
  - **neutron stars**

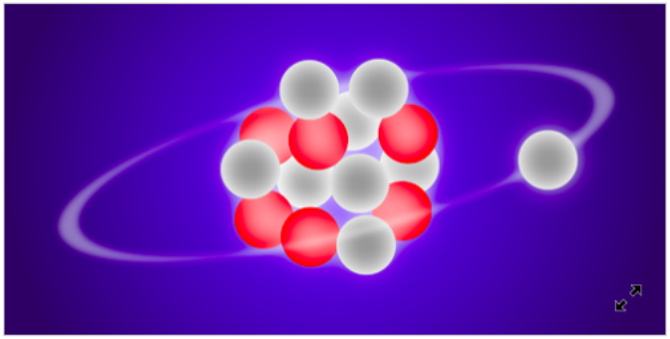


Targeting a Nuclear Halo

January 4, 2023 • *Physics* 16, s2

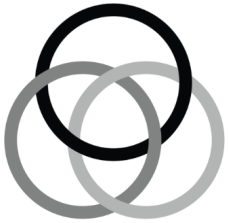
New modeling explains the relatively high fusion reaction probabilities of halo nuclei, which are composed of a dense core surrounded by a “satellite” of one or two nucleons.

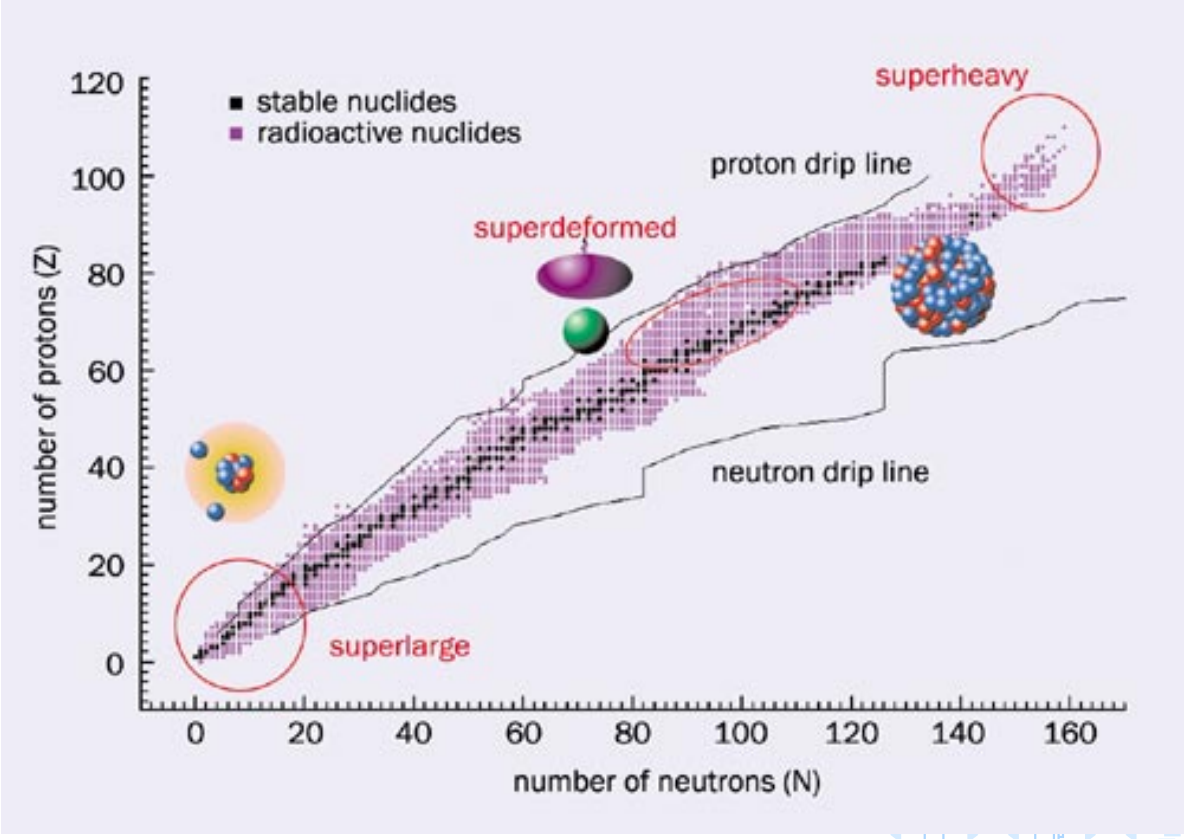




APS/Alan Stonebraker

^{11}Li ^{208}Pb

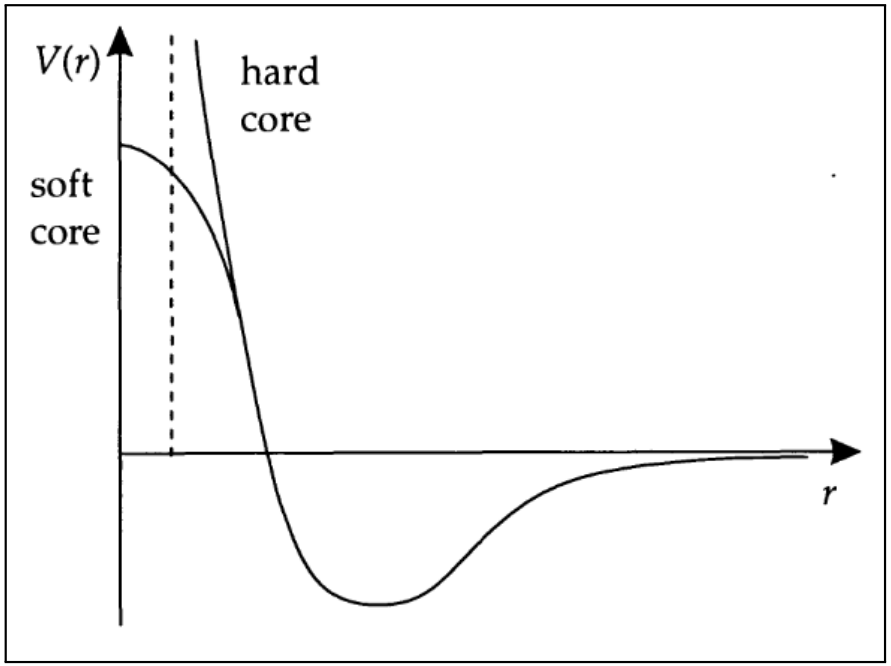


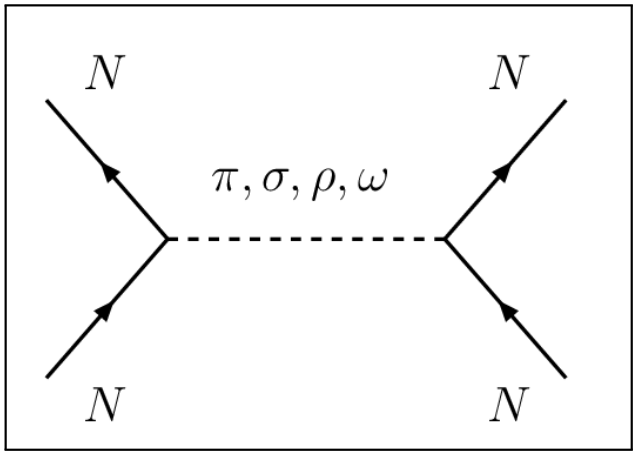


NUCLEON-NUCLEON INTERACTION

- Deviations from Rutherford formula at high energies
  $\Rightarrow$ NN-interaction is **short-range** ~ 2 fm; more n's than p's in stable heavy nuclei

- Similar densities in all nuclei
  $\Rightarrow$ **repulsive core** at short distance keeps nucleons separated



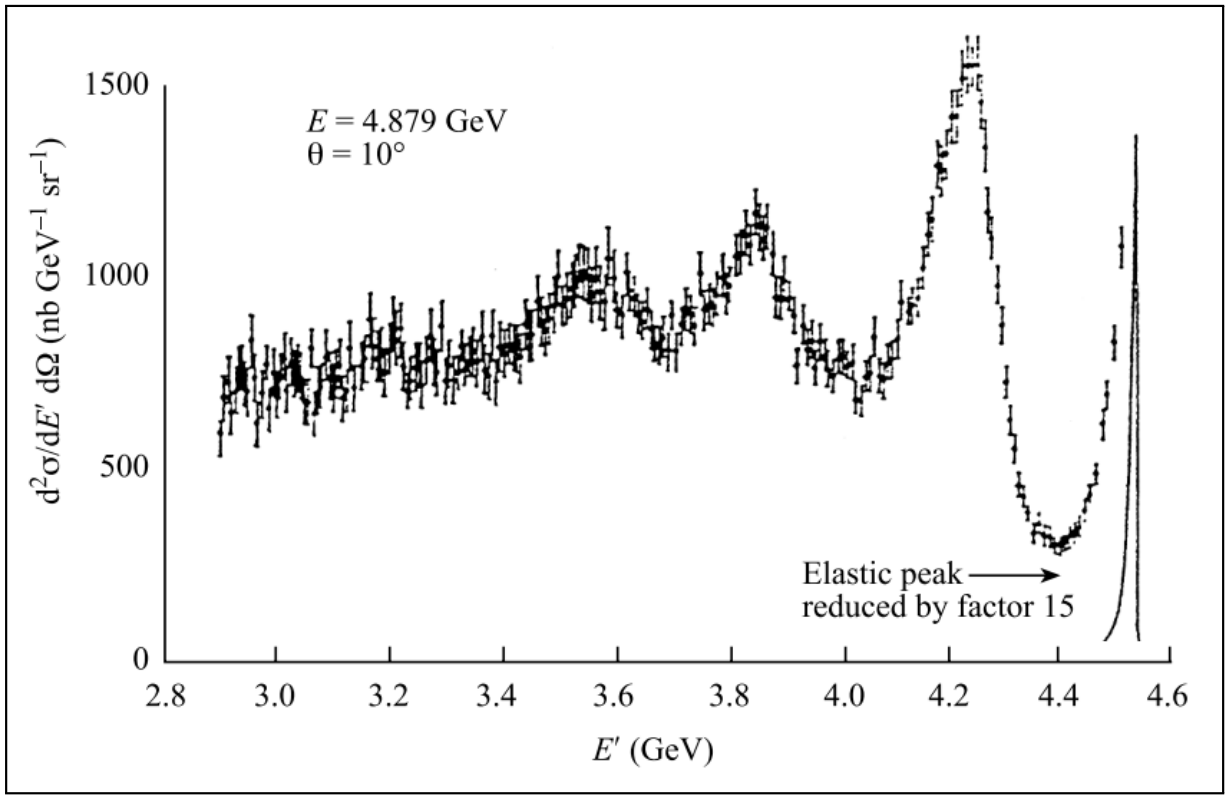


STRUCTURE OF THE NUCLEON

Question: Is the nucleon pointlike?

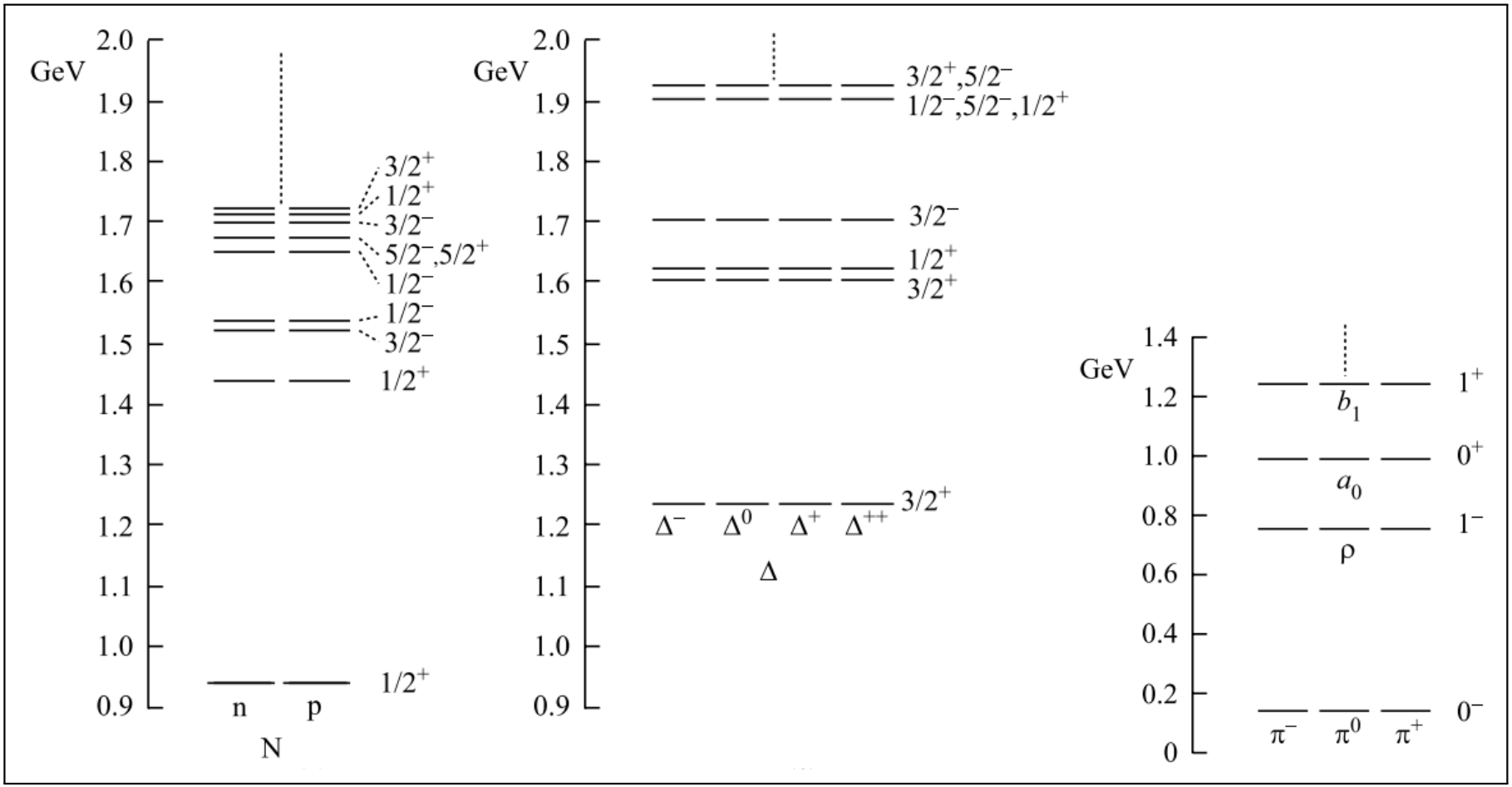
- Hofstadter et al. 1963: Elastic electron scattering from nucleons
  - proton has form factor and charge distribution with rms ~ 0.8 fm
  - proton and neutron have magnetic moment distributions

  $\Rightarrow$ nucleon is **not structureless**
- Inelastic electron scattering: Nucleon spectroscopy



- excitations of nucleon $\Rightarrow$ internal motion of **constituents**
- first inelastic peak: Δ **resonance**

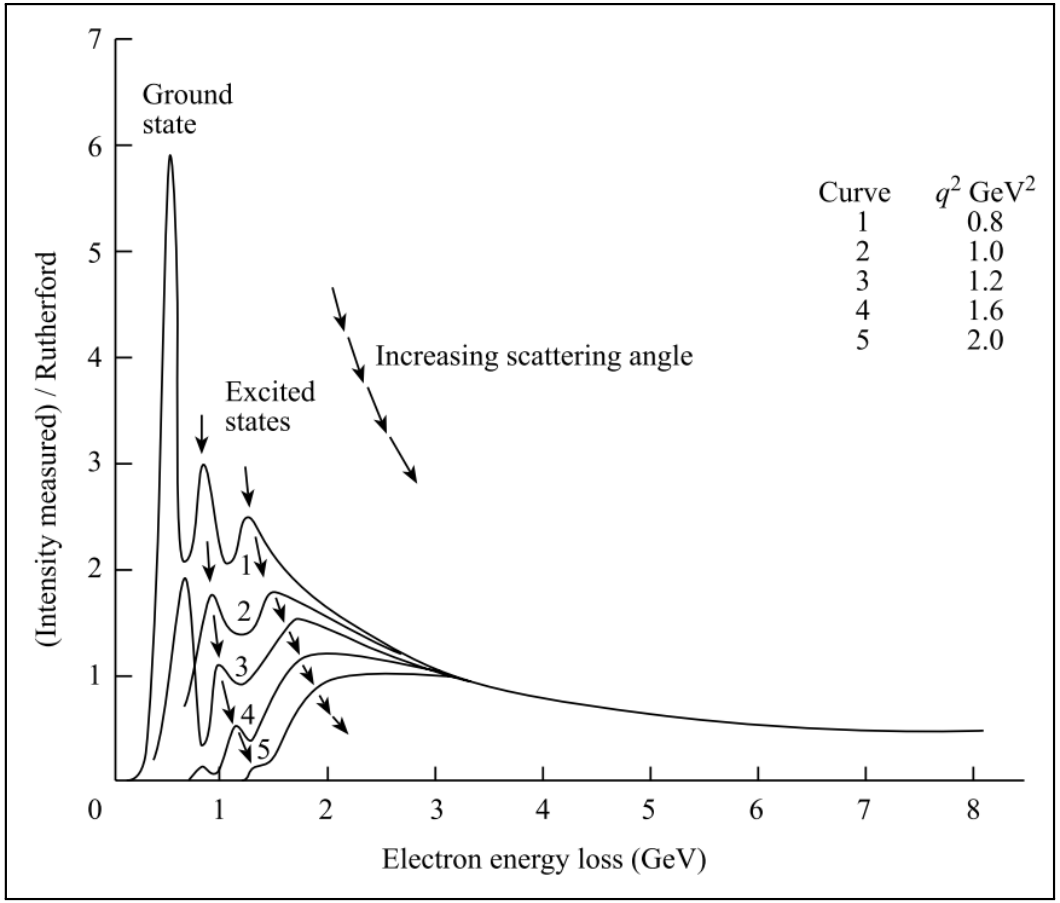
ENERGY SPECTRA OF HADRONS



- Baryons:
  - doublet: n and p as ground states
  - quartet: $\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$ ground states
- Mesons: triplet with π^-, π^0, π^+ as ground states

QUARK MODEL

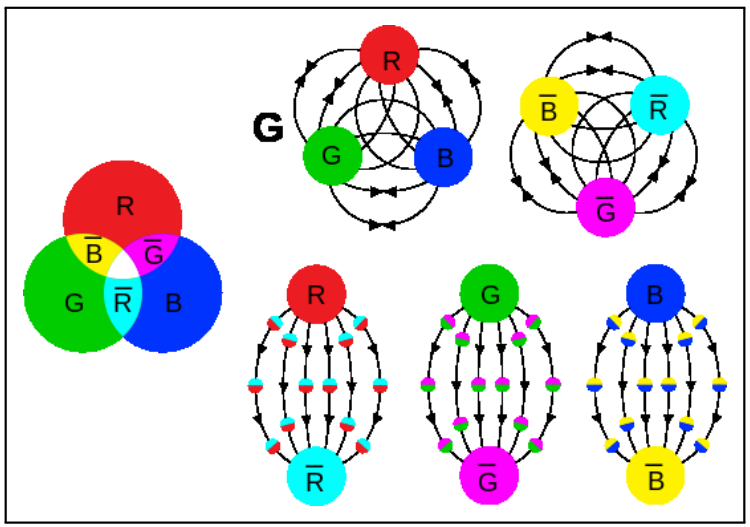
- Inelastic electron-proton scattering at large scattering angles $\Rightarrow \exists$ 'hard constituents': **Quarks**!



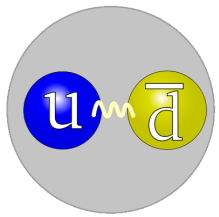
- Gell-Mann, Zweig 1964:
  - u- and d-quarks with spin-$\frac{1}{2}$ and charges $Q_u = \frac{2}{3}e$, $Q_d = -\frac{1}{3}e$
  - Baryons: **3 quarks**, e.g. $p = uud$, $n = udd$, $\Delta^{++} = uuu$
  - Mesons: **quark-antiquark**, e.g. $\pi^+ = u\bar{d}$

COLOR CHARGE AND QCD

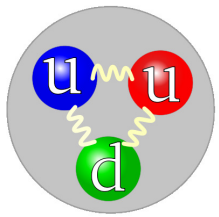
- Δ^{++}: 3-quark wave function ($\ell = 0$) would be $\frac{1}{\sqrt{4\pi}} \otimes |uuu\rangle \otimes |\uparrow\uparrow\uparrow\rangle$ **not** antisymmetric under exchange of 2 quarks!
- Need additional **color charge** to respect Pauli principle: **Red**, **Green**, **Blue** $\rightarrow \psi_{\Delta^{++}} = \frac{1}{\sqrt{4\pi}} \otimes |uuu\rangle \otimes |\uparrow\uparrow\uparrow\rangle \otimes \varepsilon_{RGB}$
- Hadrons only observed as ('white') color singlets **R+G+B=White**



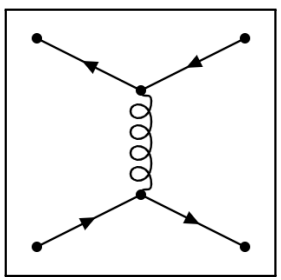
Pion π^+

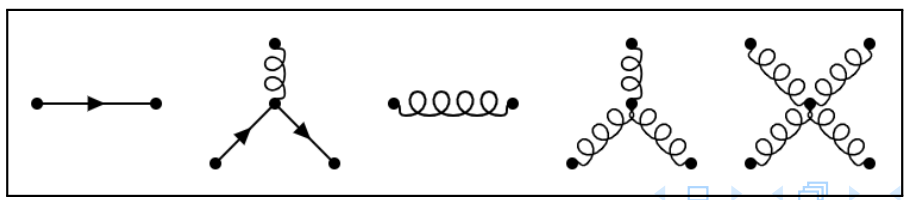


Proton



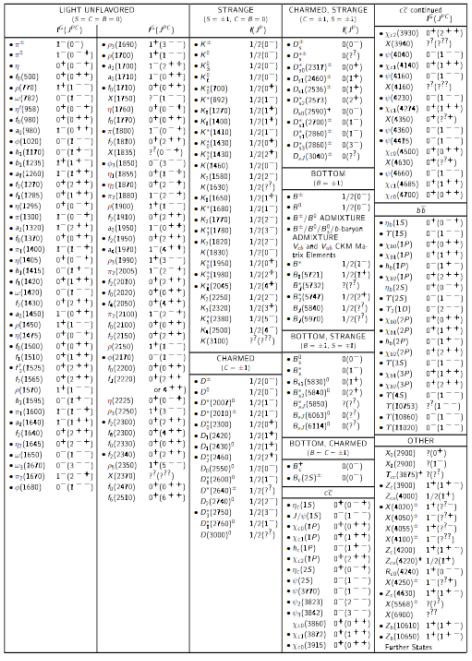
- **Quantum Chromodynamics** (QCD): fundamental theory of strong interaction between quarks and gluons



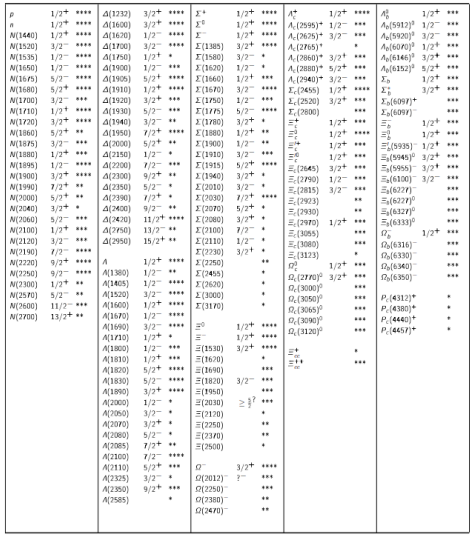


HADRONS AND MULTIQUARKS

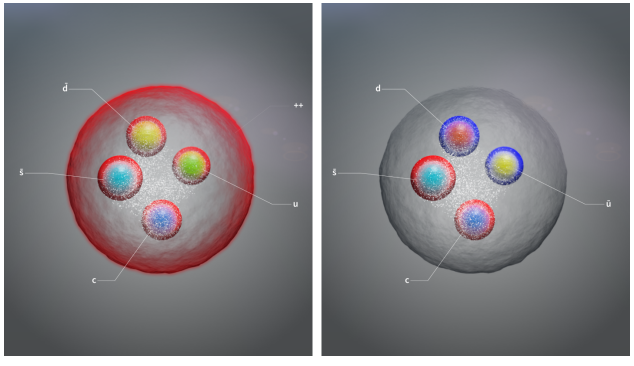
Mesons ($q\bar{q}$)



Baryons (qqq)



Tetraquarks ($qq\bar{q}\bar{q}$)
2016 discovered by LHCb



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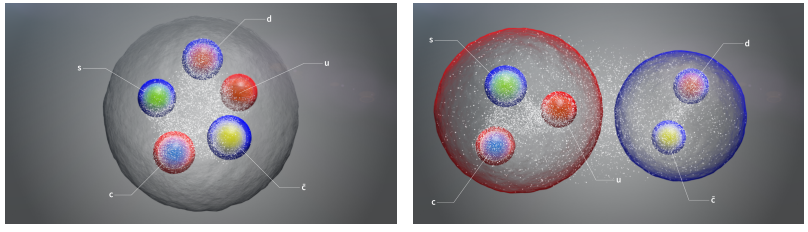
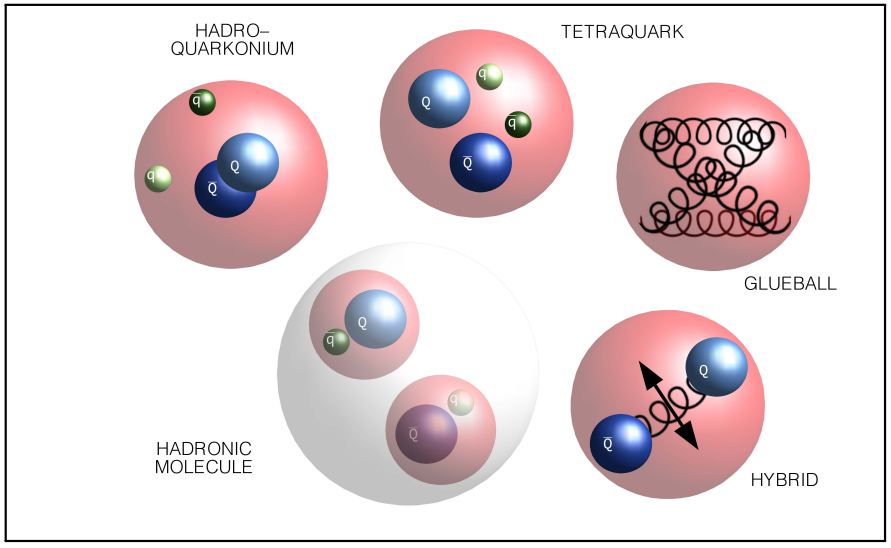
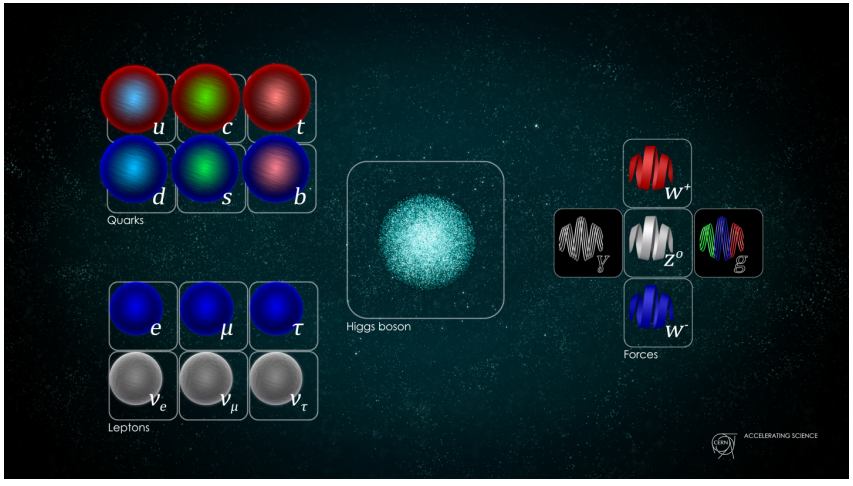


HADRON STRUCTURE – OPEN QUESTIONS

- Clusterization properties inside hadrons and multiquarks?
- Are there more multiquarks like glueballs or hybrids?
- Do quarks, leptons, Higgs and gauge bosons have substructure?

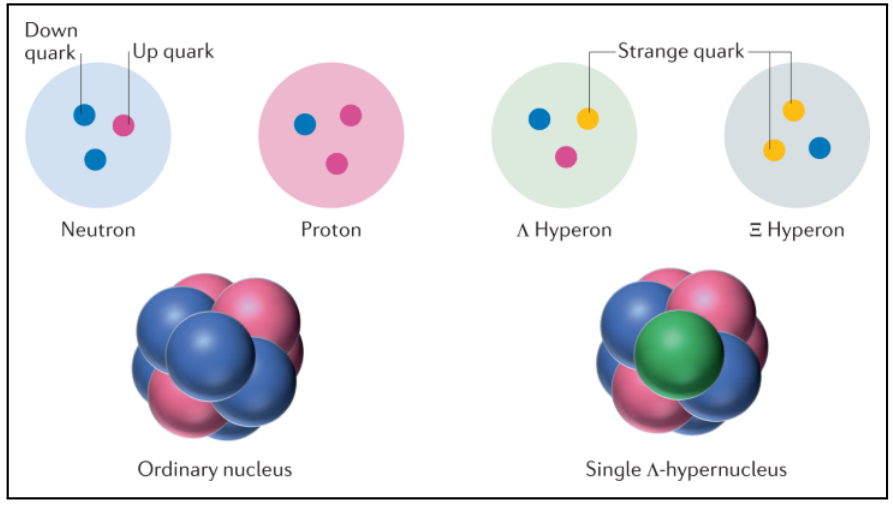
  Current understanding: Not composed of smaller constituents

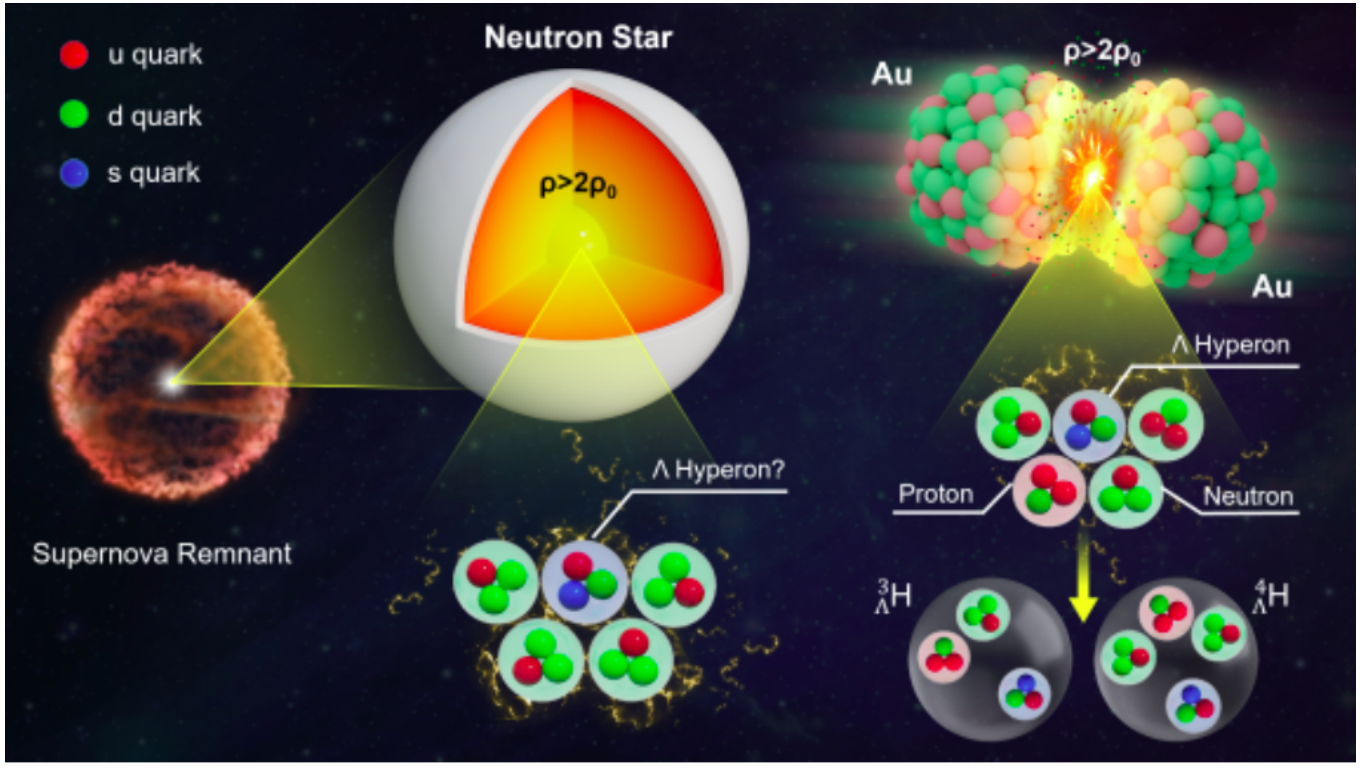




NUCLEAR STRUCTURE – OPEN PROBLEMS

- NN-interaction from QCD
- Properties of hypernuclei
- Hyperon-nucleon and hyperon-hyperon interactions





LITERATURE FOR FURTHER INFORMATION