Complexity out of simplicity in atomic nuclei

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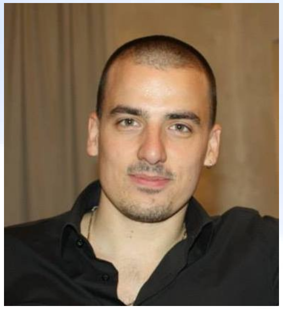


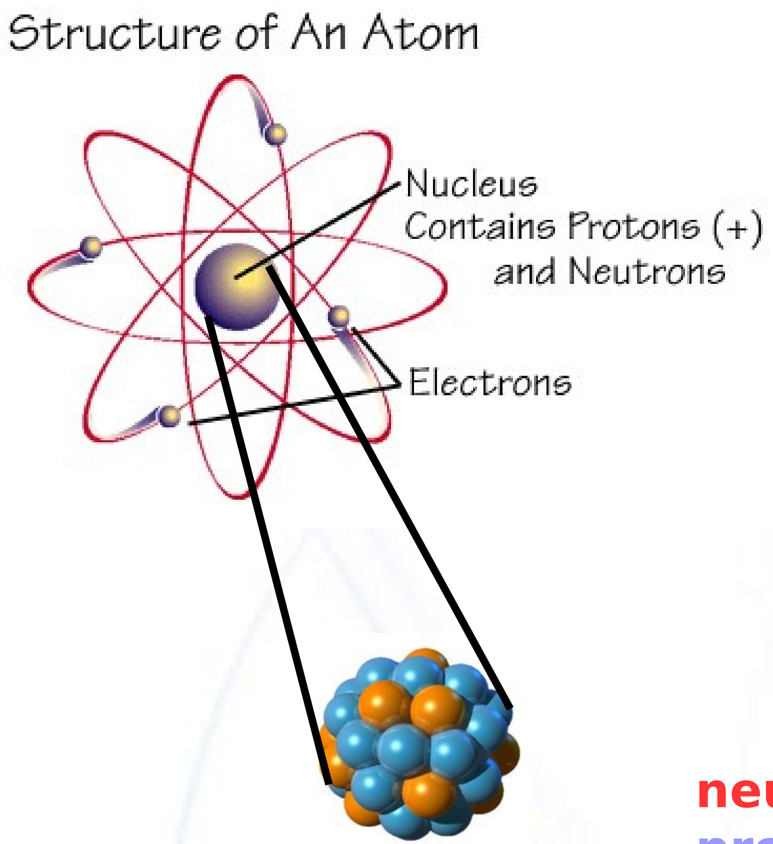
Giovanni De Gregorio

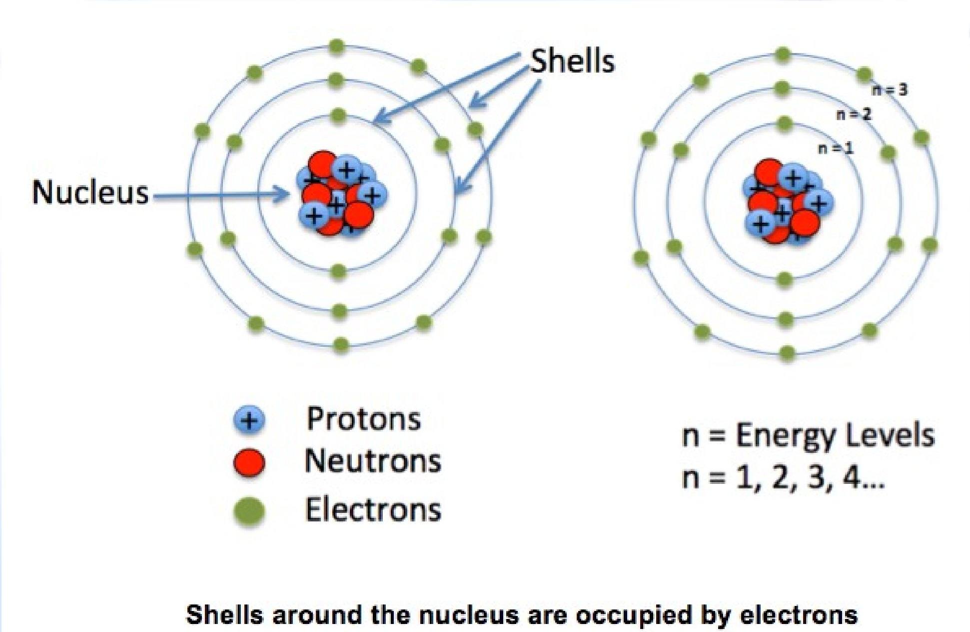
Atomic Nucleus – what is it?

We need models to imagine atoms & nuclei:

Atomic nuclei are bound systems of protons and neutrons (nucleons) – but are there protons & neutrons in nuclei?

EMC effect, Δ, mesons, α-clustering ..



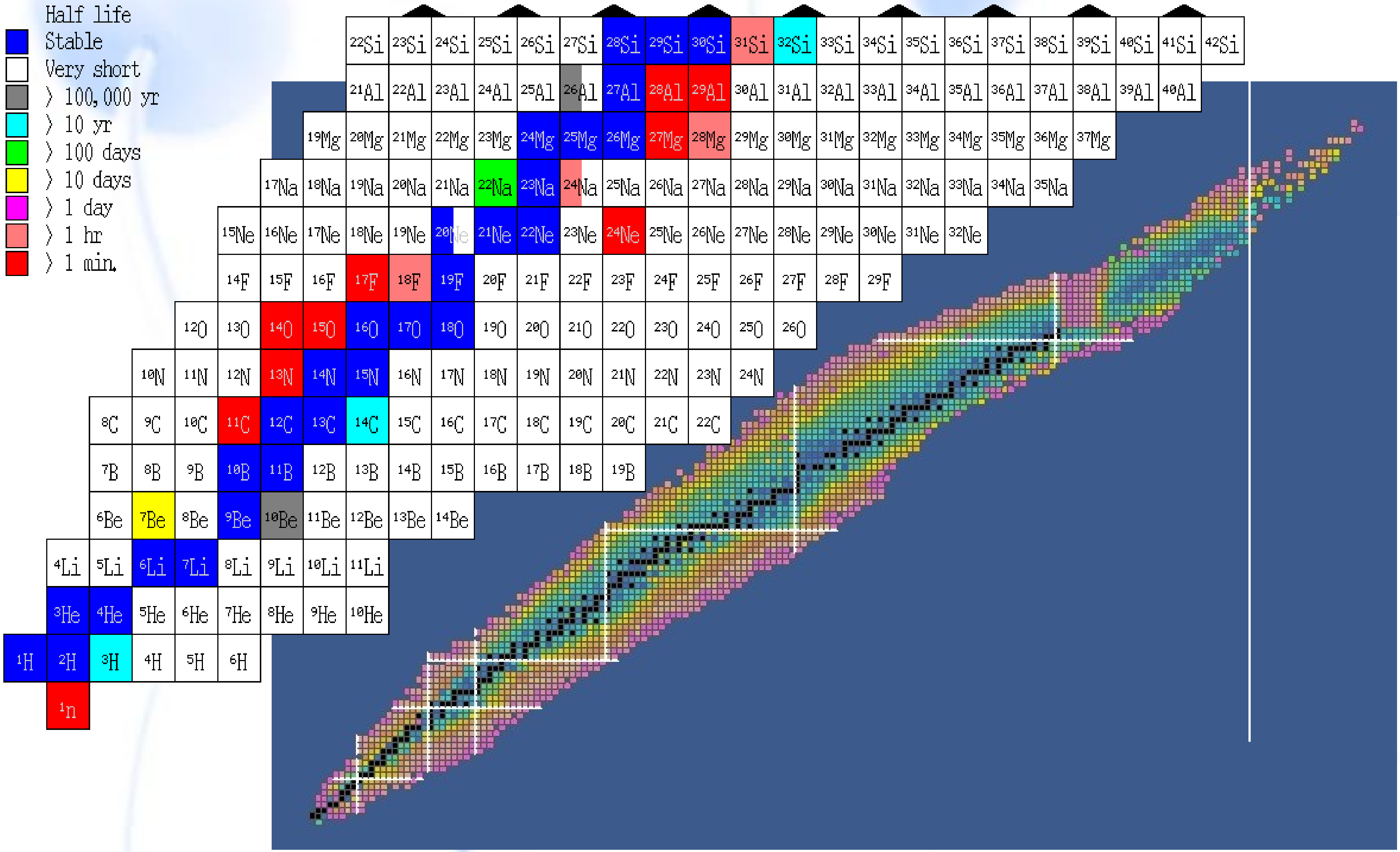


neutrons – small red balls

protons – small blue balls (with little "+")

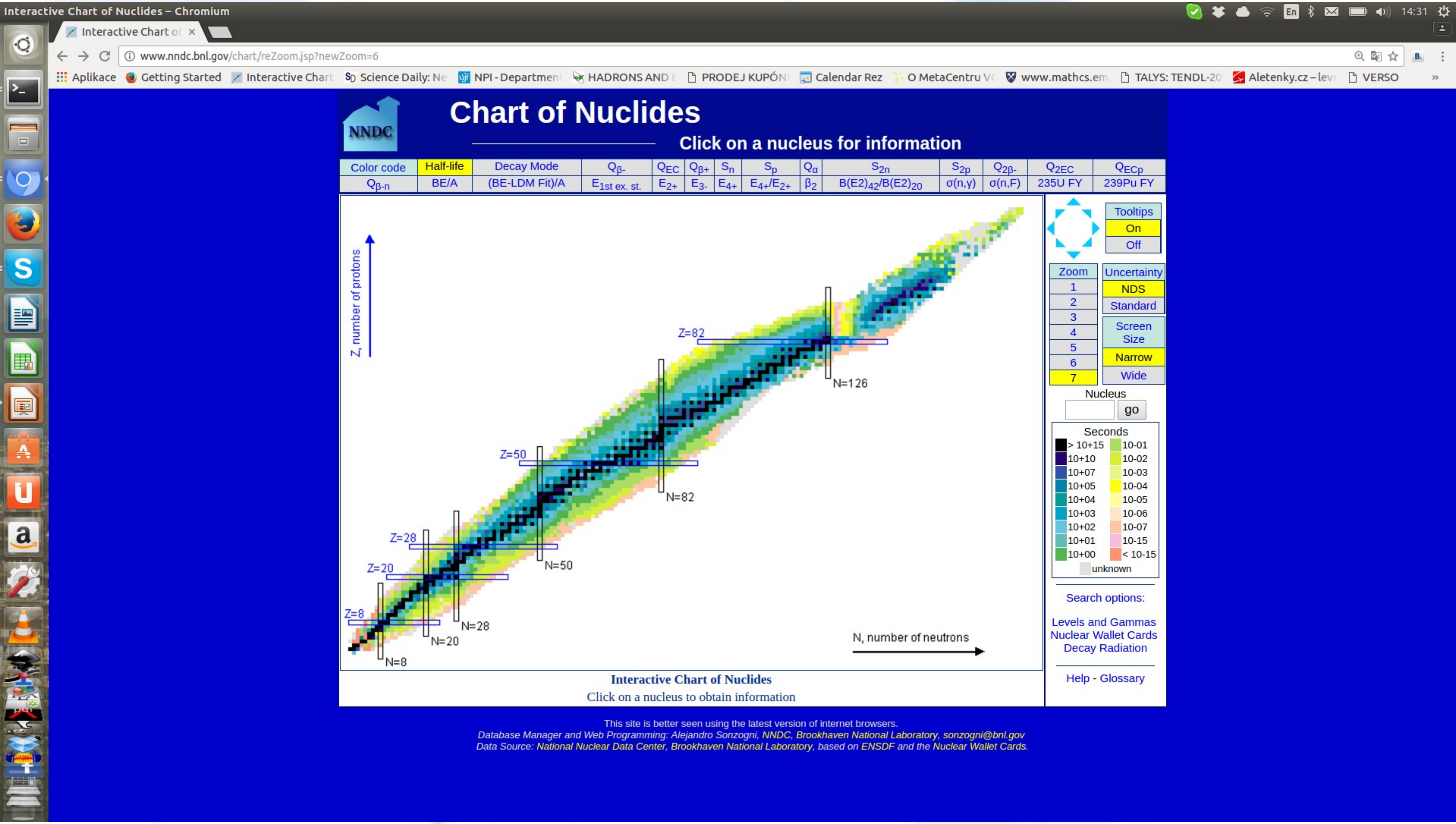
Nuclear Chart

Physics of atomic nucleus: about 2500 known isotopes, 263 stable isotopes
estimate 4000 unobserved yet



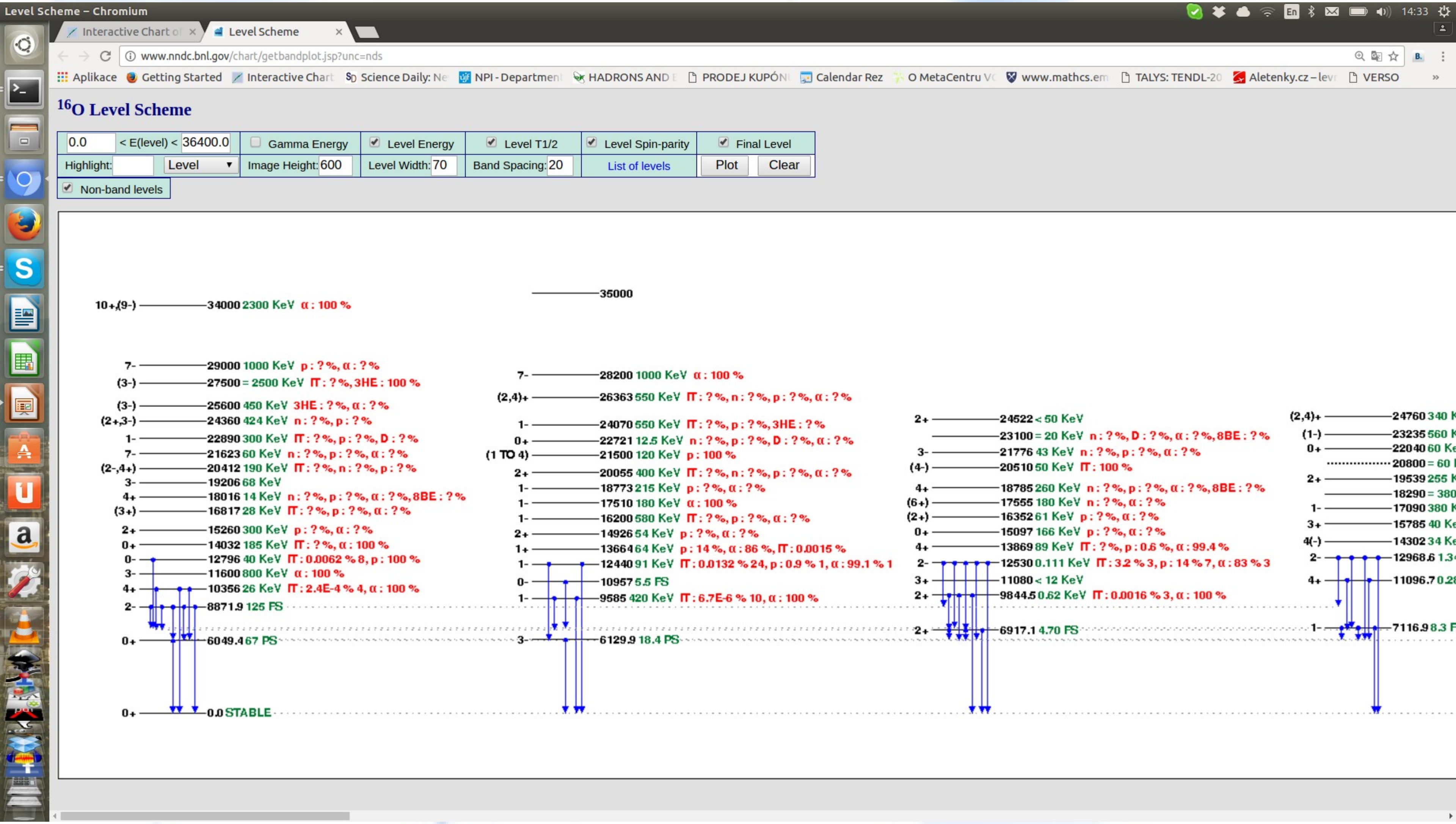
Nuclear Chart

Online database www.nndc.bnl.gov/chart/



Energy spectra

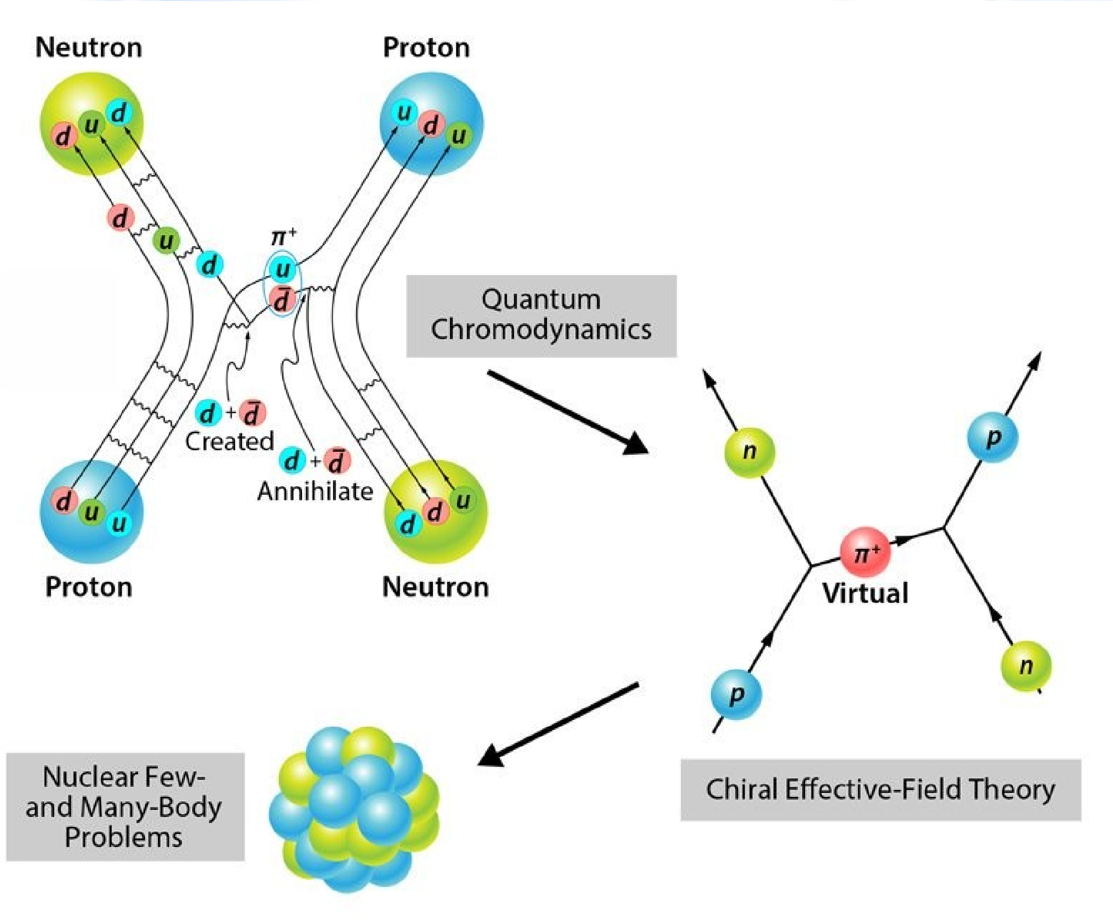
Online database www.nndc.bnl.gov/chart/



“Simplicity“

Atomic **nucleus** formed by **Z**-protons and **N**-neutrons bound together.
Nucleons interact via **strong interaction**.

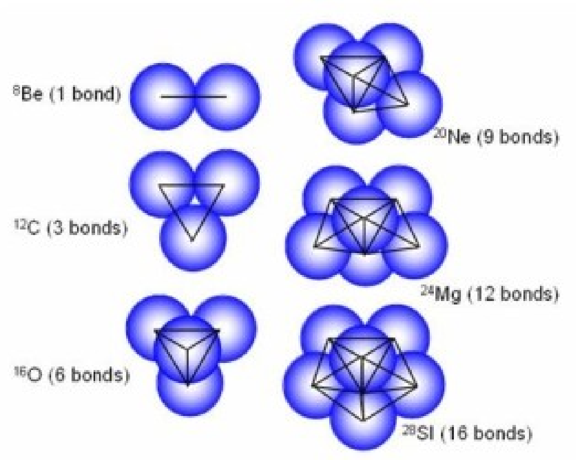
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$



My expectation of understanding of nuclear physics when I was student…

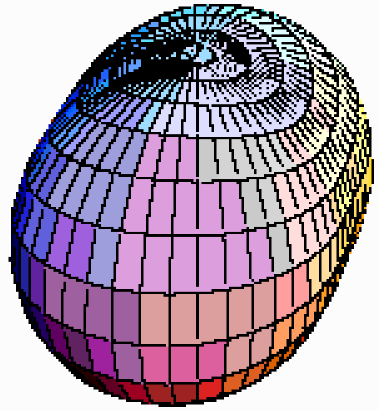
In the popular books about science and physics the things often described as “everything solved with the exception of few remaining problems regarding fundamental particles and initial moments of Big Bang..“

“Complexity“

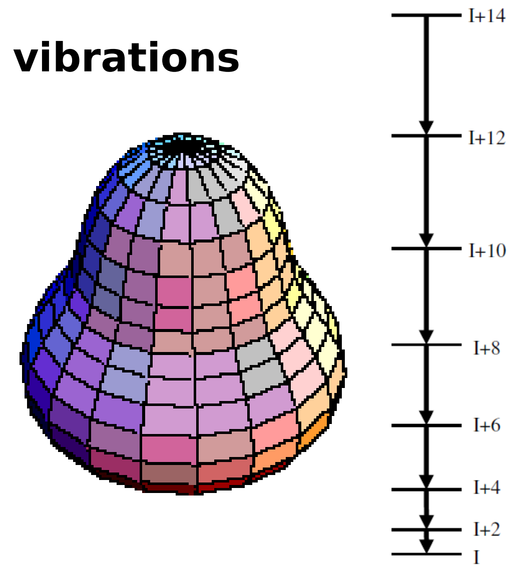


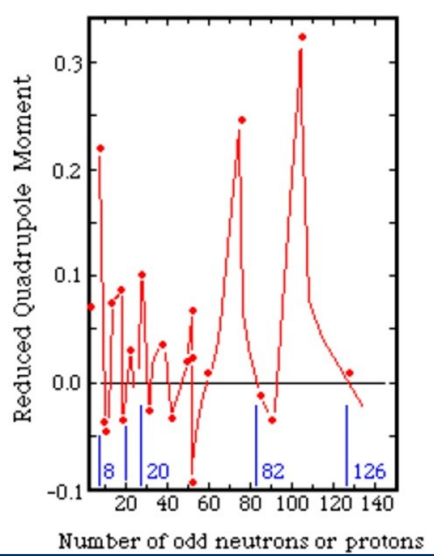
Clustering → nuclear “molecules“

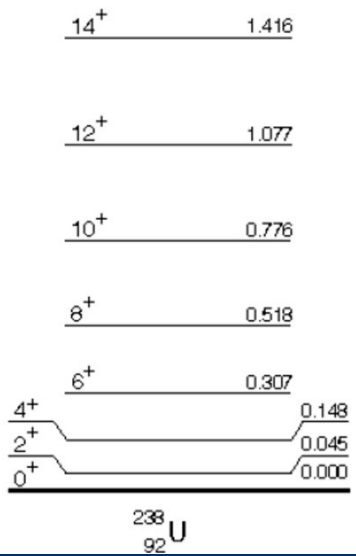
rotations



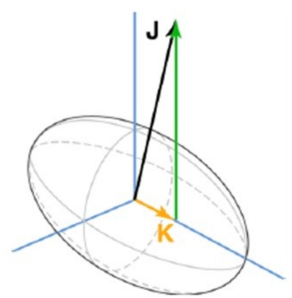
vibrations

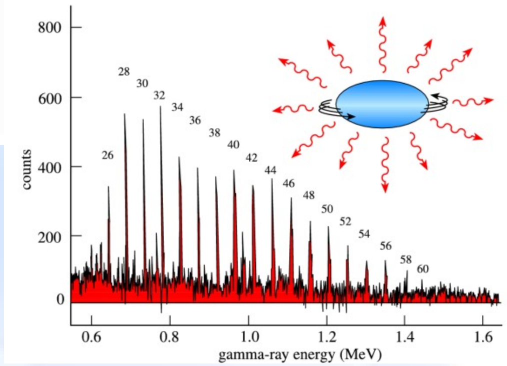


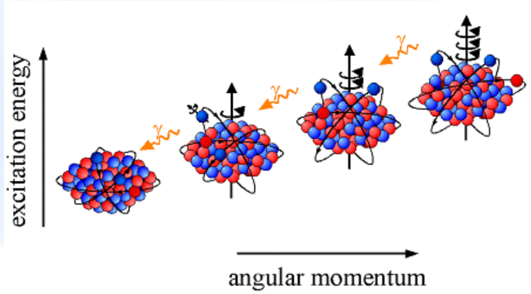




rigid rotor

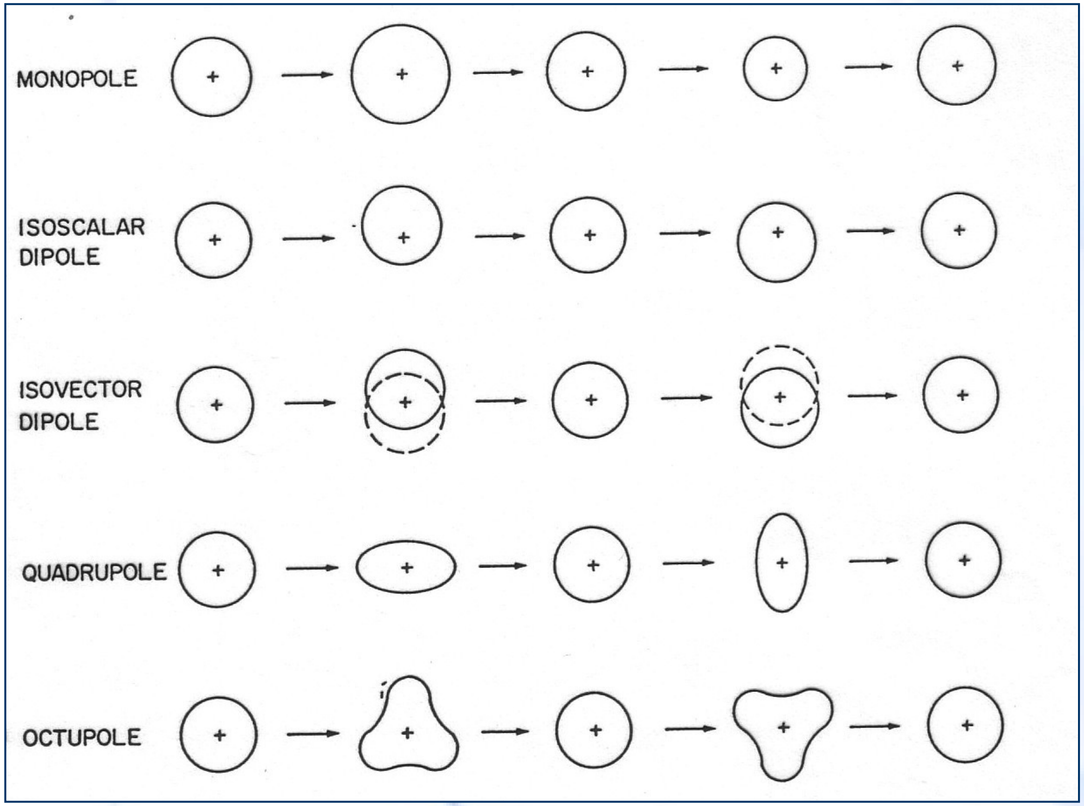






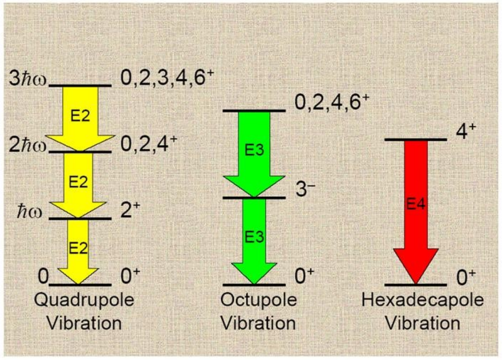
“Complexity“

Deformations:
expansion into multipoles



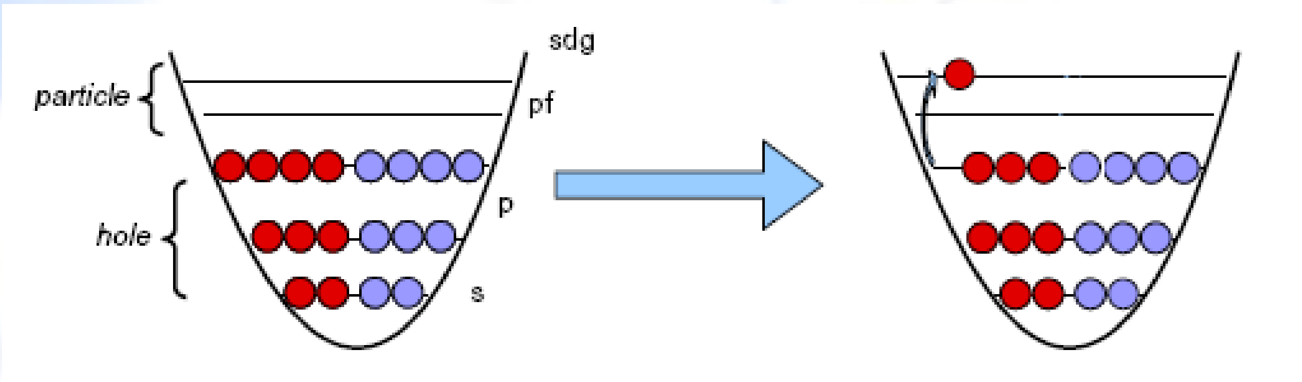
Vibrational states:

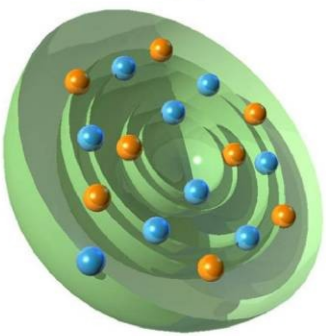
Description analogous to the excitations of Harmonic Oscillator (in collective degrees of freedom)

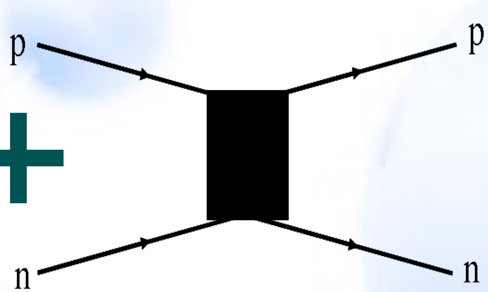


“Complexity“

“particle-hole“ excitations of “mean-field“







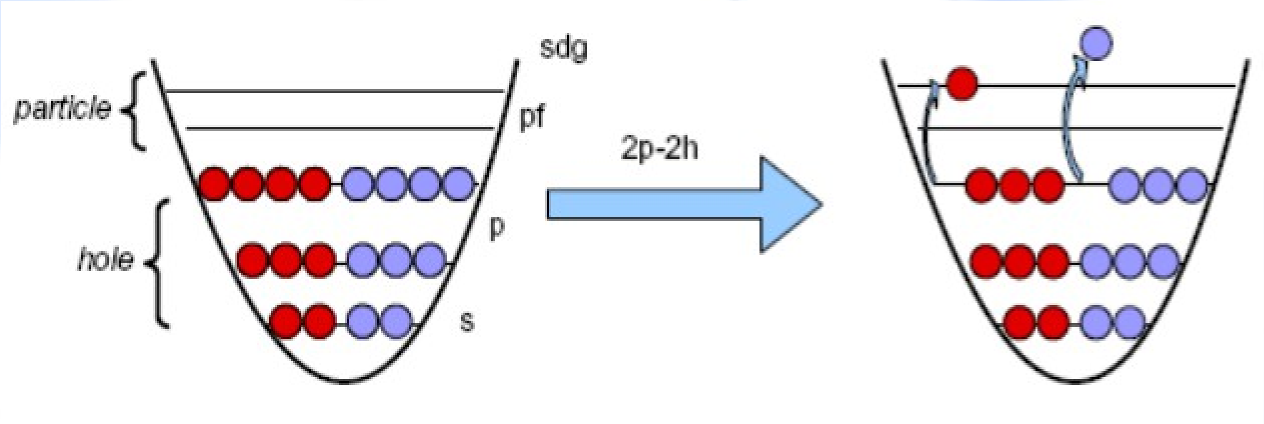
Residual interaction important..
“Mixing“ of many 1-particle configurations

Excitations due to collectivity:

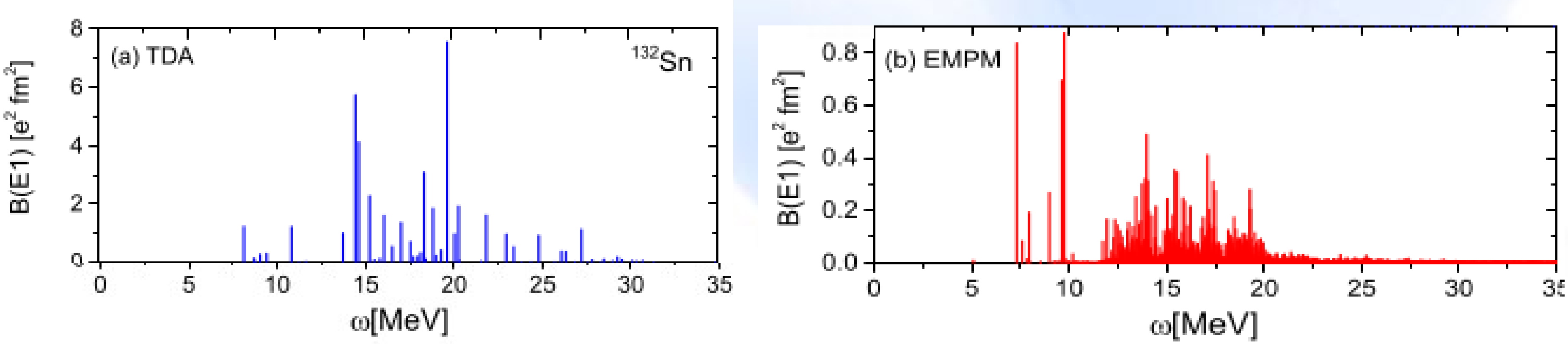
$$\gamma + (A, Z) \rightarrow (A, Z)^*$$

- excitations of 1 particle-hole type
- collective excitations (coherent superpositions of big amount of “particle-hole“ excitations)

“Complexity“

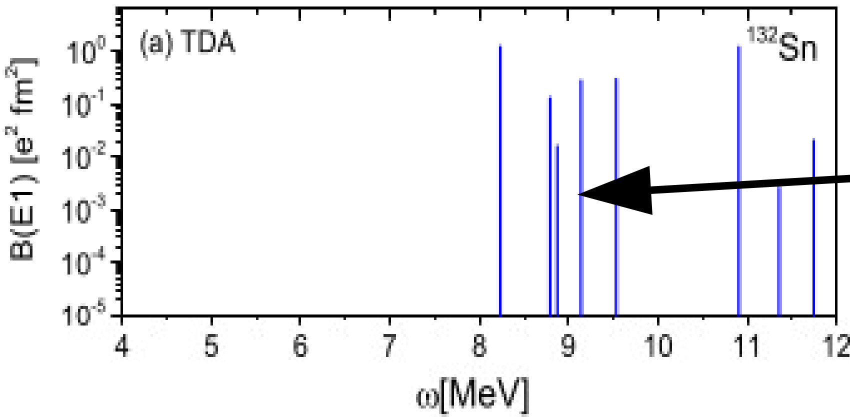


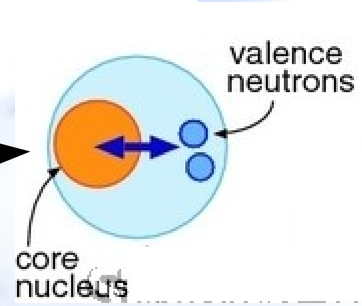
Many “particle-hole“ excitations simultaneously
More configurations → richer excitation spectra



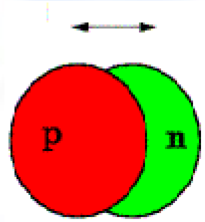
"Complexity"

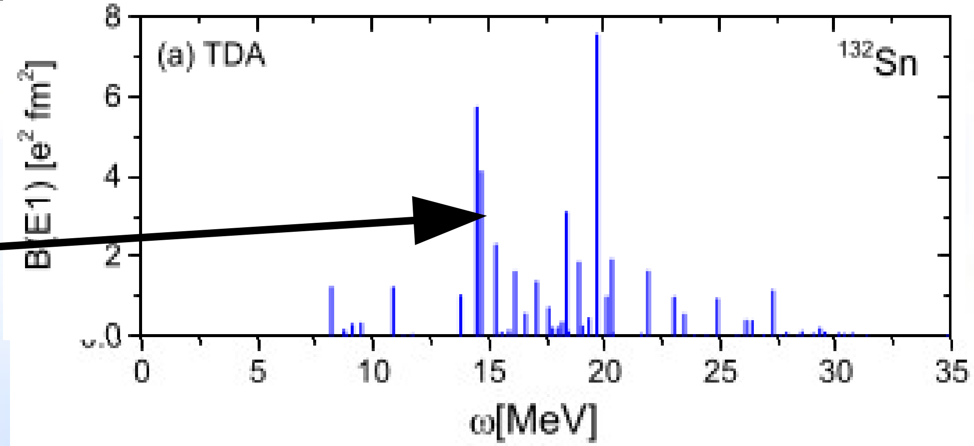
Example of excitation spectrum- ^{132}Sn





Pygmy res. - nuclei with neutron excess - oscillations of neutron skin with respect to core

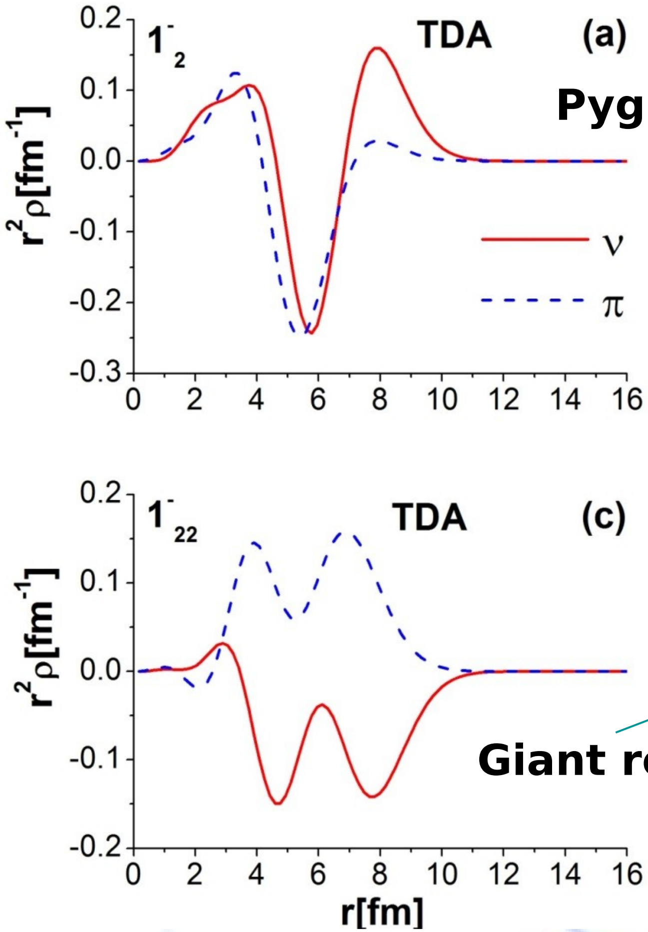




Giant dipole resonance (E1)
collective state – vibration of protons in opposite phase to neutrons

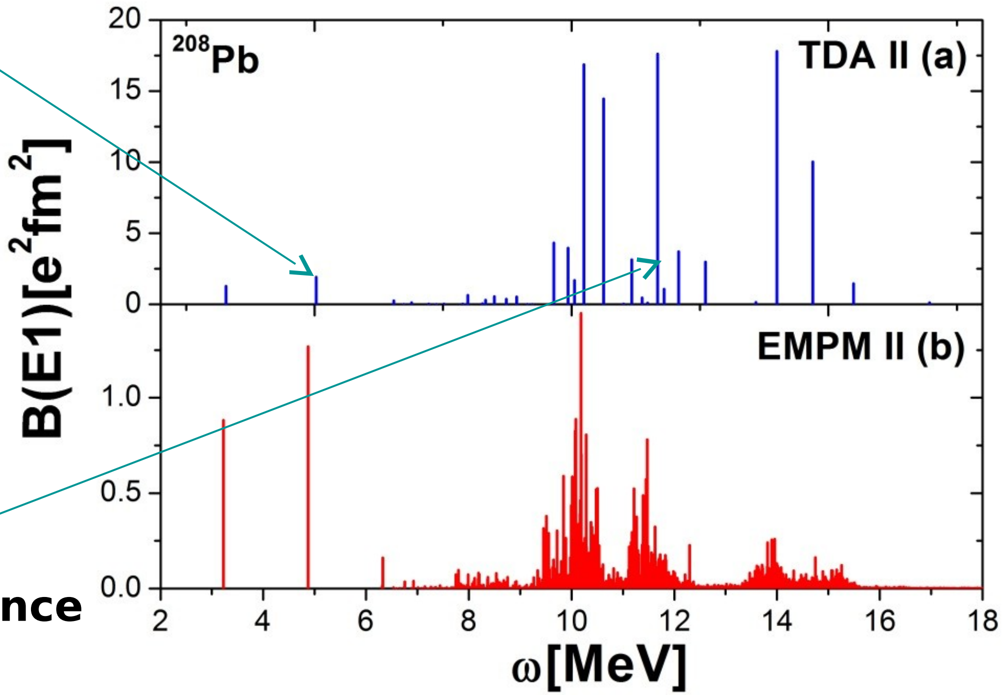
“Complexity“

Example of excitation spectrum - ^{208}Pb

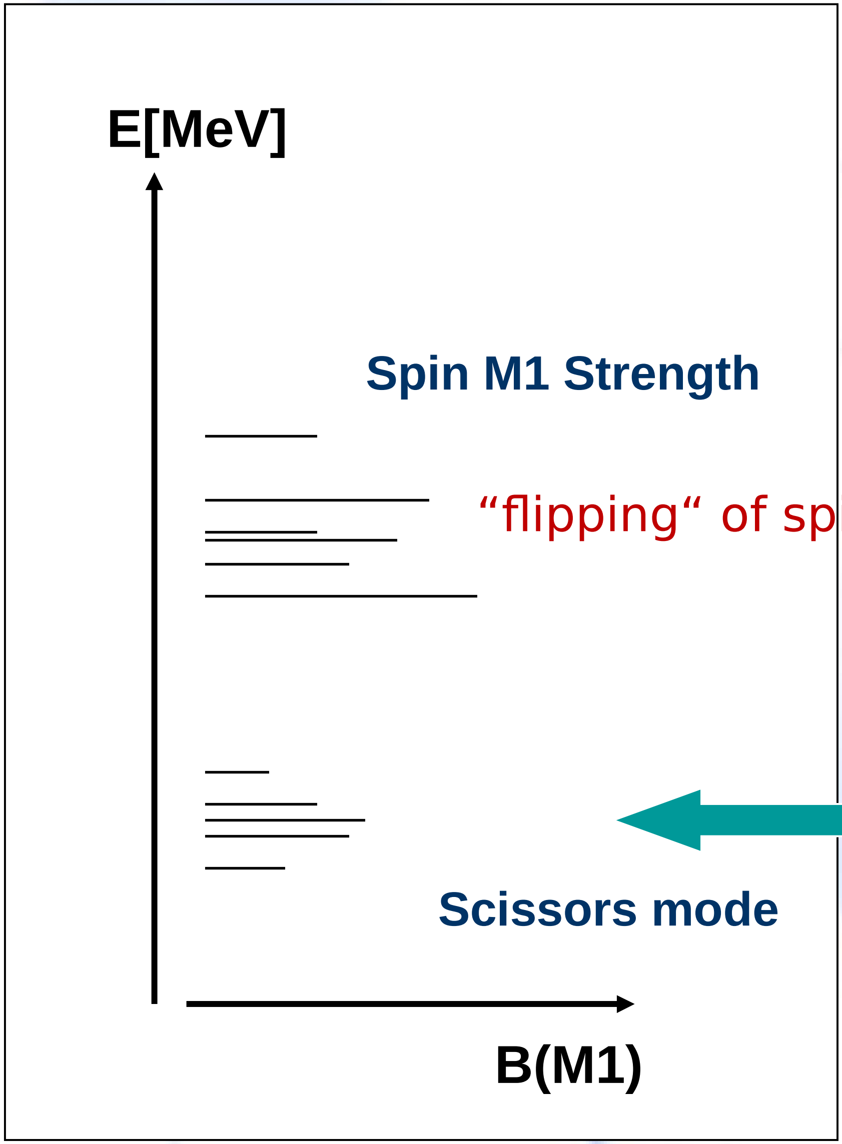


Pygmy res.

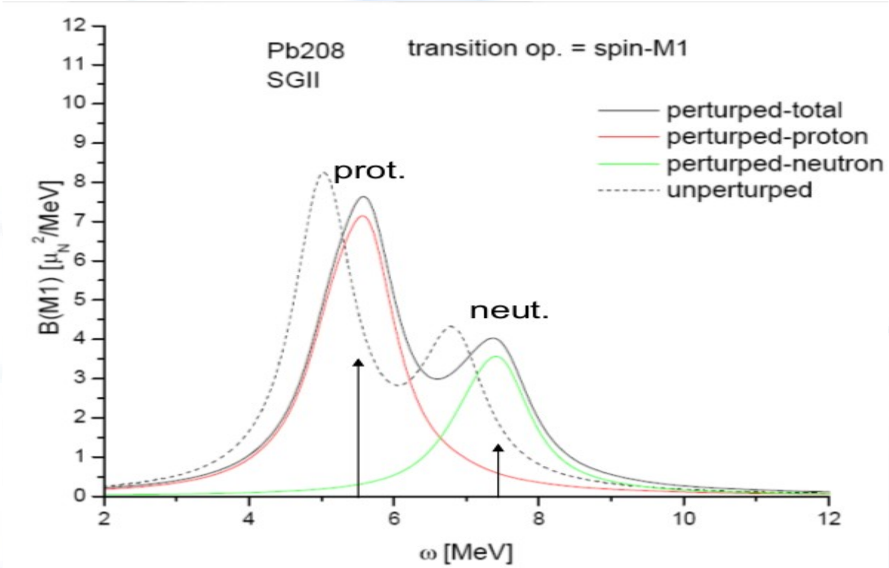
Giant resonance



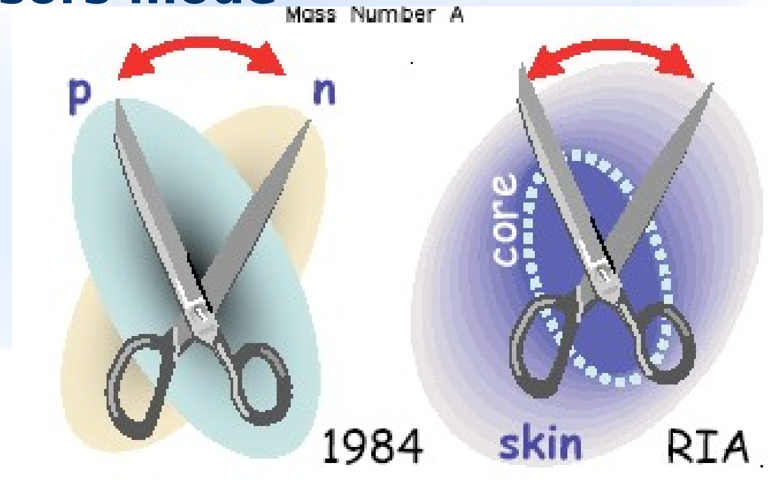
“Complexity“



“flipping“ of spin



orbital motion of protons and neutrons with opposite phase – scissors mode



Atomic nucleus – how to describe it

Implicit paradigm of theoretical nuclear physics:

Nucleus is **bound state of nucleons**. We describe nucleus by methods of **quantum mechanics** (QM) from **interactions** among **nucleons**.

This paradigm itself is not most **fundamental approach** – we should describe nuclei from **QCD.** Except of first pioneering attempts [**Phys. Rev. Lett.** 113, 252001 (2014)] **impossible**!!

Instead we employ the strategy: build **potential** among **nucleons** (**NN**, **NNN**, etc.) → solve **QMB** problem with given nucleon potential (i.e. **Hamiltonian**)

Building potentials itself is complicated task – **nucleons** as particles with the **inner structure**. Even the potentials cannot be build directly from **QCD**.

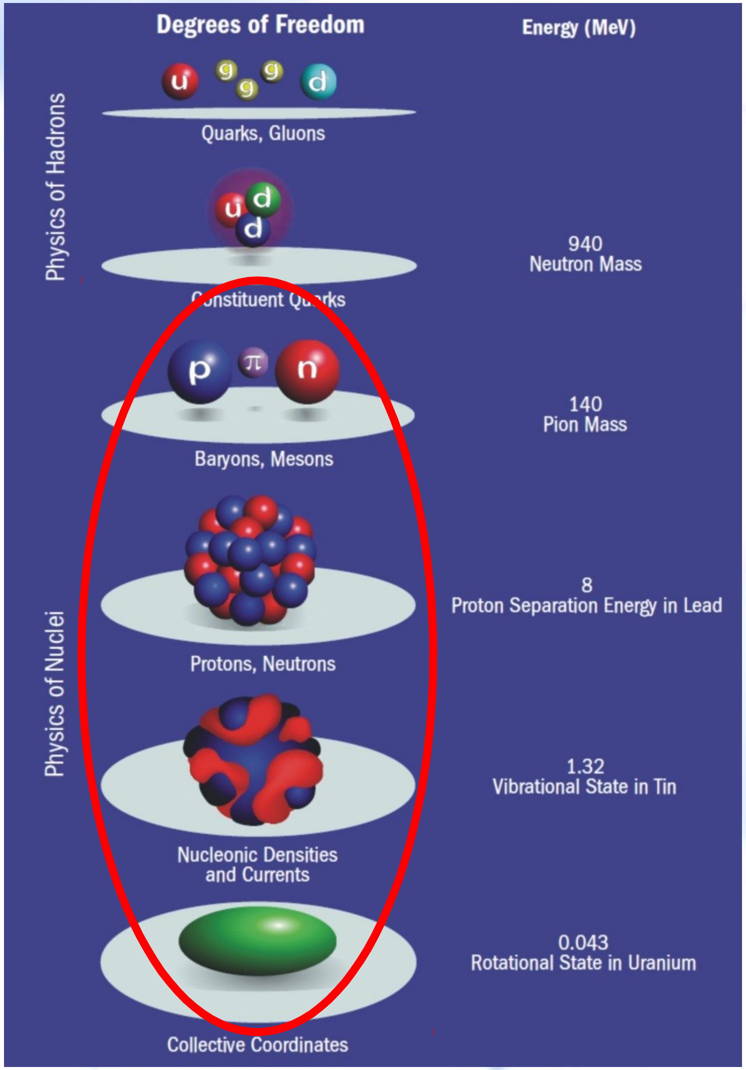
Models to describe **nucleon potentials**. For potentials suitable for nuclear calculations we need to solve **many-body nuclear problem**.

↔

Solution of the nuclear **many-body problem** strongly depend on the employed **nucleon potential**.

Atomic nucleus – how to describe it

Different scales – they are not separated of each other.



What we see depends on resolution:

- **< 0.0001 fm: quarks**
- **0.1-1 fm : baryons, mesons**
- **1 fm: nucleons**
- **10 fm : collective modes**

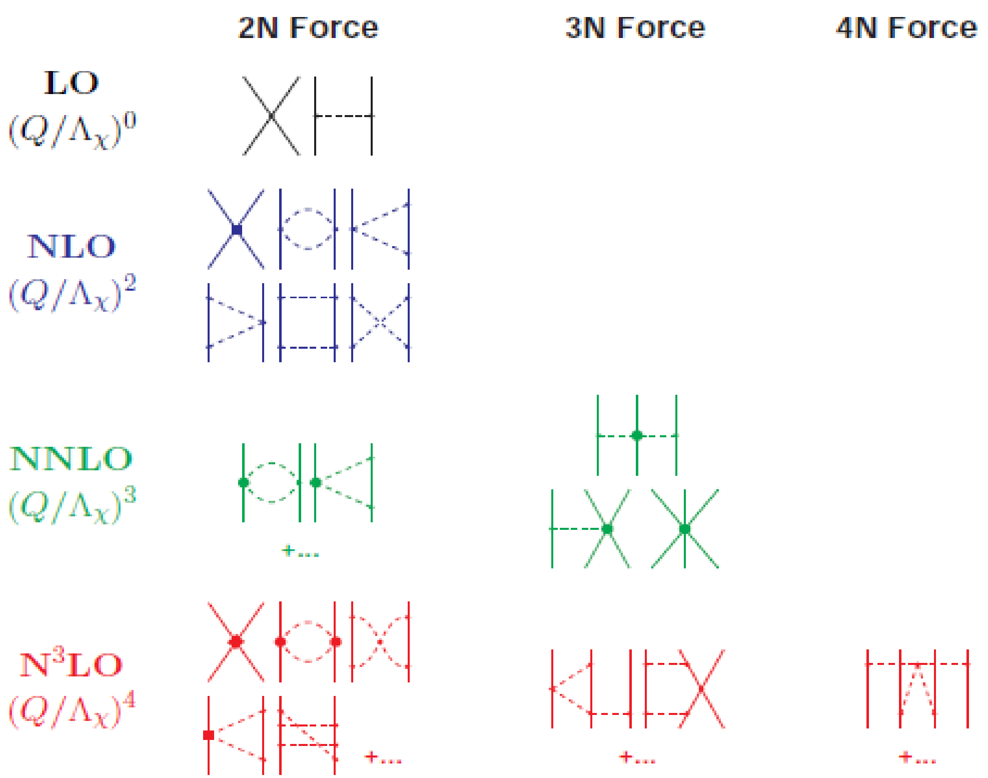
Atomic nucleus – how to describe it

Possible approach to derive NN interactions

$$\mathcal{L}_{\pi N} = \hat{\mathcal{L}}^{(1)}_{\pi N} + \hat{\mathcal{L}}^{(2)}_{\pi N} + \hat{\mathcal{L}}^{(3)}_{\pi N} + \dots$$

$$\hat{\mathcal{L}}^{(1)}_{\pi N} = \bar{N}\left[i\partial_0 - \frac{1}{4F_\pi^2}\vec{\tau}\cdot(\vec{\pi}\times\partial_0\vec{\pi}) - \frac{g_A}{2F_\pi}\vec{\tau}\cdot(\vec{\sigma}\cdot\vec{\nabla})\vec{\pi}\right]N + \dots$$

Effective field theory – instead of QCD field theory with elem. degrees of freedom (quarks, gluons) we build field theory with nucleons and pions. Must obey the same symmetries as QCD –> Chiral Perturbation Theory (ChPT)

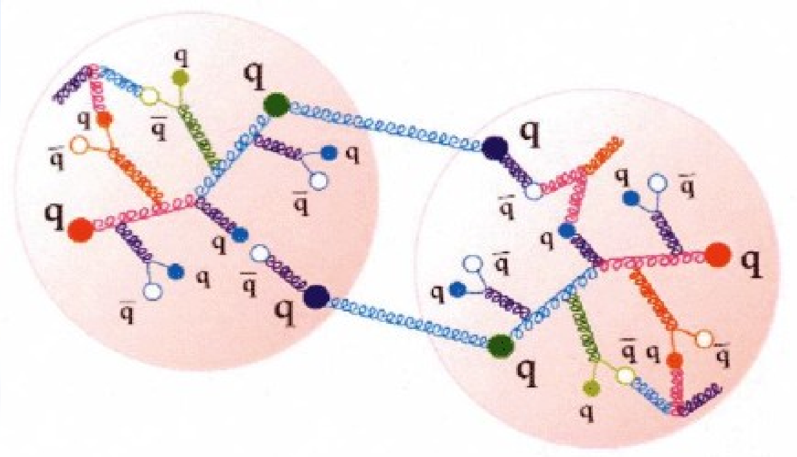


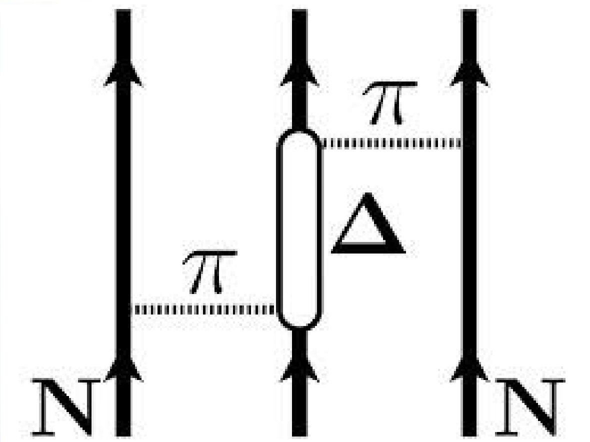
Only mesons here are pions. But pion exchanges 2π, 3π, … till any order. Multi-pion exchanges replace presence of other types of mesons.

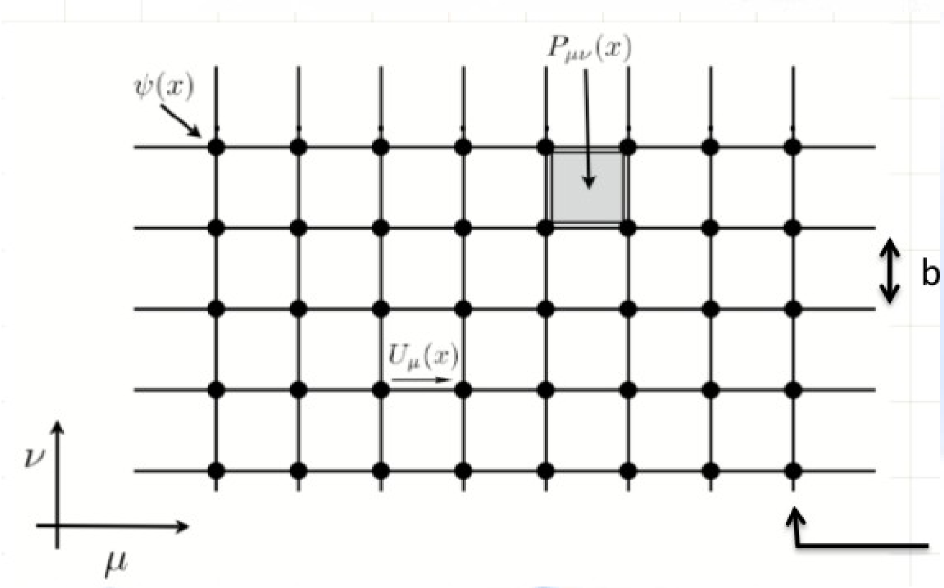
Diagrams of NN scatering can be divided to orders – perturbative theory (?)

Atomic nucleus – how to describe it

Existence of more-body interactions between nucleons
As consequence of inner structure of nucleons







In nucleus – there is lot of degrees of freedom – quark, gluons, mesons, baryons

Summary

- Atomic **nuclei** as bound microscopic **many-body** systems with very rich structure
- Huge **complexity** of different states and also different isotopes must arise from **simplicity** – relatively simple **laws** and the fact that we bind **A nucleons**
- **Single-particle** as well as **collective** modes in nuclei
- Clustering, deformations, vibrations, rotations,
- There is no any “**Standard Model**“ for atomic nuclei – theoretical description is very demanding
- We need new **bright ideas** – only young clever scientists can bring new solutions!!!

Thank you for attention!