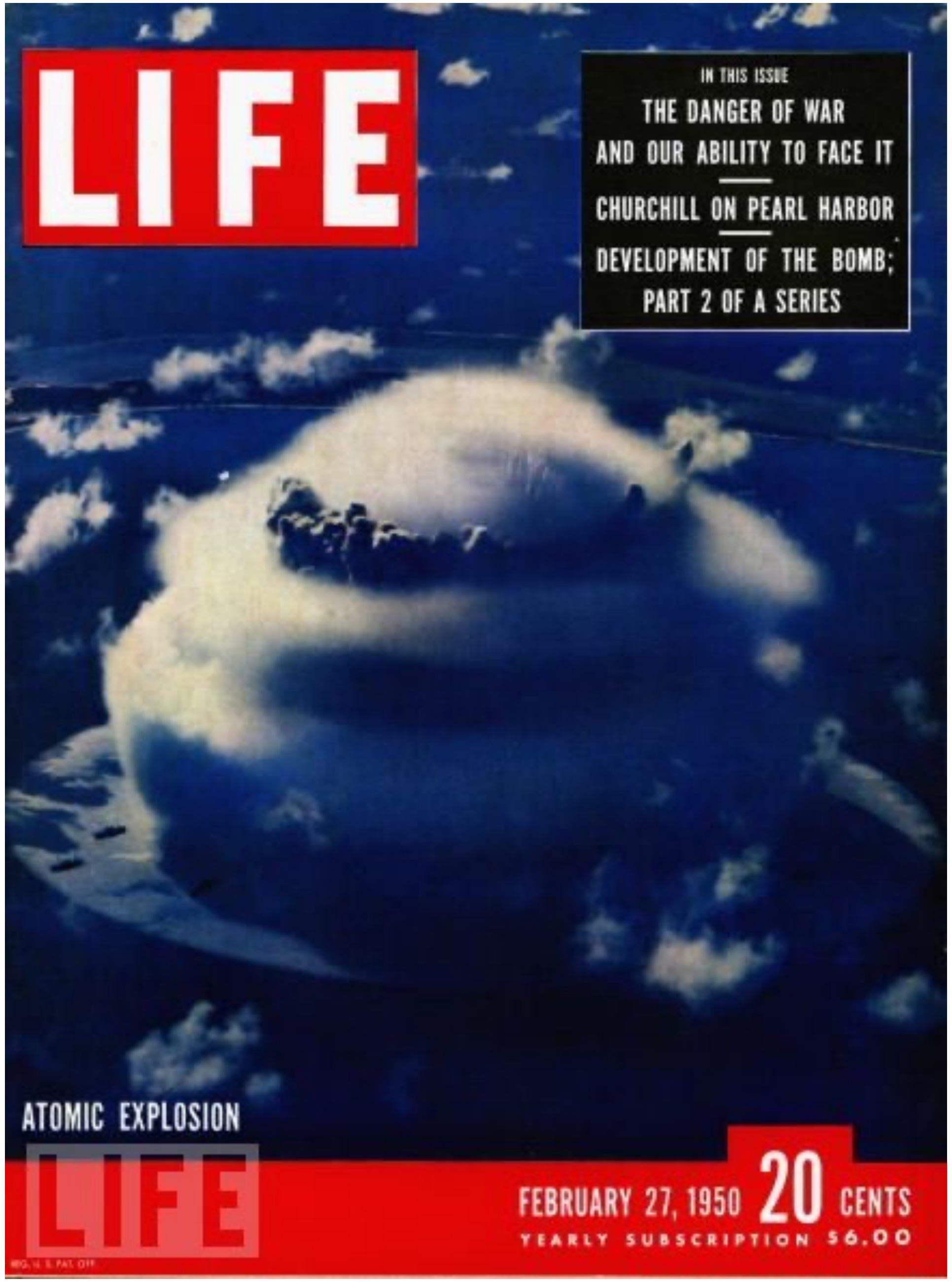
Uma viagem ao coração da Matéria

Teresa Peña

TÉCNICO LISBOA


LIFE
IN THIS ISSUE
THE DANGER OF WAR
AND OUR ABILITY TO FACE IT
CHURCHILL ON PEARL HARBOR
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Nuclear and Hadronic Physics

Studies the “core” of visible, ordinary matter (nuclei, hadrons).

- It investigates the mechanism of mass formation
- It gives the basis of the cosmic creation, reactions in stars, distribution of elements in the Universe (Cosmic Chemistry)

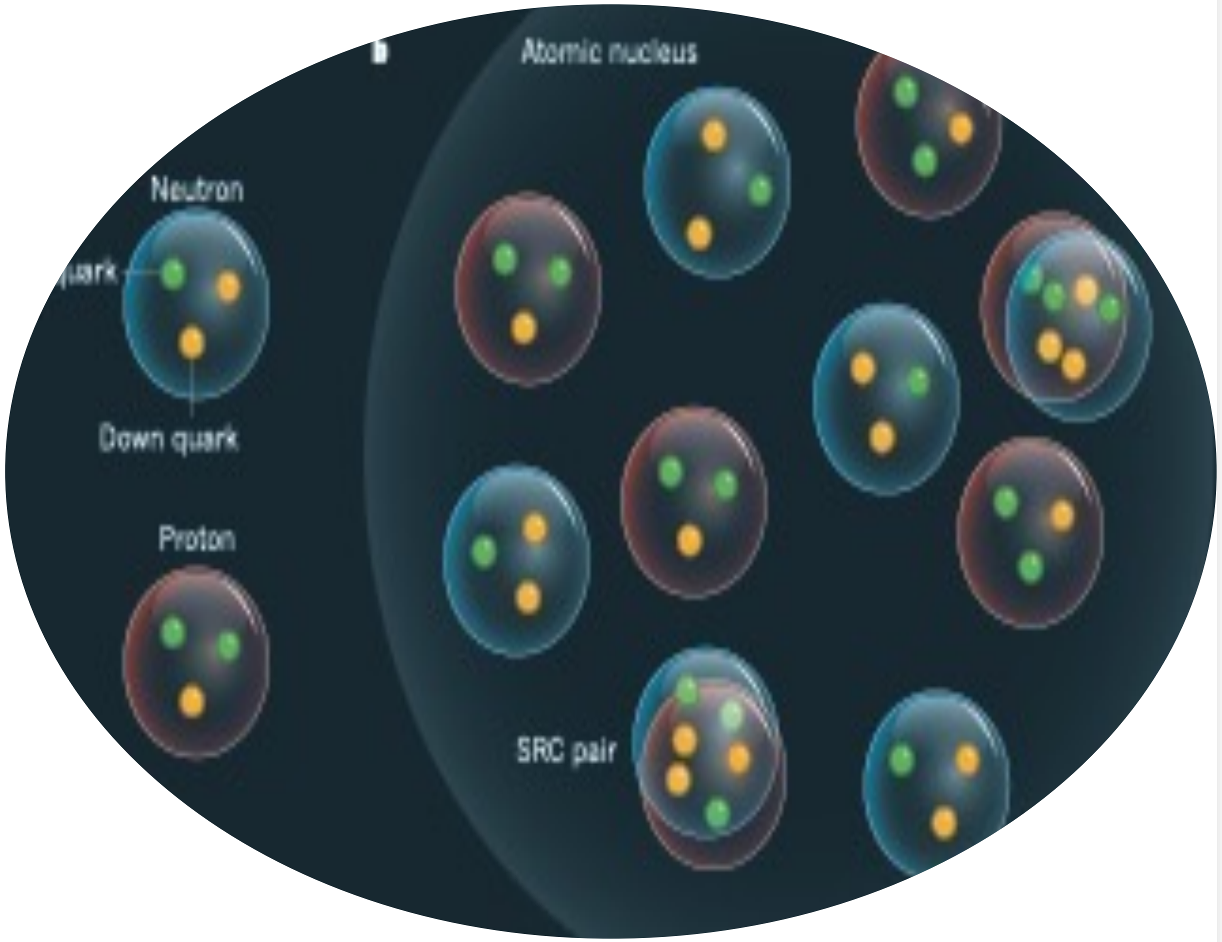
Shows that we are a cosmic nuclear accident.

Would the effective nuclear force be slightly weaker, we would not exist.
The deuteron, the first step in formation of all elements, would not have been formed.
$E_B = (2.22461 \pm 7 \times 10^{-5})$ MeV; $V_{nuclear} = 40$ MeV

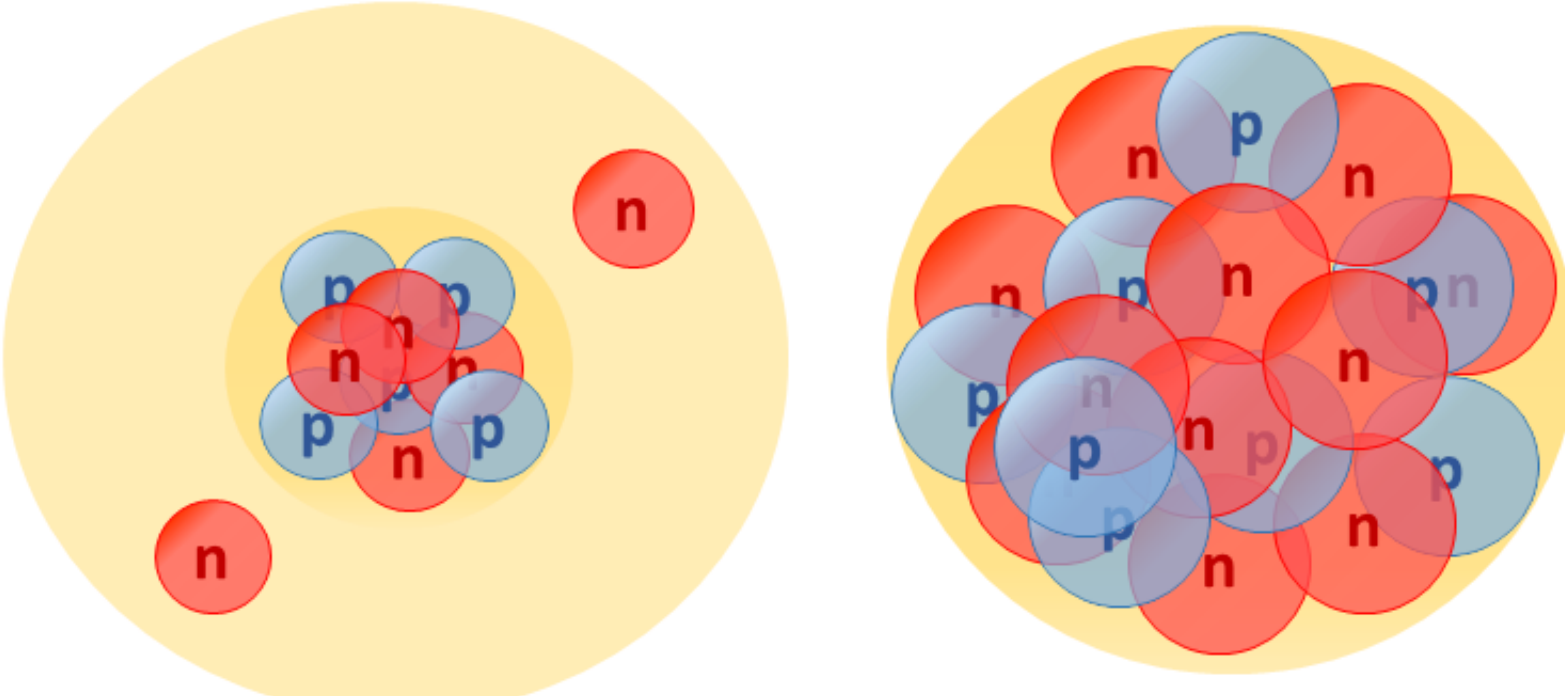
De que é feito
o núcleo de um
átomo?

?

De que é feito o núcleo de um átomo?

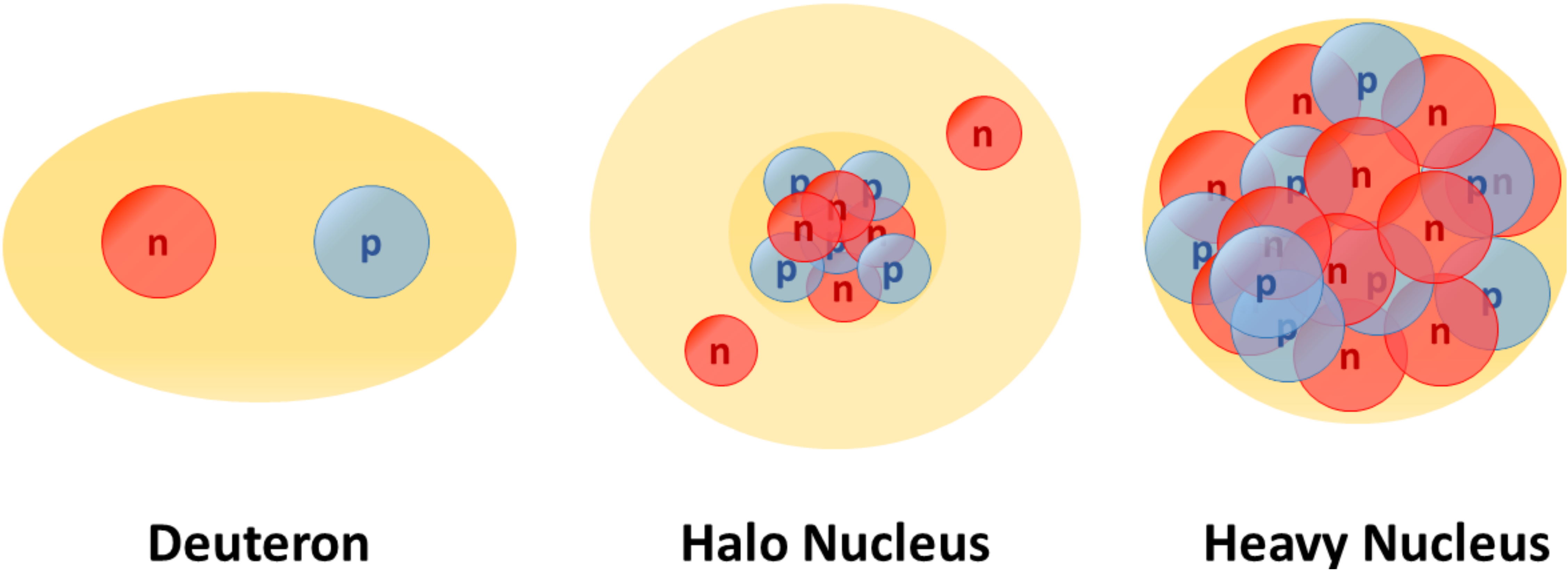


Como é feito um núcleo?



Como é feito um núcleo?

Ambas as configurações, planetárias e de empacotamento, existem!
E até configurações “moleculares”: o deuterão (neutrão - protão).



E há núcleos macroscópicos

Estrelas de neutrões

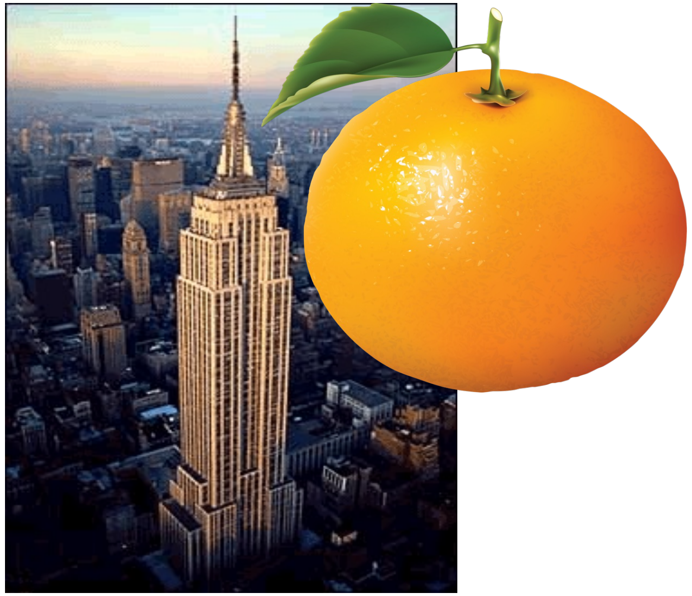
- Tamanho de uma estrela de neutrões versus o tamanho de Manhattan NY

- 20-30 km de raio.

O núcleo atómico é matéria em condições extremas

A densidade nuclear é praticamente a mesma para todos os núcleos.
E é extremamente grande

10^{39} nucleões/cm^3



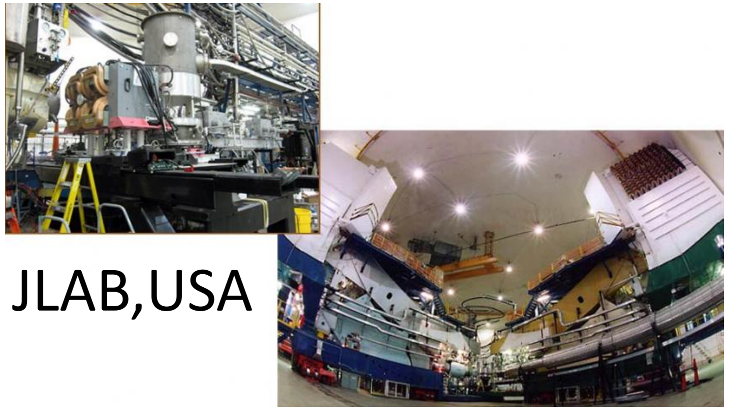
Densidade nuclear $\rho = 3.8 \times 10^{11}$ tonelada /dm^3

Densidade média na Terra 5.5 kg/dm^3

Como um líquido classico, a matéria de um núcleo é **incompressível.**

A densidade e a energia de ligação por nucleão são independentes do número de nucleões.

Os núcleos são como trufas de **chocolate**



JLAB,USA

Nuclear dermatology clinic. The vessel containing the lead sample in the PREX experiment (*left*) and the massive spectrometers used to detect the electrons scattered from the lead nuclei and measure the nuclei's skin.

Photos Courtesy of Robert Michaels

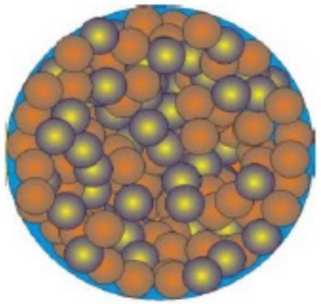
Physicists Measure the Skin of a Nucleus

By Adrian Cho | Mar. 2, 2012 , 4:16 PM

PREX Collaboration, Phys. Rev. Lett. 108, 112502 (2012)

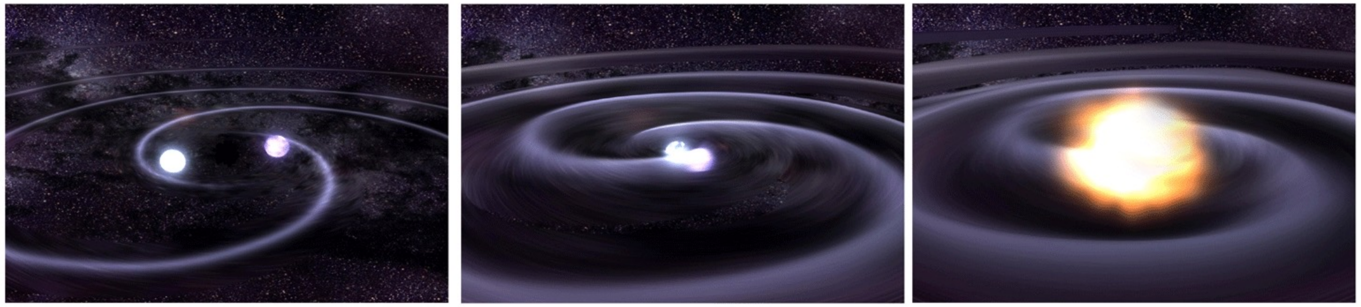
Repulsão de muito curto alcance entre 2 neutrões "sela" o núcleo:

impede o seu colapso sob a atração da força no interior entre neutrões e protões.



^{208}Pb ~ 10^{-15} m

Neutron star ~ 10^{4} m



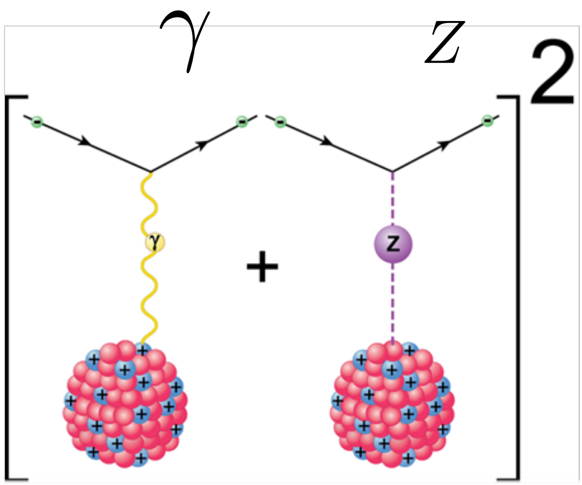
A repulsão de curto alcance entre neutrões

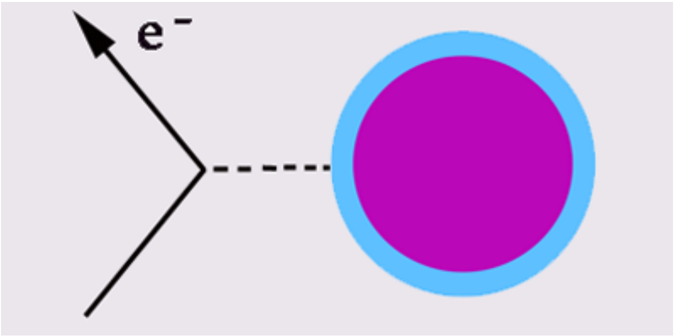
- contraria o colapso de estrelas de neutrões em buracos negros;
- explica os resultados recentes sobre ondas gravitacionais (GW) resultantes da colisão de estrelas de neutrões:

$M_{max} \geq 2M_S$ em vez de $M_{max} \geq 1{,}5M_S$ inferidos anteriormente de dados sobre os pulsars PSR J1903+0327 e PSR J0348+0432.

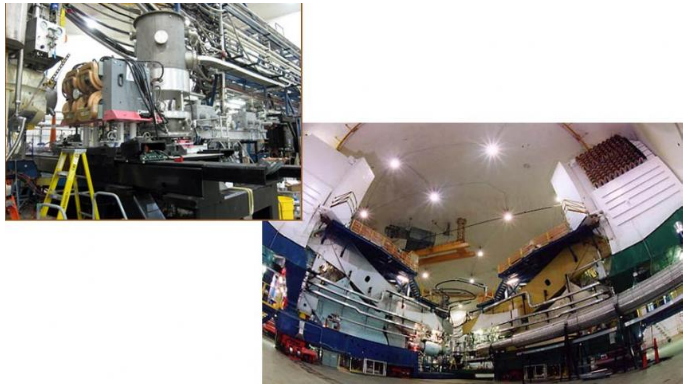
Nuclei are like chocolate truffles

Interacting electrons with nuclei gives information on a non homogeneous nuclear structure: a *skin* of neutrons at the surface of heavy nuclei is measured.





APS



Nuclear dermatology clinic. The vessel containing the lead sample in the PREX experiment (*left*) and the massive spectrometers used to detect the electrons scattered from the lead nuclei and measure the nuclei's skin.

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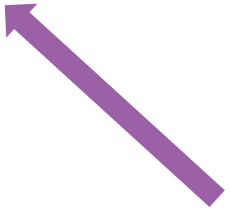
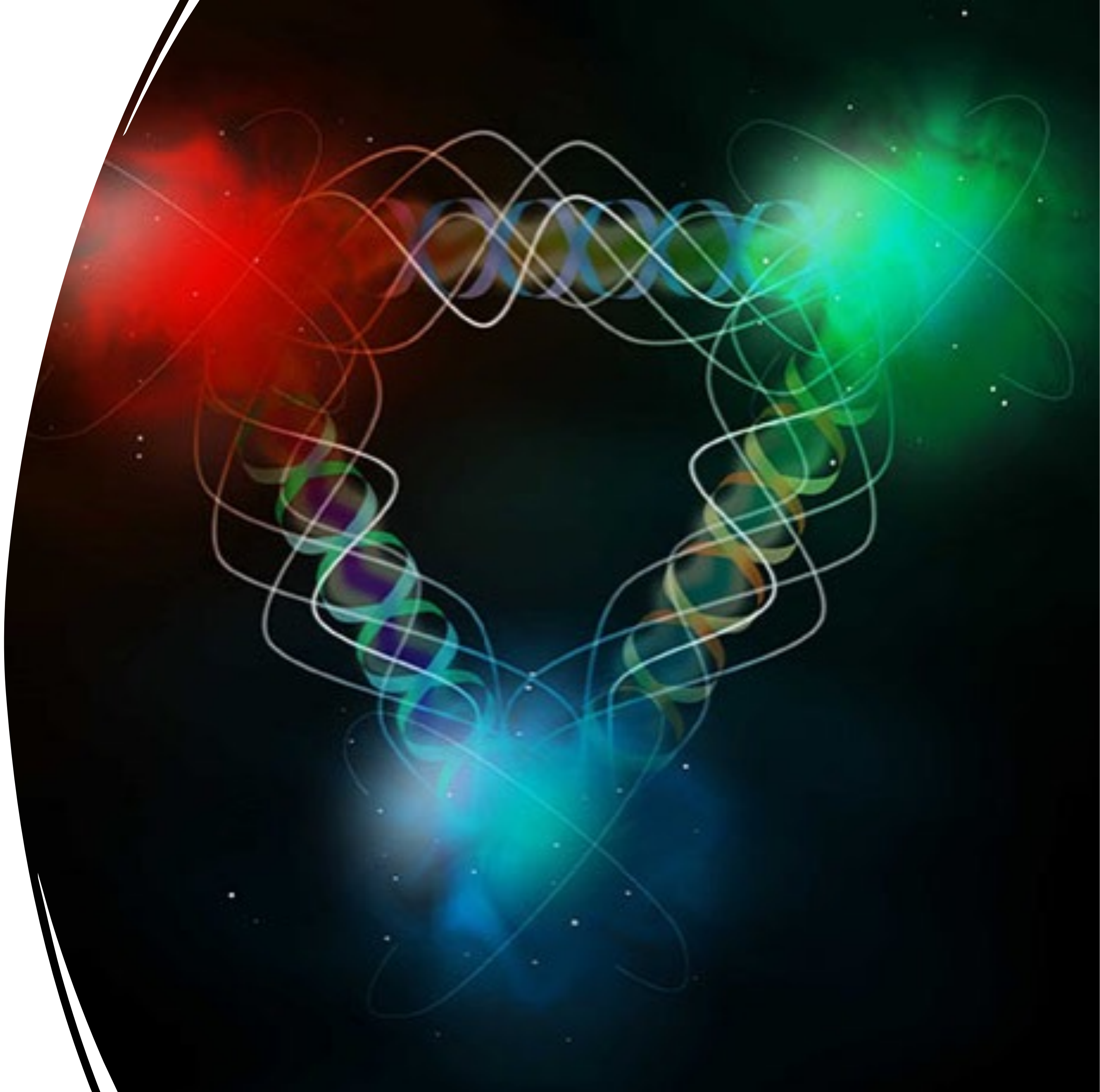


The weak neutral current creates a very small parity violation effect in the results

Interação Forte (QCD)

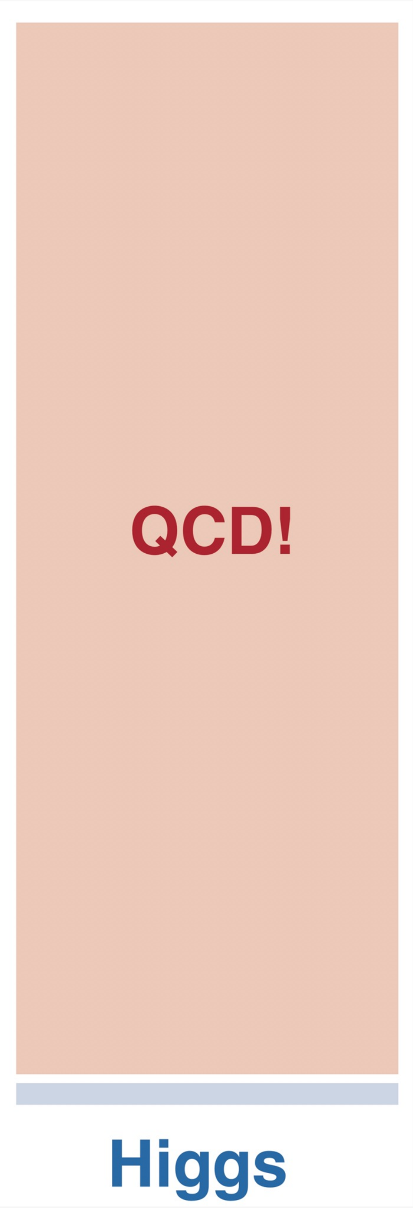
- Os quarks estão confinados dentro dos nucleões, devido a gluões que trocam entre si.

- Os gluões têm carga forte ("cor"), por isso não só medeiam a interação forte entre quarks, interagem com eles próprios.

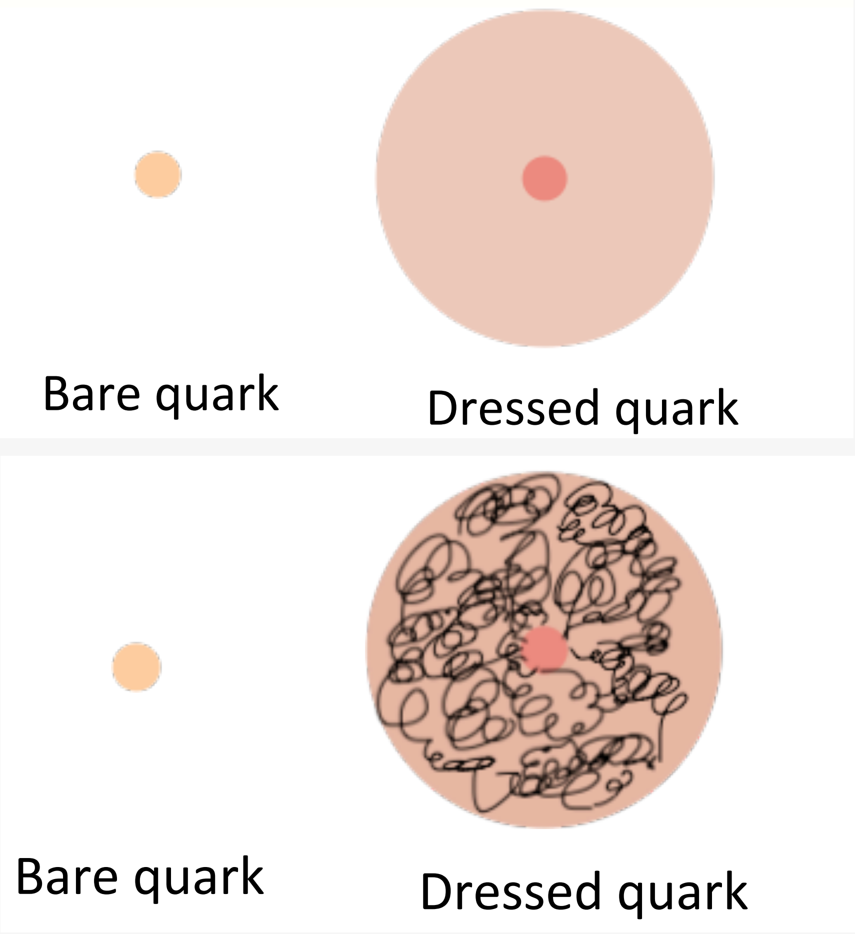


Problema em aberto 1

Massa dos quarks dentro dos nucleões



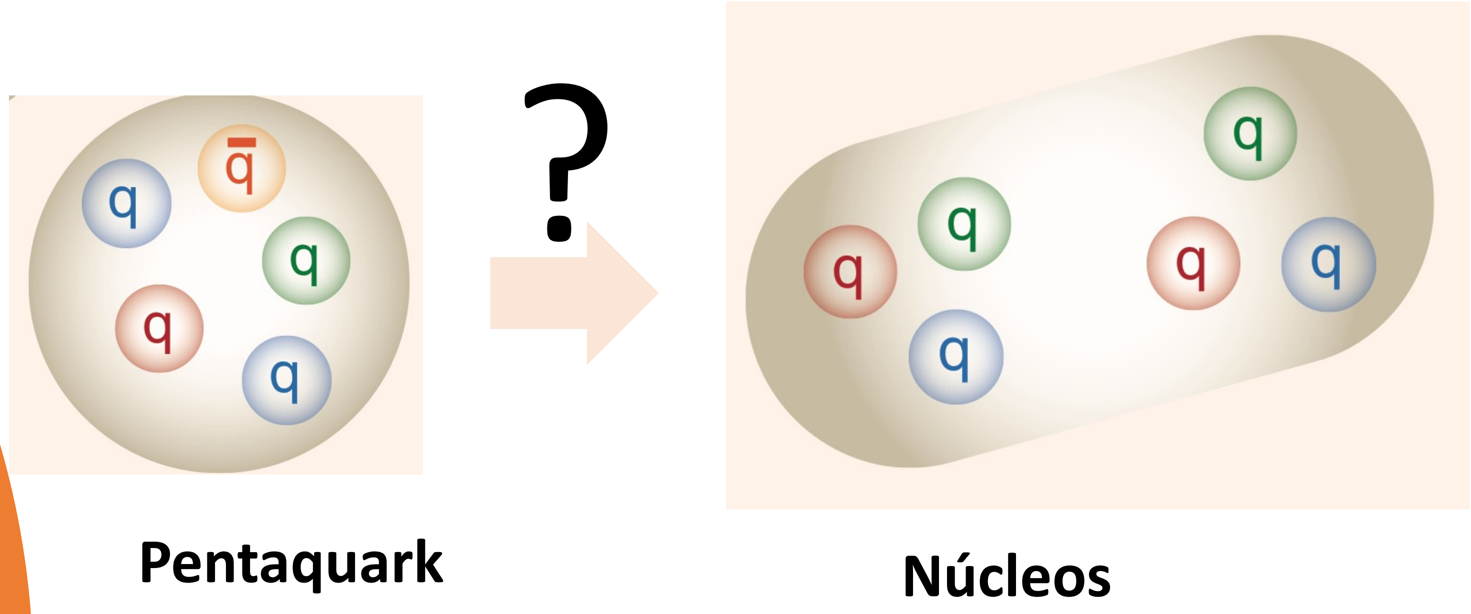
u	d	s	c	b	t	
0.003	0.005	0.1	1	4	175	GeV
0.35	0.35	0.5	1.5	4.5	175	

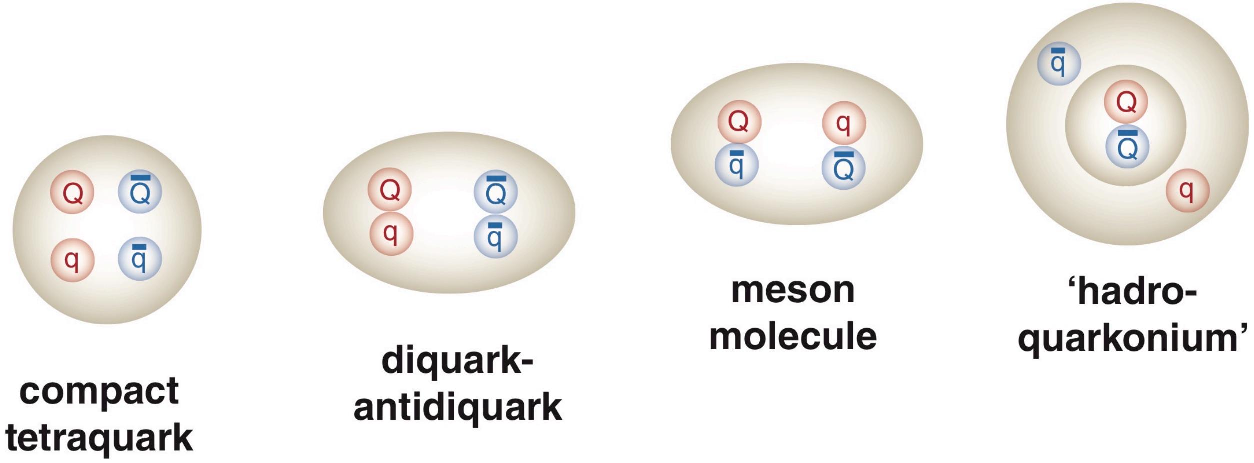


Problema em aberto 2
Interação entre núcleos a partir da interação forte

?

Problema
em aberto 2
Interação entre núcleos
a partir da interação
forte





Take-home message

- o “coração ” da matéria visível no universo,
(**núcleos**, hadrões) pode ter estruturas diversas
e é matéria em condições extremas.

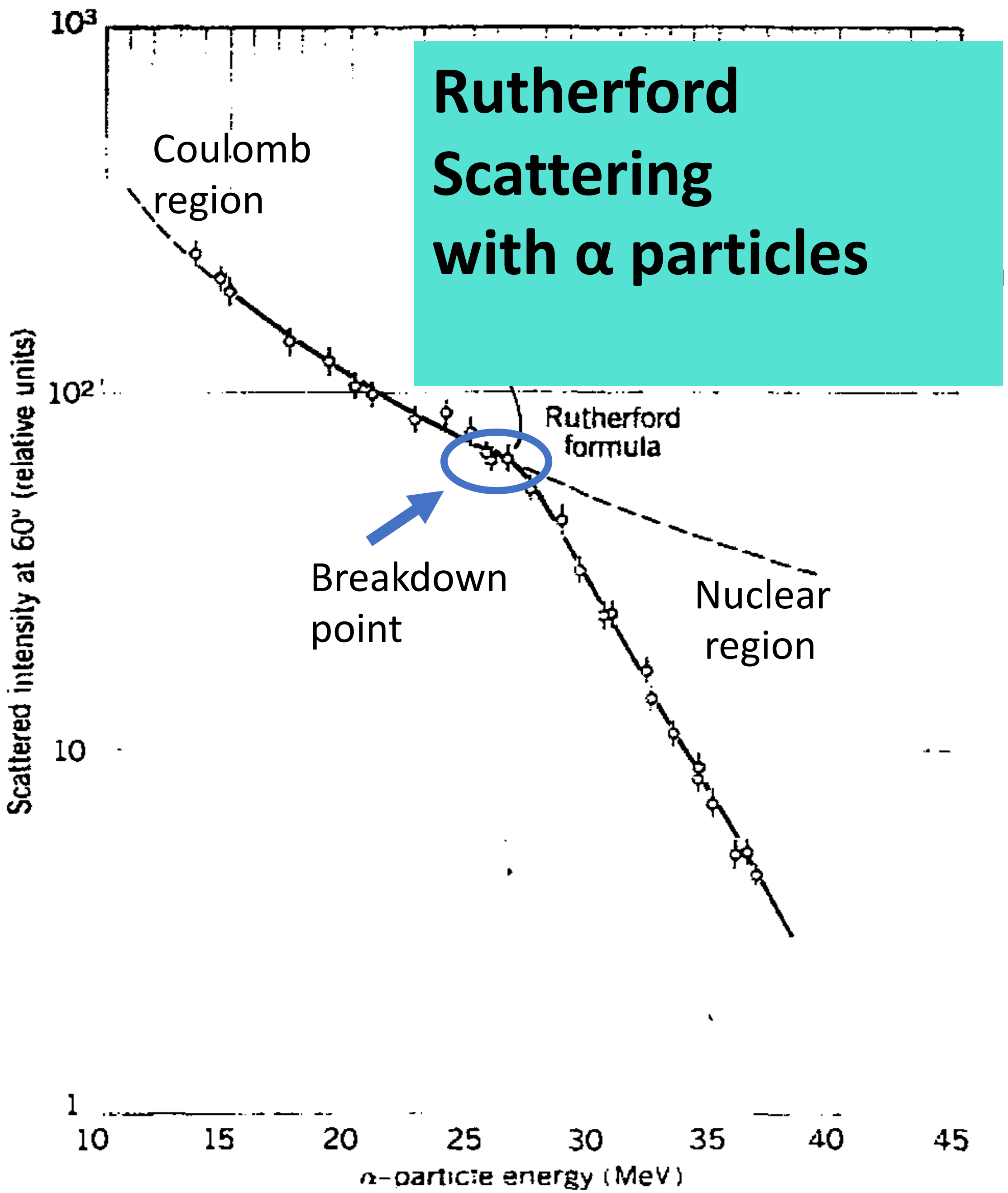
- o mecanismo da formação de massa e a interação nuclear
a partir da interação de quarks e gluões (QCD)
são problemas em aberto da Física Nuclear e Hadrónica.

One can determine the nuclear Radius from nuclear scattering

This is possible because of the relation between impact parameter, scattering angle and beam energy

$$b = C\frac{cotg(\theta/2)}{E}$$

A first estimate of the nuclear radius is obtained from *b* at the scattering angle and energy where there the breakdown of the Coulomb results is seen.



Are there other measurements of size?

Wavelength of light that is needed must be small.

Wavelength of a proton with kinetic energy of 5 MeV that collides to a nucleus.

This proton is non-relativistic.

$$p = \sqrt{2mE} \qquad \lambda = \frac{h}{p} \qquad \lambda = 5.76\ fm \qquad d \approx 1 fm \qquad \lambda \approx d$$

The condition $\lambda << d$ does not hold.

Geometric optics is not valid.

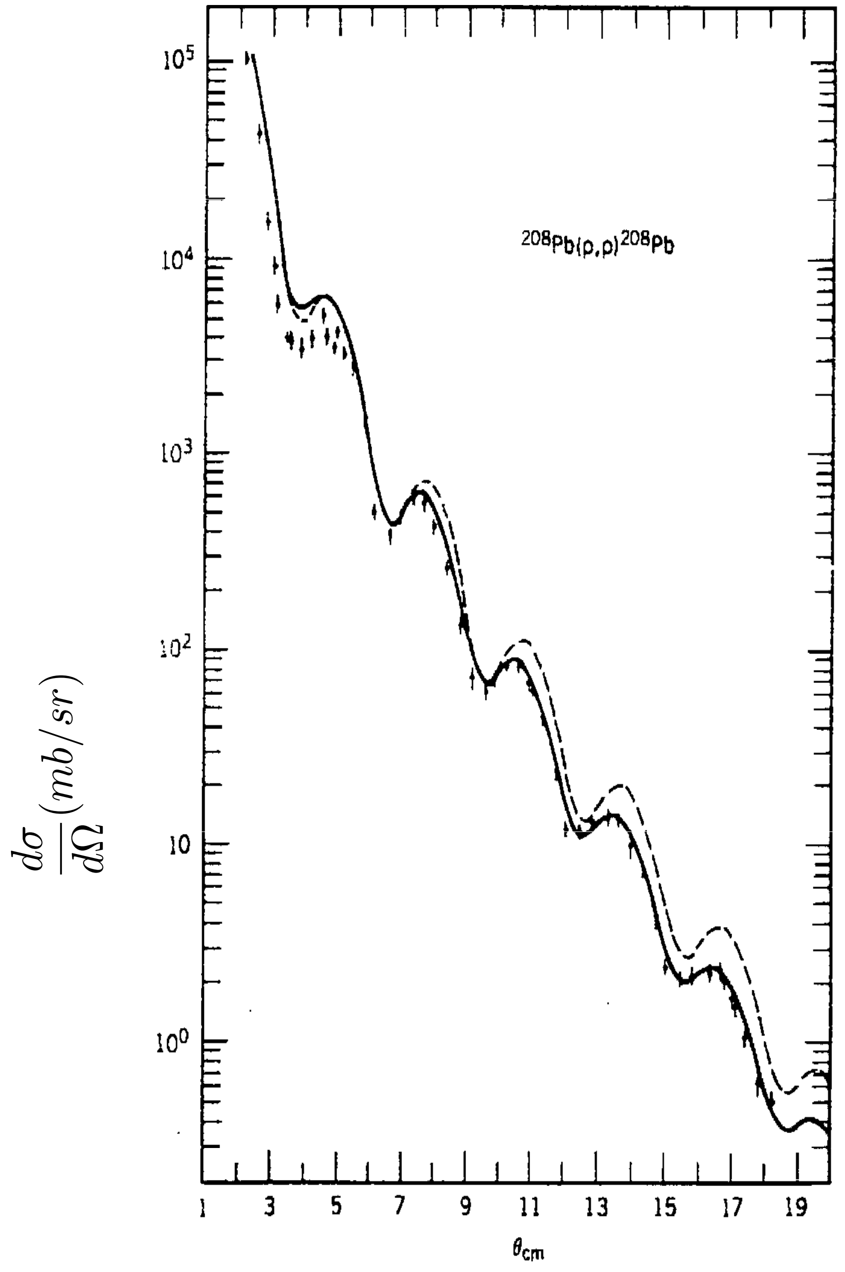
Diffraction occurs when a proton scatters from another nucleus.

This does not happen in the scattering of two classical particles.

Nucleons have a quantum mechanical behavior.

Proton beam
of 1.050 GeV
on a Pb target

Diffraction patterns are obtained and the position of minima give information on the proton size

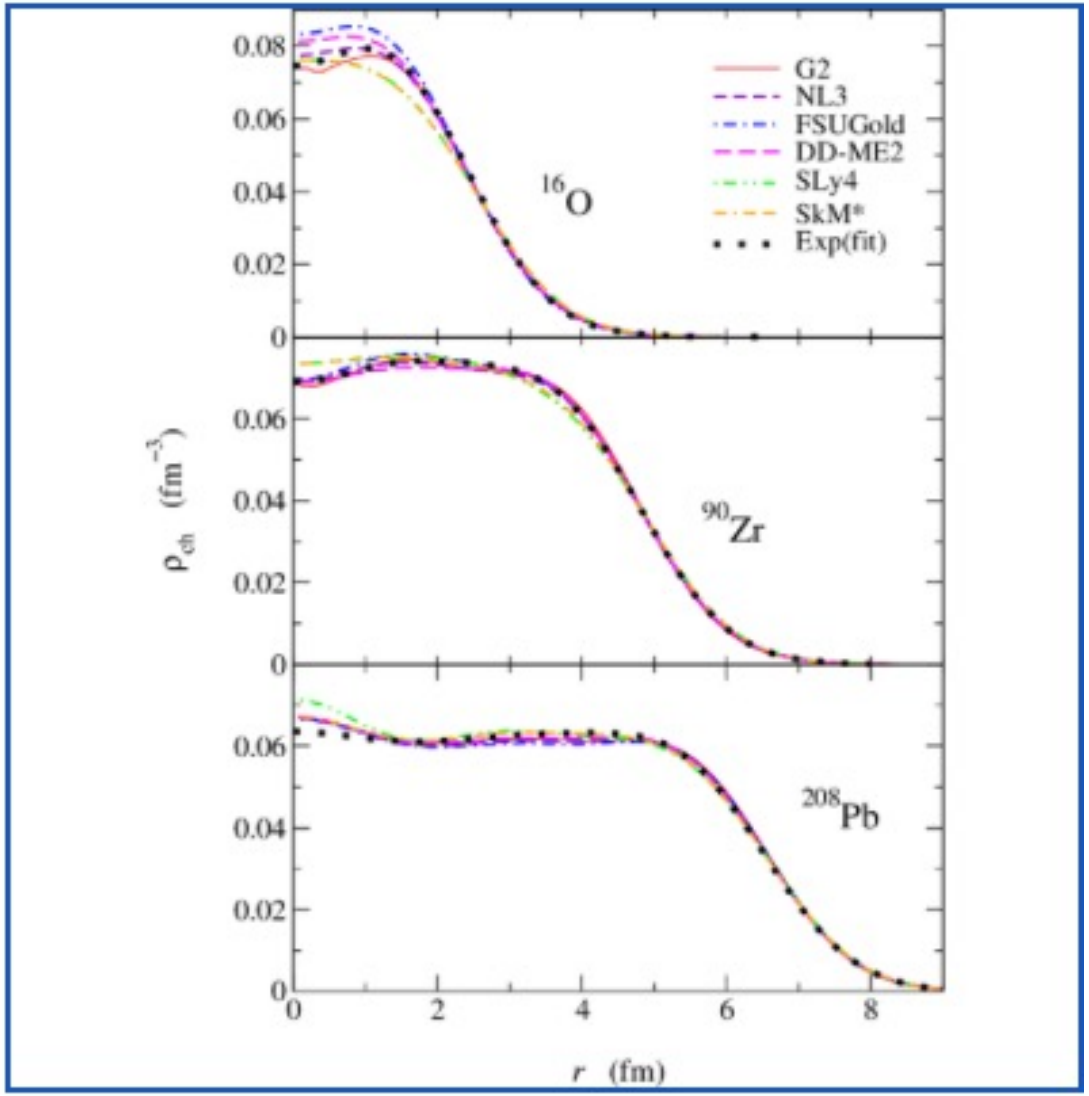


Minima are not sharp: “Difuseness” of radius

Determination of radius with nucleon-nucleus scattering is not precise.

Electron scattering cross section factorizes
into the cross section for a point nucleus scattering and
the Fourier Transform of the charge distribution

Recent results for charge distributions in some nuclei



DOI:10.1103/PhysRevC.78.044332

1. The shape of the nuclear density is almost the same for all nuclei with large nucleon number

2. It is practically constant at the core until it starts to decrease near the surface.

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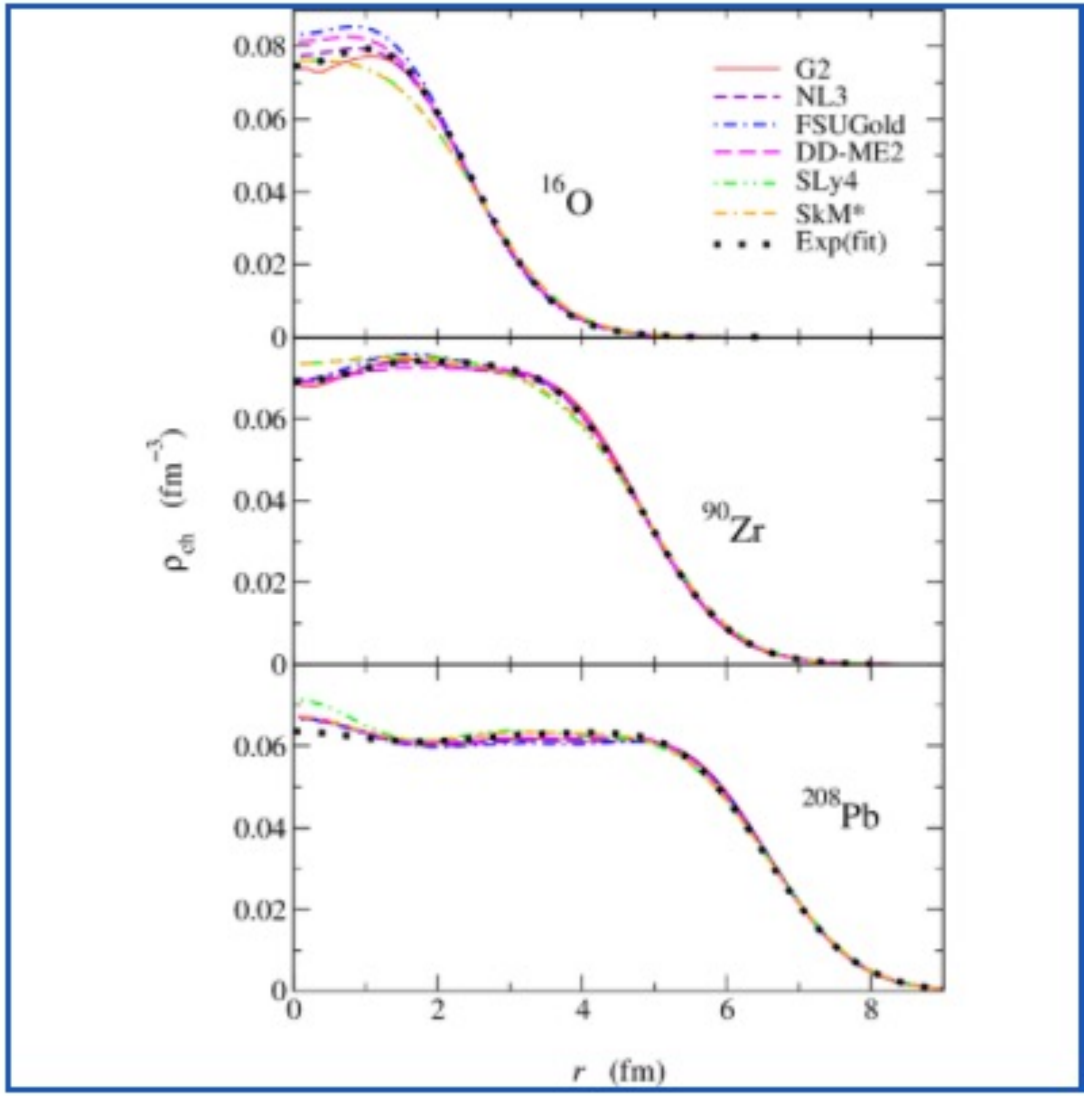

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$$\rho = \frac{m_N A}{\frac{4}{3}\pi R^3} = Const.$$

$$R = R_0 A^{1/3}$$

What does the size and matter distributions of nuclei tell us on the nuclear interaction?

Take-home message

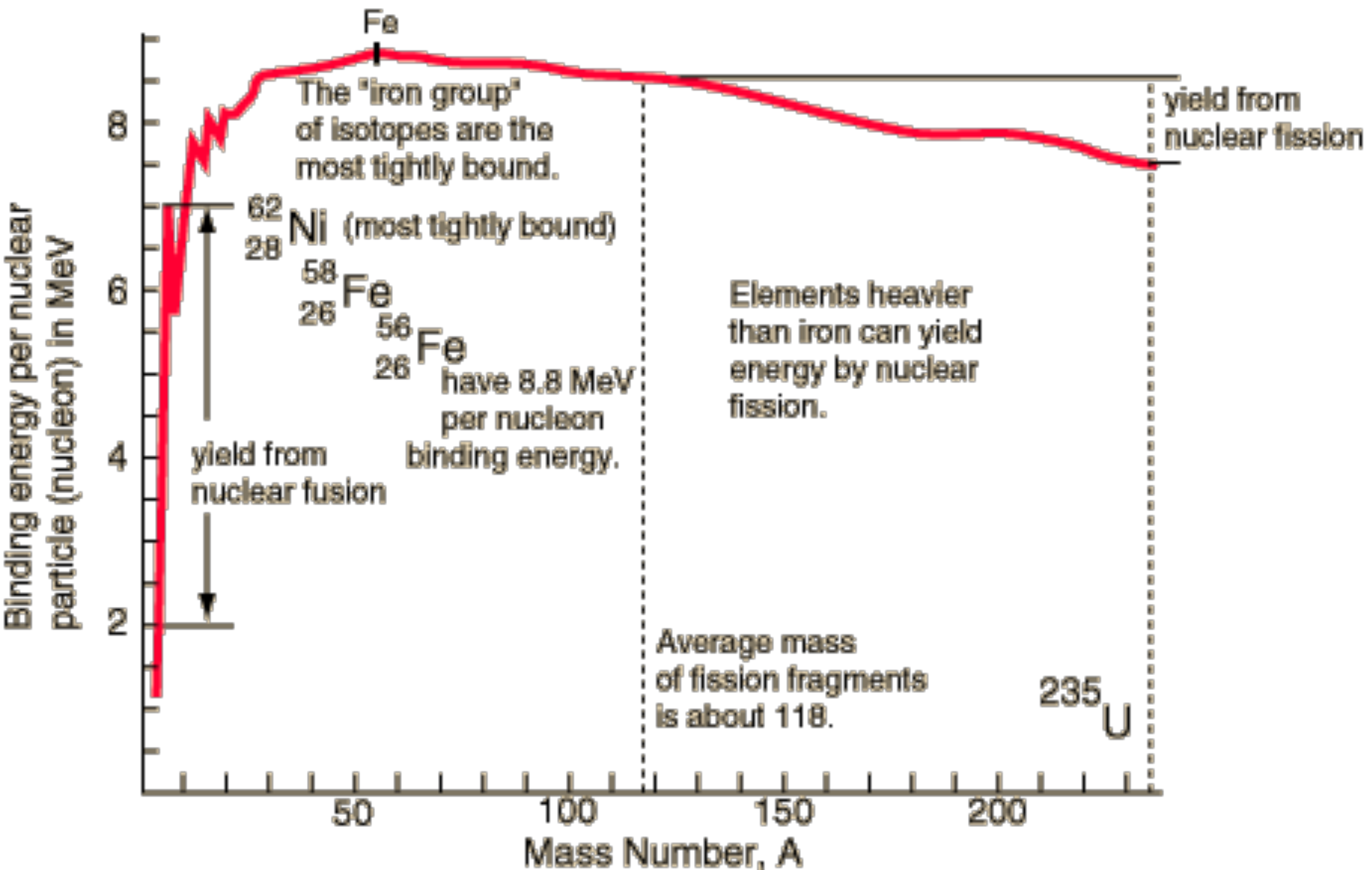
Small impact parameter (small size of nuclei) to obtain deviations from the Rutherford (Coulomb) cross section ⇒

Short-range character of nuclear interaction

Nuclei charge distributions depict nuclei as being incompressible i.e. density is independently of the number of particles ⇒

Repulsive short-range core characterizes the nuclear interaction

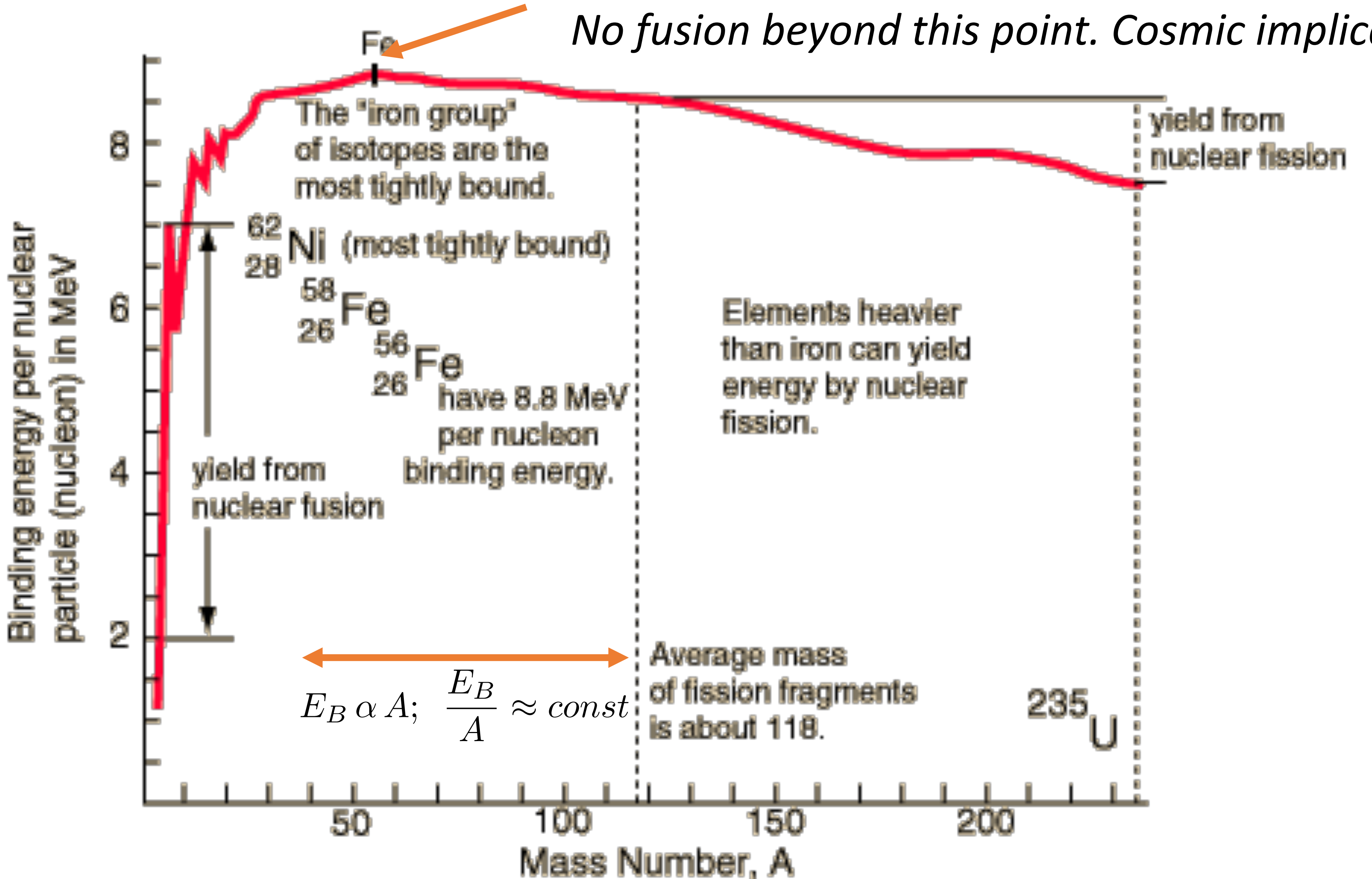
(This repulsion can also be deduced from experimental results from several nuclei showing nucleon pairs of have total momentum 0 and large relative momentum)



Fe
The "iron group"
of isotopes are the
most tightly bound.
62
28 Ni (most tightly bound)
58
26 Fe
56
26 Fe
have 8.8 MeV
per nucleon
binding energy.
yield from
nuclear fission
Elements heavier
than iron can yield
energy by nuclear
fission.
yield from
nuclear fusion
Average mass
of fission fragments
is about 118.
235 U
Binding energy per nuclear
particle (nucleon) in MeV
8
6
4
2
50
100
150
200
Mass Number, A

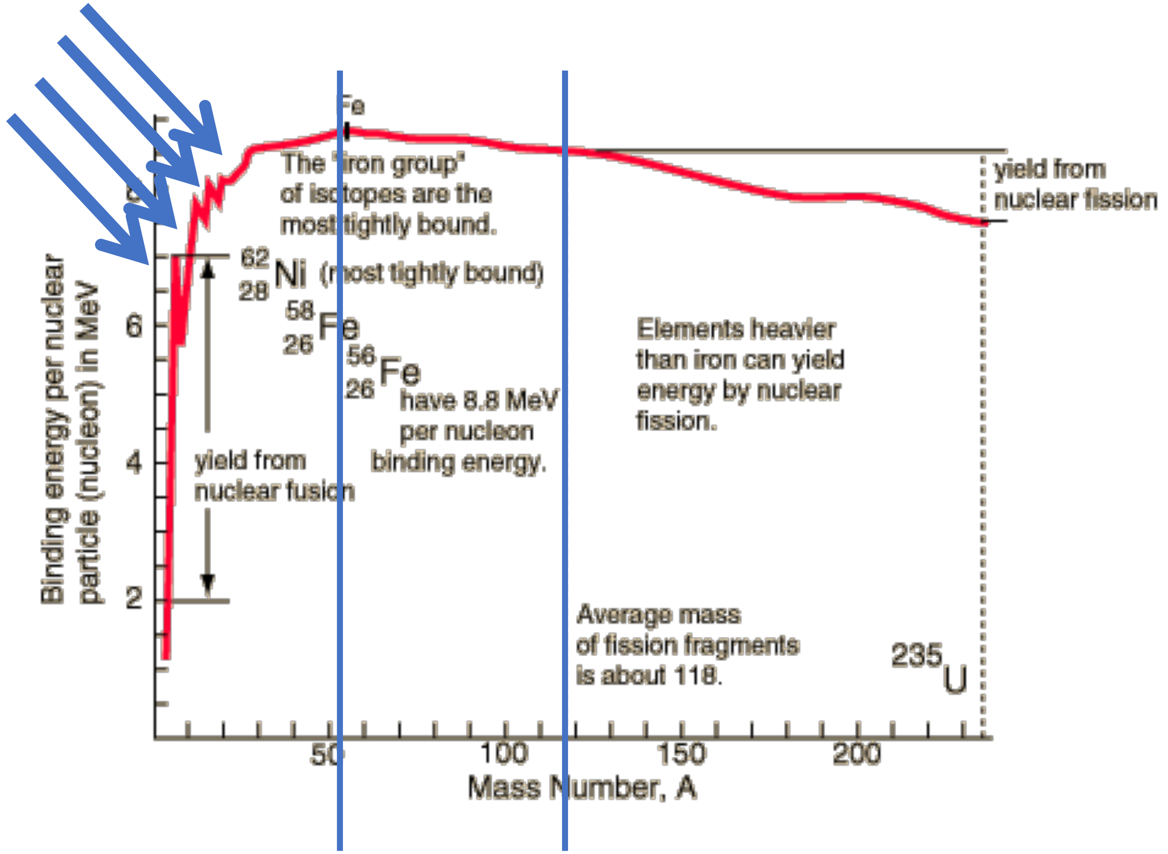
Saturation of binding : ***beyond a certain number of nucleons****, the binding energy per nucleon does not vary much with A.*

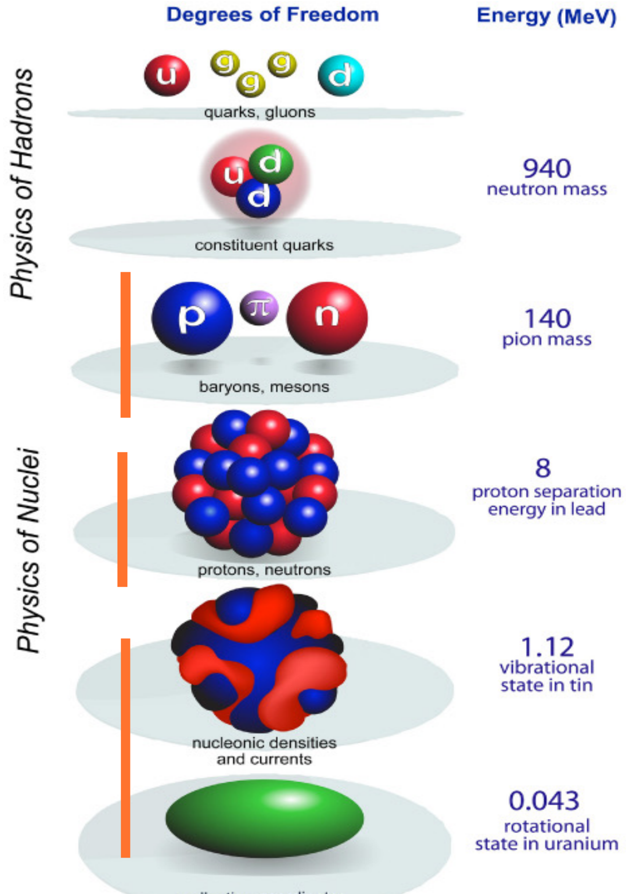
No fusion beyond this point. Cosmic implications



There are **3 regimes** in the evolution of the binding energy with A:

^4He, ^8Be, ^{12}C, ^{16}O





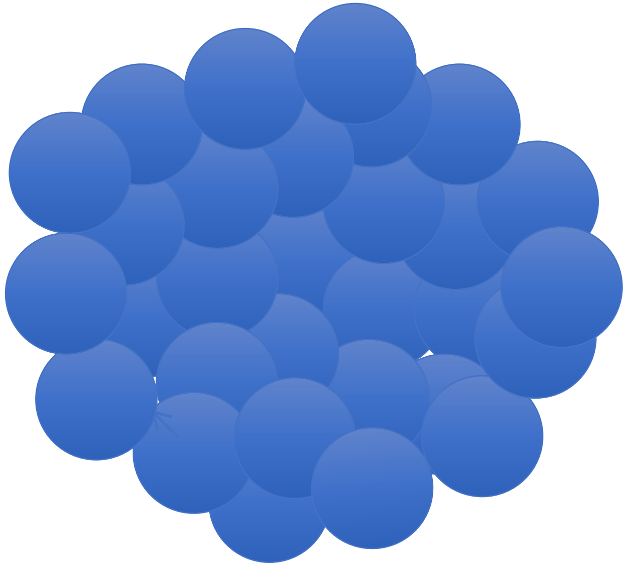
Apart from the spikes for certain A values,

-the nuclear binding energy per nucleon grows with A for small A

-saturation appears and the binding energy per nucleons is constant with A or large A

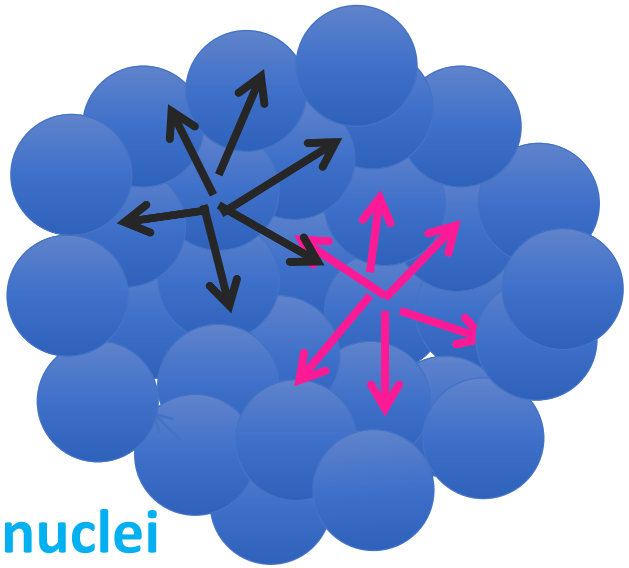
-the binding per nucleon decreases for very large A due to Coulomb repulsion

Binding Energy per nucleon: what does saturation + uniform density say about the range of the nuclear force?



Binding Energy per nucleon: what does saturation + uniform density say about the range of the nuclear force?

$$E_B \, \alpha \, A; \quad \frac{E_B}{A} \approx const$$



In the interior of **heavy nuclei**
each nucleon contributes the same to the binding.

This comes from all nucleons having the same number
of neighbors (due to the high density and uniform distribution)

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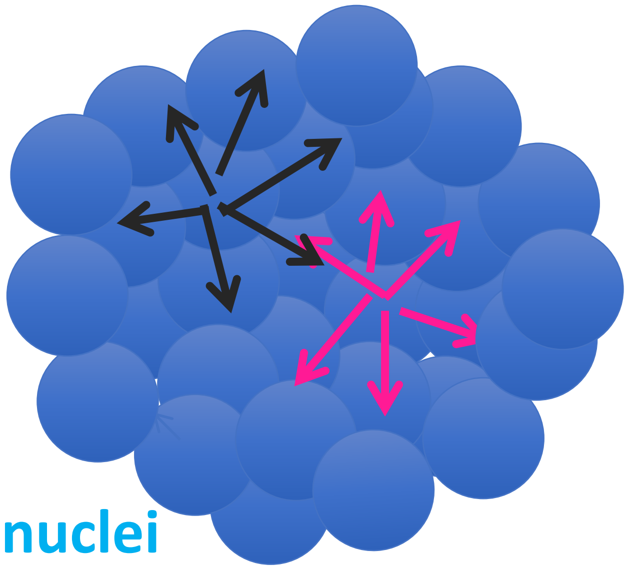


In the interior of **heavy nuclei**
each nucleon contributes the same to the binding.

This comes from all nucleons having the same number
of neighbors (due to the high density and uniform distribution),

and because each nucleon interacting only with the near by or first neighbors
(due to the short range of the nuclear force, about the diameter of the nucleons).

Take-home message

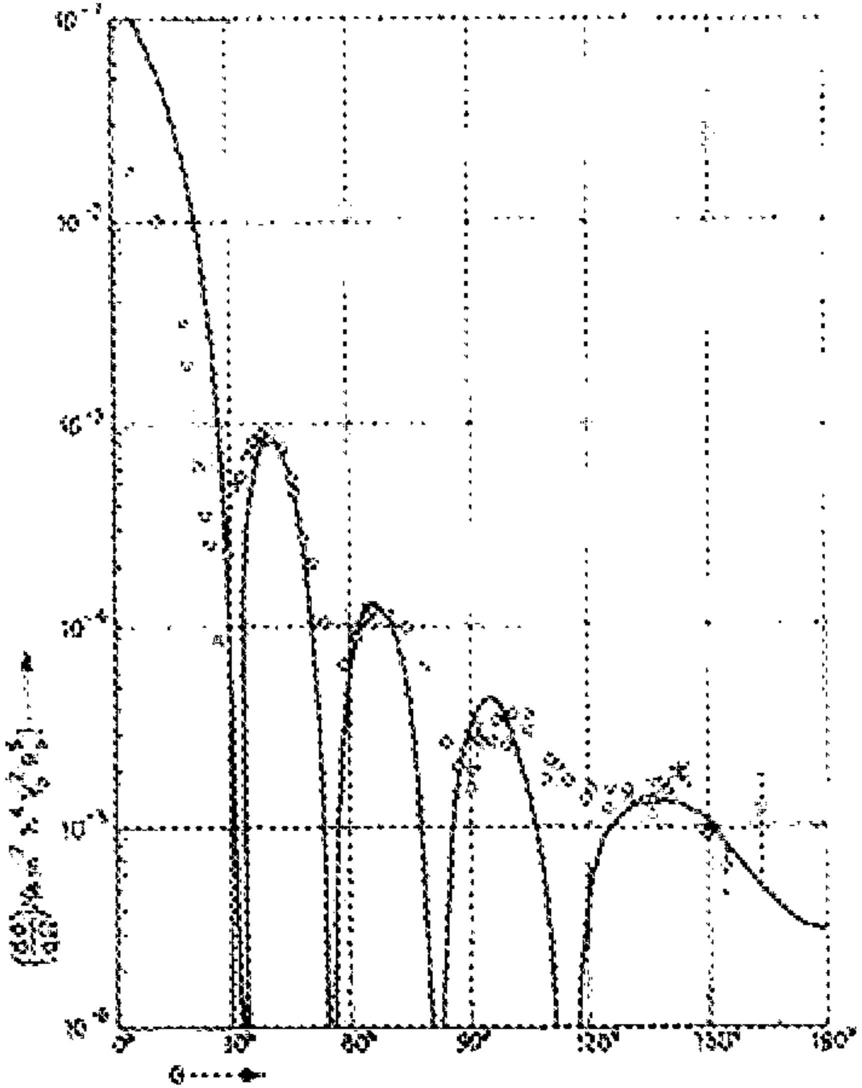
Three different A regions of nuclei demand different emphasis on independent and collective and particle degrees of freedom.

The evolution of binding energy with A affects the creation and abundancy of elements from cosmic events.

Nuclear and Hadronic Physics determine the reactions in stars amd the evolution of the universe.

Neutron beam of
14,5 MeV
on a Pb target

Diffraction patterns
again

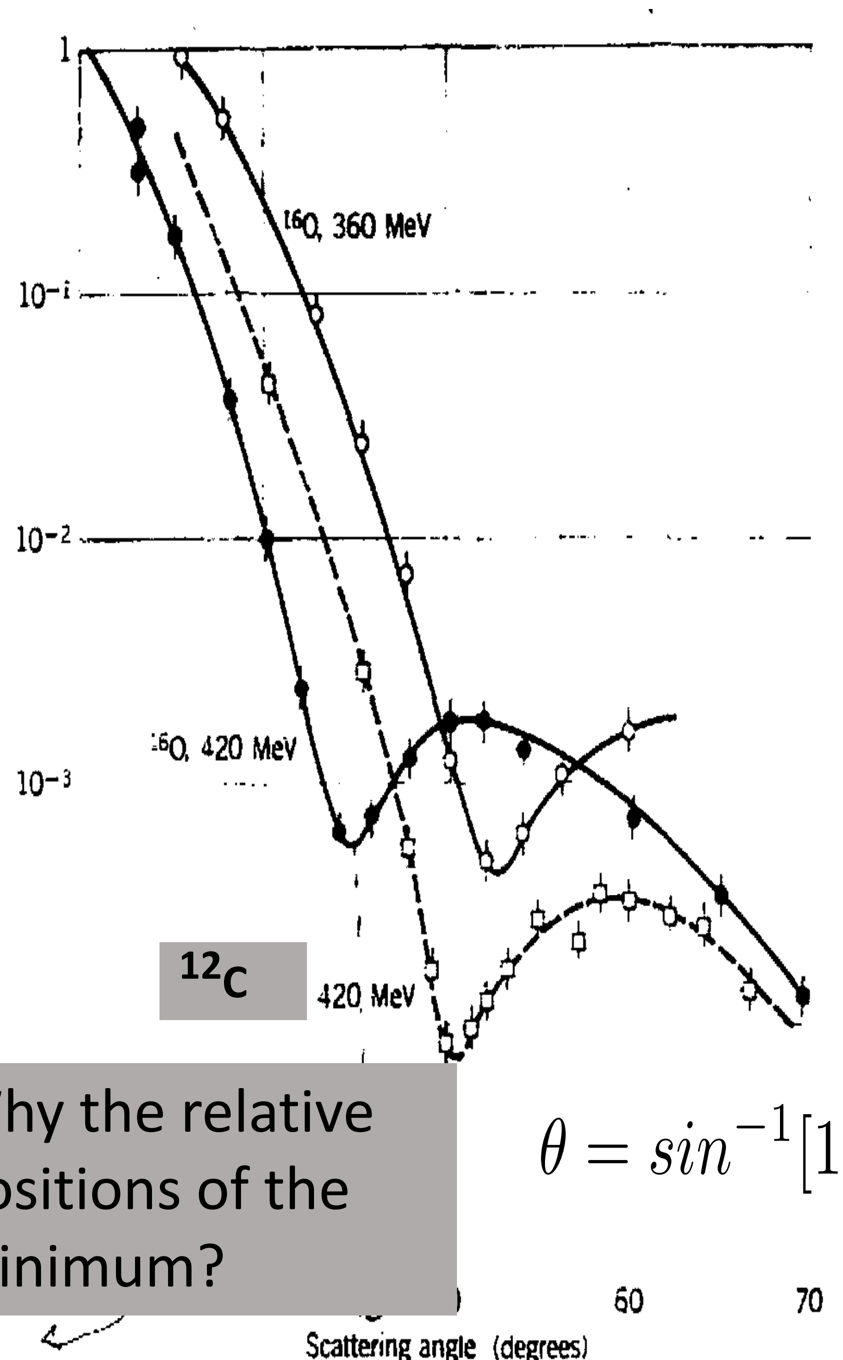


Neutron- nucleus scattering probe nuclear mass distribution and not charge distributions

Figure 1b.3. Angular distribution for elastic scattering on the square-well potential, as discussed in the text, obtained using the Born approximation with plane waves (see equation I.b.20) and with $kR_0 = 8.35$. The data correspond to 14.5 MeV neutron scattering on Pb. (Taken from Mayer-Kuckuk 1979.)

The Diffraction patters from Electron scattering experiments give more precise results for the nuclear radius.

One can check that the positions of the first minima are consistent with the beam energies, and the larger radius of oxygen 16



Why the relative positions of the minimum?

$$\theta = sin^{-1}[1.22\frac{\lambda}{d}]$$

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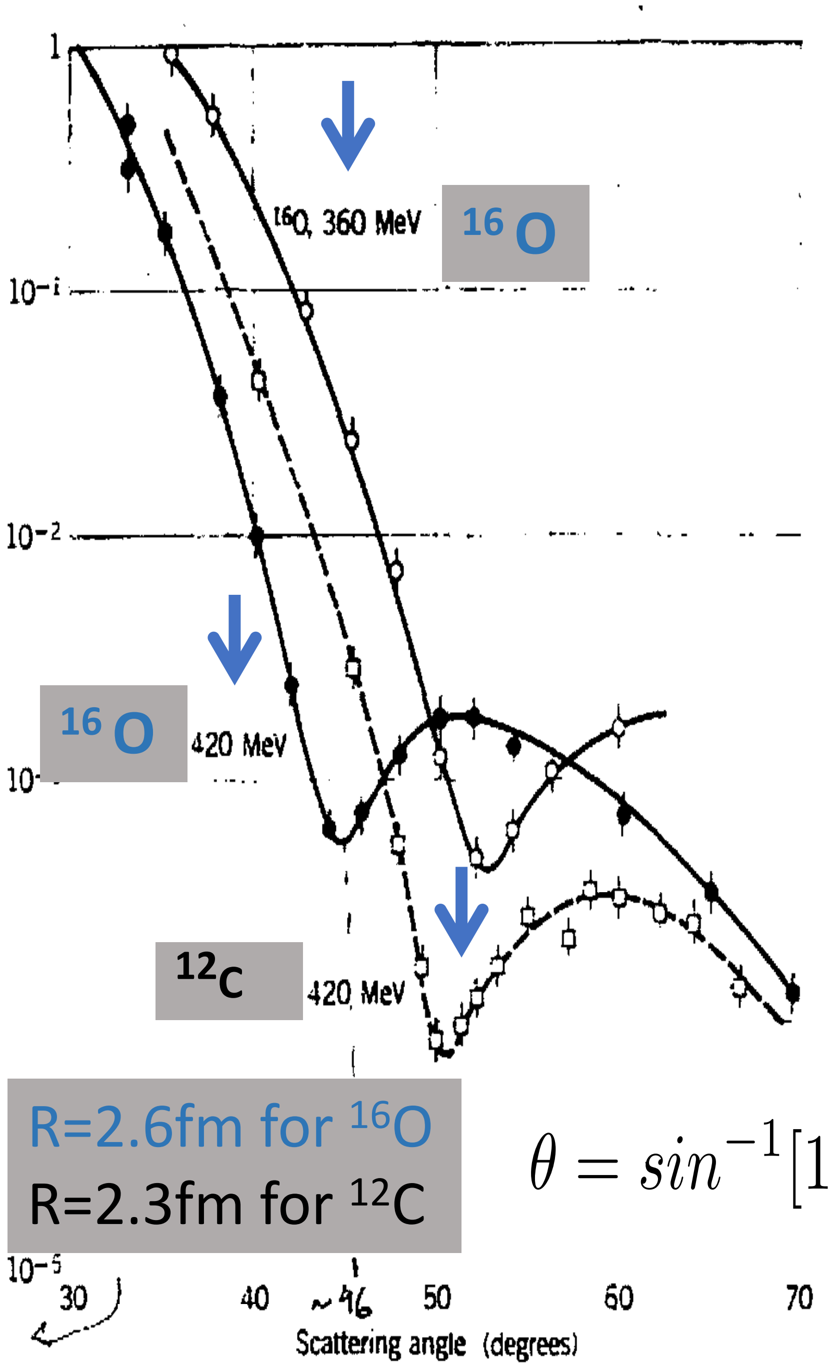


R=2.6fm for ^{16}O
R=2.3fm for ^{12}C

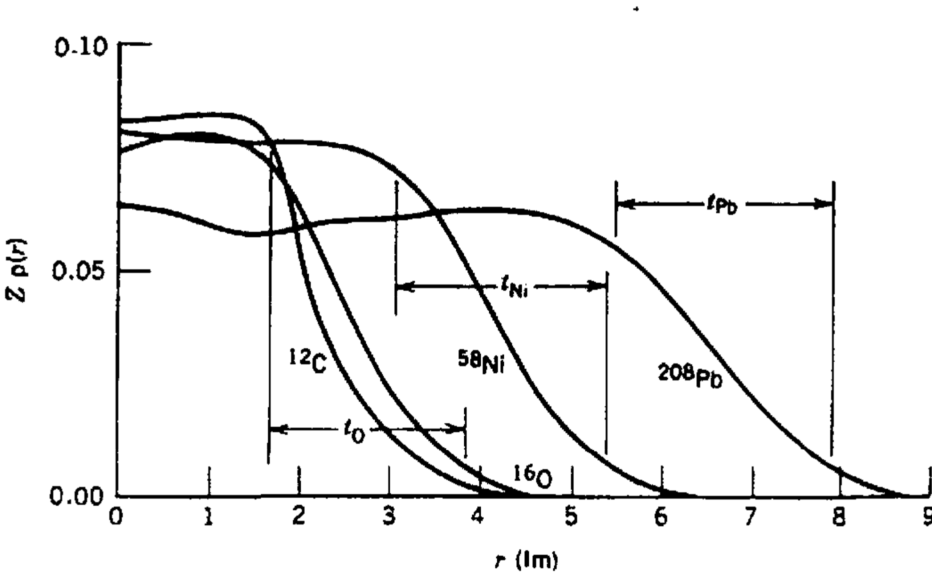
$$\theta = sin^{-1}[1.22\frac{\lambda}{d}]$$

Nucleon charge distribution

1. The shape of the nuclear density is almost the same for all nuclei with large nucleon number

2. It is practically constant at the core until it starts to decrease near the surface.

3. The distance for it to drop to zero is almost the same for all nuclei. It drops from 90% to 10% of the central value in 2.3fm for almost all nuclei. (surface thickness). One can speak of a nucleus skin.



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In[52]:= Manipulate[Plot[(1 + Exp[(r - R) / a])^-1, {r, 0, 10}, PlotRange → All],
           {a, 0.1, 0.6}, {R, 1, 10}]
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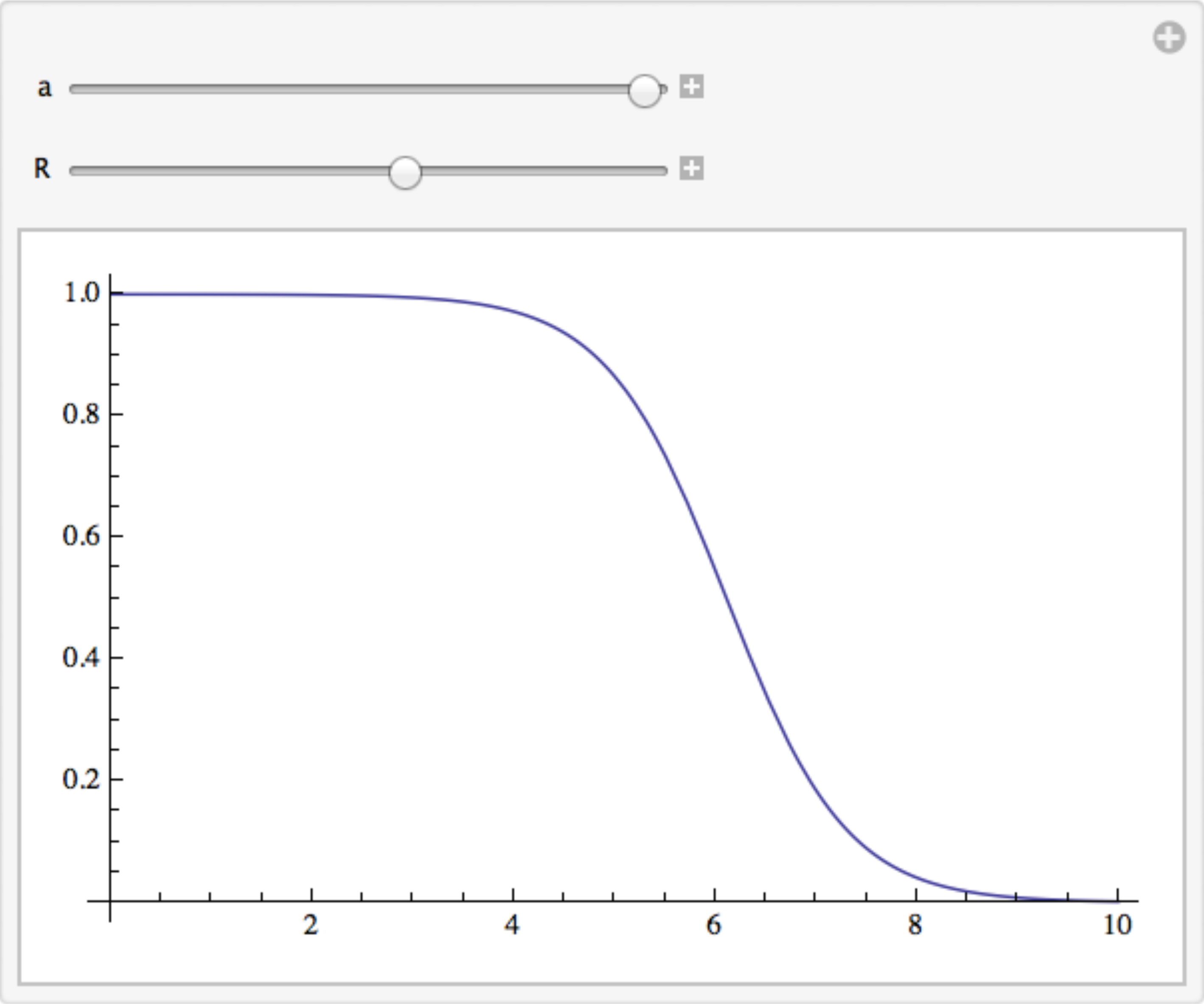
Out[52]=



$$\rho(r) = \frac{1}{1+exp\frac{r-R}{a}}$$

For nuclei of large mass number A the radius of the charge and neutron distributions is about the same

The radii of charge and nucleon distribution differ by only about 0.1fm and both vary with the nucleon number A in the same way.

$$R = R_0 A^{1/3}$$

This result is intriguing because there are more neutrons (n) than protons (p) in heavy nuclei.

The proton-neutron nuclear attraction is responsible for this effect.

- Neutrons attract protons counteracting the Coulomb force between them.
- The neutron-proton attraction is stronger than the proton-proton nuclear attraction.

(we see the signature of this in Nature: the deuteron is bound but there is no di-neutron or di-proton bound state).

- The neutron-proton attraction is so strong that protons and neutrons overlap and mix, making the radii of the charge and neutron distributions aboutequal.

What does the size and matter distributions of nuclei tell us on the nuclear interaction?

Nuclear Physics

Exploring the Heart of Matter

Committee on the Assessment of and Outlook for Nuclea

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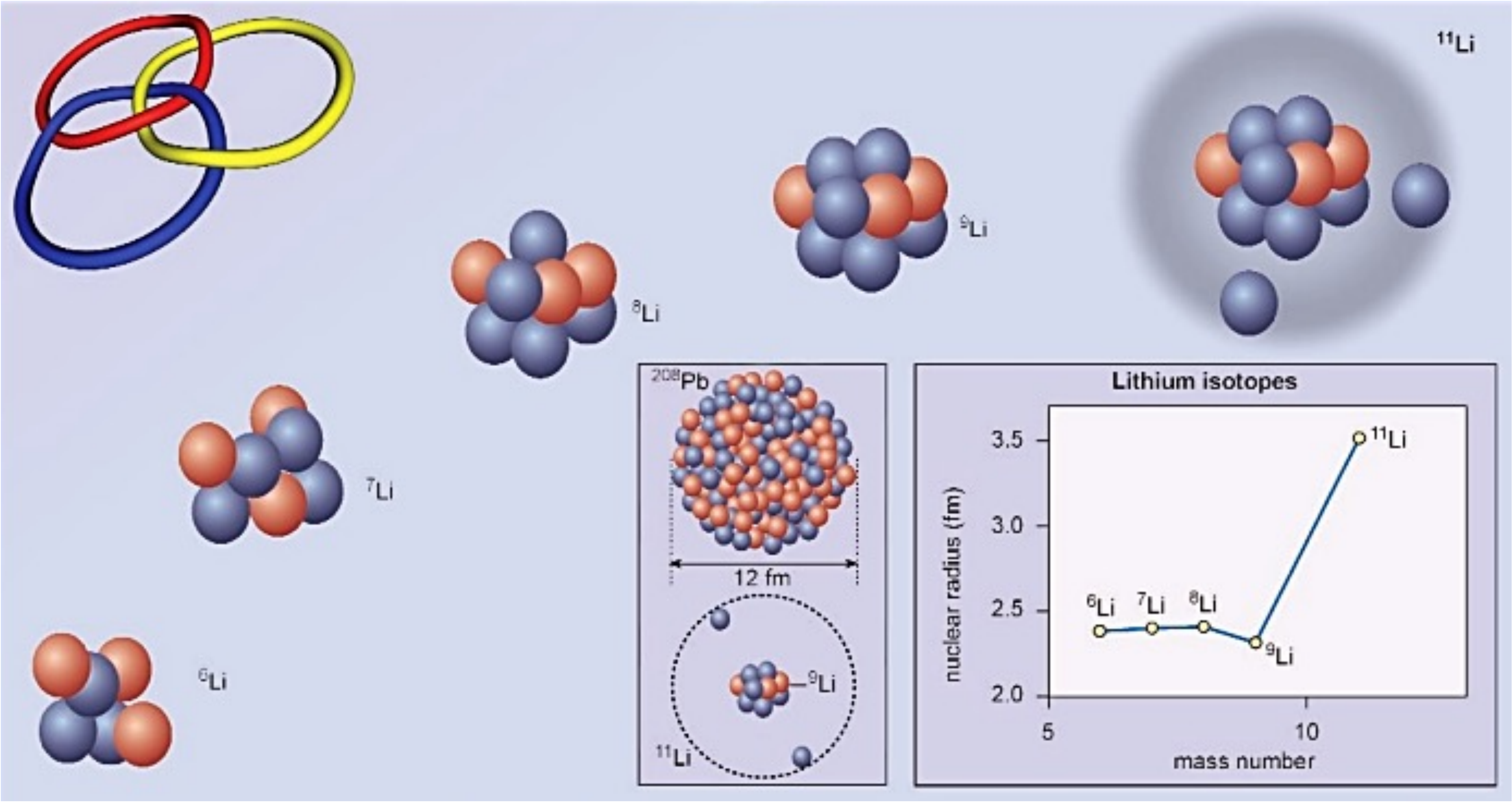

11Li
9Li
8Li
7Li
6Li
208Pb
12 fm
9Li
11Li
Lithium isotopes
nuclear radius (fm)
3.5
3.0
2.5
2.0
5
10
mass number
6Li
7Li
8Li
9Li
11Li