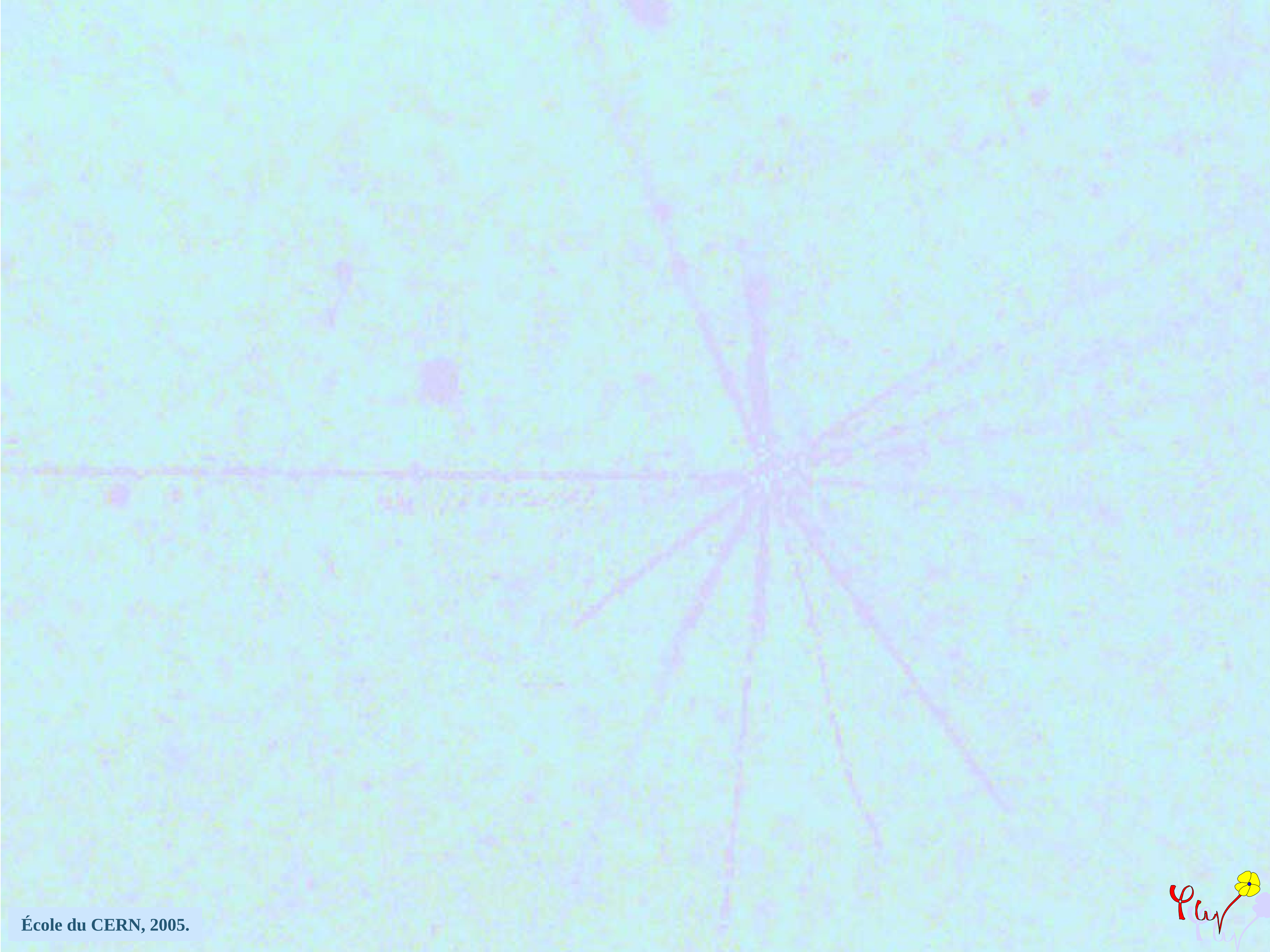
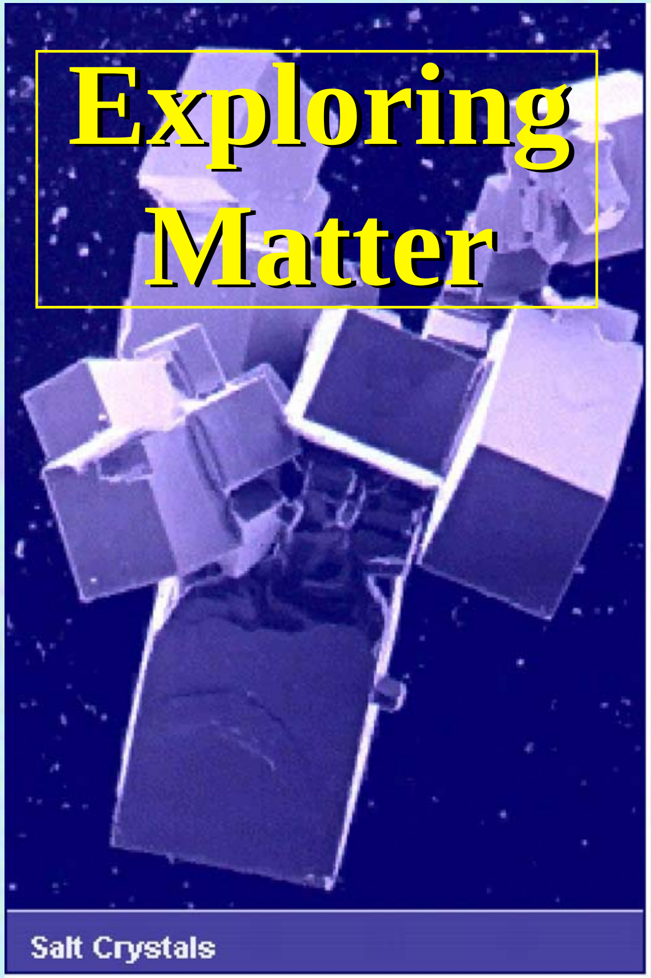
Nuclear Physics

an Introduction

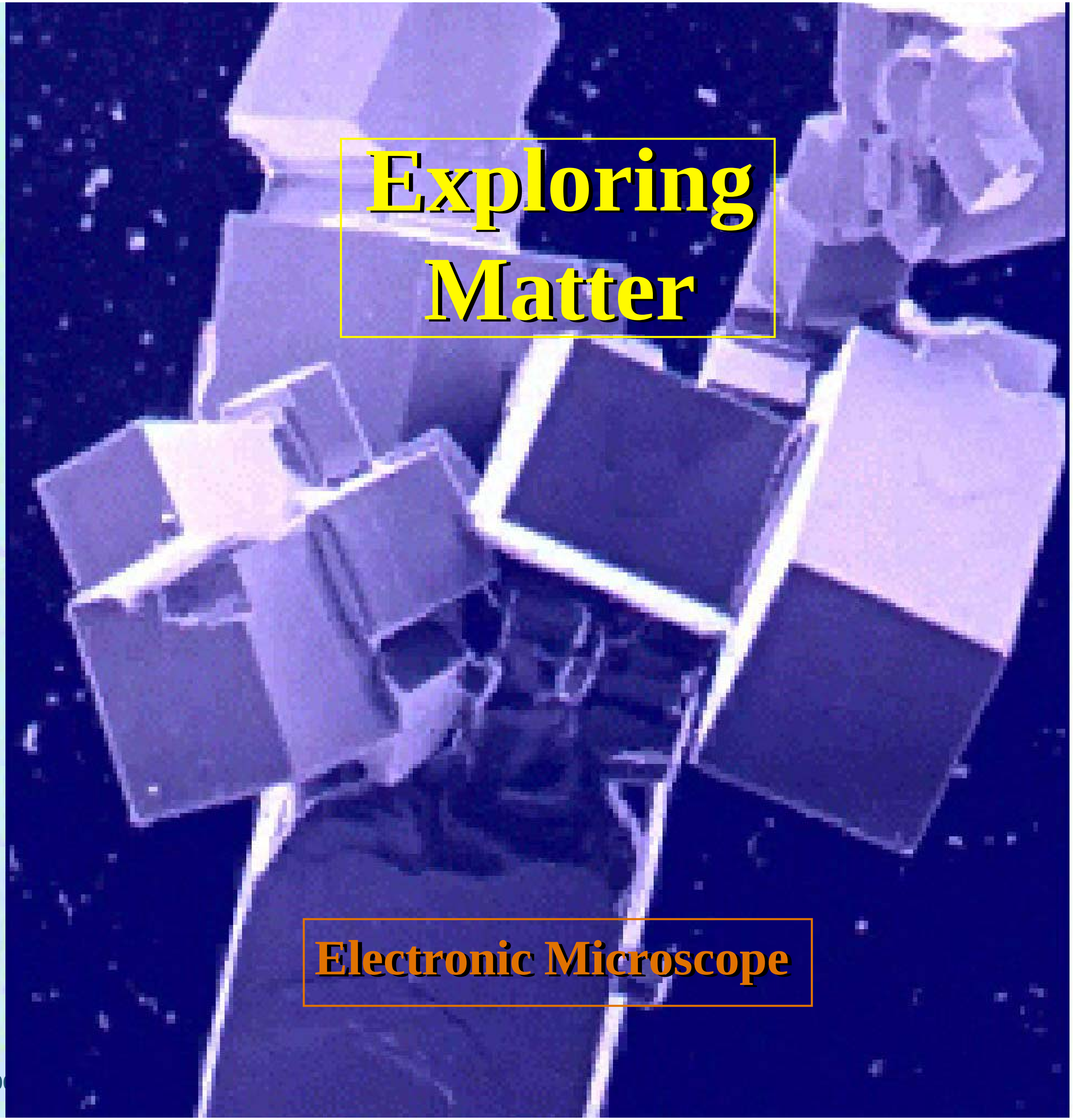
Philippe CHOMAZ
GANIL-CAEN



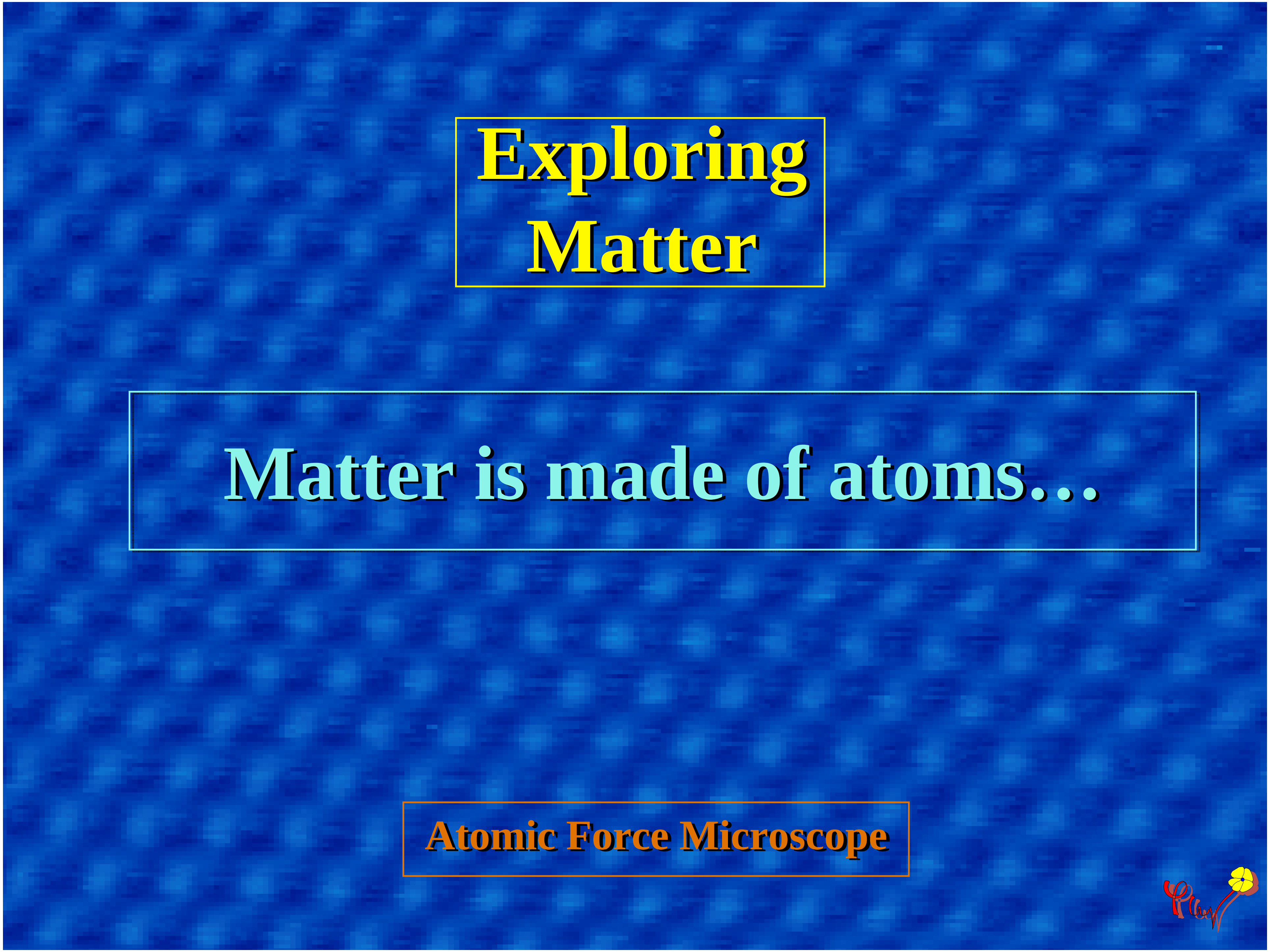
Exploring Matter



Electronic Microscope


Exploring
Matter
Electronic Microscope

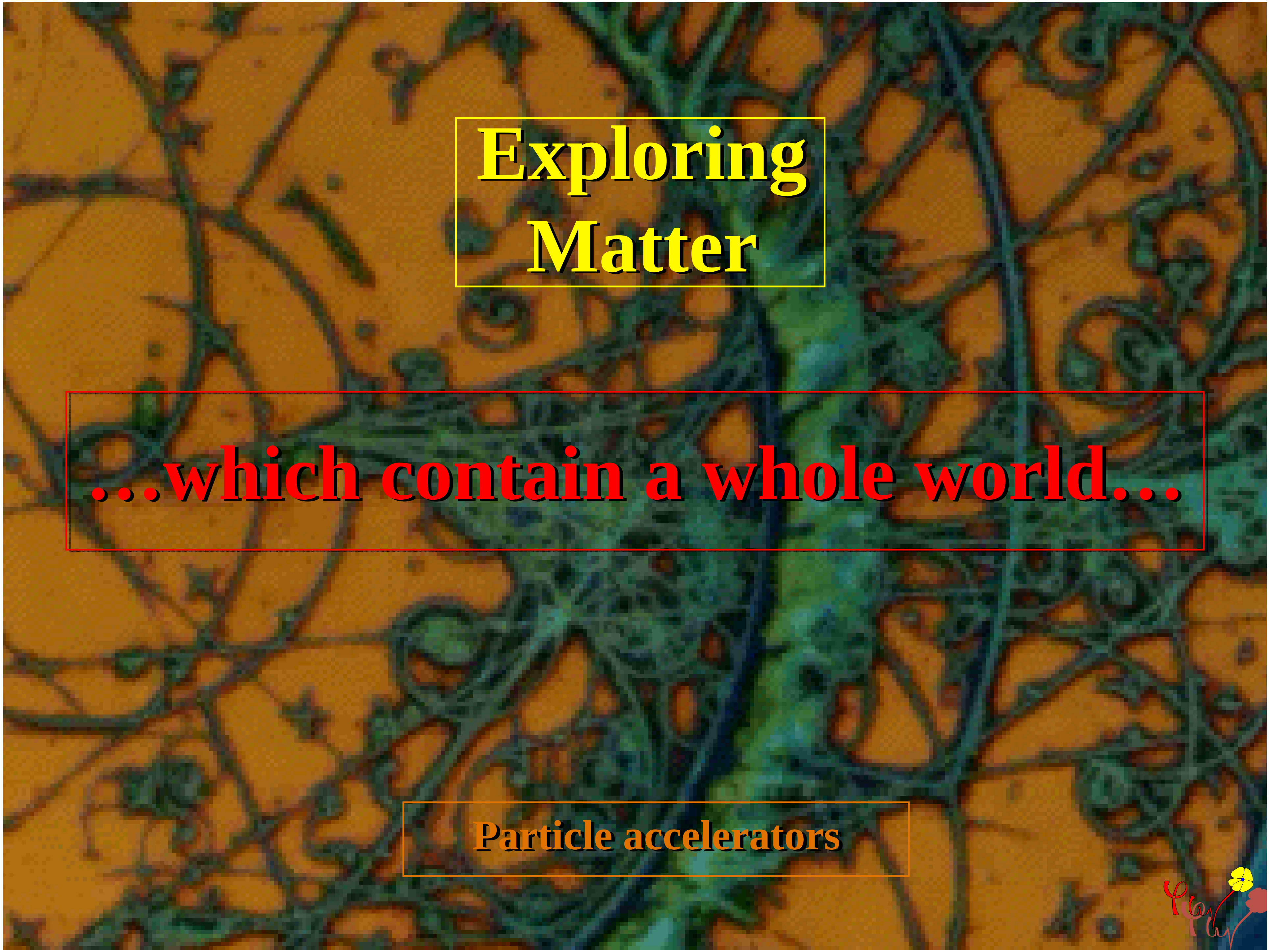

Exploring Matter
Electronic Microscope

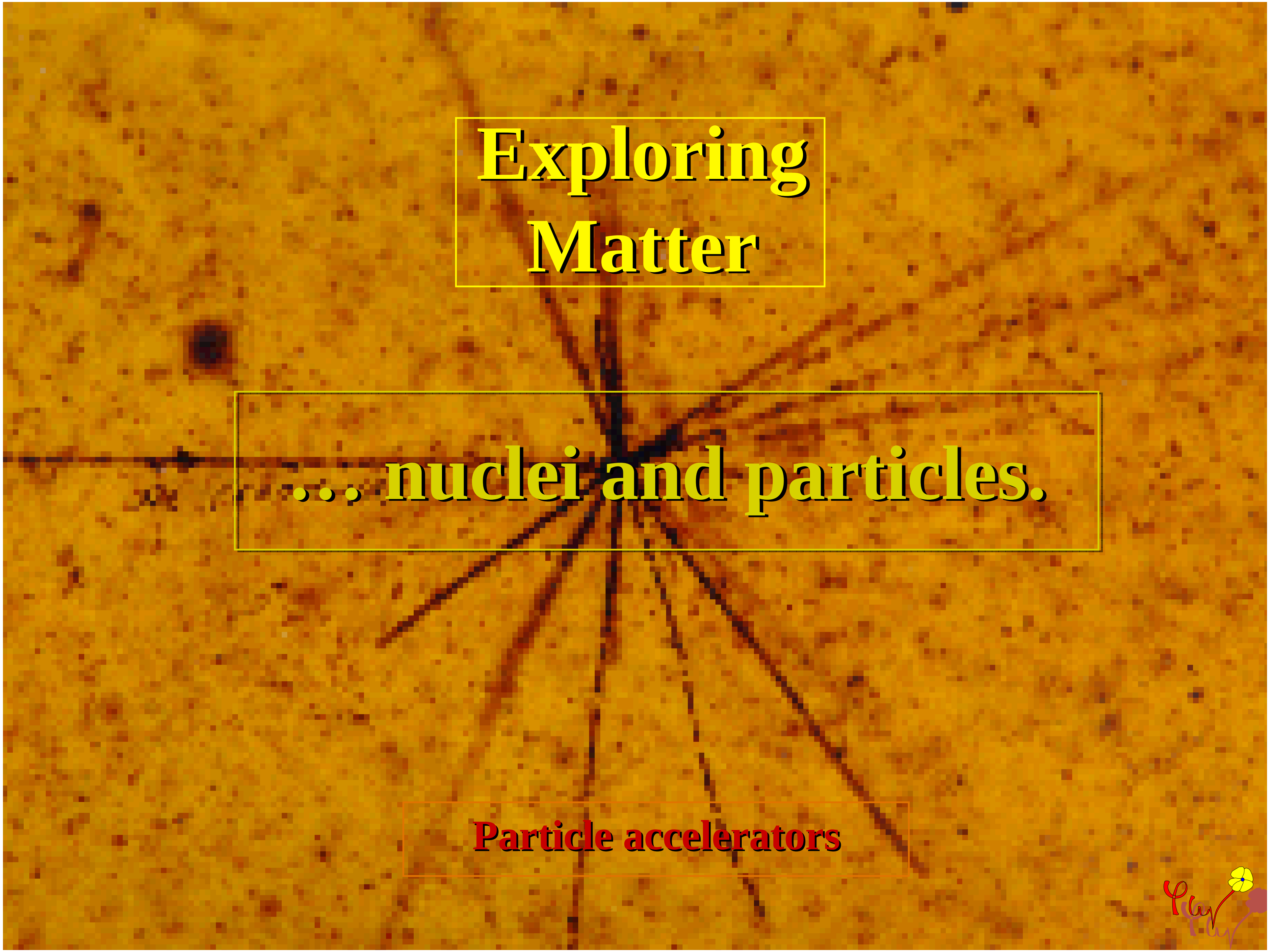

Exploring
Matter
Matter is made of atoms…
Atomic Force Microscope

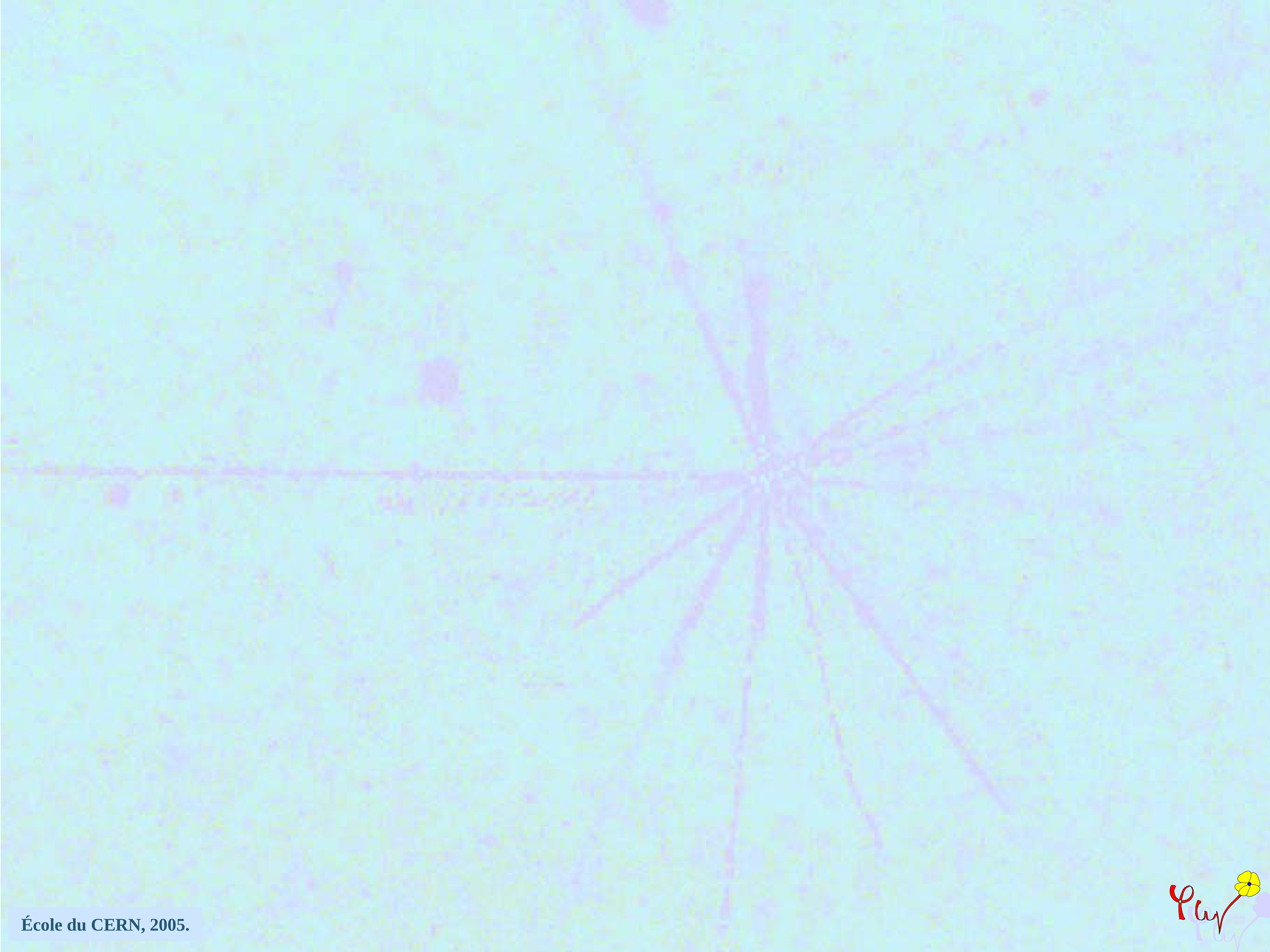
Exploring Matter

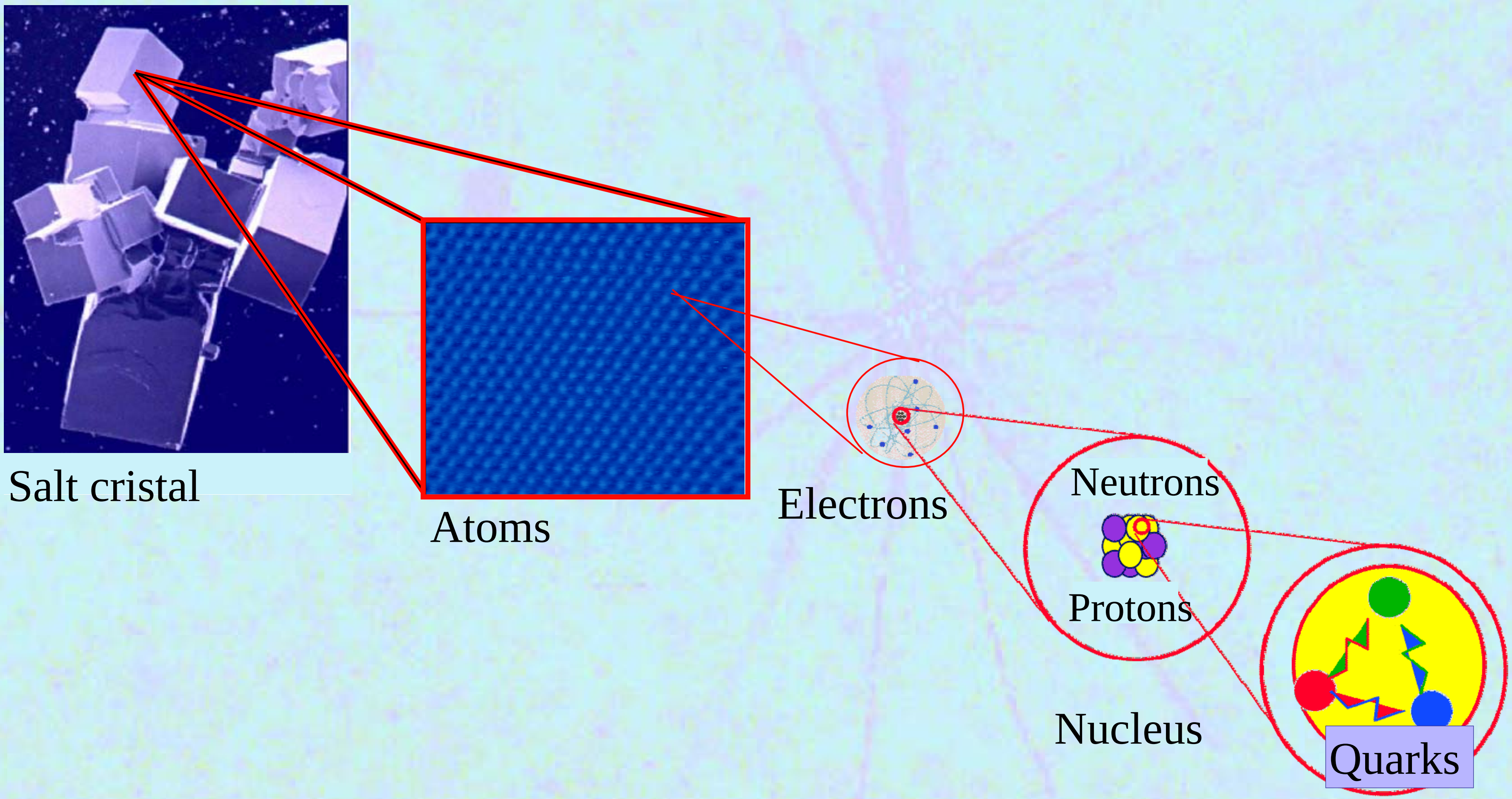
Matter is made of atoms…

Atomic Force Microscope

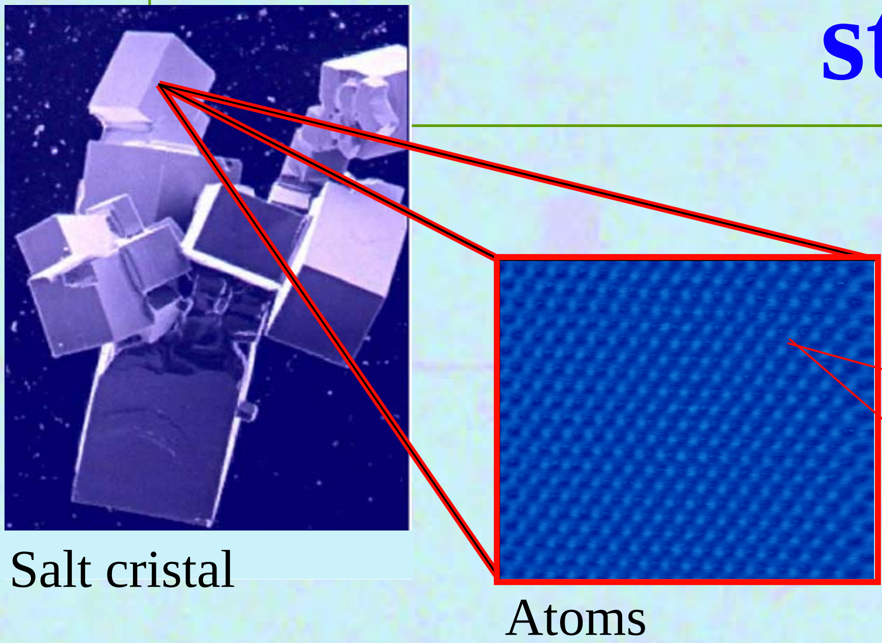

Exploring
Matter
…which contain a whole world…
Particle accelerators

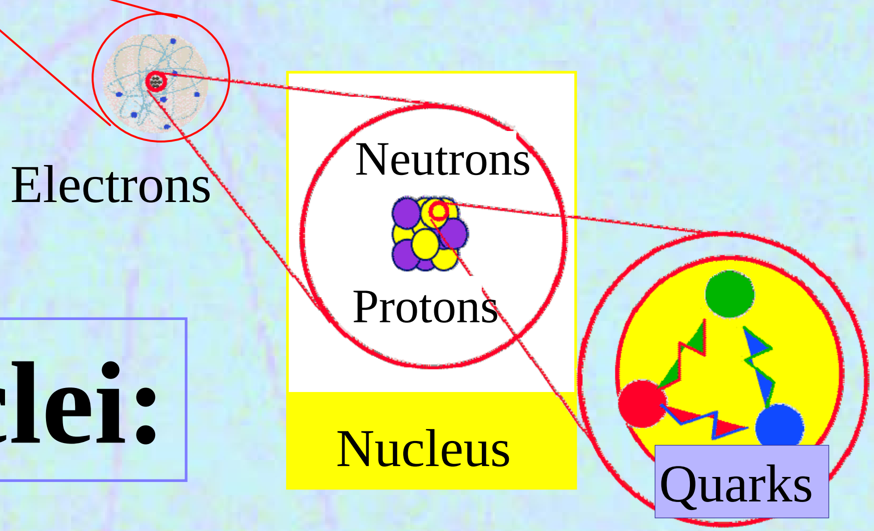

Exploring
Matter
… nuclei and particles.
Particle accelerators



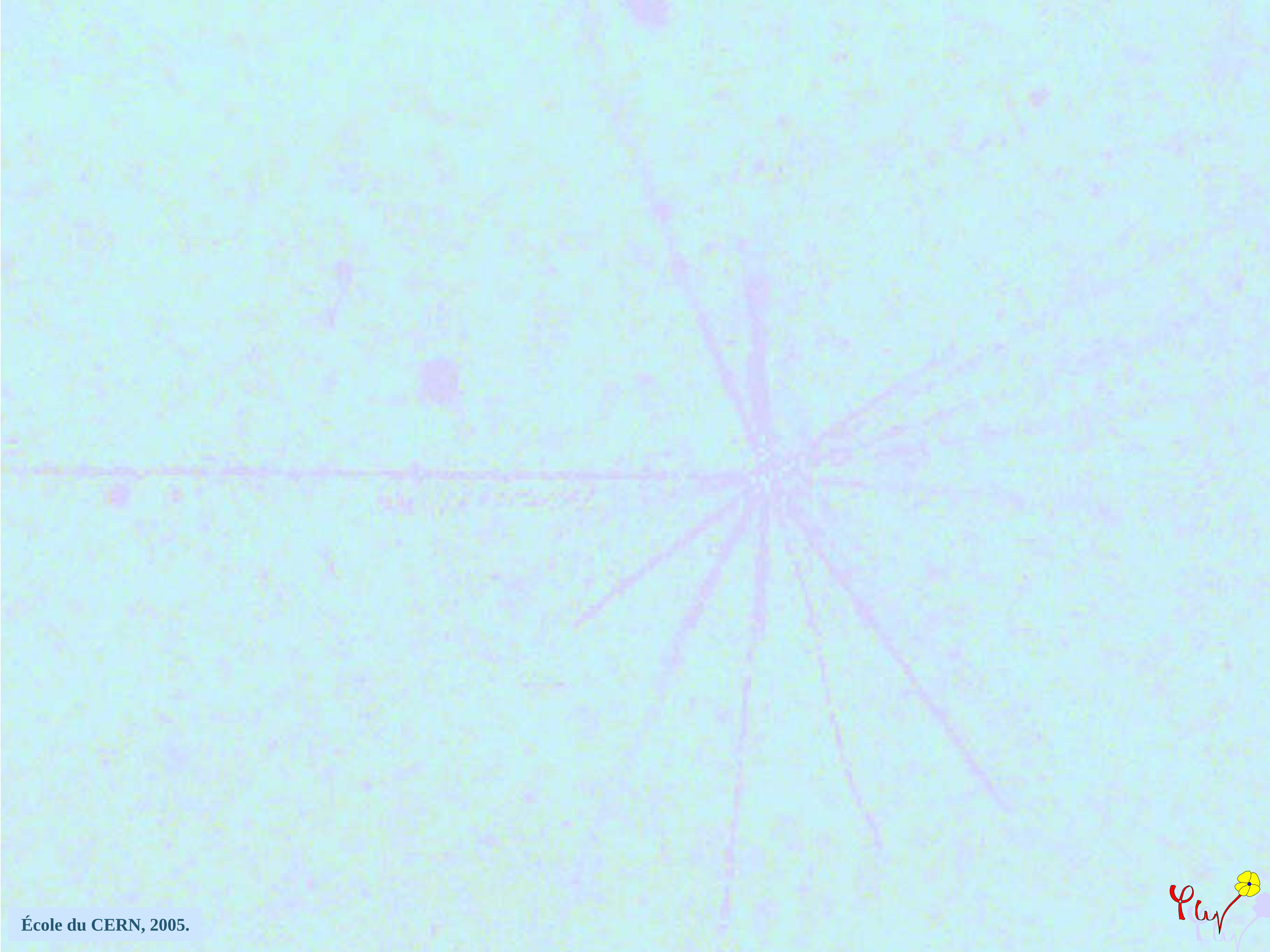

Salt cristal
Atoms
Electrons
Neutrons
Protons
Nucleus
Quarks

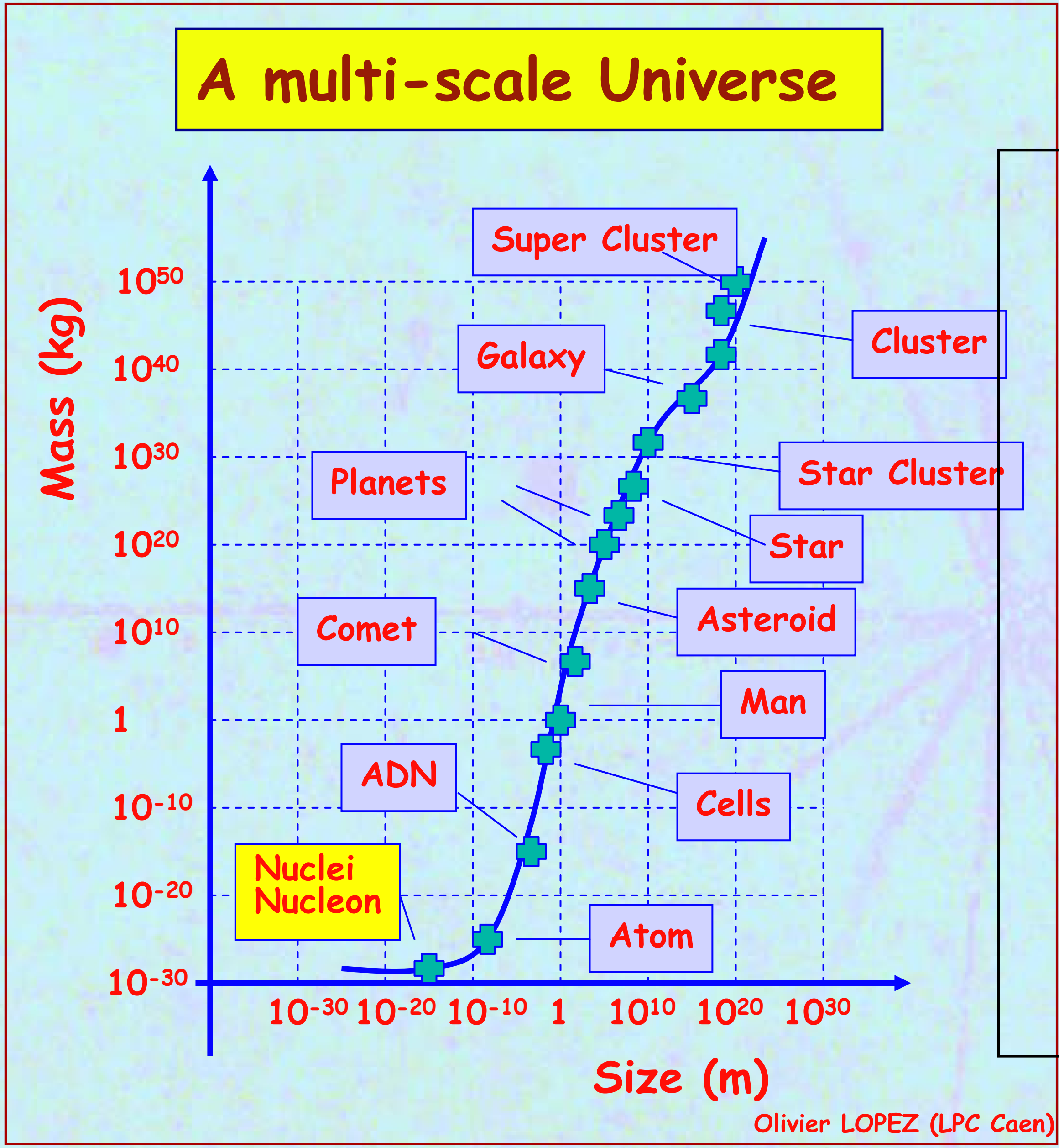
Steps toward the elementary structure of matter





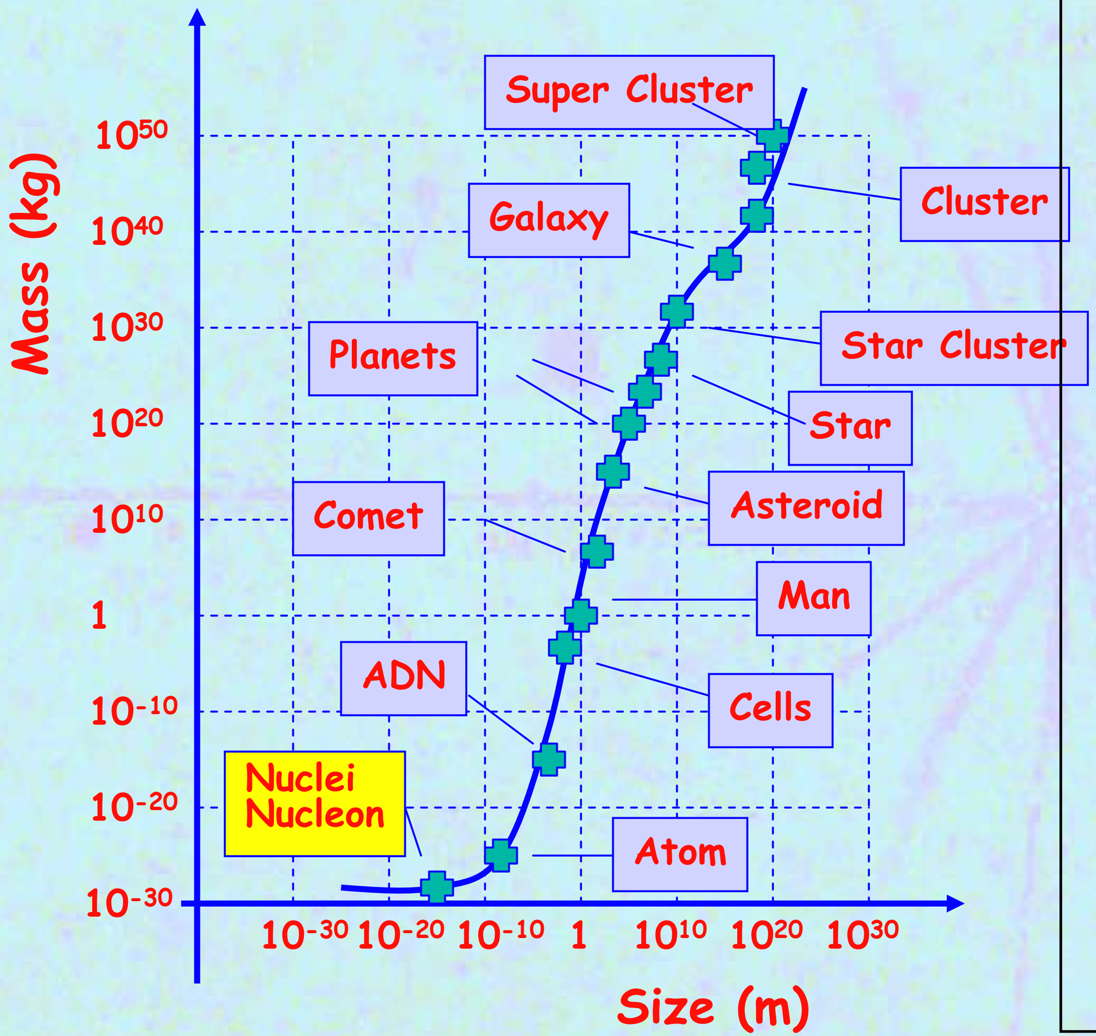
Nucleons and nuclei:





Nucleons and nuclei the first steps in the hierarchy of complex systems

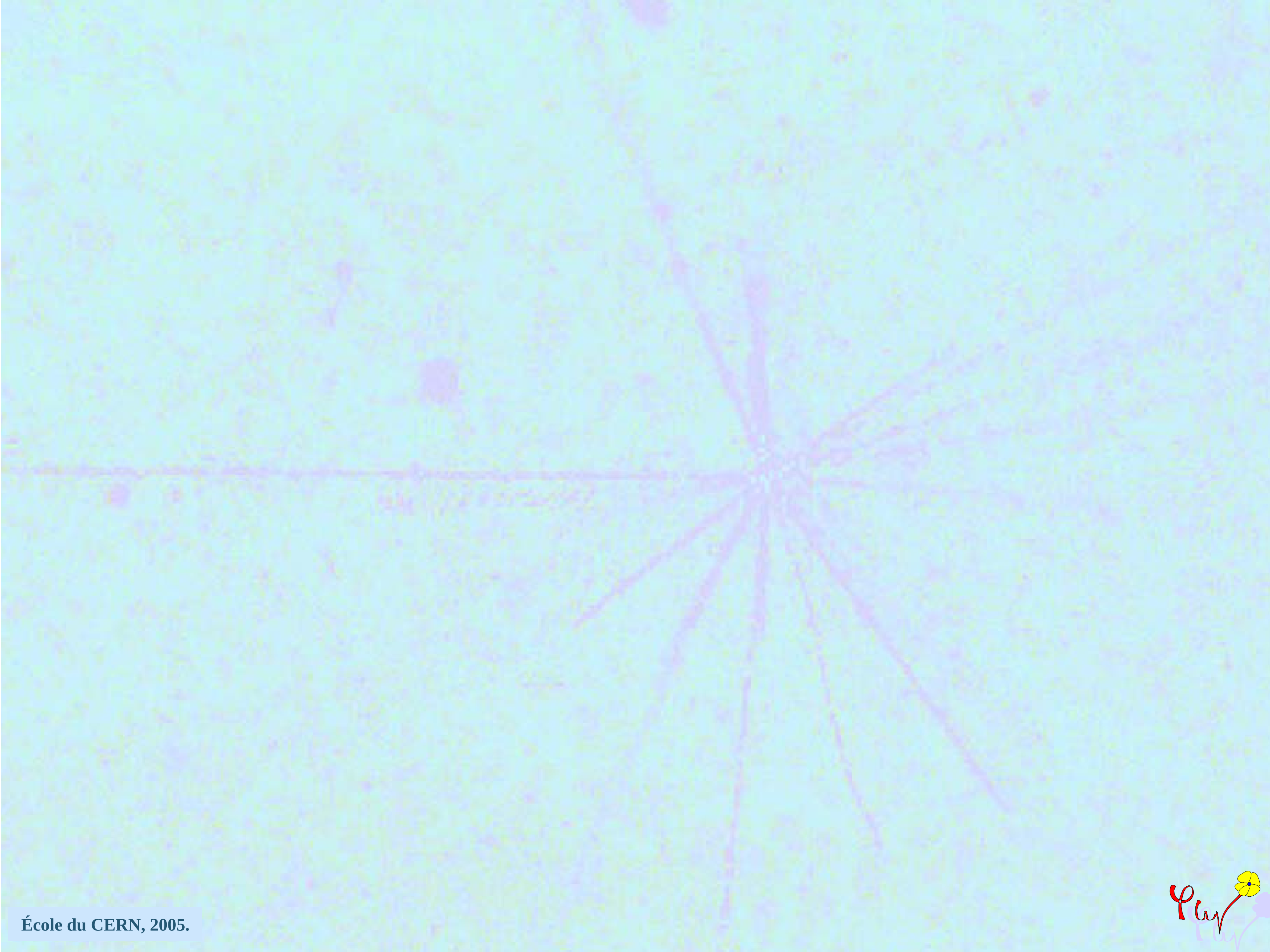
A multi-scale Universe



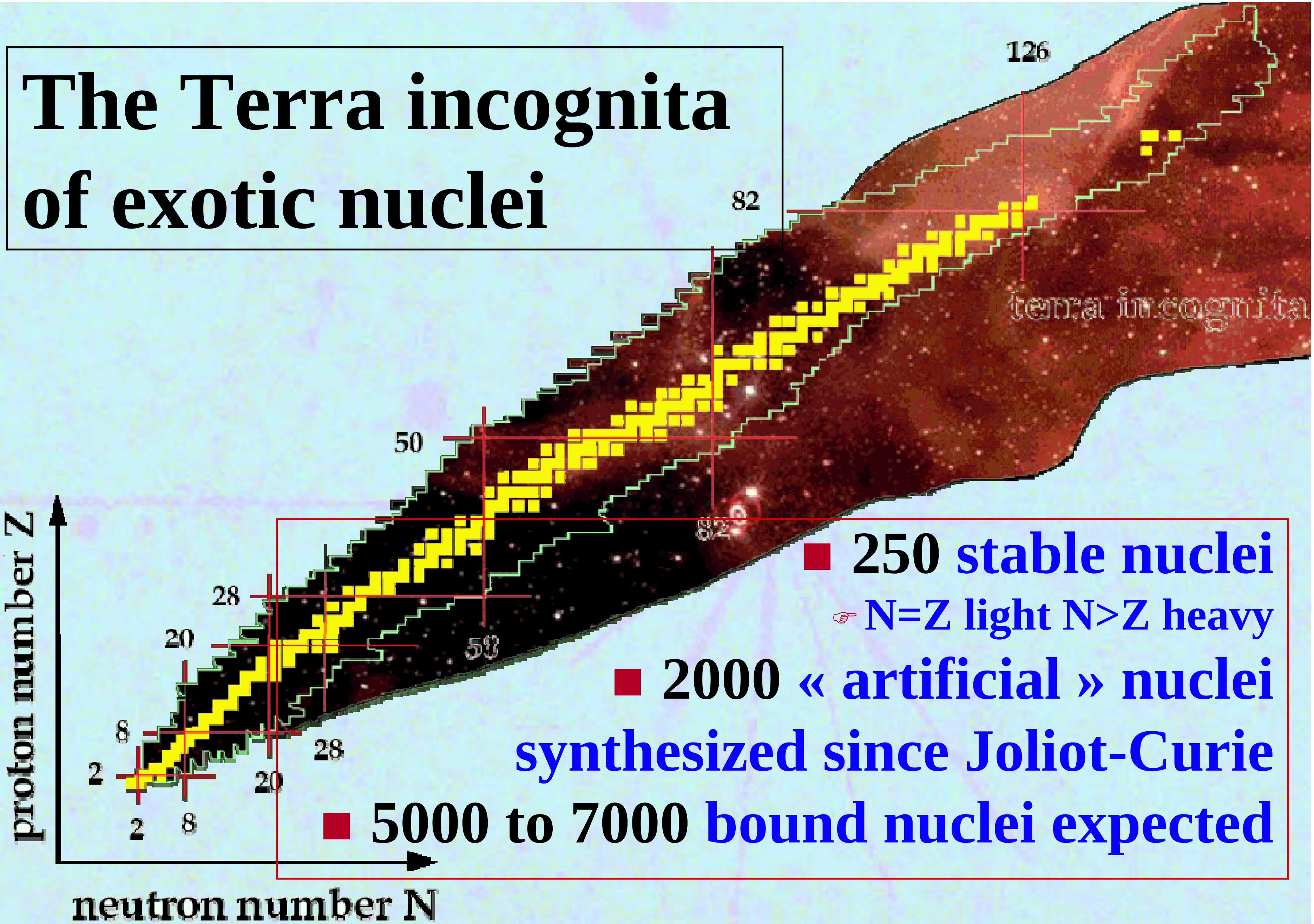
Olivier LOPEZ (LPC Caen)

Fundamental Questions:

- Relevant degree of freedom
- Effective interaction
- Complex structure
- Connection with elementary level

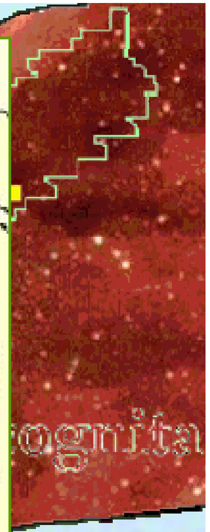


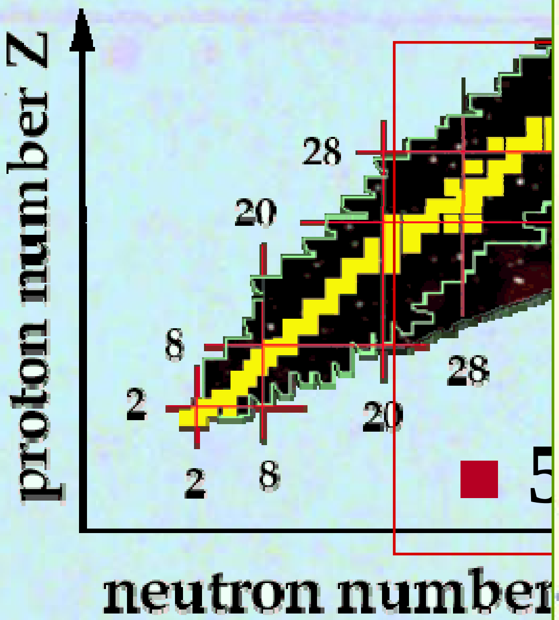
The Terra incognita of exotic nuclei

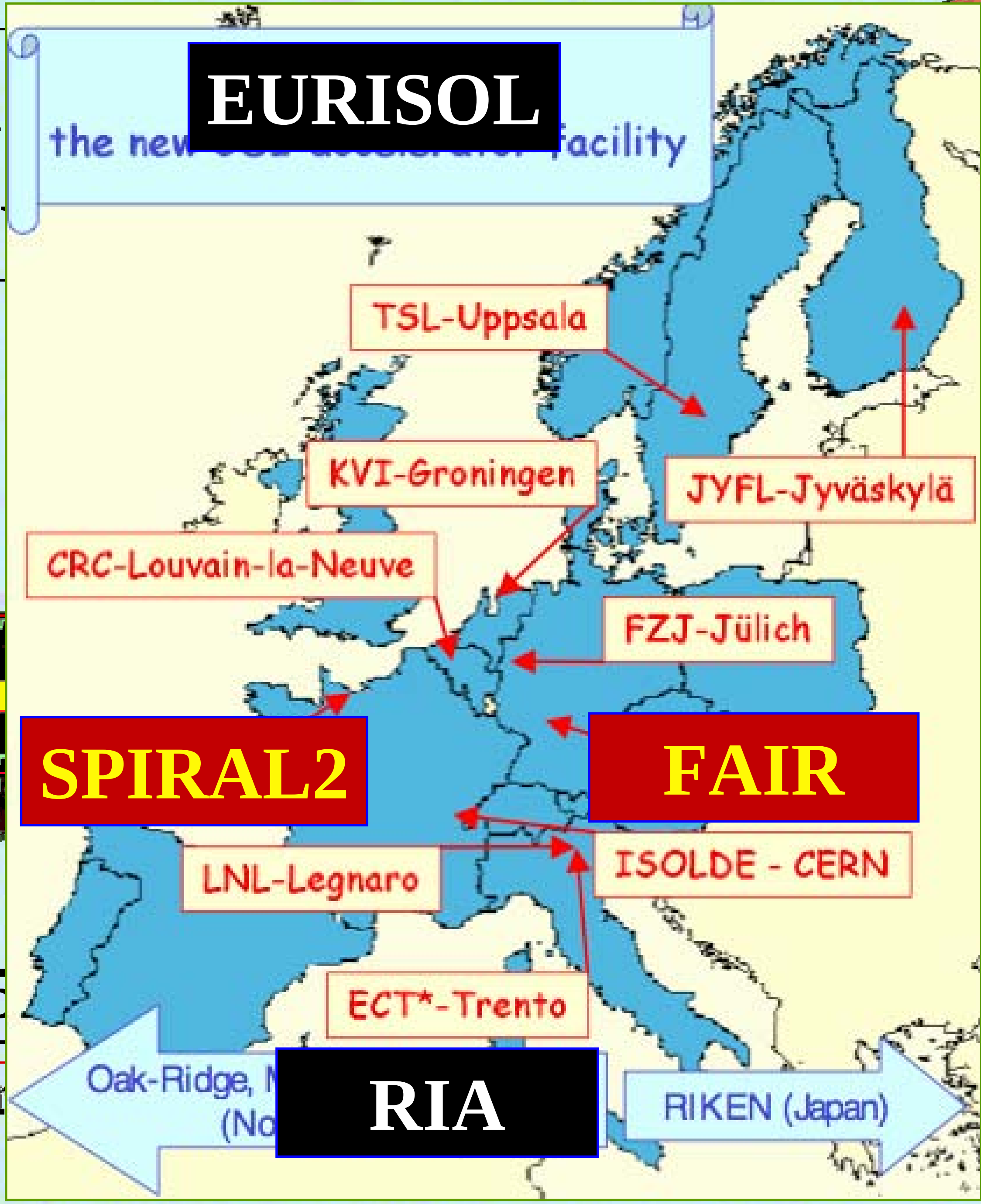


- 250 **stable nuclei**
  - ☞ N=Z light N>Z heavy
- 2000 « **artificial** » **nuclei synthesized since Joliot-Curie**
- 5000 to 7000 **bound nuclei expected**

The Terra
of exotic n







uclei
heavy
uclei
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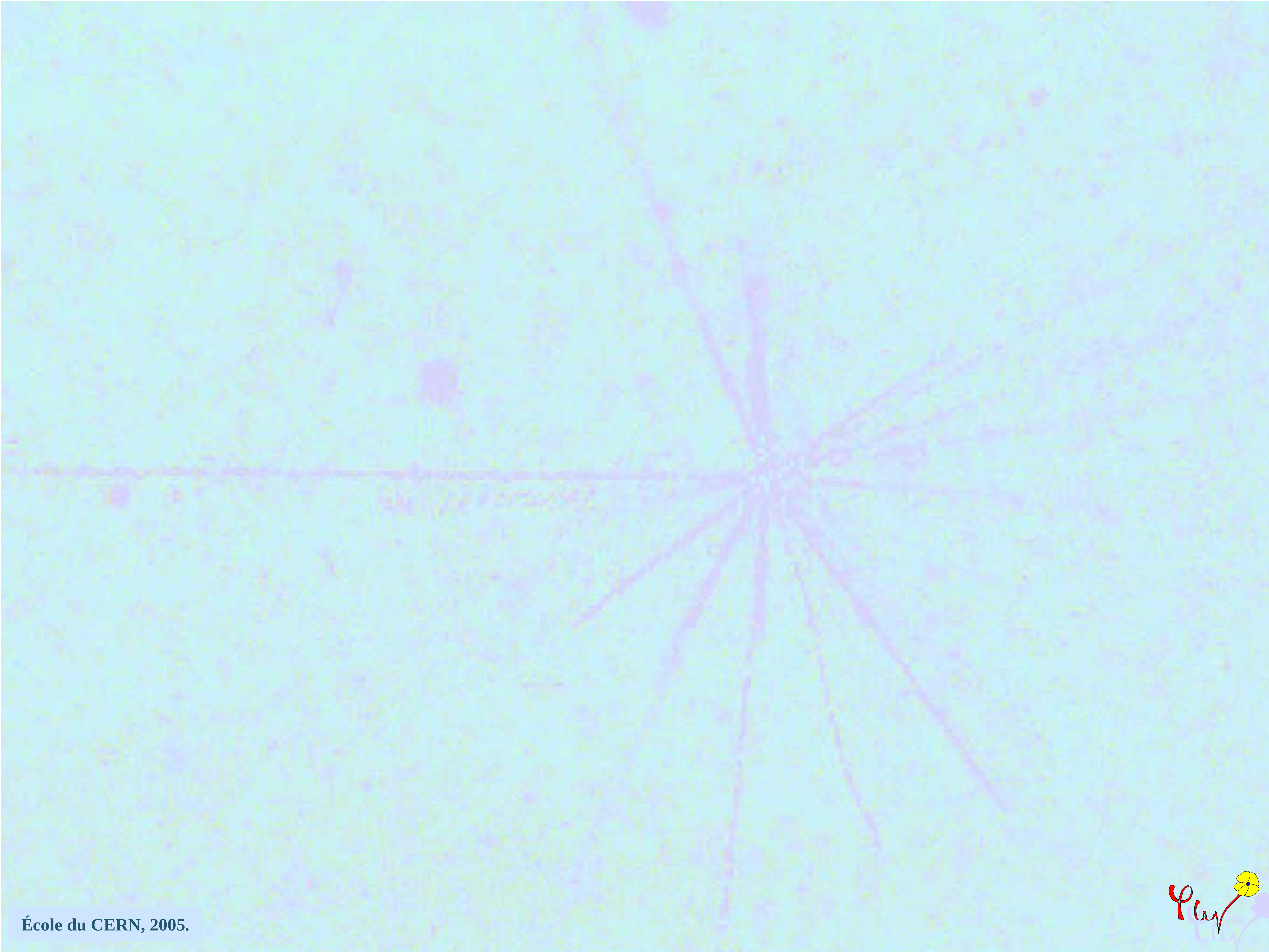
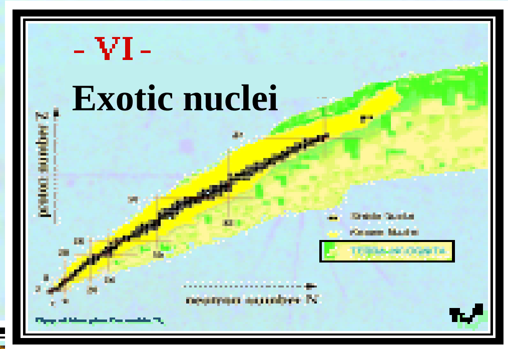
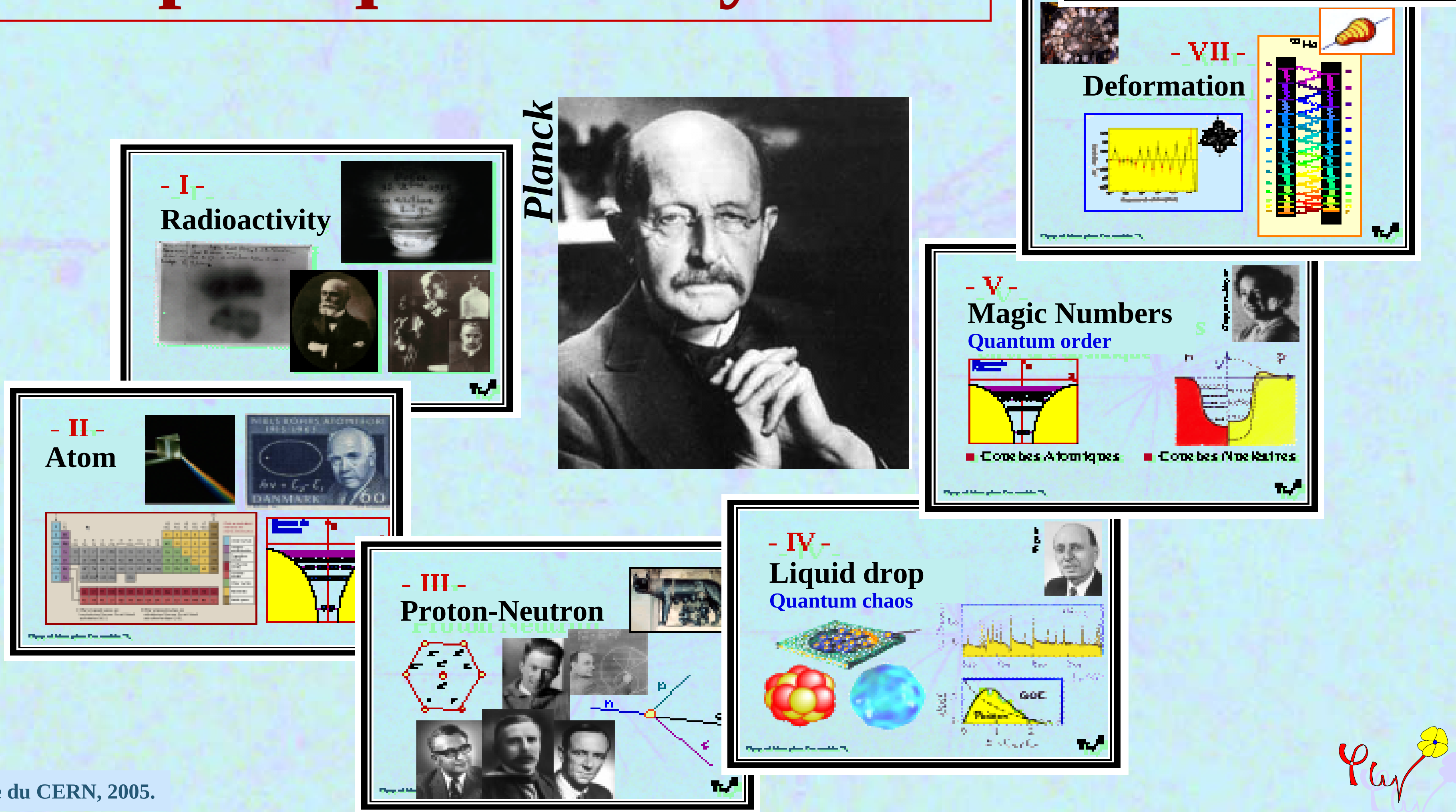


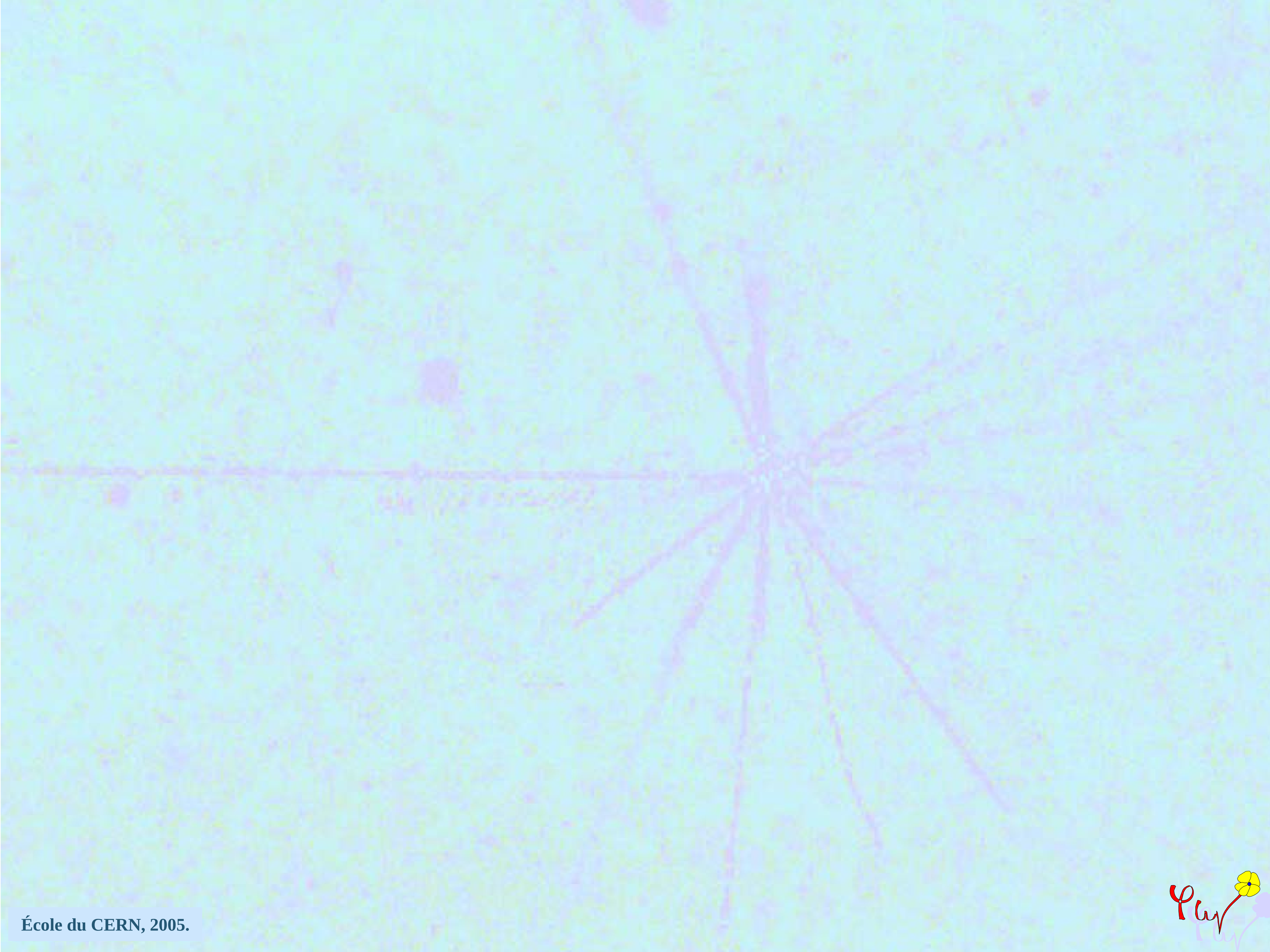
Atomic Nuclei

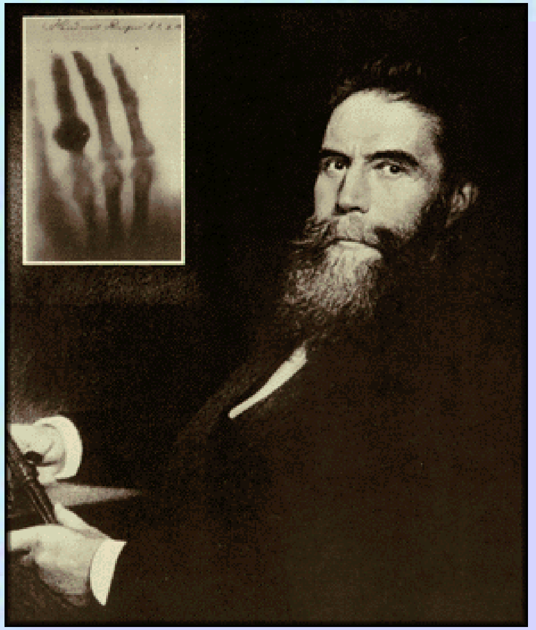
Complex quantum systems





École du CERN, 2005.





1895 Rœntgen
Discovery of X rays

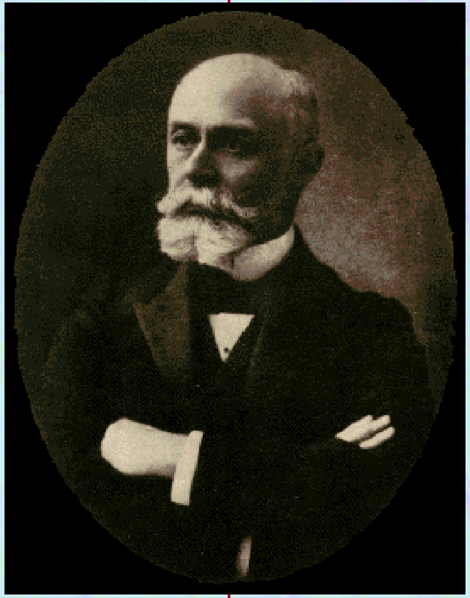
- I -

Radioactivity

- I -
Radioactivity

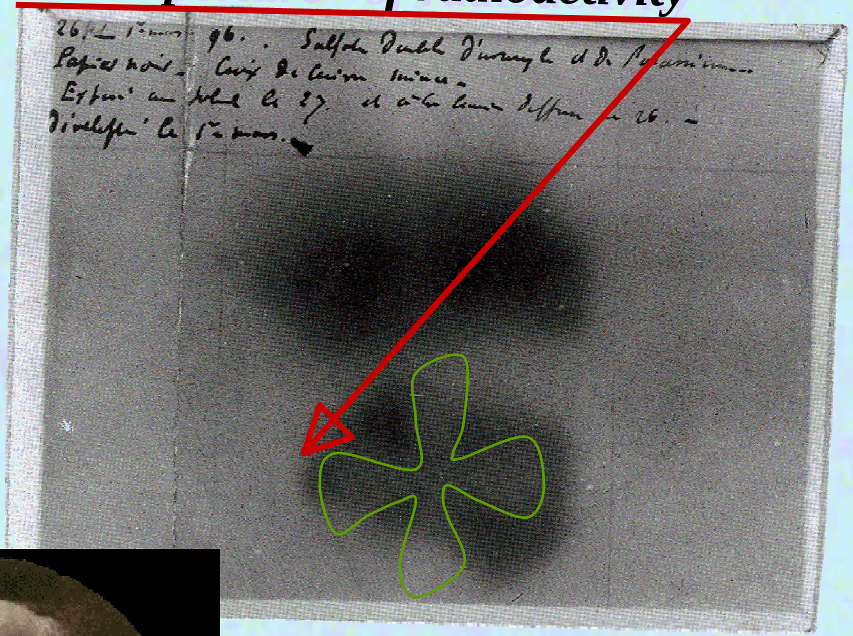
- I -
Radioactivity

- **1896:** **Becquerel**



- I -
Radioactivity

First "picture" of radioactivity



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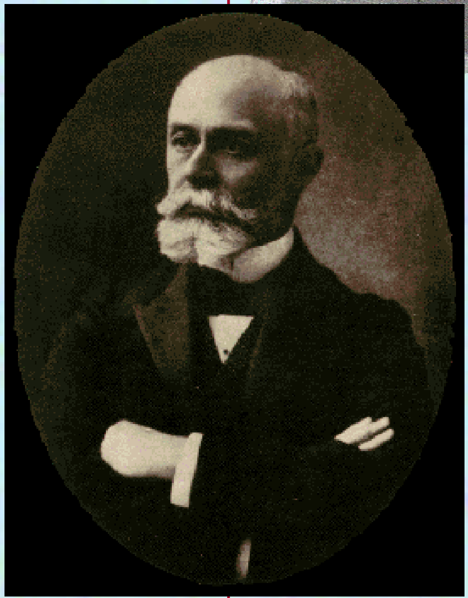
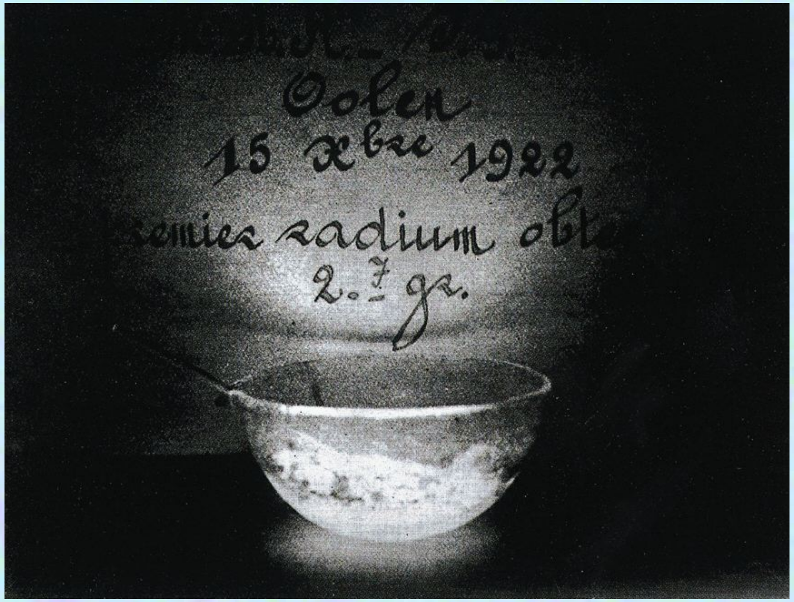
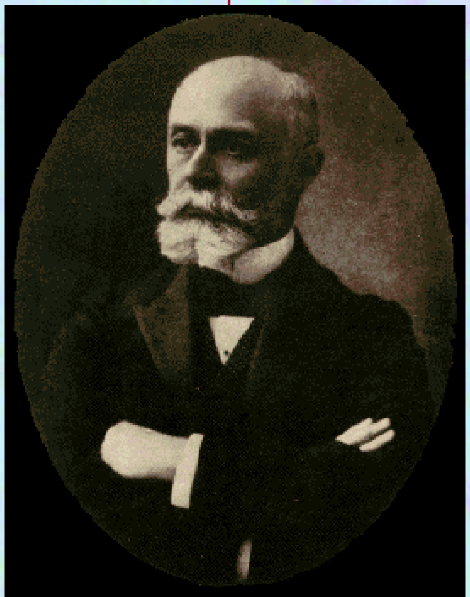
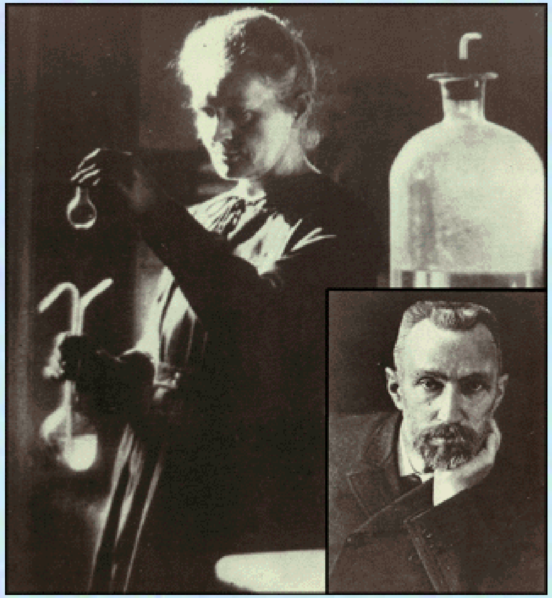


- I -
Radioactivity



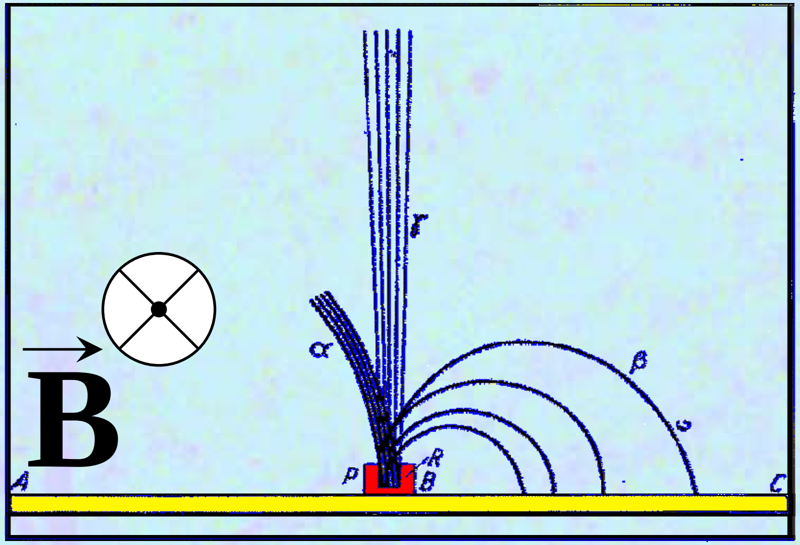
- **1896:** Becquerel
- **1898:** Curie



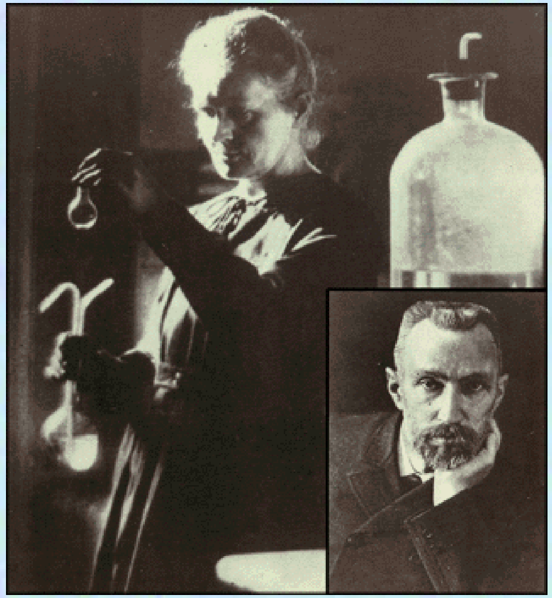


- I -

Radioactivity

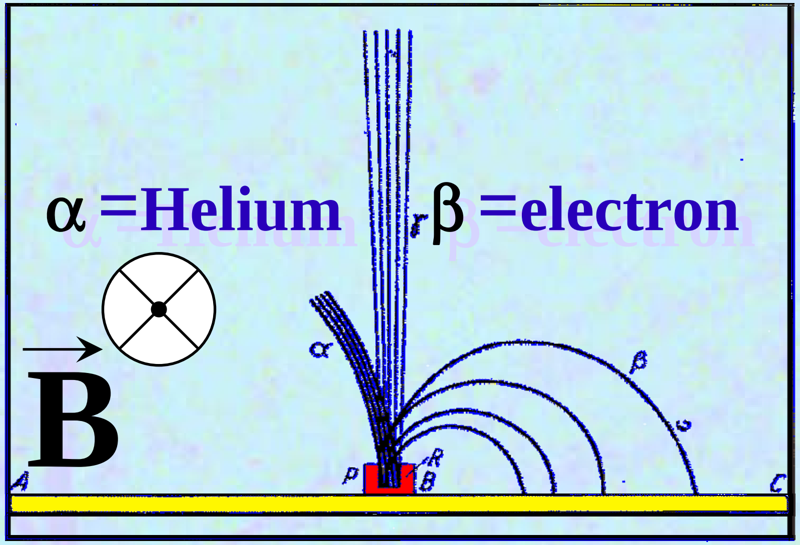


- **1896:** **Becquerel**
- **1898:** **Curie**
- **3 types:** α, β, γ

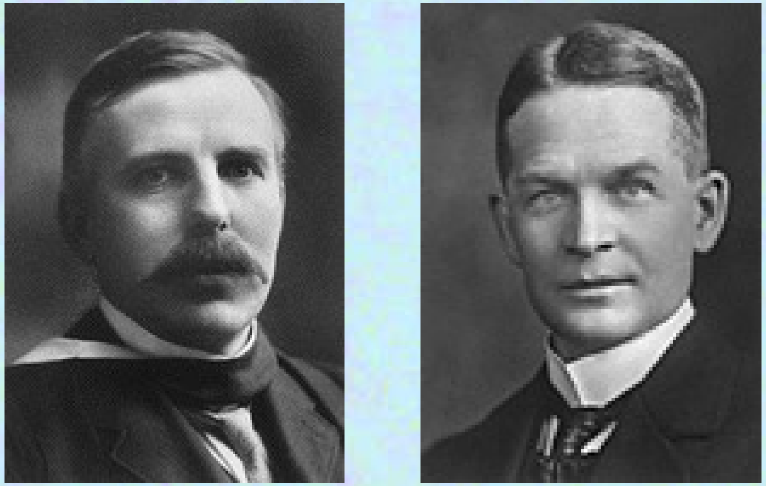


- I -

Radioactivity



- **1896:** **Becquerel**
- **1898:** **Curie**
- **3 types:** α, β, γ
- **Transmutation 1901:**



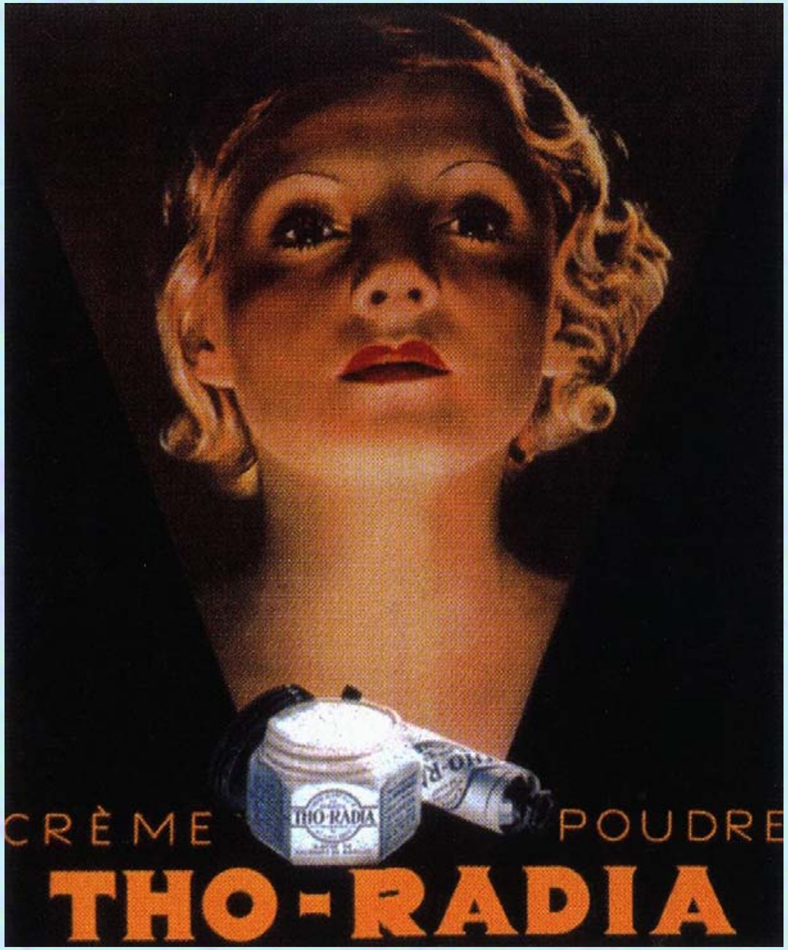
Rutherford et Soddy

- I -

Radioactivity

Mystery

- **Finite life time but always young**
- **Transmutation**



- I -

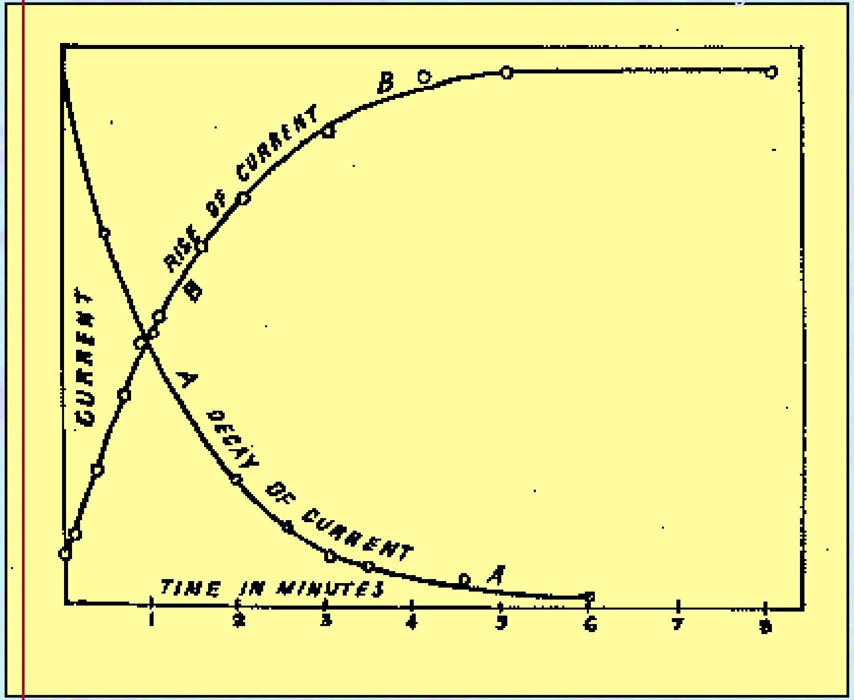
Radioactivity

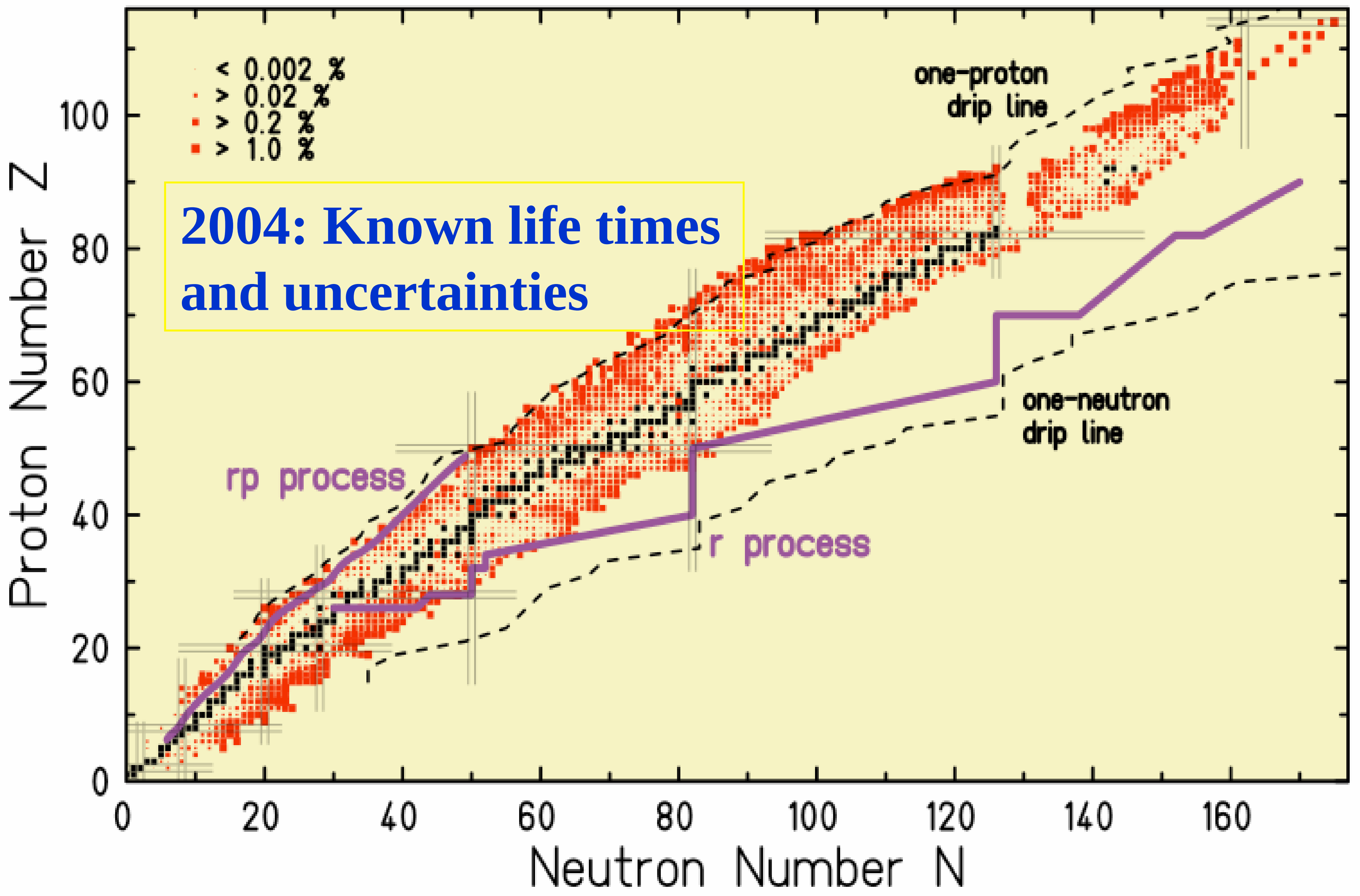
Mystery

- **Exponential decay**
  $dN/dt = -N/T_{life}$
- **Finite life time but always young**
- **Transmutation**

Rutherford

1902: First measure of decay laws





< 0.002 %
> 0.02 %
> 0.2 %
> 1.0 %
2004: Known life times
and uncertainties
one-proton
drip line
one-neutron
drip line
rp process
r process
Proton Number Z
Neutron Number N
0
20
40
60
80
100
120
140
160

- I -

Radioactivity

Mystery solved

Gamov

- **Exponential decay**
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- I -

Radioactivity

Quantum property

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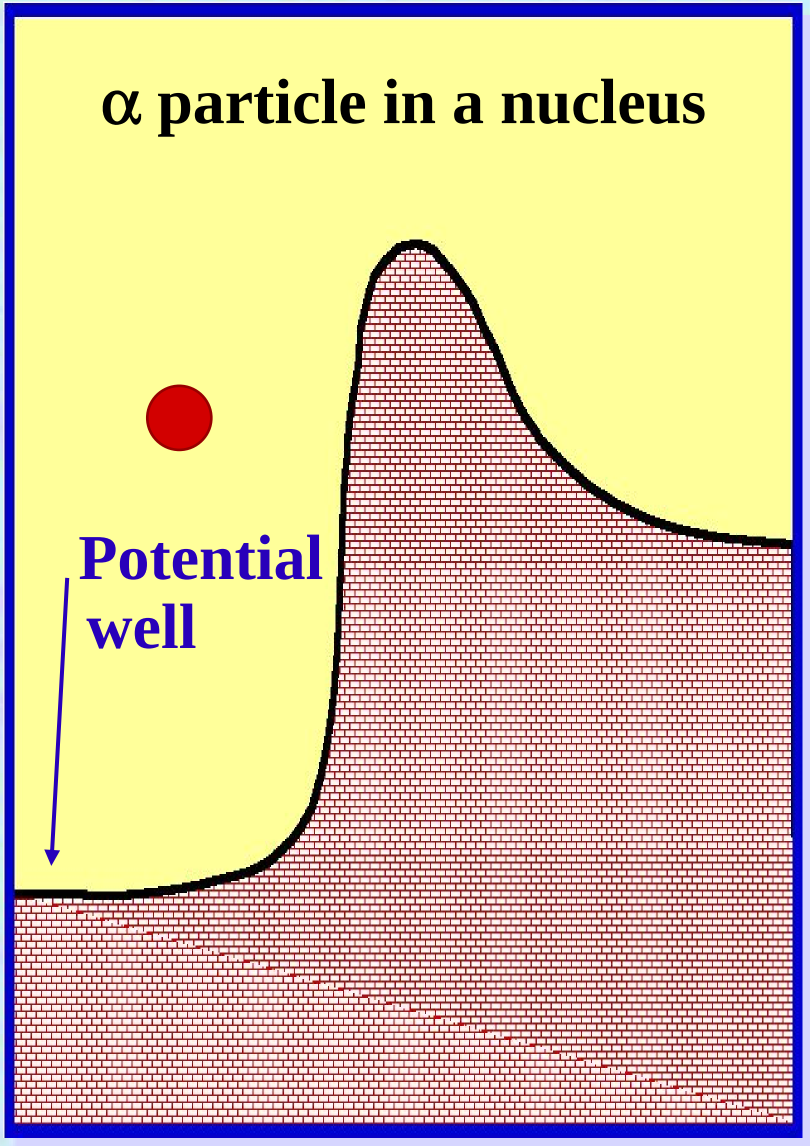

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Radioactivity

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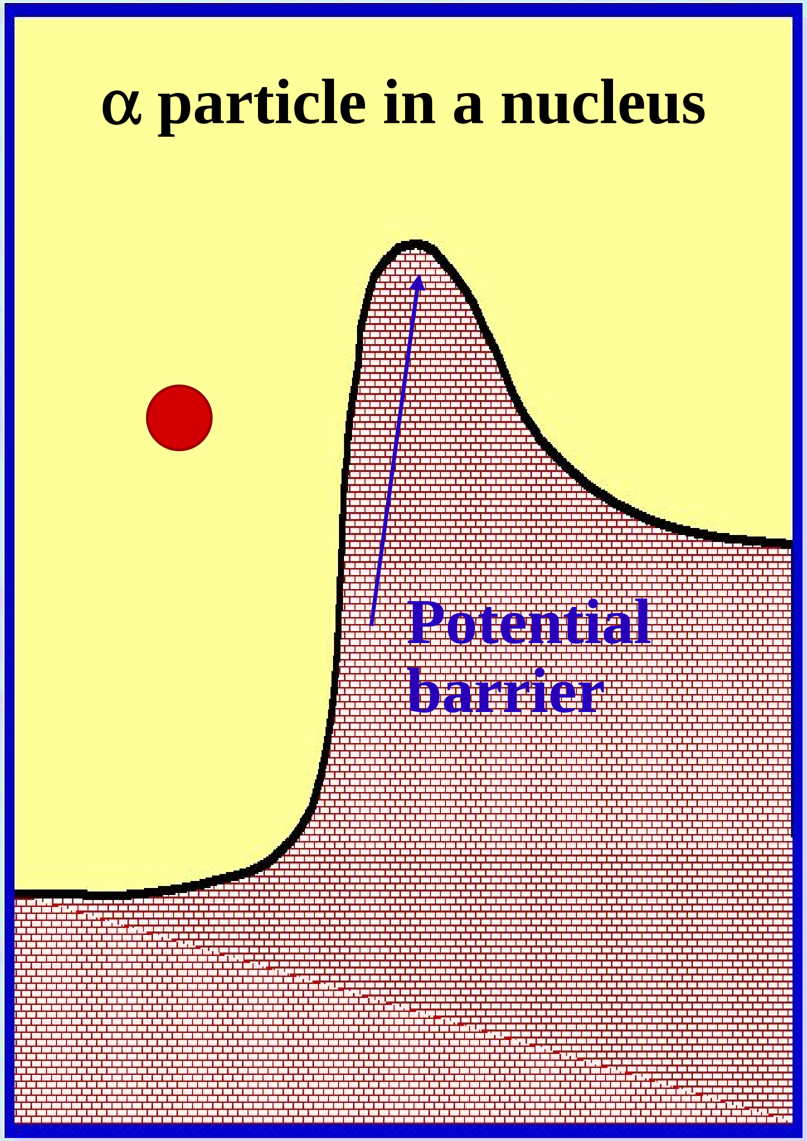

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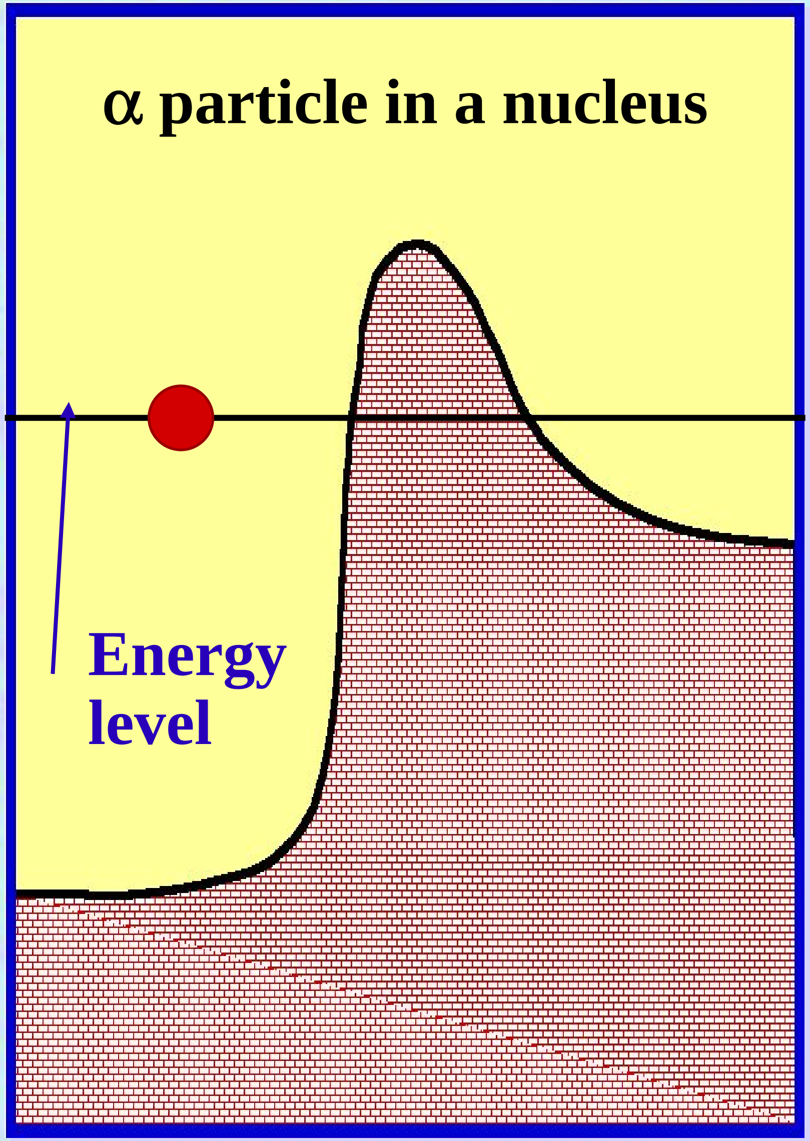

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Radioactivity

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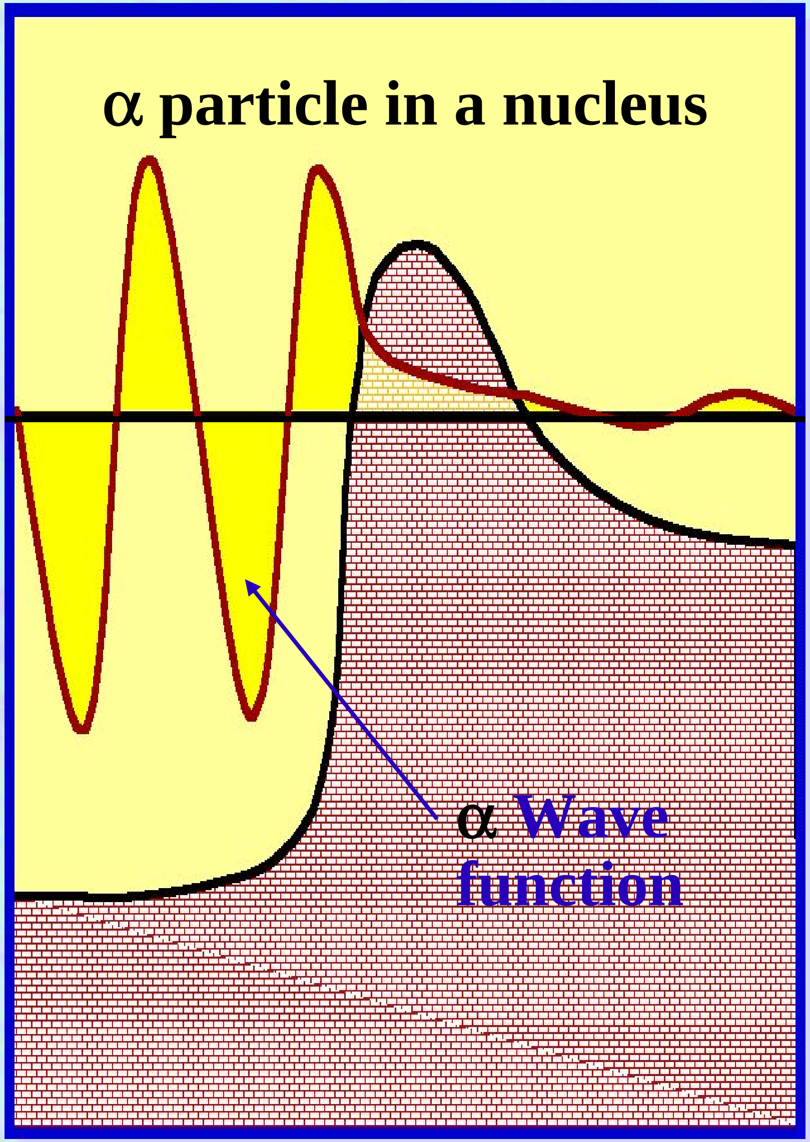

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Radioactivity
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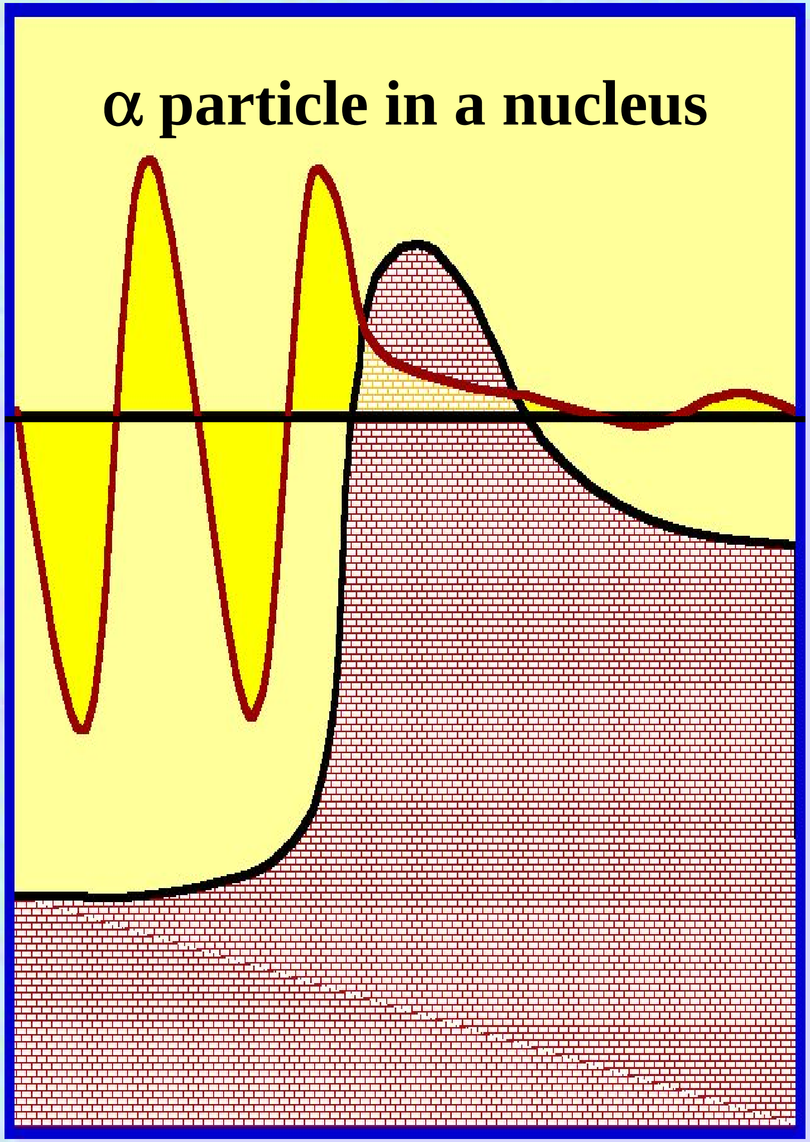

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Radioactivity
Quantum property

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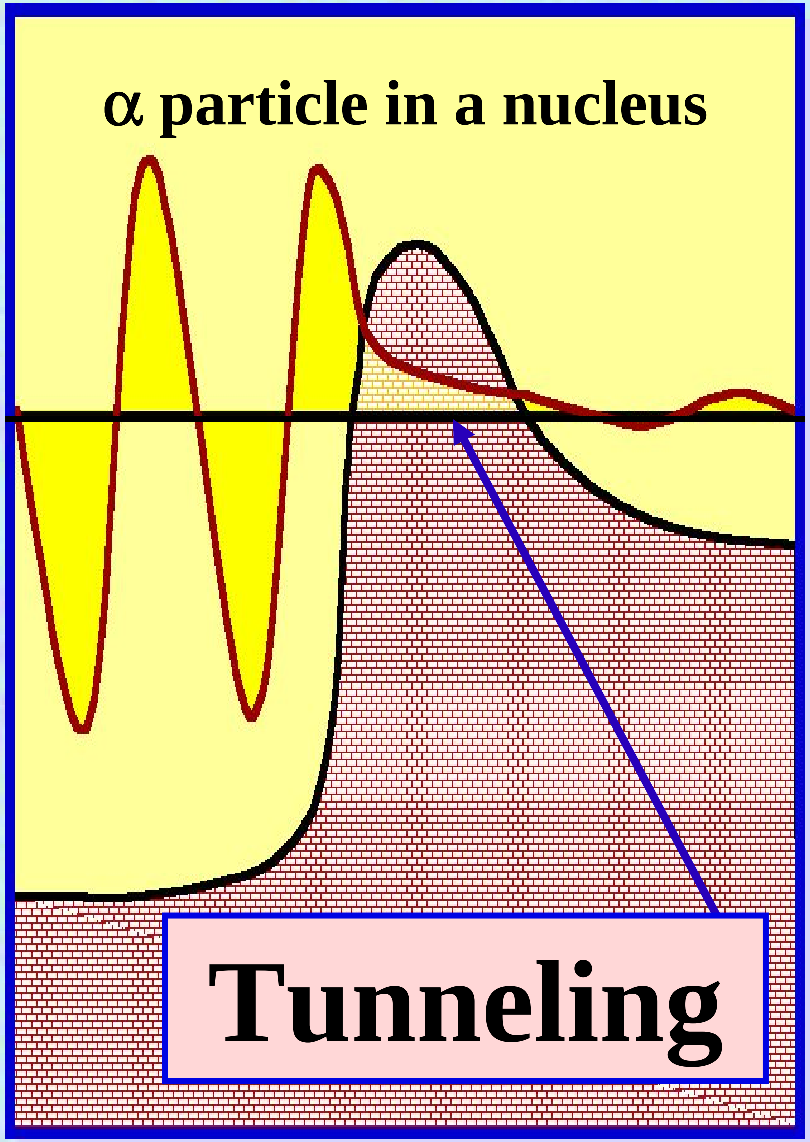


- I -
Radioactivity

- I -

Radioactivity

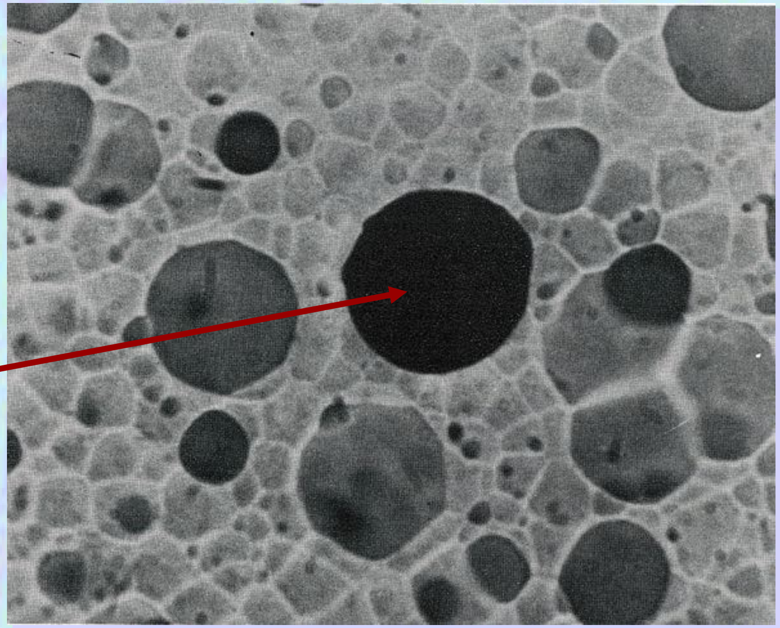
Still a mystery

- Radioactivity of nuclei
- Fission
- 2p or ^{2}He

- I -
Radioactivity
Still a mystery

- **Radioactivity of nuclei**

^{14}C trace one ^{14}C for 10^{6-8} α



- I -

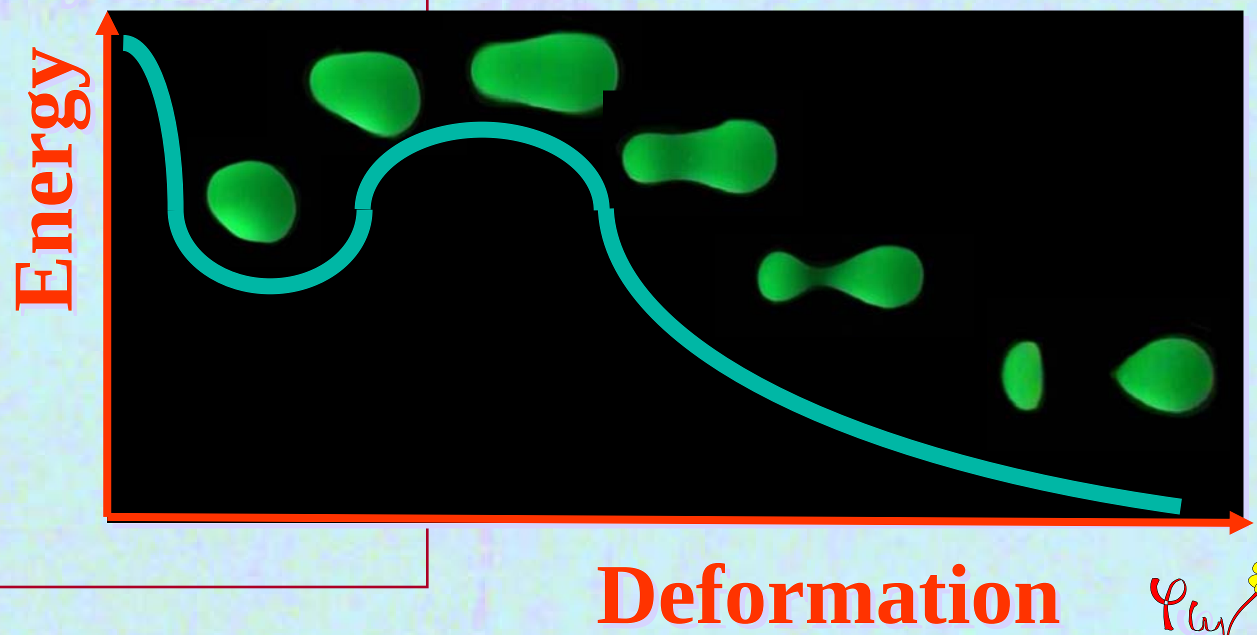
Radioactivity

Still a mystery

- Radioactivity of nuclei
- Fission

Joliot-Curie

Meitner



- I -

Radioactivity

Still a mystery

- Radioactivity of nuclei
- Fission

Fermi

QuickTime™ et un décompresseur GIF sont requis pour visualiser cette image.

- I -

Radioactivity

Still a mystery

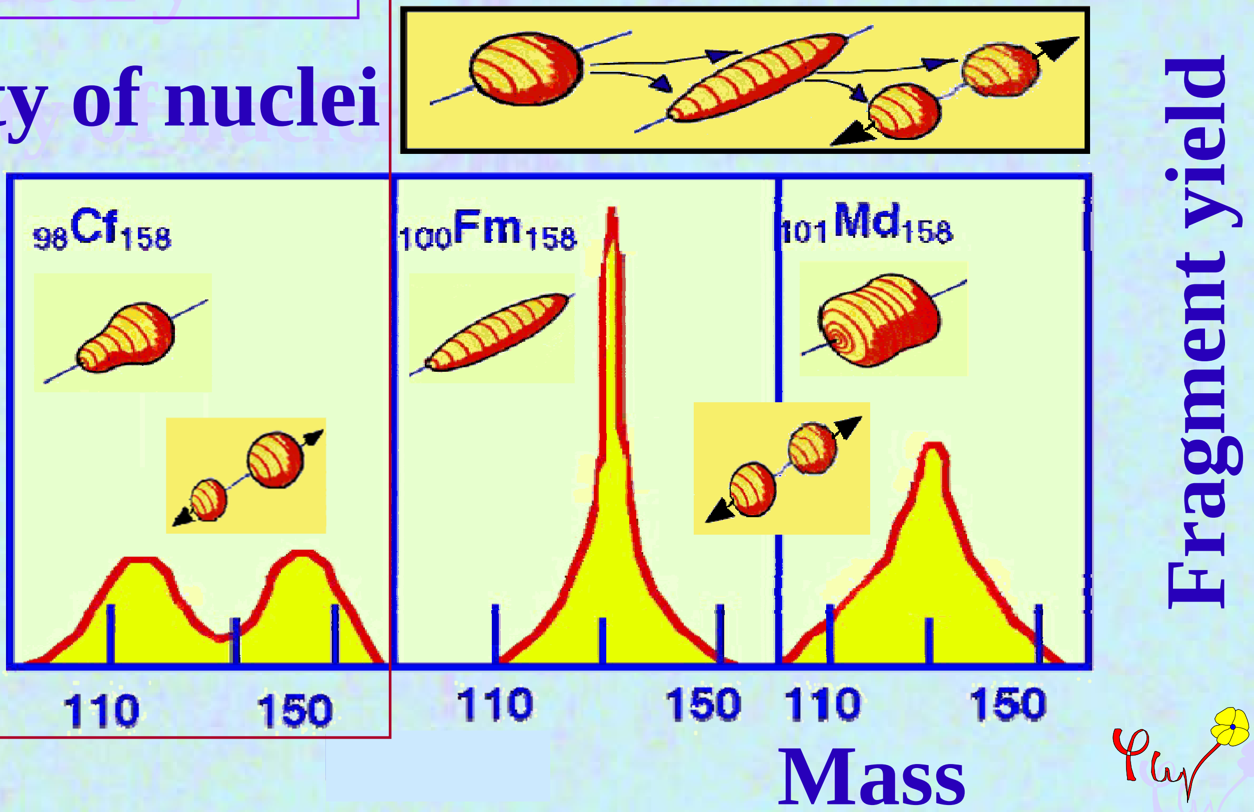
- Radioactivity of nuclei
- Fission

- I -

Radioactivity

Still a mystery

- Radioactivity of nuclei
- Fission
- Shapes and Symmetry breaking



- I -

Radioactivity

Still a mystery

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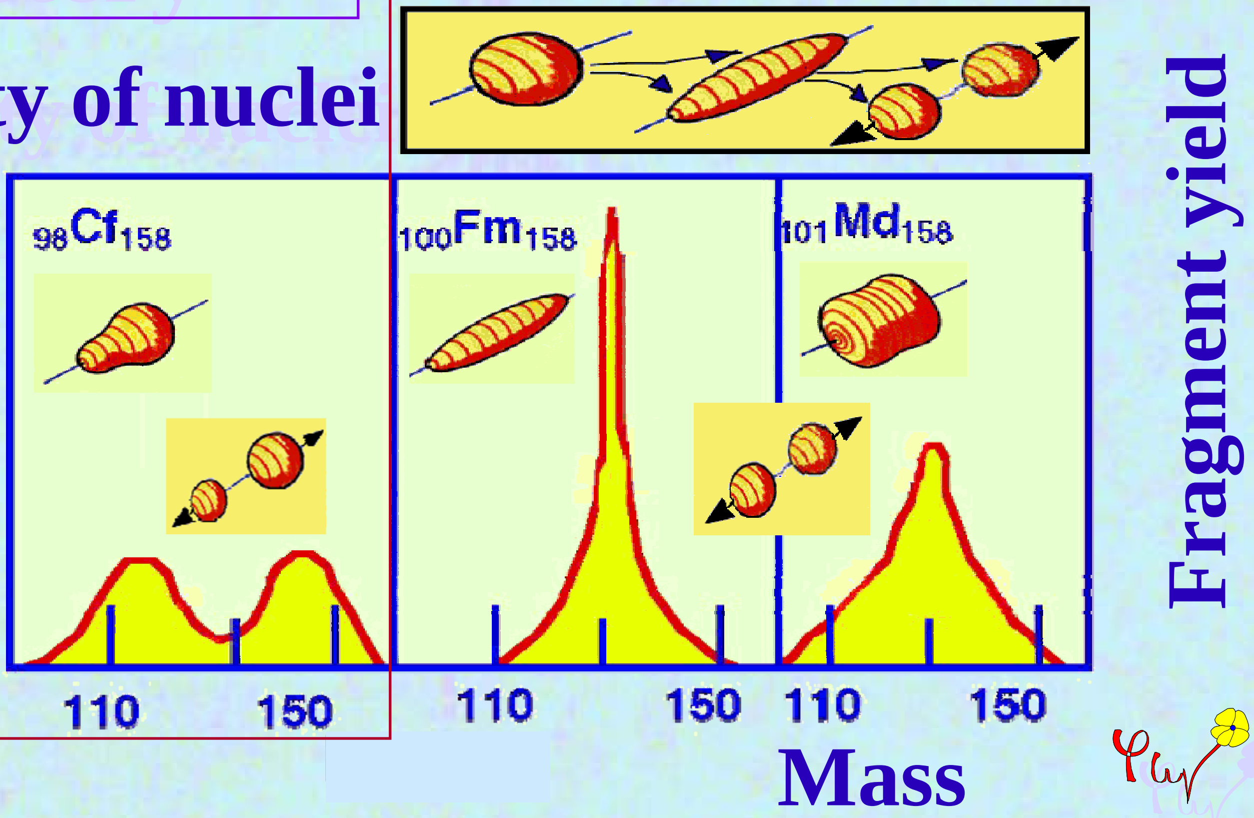
- Shapes and Symmetry breaking



- I -

Radioactivity

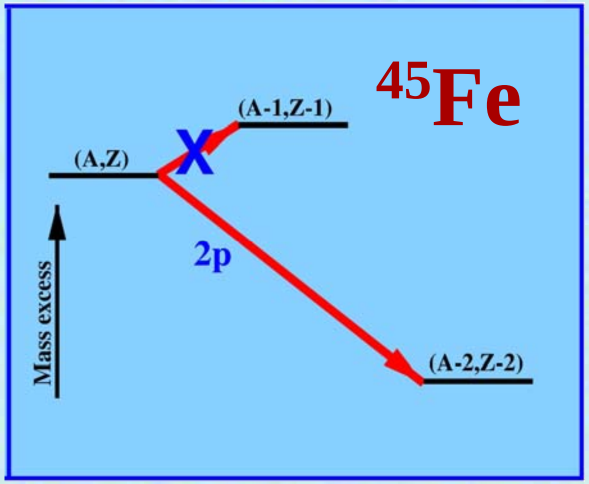
Still a mystery

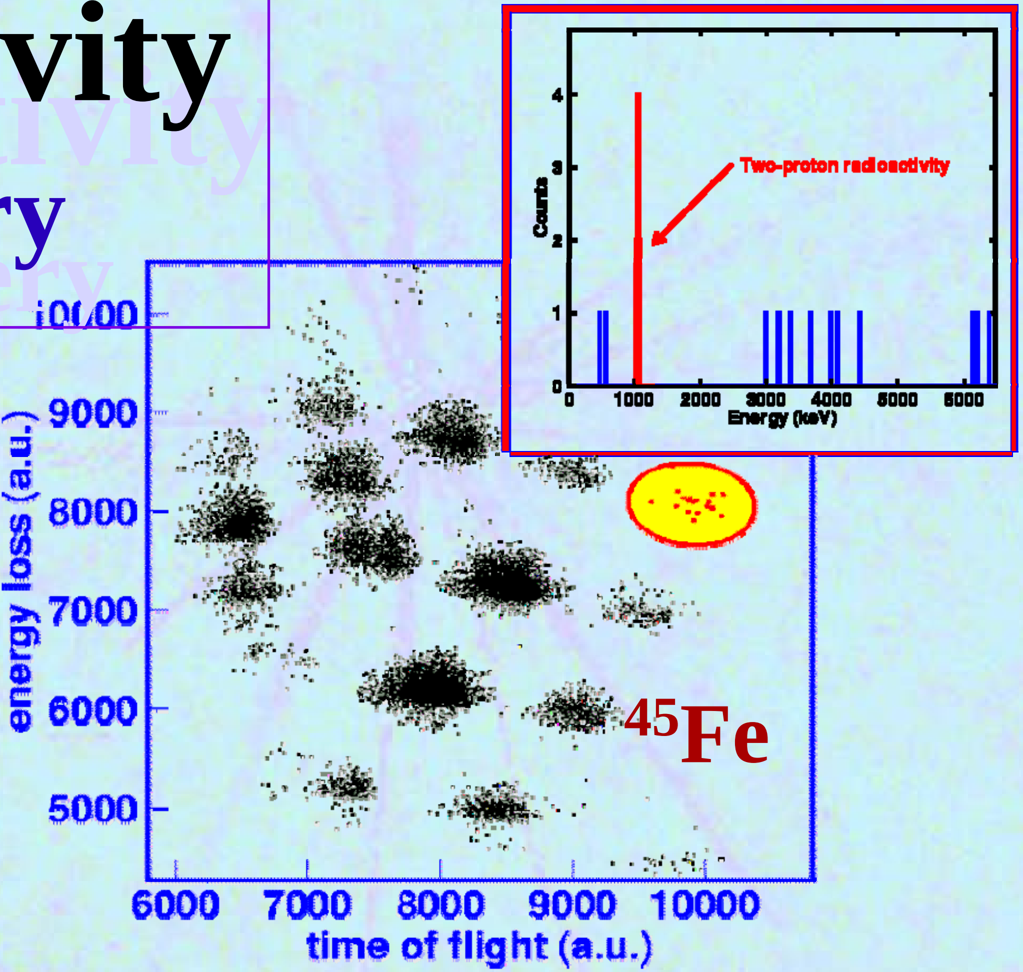
- I -

Radioactivity

Still a mystery

- 2p radioactivity





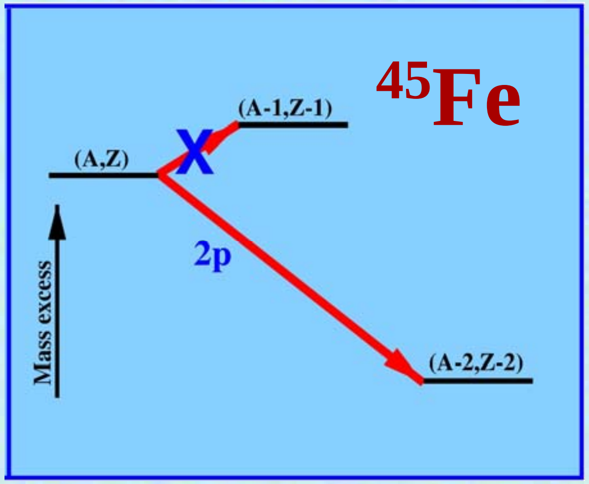
Blank et al, 2003

- I -

Radioactivity

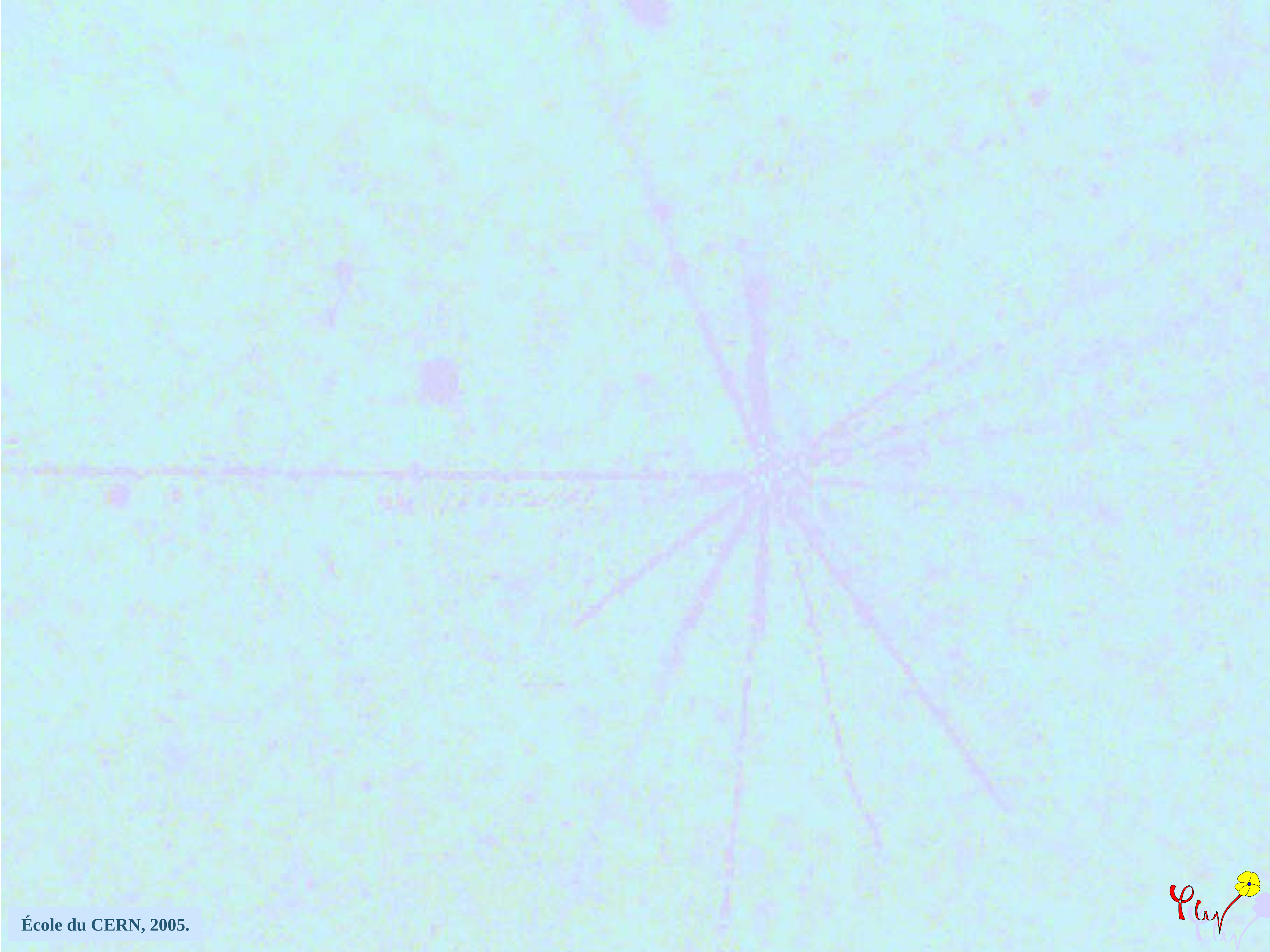
Still a mystery

- 2p radioactivity



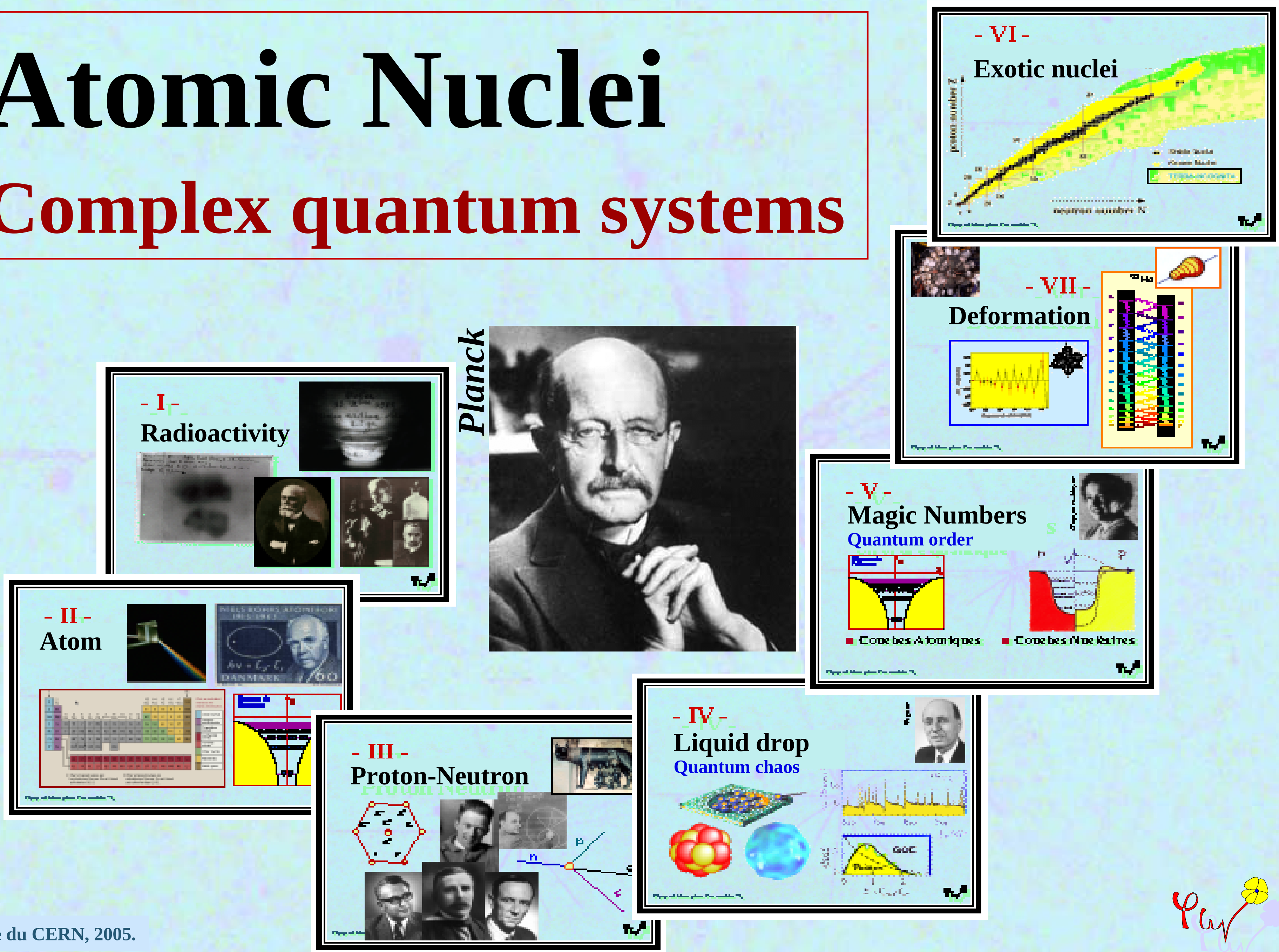
- Sequential decay
- Tunneling of complex system ^{2}He?
- Correlations in ^{45}Fe?

Blank et al, 2003

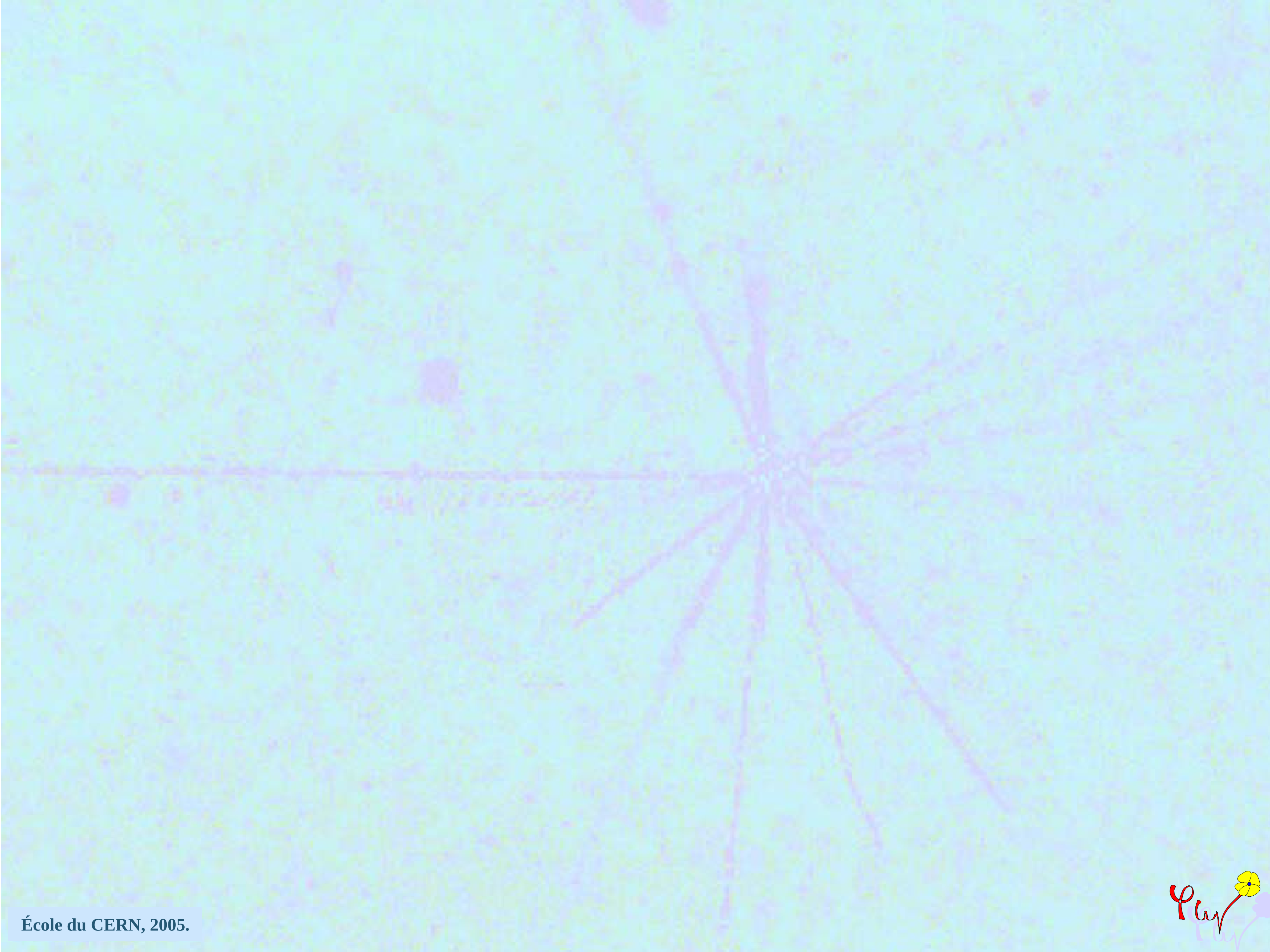


Atomic Nuclei

Complex quantum systems



École du CERN, 2005.



École du CERN, 2005.

- II -
Exploring atom

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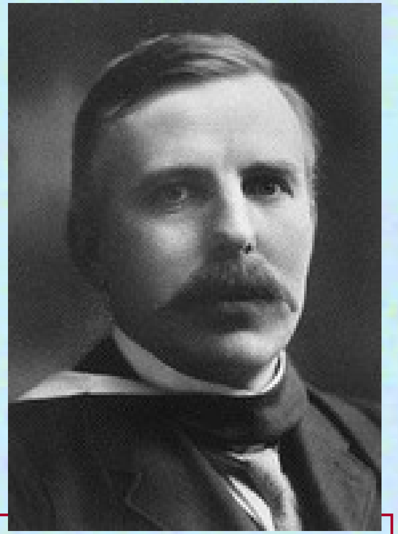
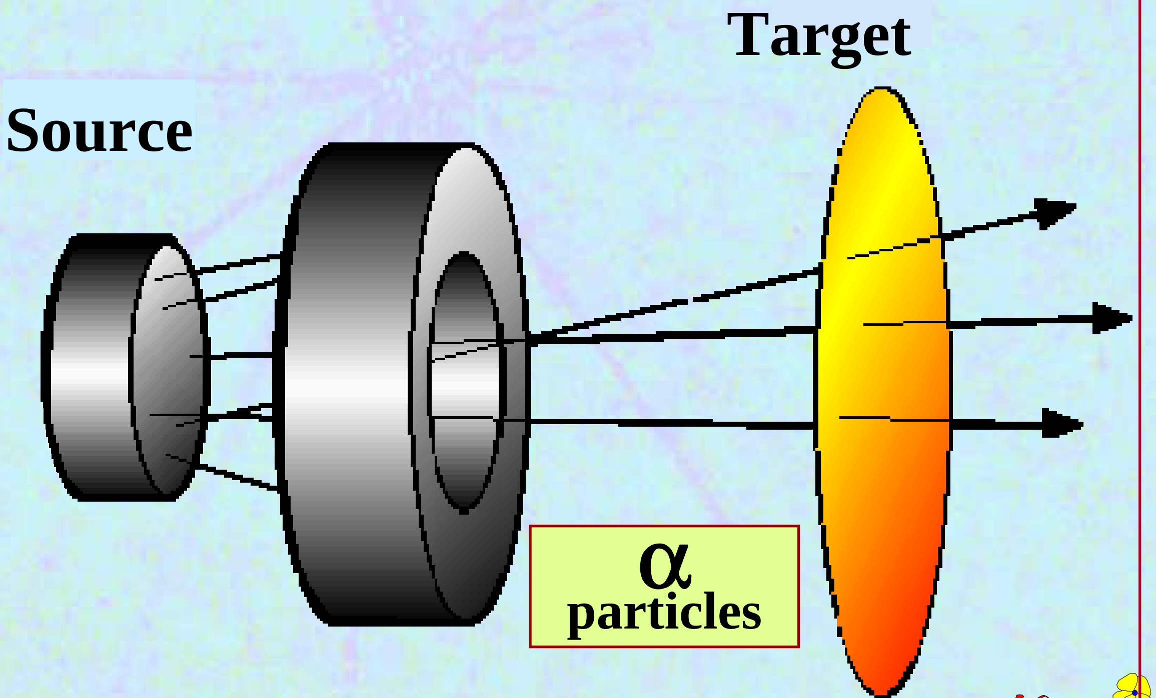
Exploring atom

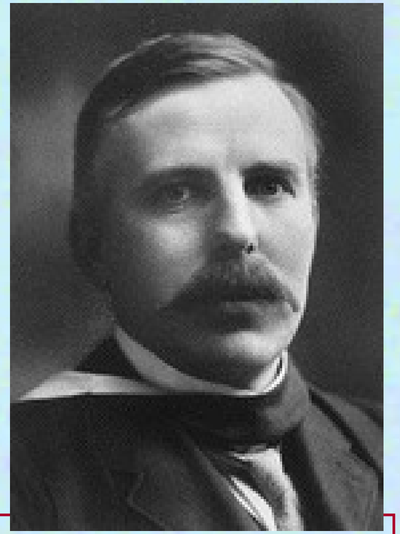


- **1911**



- II -
Exploring atom

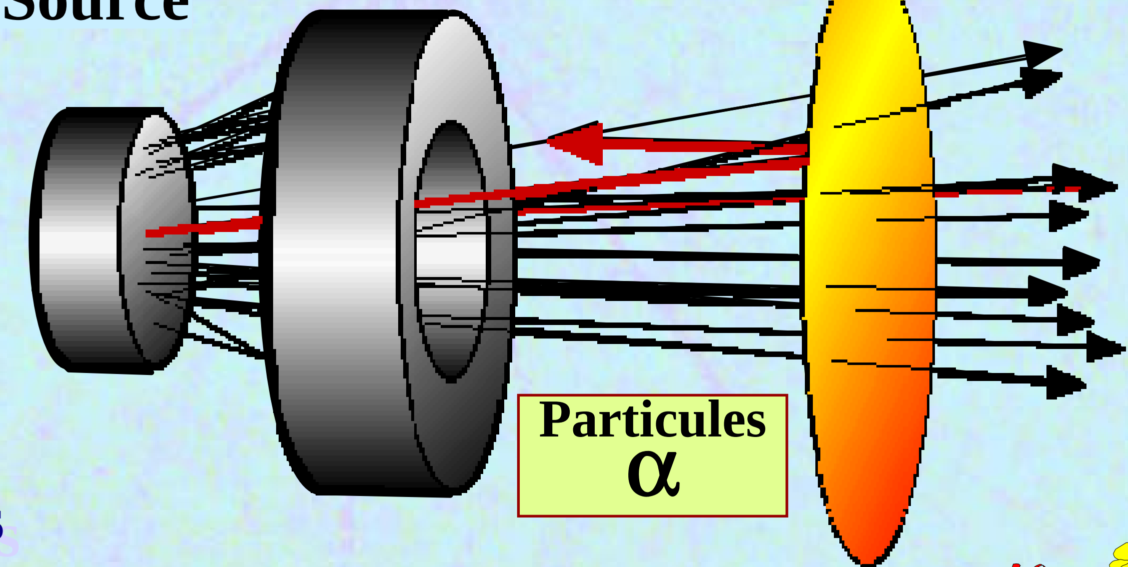
Rutherford



- **1911**

Atoms are almost empty

Except a hard scattering center:
The atomic nucleus



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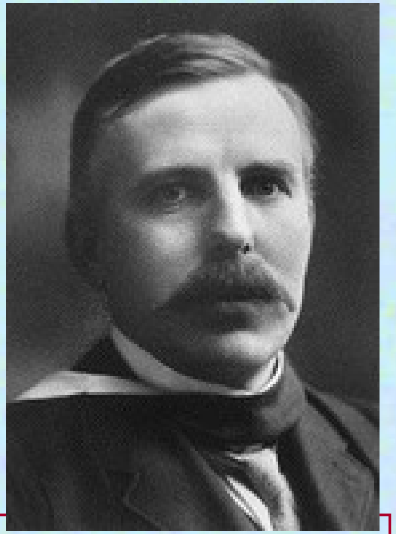
- II -
Exploring atom

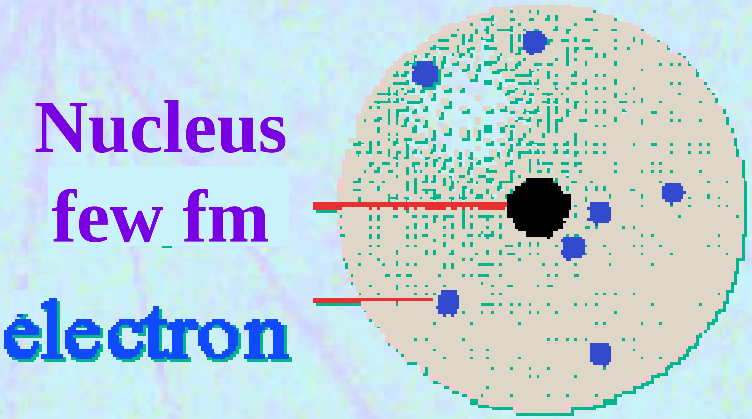
Rutherford



Atomic Models

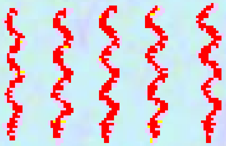
Atoms are almost empty

Except a hard scattering center:
The atomic nucleus



Modern measures

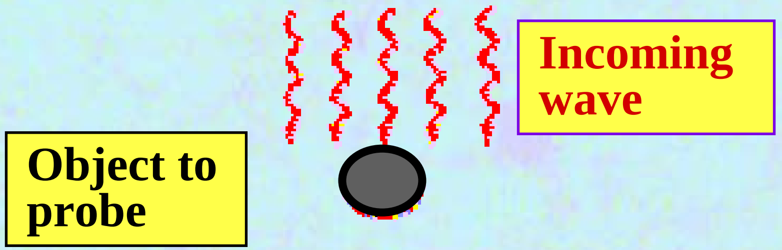
- Scattering of particles



Incoming wave

Modern measures

- Scattering of particles



Modern measures

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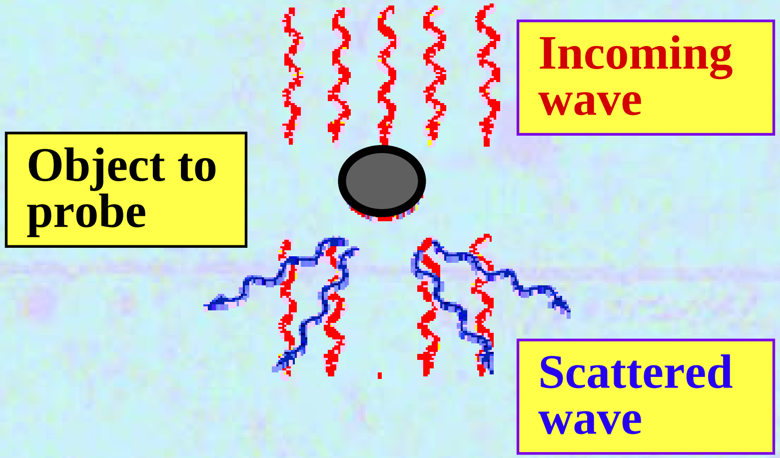
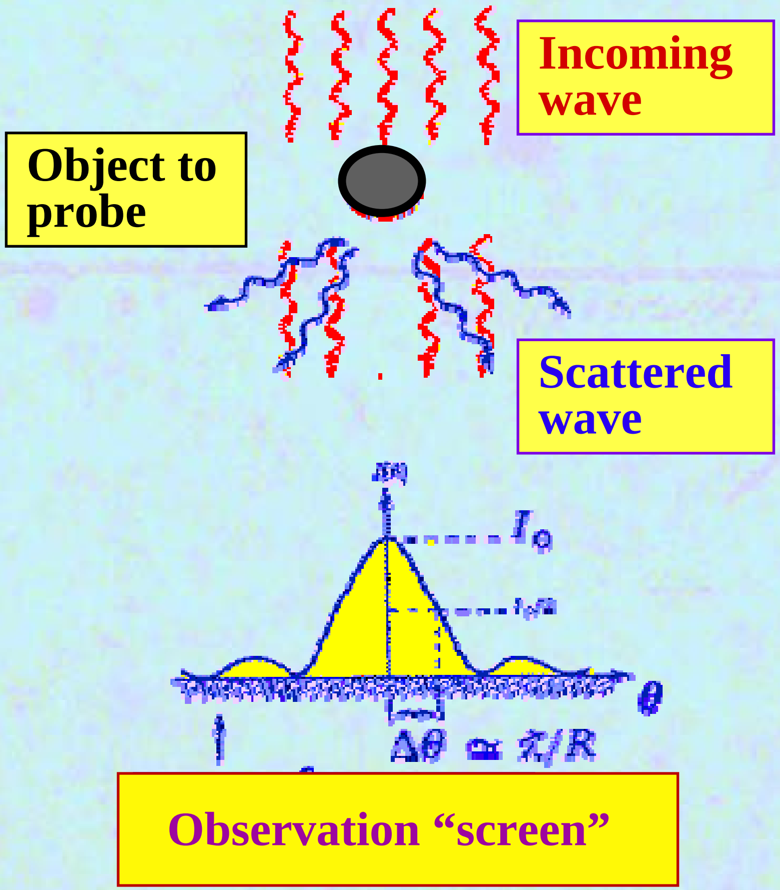


Modern measures

☞ Scattering of particles



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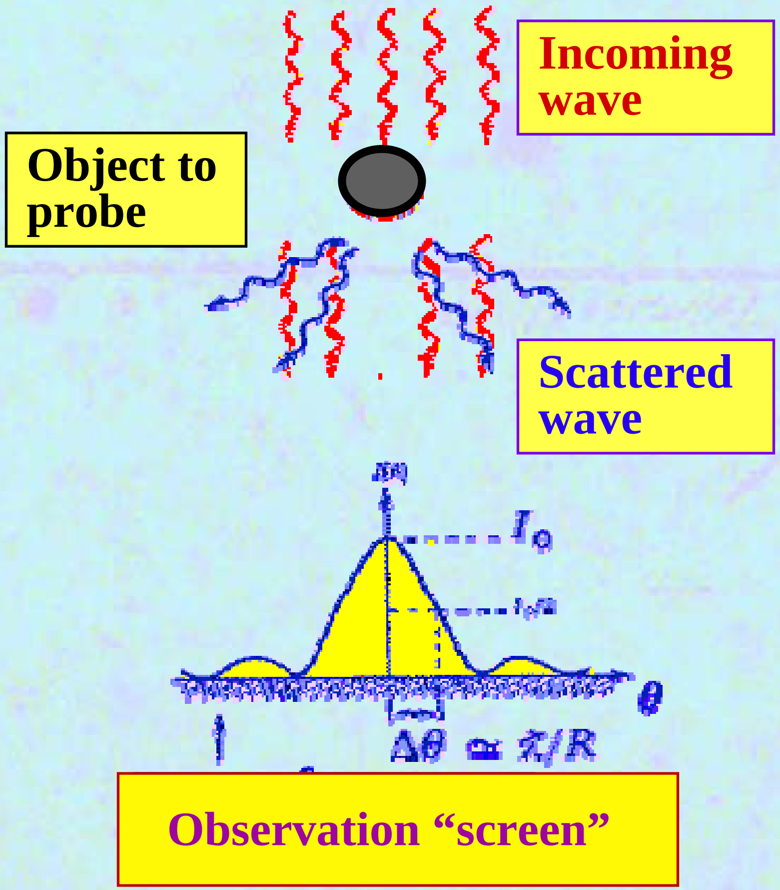
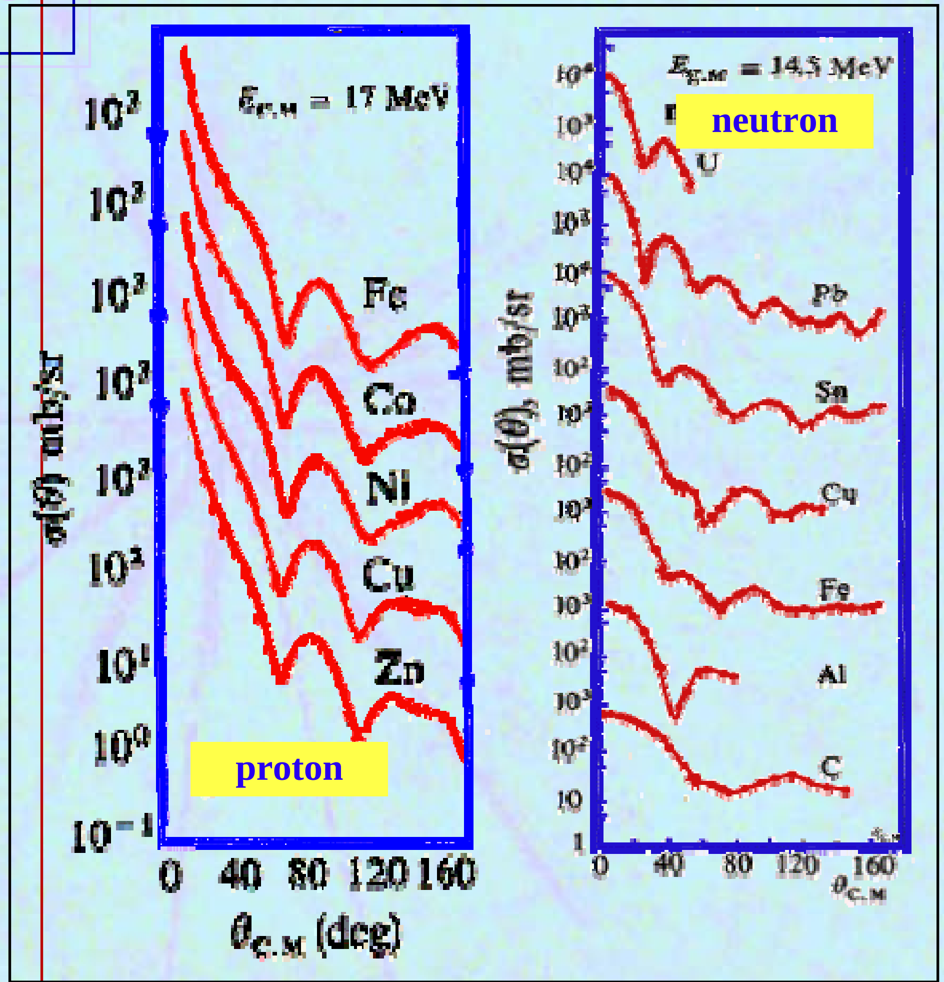
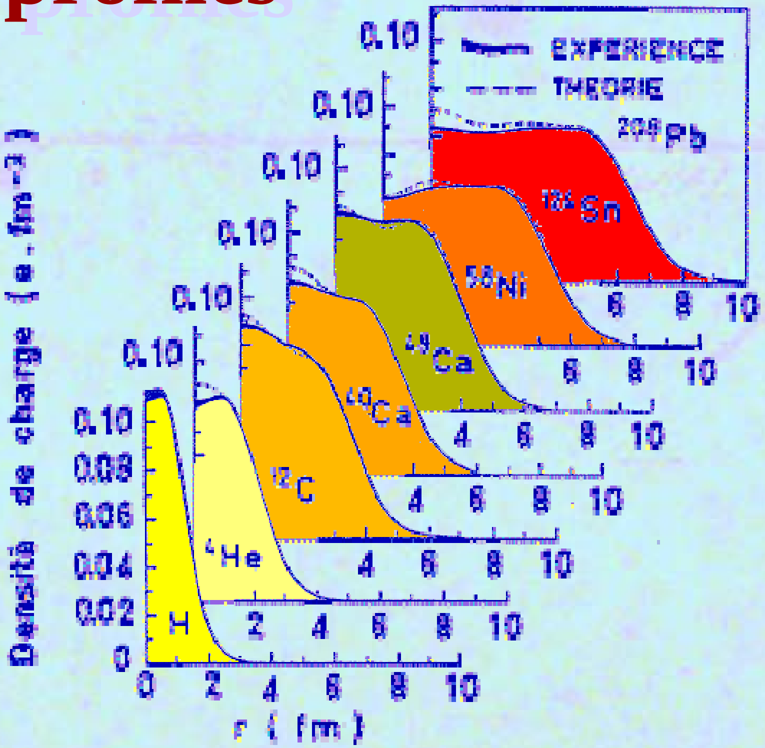


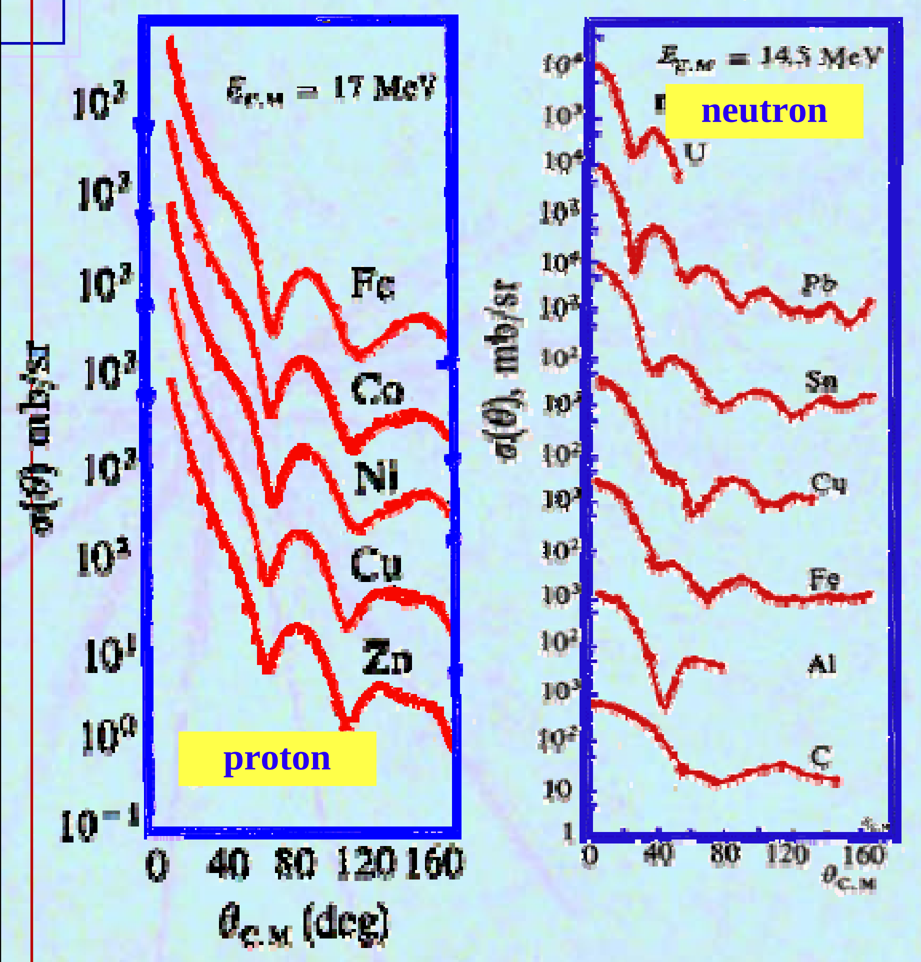


Modern measures

- Scattering of particles

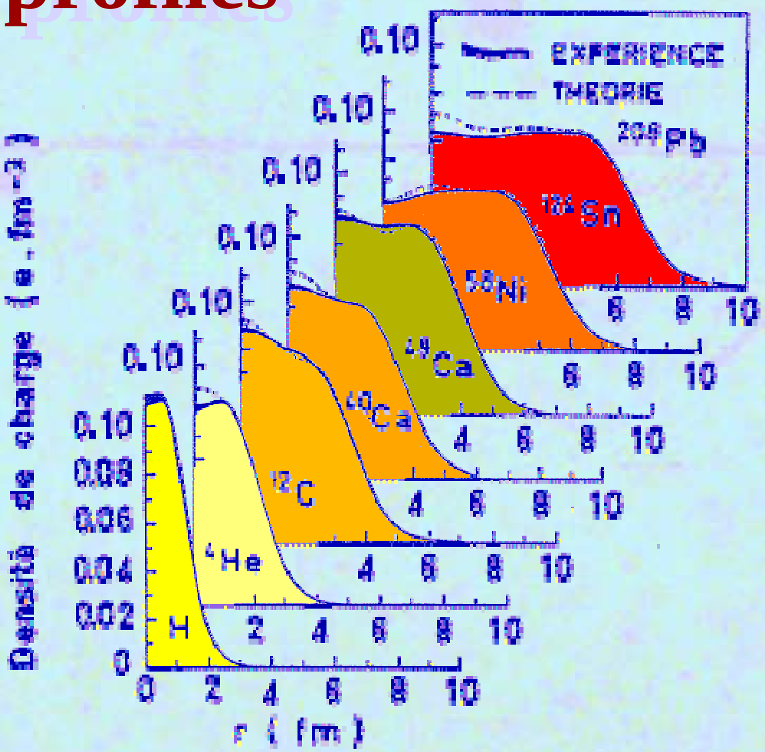
Nuclei density profiles

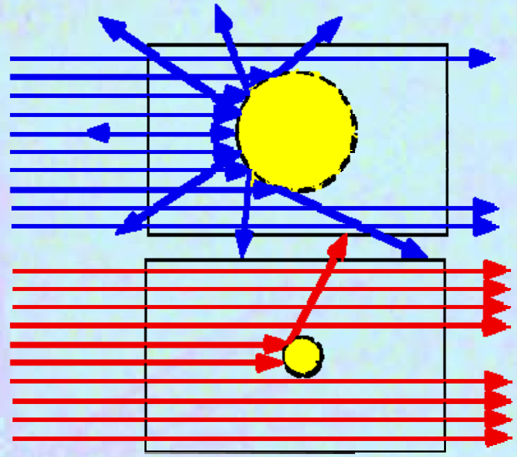




- **Modern measures**
  - **Scattering of particles**

- **Nuclei density profiles**

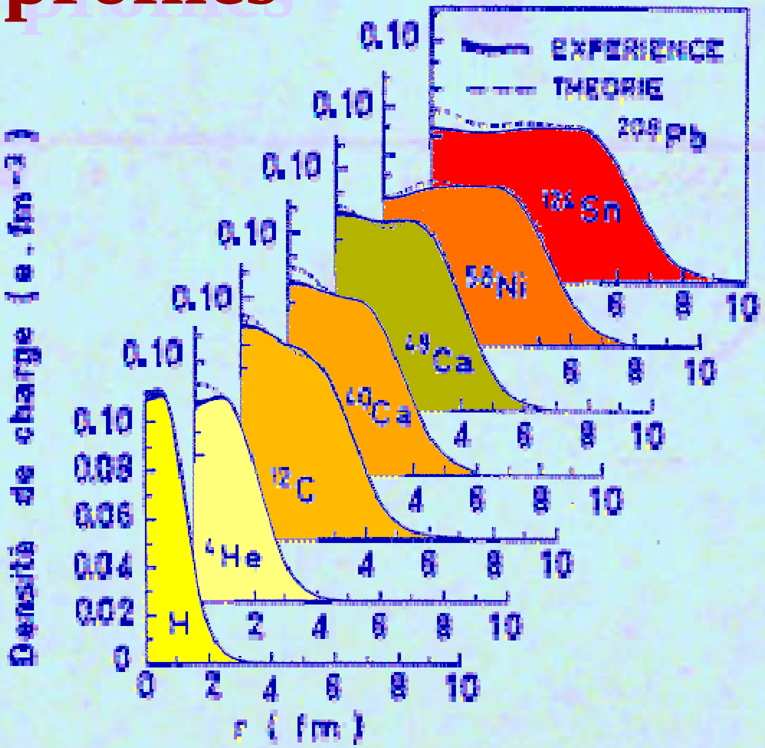


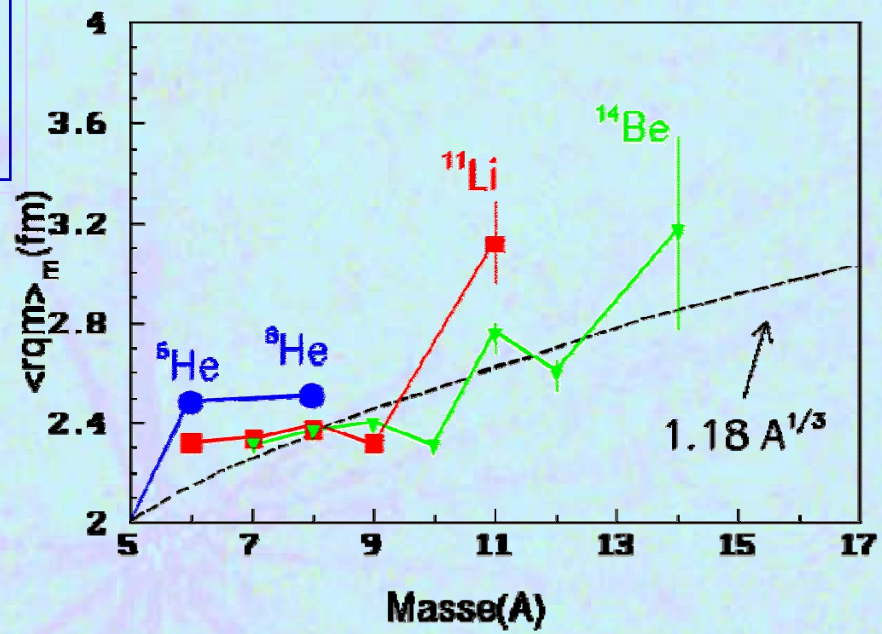


Rutherford experiment

- **Measure of reaction cross-section:** $\sigma = \pi < R^2 >$

- **Modern measures**
  - ☞ Scattering of particles
- **Nuclei density profiles**

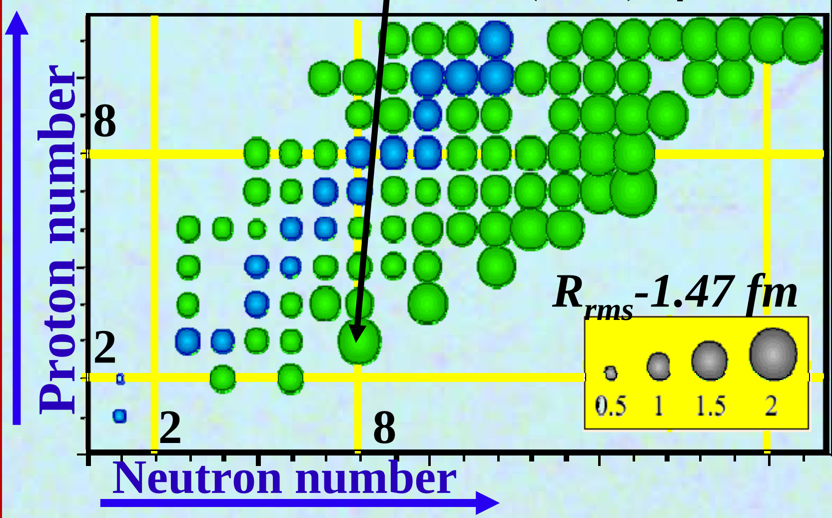


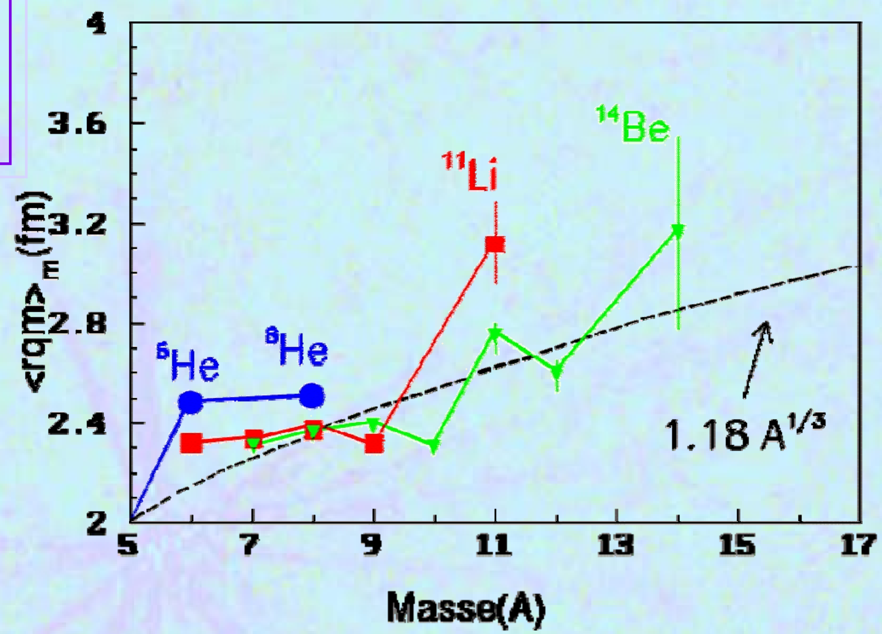


- **Measure of reaction cross-section:** $\sigma = \pi < R^2 >$
- **Drip line nuclei anomalously large**

Discovery of halo nuclei

^{11}Li



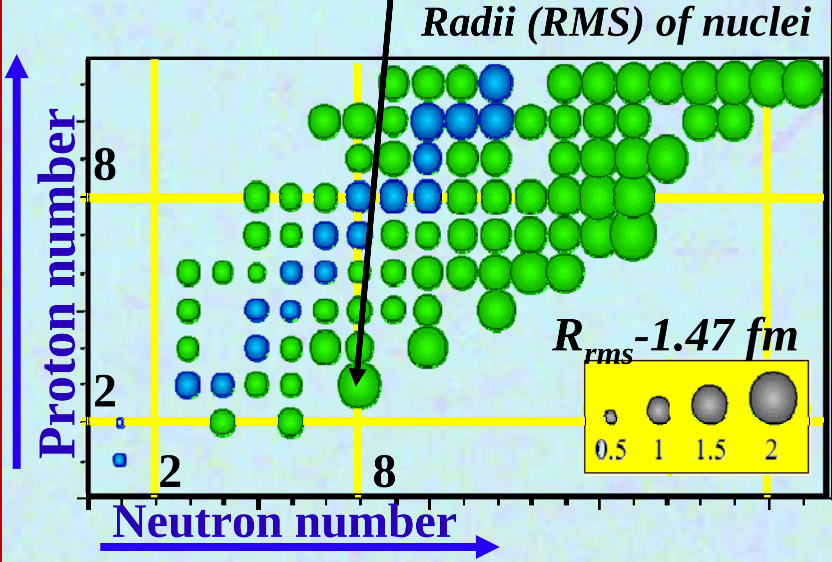


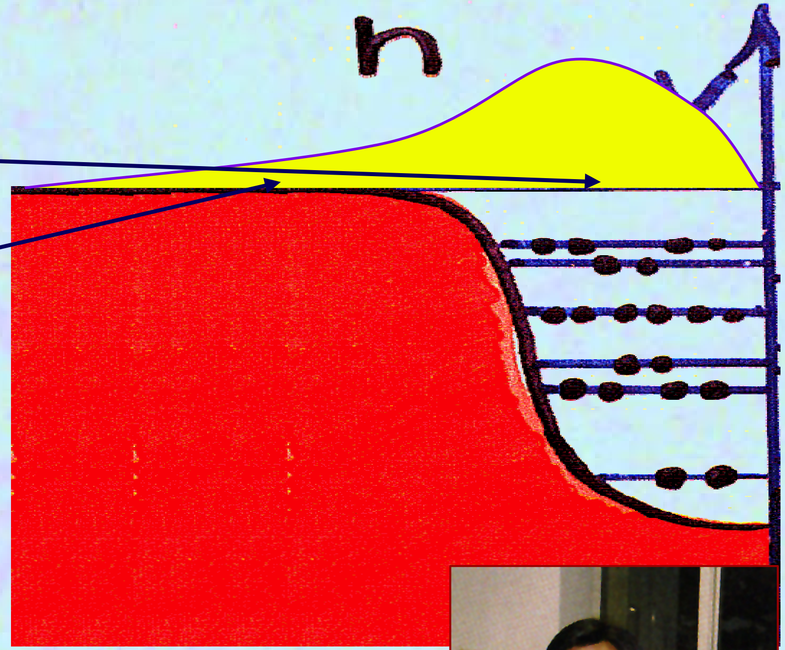
- **Measure of reaction cross-section:** $\sigma = \pi < R^2 >$
- **Drip line nuclei anomalously large**

Discovery of halo nuclei

- Weakly bound n
- Tunnel effect

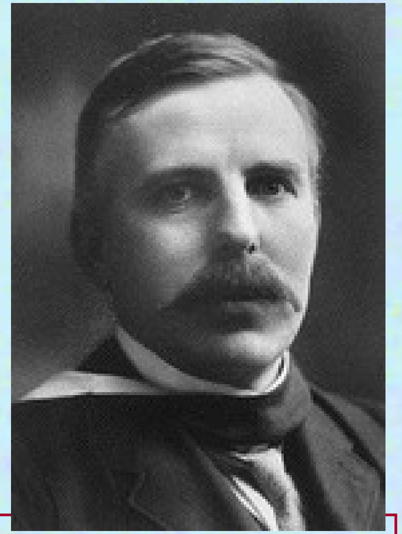
^{11}Li





- Halo nuclei

- II -
Exploring atom

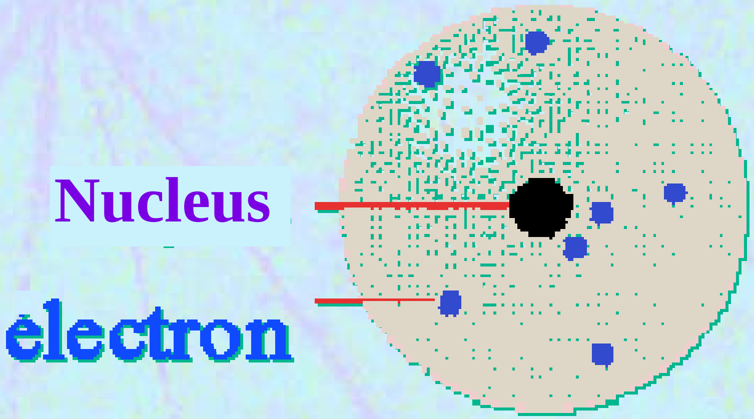


Rutherford

■ Atomic Models

Atoms are almost empty

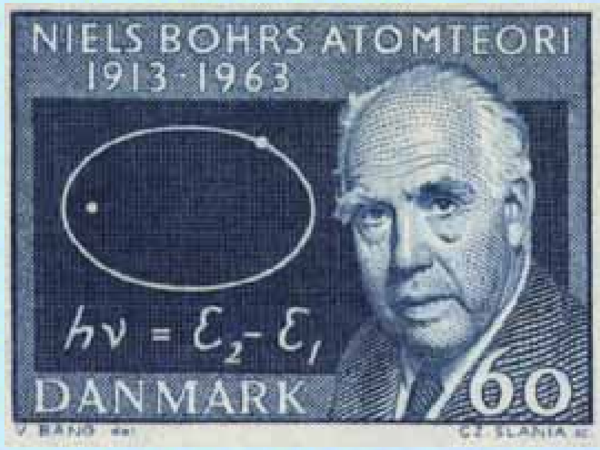
Except a hard scattering center:
The atomic nucleus



- II -

Exploring atom

Quantum object



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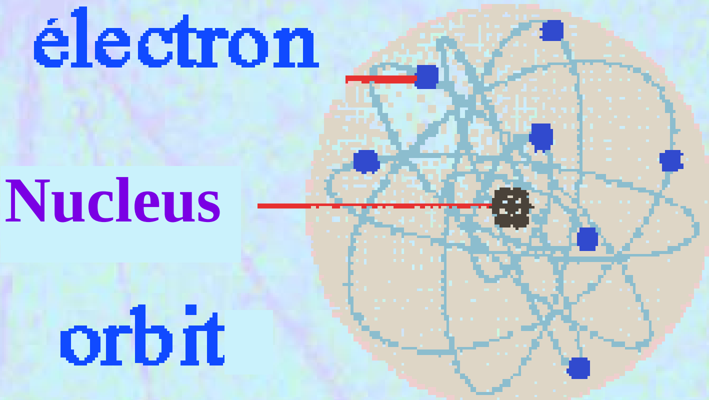

- II -

Exploring atom

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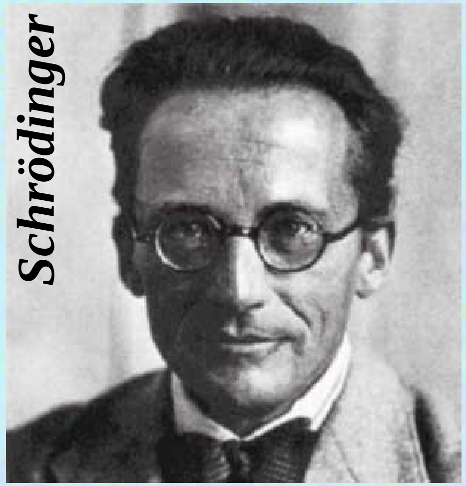

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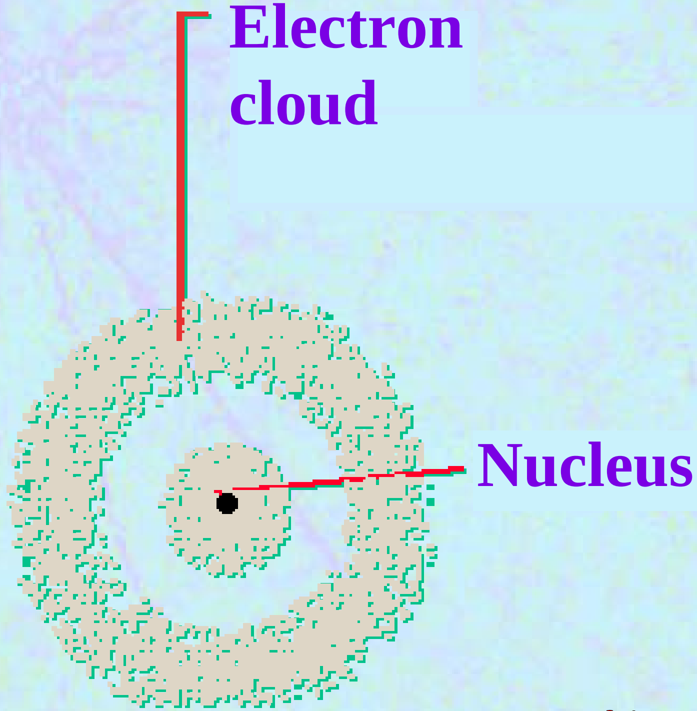
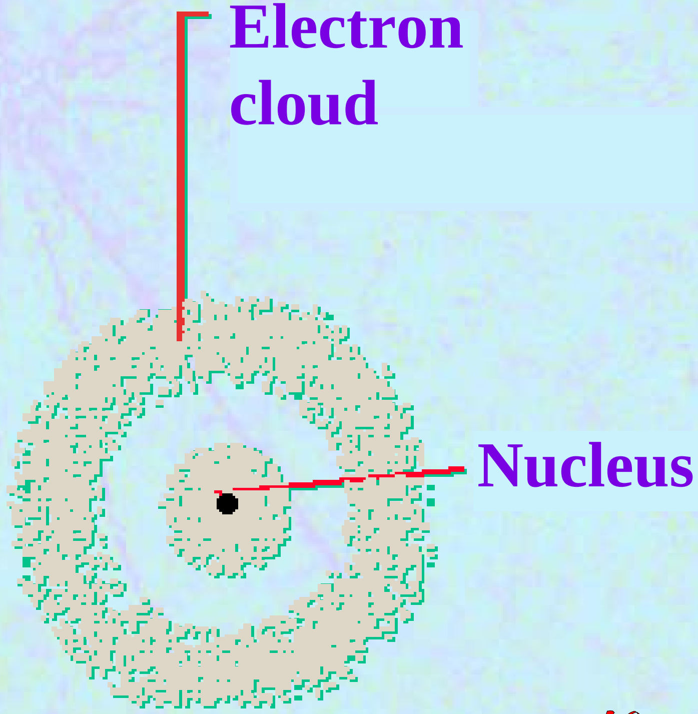


- II -
Exploring atom
Quantum object



- II -
Exploring atom
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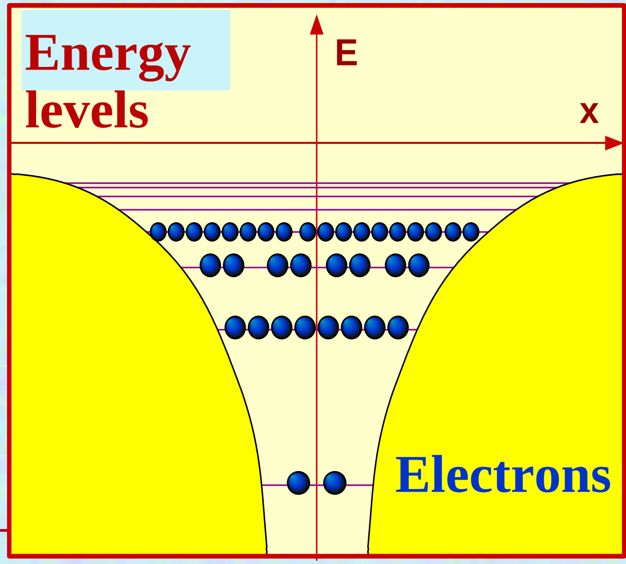
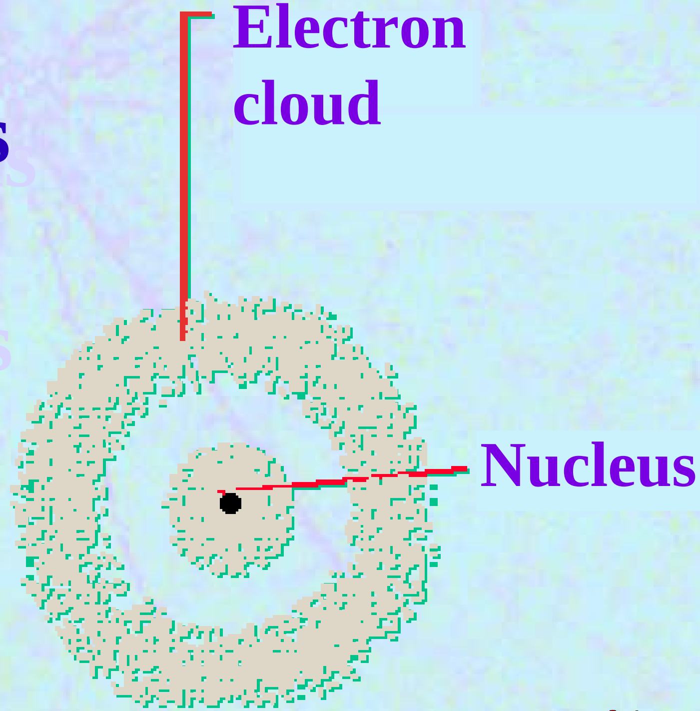
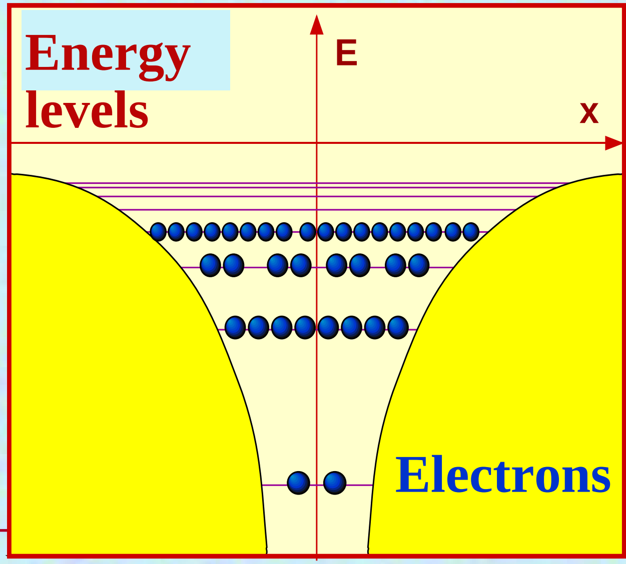


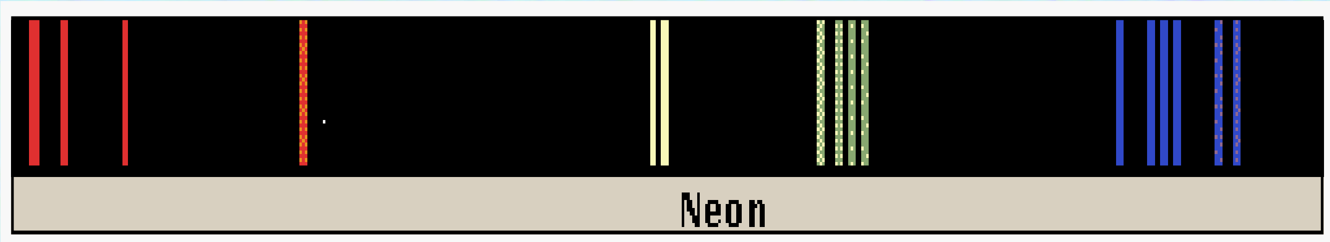
- Electrons on energy levels orbiting around a tiny heavy center: the nucleus

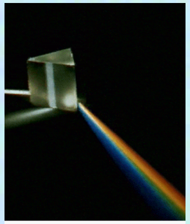


- II -
Exploring atom
Quantum object



- Electrons on energy levels orbiting around a tiny heavy center: the nucleus
- Quantized transitions



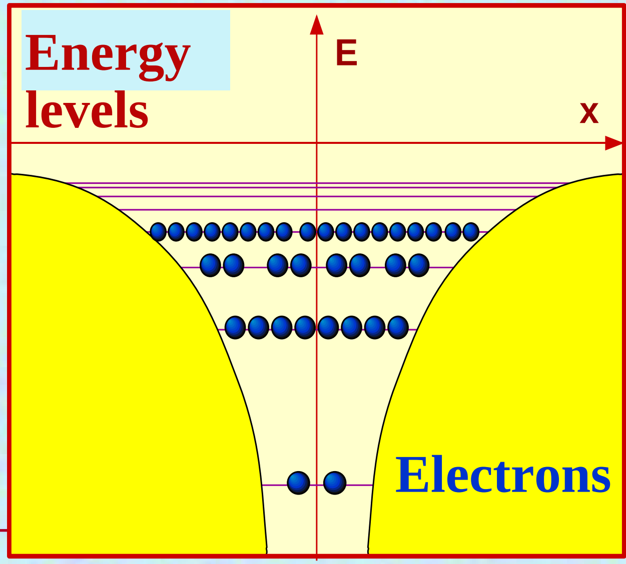


Decomposition of the light

- II -

Exploring atom

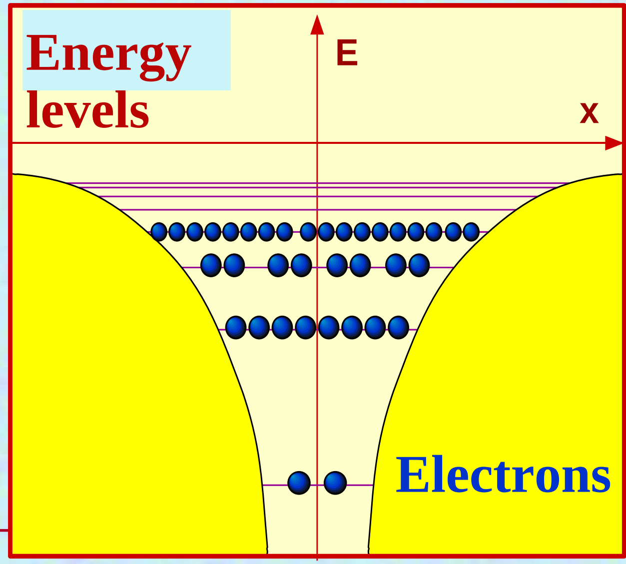
Quantum object



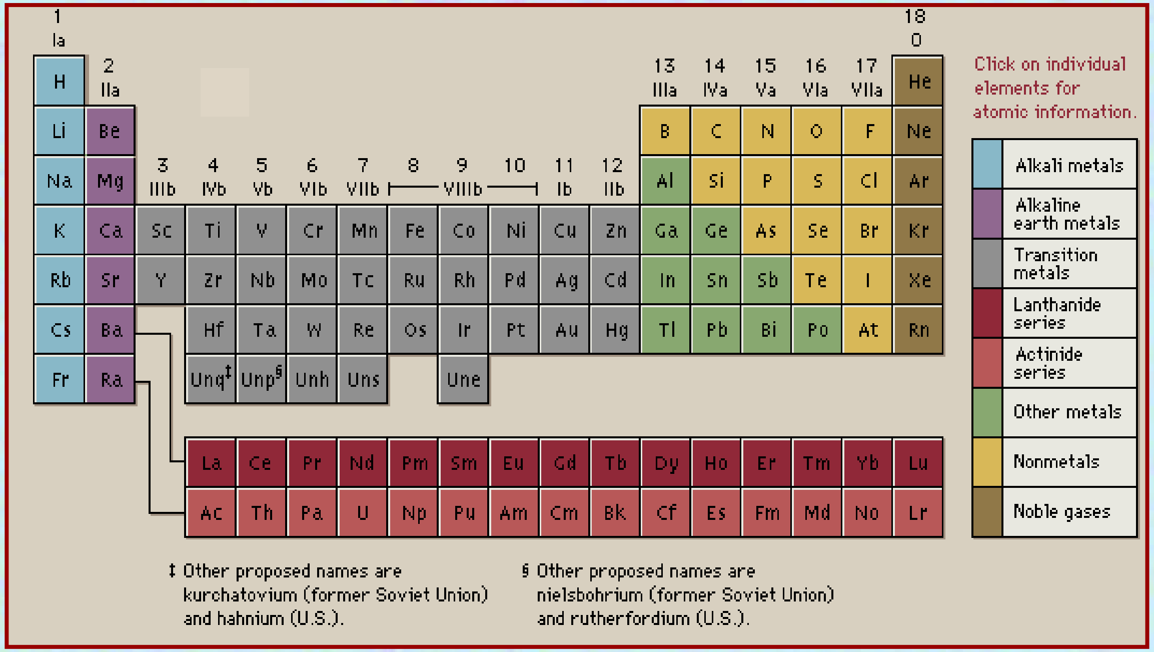
- II -

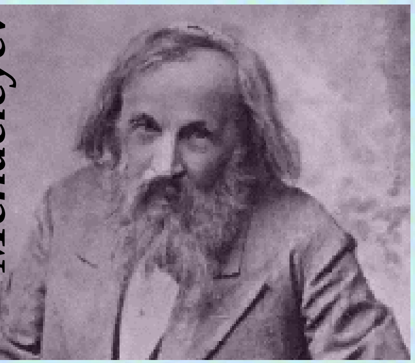
Exploring atom

Quantum object



- **Periodic properties**



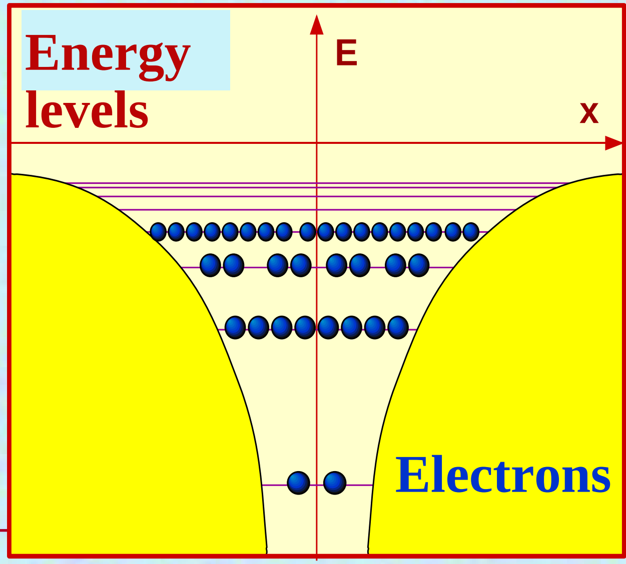


Mendeleyev

- II -

Exploring atom

Quantum object

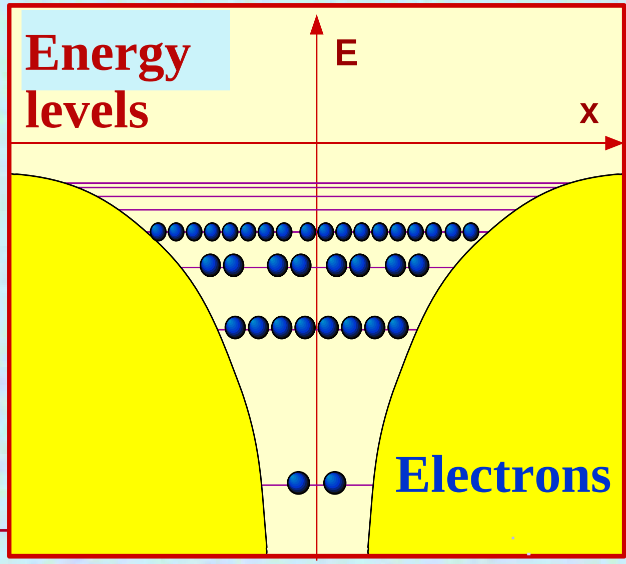


- Periodic properties

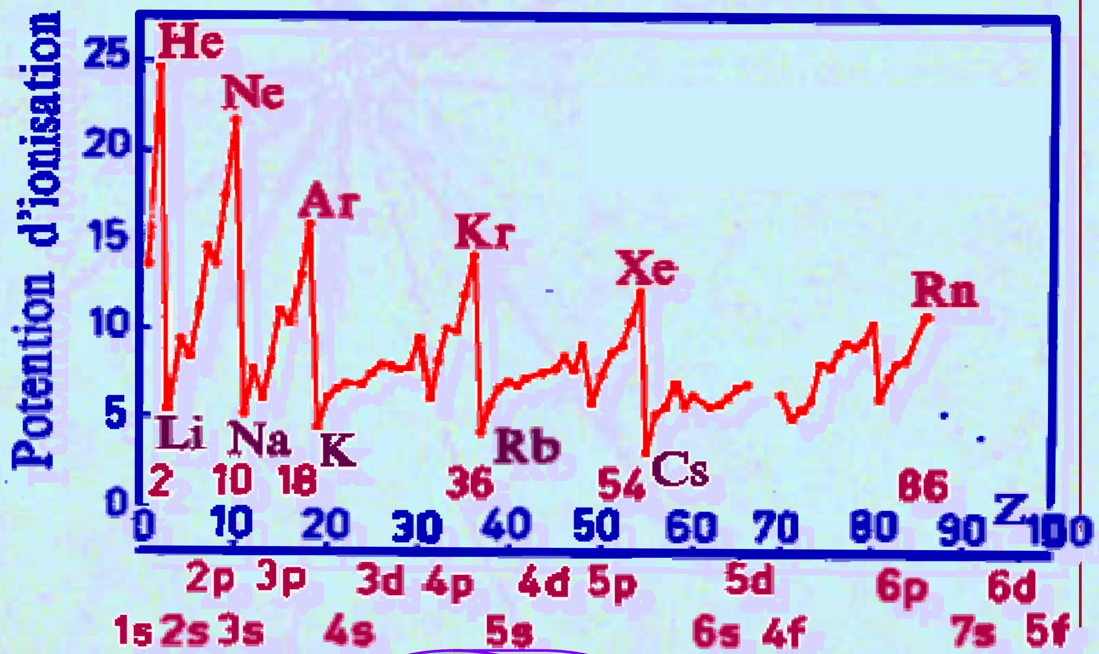
- II -

Exploring atom

Quantum object



- Periodic properties
- Magic numbers



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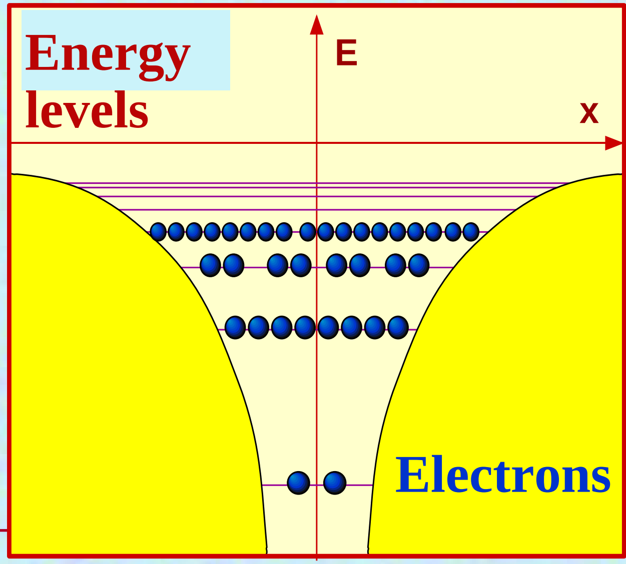
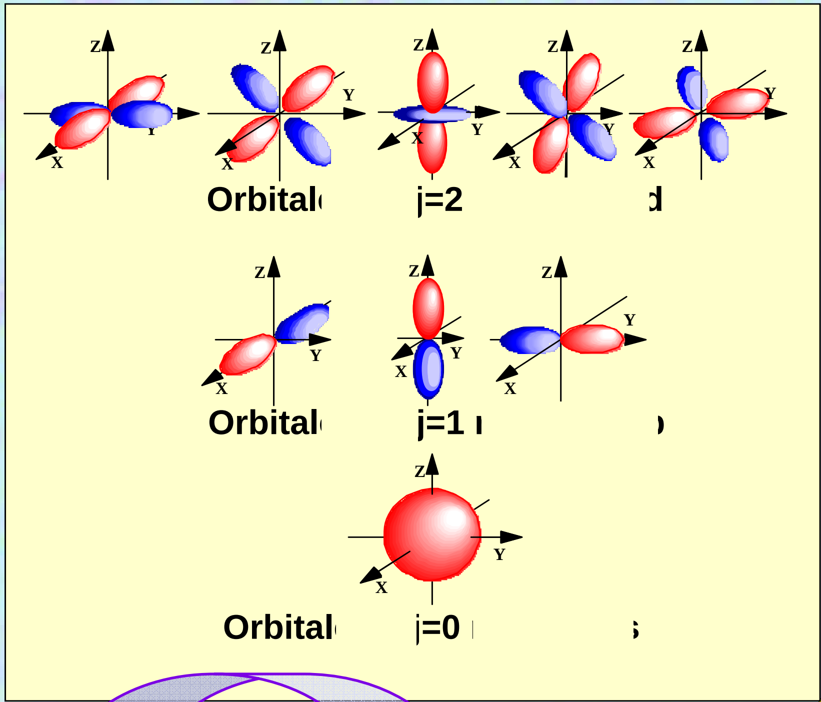
Quantum object



- Orbitals and shapes
- Symmetry, <u>quantum numbers</u> and <u>degeneracy</u>

$$[\hat{H},\hat{Q}]=0$$

$$\hat{Q}|\varphi\rangle = q|\varphi\rangle;\ \hat{H}|\varphi\rangle = E_q|\varphi\rangle$$



Definition of symmetry

- A hamiltonian H has symmetry G (is invariant under G) if

$$\forall g \in G: \quad [H, g] = 0$$

- The transformations g are assumed to form a Lie algebra.

Consequences of symmetry

- Degeneracy:

$$H|\Gamma\rangle = E|\Gamma\rangle \quad \Rightarrow \quad Hg|\Gamma\rangle = Eg|\Gamma\rangle$$

- State labelling:

$$H|\Gamma\gamma\rangle = E(\Gamma)|\Gamma\gamma\rangle$$

- Action of transformations g:

$$g|\Gamma\gamma\rangle = \sum_{\gamma'} a^{\Gamma}_{\gamma\gamma'}(g)|\Gamma\gamma'\rangle$$

- The a-matrices constitute a representation of the elements g of G.

Definition of a Lie algebra

- A Lie group contains an infinite number of elements that depend on a set of continuous variables.
- The corresponding Lie algebra is obtained from (a finite number of) infinitesimal operators, called generators.
- An algebraic structure over the generators is defined through commutation relations in terms of structure constants:

$$[g_i, g_j] \equiv g_i \circ g_j - g_j \circ g_i = \sum_k c^k_{ij} g_k$$

- Structure constants are antisymmetric in i and j.
- Generators satisfy the Jacobi identity:

$$[g_i, [g_j, g_k]] + [g_j, [g_k, g_i]] + [g_k, [g_i, g_j]] = 0$$

Definition of symmetry

Definition of a Lie algebra

Transformation $|\varphi\rangle \rightarrow \hat{U}(\theta)|\varphi\rangle$ $\theta\vec{u}$

Operators $\hat{U}(\delta\theta) = 1 + i\,\delta\theta\hat{Q}$ $\hat{\vec{L}} \Rightarrow \hat{L}^2$

Eigenstates $\hat{Q}|\varphi_q\rangle = q|\varphi_q\rangle$ $\hat{L}_Z|l,m\rangle = m|l,m\rangle$

Symmetry $[\hat{H},\hat{Q}] = 0$ $\hat{L}^2|l,m\rangle = l(l+1)|l,m\rangle$

$\hat{H}|\varphi_q\rangle = E_q|\varphi_q\rangle$ $H|l,m\rangle = E_l|l,m\rangle$

Degeneracy $E_q = E_{q'}$ if $\hat{U}|\varphi_q\rangle = |\varphi_{q'}\rangle$

Transitions $\langle\varphi_{q'}|\hat{Q}'|\varphi_q\rangle$ $\hat{L}_{x/y}|l,m\rangle \Rightarrow |l,m\pm 1\rangle$

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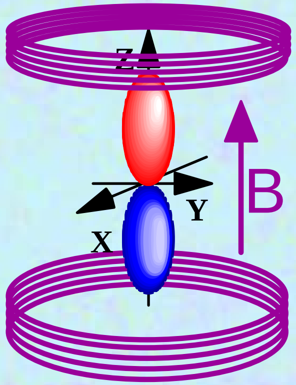
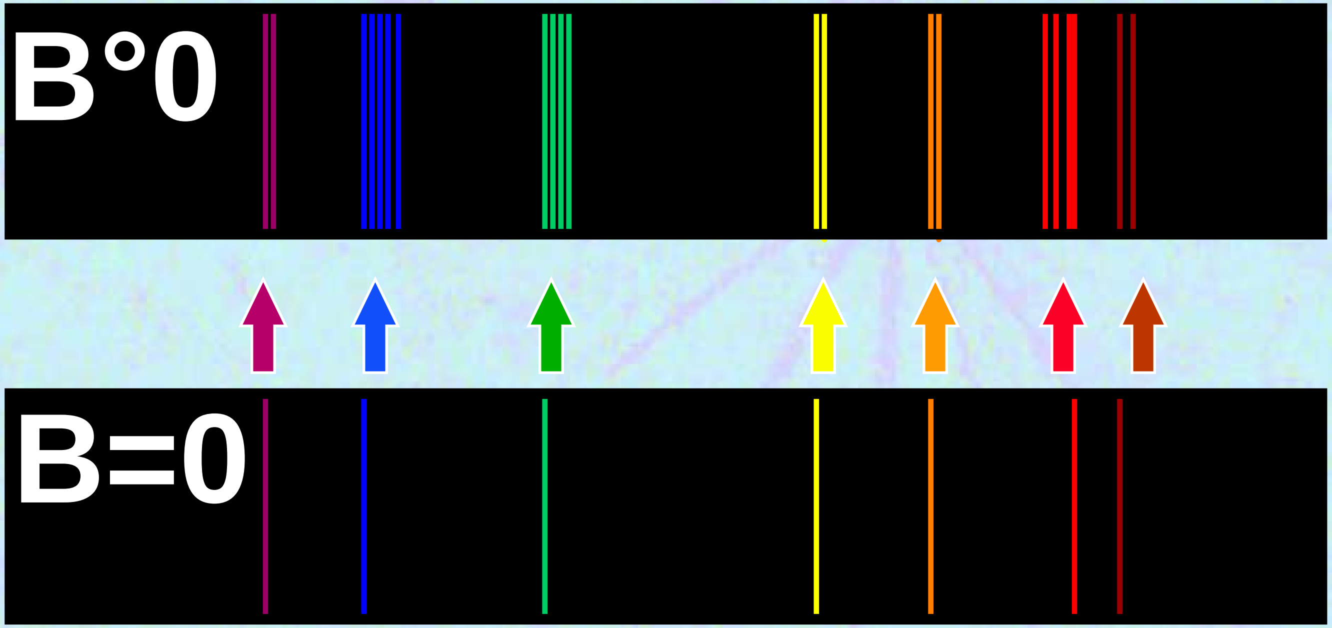
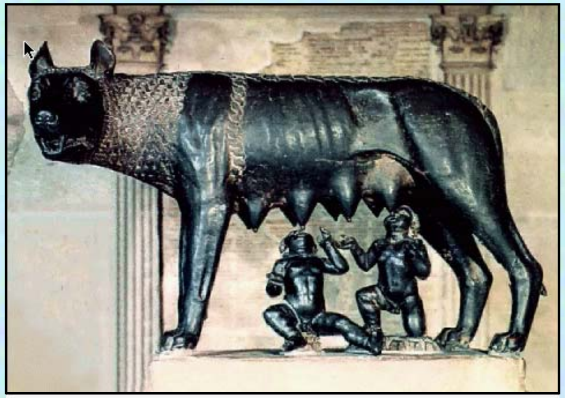
Symmetry breaking

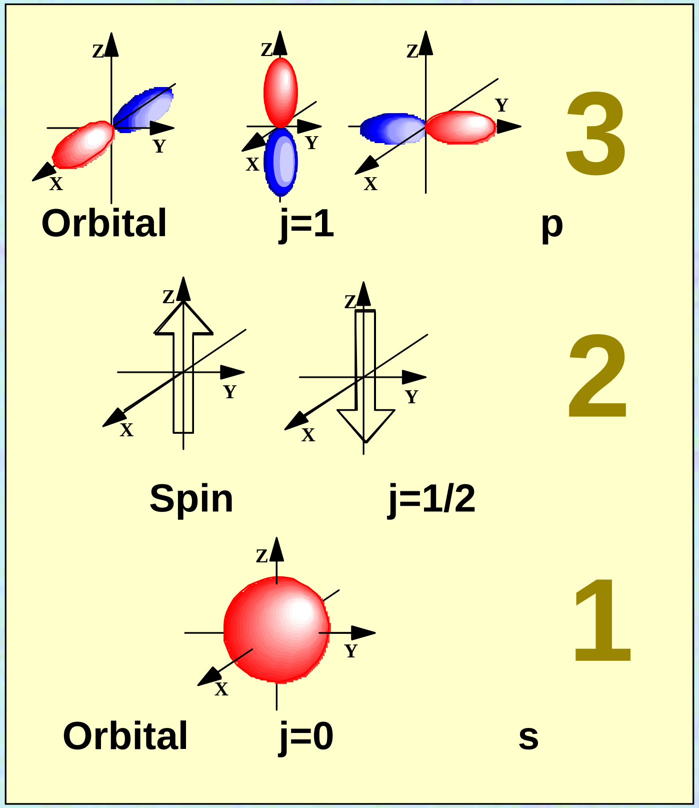


- **Breaking degeneracy**

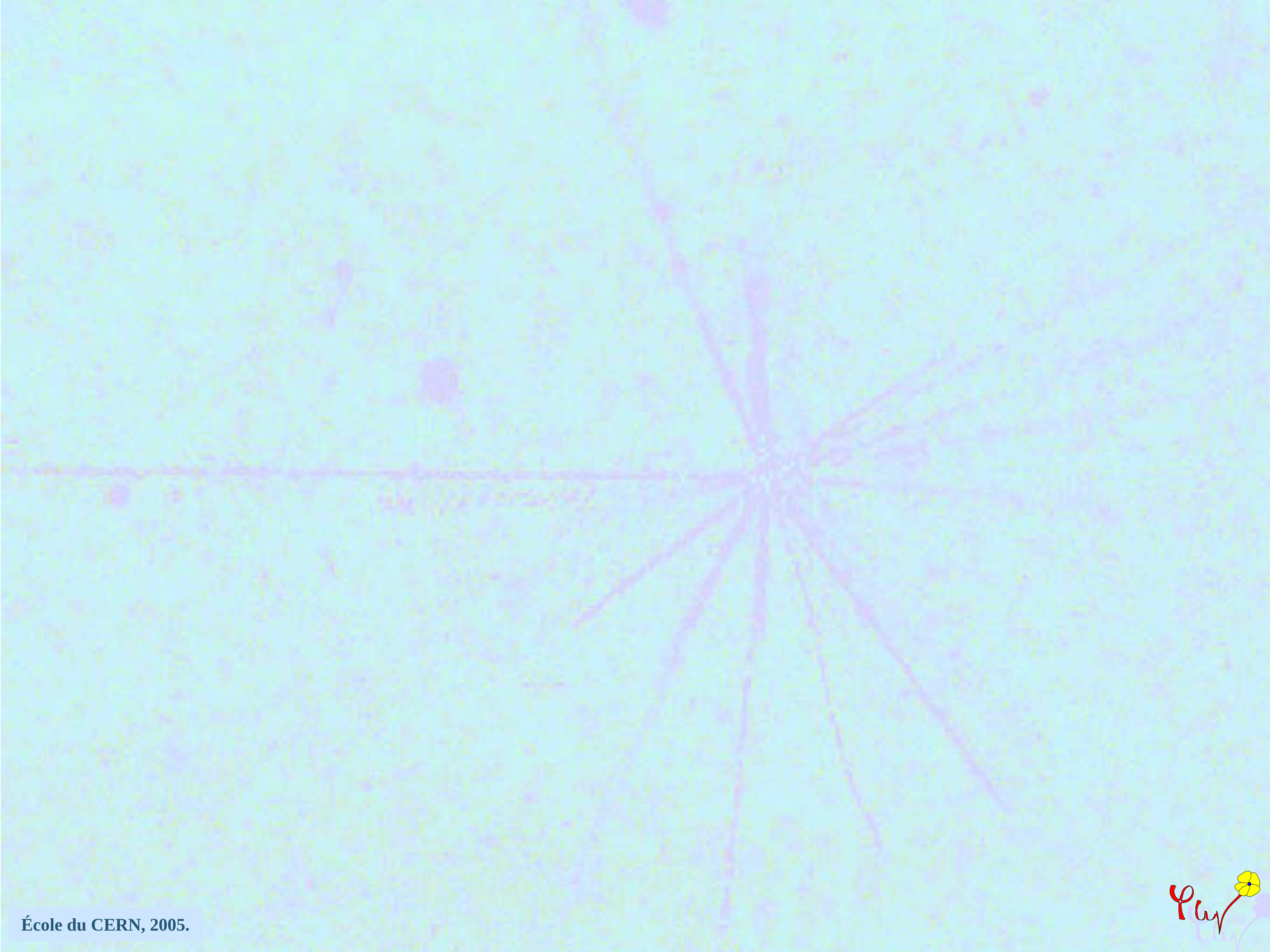


Spin 1/2
Internal symmetry



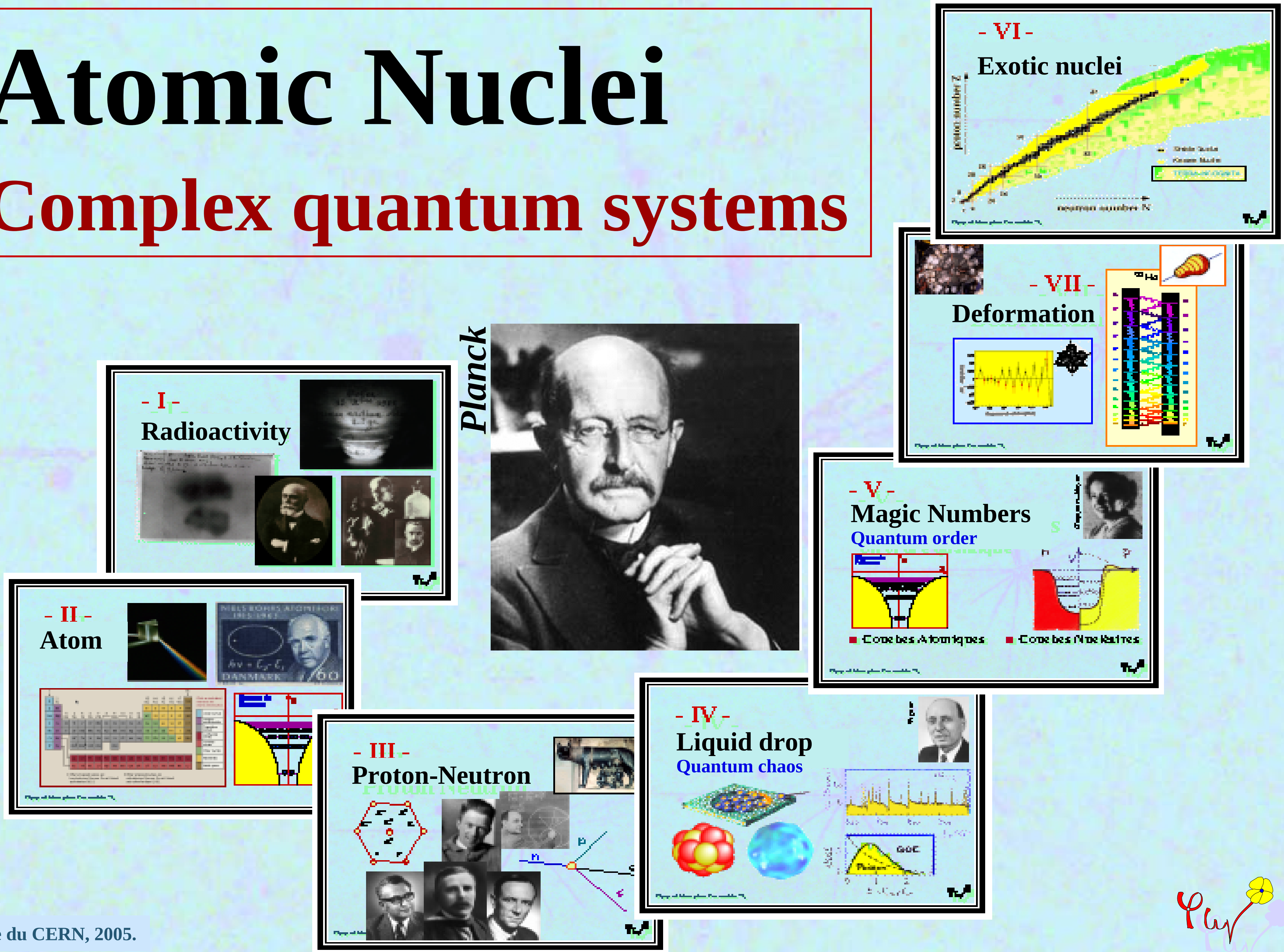


- **"Those doublets and their anomalous Zeeman effects, are manifestations of an intrinsic electron ambivalence** (Zweideutigkeit)**"**
  - **Pauli 1925**
- **Zweideutigkeit => spin**

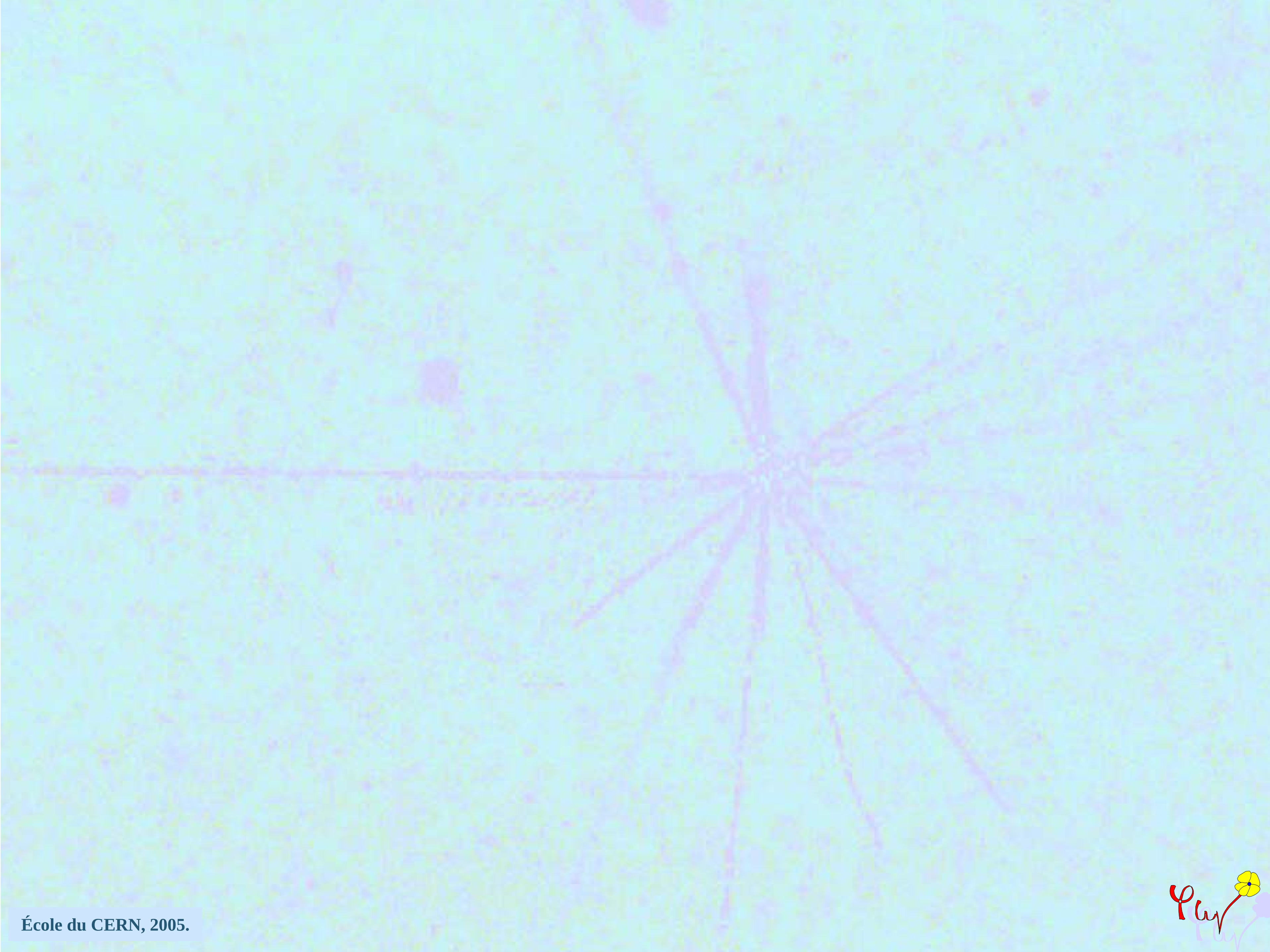


Atomic Nuclei

Complex quantum systems



École du CERN, 2005.



- V -

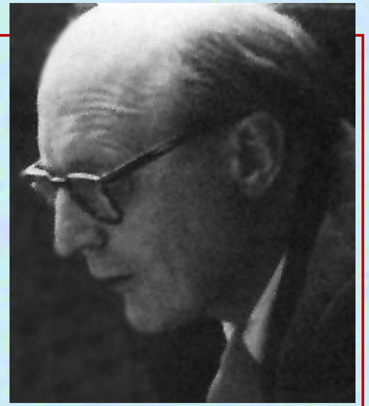
Magic Numbers

Quantum order

- V -

Magic Numbers

Goeppert-Mayer

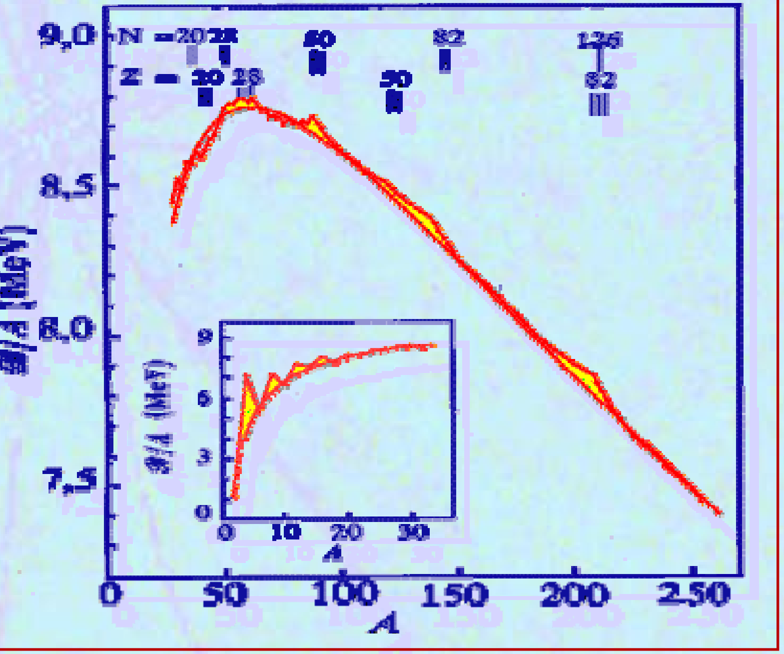


Jensen

- **Striking regularities**

- V -
Magic Numbers

Goeppert-Mayer



- Striking regularities

- V -

Magic Numbers

Goeppert-Mayer

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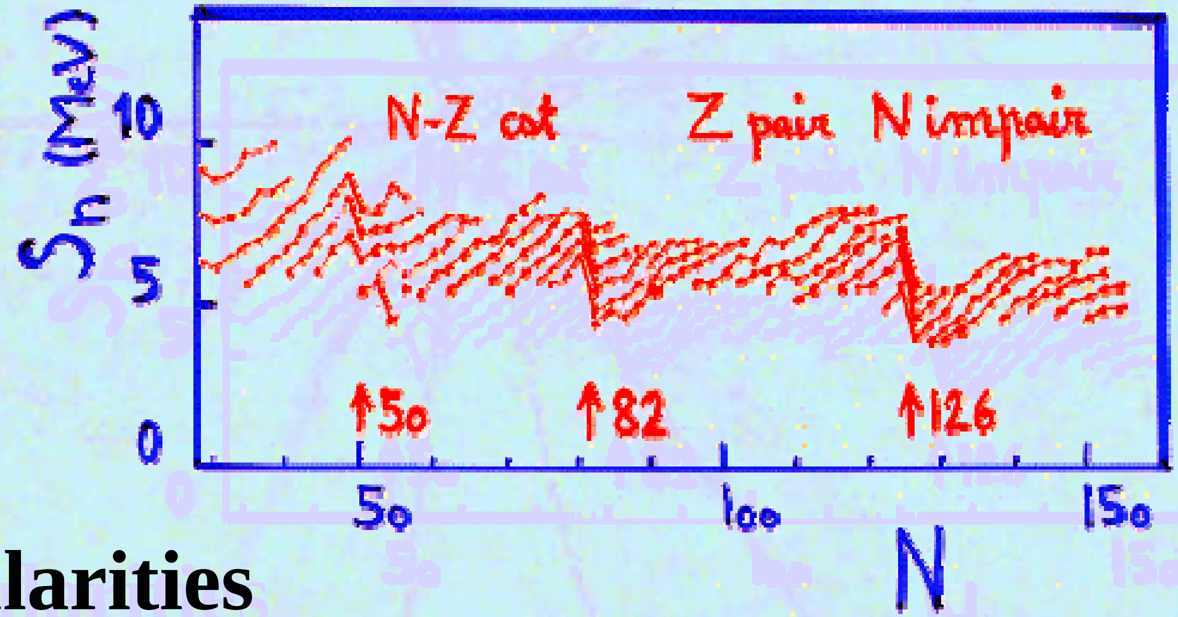
Magic Numbers



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- V -
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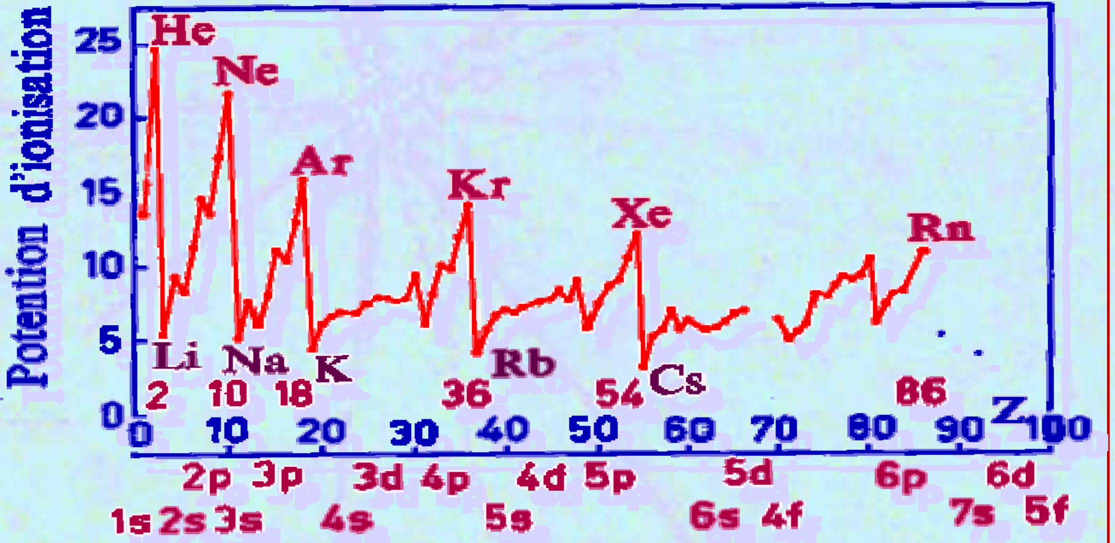
Goeppert-Mayer



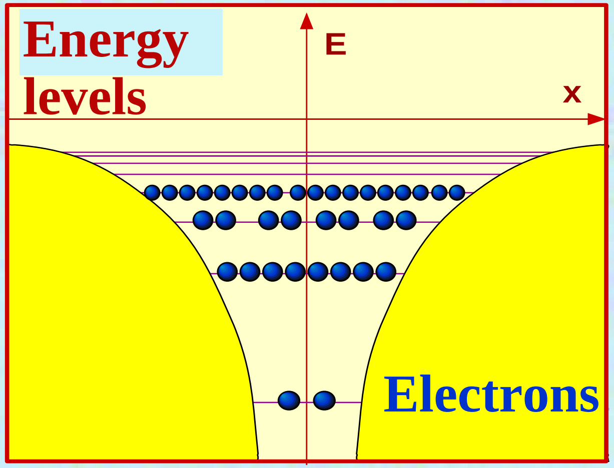
- Cf Atomic shells

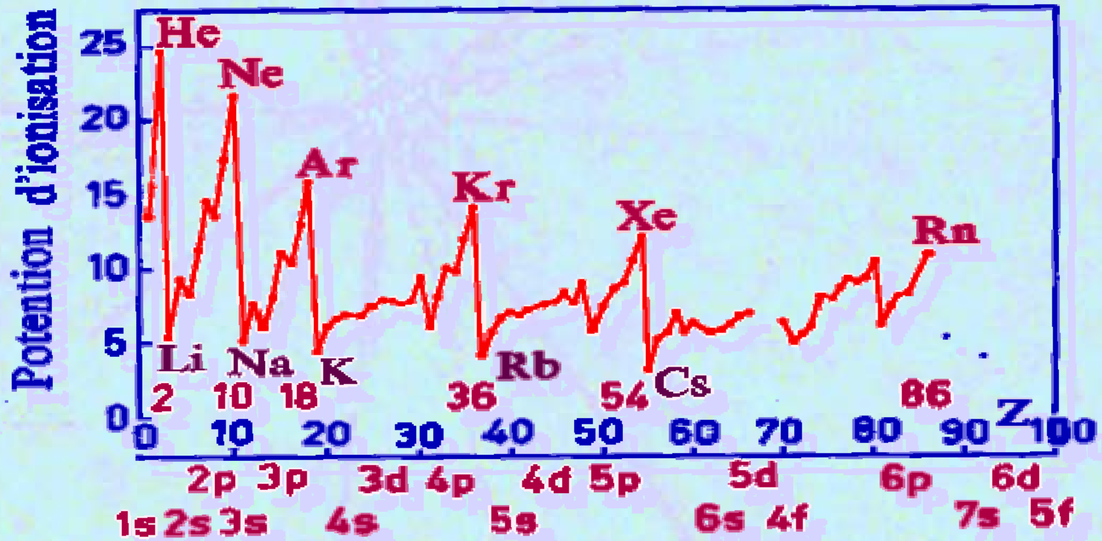
- V -

Magic Numbers

Quantum order

Goeppert-Mayer



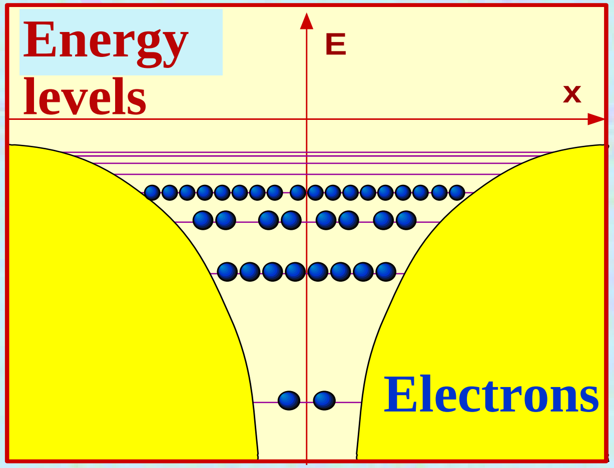


- Atomic shells

- V -

Magic Numbers

Quantum order



- Atomic shells

- V -

Magic Numbers

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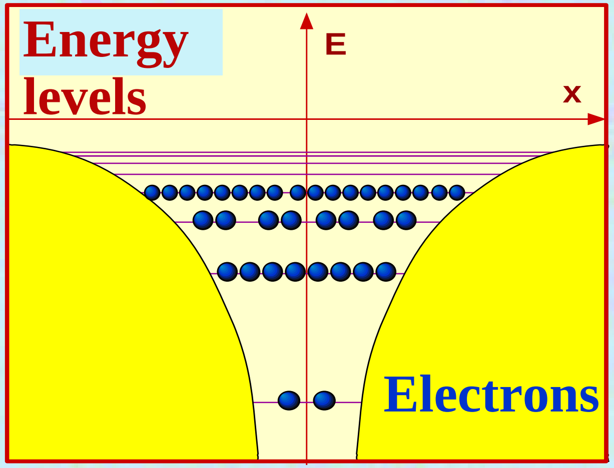
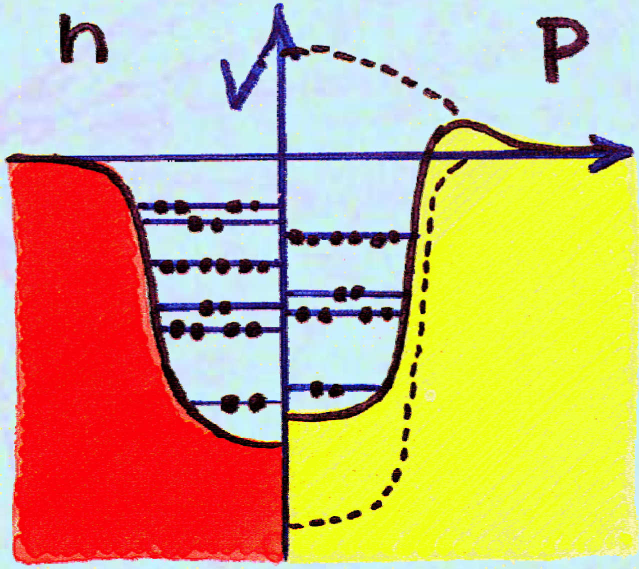
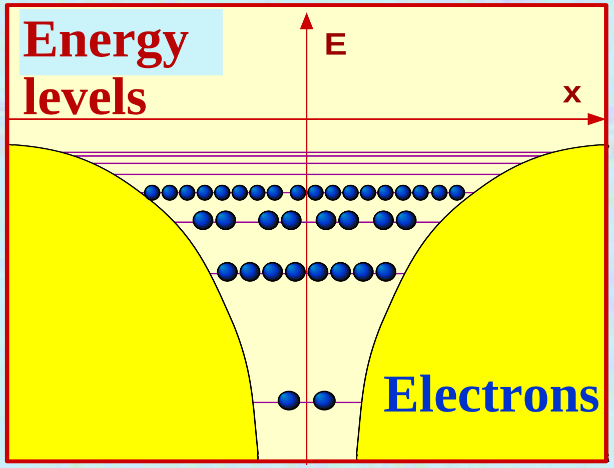


- Atomic shells

Goeppert-Mayer



- Nuclear shells



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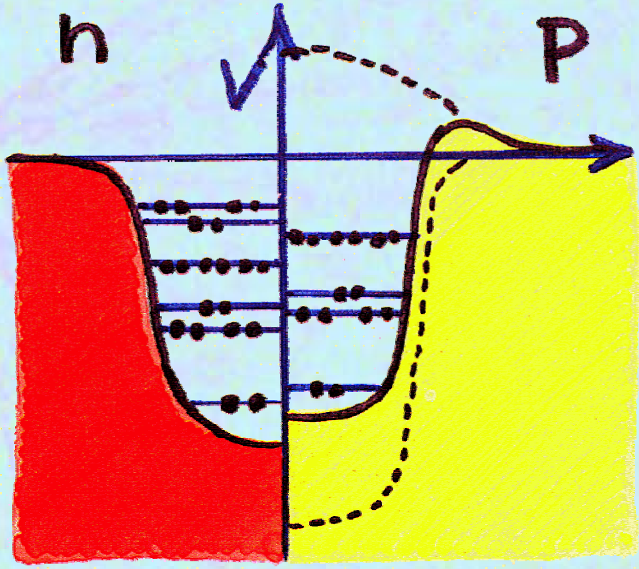

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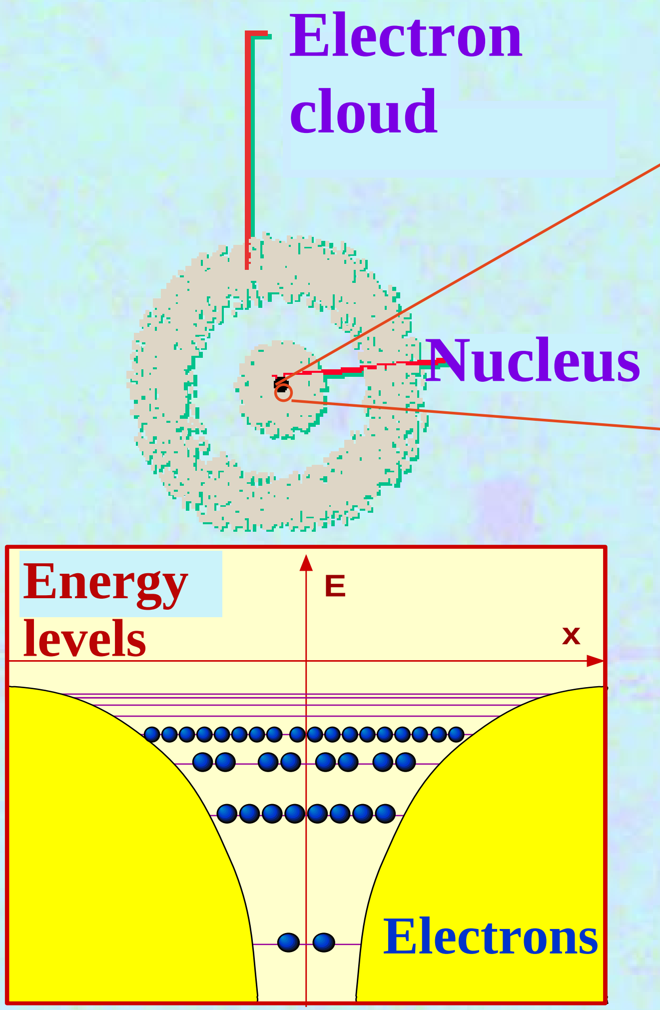

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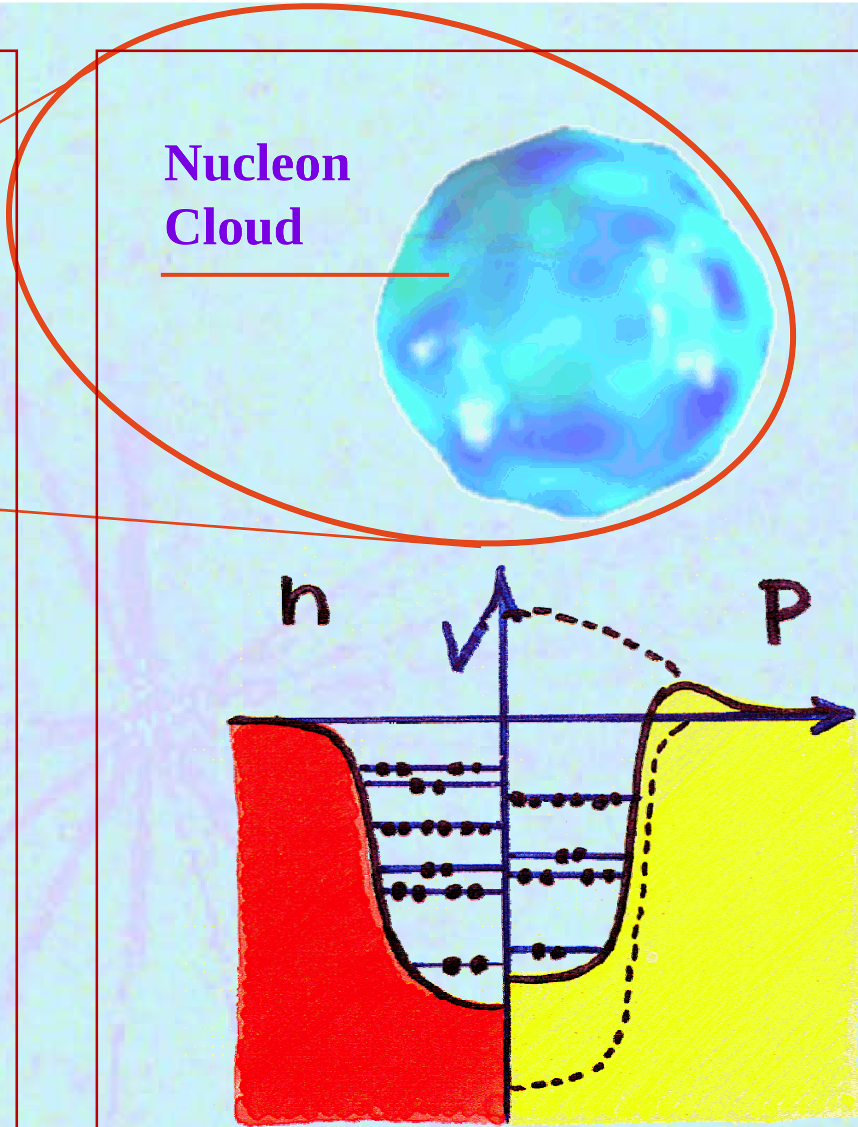

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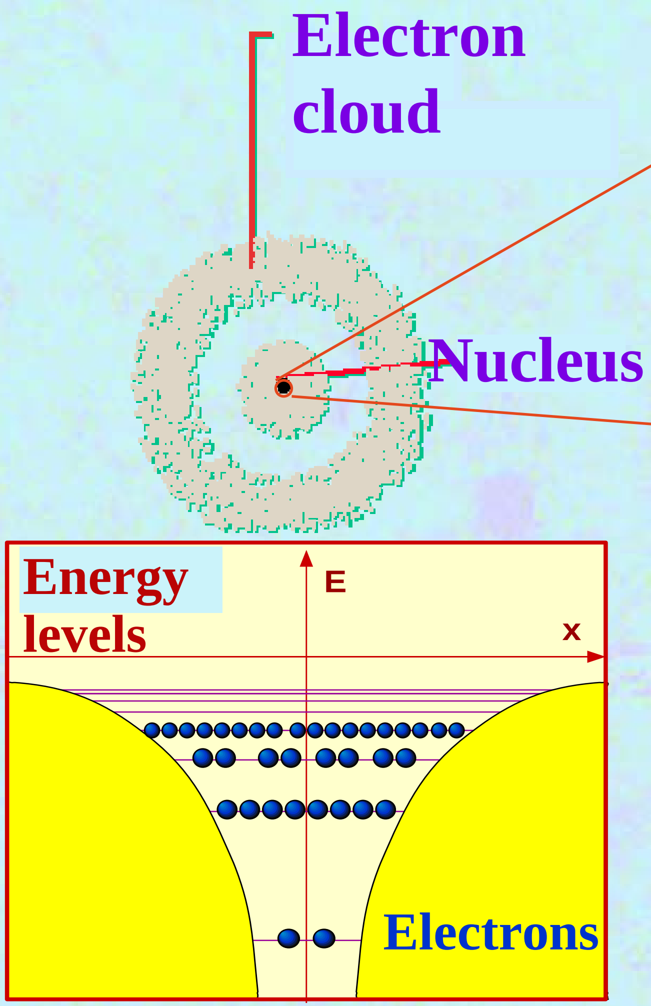
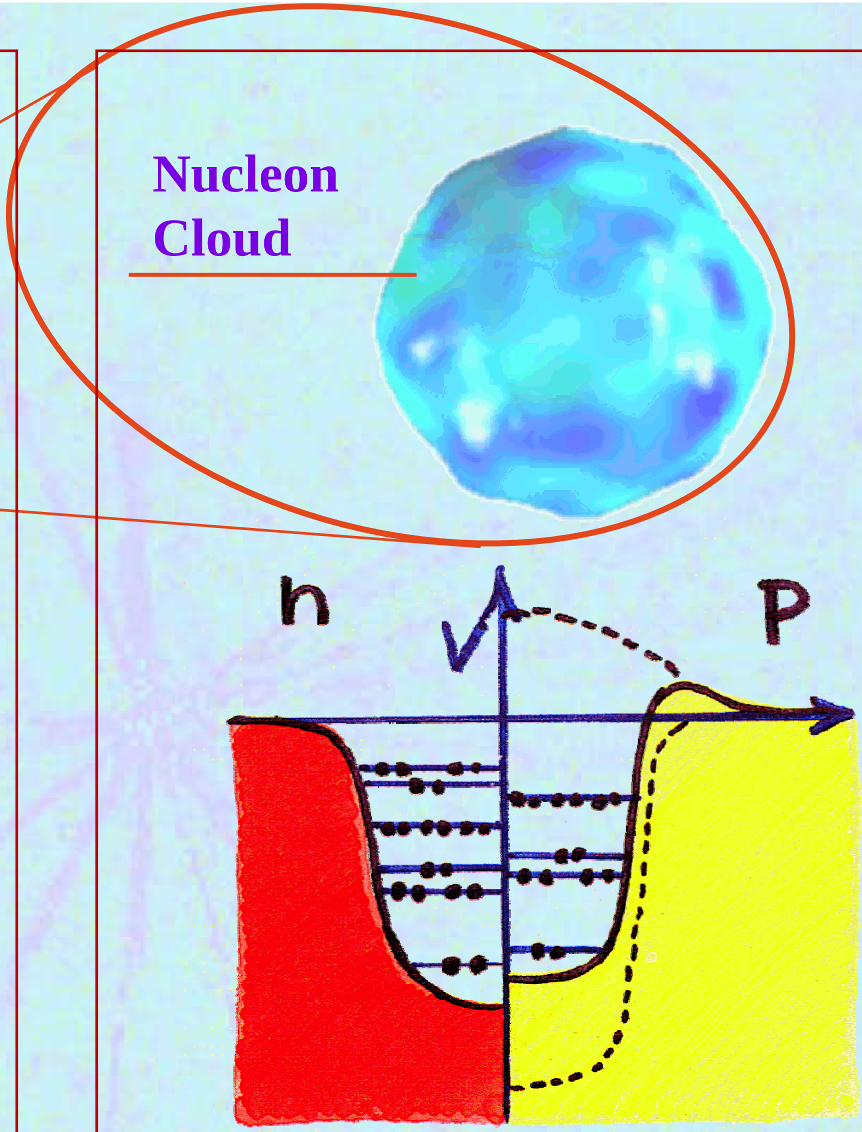
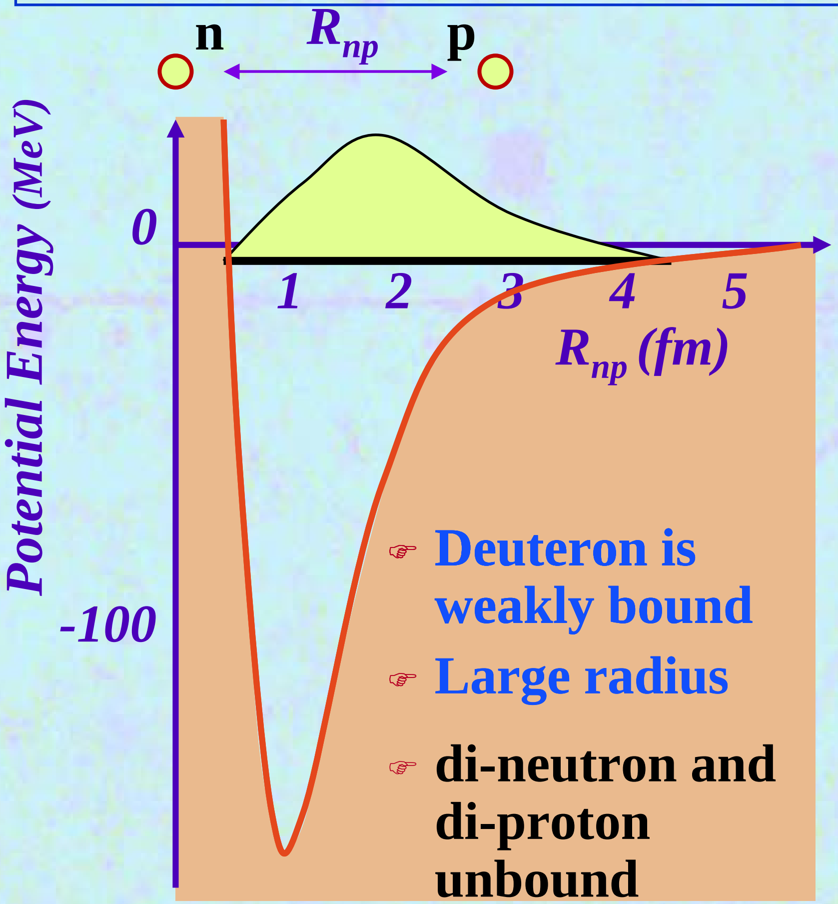




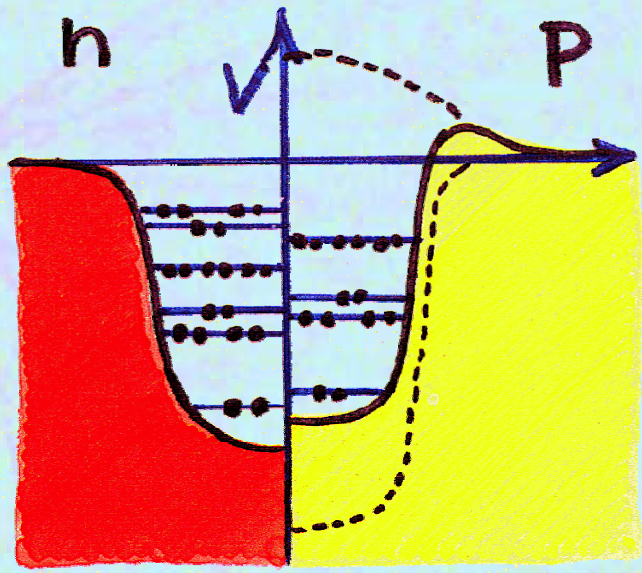
- Electrons organized by the atomic nucleus

- Nucleons are self-organized in nuclei

- To understand, let us look at the nucleon-nucleon interaction:



- Deuteron is weakly bound
- Large radius
- di-neutron and di-proton unbound

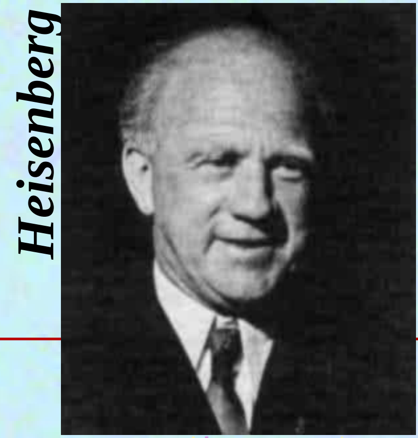


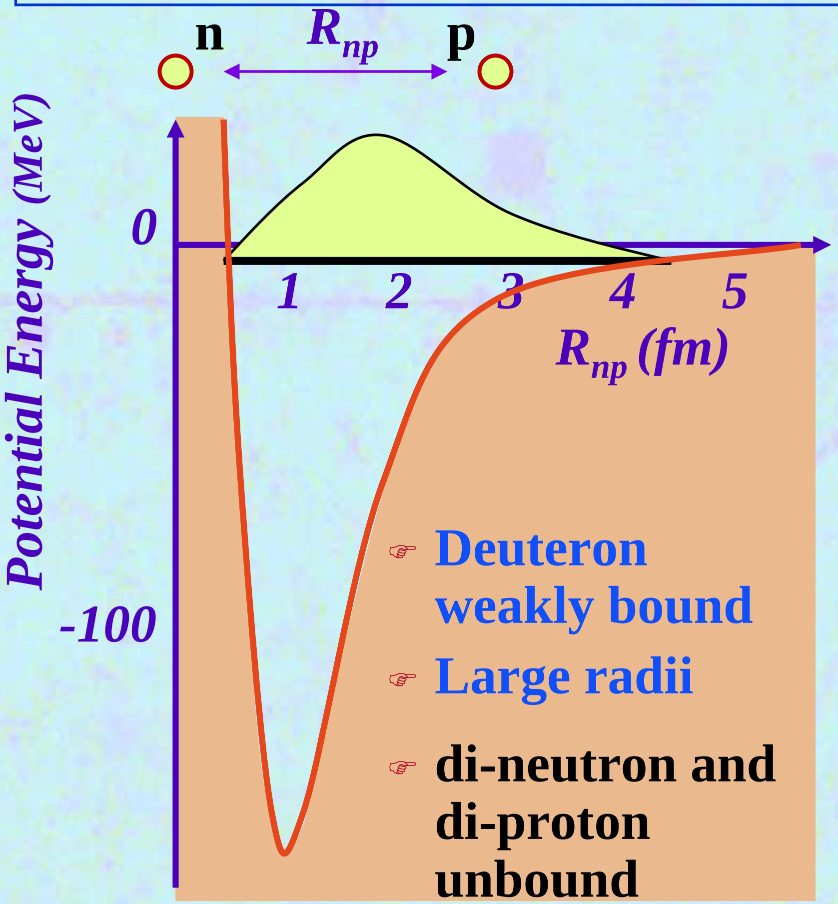
- Nucleons are self-organized in nuclei

17

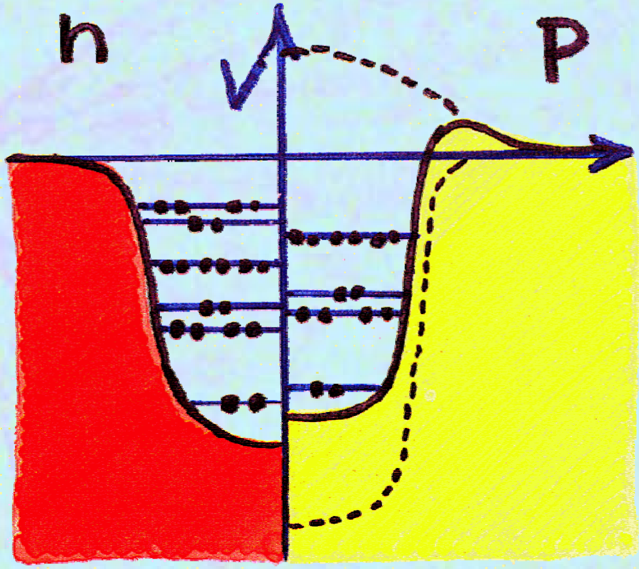
- **Uncertainty principle:** $\Delta x \Delta p \geq \hbar$

imposes delocalized nucleons occupying all the nucleus





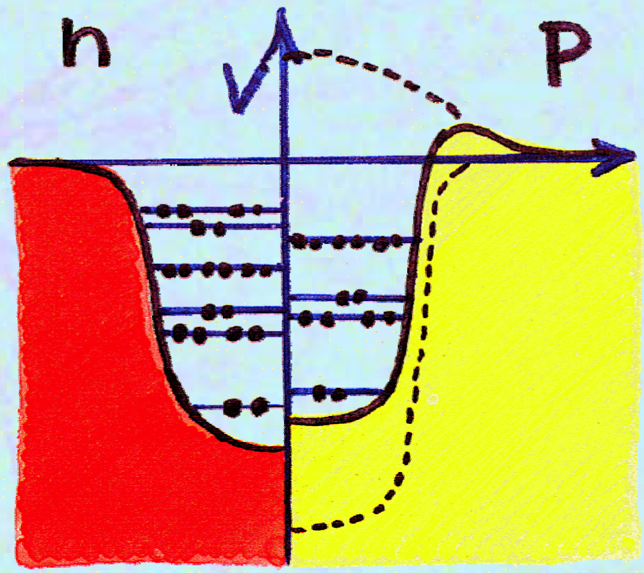
- **Deuteron weakly bound**
- **Large radii**
- **di-neutron and di-proton unbound**



- **Nucleons are self-organized in nuclei**

- **Measuring waves**
  - ☞ **Scattering of particles**

- **Many confirmations**



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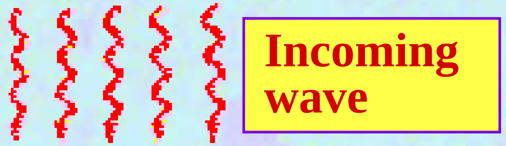
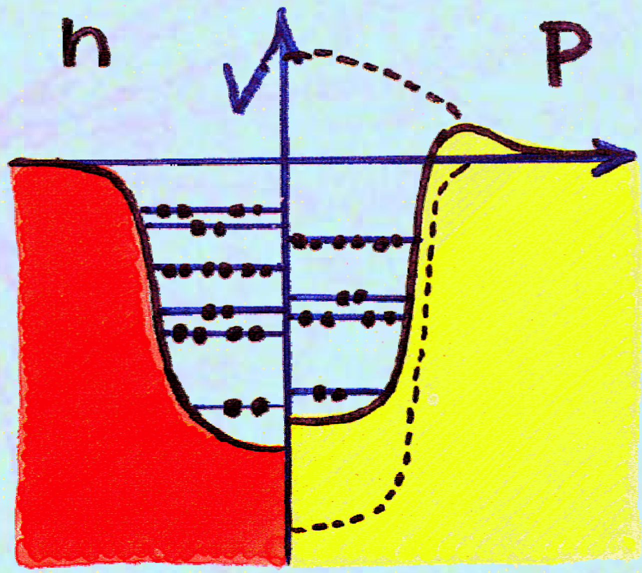


- Many confirmations



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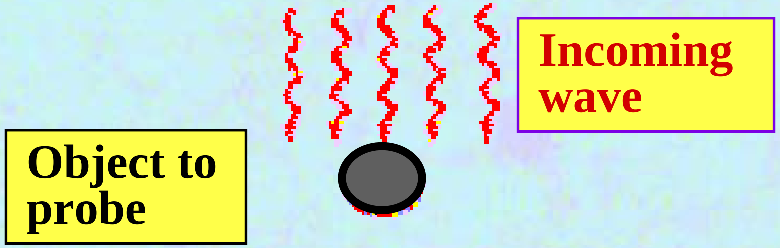
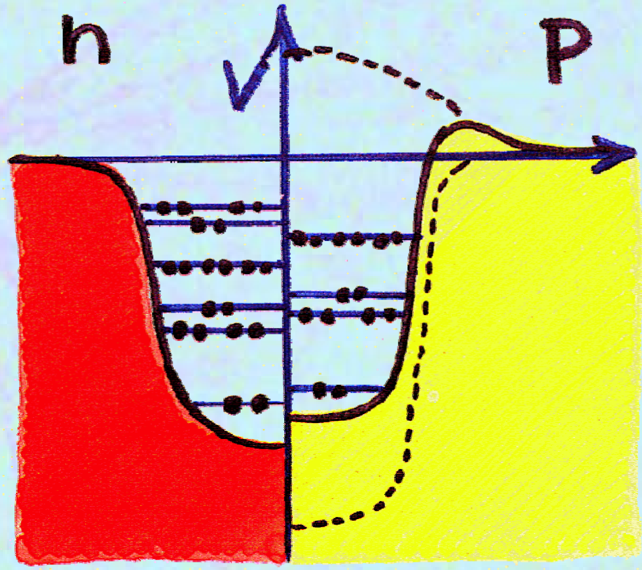


- **Many confirmations**



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Measuring waves

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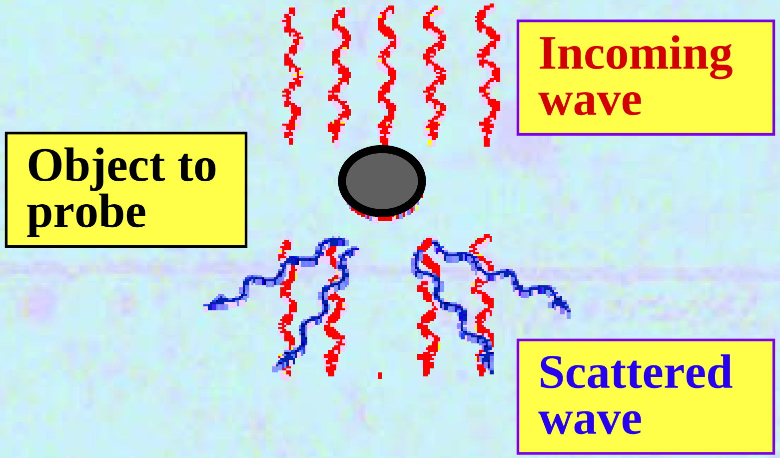
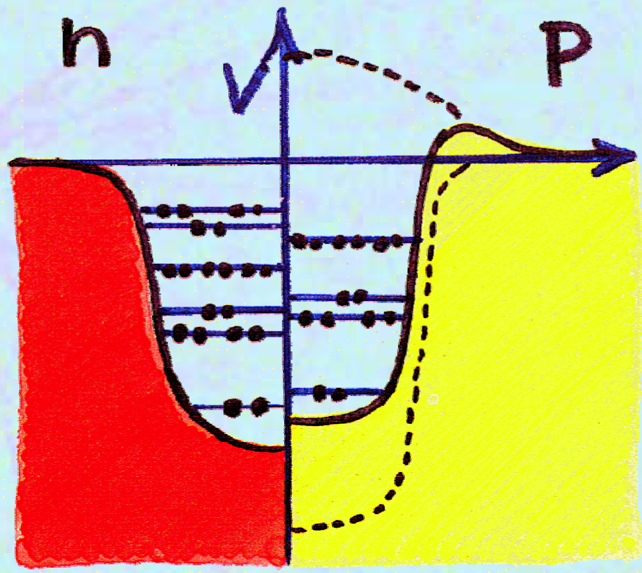


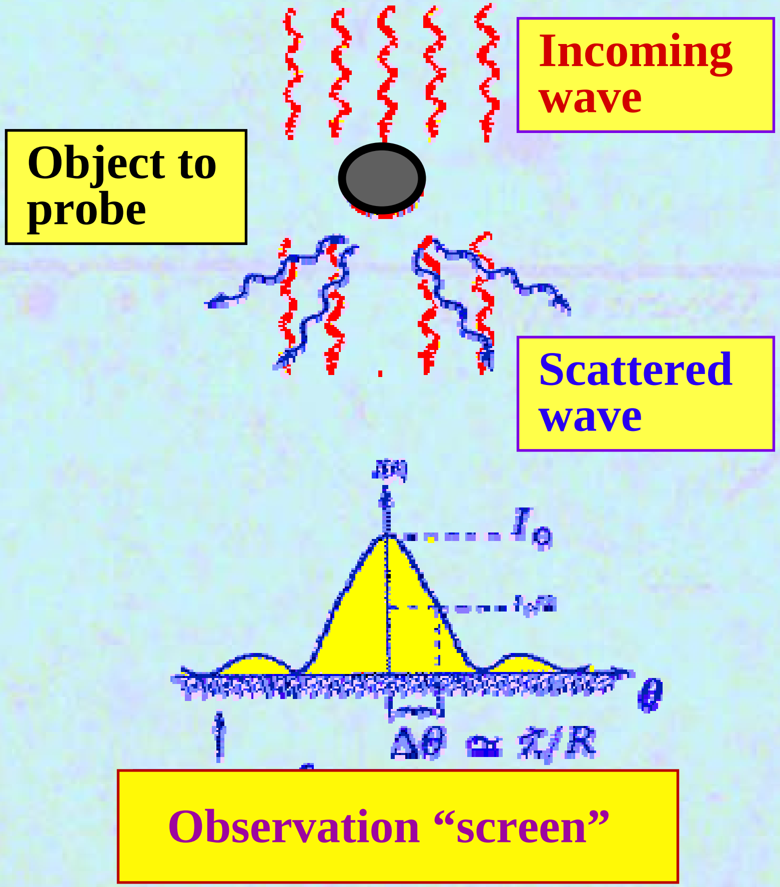
Many confirmations



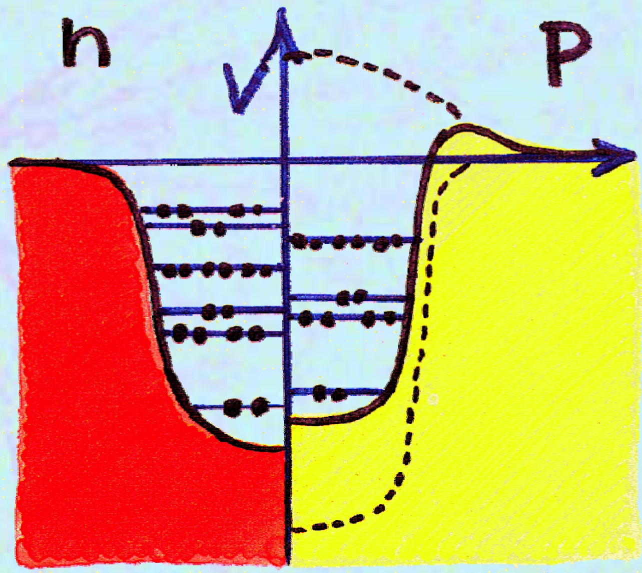
- Nucleons are self-organized in nuclei

Measuring waves

- Scattering of particles



Many confirmations



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- **Measuring waves**
  - ☞ Scattering of particles

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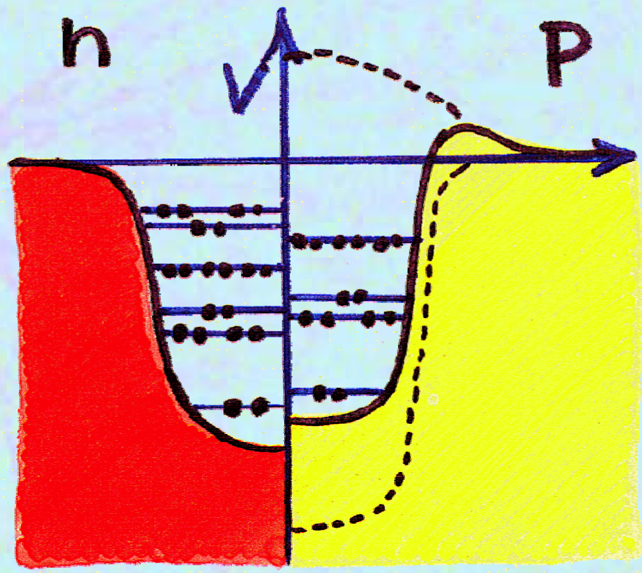

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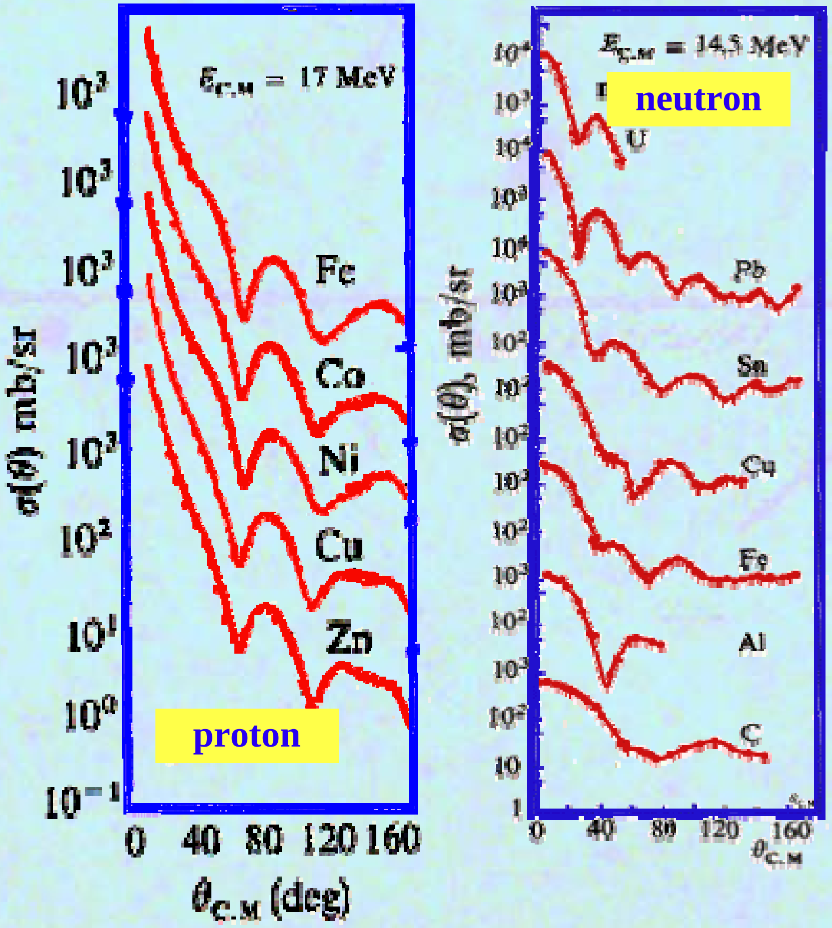
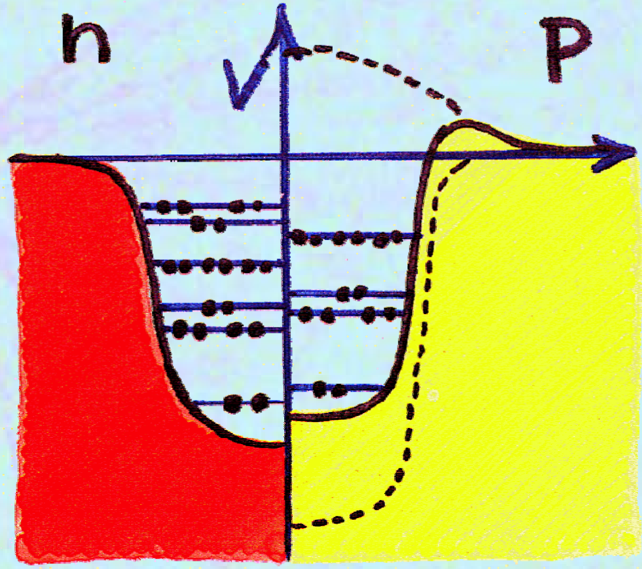
Measuring waves

- Scattering of particles



Many confirmations



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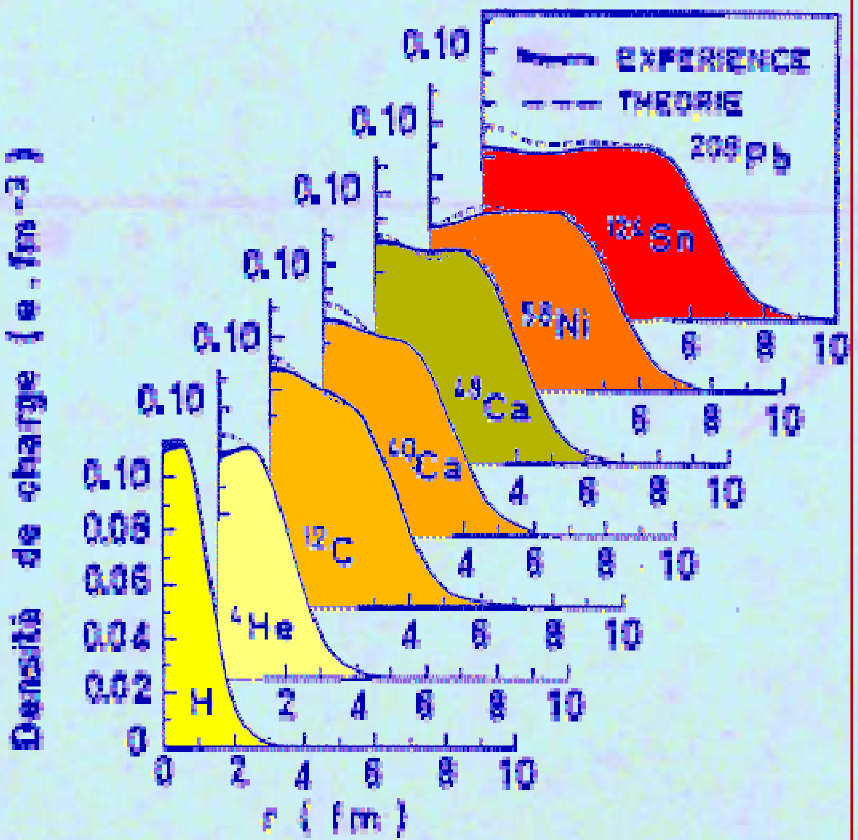
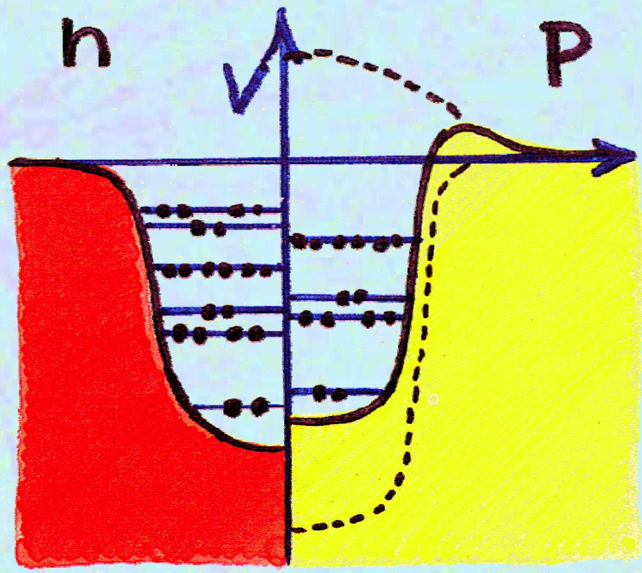
Measuring waves

- Scattering of particles



Many confirmations



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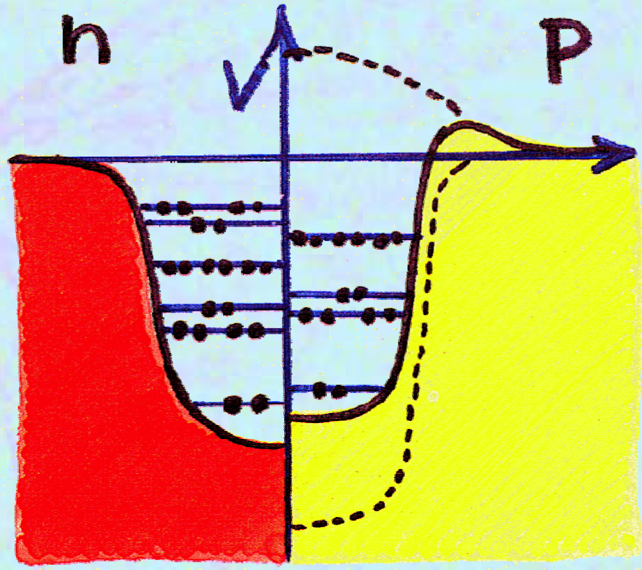

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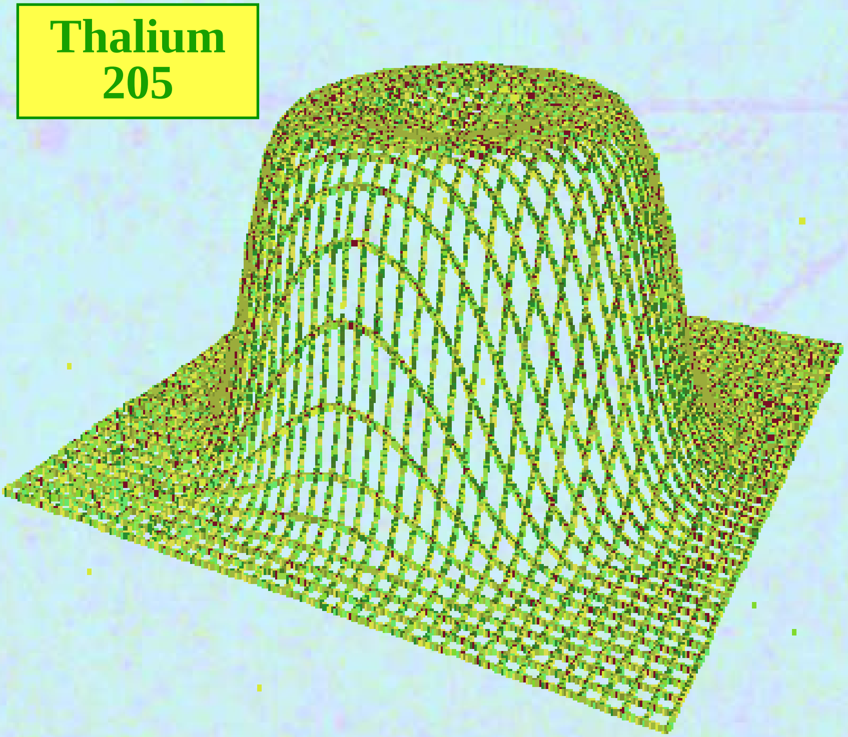
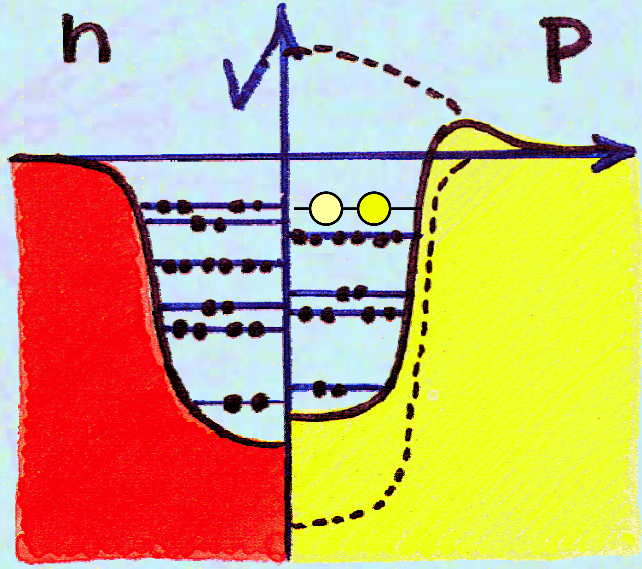
- **Measuring waves**
  - **Scattering of particles**

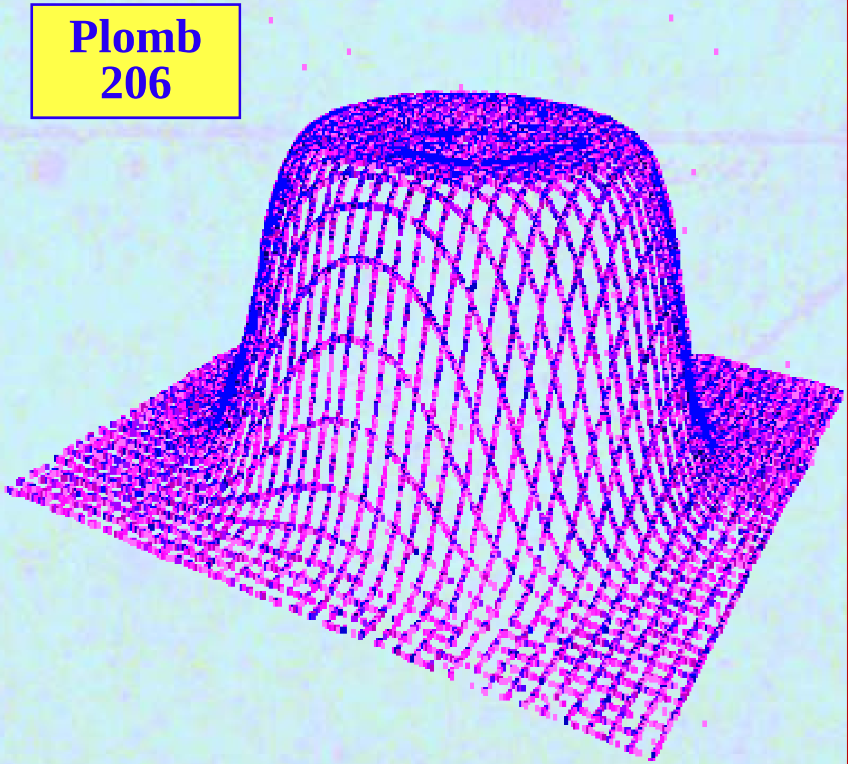


- **Many confirmations**

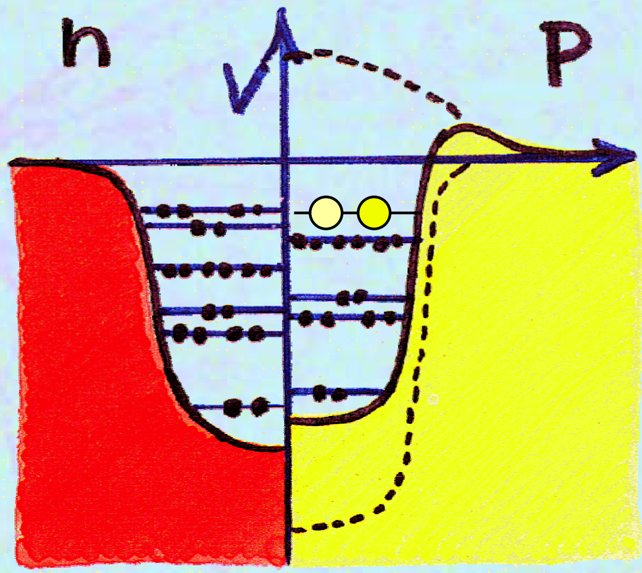


- **Nucleons are self-organized in nuclei**

- **Measuring waves**
  - ☞ **Scattering of particles**



- **Many confirmations**



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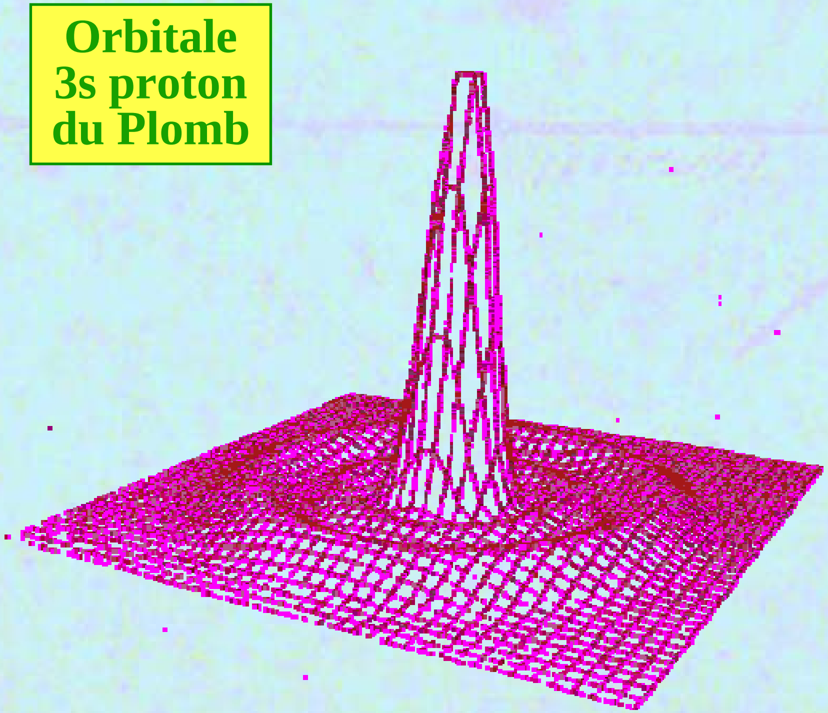
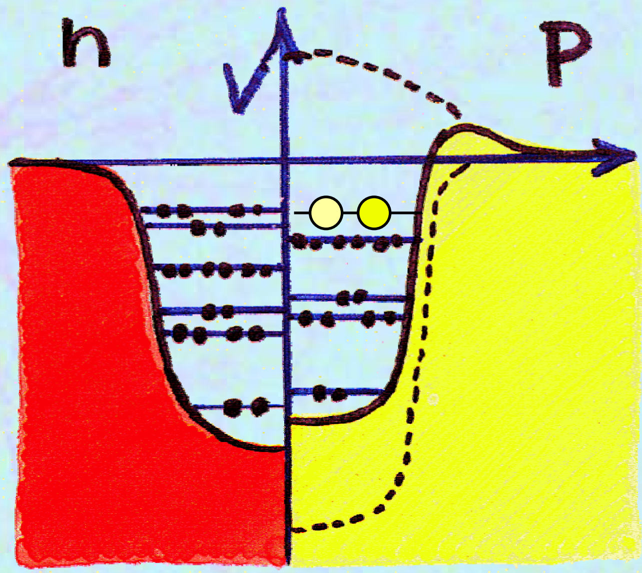
Measuring waves

- Scattering of particles



Many confirmations

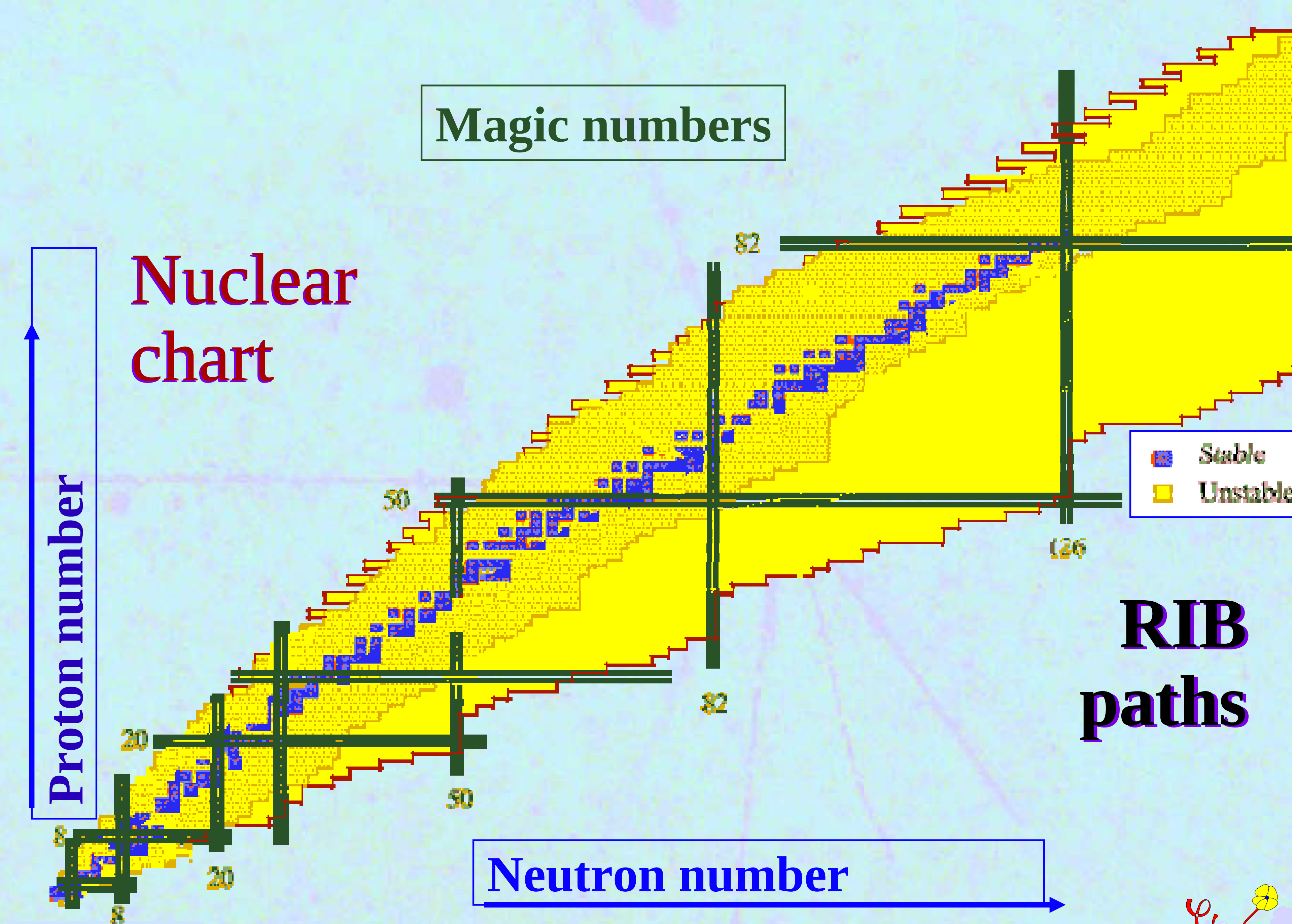


- **Nucleons are self-organized in nuclei**

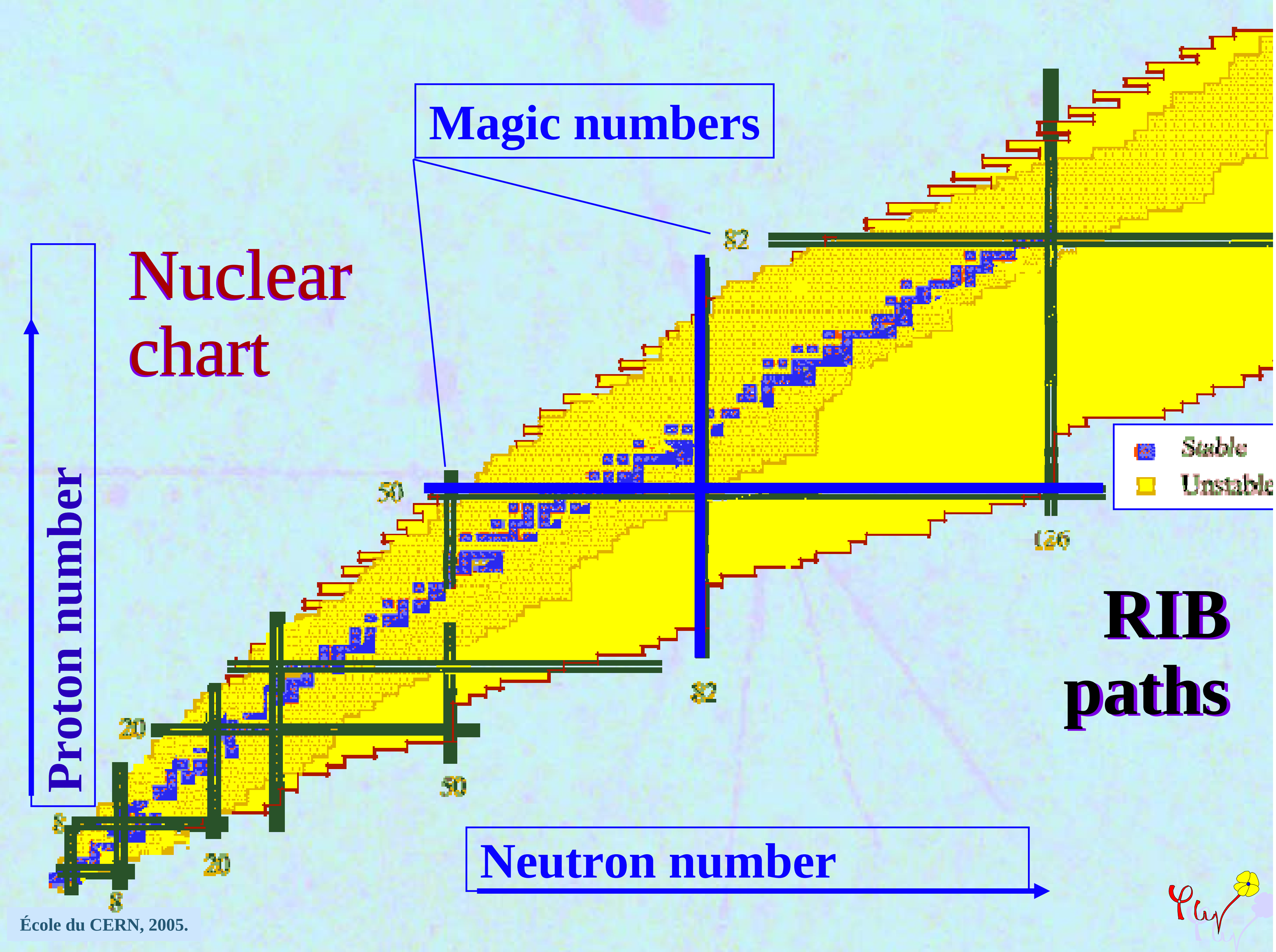
Nuclear chart

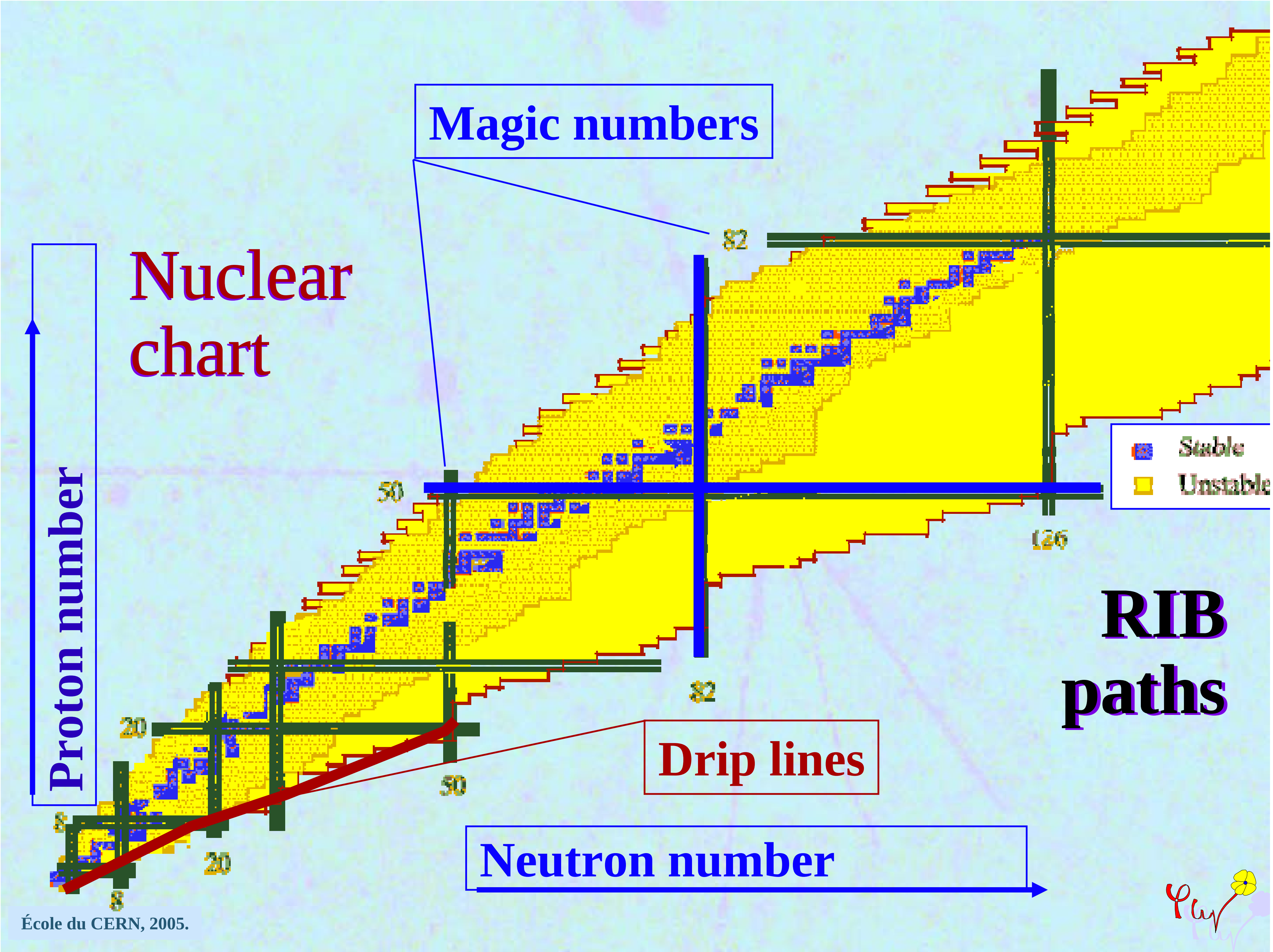
Proton number

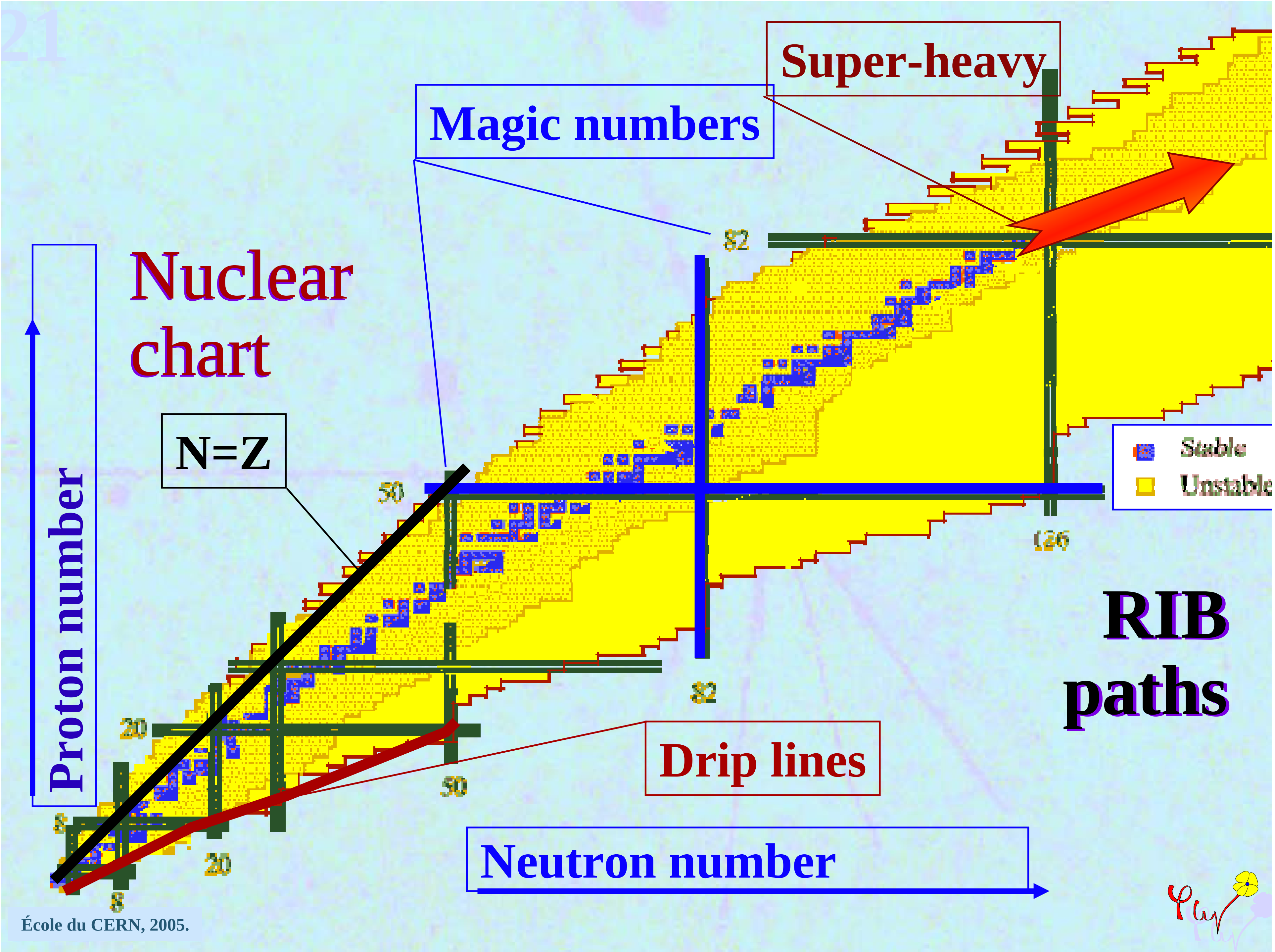
Neutron number

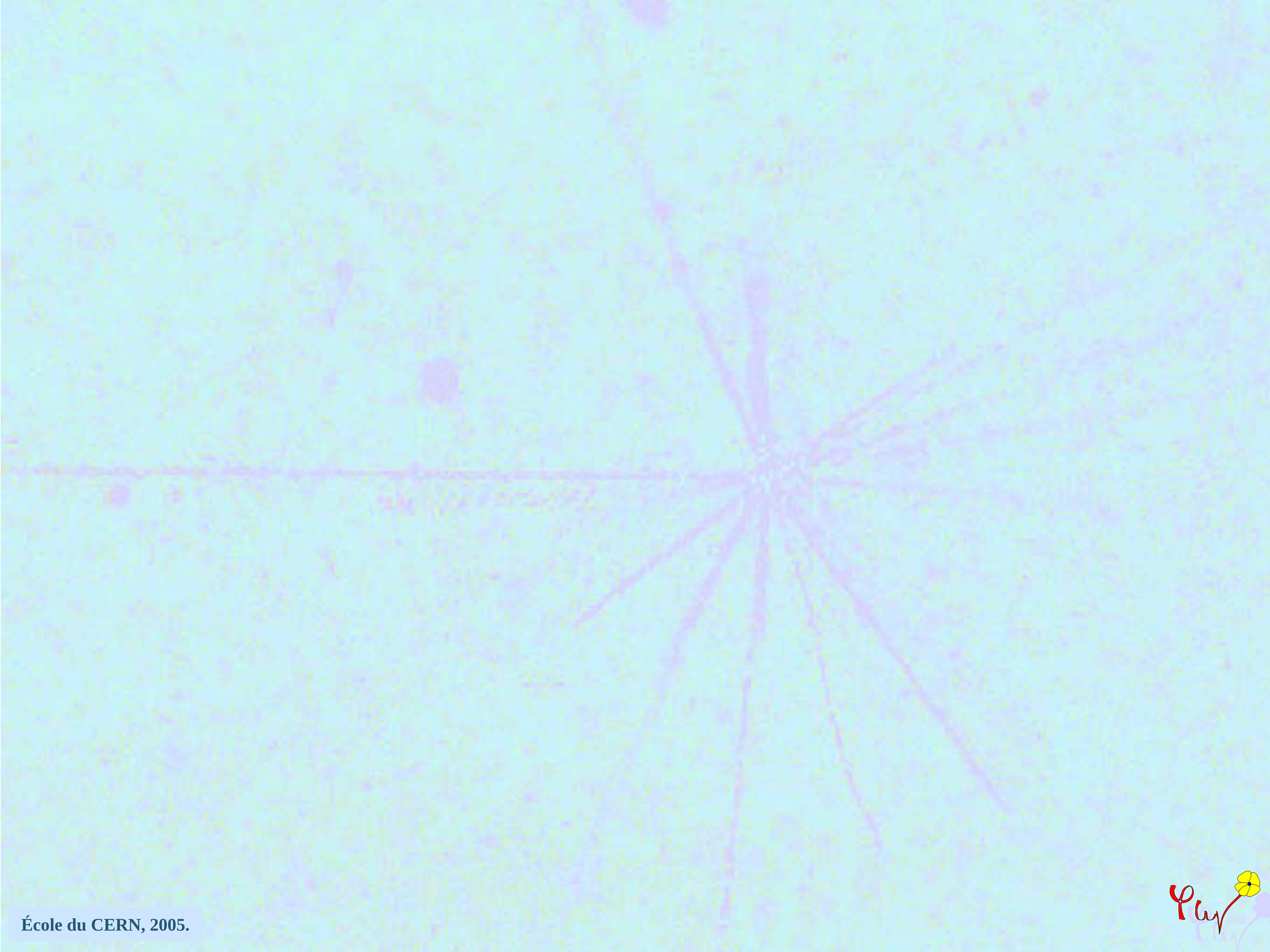


École du CERN, 2005.


Magic numbers
Nuclear
chart
Proton number
82
50
20
8
8
20
50
82
126
Stable
Unstable
RIB
paths
Neutron number
École du CERN, 2005.


Magic numbers
Nuclear chart
Proton number
82
50
20
8
126
Stable
Unstable
RIB paths
Drip lines
Neutron number
École du CERN, 2005.

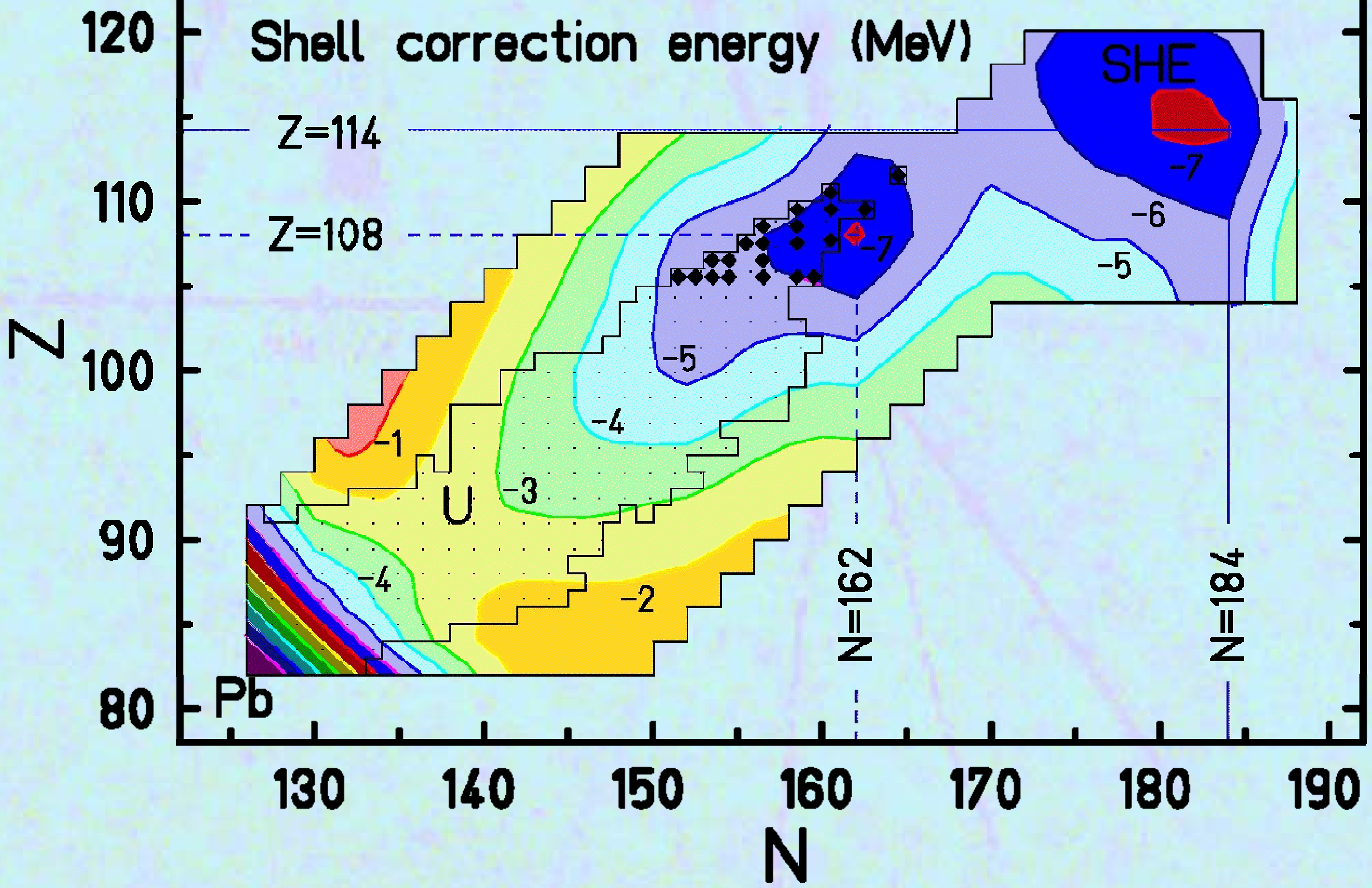

21
Super-heavy
Magic numbers
Nuclear chart
N=Z
Proton number
Neutron number
Drip lines
RIB paths
Stable
Unstable
82
50
20
8
126
École du CERN, 2005.



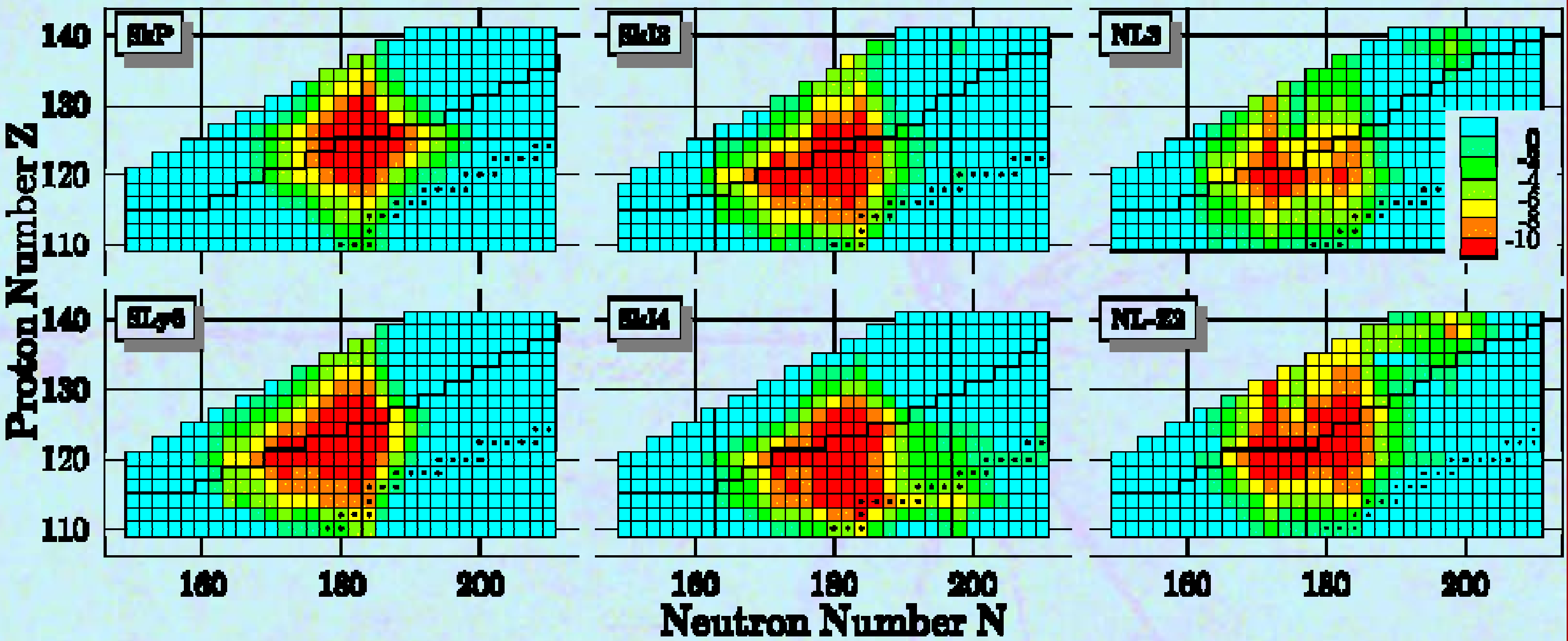
Nuclear shell: Super-heavy

Nuclear shell: Super-heavy

R. Smolanczuk, Phys. Rev. C56 (1997) 812

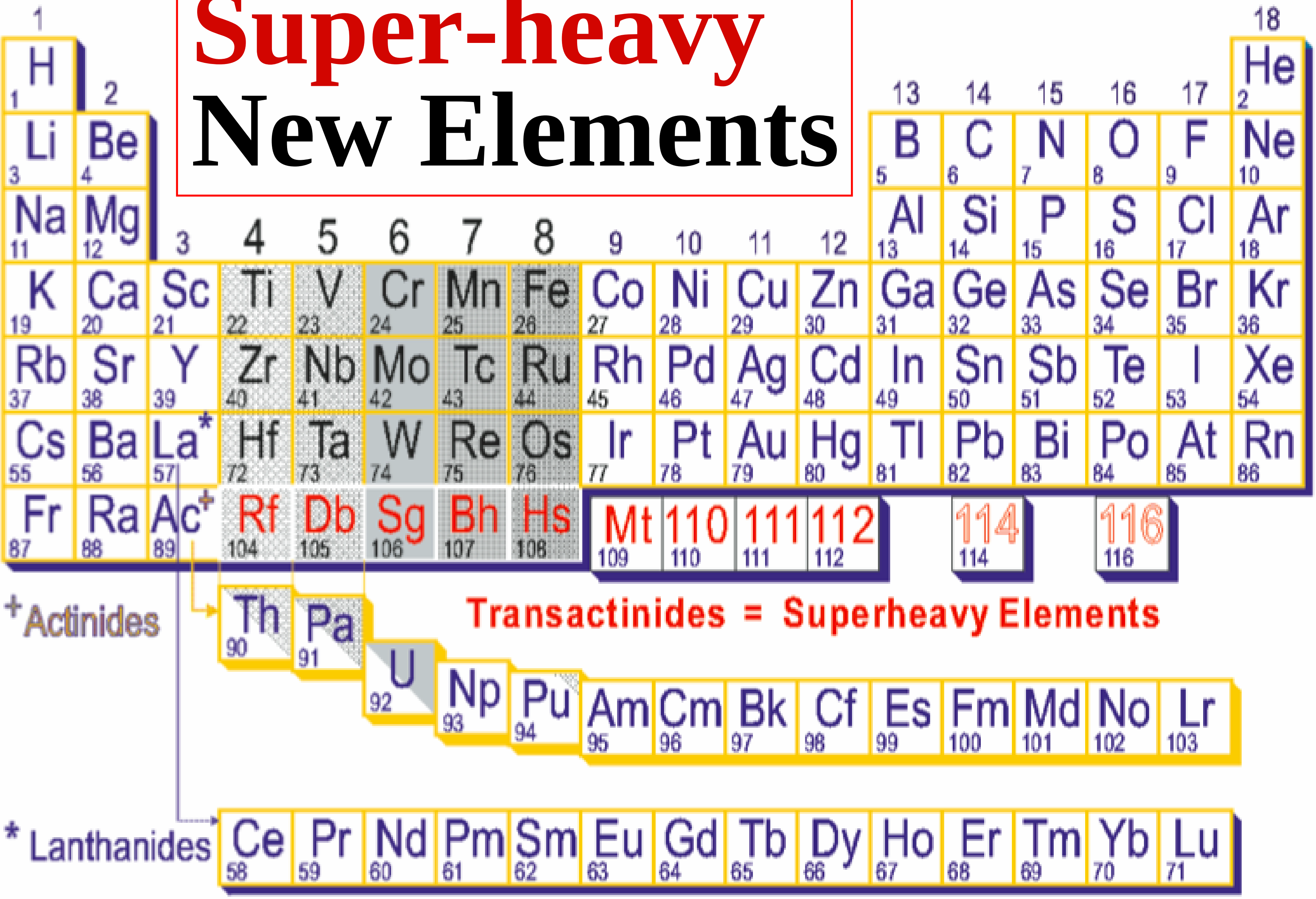


Nuclear shell: Super-heavy

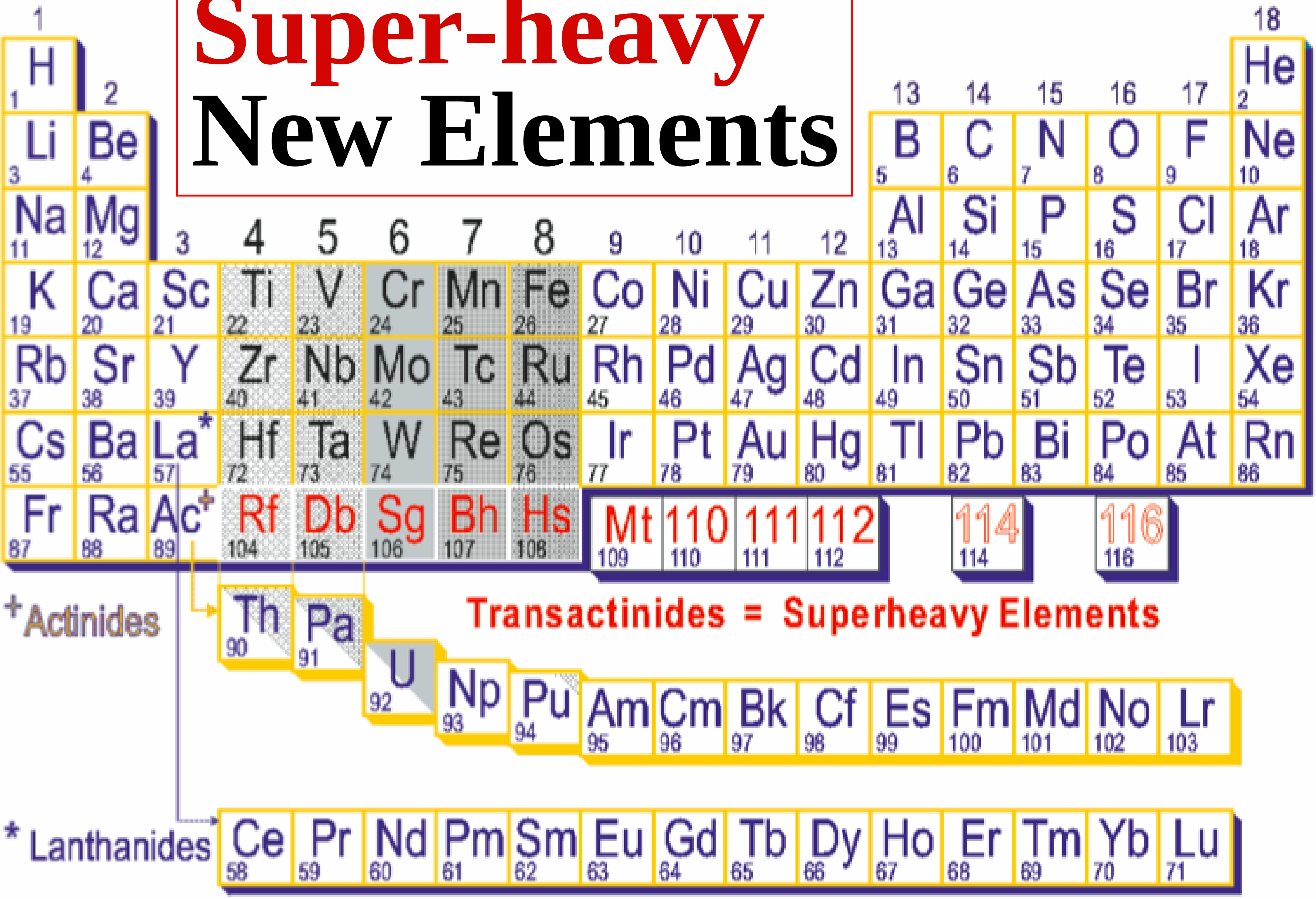


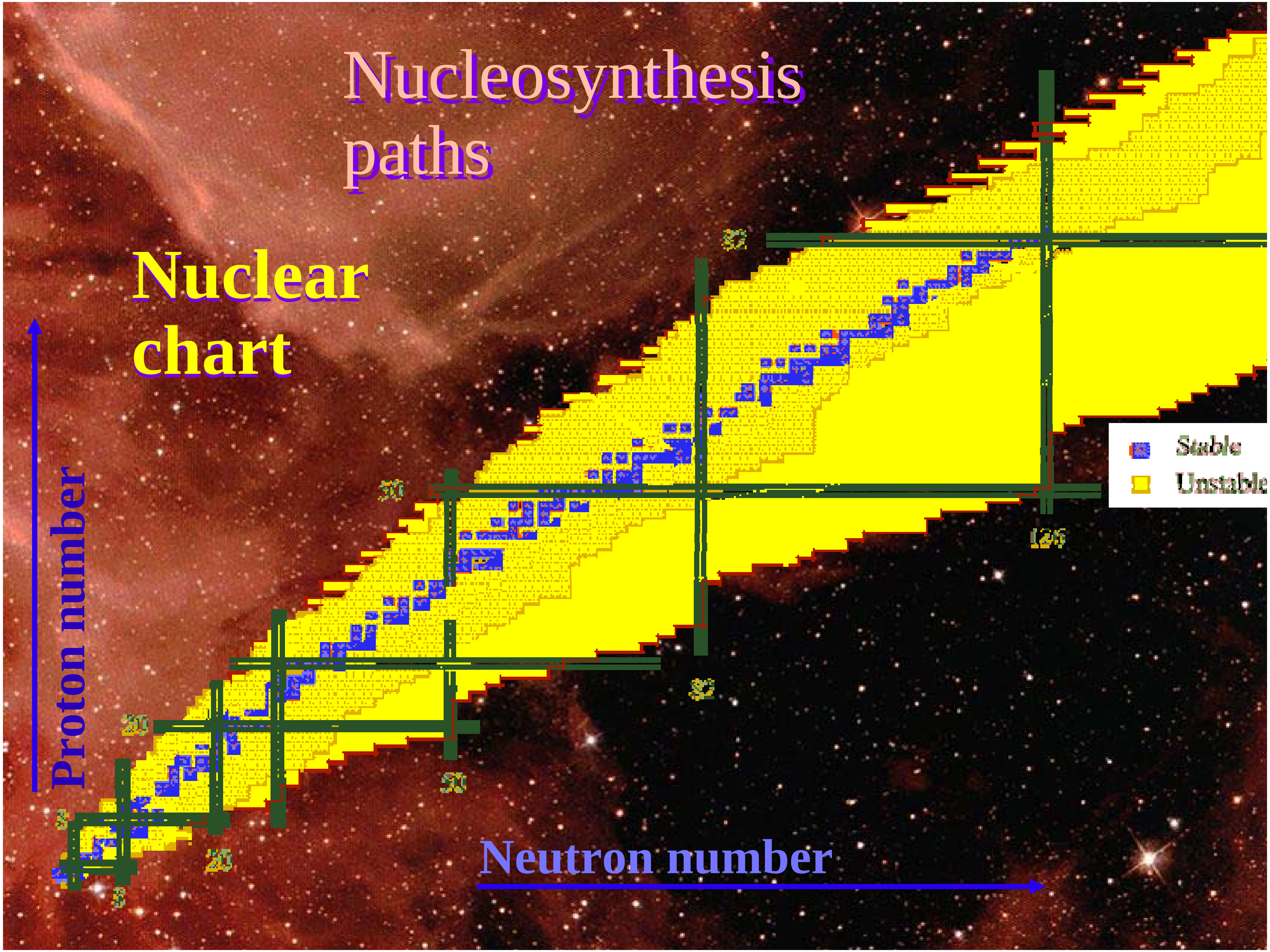
- 114, 120, 126 ? Theories disagree on superheavy magic number.

Super-heavy
New Elements

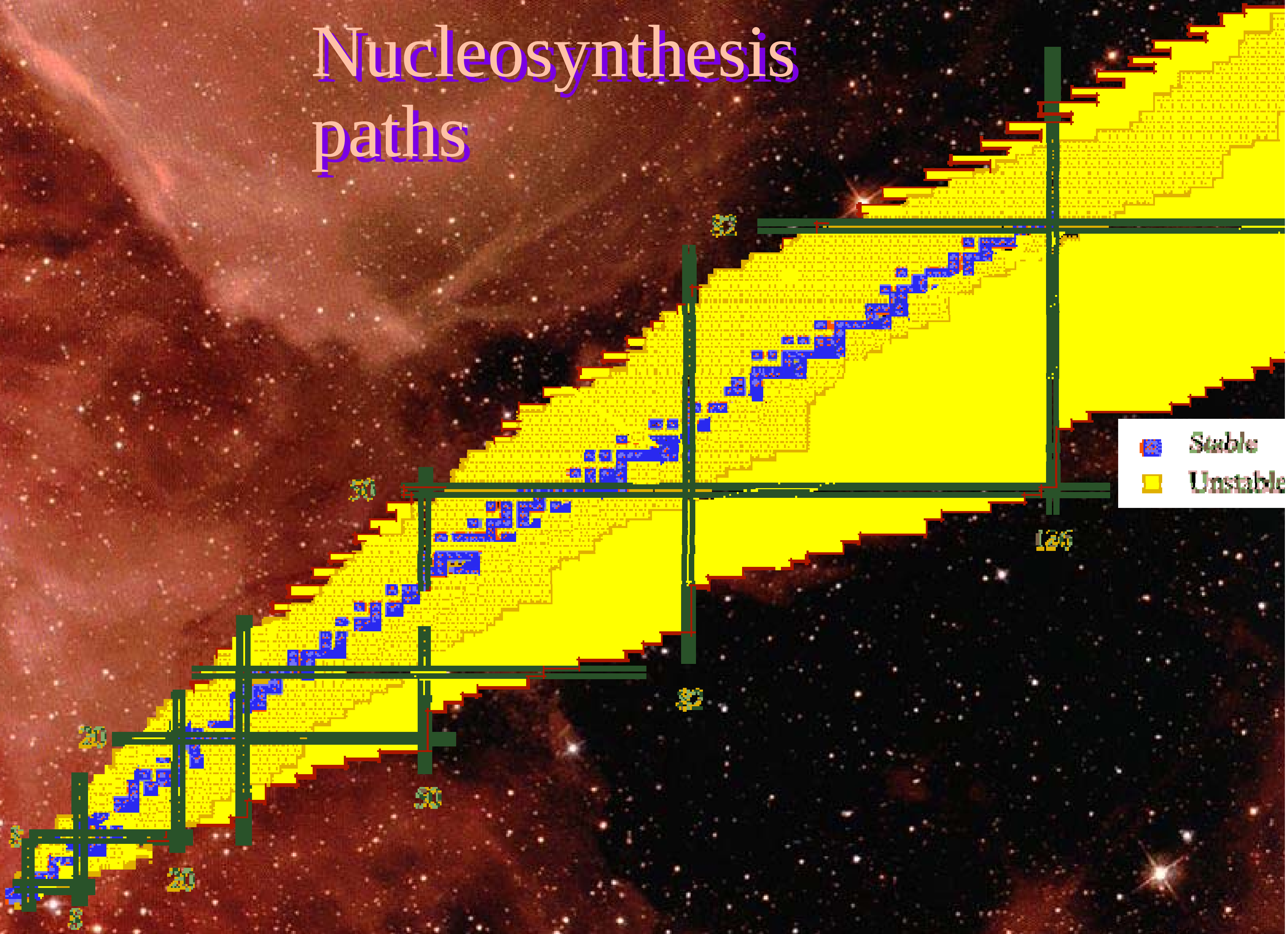


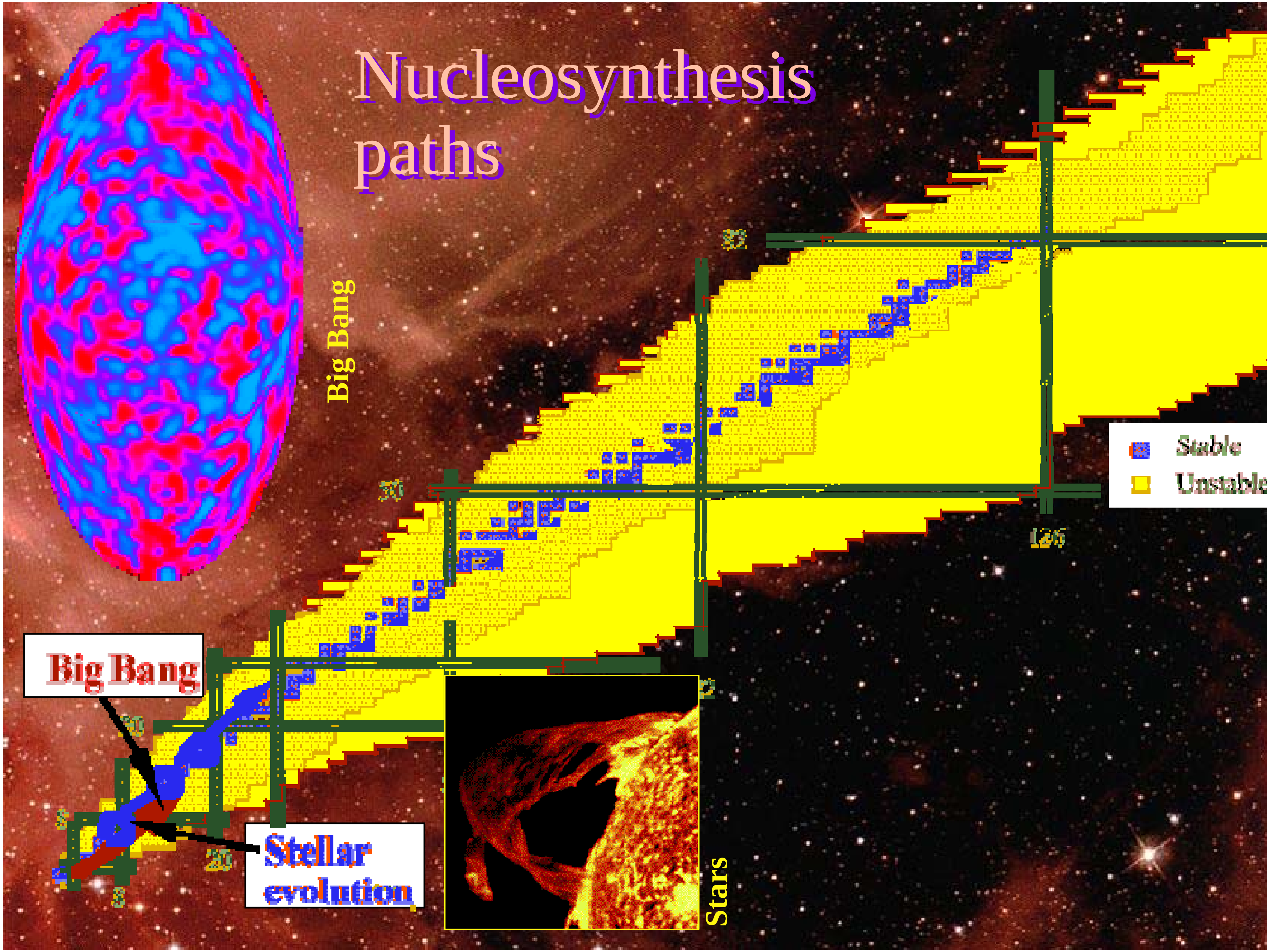
Super-heavy
New Elements



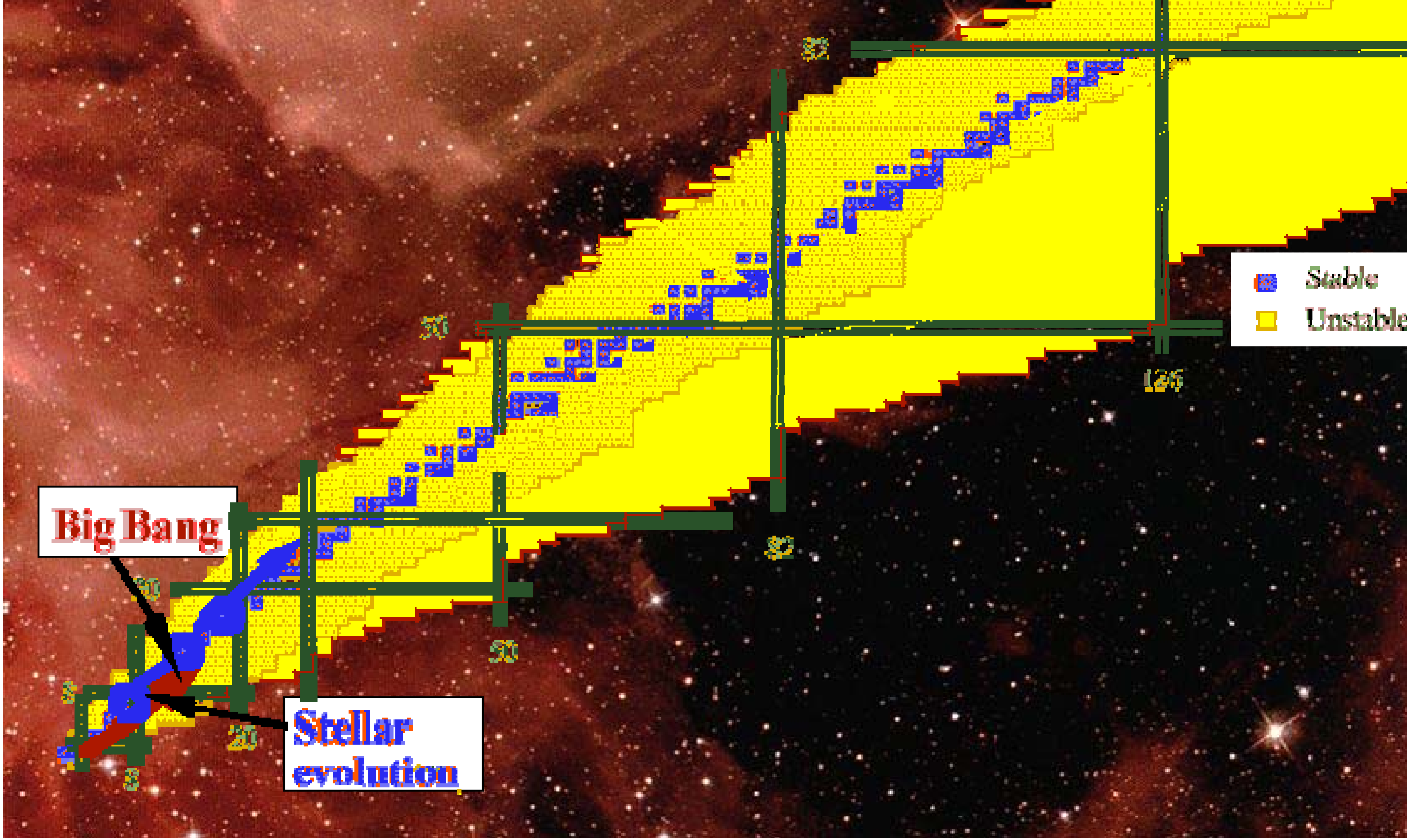

Nucleosynthesis
paths
Nuclear
chart
Proton number
Neutron number
Stable
Unstable
8
20
28
50
82
126

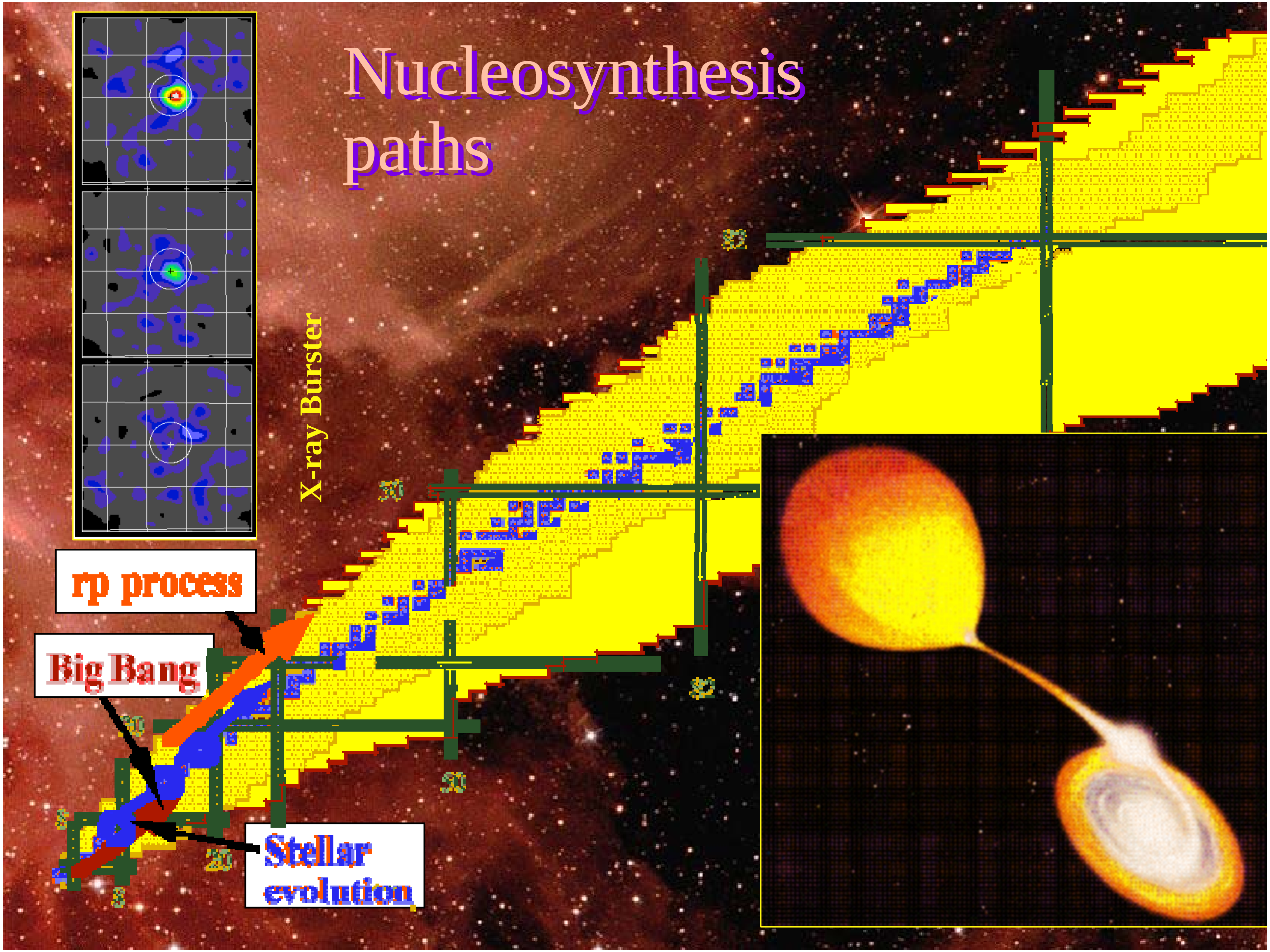
Nucleosynthesis paths



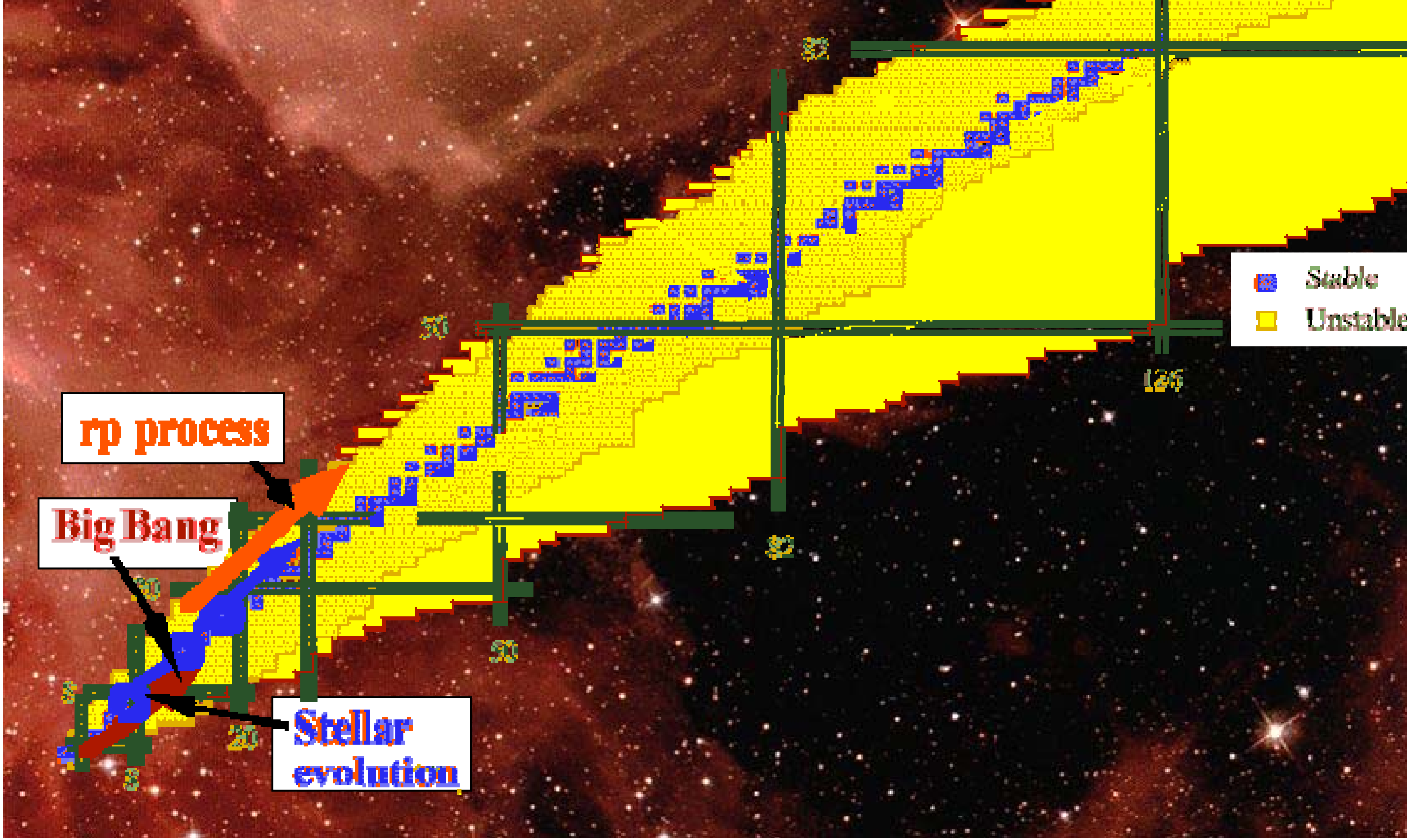

Nucleosynthesis paths
Big Bang
Big Bang
Stellar evolution
Stars
Stable
Unstable
126

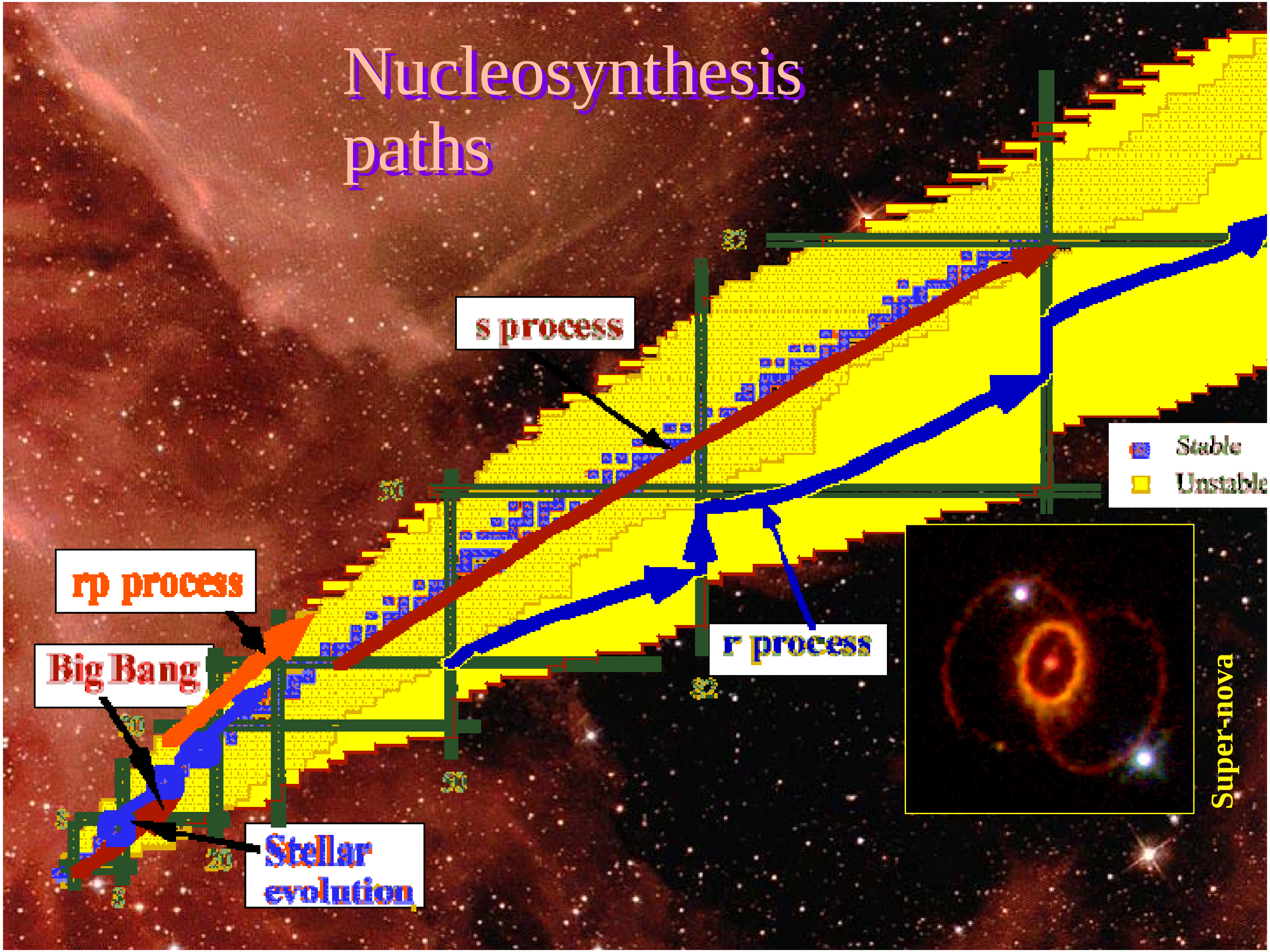
Nucleosynthesis paths



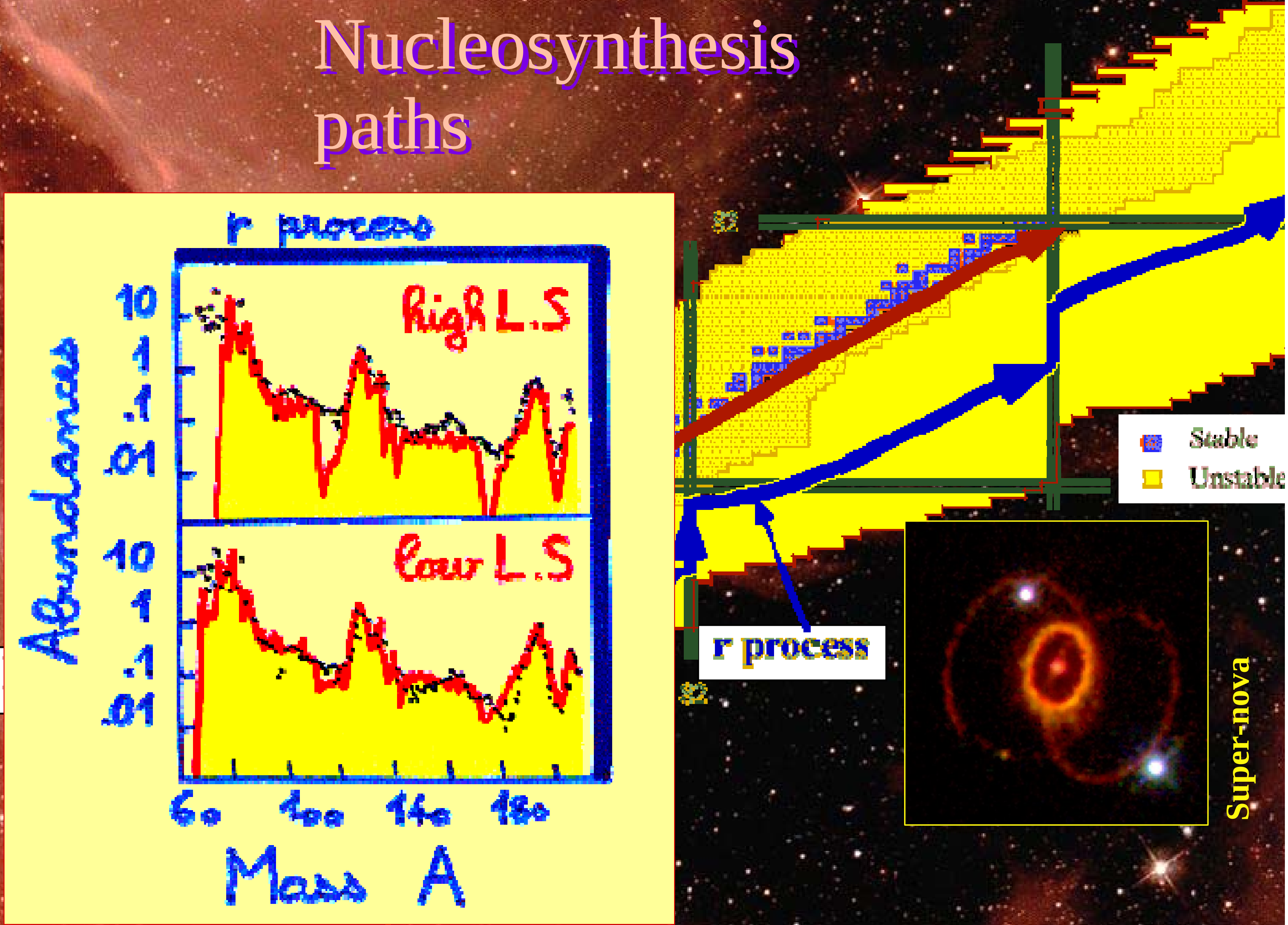

Nucleosynthesis paths
X-ray Burster
rp process
Big Bang
Stellar evolution

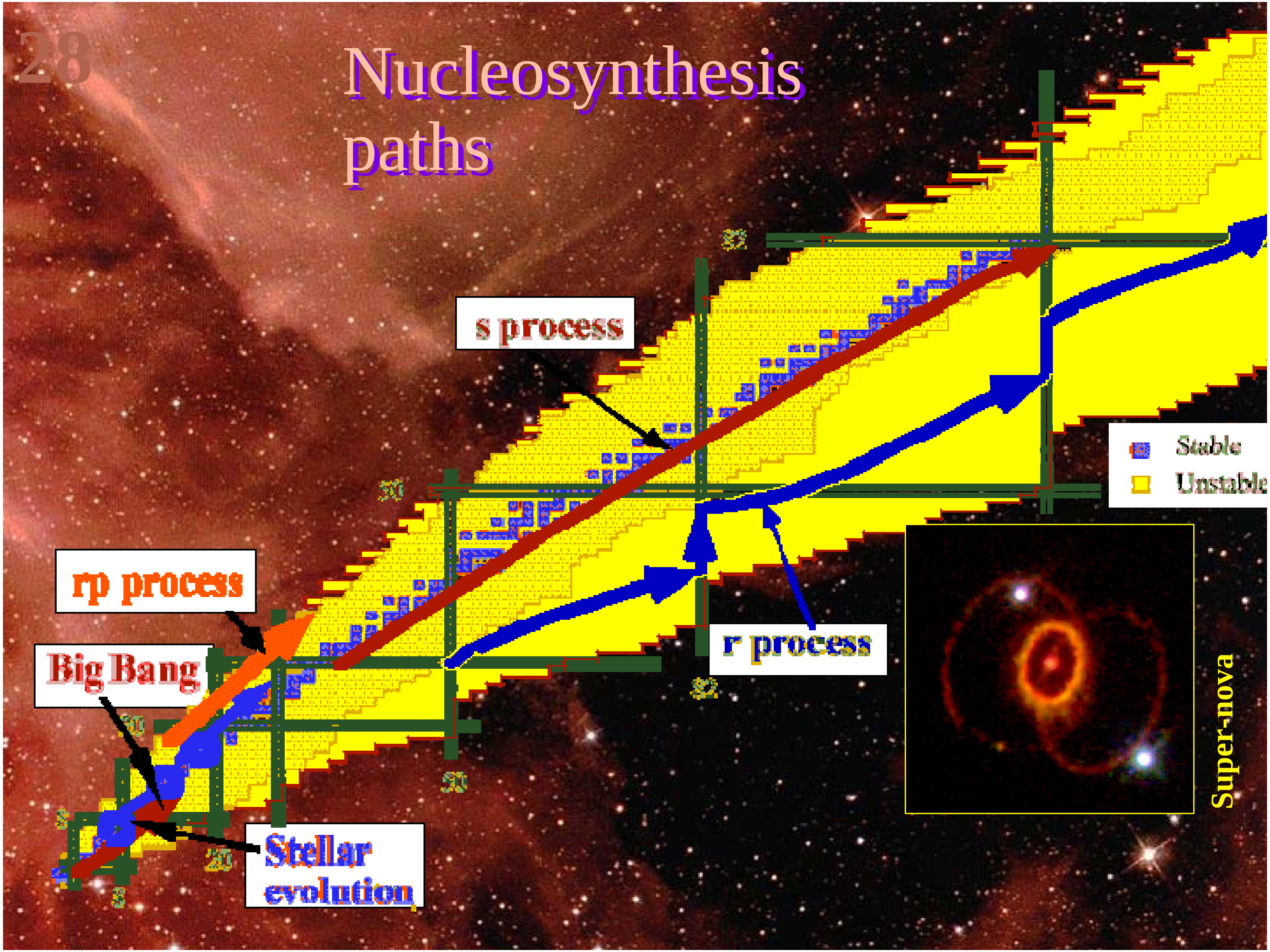
Nucleosynthesis paths

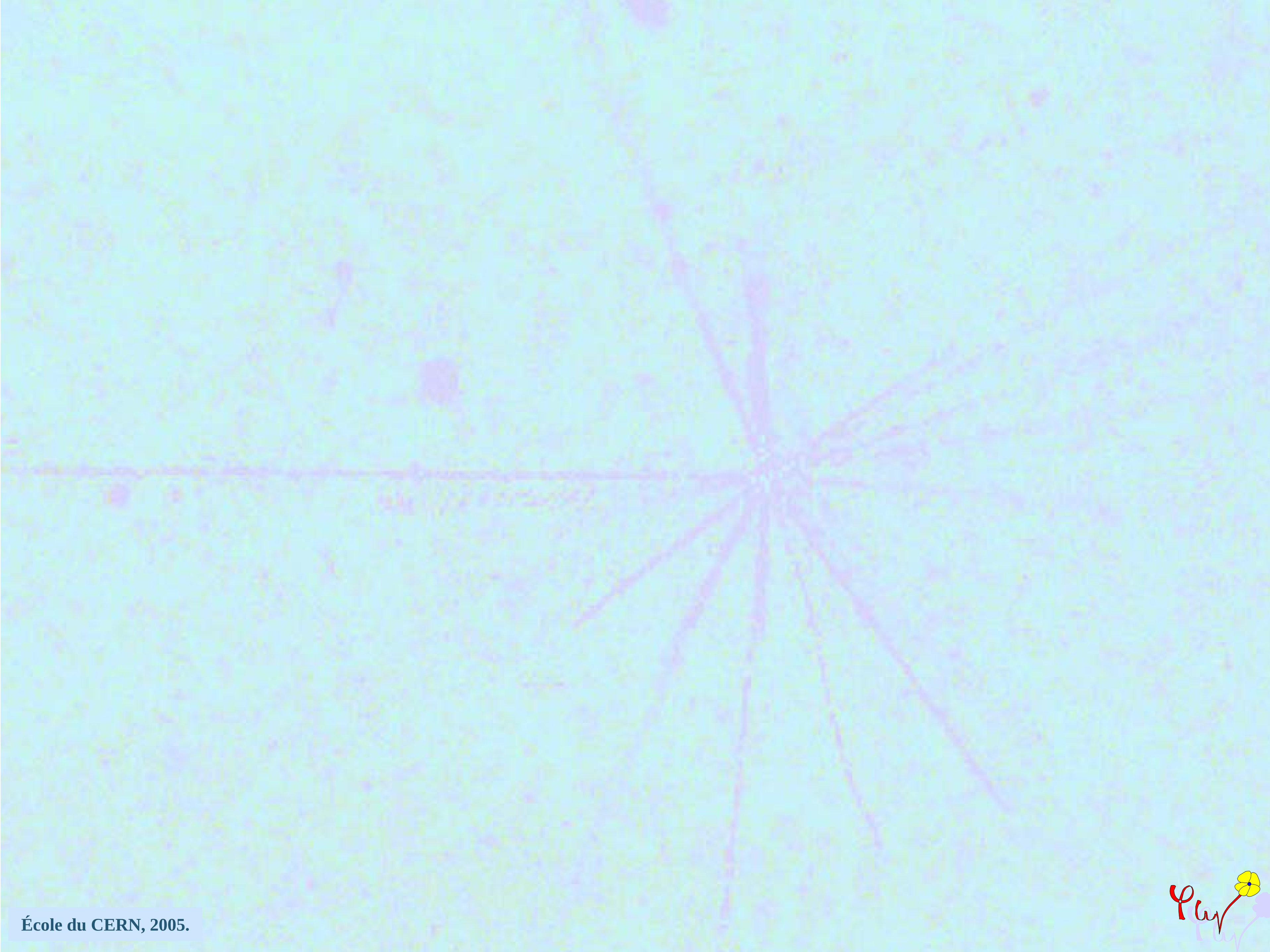



Nucleosynthesis
paths
s process
rp process
Big Bang
Stellar
evolution
r process
Stable
Unstable
Super-nova
82
50
82
50
20

Nucleosynthesis paths




28
Nucleosynthesis paths
s process
rp process
Big Bang
Stellar evolution
r process
Stable
Unstable
Super-nova

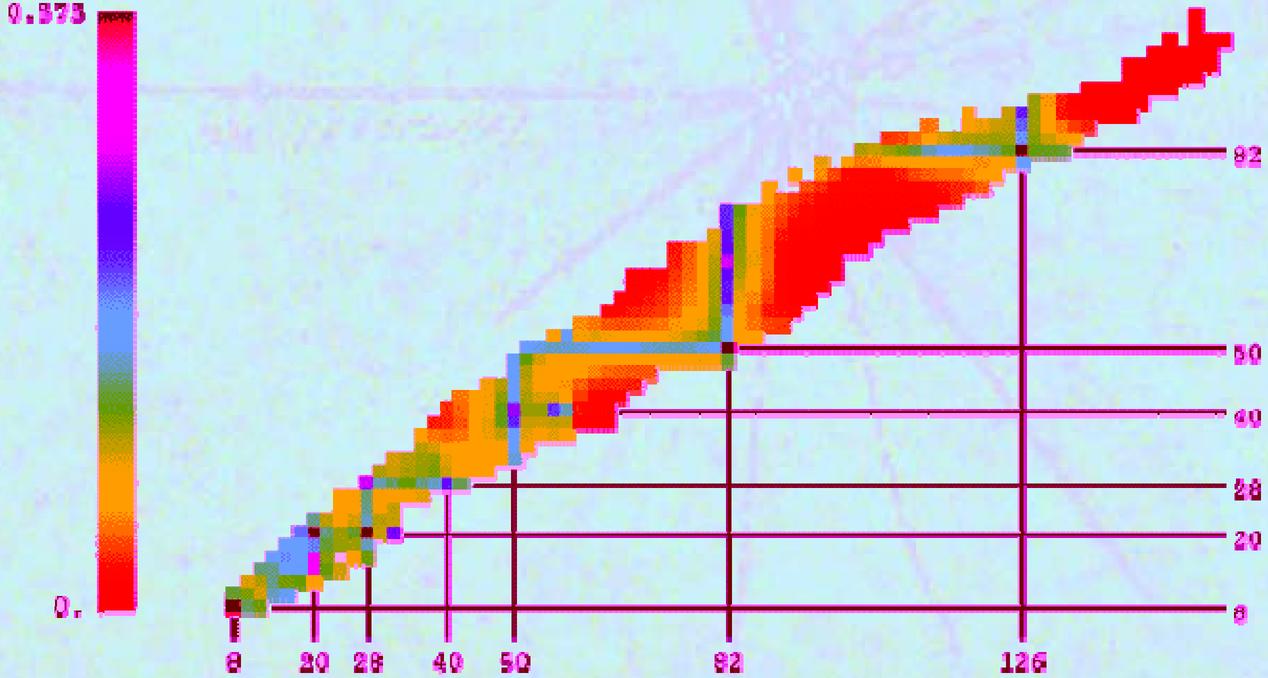


École du CERN, 2005.

Nuclear shells: systematics

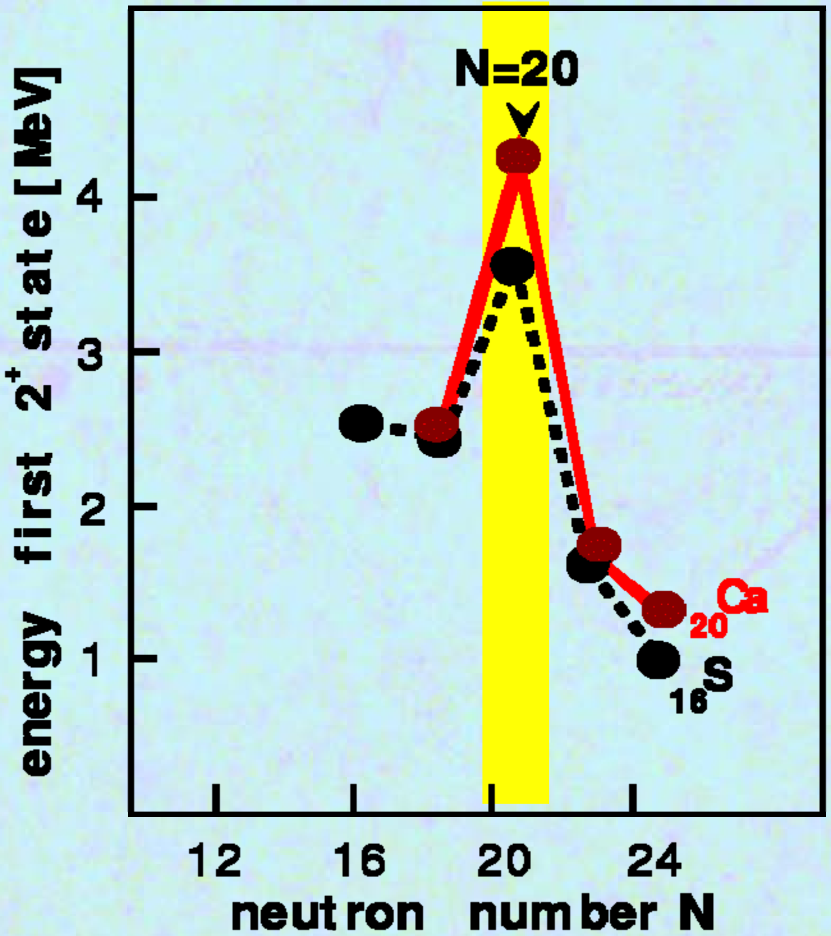
Shell structure from $E_x(2_1)$

- High $E_x(2_1)$ indicates stable shell structure:



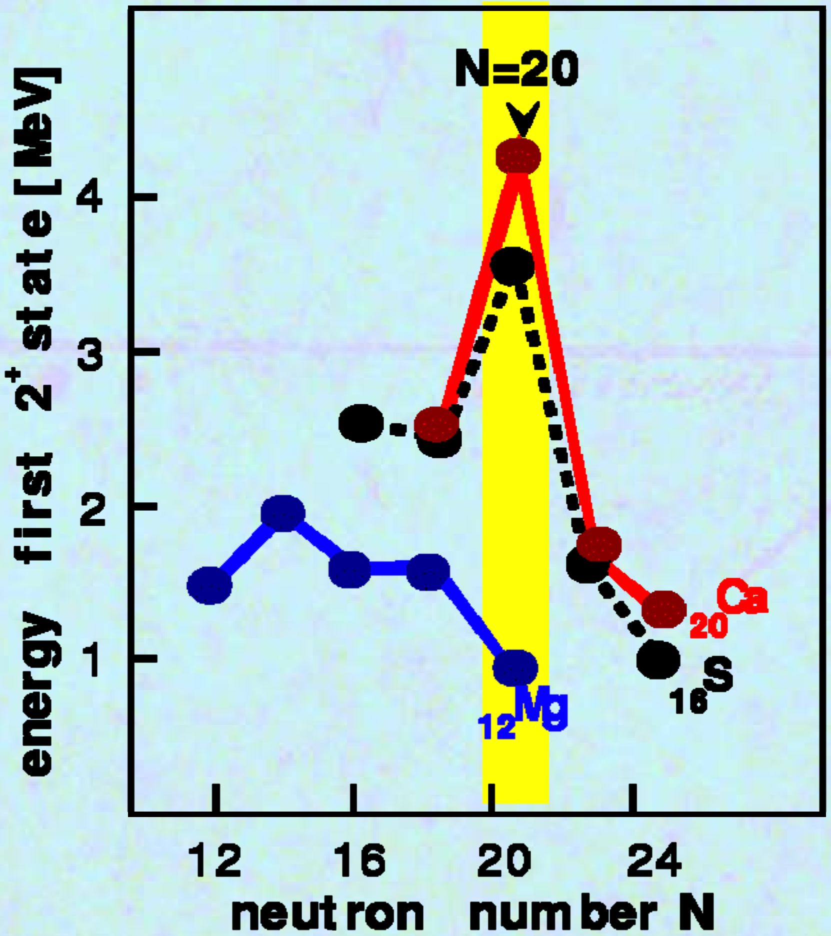
IAEA Workshop on NSDD, Trieste, November 2003

Nuclear shells:



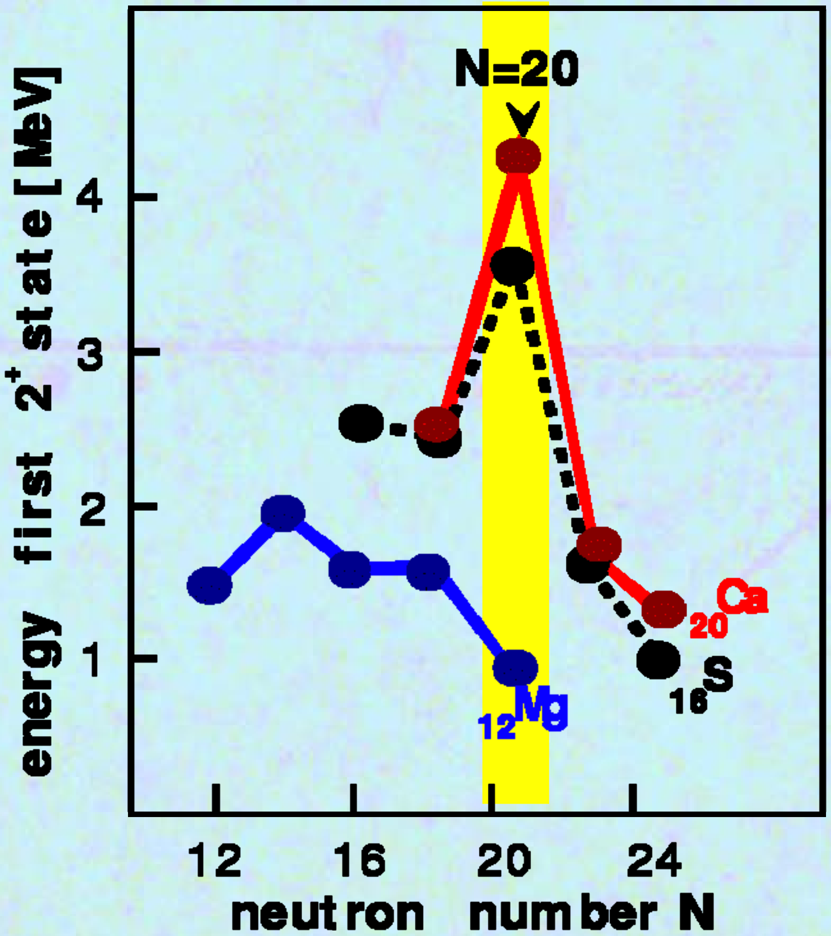
- **High E_{2+} and shell closure**
  - ☞ **Ex: N=20?**

Nuclear shells: neutron rich



- High E_{2+} and shell closure
  - ☞ Ex: N=20?
- Magic number disappears far from stability

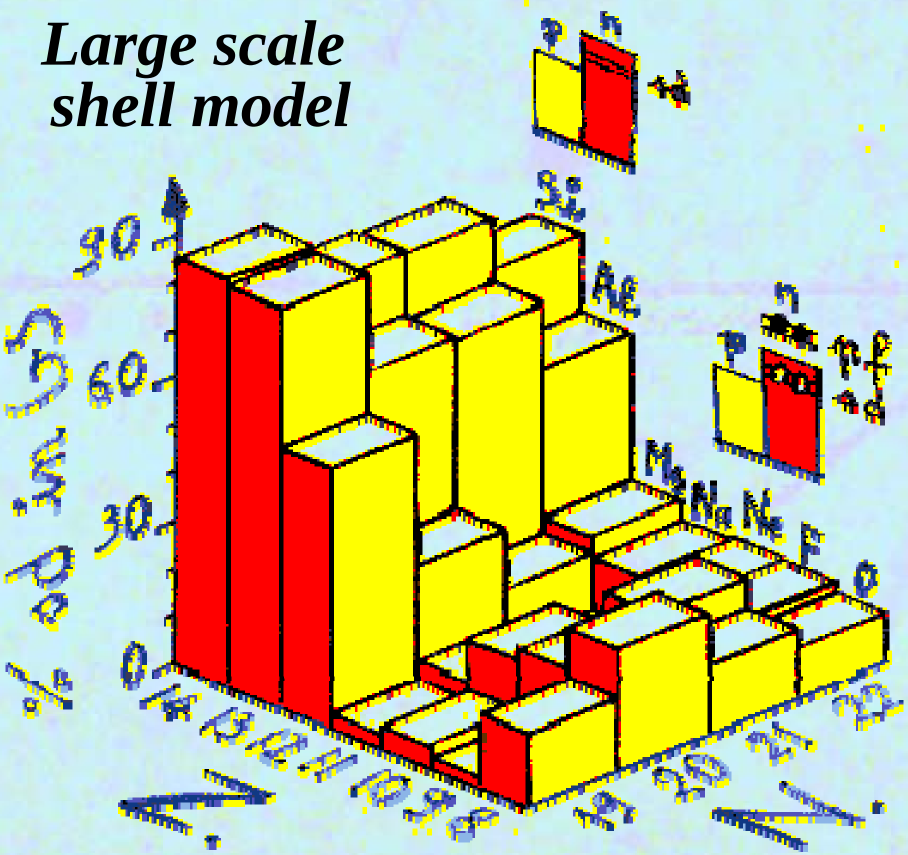
Nuclear shells: neutron rich



- High E_{2+} and shell closure
  - ☞Ex: N=20?
- Magic number disappears far from stability

Nuclear shells: neutron rich

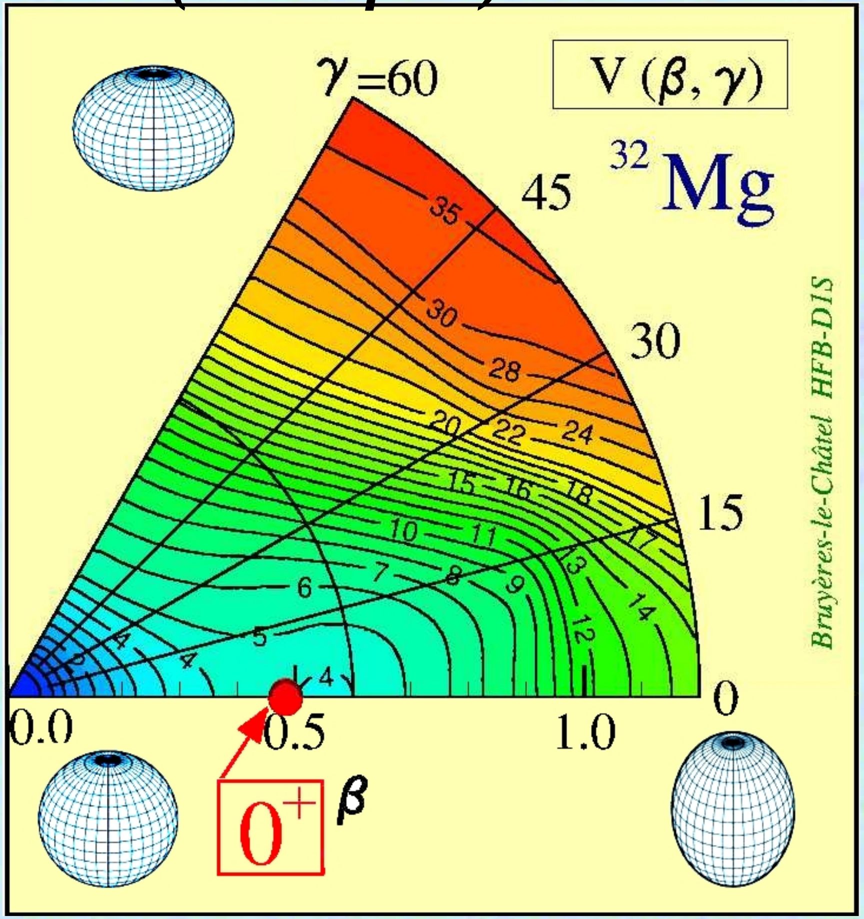
Large scale shell model



- **High E_{2+} and shell closure**
  - ☞ **Ex: N=20?**
- **Magic number disappears far from stability**
- **Configuration mixing**

Nuclear shells: neutron rich

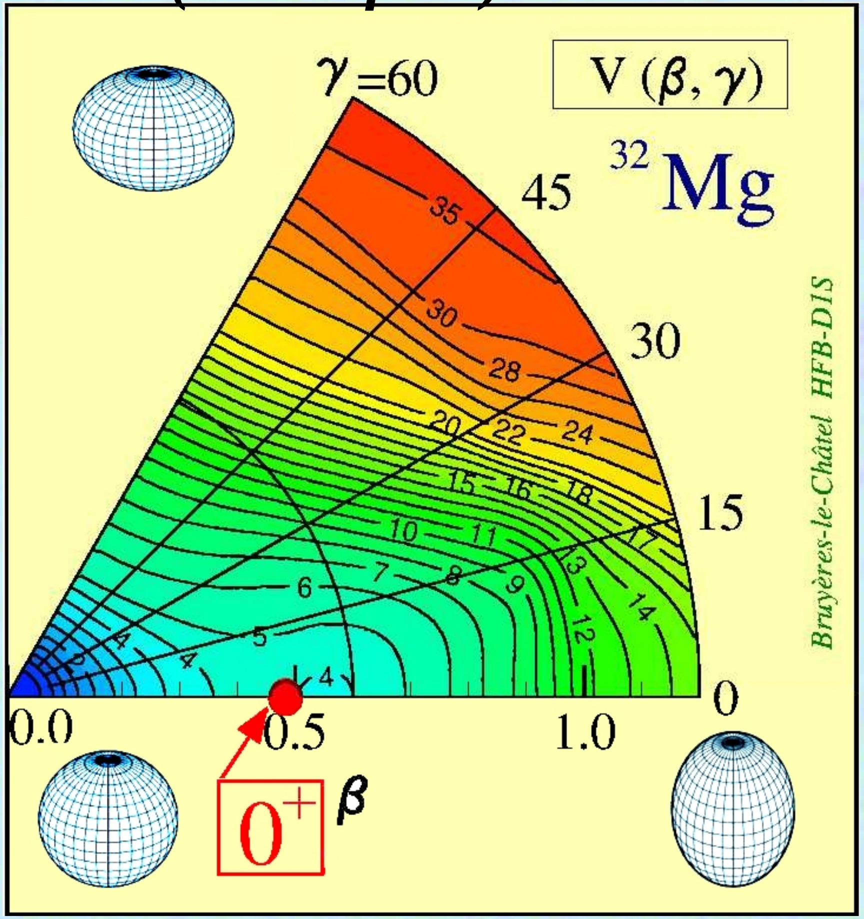
HFB (Mean-field) +CGM



- **What about the lighter shells?**
  - ☞**Ex: N=20?**
- **Magic number disappears far from stability**
- **Island of deformation**

Nuclear deformation

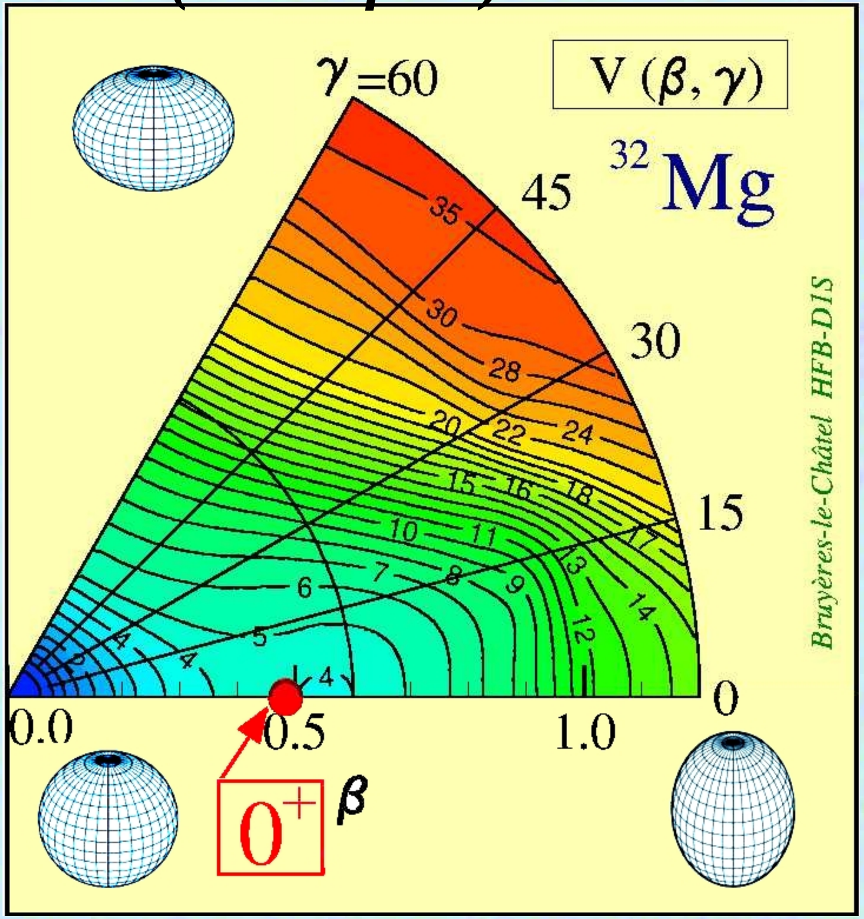
HFB (Mean-field) +CGM



- **Island of deformation**

Nuclear deformation

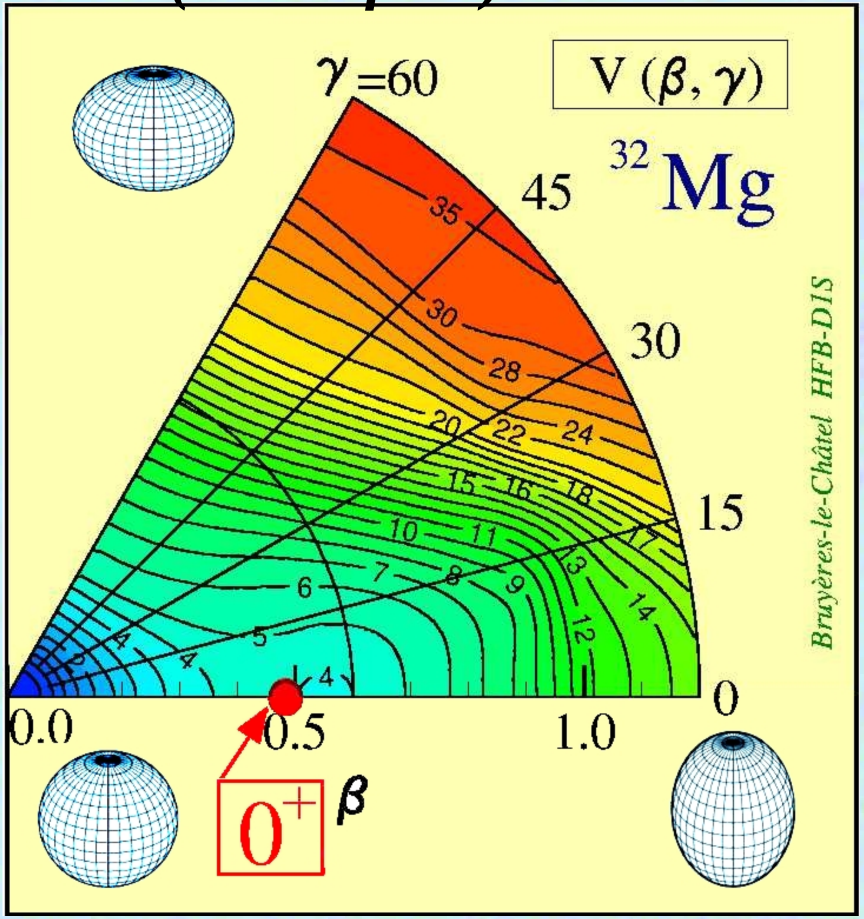
HFB (Mean-field) +CGM



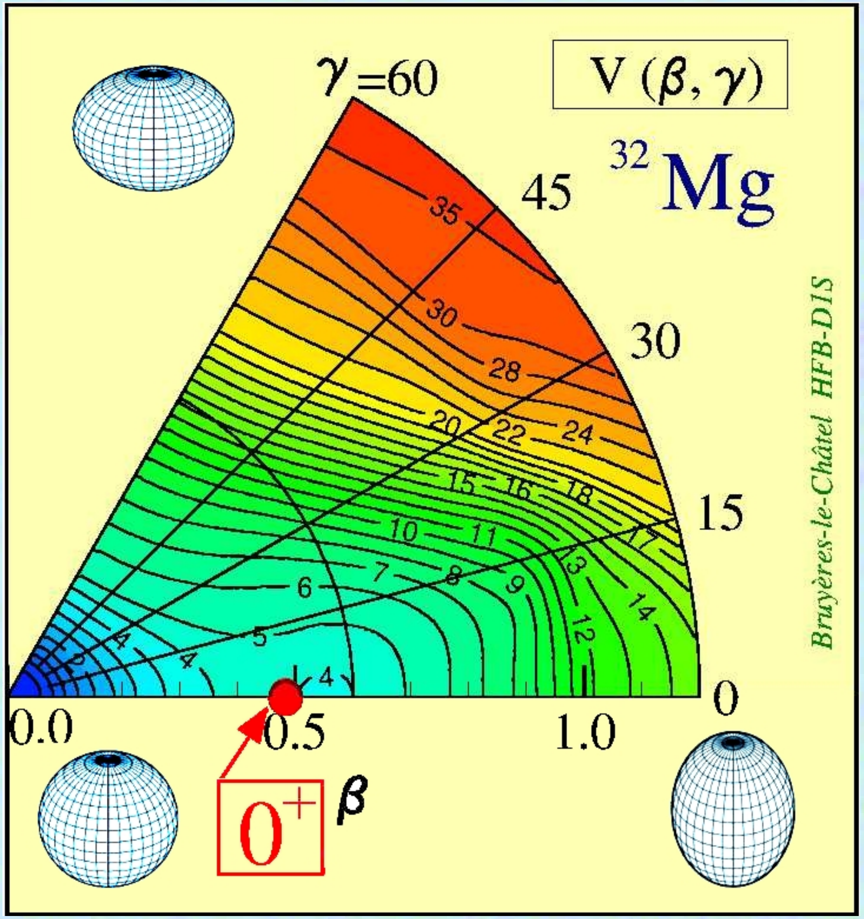
- **Island of deformation**

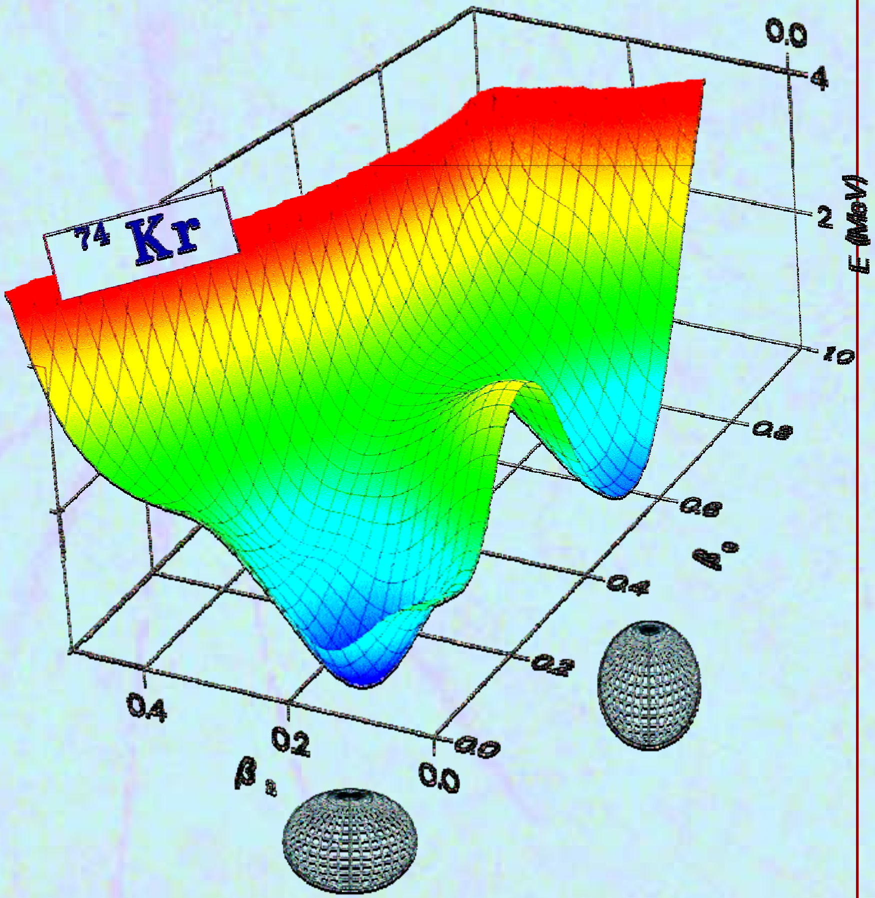
Nuclear deformation

HFB (Mean-field) +CGM



Nuclear deformation

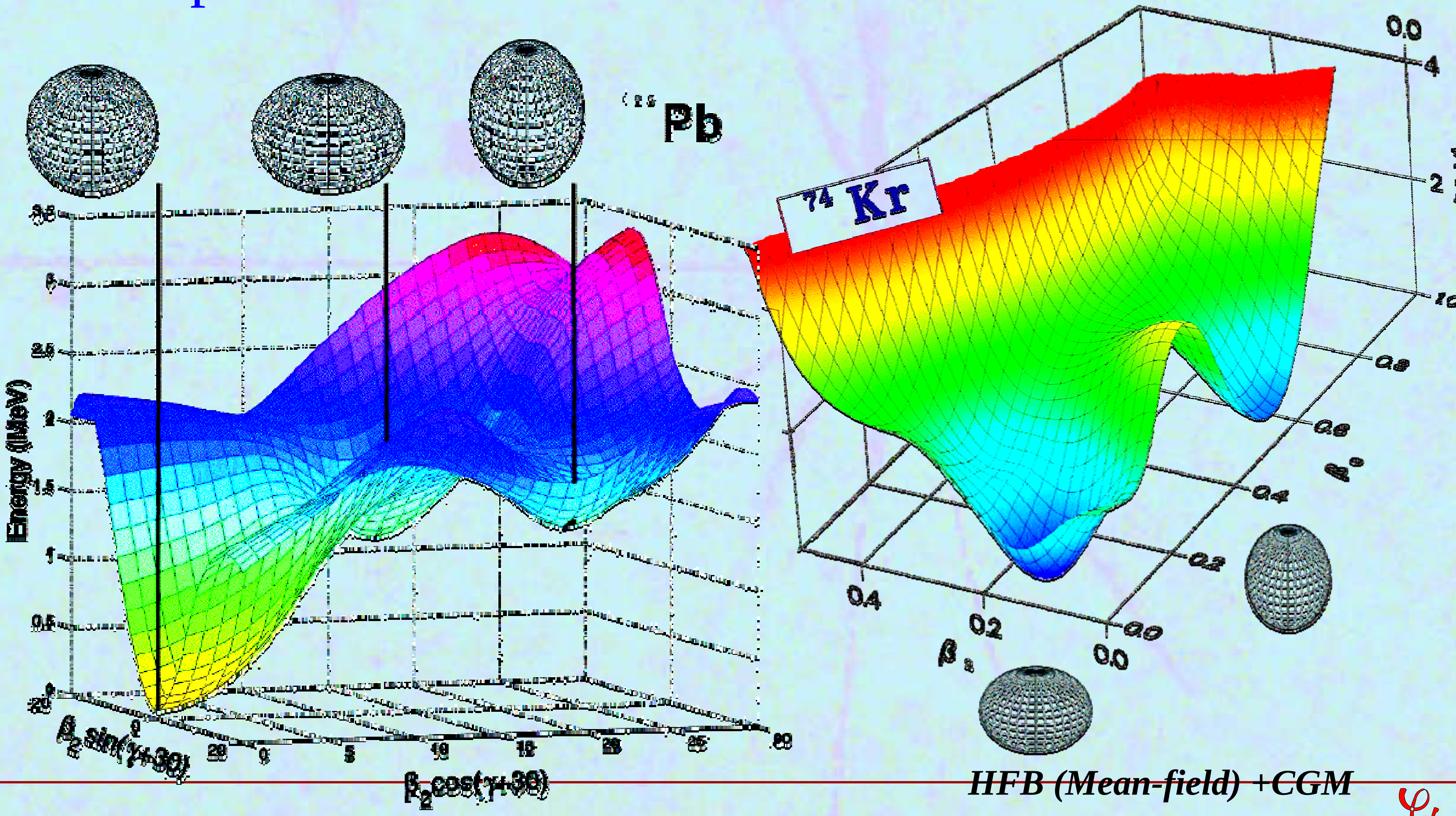




HFB (Mean-field) +CGM

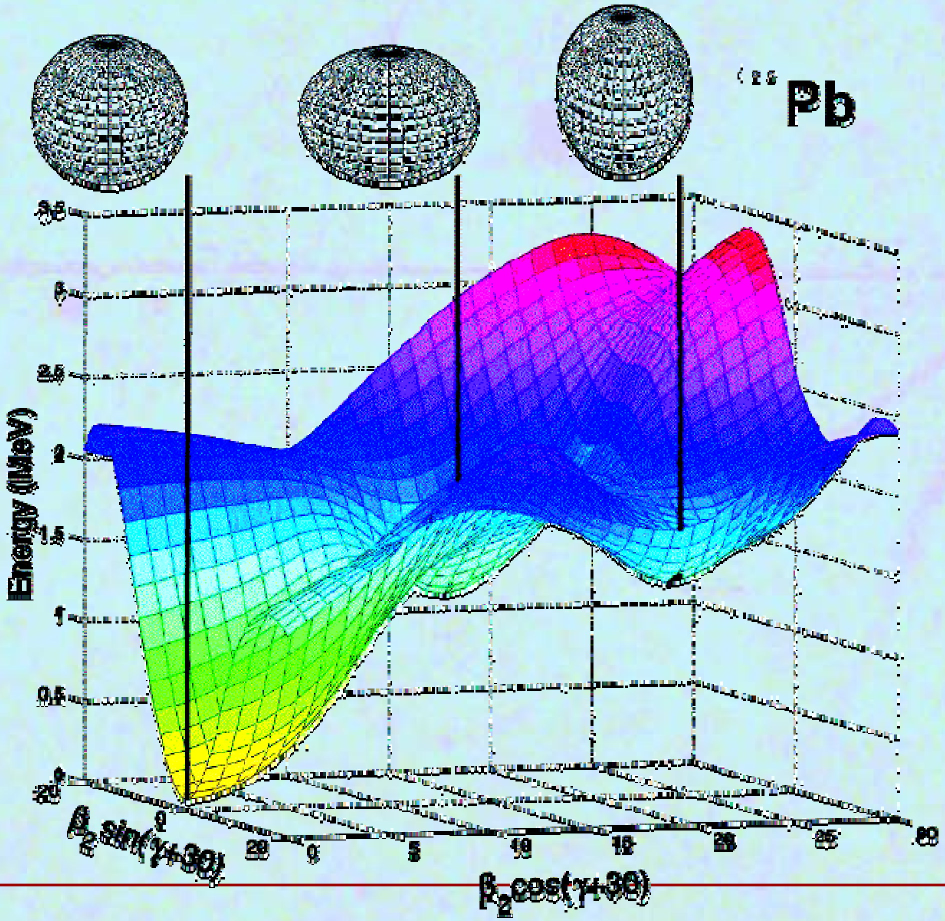
Nuclear deformation

- Shape coexistence and isomers

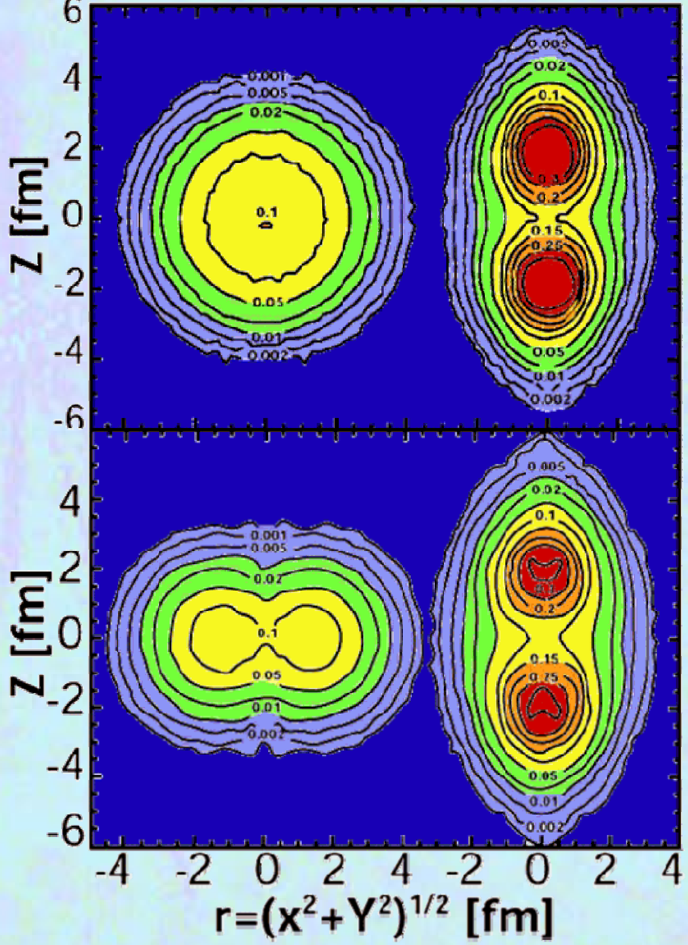


HFB (Mean-field) +CGM

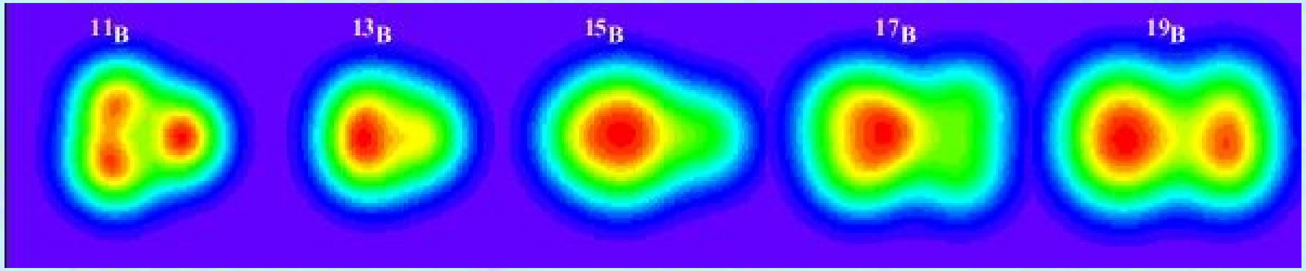
Nuclear deformation



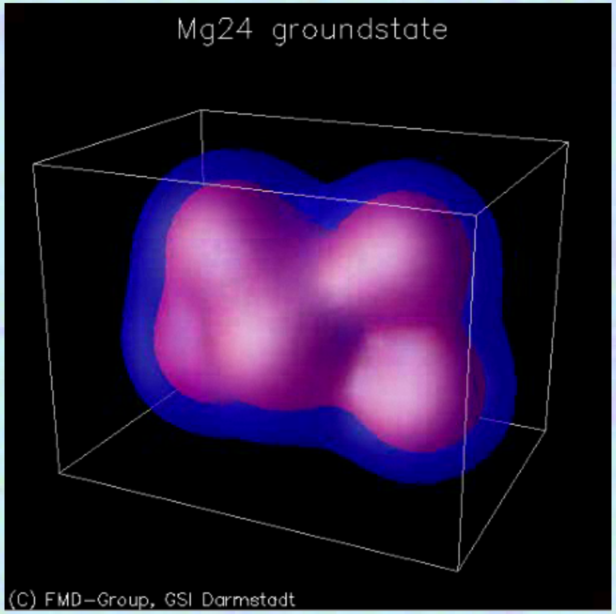
Exact Ab-initio calculations



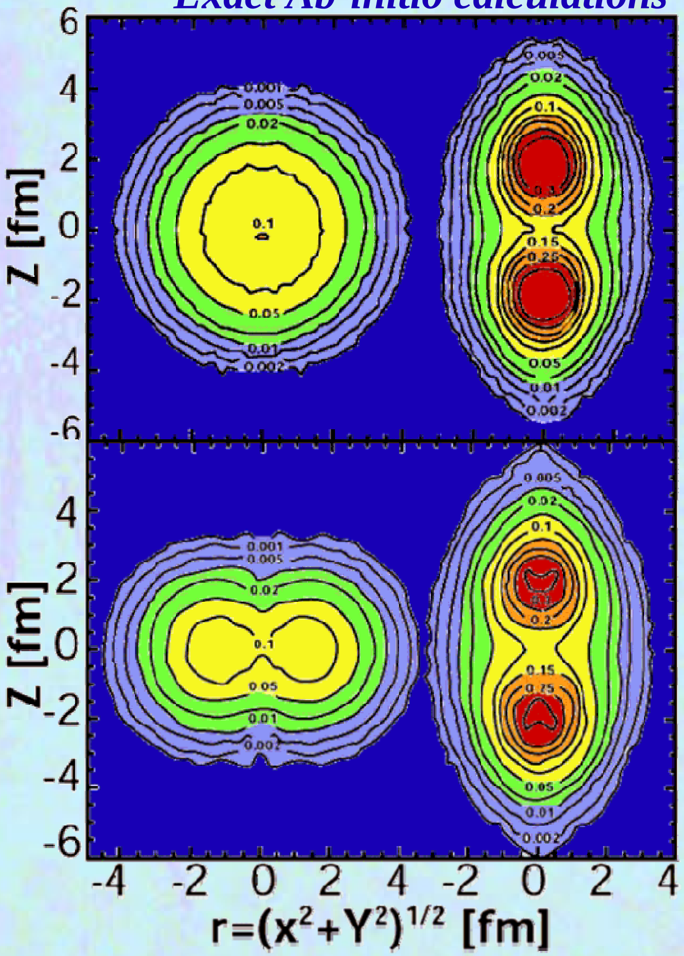
Deformation



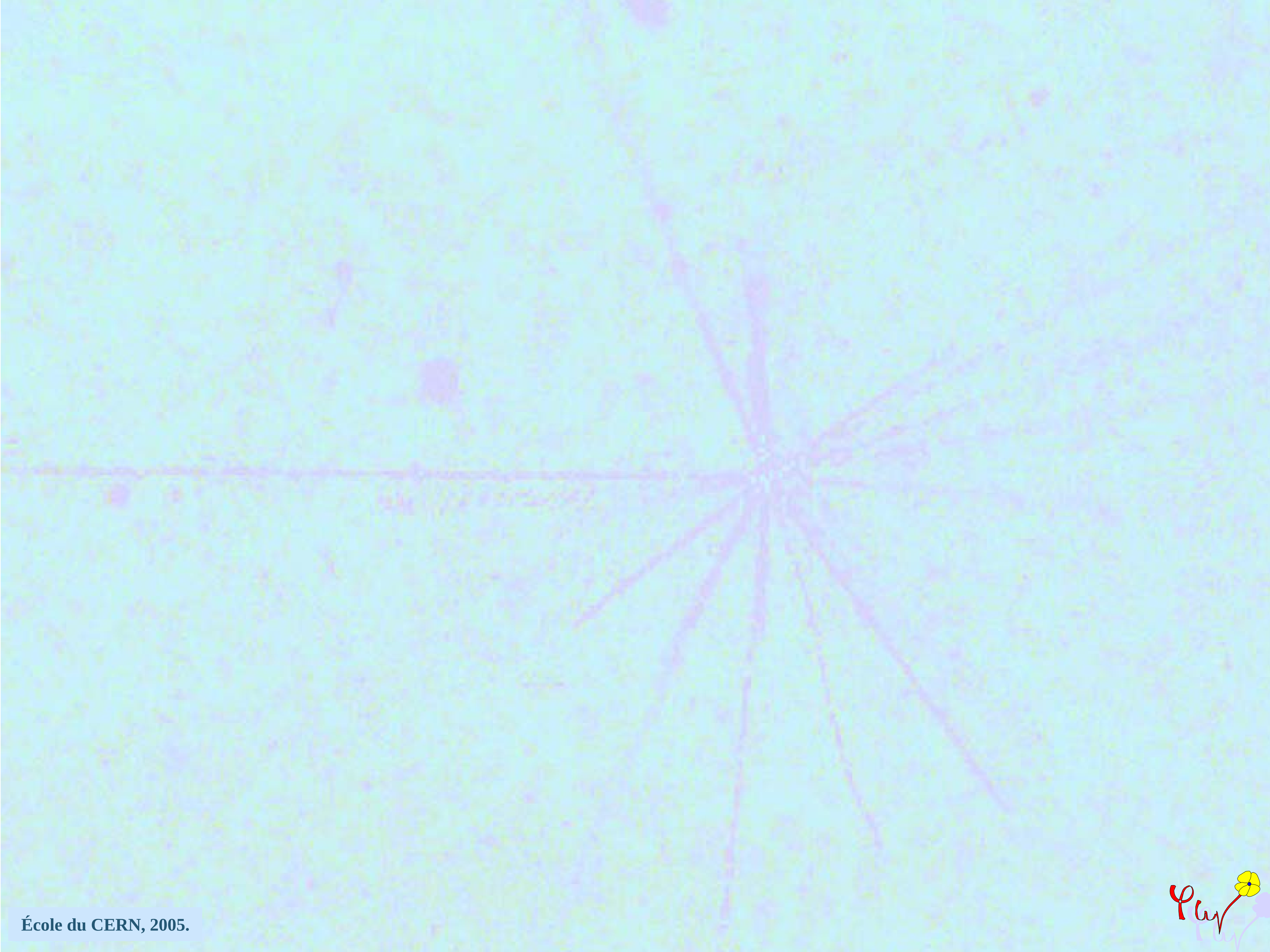
Quantum molecular approach



Exact Ab-initio calculations

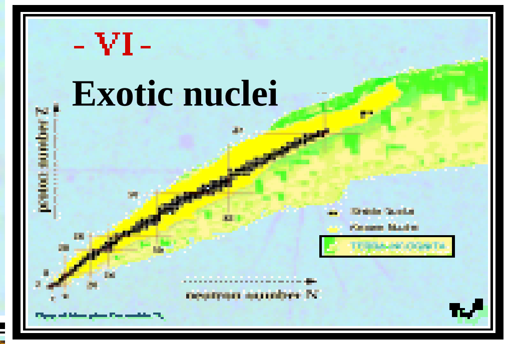


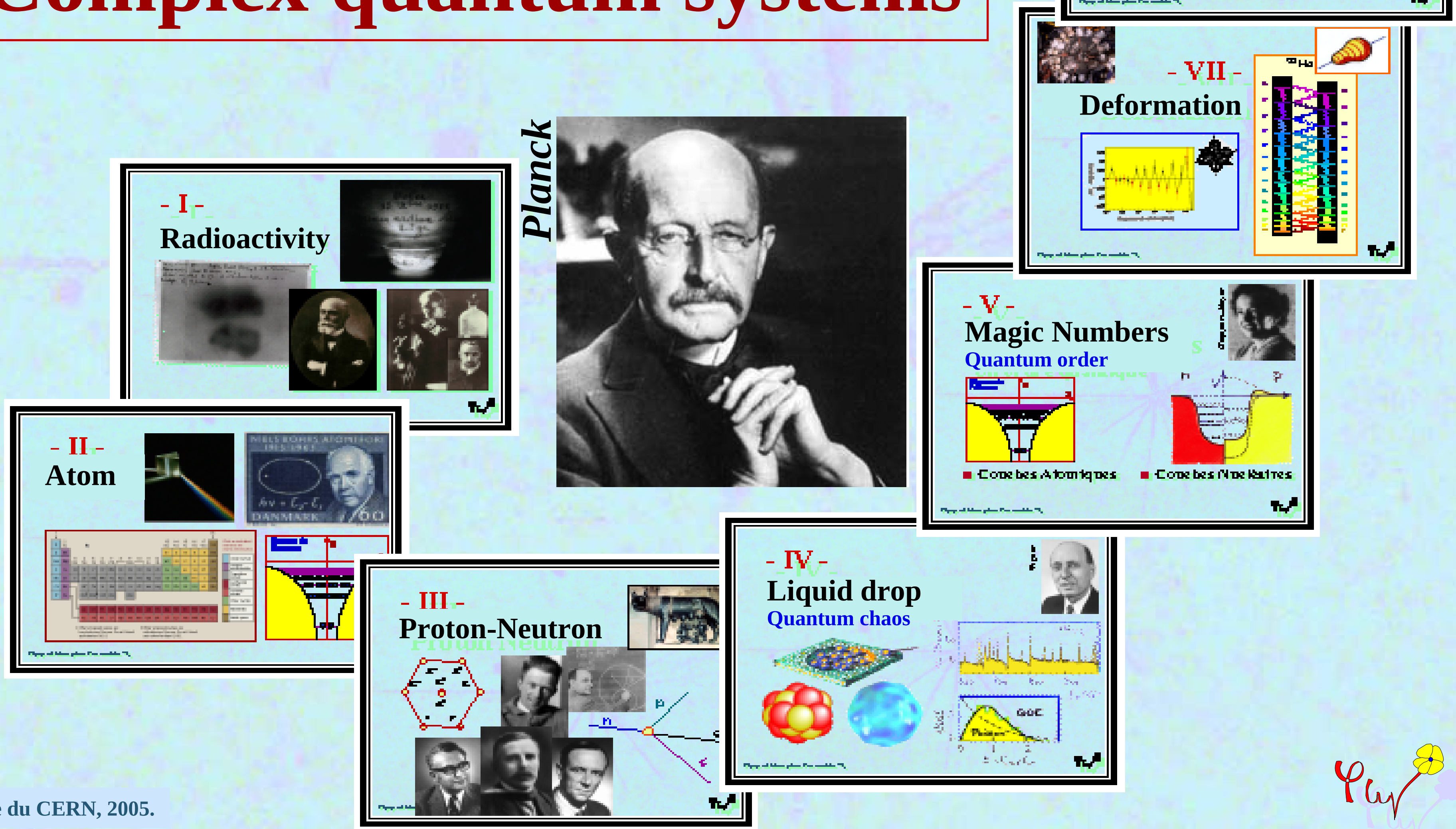
Dramatic effect in small sytem

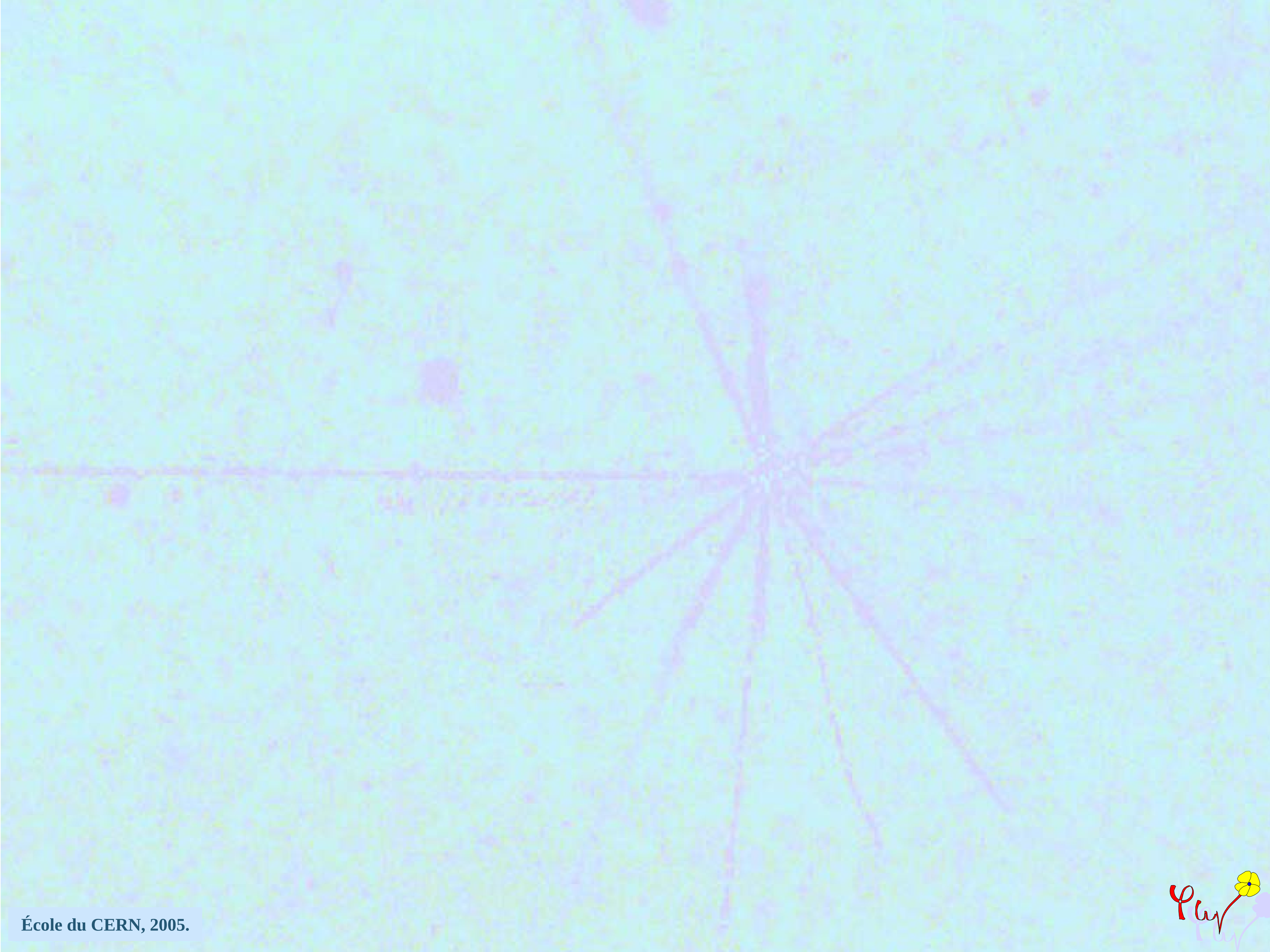


Atomic Nuclei

Complex quantum systems





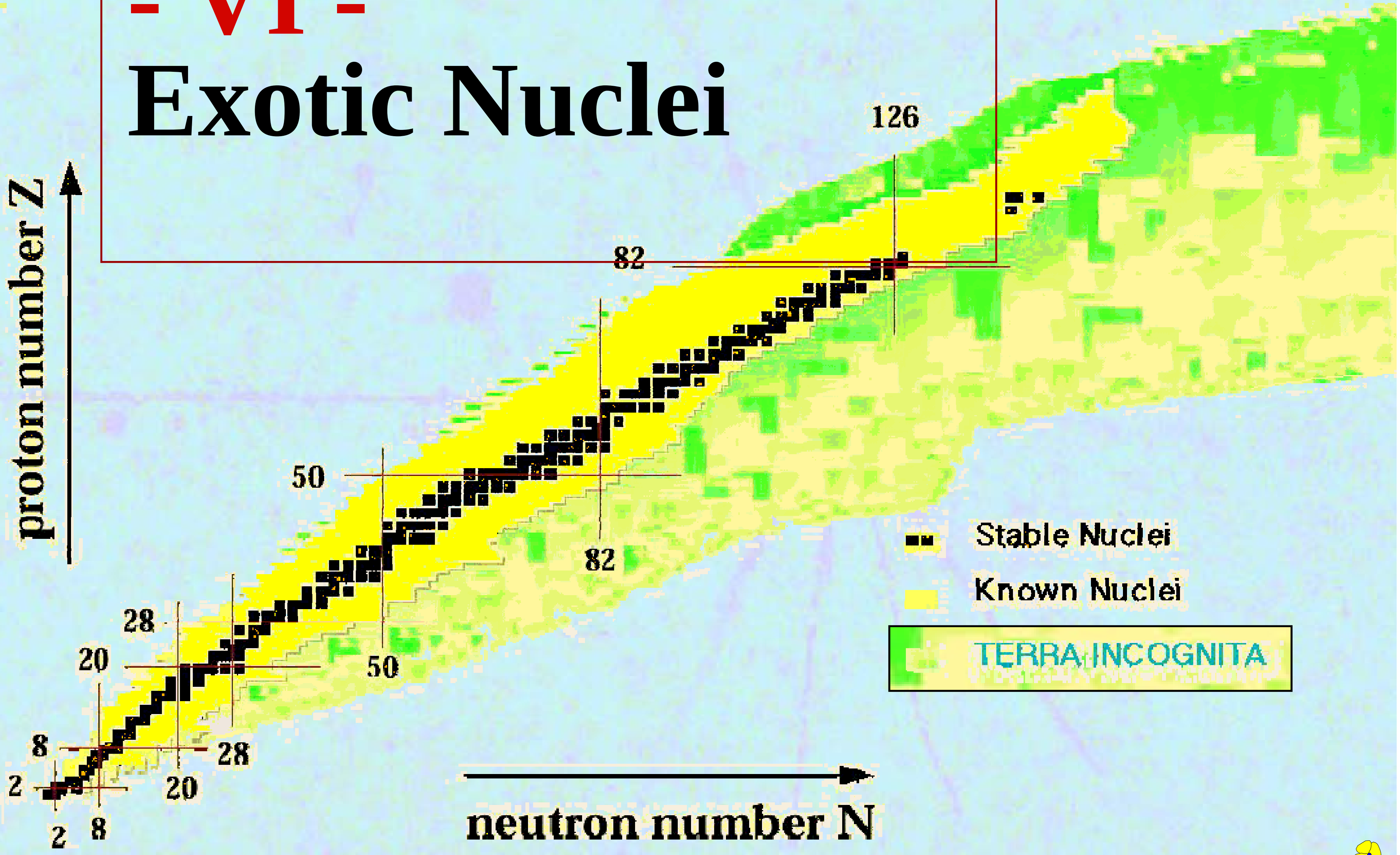


École du CERN, 2005.

- VI -
Exotic Nuclei
New Quantum structures

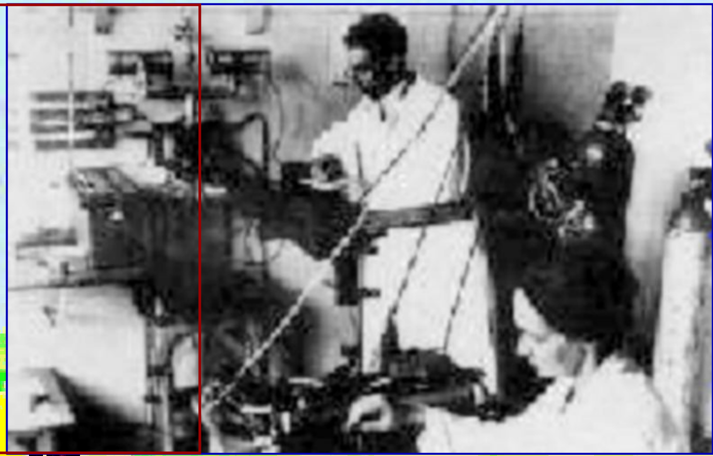
- VI -
Exotic Nuclei

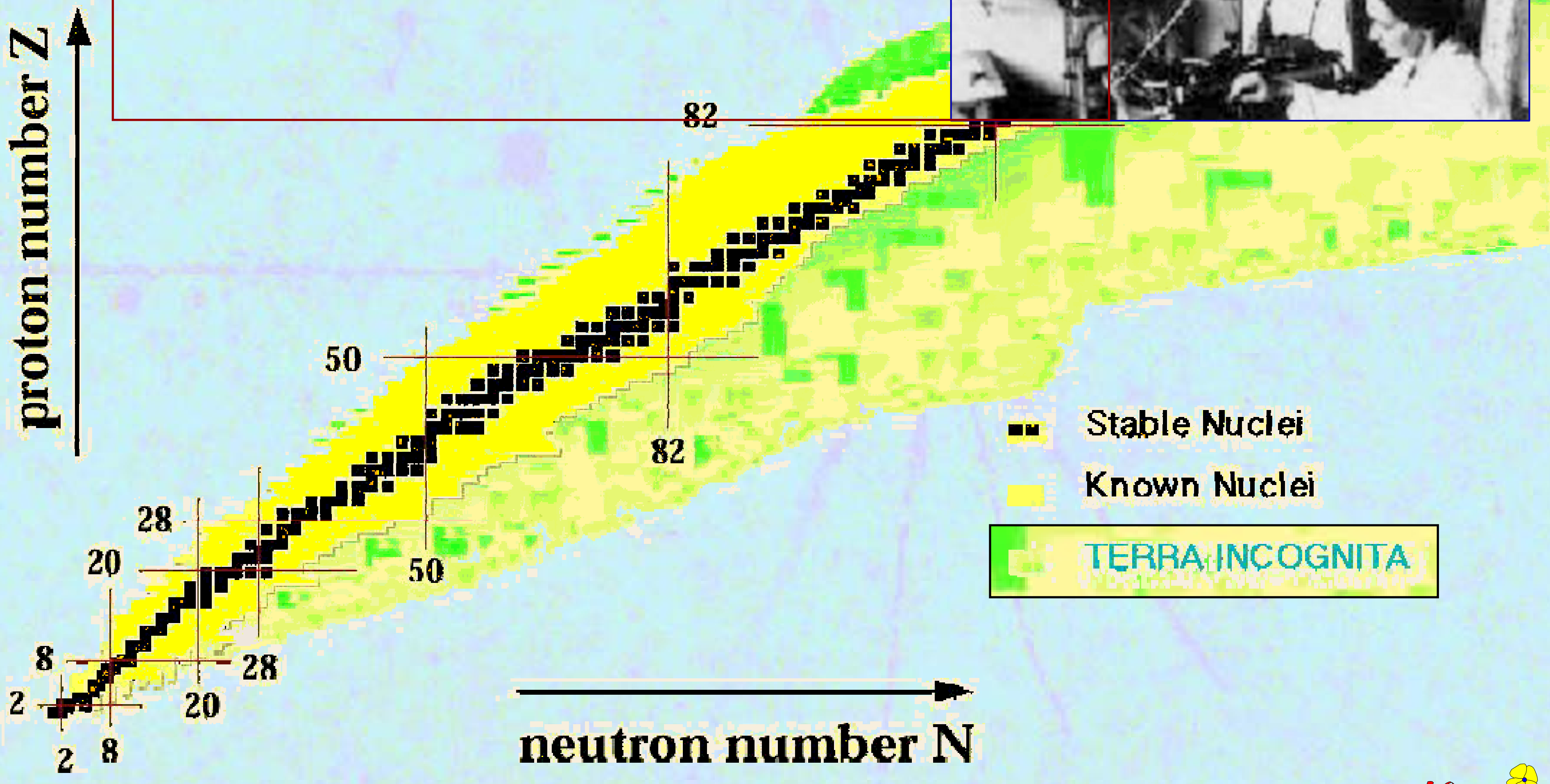
- VI -
Exotic Nuclei



- VI -
Exotic Nuclei

Joliot-Curie

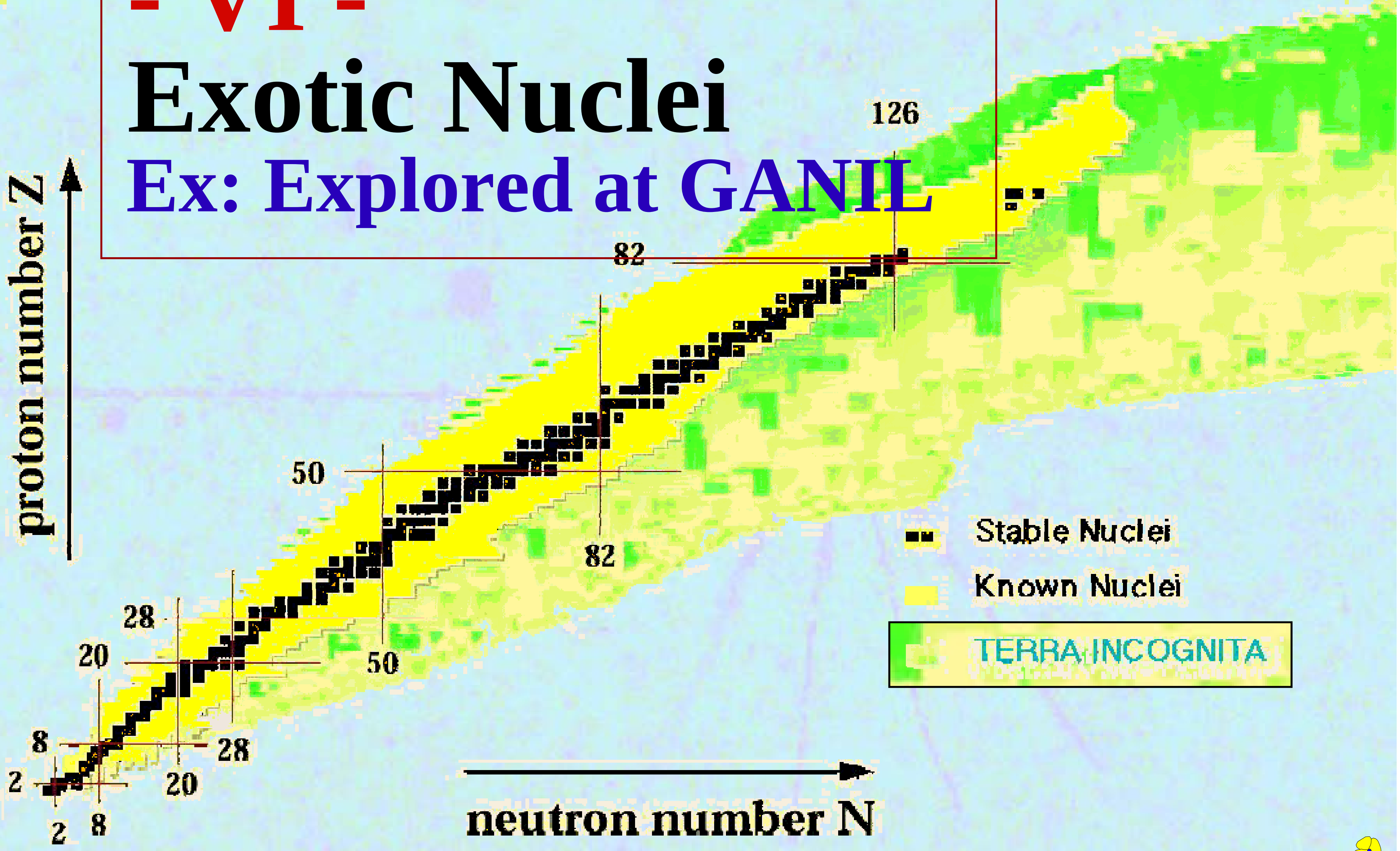




- VI -

Exotic Nuclei

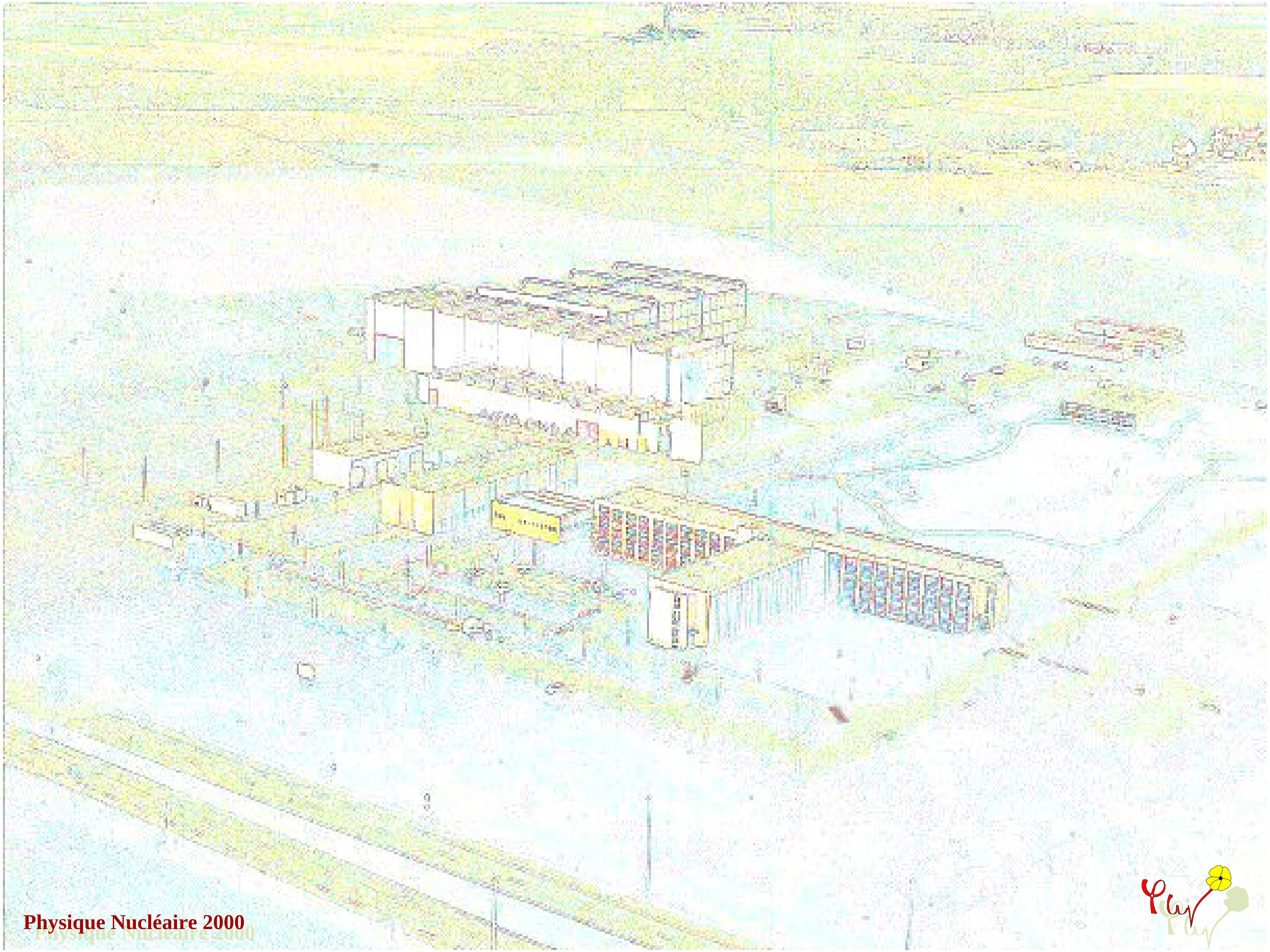
Ex: Explored at GANIL



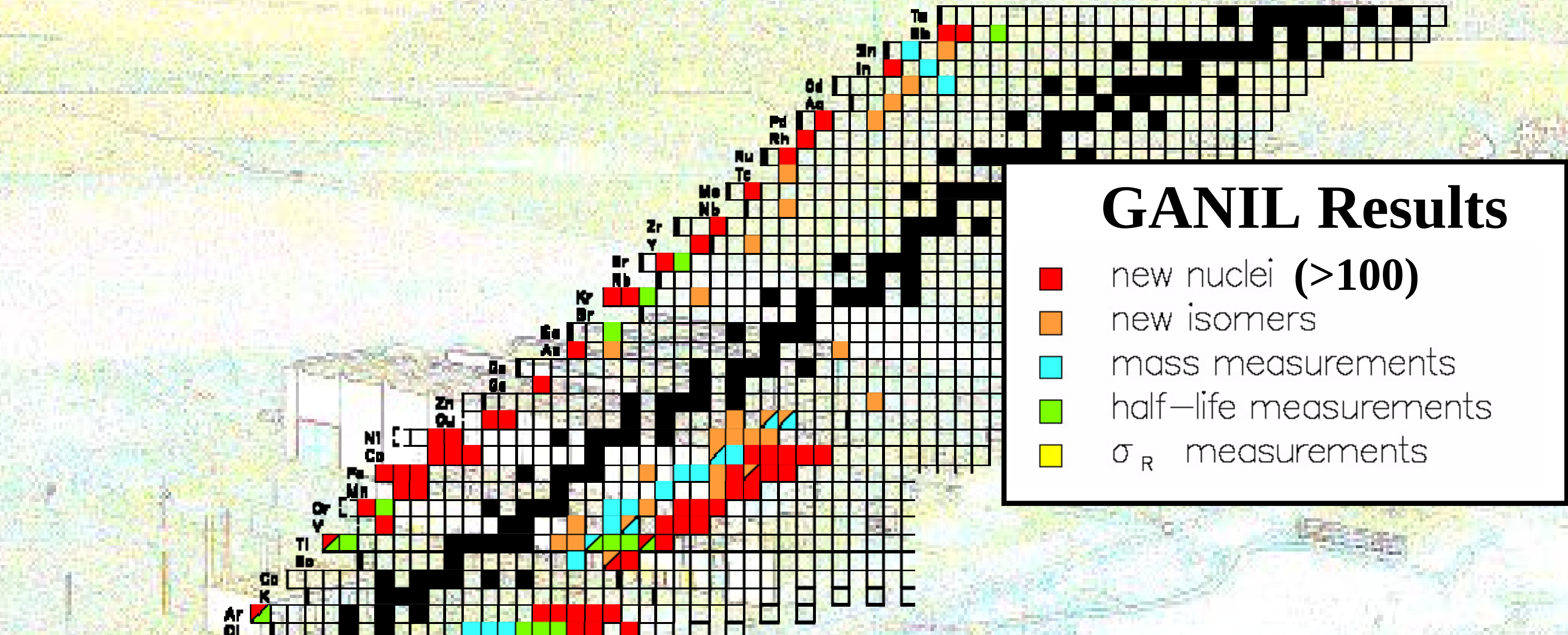
- VI -

Exotic Nuclei

Ex: Explored at GANIL

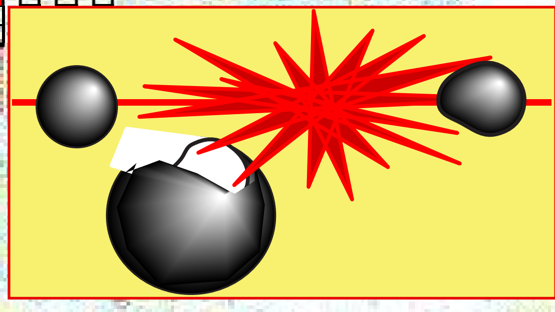


Physique Nucléaire 2000



Protons number

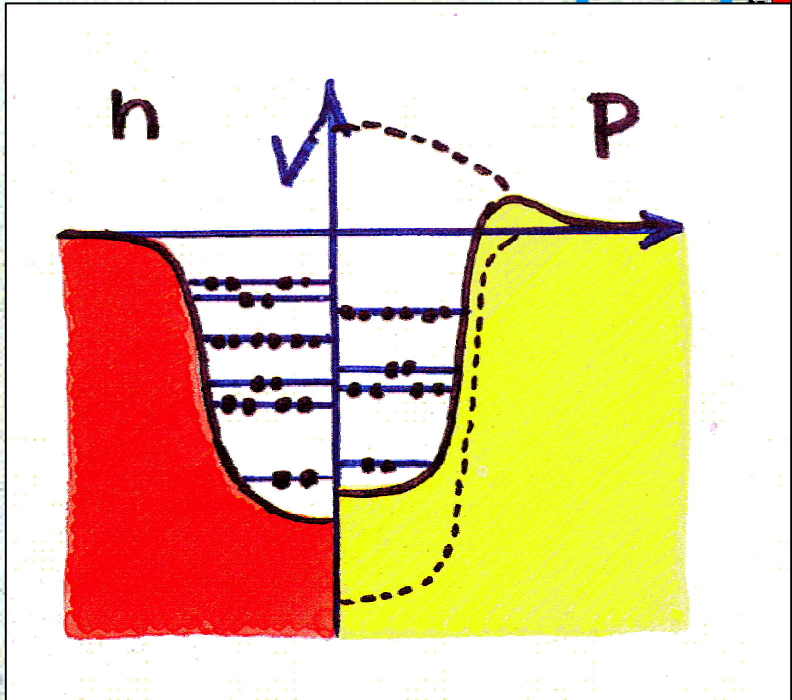
Neutrons number

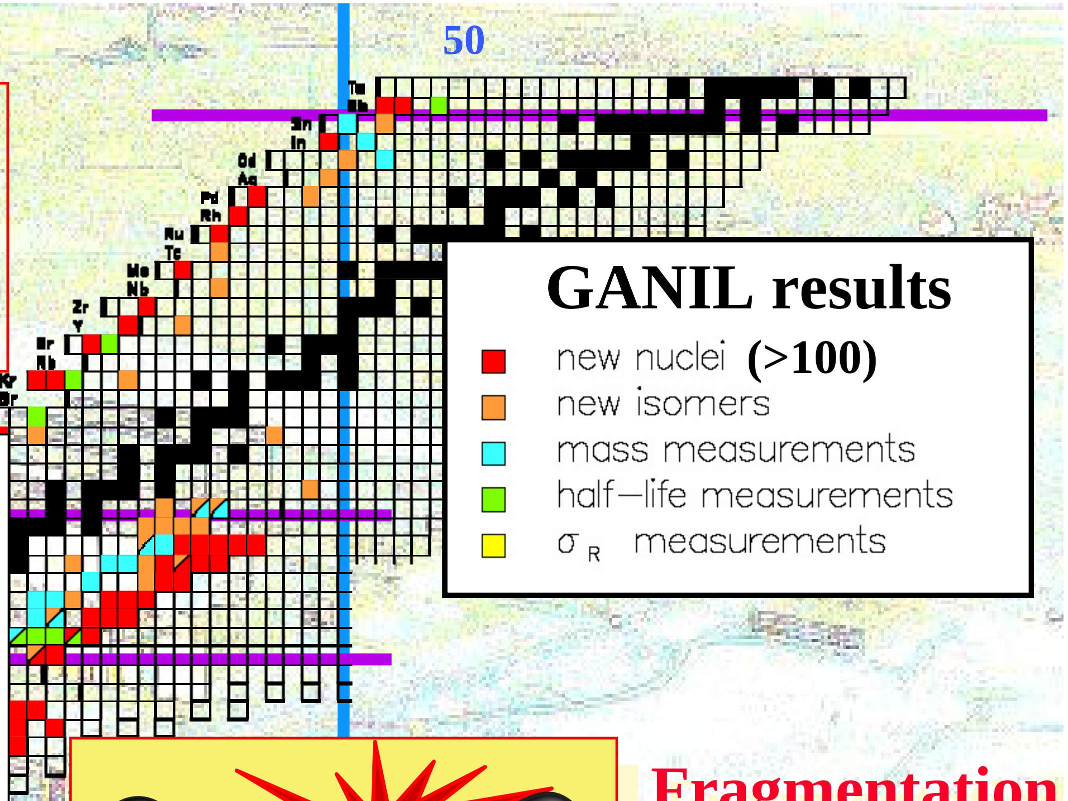


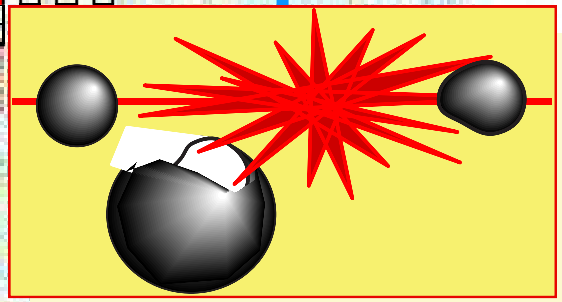
Fragmentation of projectiles

Exotic Nuclei

Magic Numbers

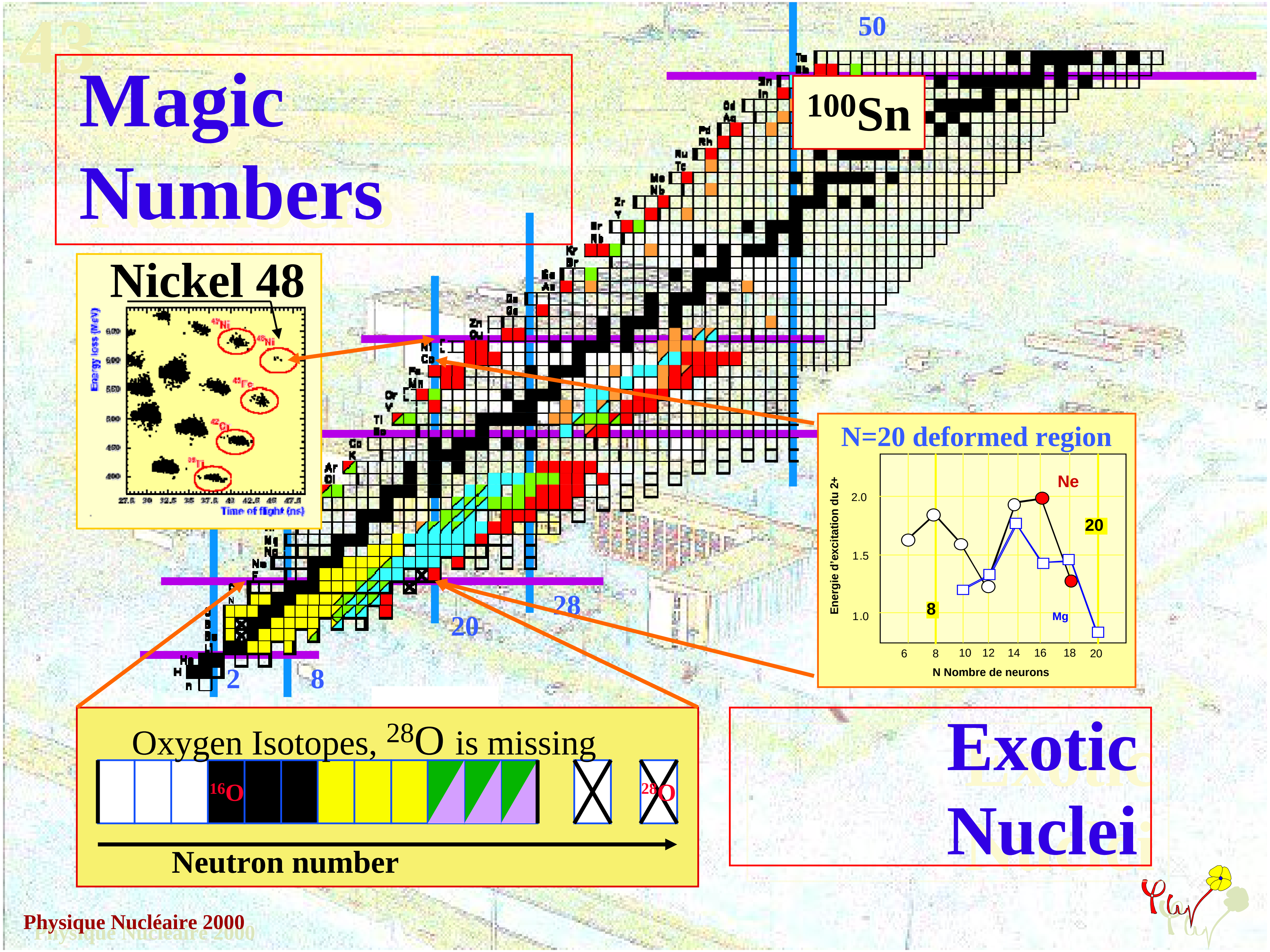






Fragmentation of projectile

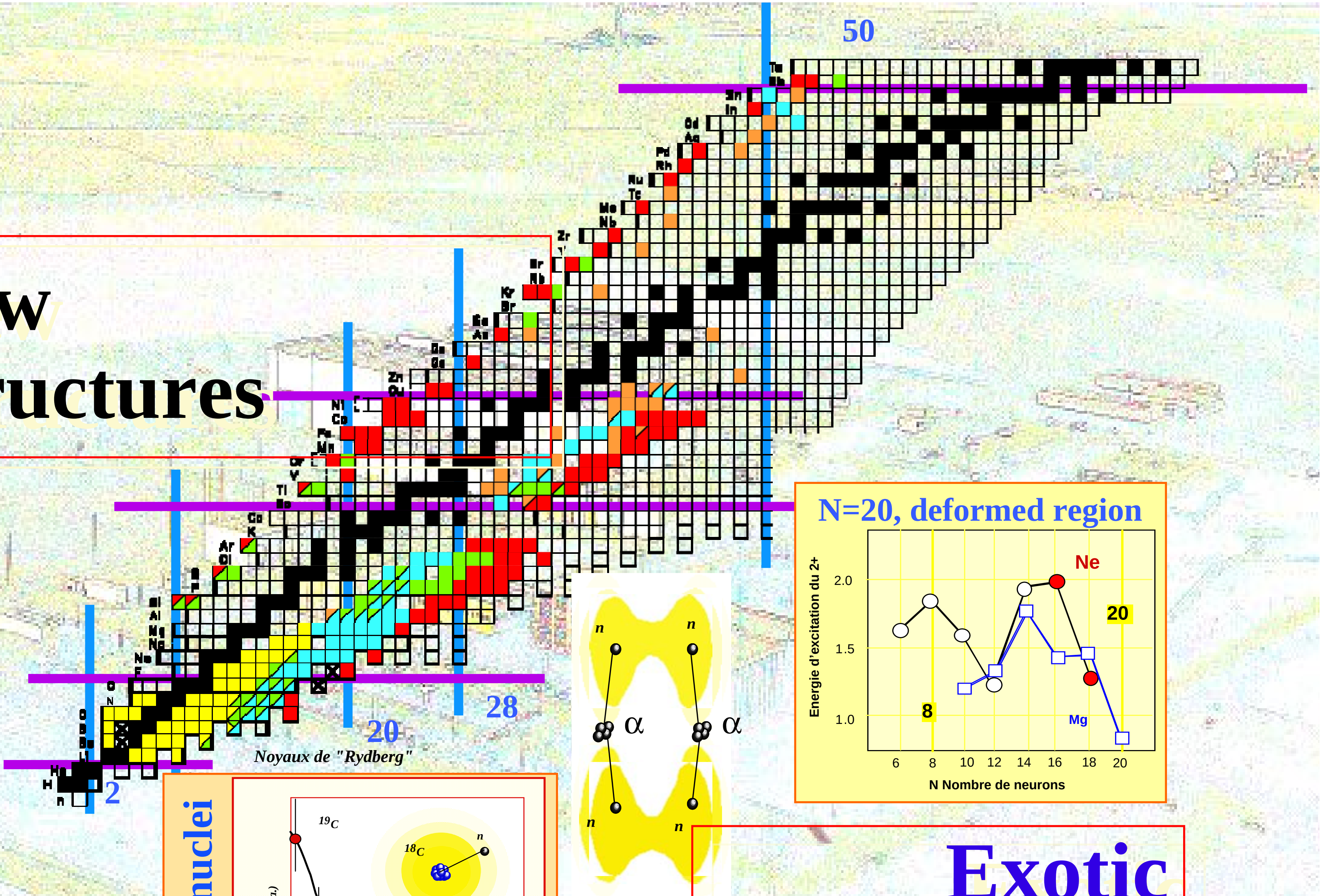
Exotic Nuclei



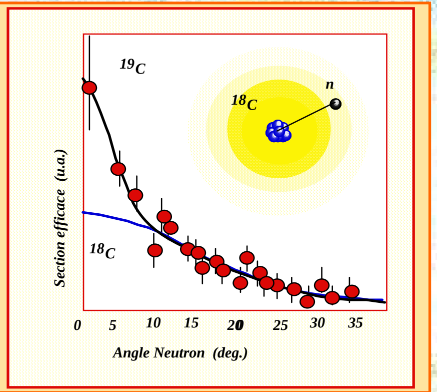
Magic Numbers
Nickel 48
Time of flight (ns)
Energy loss (MeV)
100Sn
50
28
20
8
2
N=20 deformed region
Ne
Mg
20
8
Energie d'excitation du 2+
N Nombre de neurons
Oxygen Isotopes, 28O is missing
16O
28O
Neutron number
Exotic Nuclei

45

New Structures

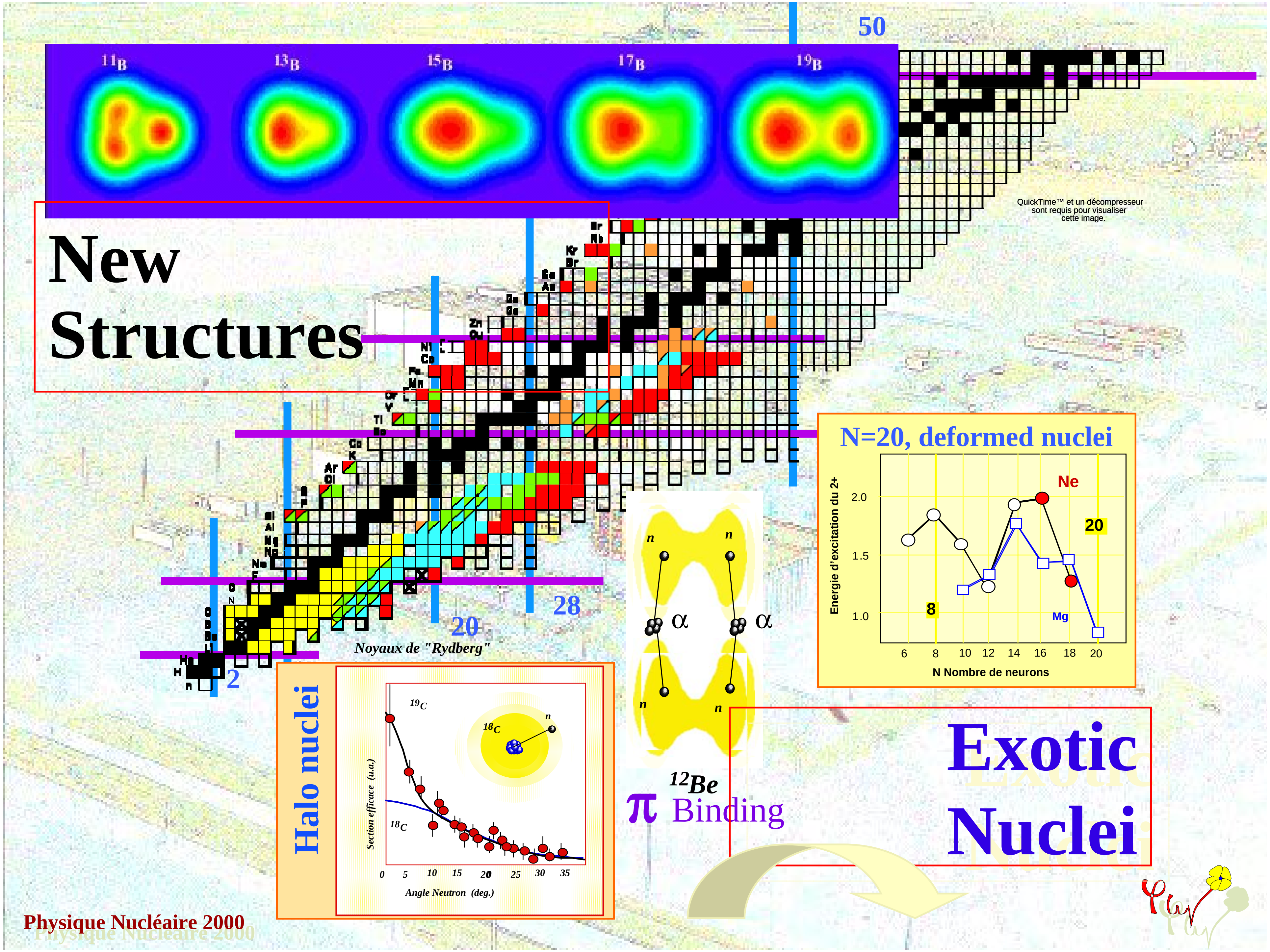


Halo nuclei



π Binding

Exotic Nuclei

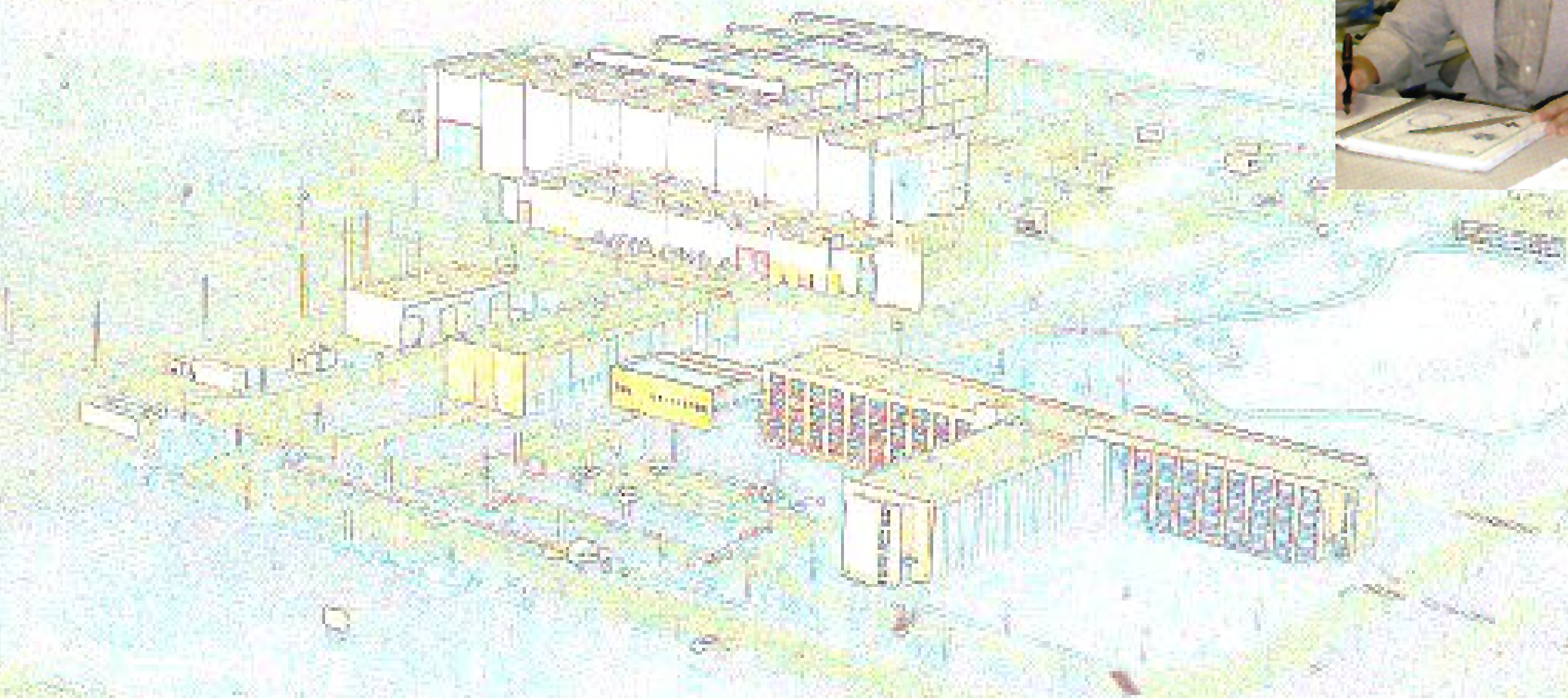


New Structures
Exotic Nuclei
Halo nuclei
N=20, deformed nuclei
Ne
Mg
20
8
Energie d'excitation du 2+
N Nombre de neurons
Noyaux de "Rydberg"
^{12}Be
π Binding
α
n
^{11}B
^{13}B
^{15}B
^{17}B
^{19}B
^{19}C
^{18}C
Section efficace (u.a.)
Angle Neutron (deg.)
2
20
28
50
QuickTime™ et un décompresseur sont requis pour visualiser cette image.
Physique Nucléaire 2000

Halo nuclei

Tanihata

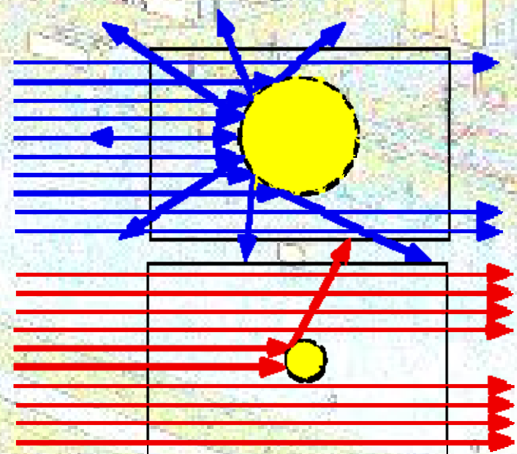
Tanihata



Physique Nucléaire 2000

Halo nuclei

Tanihata

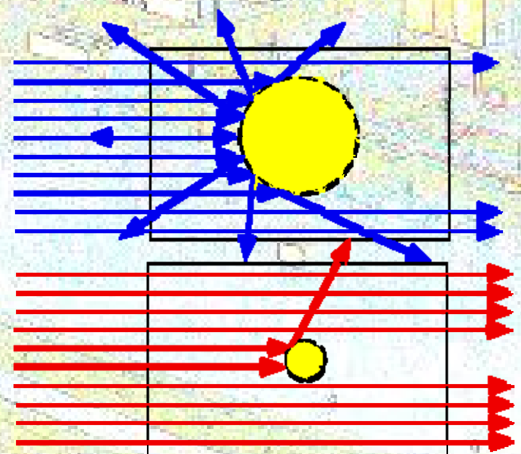


Rutherford experiment

Halo nuclei

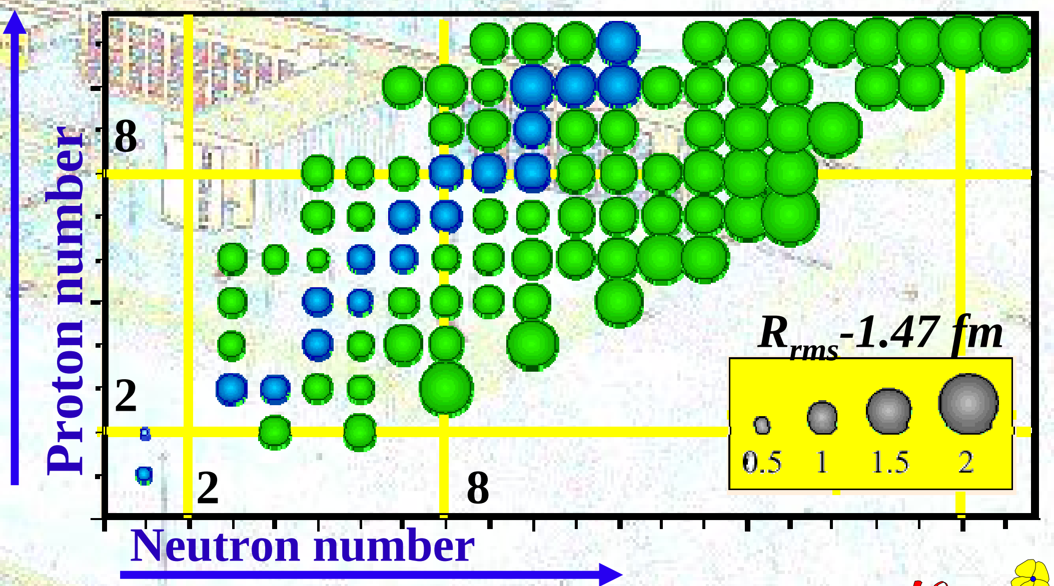
Tanihata

- **Abnormal size of neutron rich nuclei**



Rutherford experiment

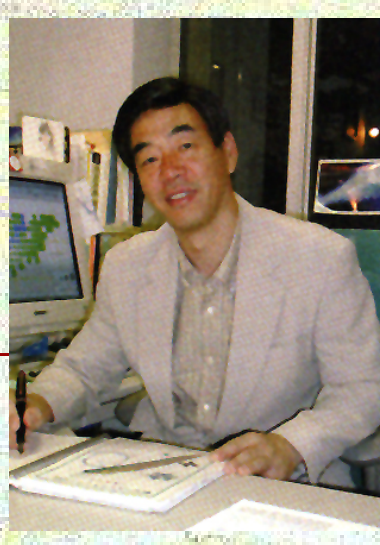
Radii (RMS) of nuclei



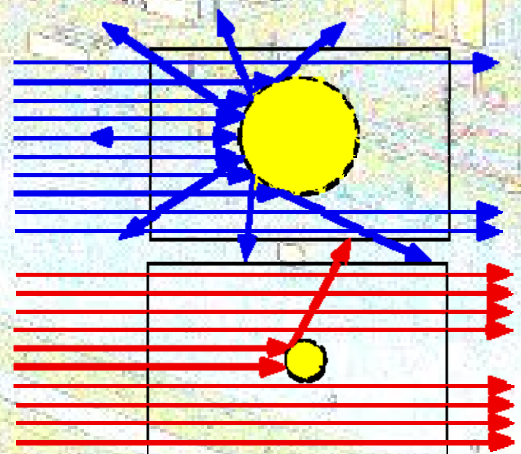
Physique Nucléaire 2000

Halo nuclei

Tanihata

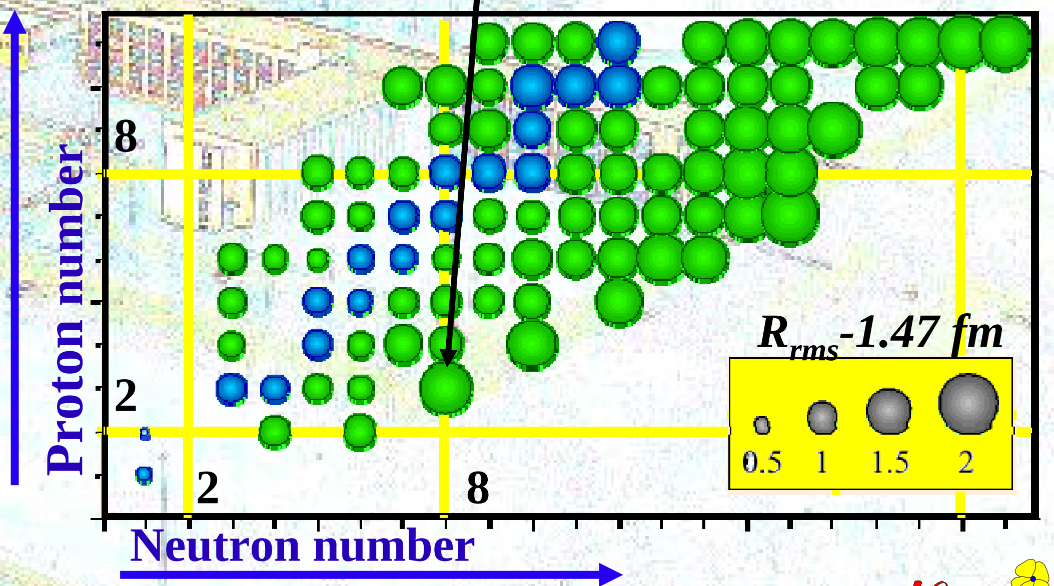


- Abnormal size of neutron rich nuclei ^{11}Li



Rutherford experiment

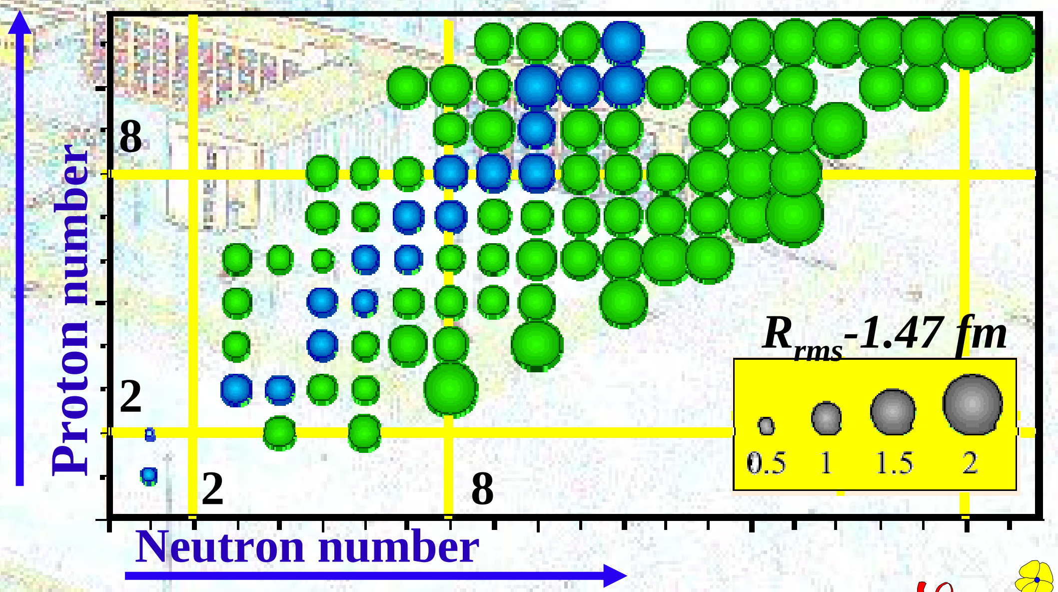
Radii (RMS) of nuclei



Halo nuclei

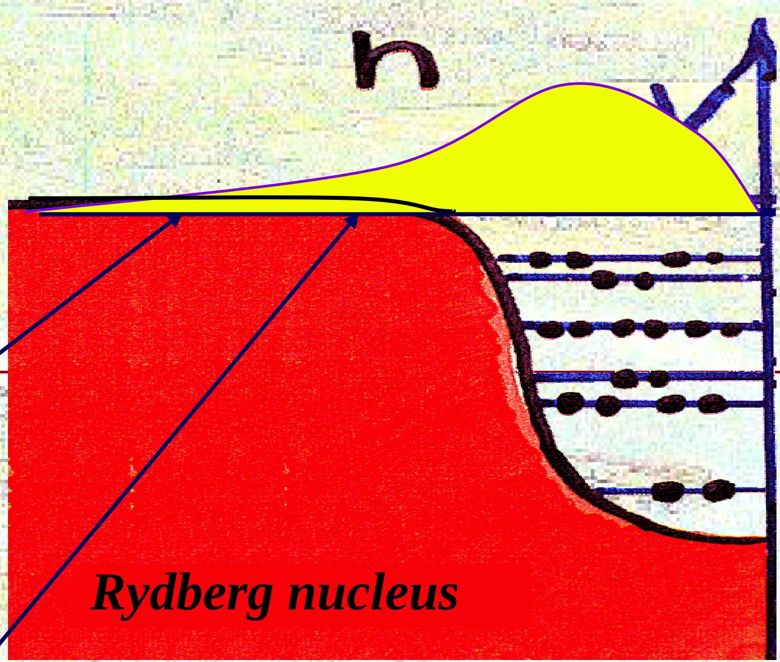
- **Abnormal size of neutron rich nuclei**

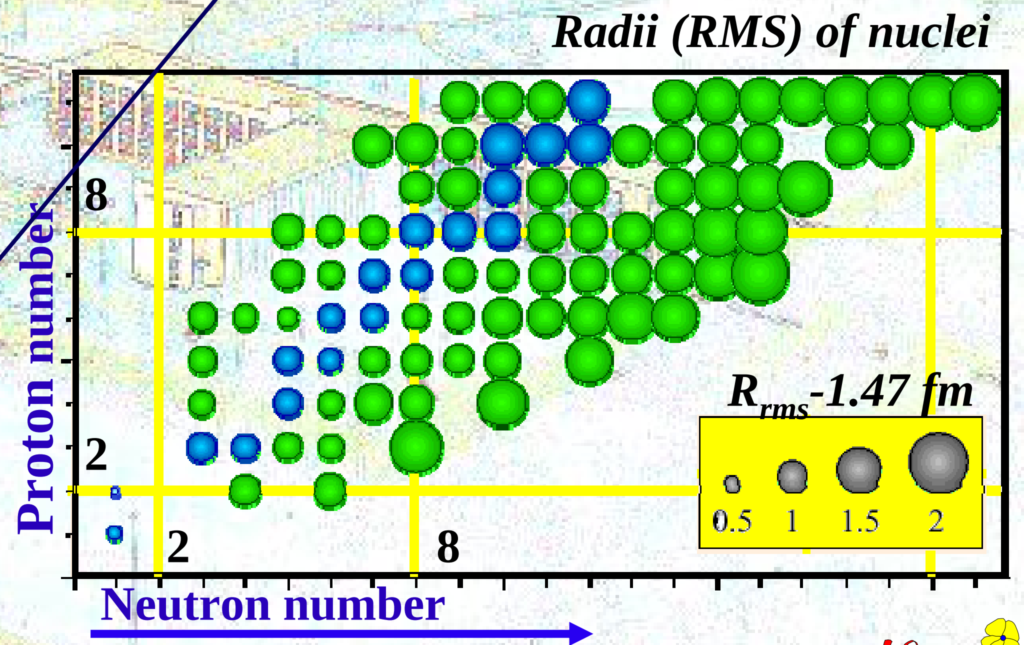
Radii (RMS) of nuclei



Halo nuclei

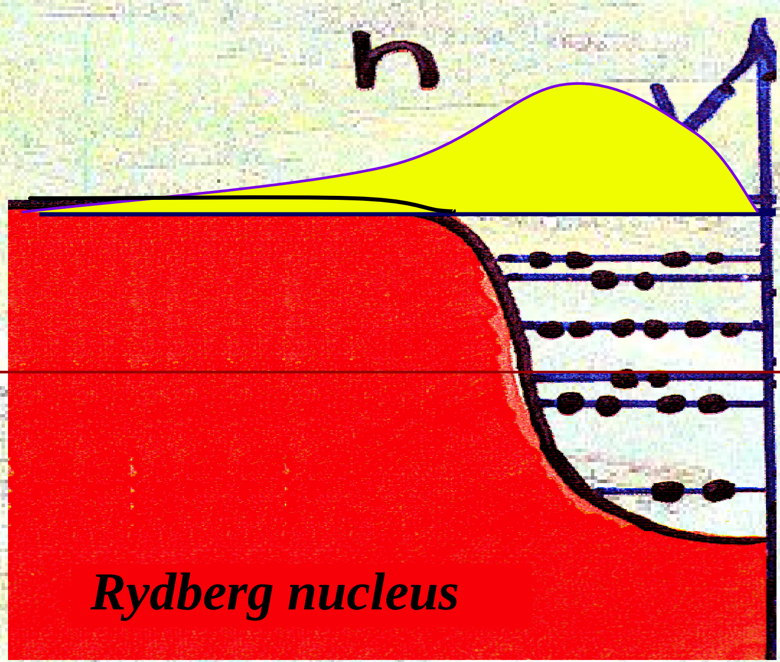
- Abnormal size of neutron rich nuclei
- Weakly bound
- Tunnel effect



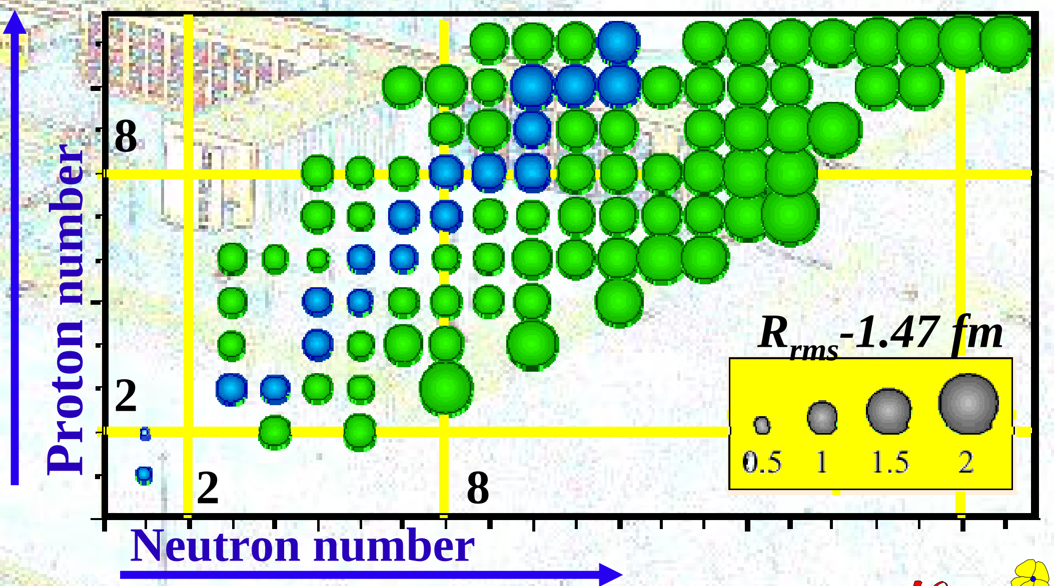


Halo nuclei

- **Abnormal size of neutron rich nuclei**
- **Weakly bound**
- **Tunnel effect**
  THE HALO



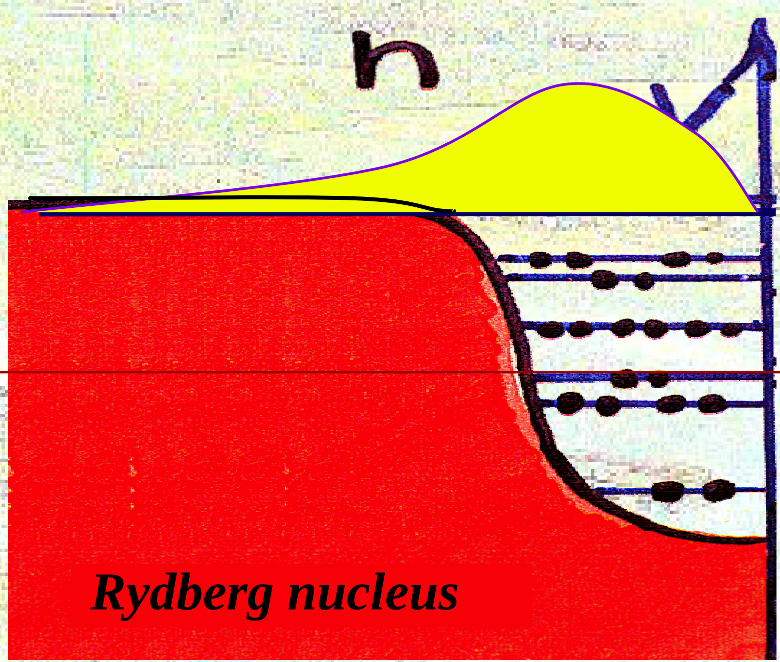
Radii (RMS) of nuclei

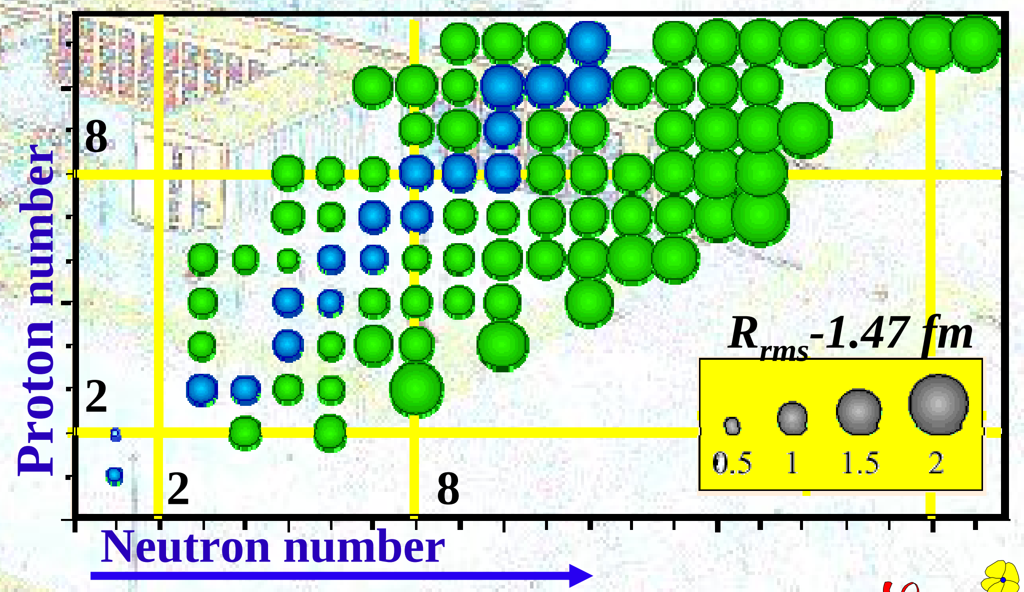


Halo nuclei

- **Abnormal size of neutron rich nuclei**
- **Weakly bound**
- **Tunnel effect**

THE HALO

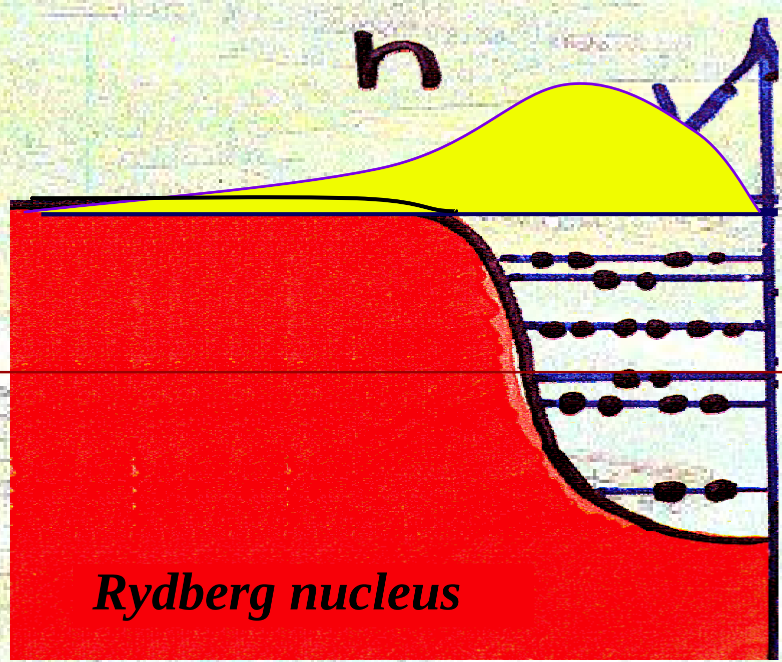




Physique Nucléaire 2000

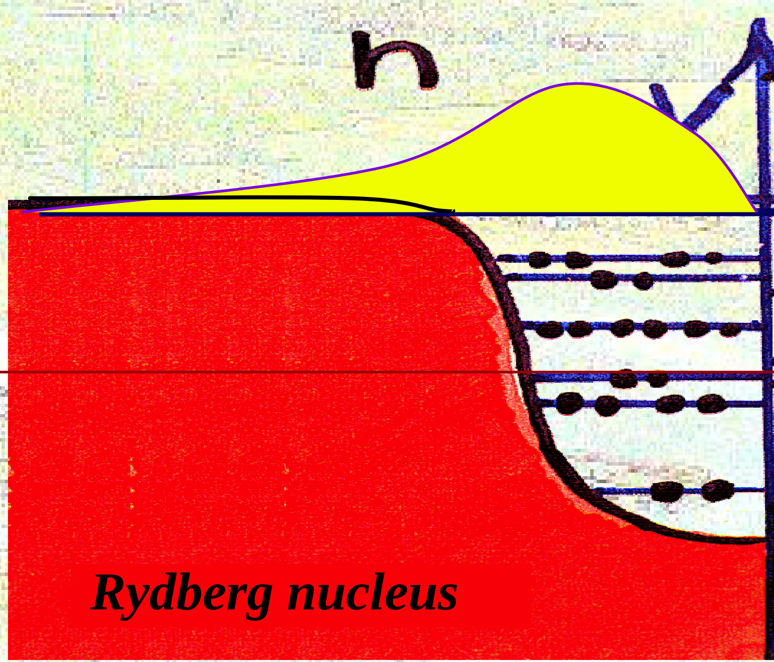
Halo nuclei

- Confirmed by nuclear reaction



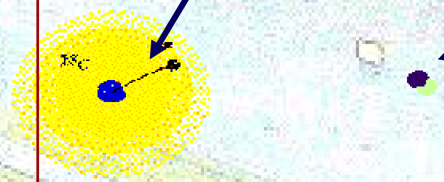
Physique Nucléaire 2000

Halo nuclei



- **Confirmed by nuclear reaction**

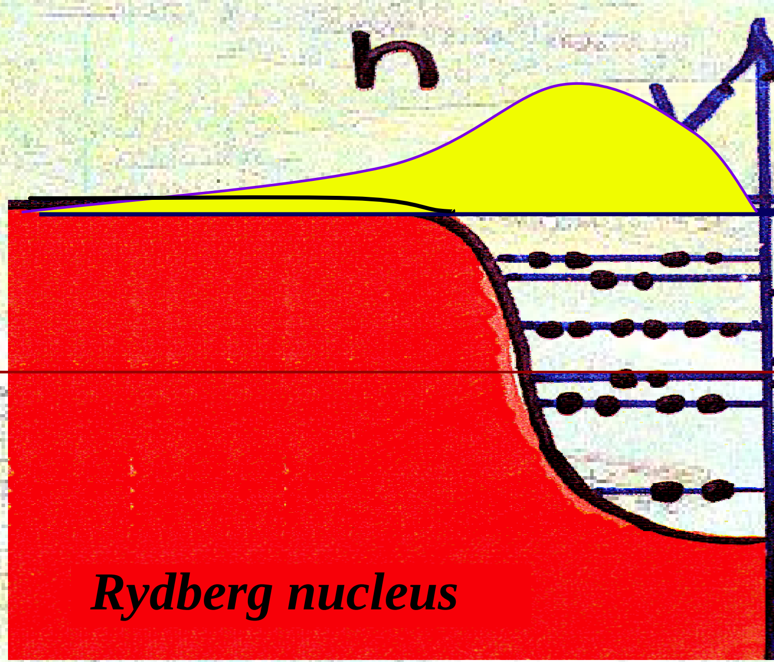
Halo nucleus bombarding a target nucleus

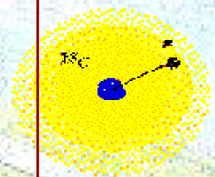


Physique Nucléaire 2000

Halo nuclei

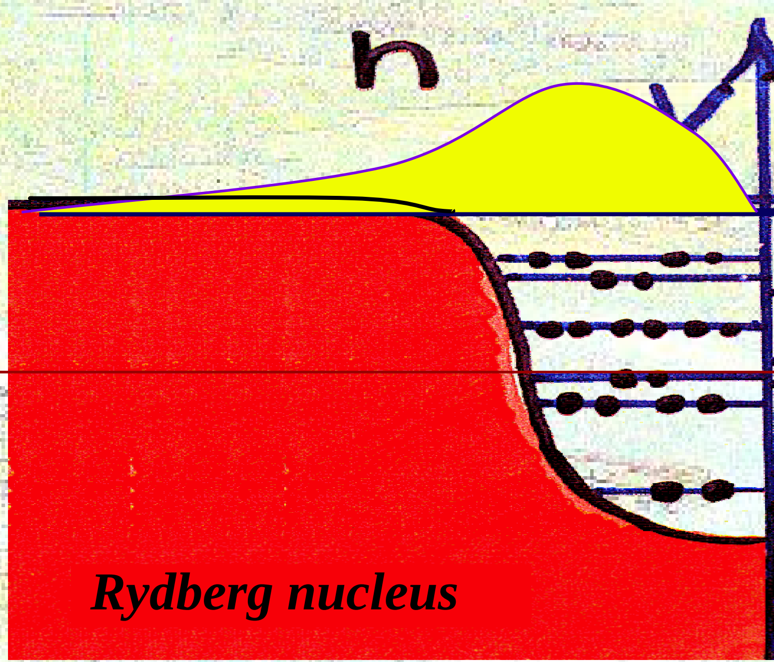
- **Confirmed by nuclear reaction**

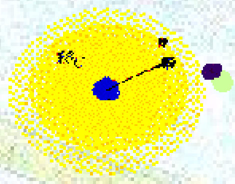




Halo nuclei

- **Confirmed by nuclear reaction**

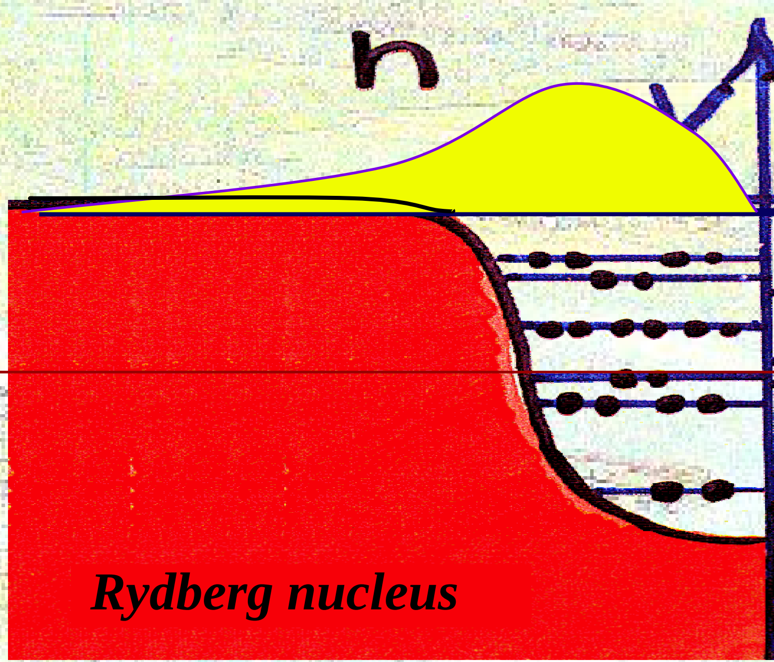


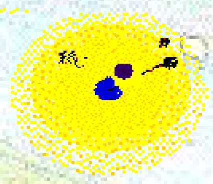


Physique Nucléaire 2000

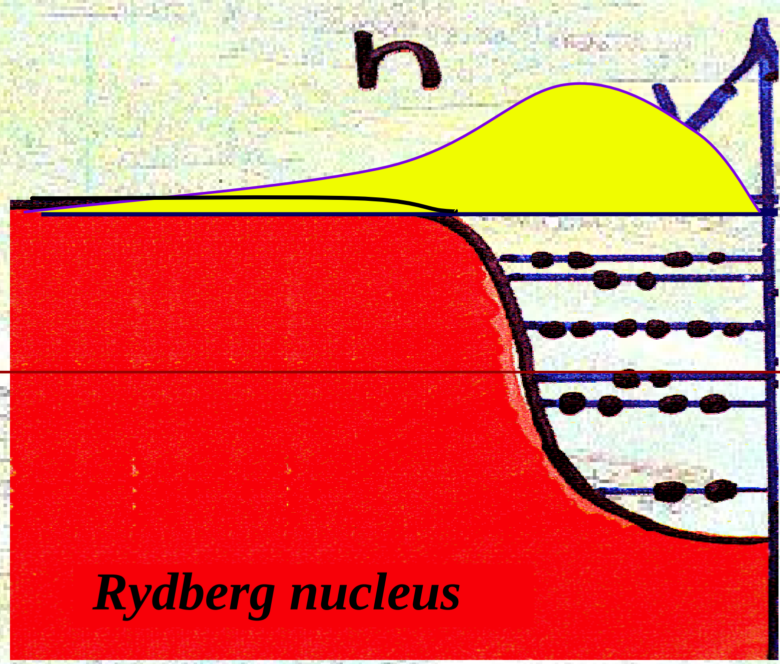
Halo nuclei

- Confirmed by nuclear reaction

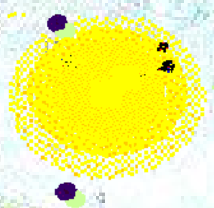




Halo nuclei



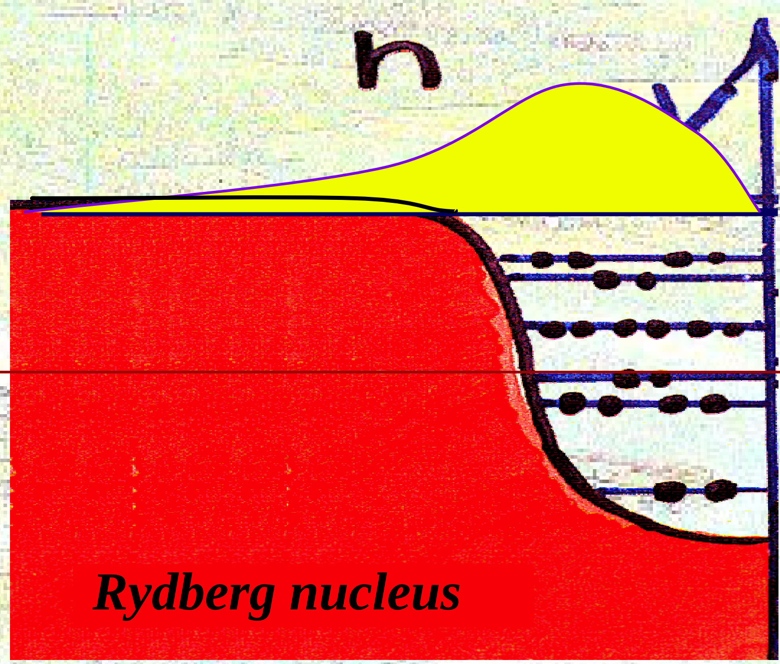
- **Confirmed by nuclear reaction**



Physique Nucléaire 2000

Halo nuclei

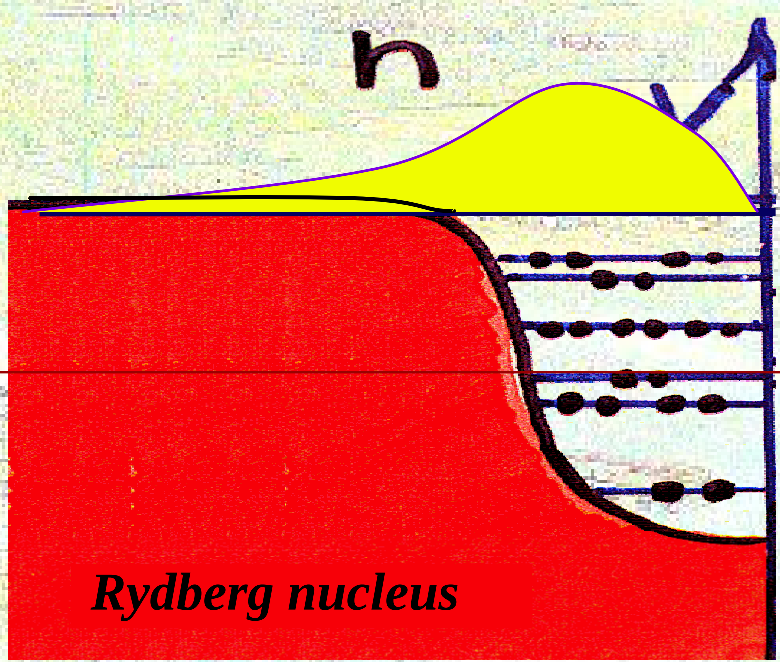
- **Confirmed by nuclear reaction**



Physique Nucléaire 2000

Halo nuclei

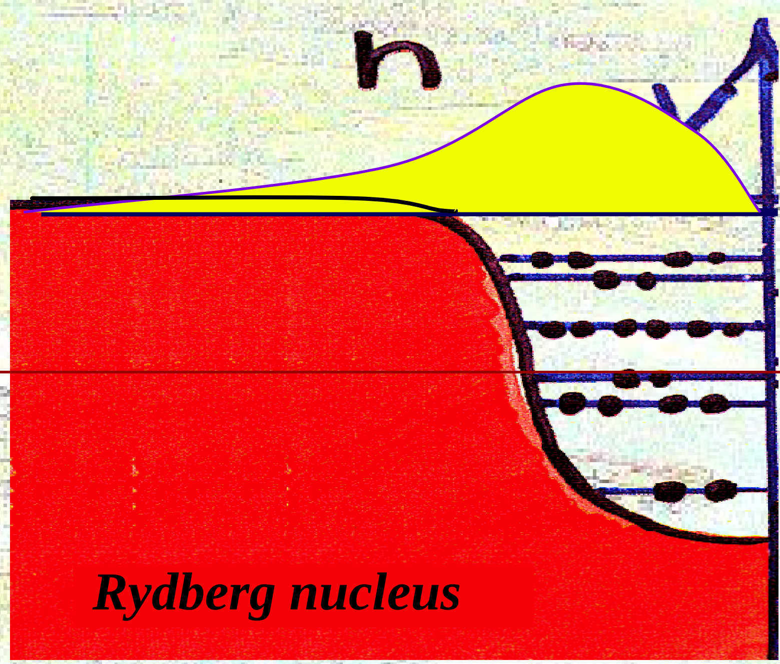
- Confirmed by nuclear reaction



Physique Nucléaire 2000

Halo nuclei

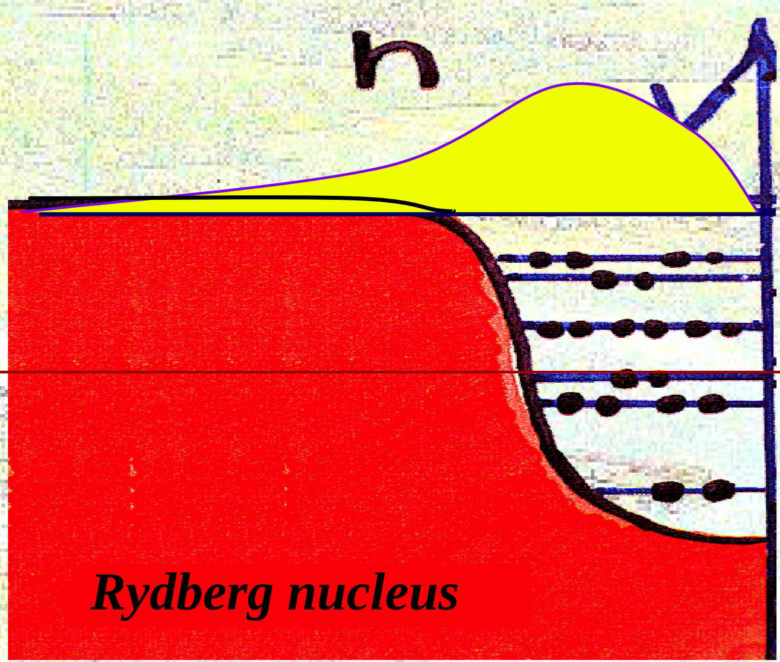
- **Confirmed by nuclear reaction**



Physique Nucléaire 2000

Halo nuclei

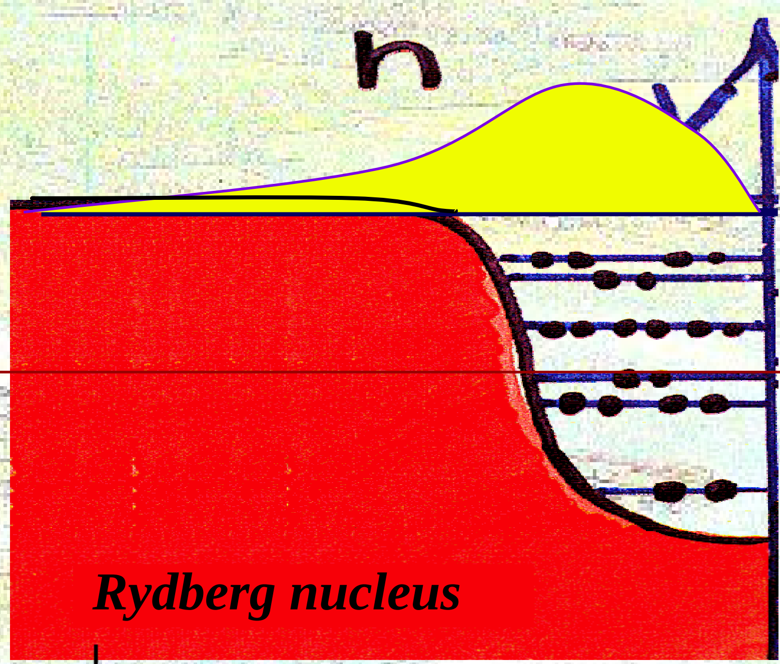
- Confirmed by nuclear reaction

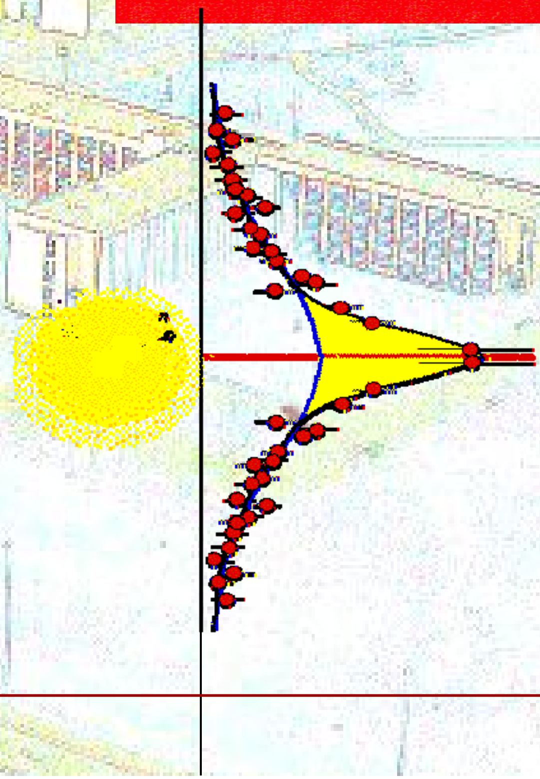


Physique Nucléaire 2000

Halo nuclei

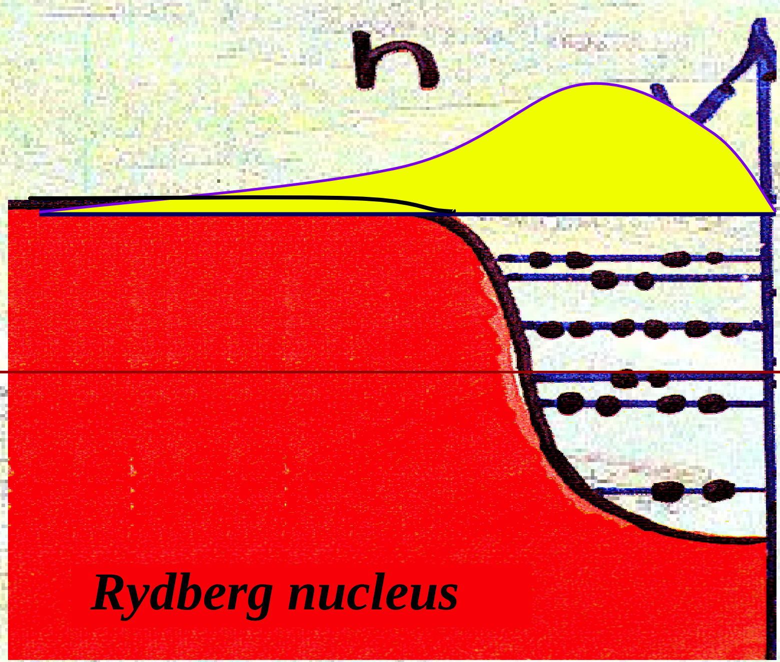
- **Confirmed by nuclear reaction**





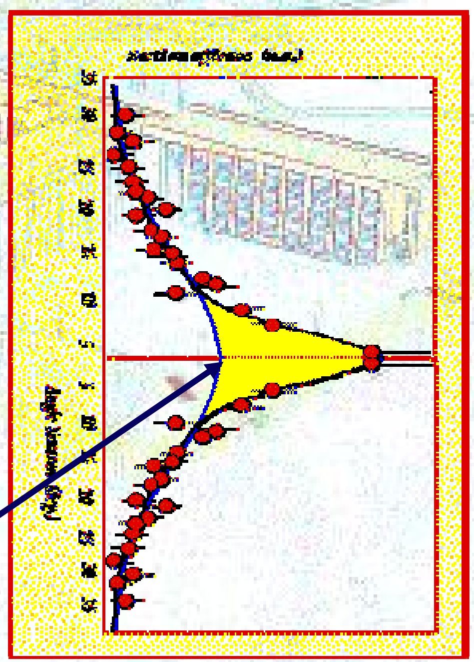
Physique Nucléaire 2000

Halo nuclei



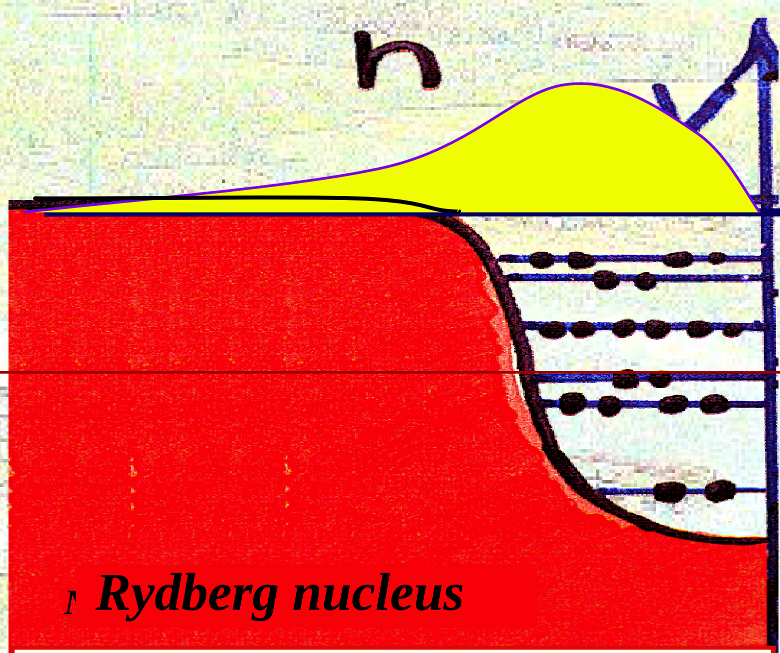
- Confirmed by nuclear reaction

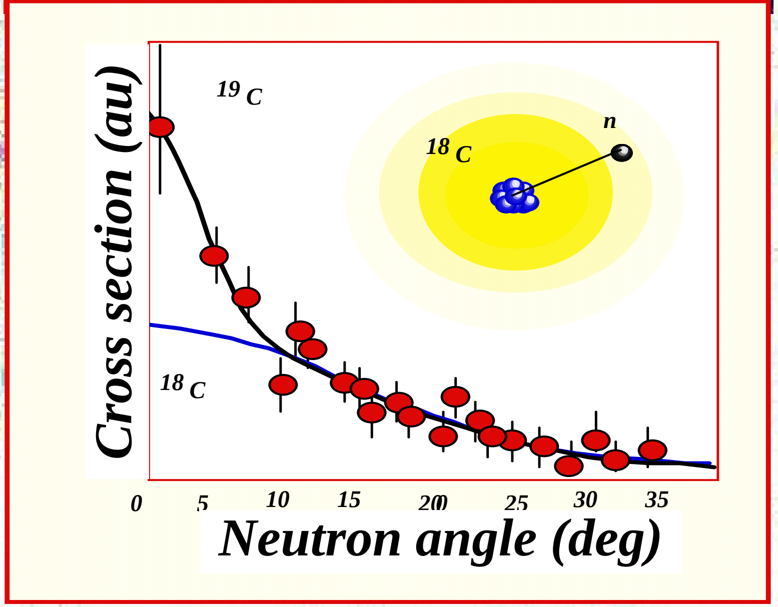
- Direct measure of the wave function in p



Halo nuclei

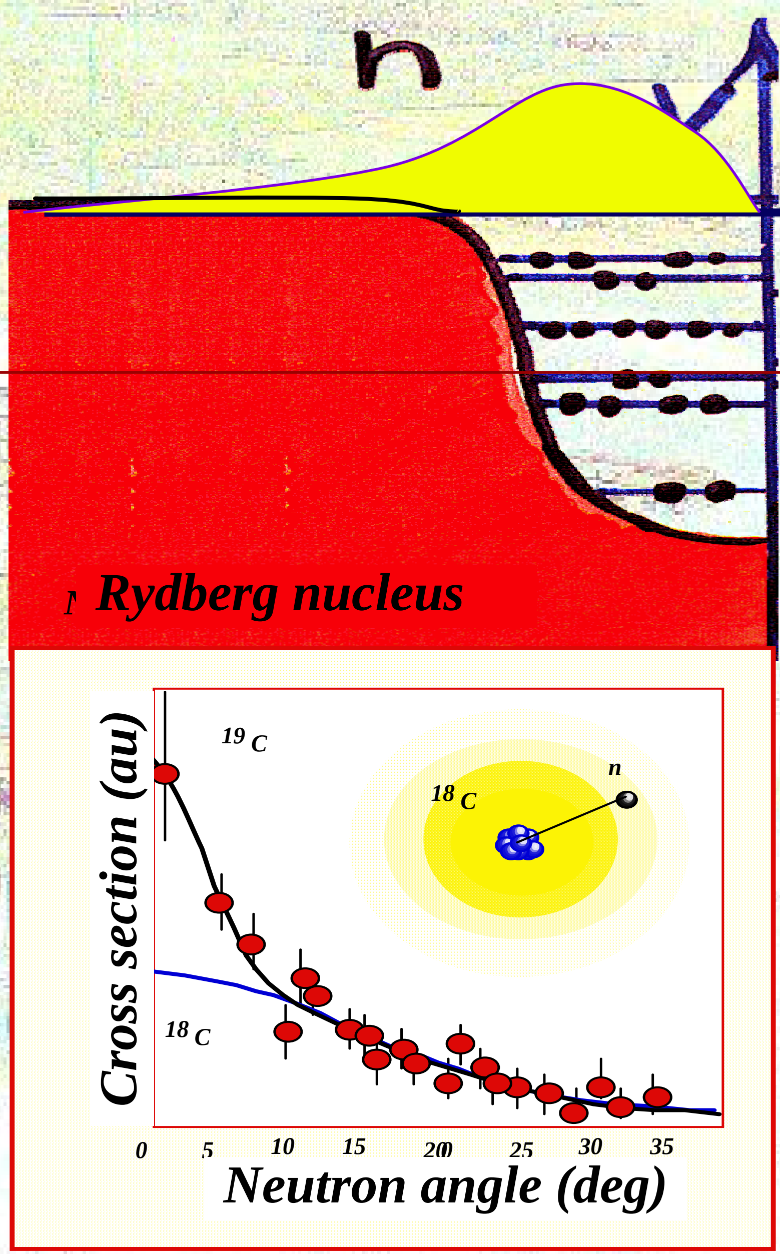
- Confirmed by nuclear reaction
- Uncertainty principle, $\Delta x \Delta p \geq \hbar$: Δp small => Δx big => a Halo
- Direct measure of the wave function in p





Physique Nucléaire 2000

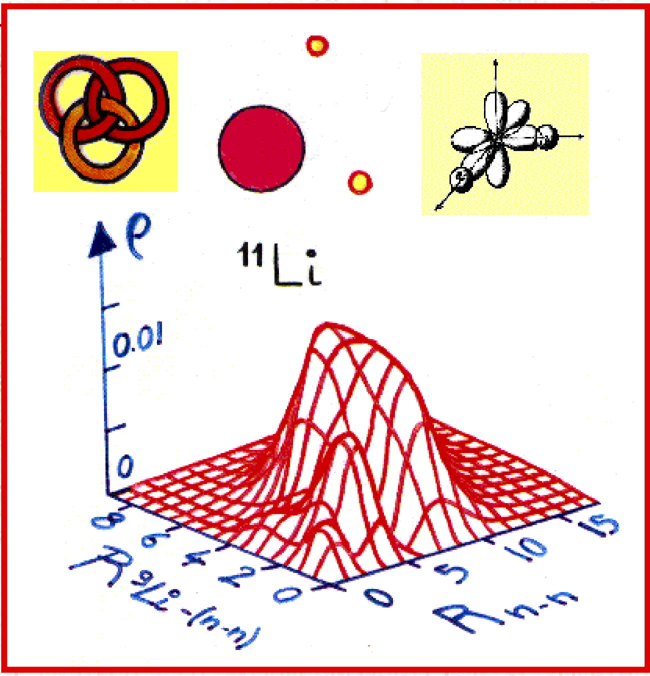
Halo nuclei

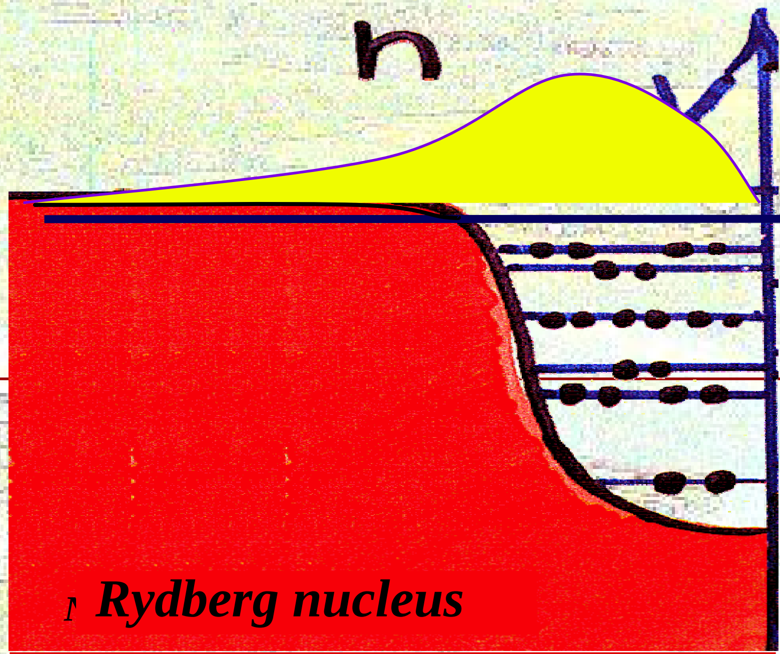


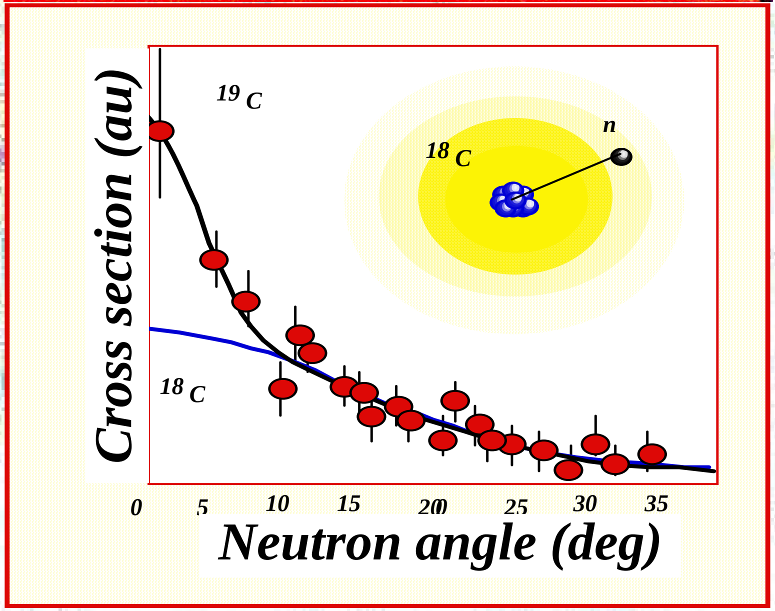
- **Borromean Systems**

Physique Nucléaire 2000

Halo nuclei





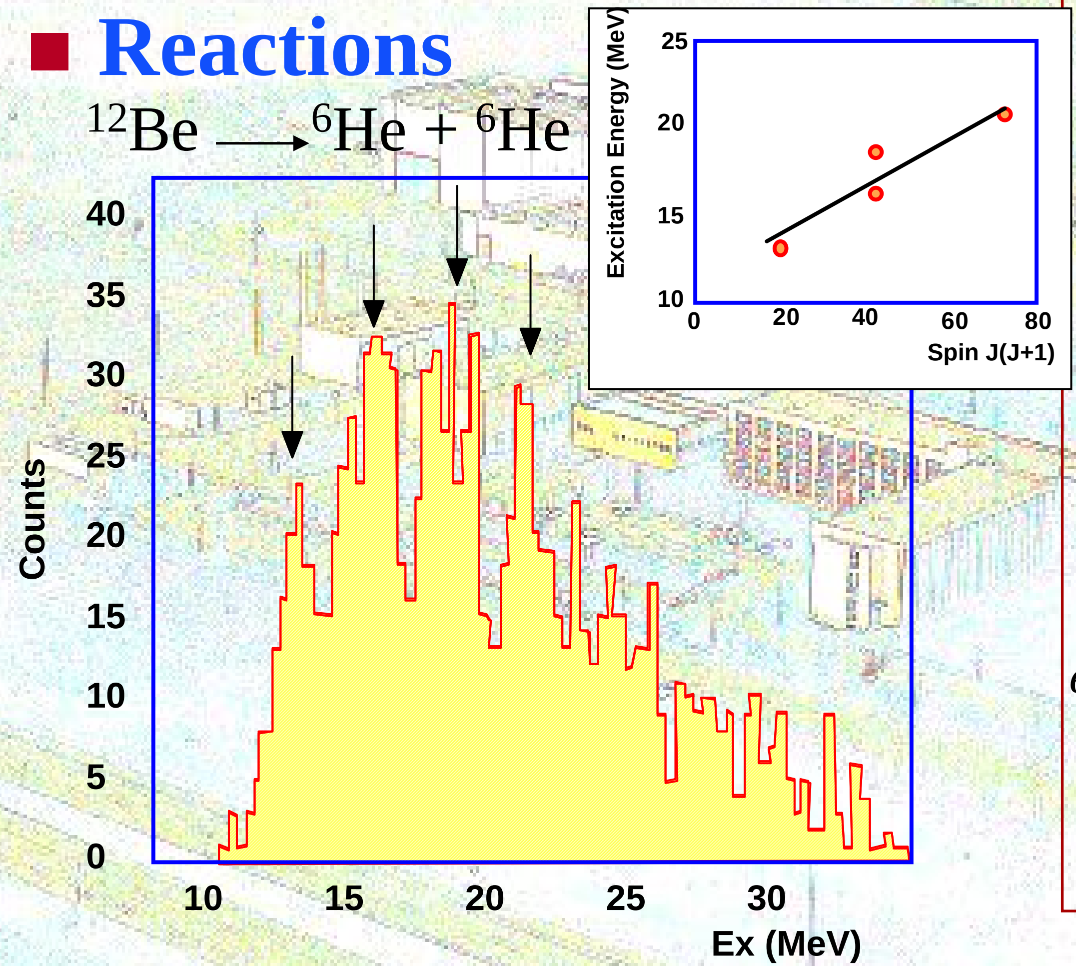


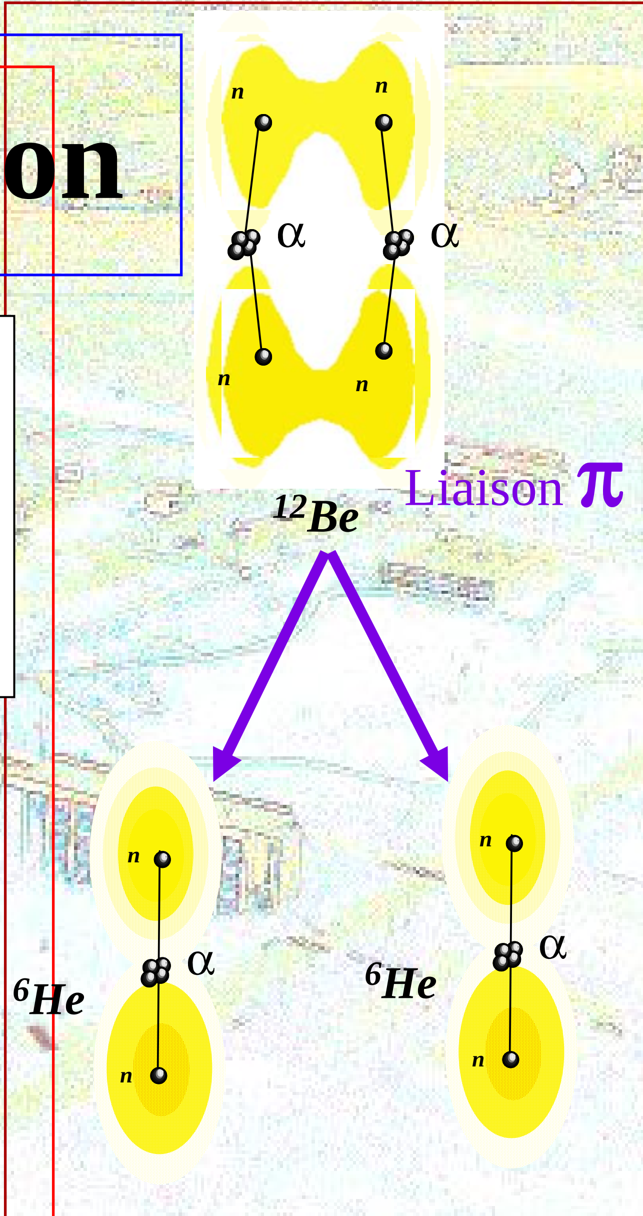
- **Borromean Systems**

Nuclear Polymerization

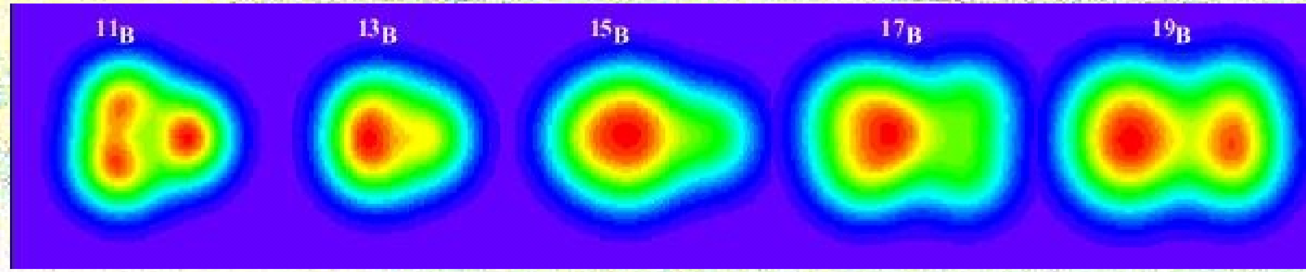
- **Reactions**

$^{12}Be \longrightarrow {}^{6}He + {}^{6}He$

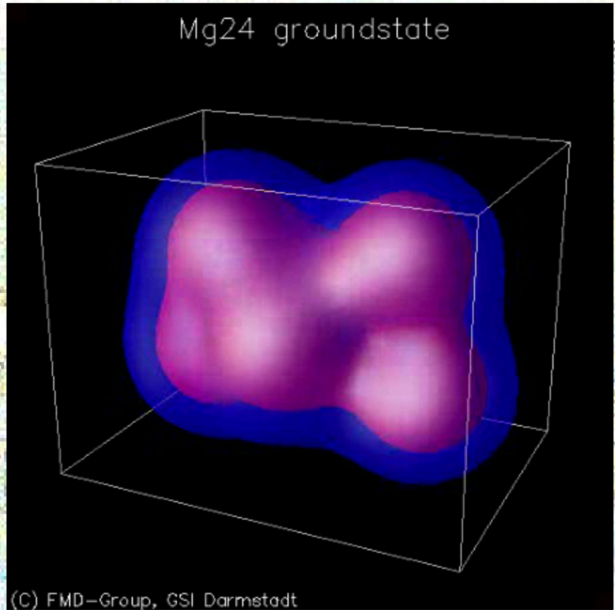




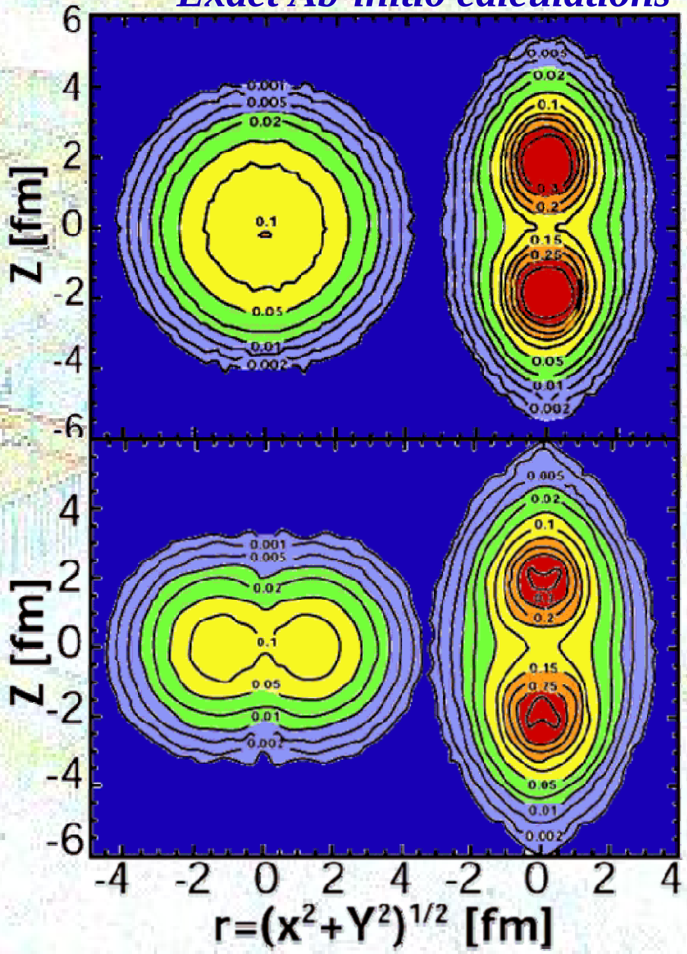
Deformation



Quantum molecular approach



Exact Ab-initio calculations



Clusters and alpha in small sytem

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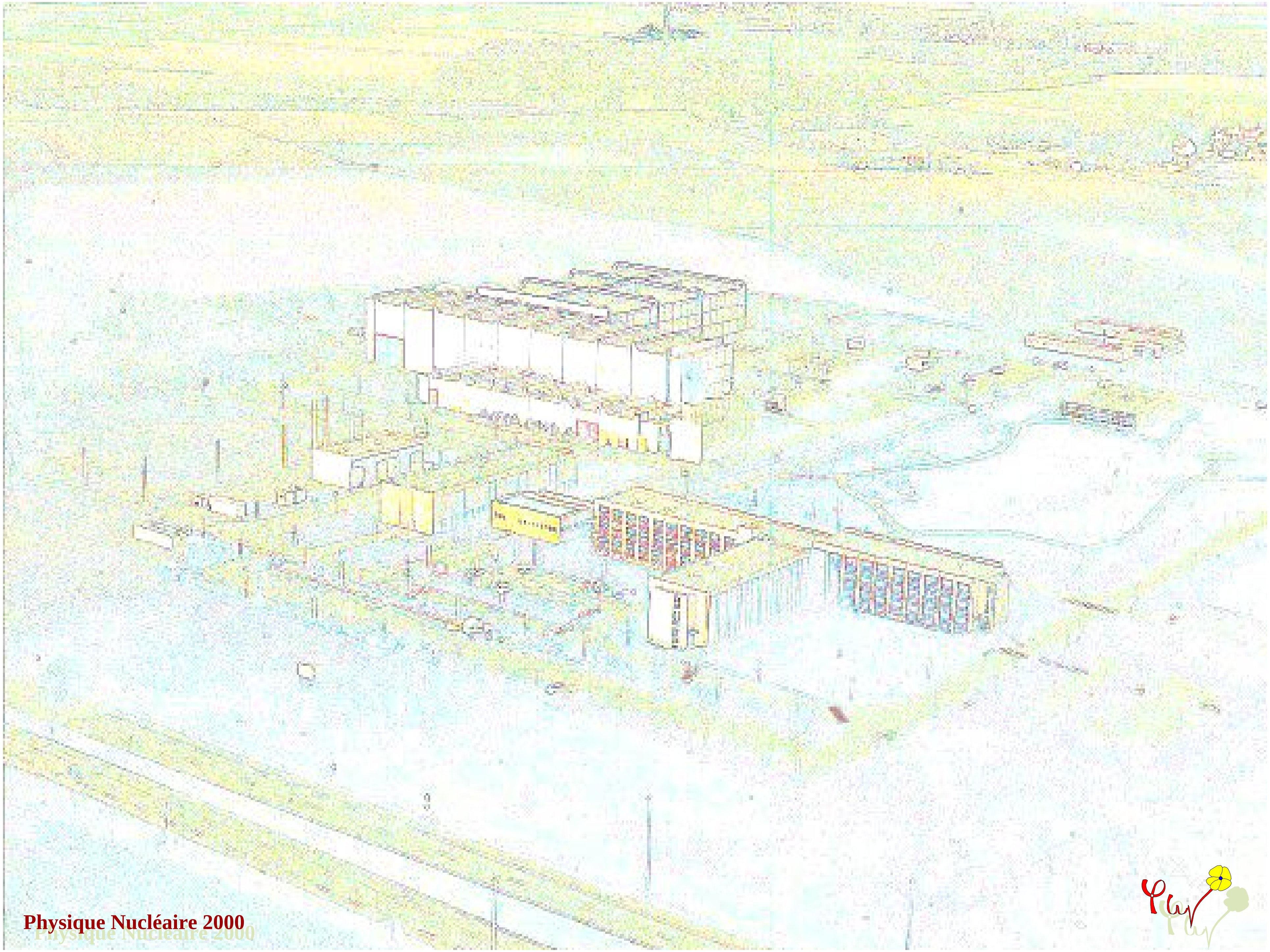
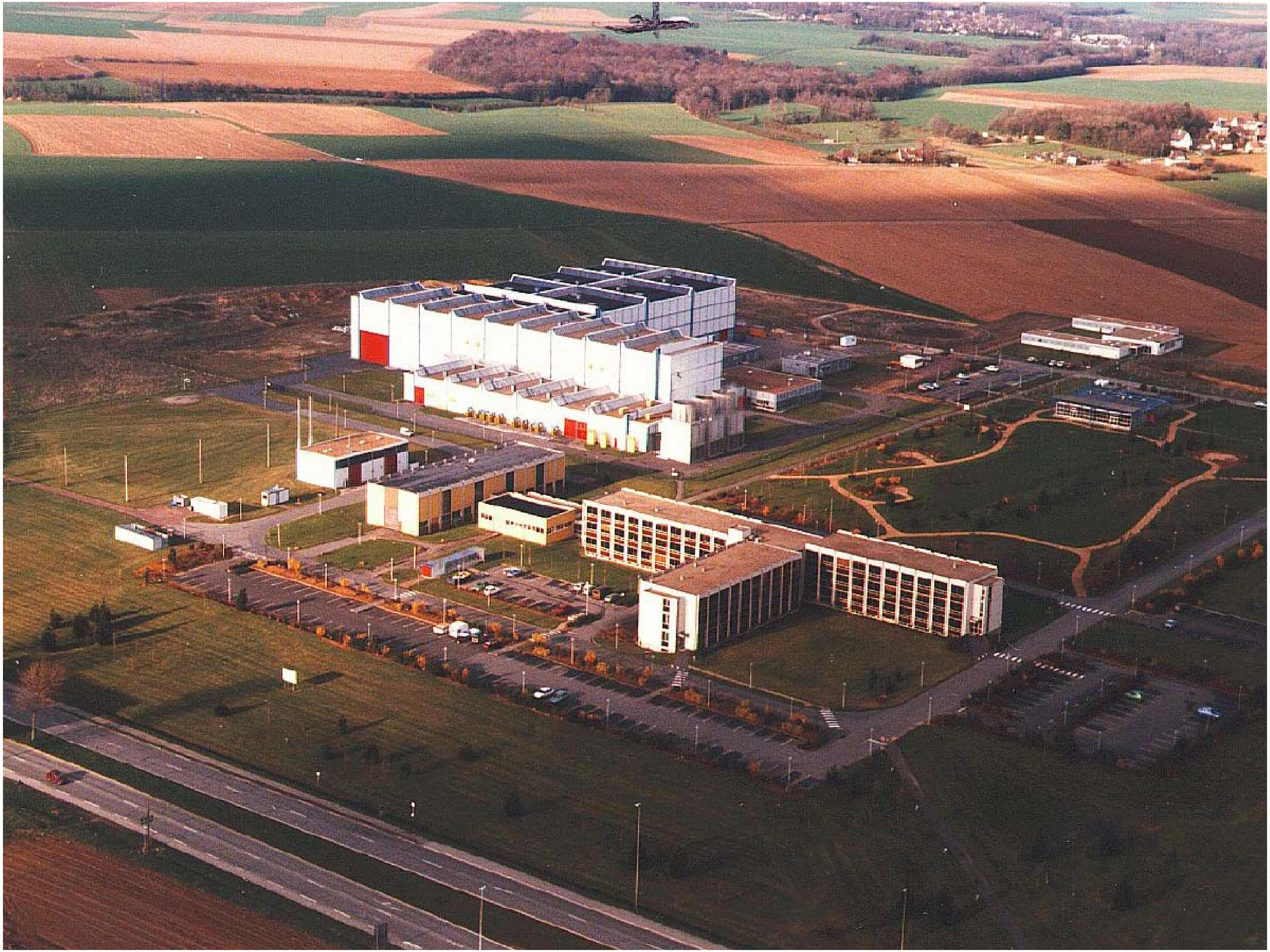
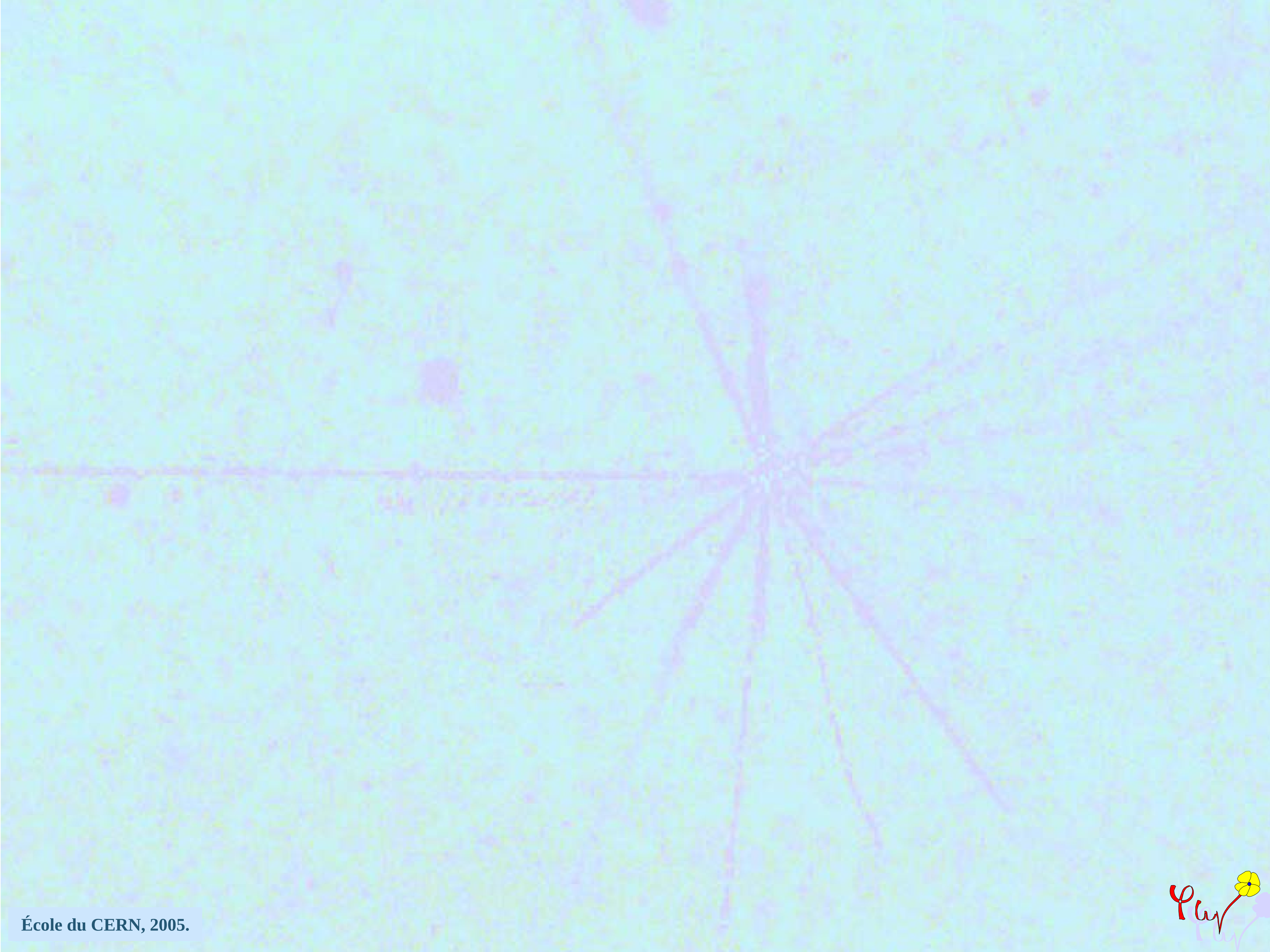


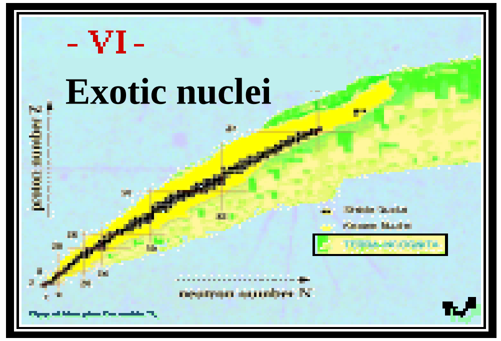
Physique Nucléaire 2000

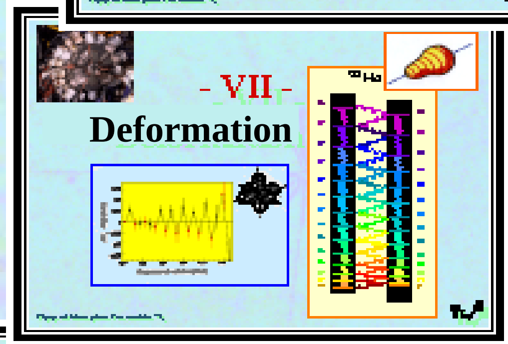




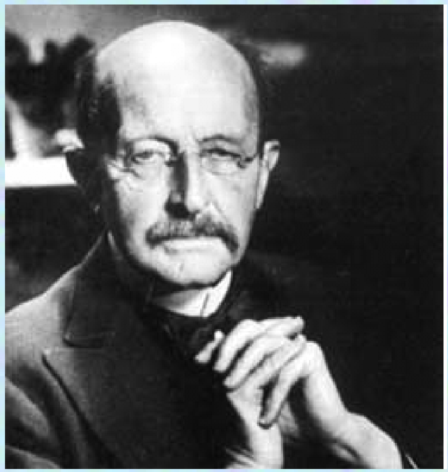
Atomic Nuclei

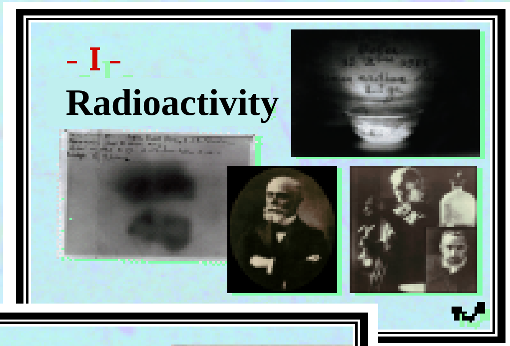
Complex quantum systems

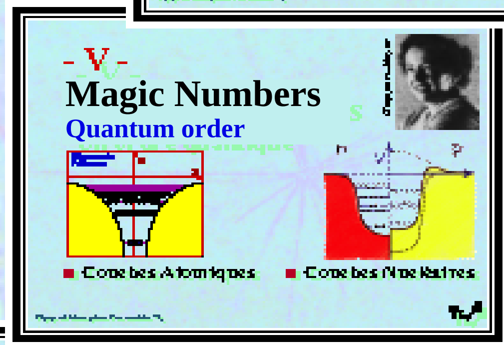


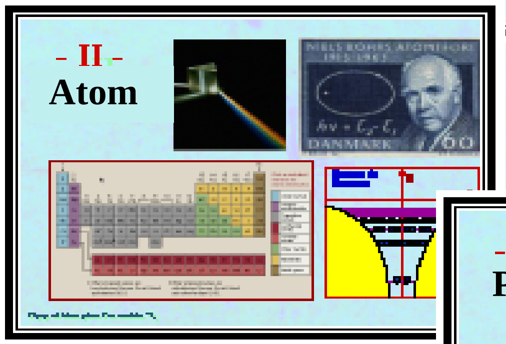


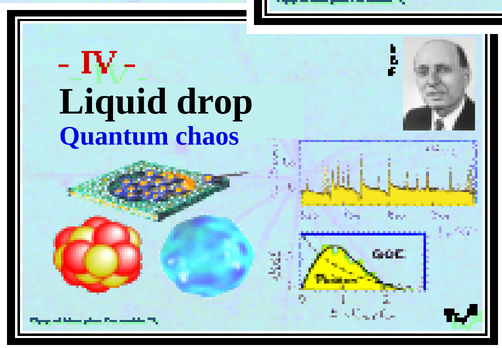
Planck

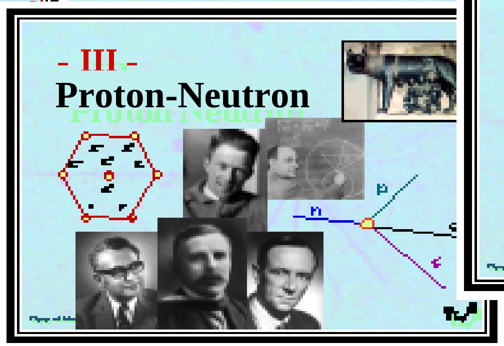




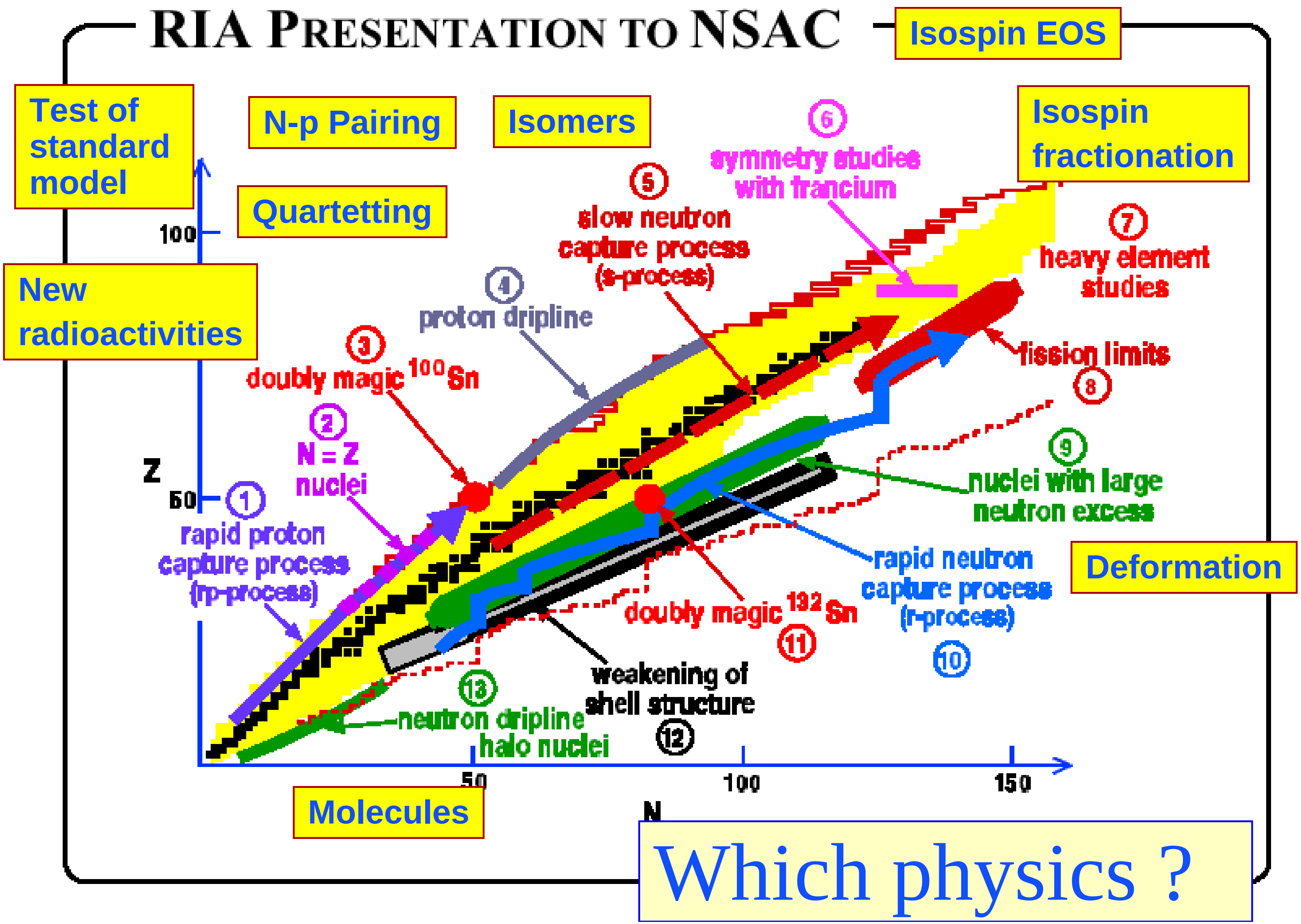




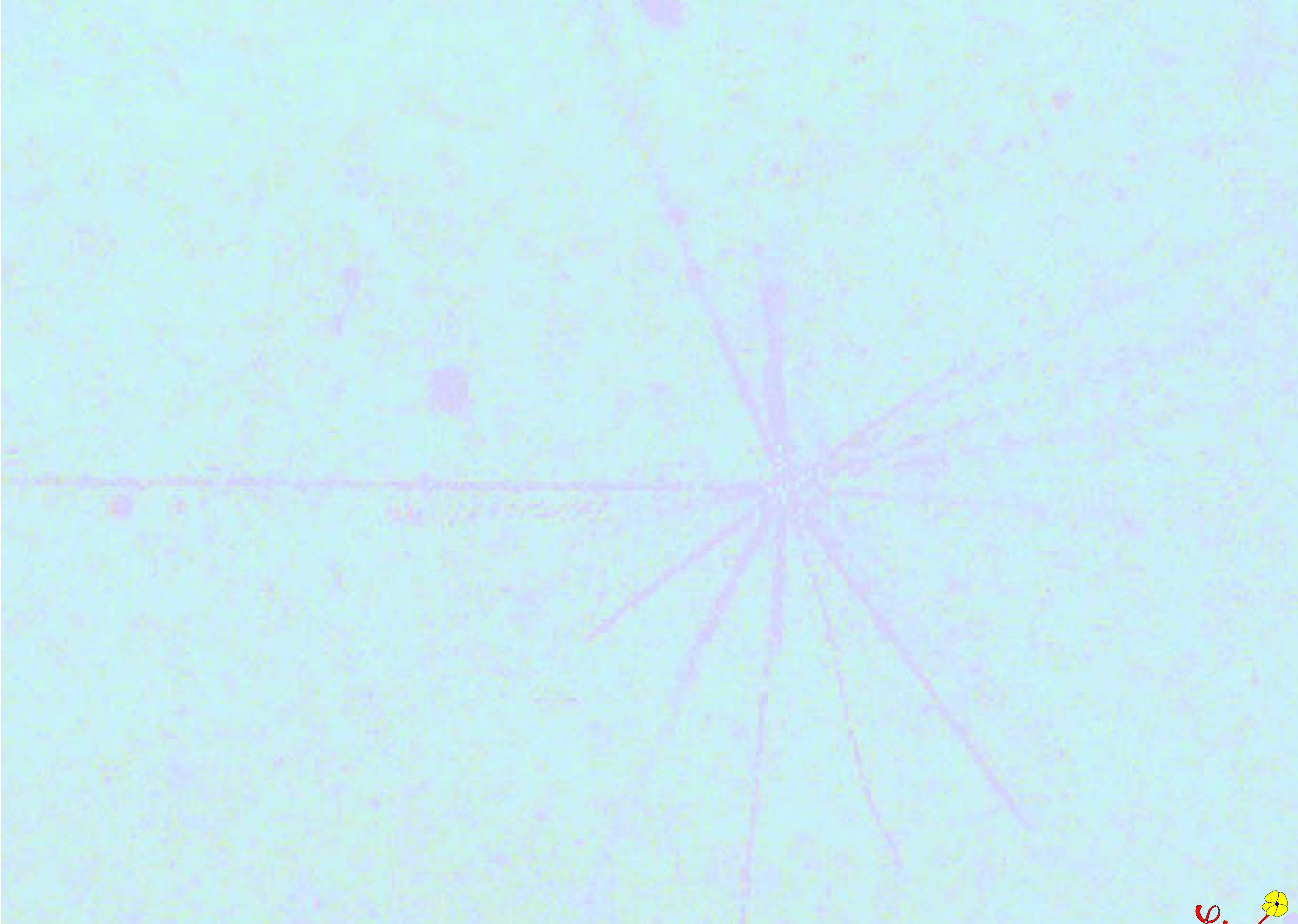




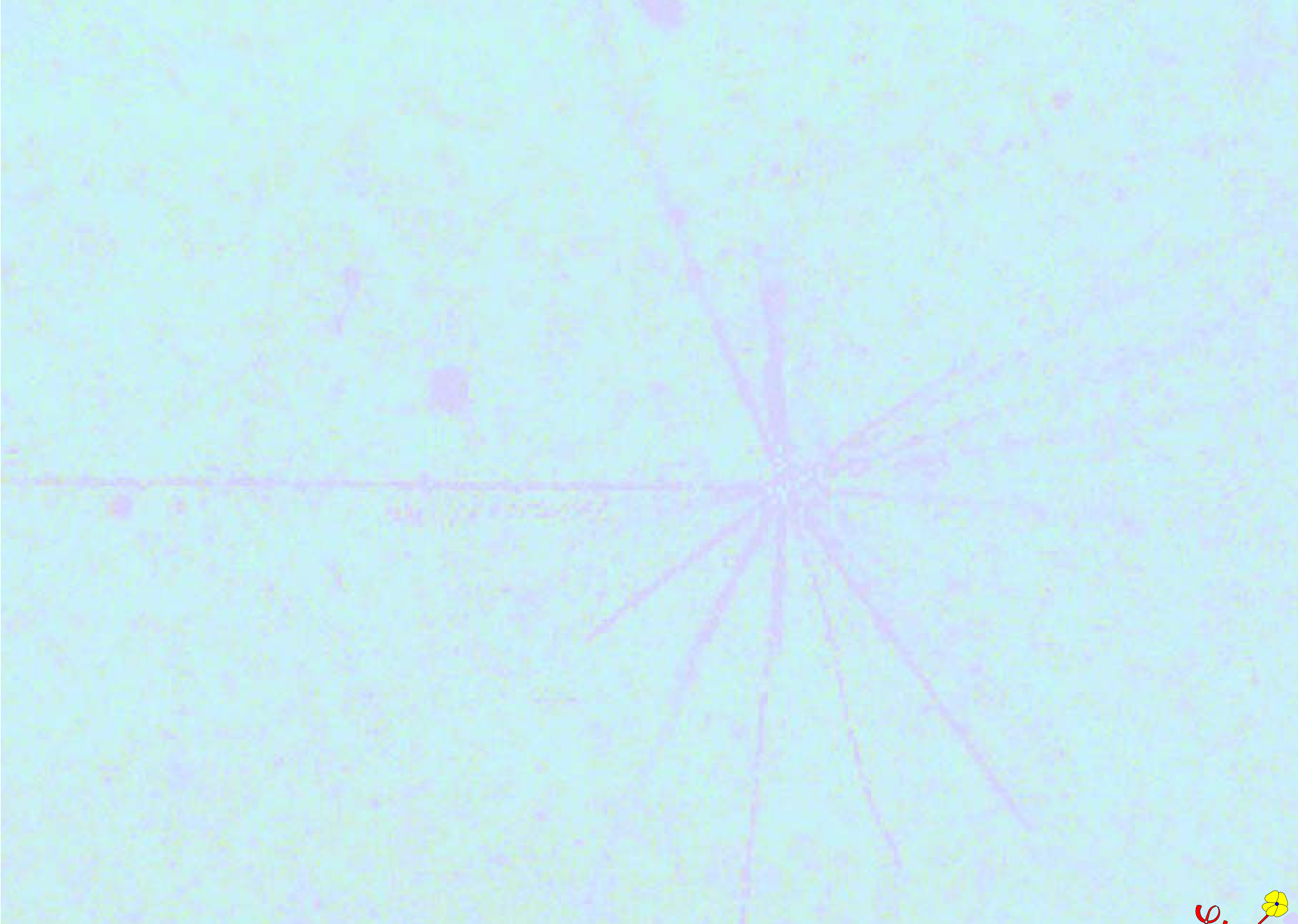
École du CERN, 2005.



RIA PRESENTATION TO NSAC
Isospin EOS
Test of standard model
N-p Pairing
Isomers
Quartetting
Isospin fractionation
New radioactivities
6 symmetry studies with francium
5 slow neutron capture process (s-process)
4 proton dripline
3 doubly magic 100Sn
2 N = Z nuclei
1 rapid proton capture process (rp-process)
7 heavy element studies
fission limits 8
9 nuclei with large neutron excess
rapid neutron capture process (r-process) 10
doubly magic 132Sn 11
weakening of shell structure 12
13 neutron dripline halo nuclei
Deformation
Z
100
50
N
50
100
150
Molecules
Which physics ?



- VIII -
Fin



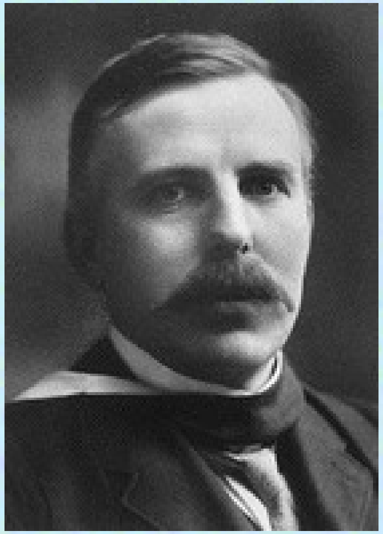
- III -

Proton Neutron

Novel Quantum Symmetry

- III -
Proton Neutron

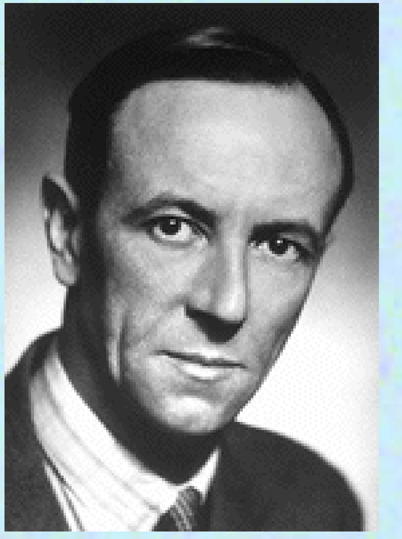
Rutherford



- **1919:** H nuclei in nuclei => protons

- III -
Proton Neutron

Chadwick



- **1919:** **Protons**
- **1932:** **Discovery of neutrons**

- III -
Proton Neutron
Novel symmetry

Heisenberg

- **1919: Protons**
- **1932: Neutrons**
- **1932: Twin particles ($m_n \approx m_p$)**
  - ☞ **Proton : nucleon with the isotopic spin +1/2**
  - ☞ **Neutron : nucleon of isospin -1/2**

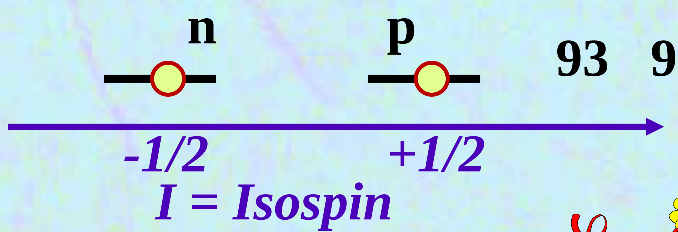
- III -

Proton Neutron

Novel symmetry

Energies
Masses
(MeV)

- ☞ New quantum number
- ☞ Proton ↔ neutron



- III -

Proton Neutron

Novel symmetry

- **Symmetric nuclei**
  - ☞ **Mirror nuclei: N ↔ Z**
  - ☞ **Proton ↔ neutron**

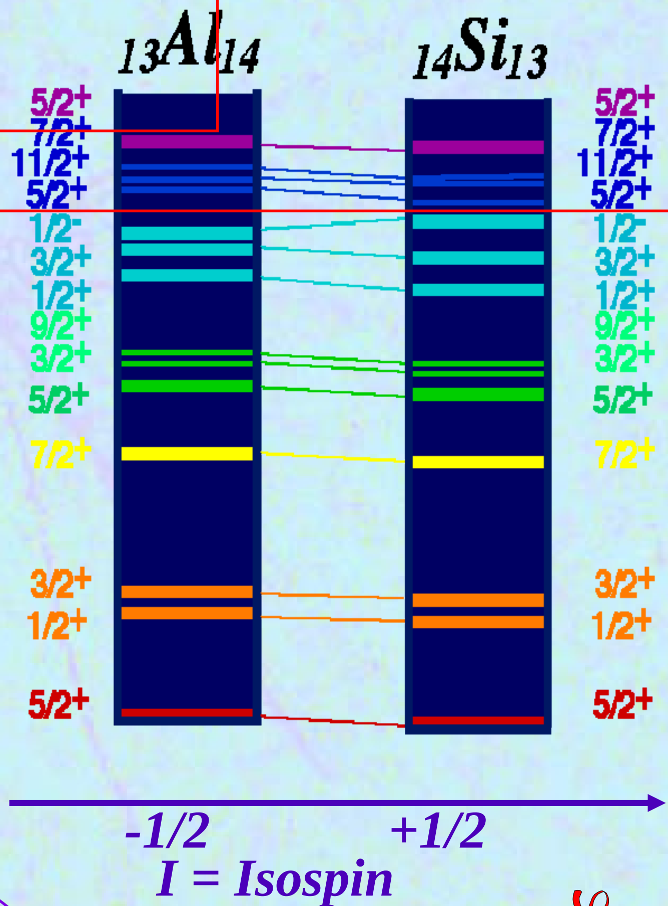
-1/2 *+1/2*

I = Isospin

- III -

Proton Neutron

Novel symmetry



- **Symmetric nuclei**
  - Mirror nuclei, N ↔ Z
  - Isospin multiplets,
  - A tool for structure studies
  - Proton ↔ neutron

- III -

Proton Neutron

Novel symmetry

- **Symmetric nuclei**
  - **Mirror nuclei**
  - **Isospin multiplets,**
  - **A tool for structure studies**
  - **Proton ↔ neutron**

-1 -1/2 0 +1/2 +1

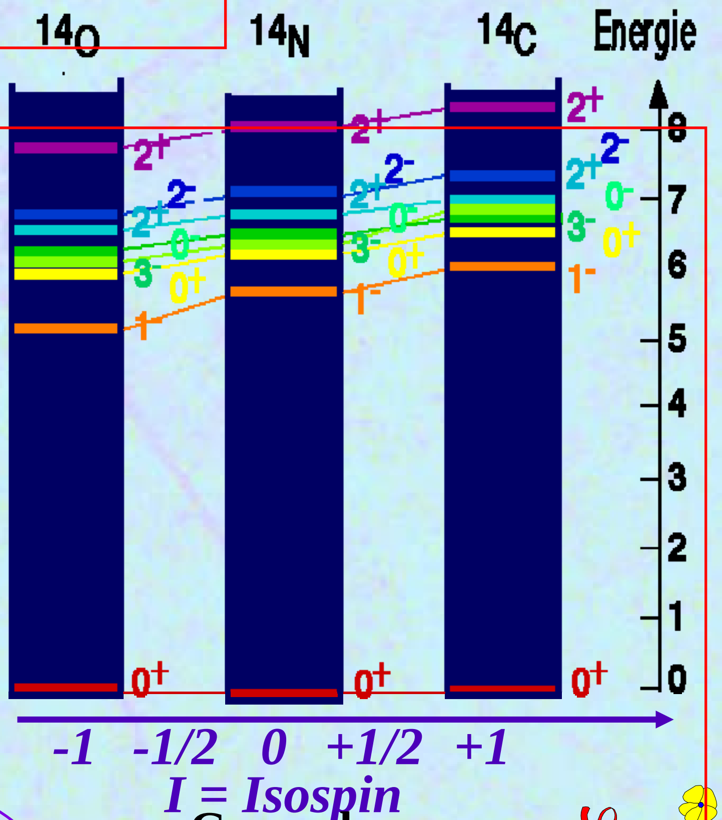
I = Isospin

- III -

Proton Neutron

Novel symmetry

- **Symmetric nuclei**
  - ☞ **Mirror nuclei**
  - ☞ **Isospin multiplets, triplets, quadruplets, ...**
  - ☞ **A tool for structure studies**
  - ☞ **Proton ↔ neutron**



Ground state

- III -

Proton Neutron

Novel symmetry

☞ Proton ↔ neutron

-1 -1/2 0 +1/2 +1

I = Isospin

- III -

Proton Neutron

Novel symmetry

$J^\pi = 1/2^+$

■ **Many particles**

Masses (MeV)

n p

93 9

-1 -1/2 0 +1/2 +1

I = Isospin

☞ **Proton ↔ neutron**

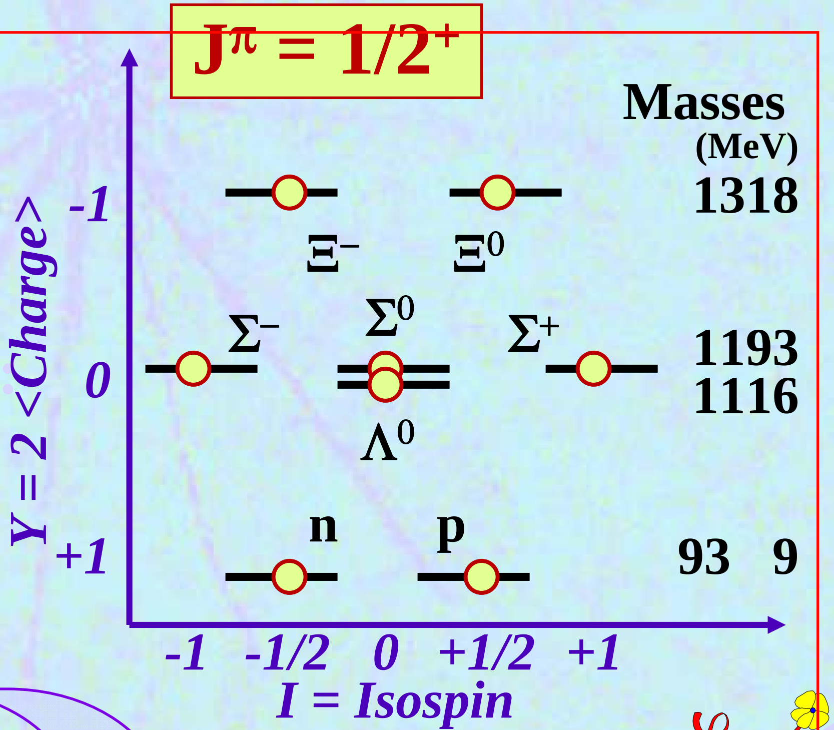
- III -

Proton Neutron

Novel symmetry

Gell Man

- **Many particles**
  - Many twins
  - Novel quantum number: The hypercharge : Y



- III -

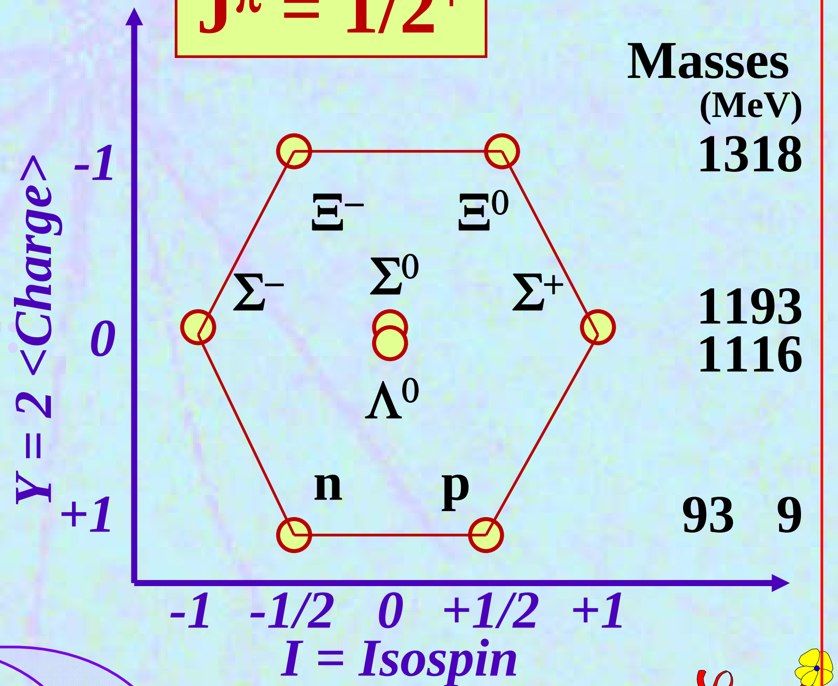
Proton Neutron

Novel symmetry

Gell Man

$J^{\pi} = 1/2^{+}$

- **Many particles**
  - Many twins
  - Novel quantum number: The hypercharge : Y



- III -

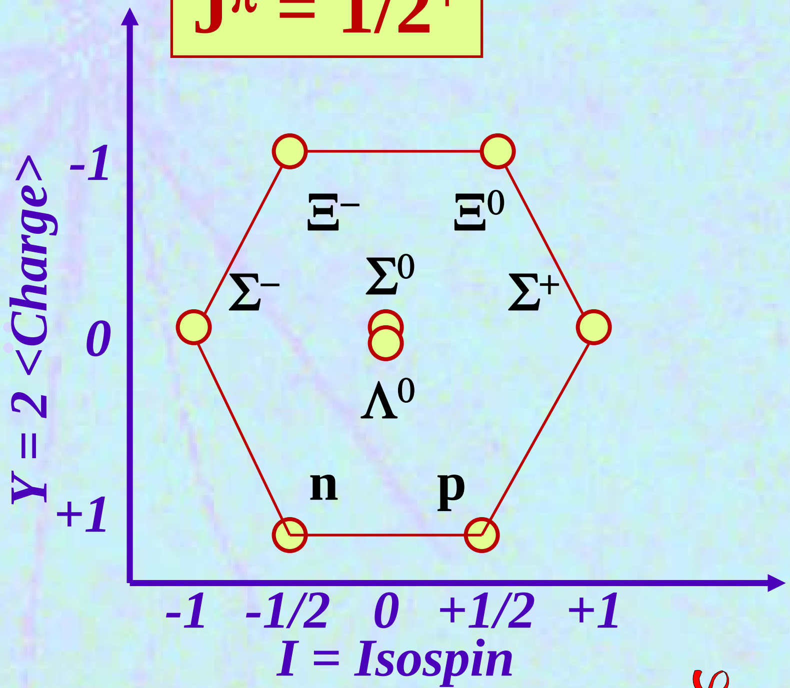
Proton Neutron

Novel symmetry

Gell Man

- Many particles
  - ☞ Many twins
  - ☞ Novel quantum number: The hypercharge : Y
- 3 Quarks in baryons

$J^{\pi} = 1/2^{+}$



- III -

Proton Neutron

Novel symmetry

Gell Man

- Many particles
  - Many twins
  - Novel quantum number: The hypercharge : Y
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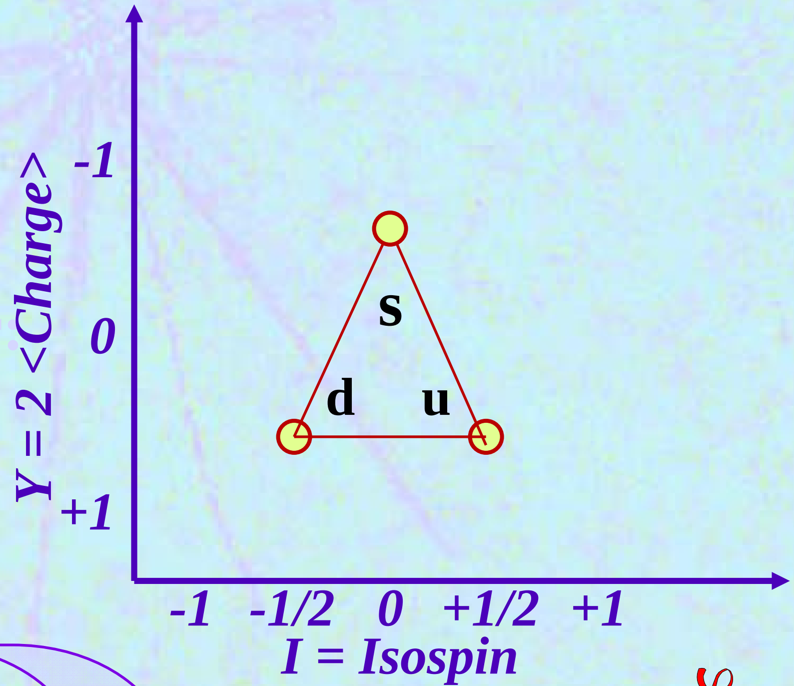


- III -

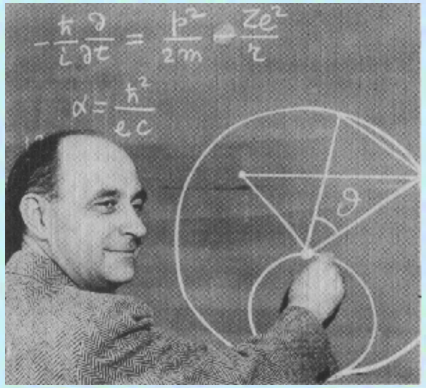
Proton Neutron

Novel symmetry

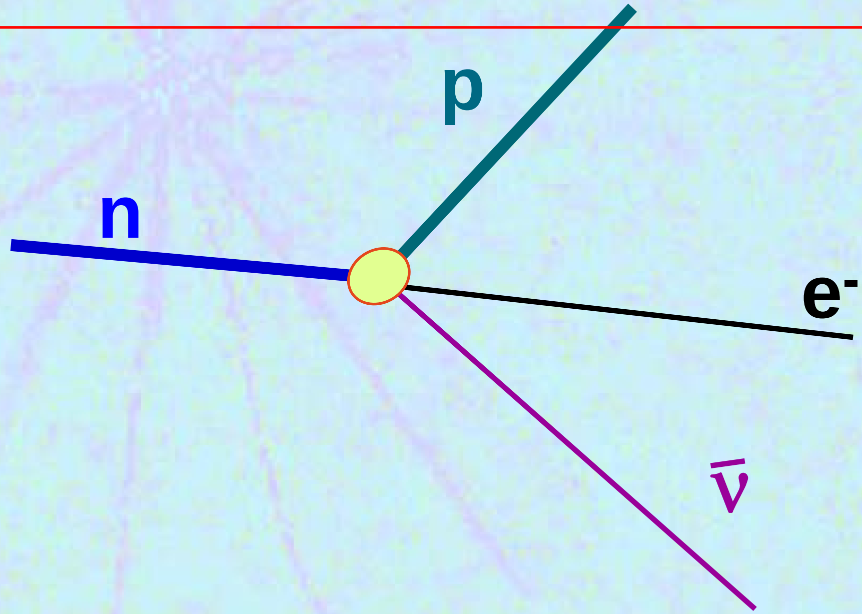
- 3 Quarks in baryons
  - ☞ Today 6 flavors and 3 colors (QCD)

- III -
Proton Neutron
Novel symmetry

Fermi



- β Radioactivity



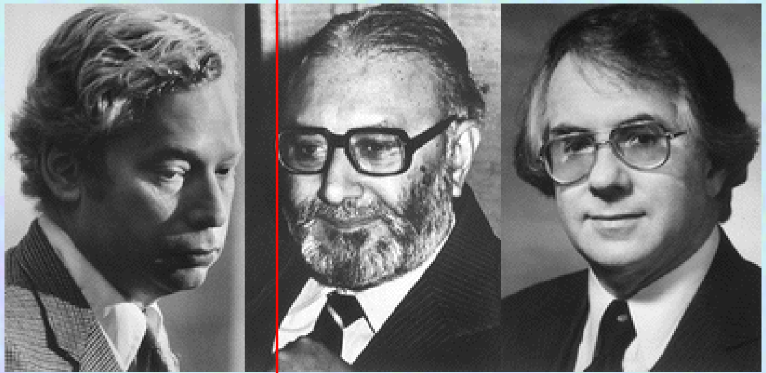
- 3 Quarks in baryons
  - ☞ Today 6 flavors and 3 colors (QCD)

- III -

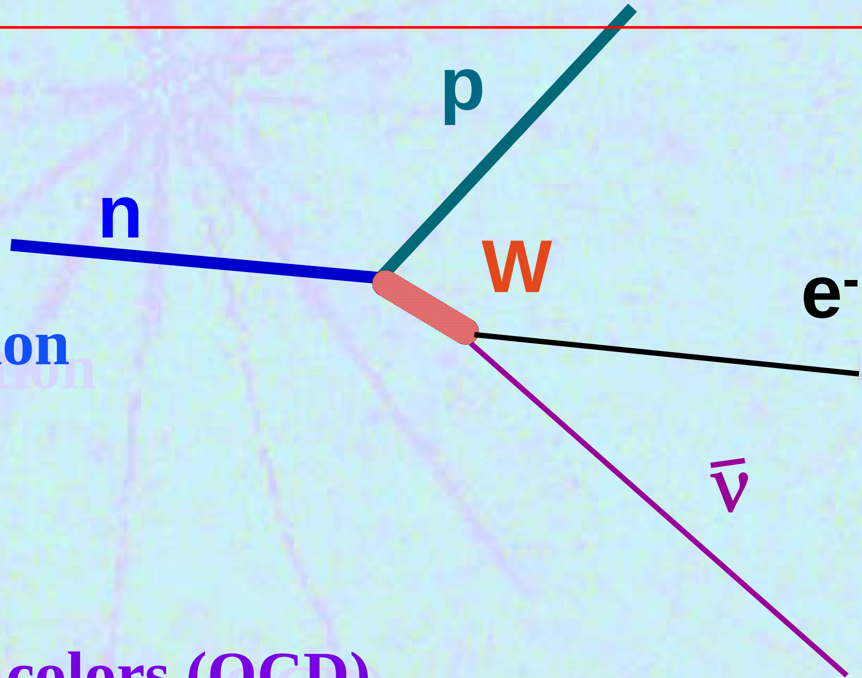
Proton Neutron

Novel symmetry

Weinberg *Salam* *Glashow*



- β Radioactivity
  - Isospin (weak)
  - Electro-weak unification
  - Gauge Theory



- 3 Quarks in baryons
  - Today 6 flavors and 3 colors (QCD)

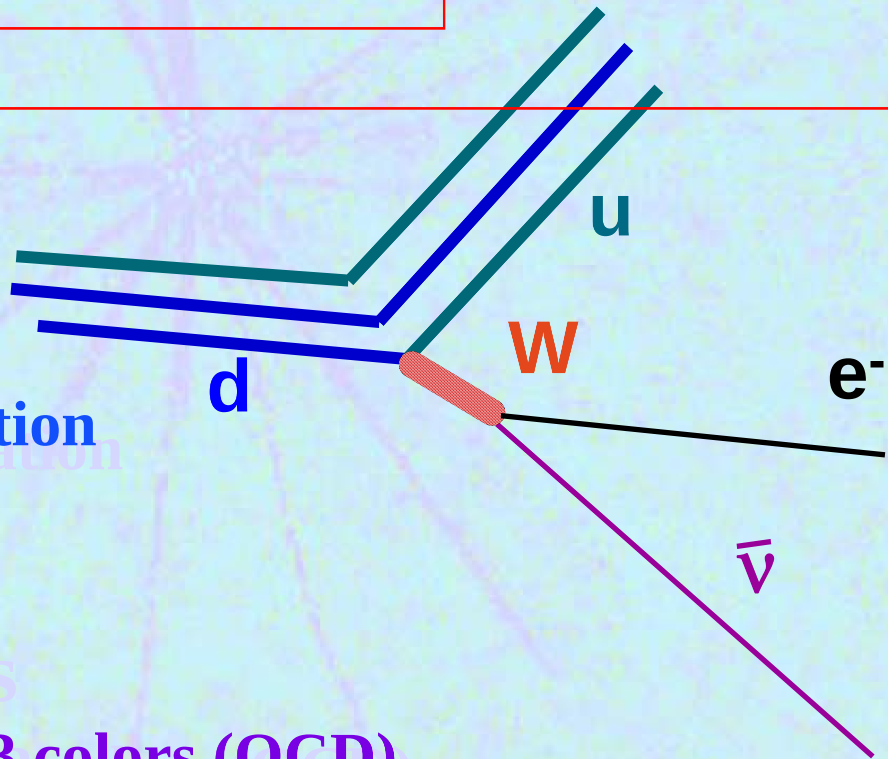
- III -

Proton Neutron

Novel symmetry

Weinberg *Salam* *Glashow*

- **β Radioactivity**
  - Isospin (weak)
  - Electro-weak unification
  - Gauge Theory
- **3 Quarks in baryons**
  - Today 6 flavors and 3 colors (QCD)

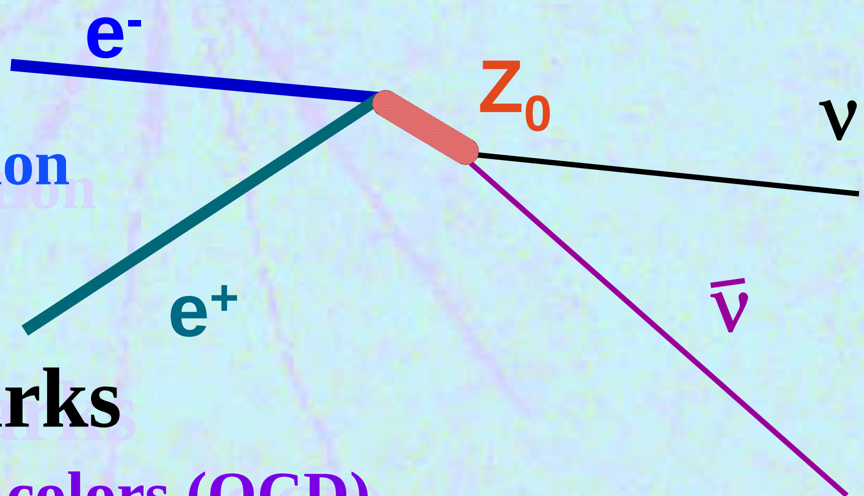


- III -

Proton Neutron

Novel symmetry

- **Weak Interaction**
  - Isospin (weak)
  - Electro-weak unification
  - Gauge theory



- **Structure with 3 Quarks**
  - Today 6 flavors and 3 colors (QCD)

Quarks and gluons in Nuclei

- Nuclei: Laboratories for elementary properties
  - ☞ β radioactivity and weak interaction (neutrinos)
  - ☞ β radioactivity and CKM matrix
  - $\Rightarrow$ Nuclear structure should be under control

Quarks and gluons in Nuclei

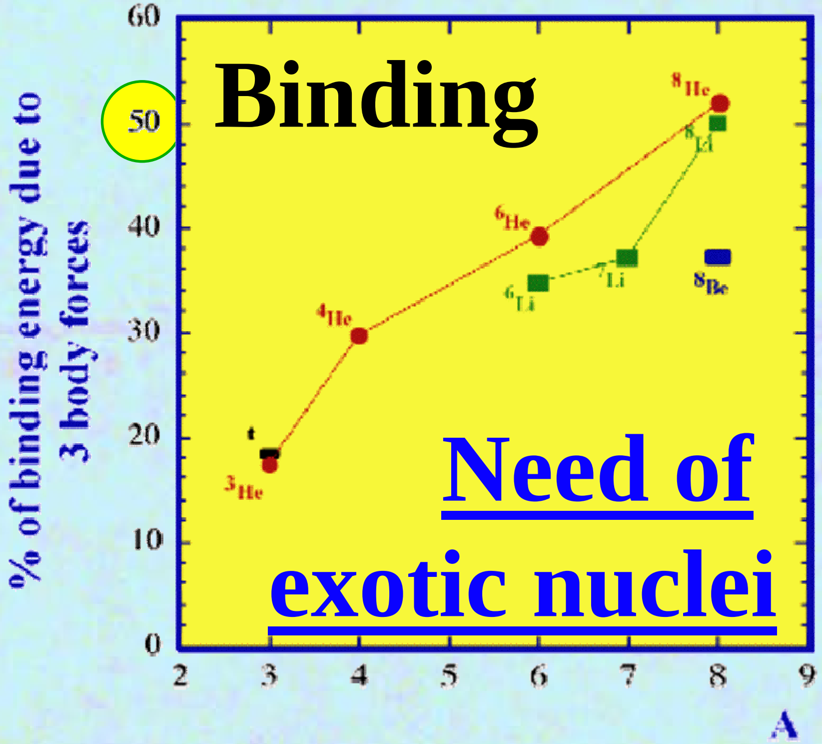
- **Nuclei: Laboratories for elementary properties**
  - ☞**β radioactivity and weak interaction (neutrinos)**
  - ☞**β radioactivity and CKM matrix**
  - ⇒**Nuclear structure should be under control**

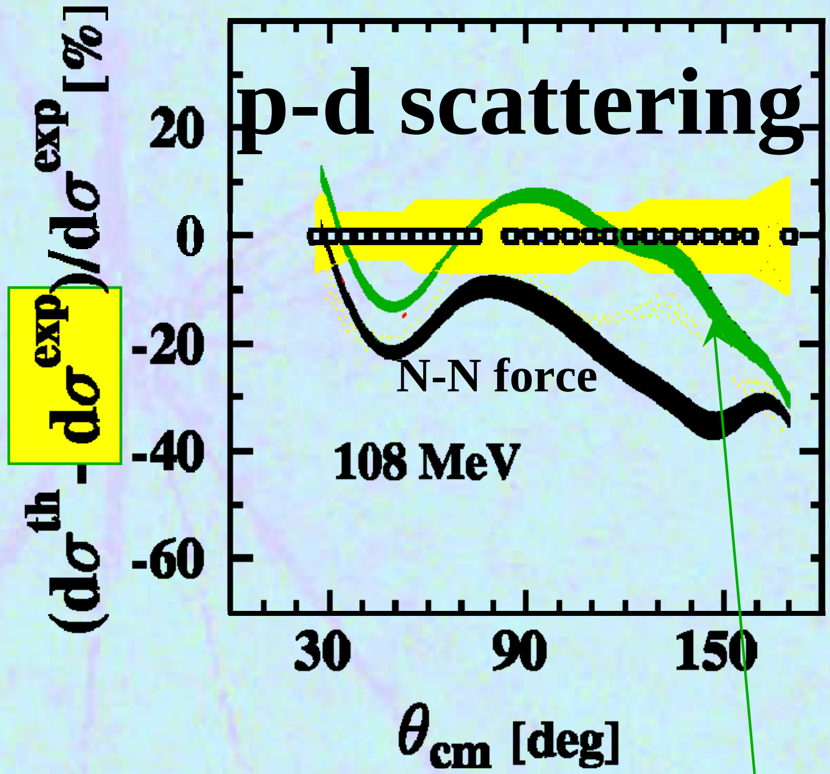
- **QCD for nuclei far to be possible (non-perturbative)**
  - ☞**Decoupling of the various scales =>** nucleons
  - ☞**Effective interaction for nucleon (**measured **?)**

  => Coming from QCD constraints (chiral symmetry)

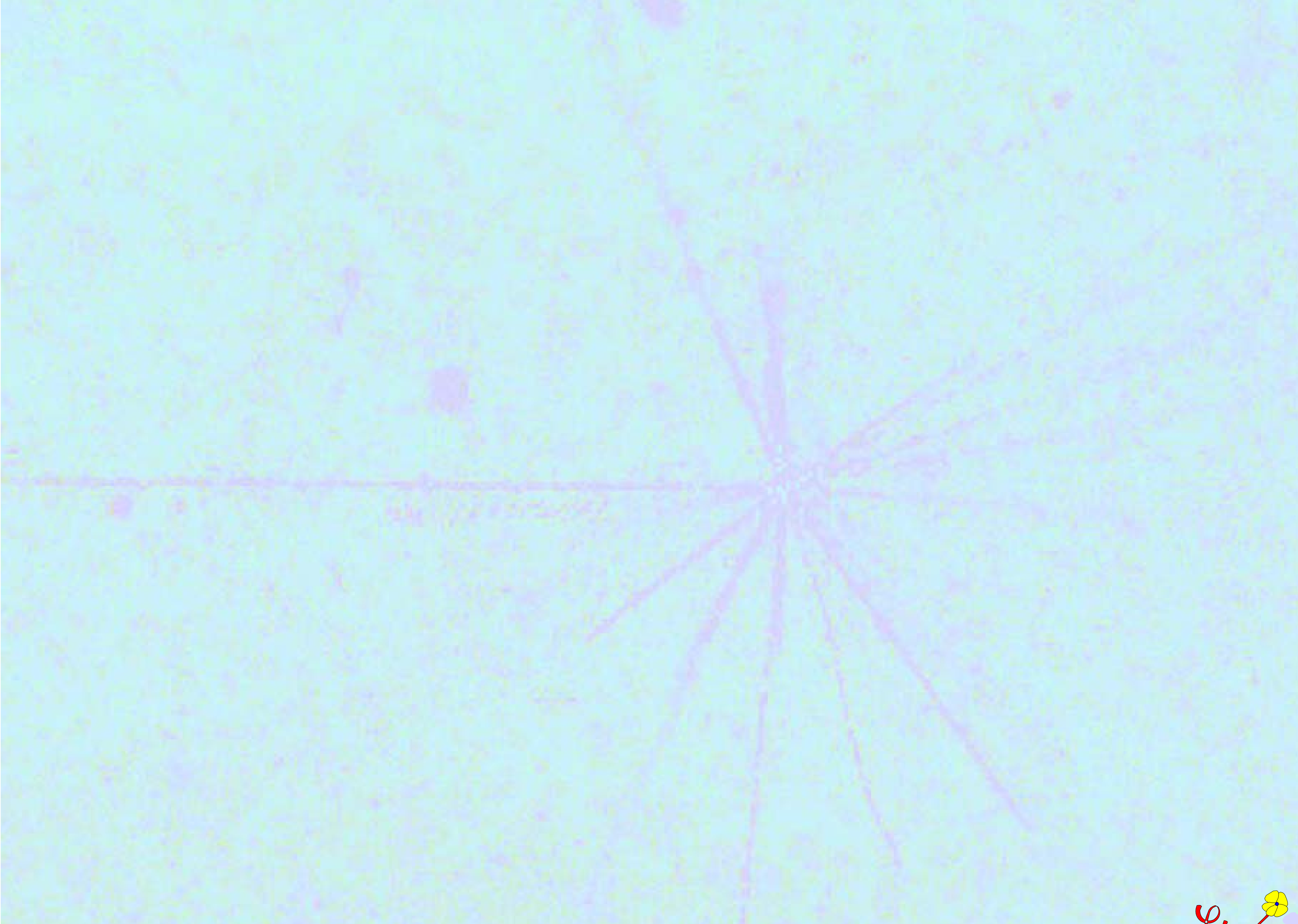
N-N forces not enough=>3-body

Ab initio calculation





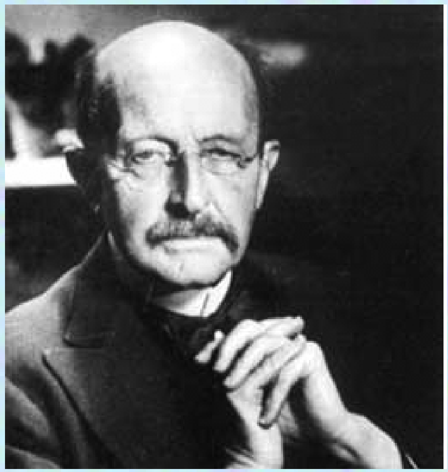
=> Coming from QCD constraints (chiral symmetry)

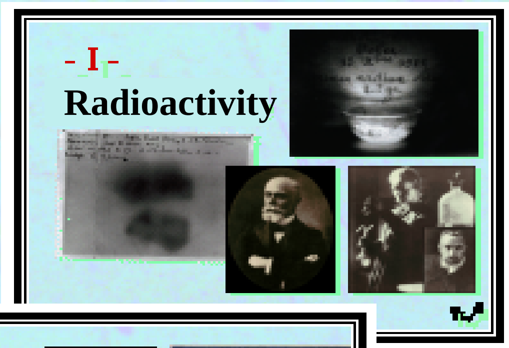


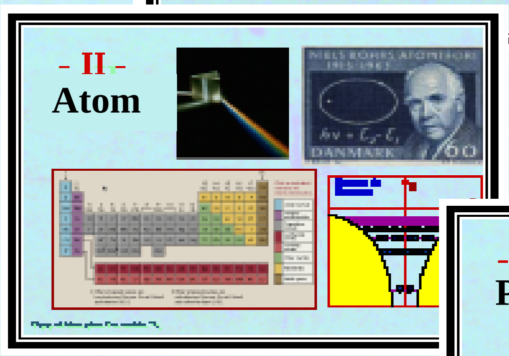
Atomic Nuclei

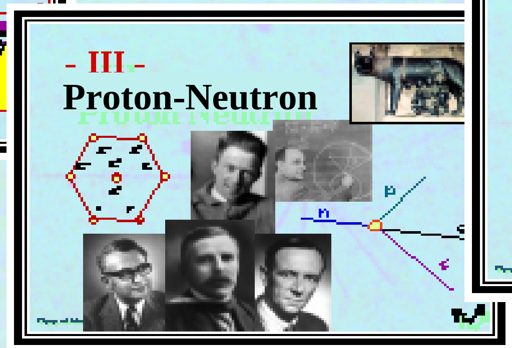
Complex quantum systems

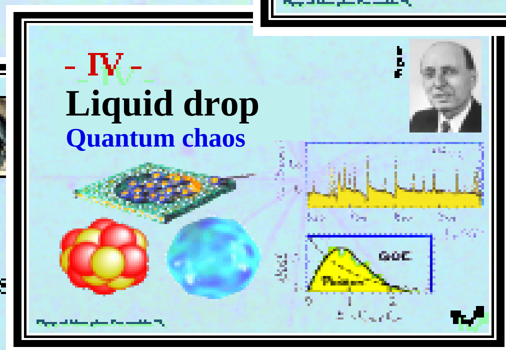
Planck

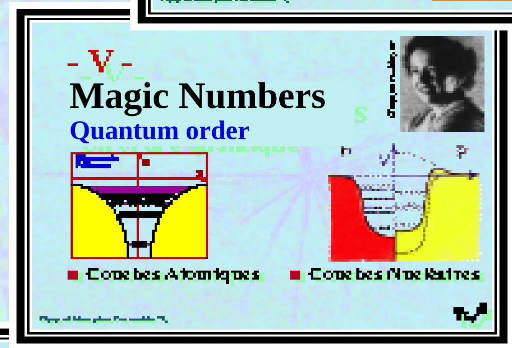


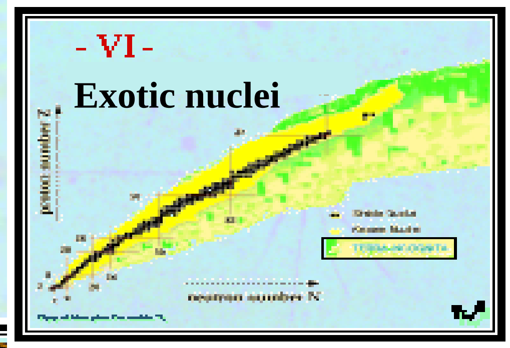


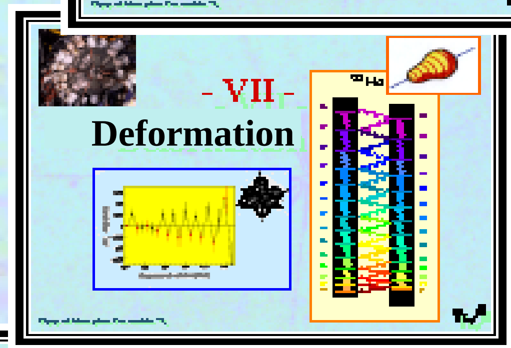


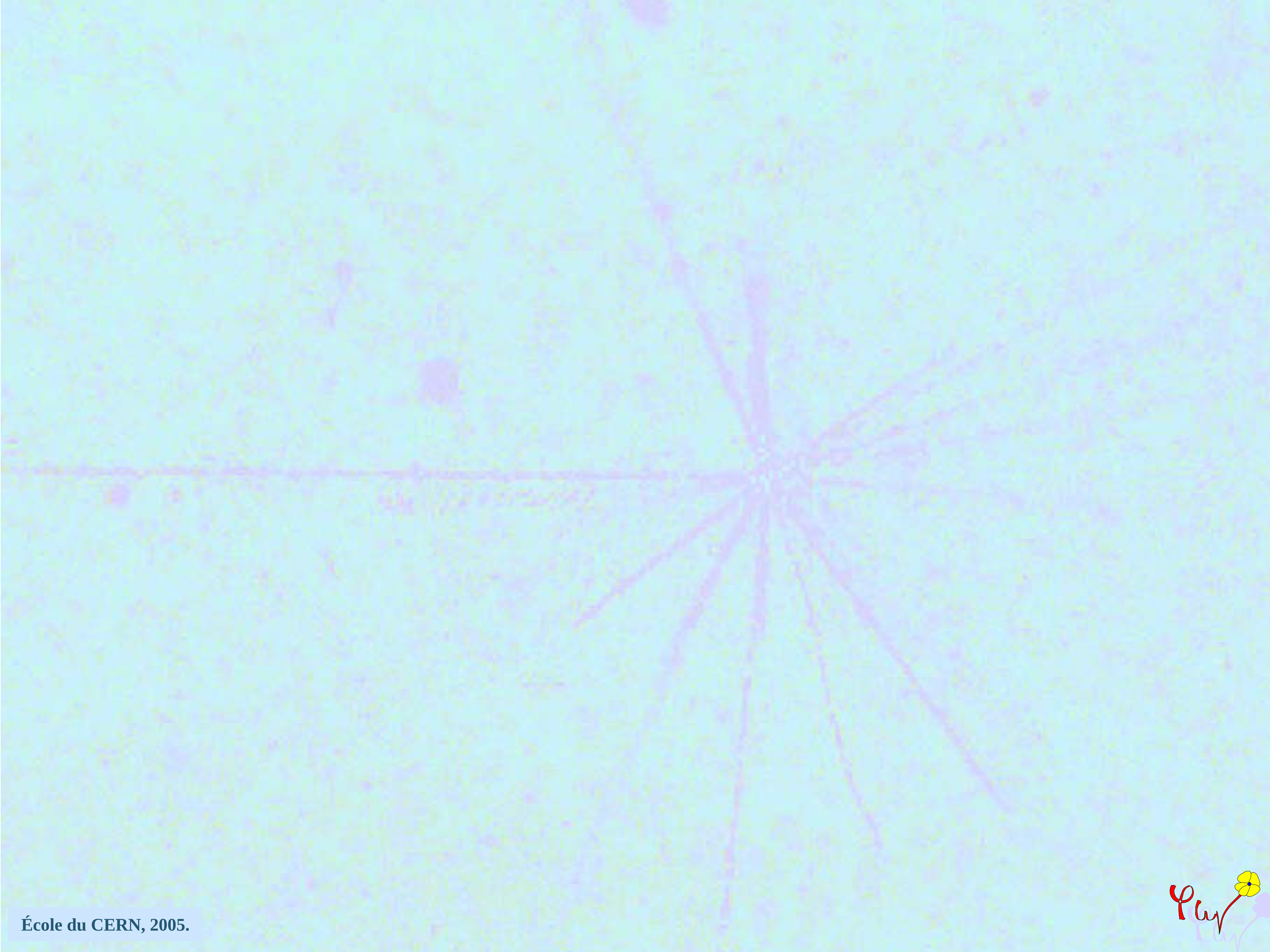










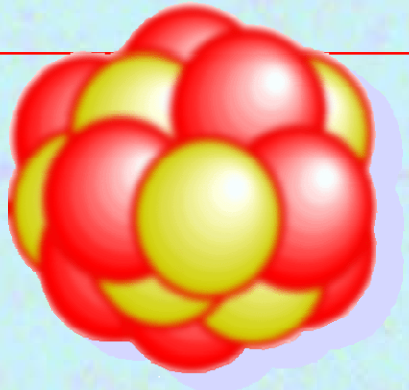


- IV -

Liquid Drop

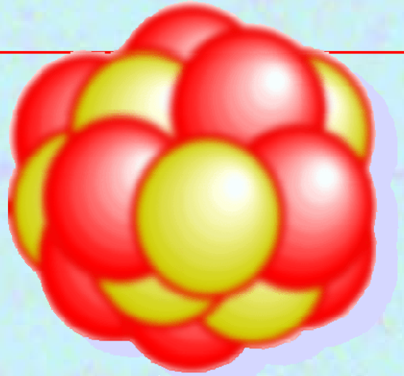
Quantum Chaos

- IV -
Liquid Drop

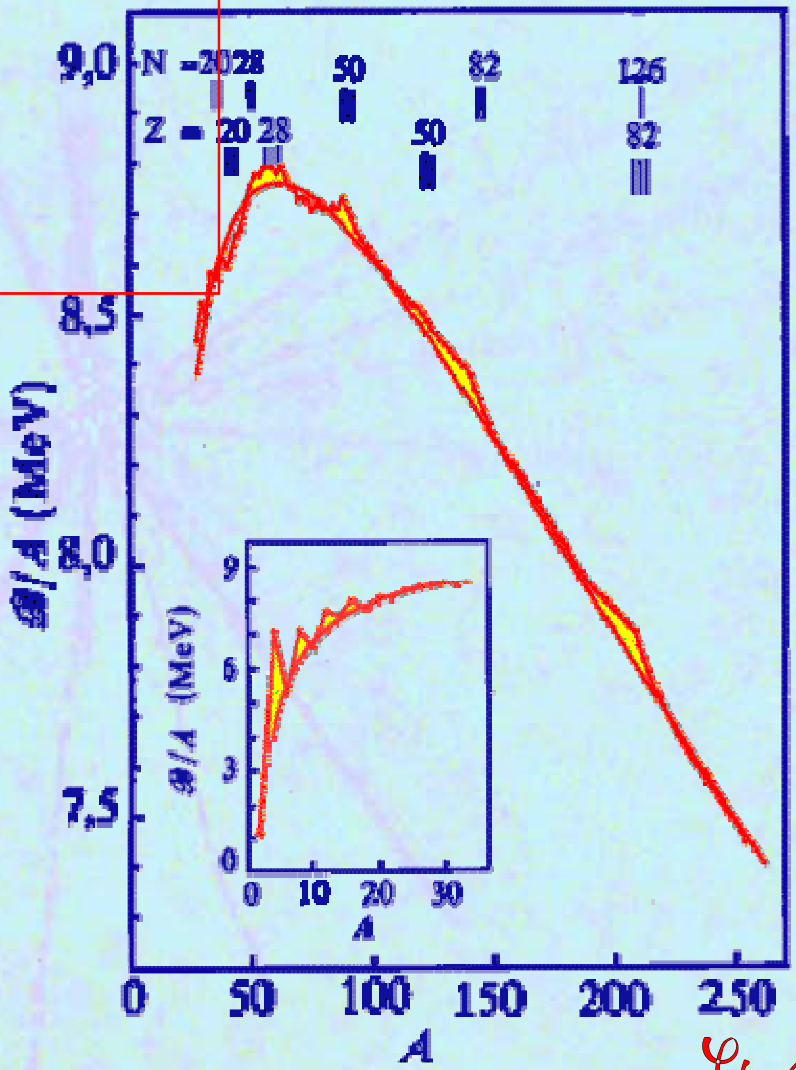


- **Binding**
  - ☞ **Energy**

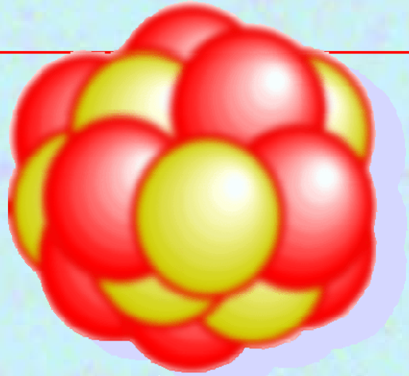
- IV -
Liquid Drop

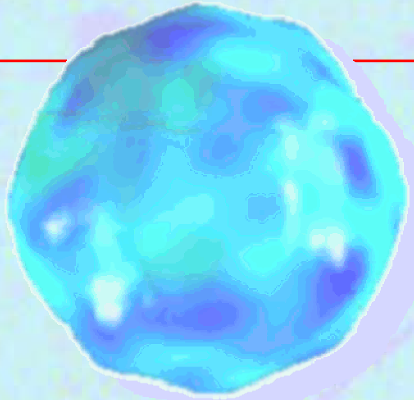


- **Binding**
  - ☞ **Energy**



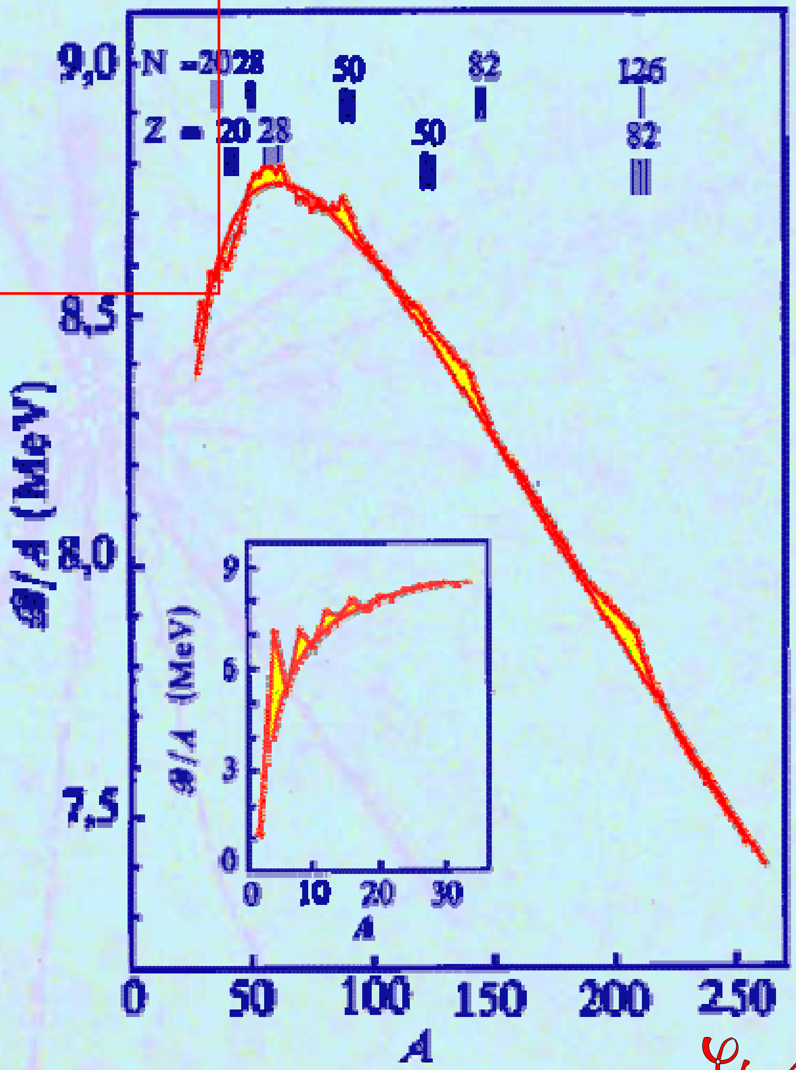
- IV -
Liquid Drop



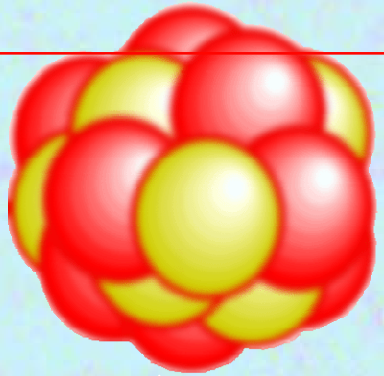


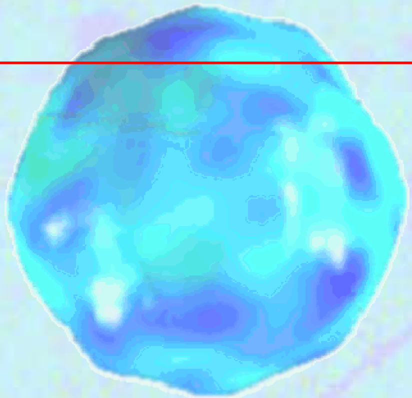
■ **Bond like a drop**

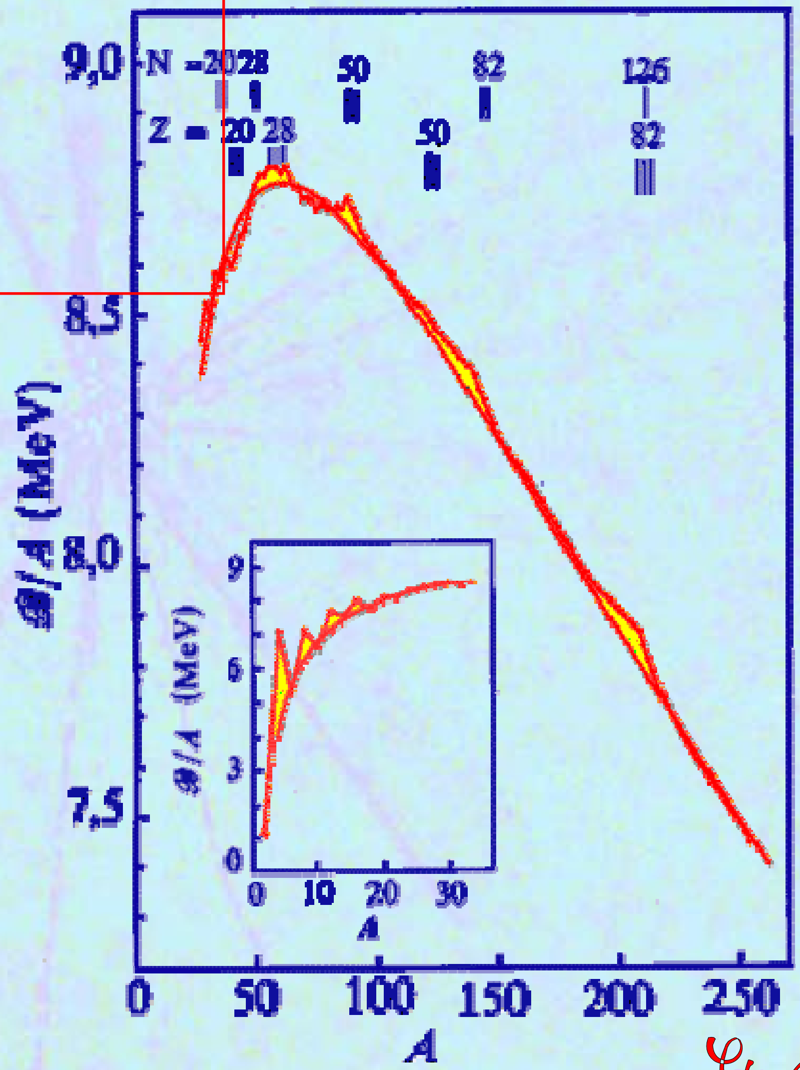
- **Energy proportional to the number of particles**



- IV -
Liquid Drop

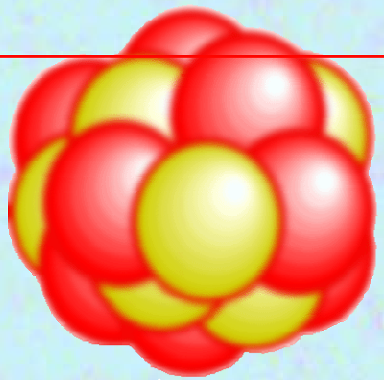


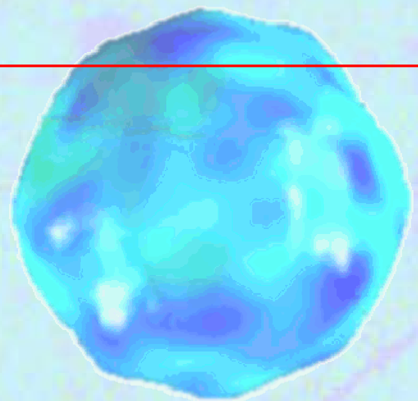


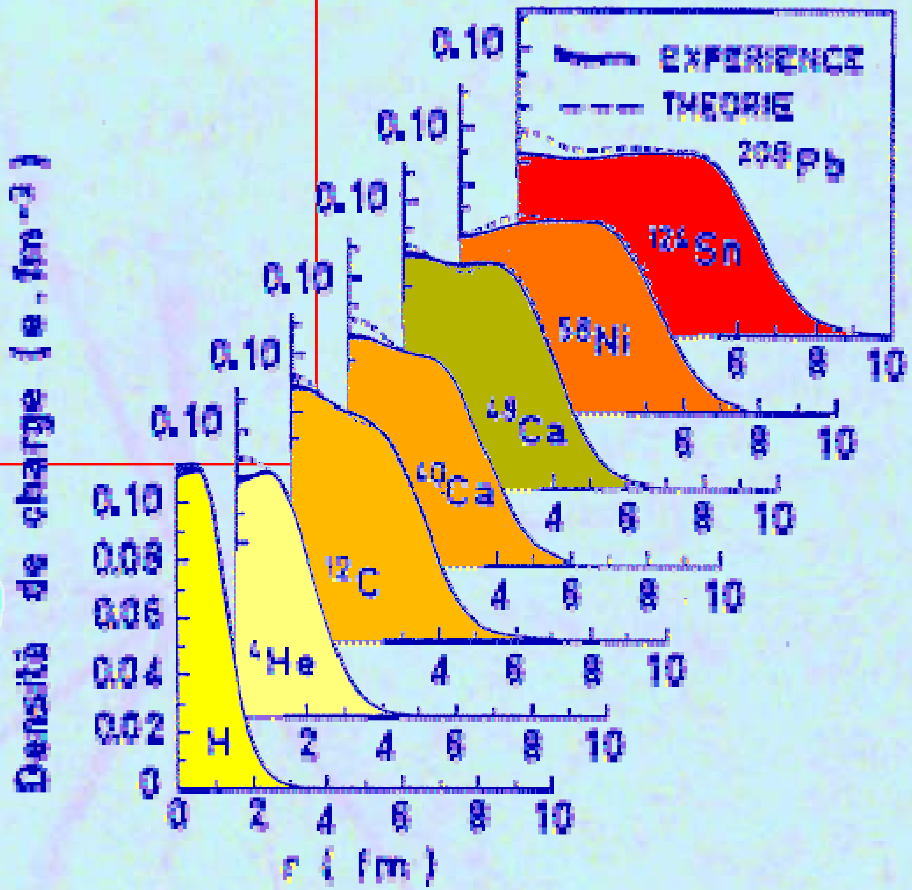


- **Bond like a drop**
  - **Energy proportional to the number of particles**
    E/A = -16 MeV
  - **Strong force short range**

- IV -
Liquid Drop



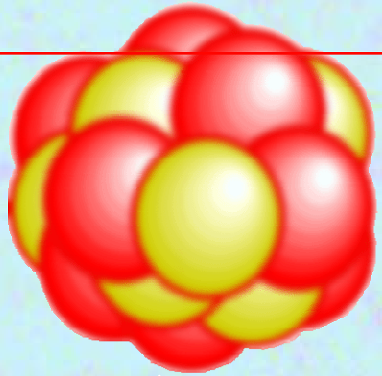


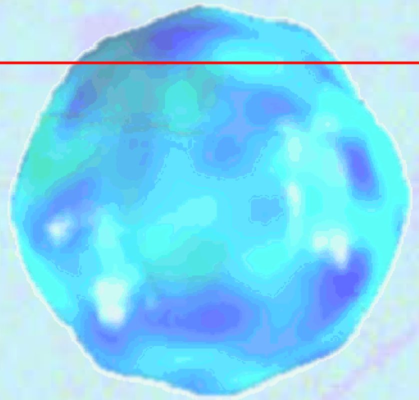


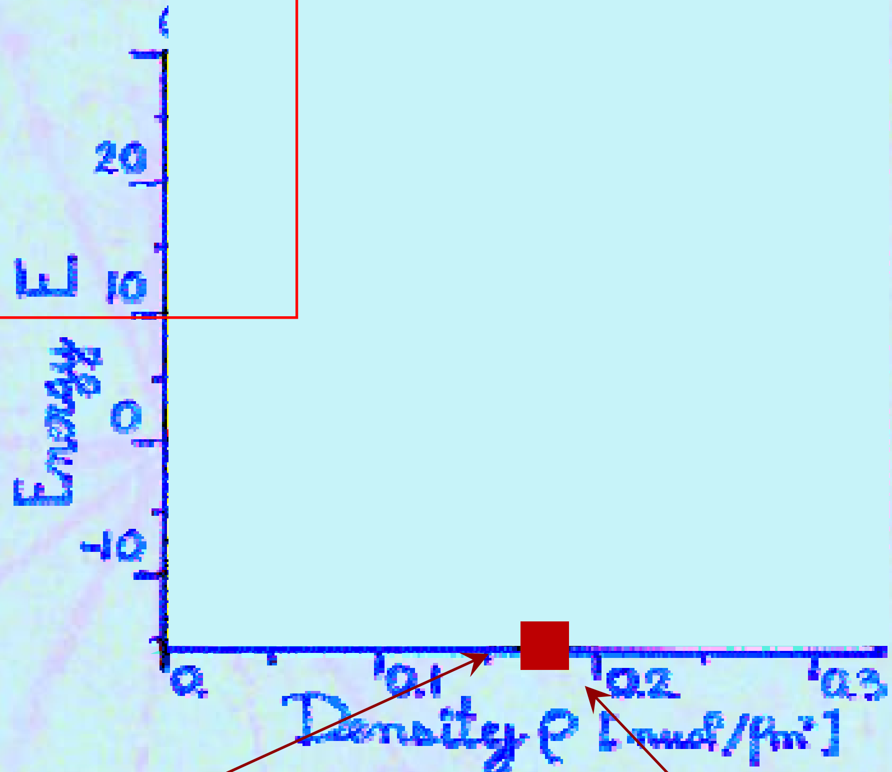
- **Bond like a drop**
  - ☞ Energy proportional to the number of particles
    E/A = -16 MeV
  - ☞ Strong force short range

- **Drop density profile**
  - ☞ Central density
    ρ = 0.17 nucleon/fm^3

- IV -
Liquid Drop







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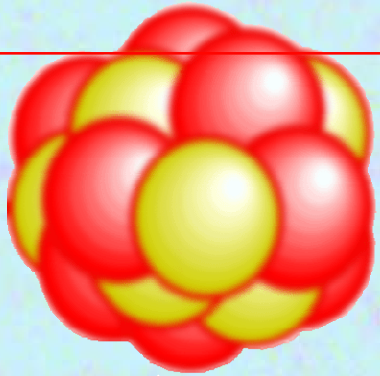
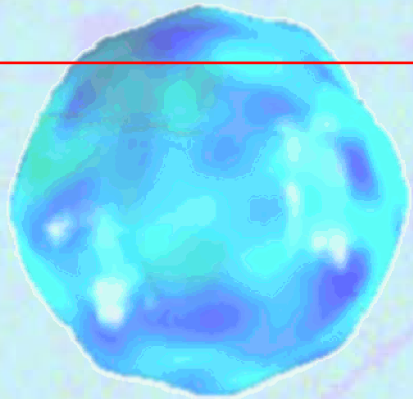
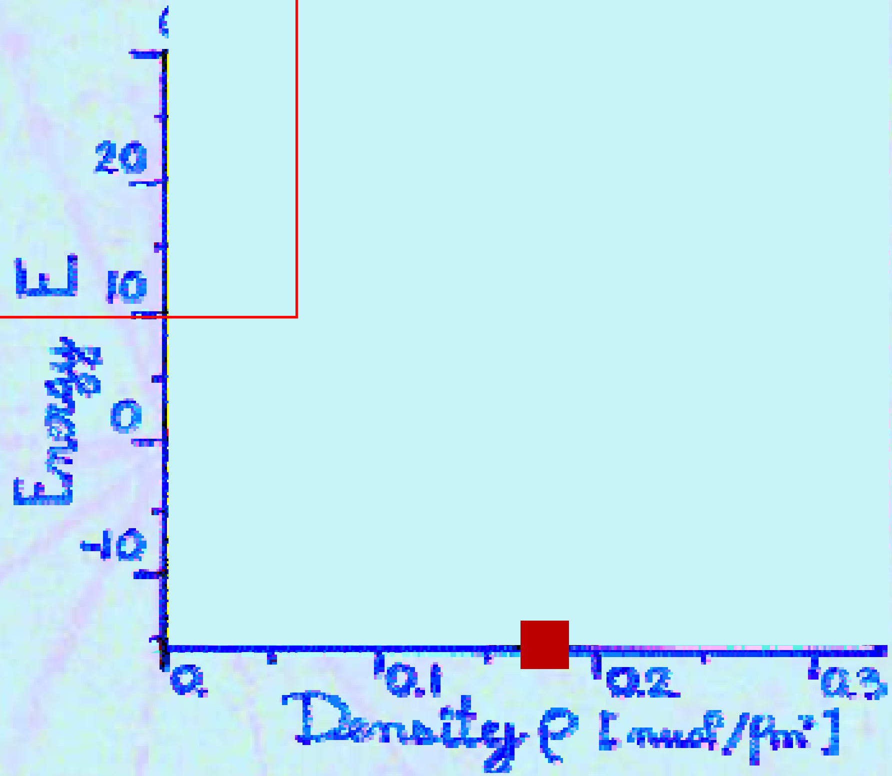
- IV -
Liquid Drop

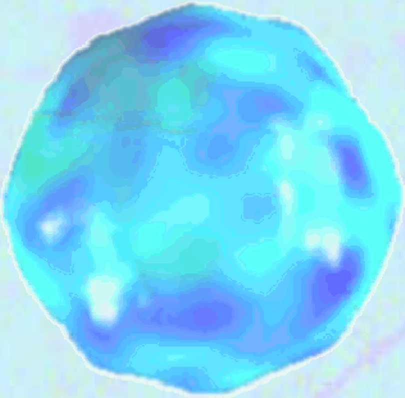
- IV -
Liquid Drop

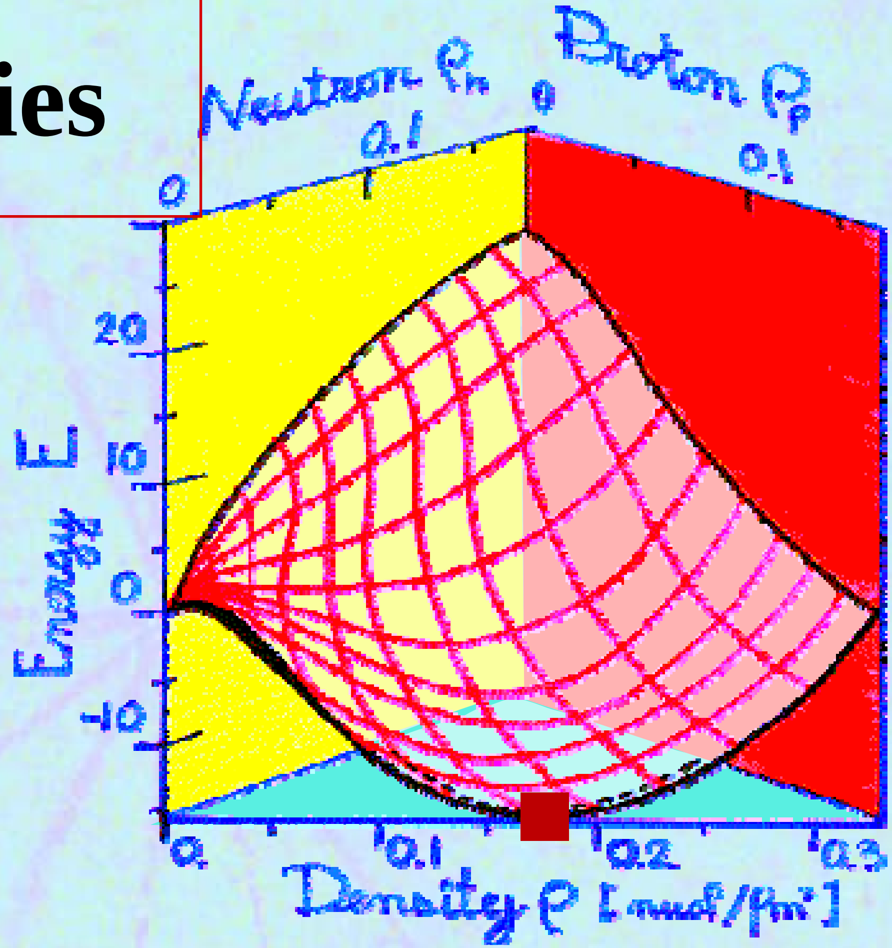






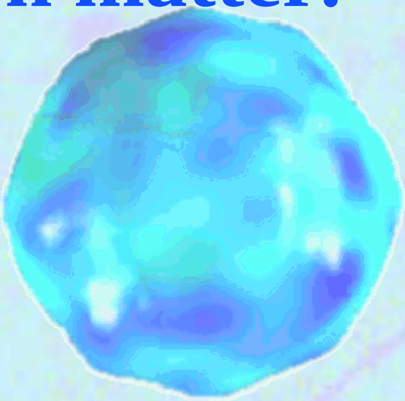
Mechanical properties

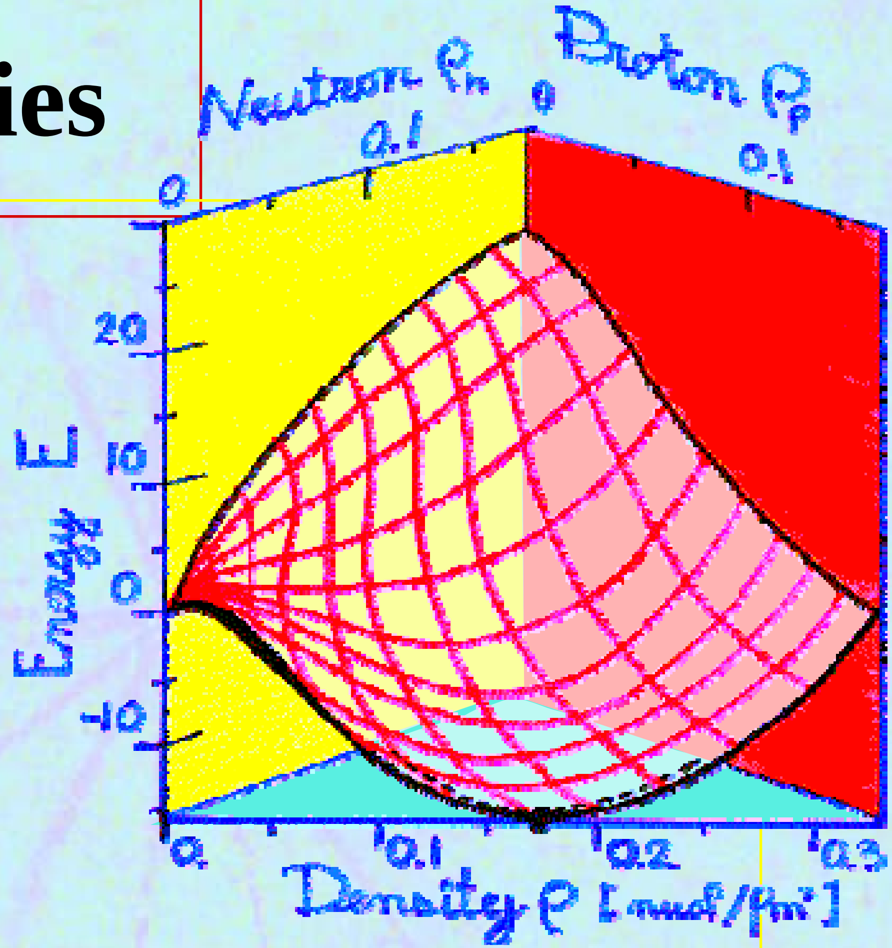




Mechanical properties

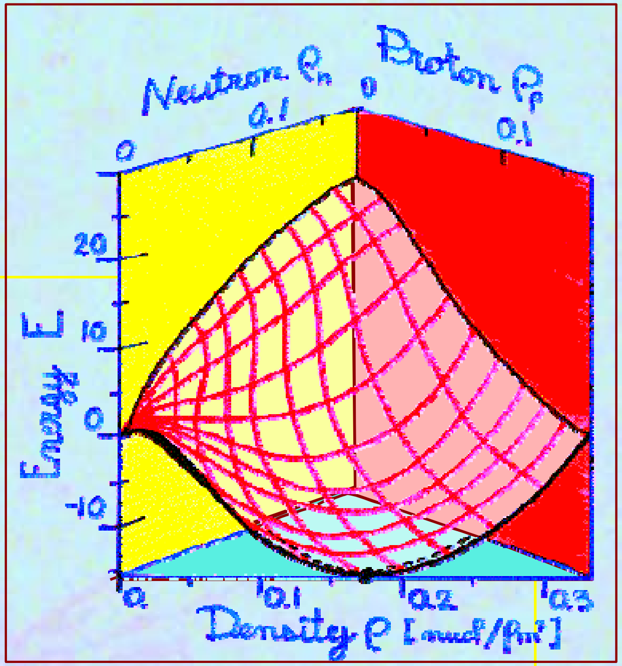
- **Still badly known for neutron matter.**

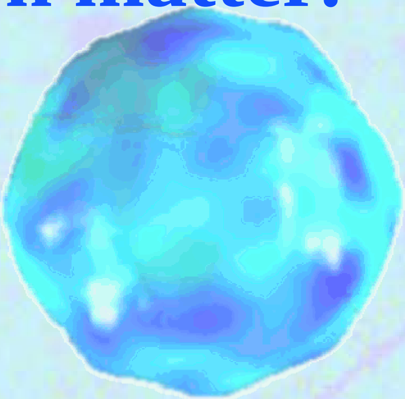




Mechanical properties

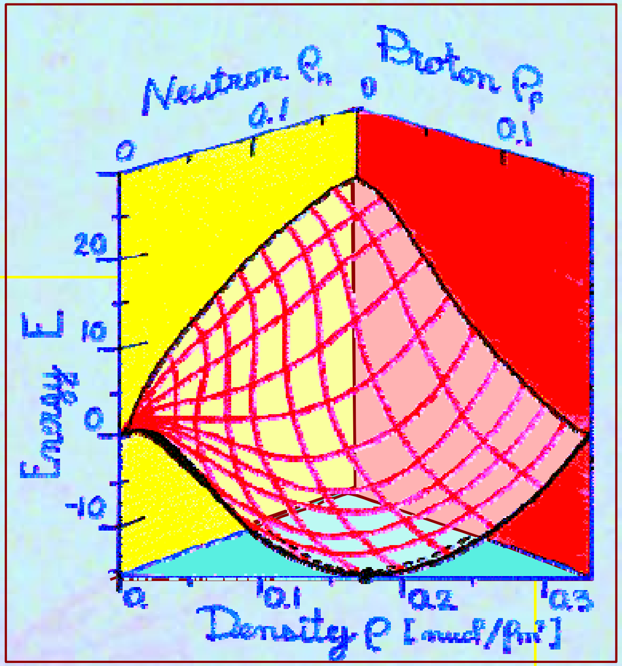
- Still badly known for neutron matter.



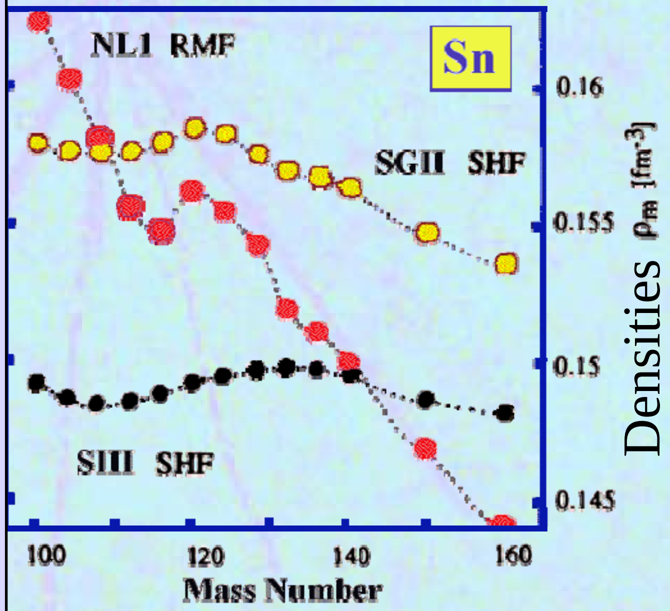


Mechanical properties

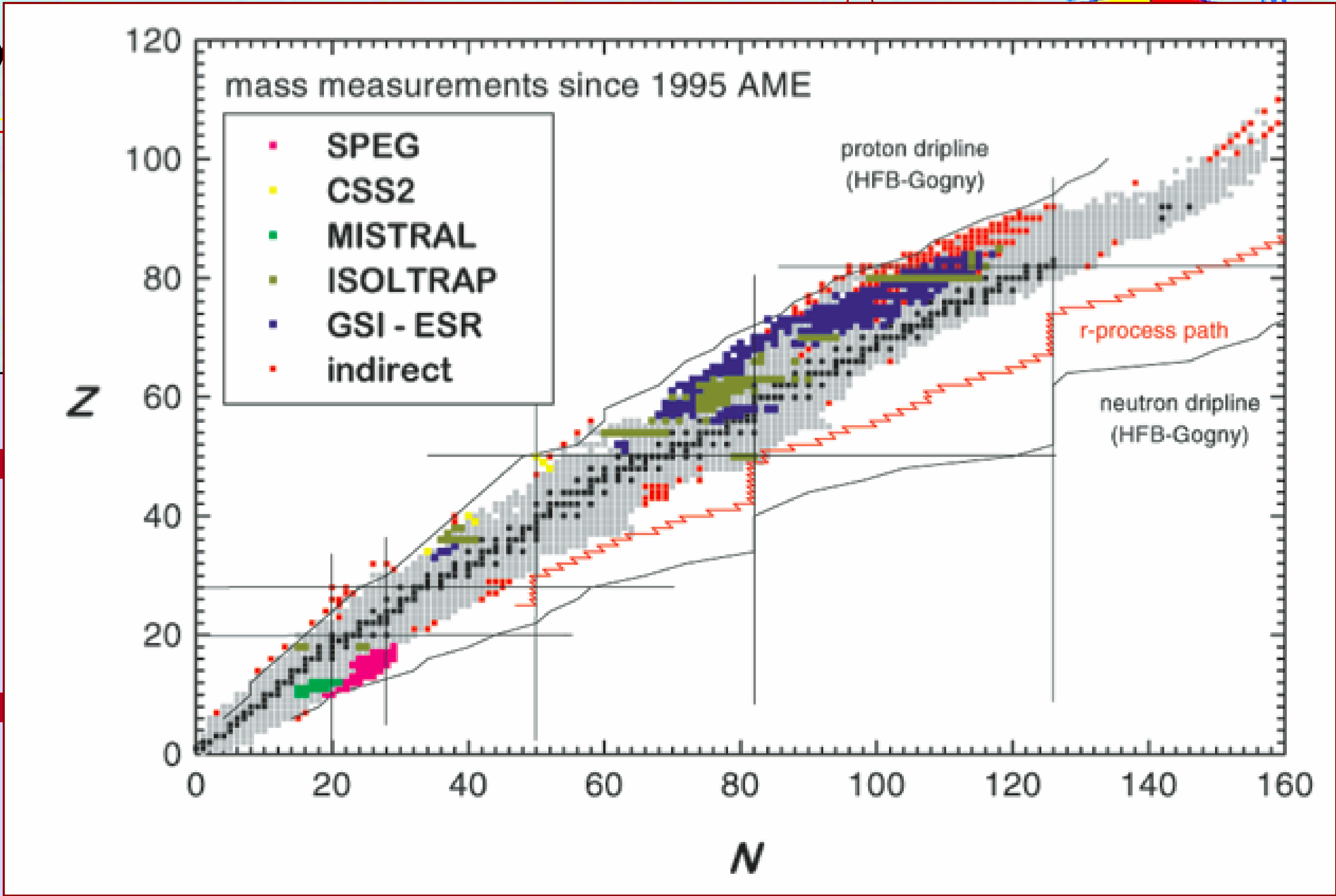
- **Still badly known for neutron matter.**



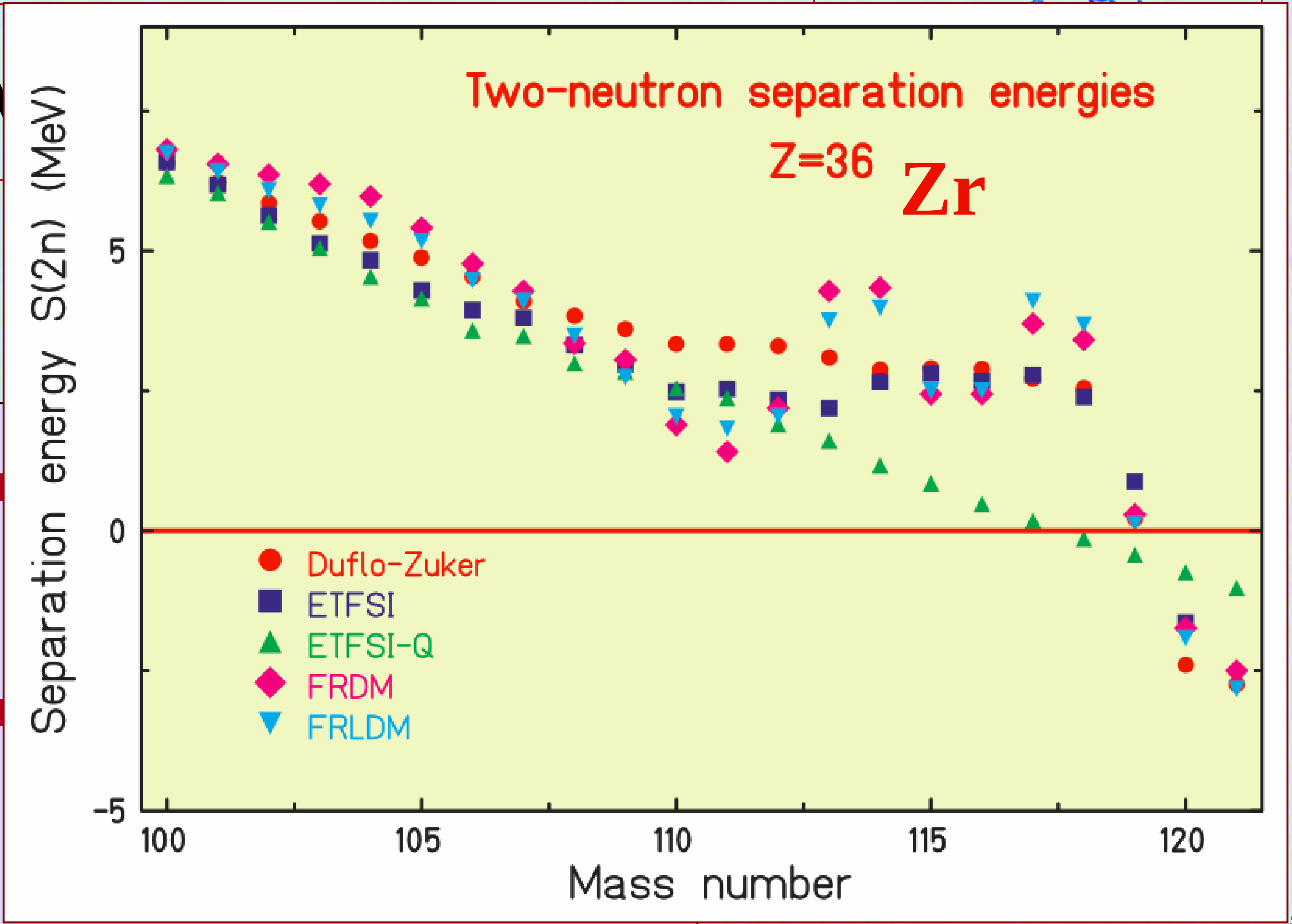
- **Isospin dependence:**
  Radii, densities
  Masses and energies
- **Compressibility:**
  Breathing mode, reactions and flow

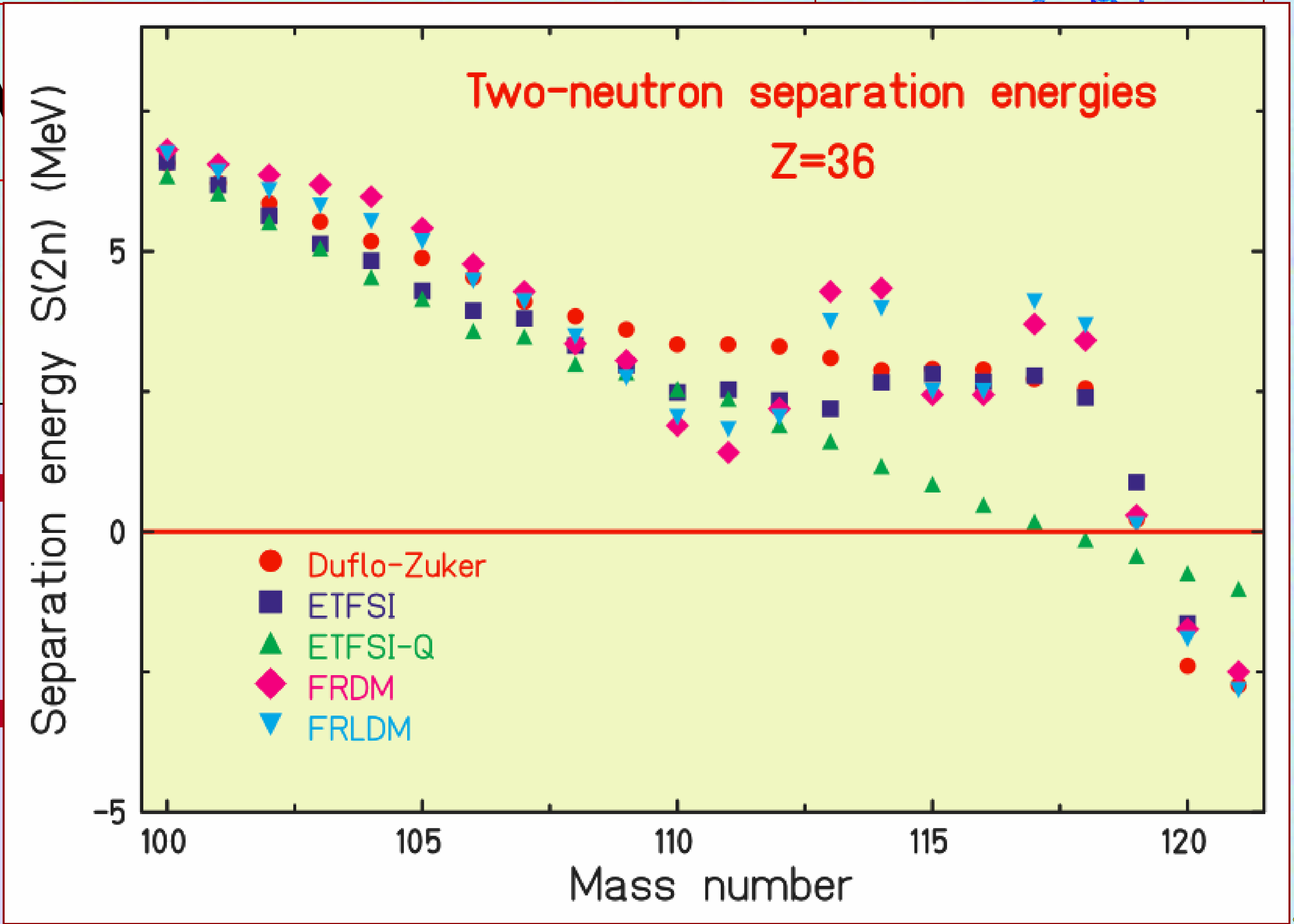


M



Mass Number


Two-neutron separation energies
Z=36
Zr
Separation energy S(2n) (MeV)
Mass number
5
0
−5
100
105
110
115
120
Duflo-Zuker
ETFSI
ETFSI-Q
FRDM
FRLDM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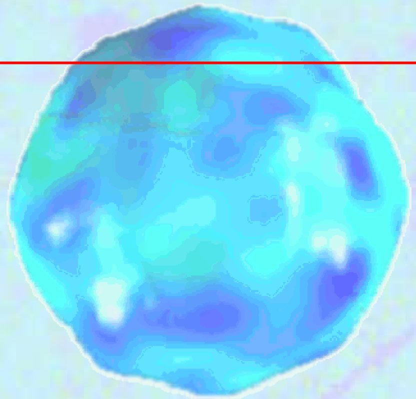
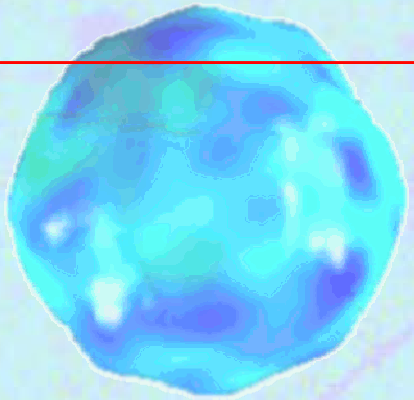
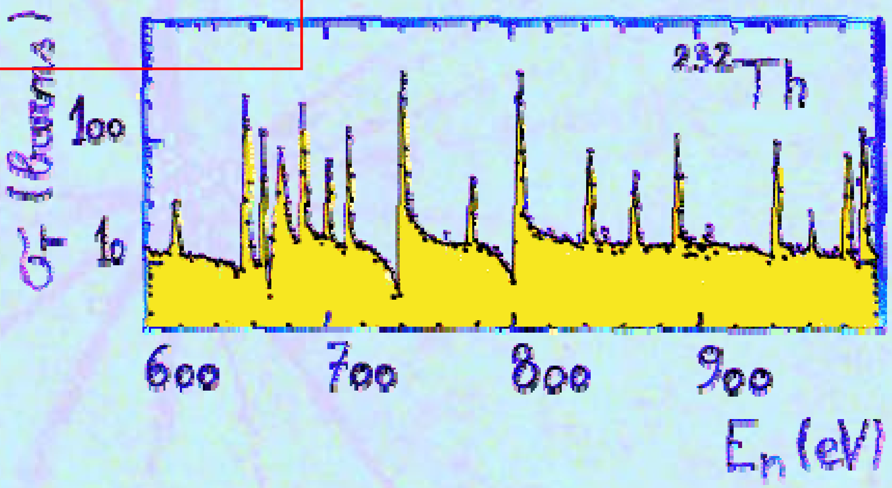
- IV -
Liquid Drop



☞ **Neutron absorption**

- IV -
Liquid Drop

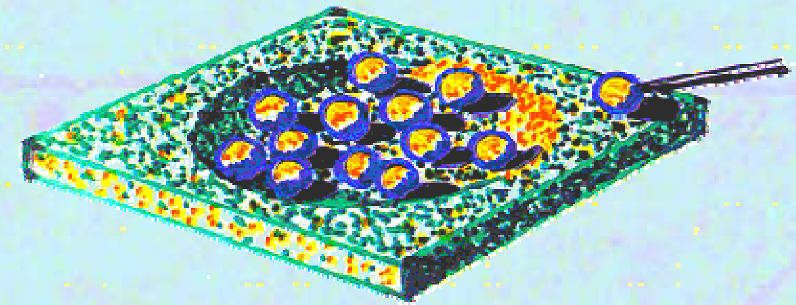


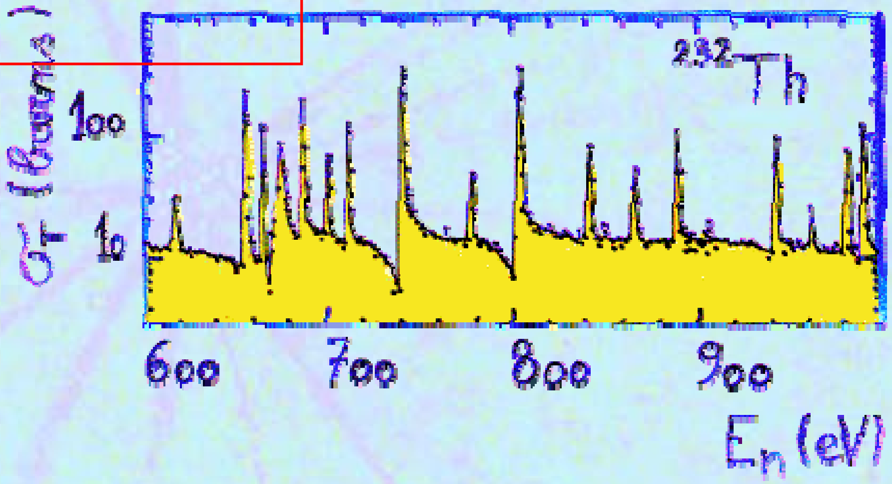


- **React like a liquid**
  - **Neutron absorption**
  - **State in disorder**

- IV -
Liquid Drop

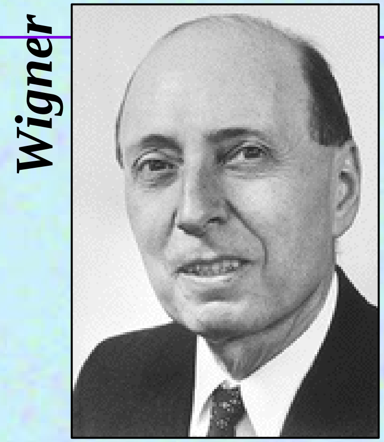
Bohr

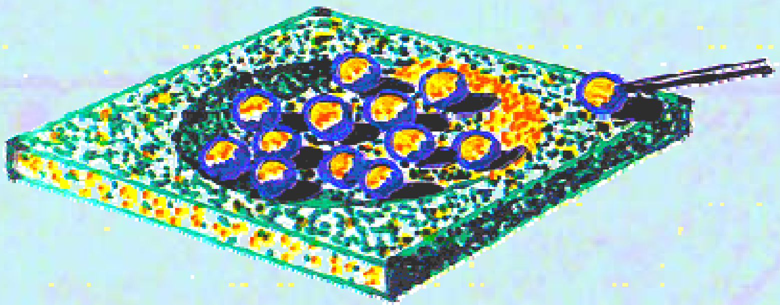


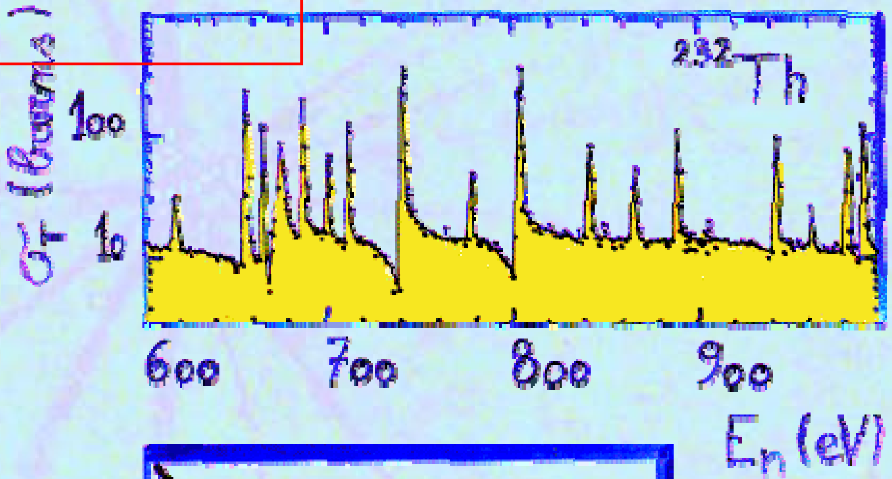


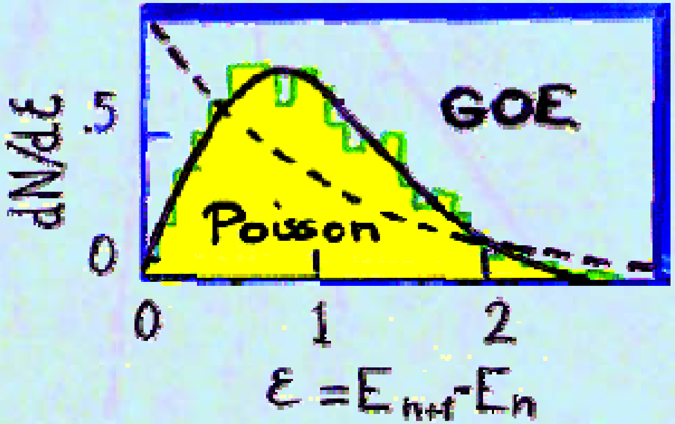
- **React like a liquid**
  - ☞ **Neutron absorption**
  - ☞ **State in disorder**

- IV -
Liquid Drop









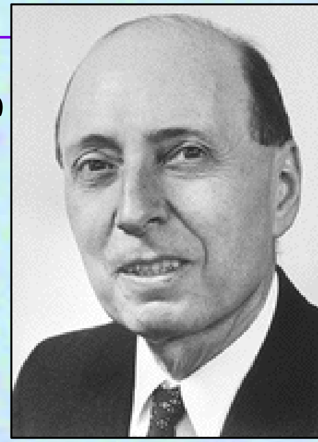
- **React like a liquid**
  - **Neutron absorption**
  - **State in disorder**

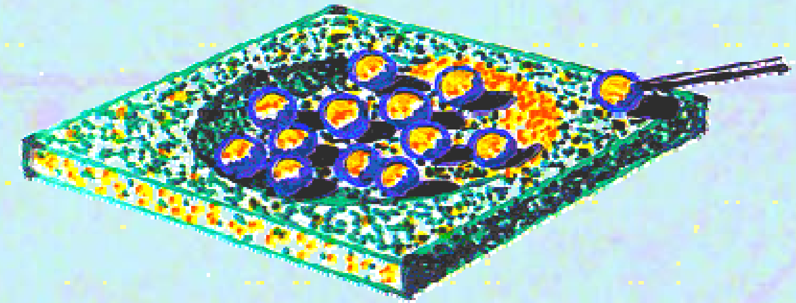
- IV -

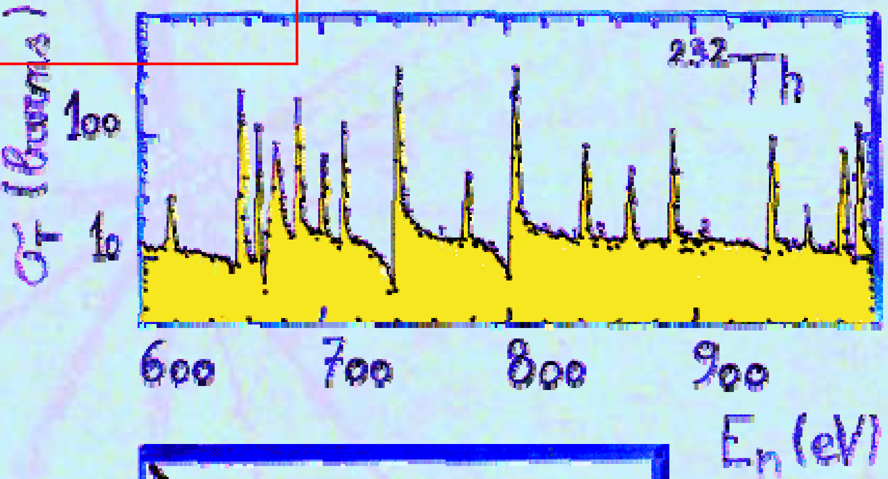
Liquid Drop

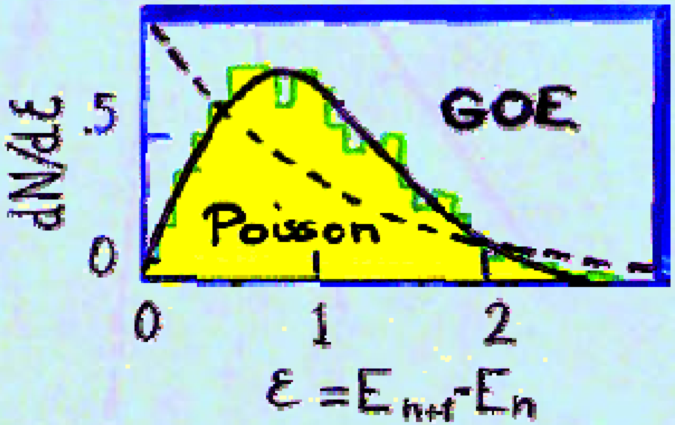
Quantum Chaos

Wigner









- **React like a liquid**
  - ☞ **Neutron absorption**
  - ☞ **State in disorder**

- IV -

Liquid Drop

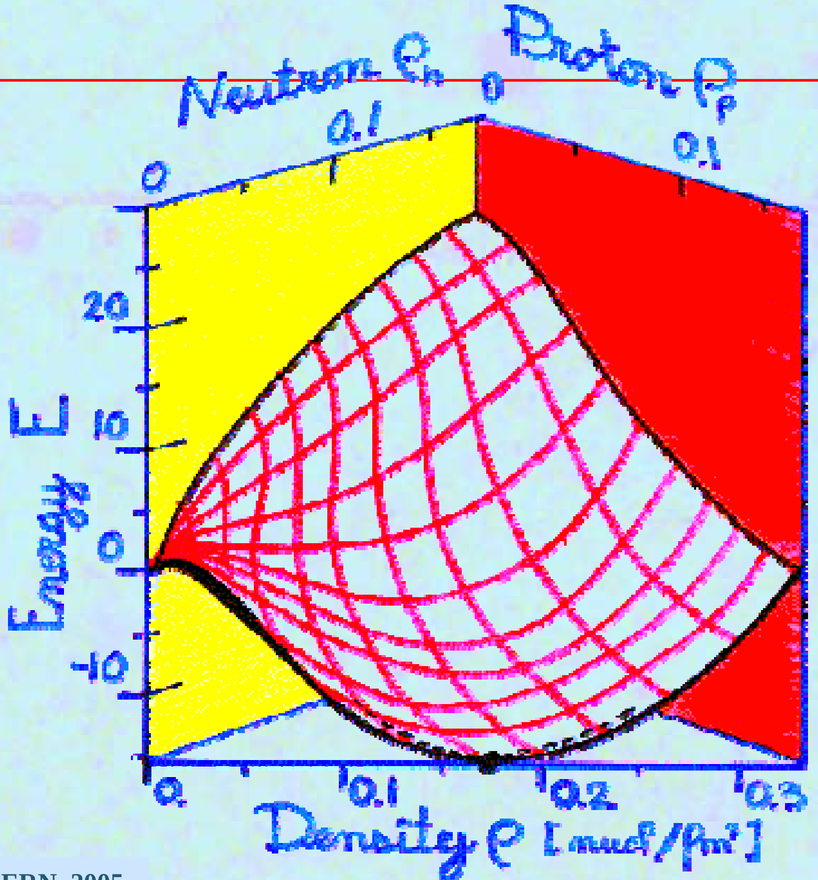
Quantum Chaos

- **Thermodynamics**
  - **Liquid-gas phase transition**

- **React like a liquid**
  - ☞ **Neutron absorption**
  - ☞ **State in disorder**

- IV -
Liquid Drop

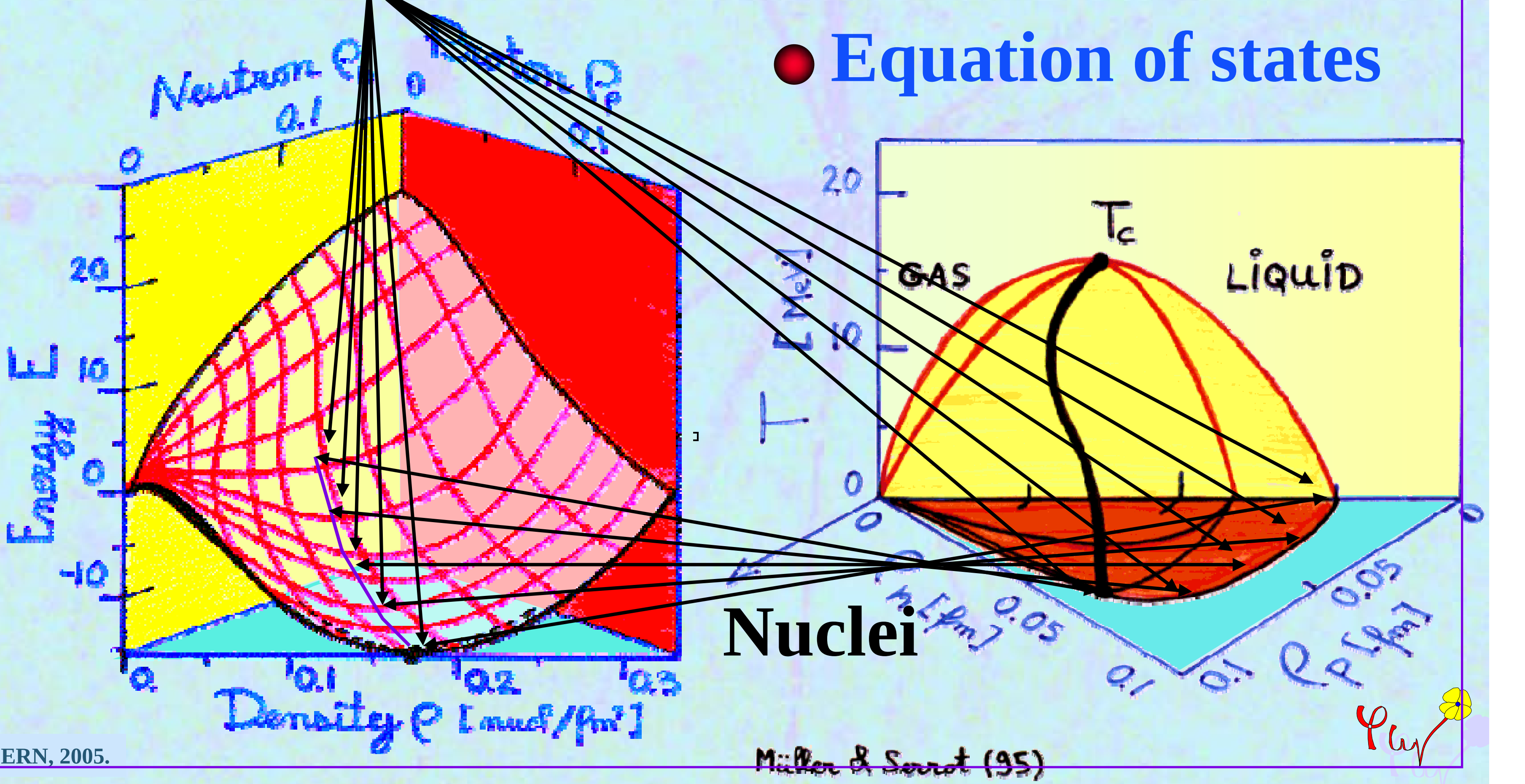
- **Thermodynamics**
  - **Liquid-gas phase transition**



- **Thermodynamics**
  - **Liquid-gas phase transition**

- **Saturation**

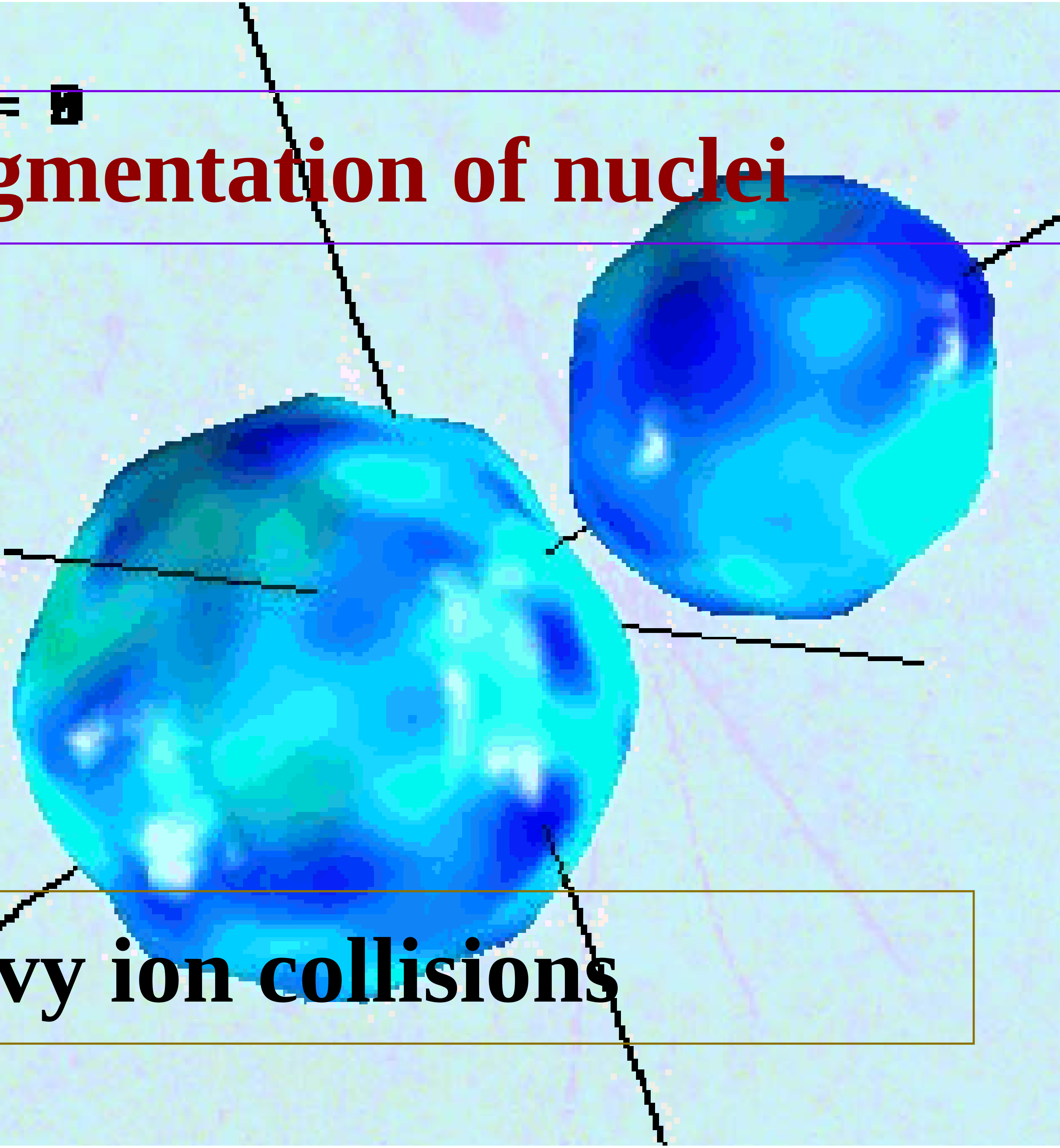
- **Equation of states**



Fragmentation of nuclei

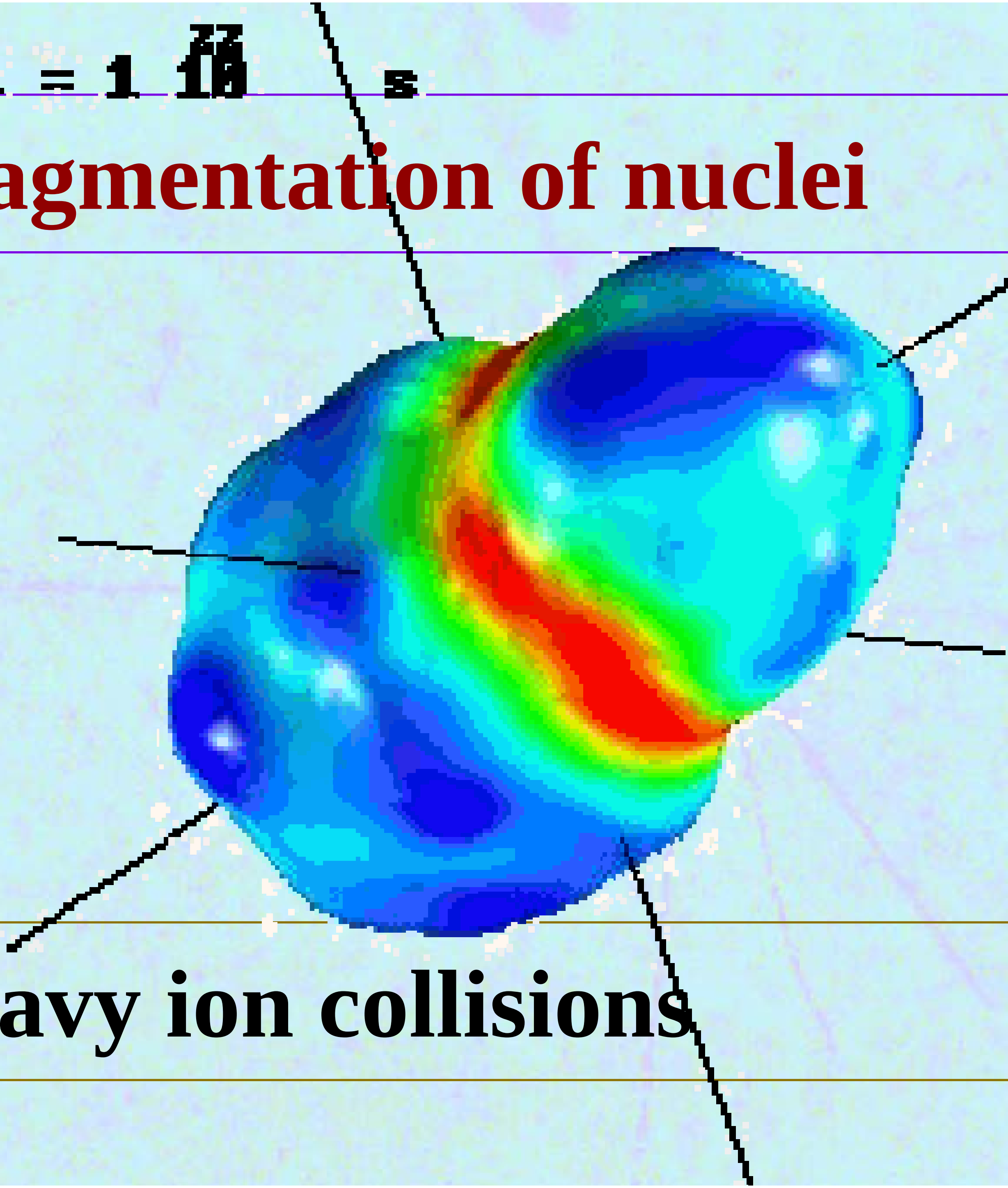
Heavy ion collisions

Fragmentation of nuclei

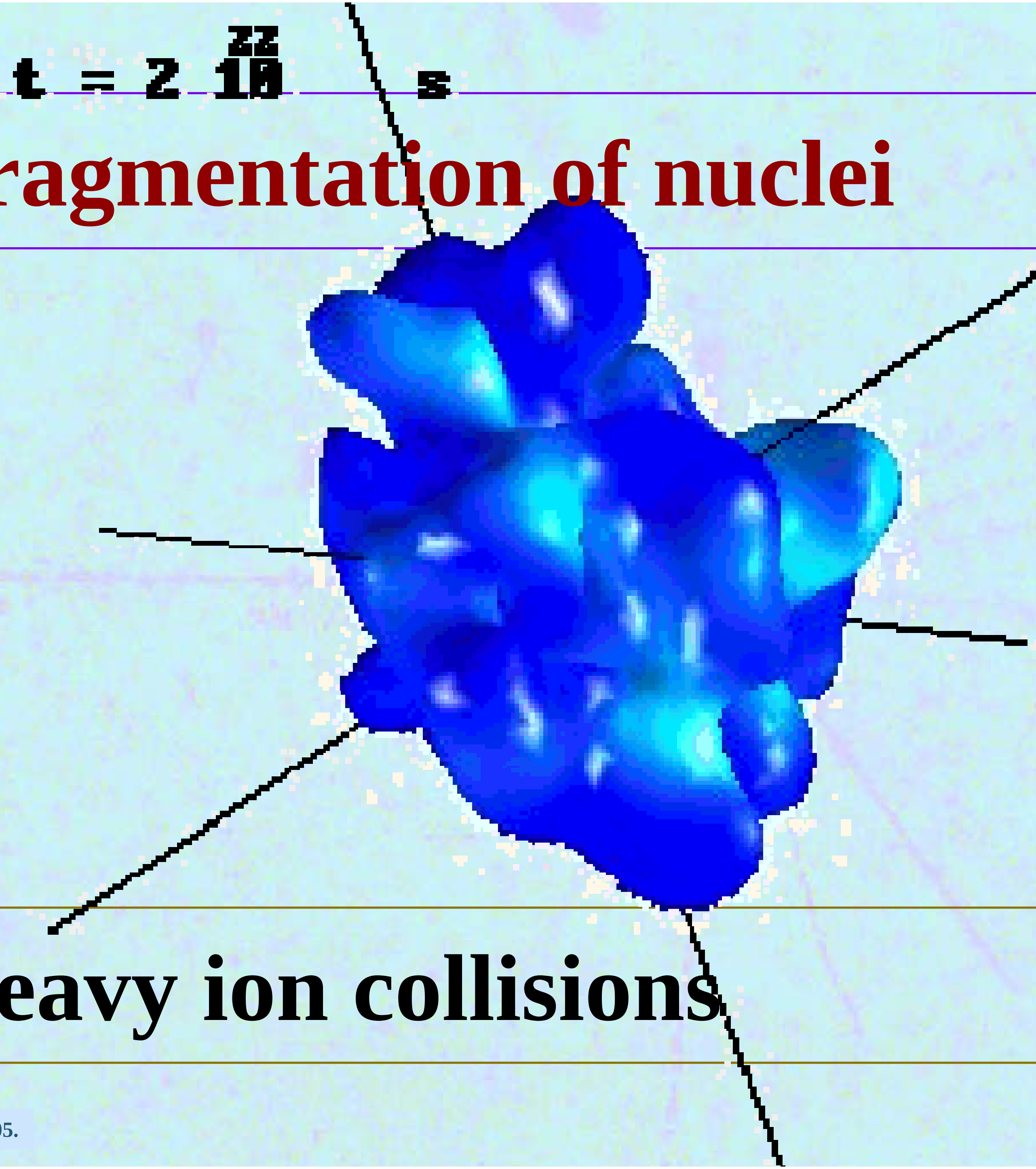


Heavy ion collisions

Fragmentation of nuclei



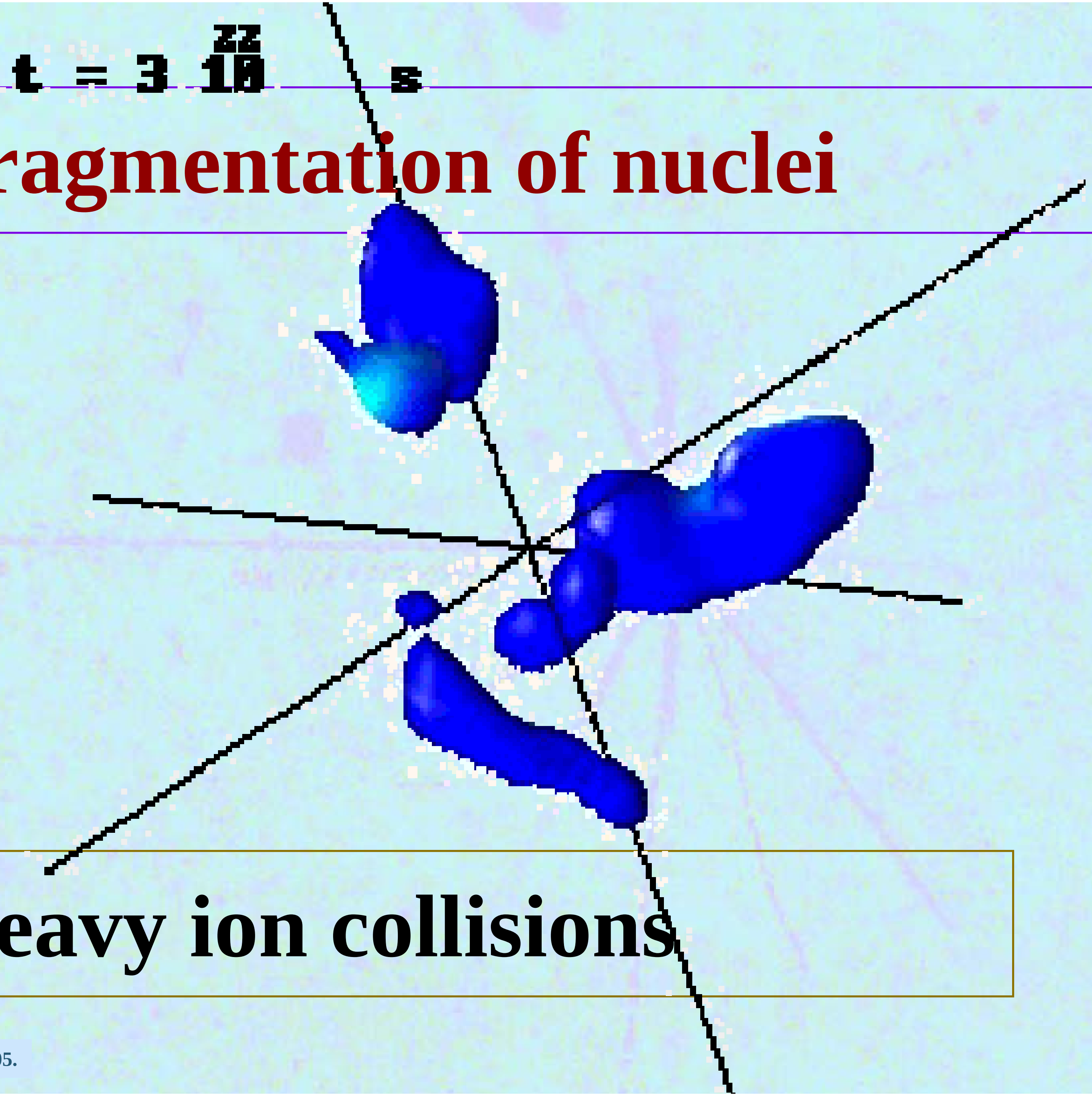
Heavy ion collisions



Fragmentation of nuclei

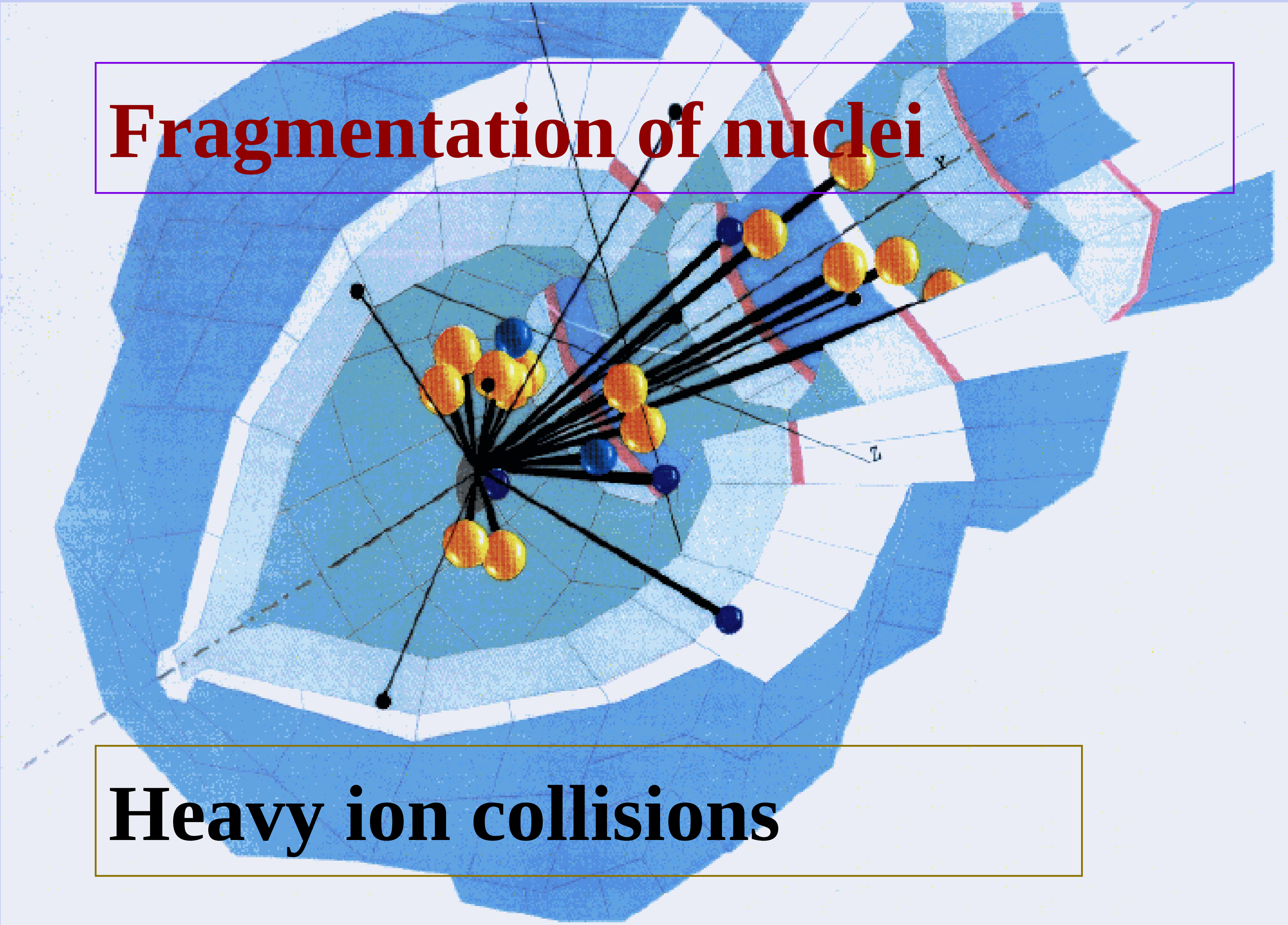
Heavy ion collisions

Fragmentation of nuclei



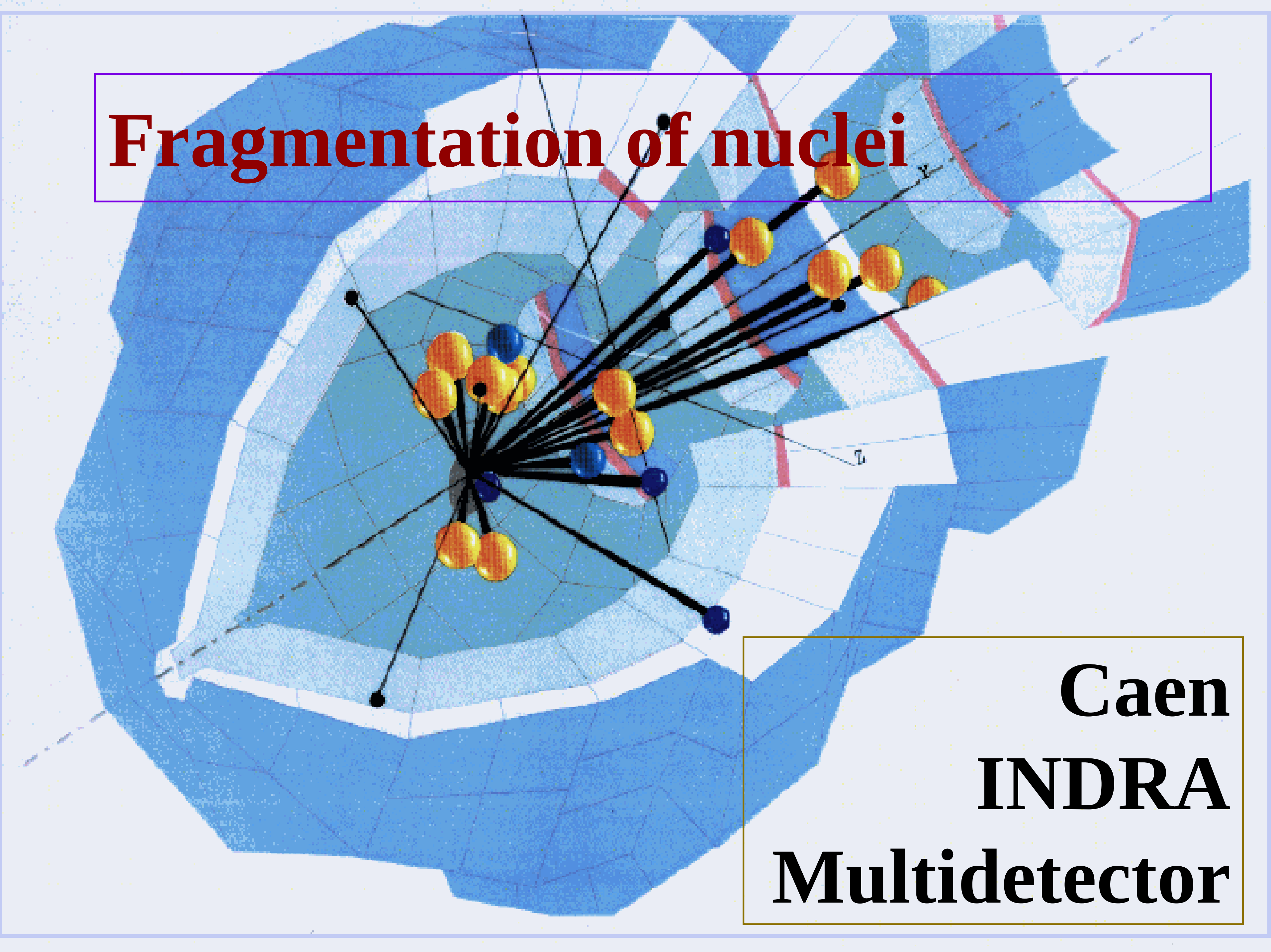
Heavy ion collisions

Fragmentation of nuclei

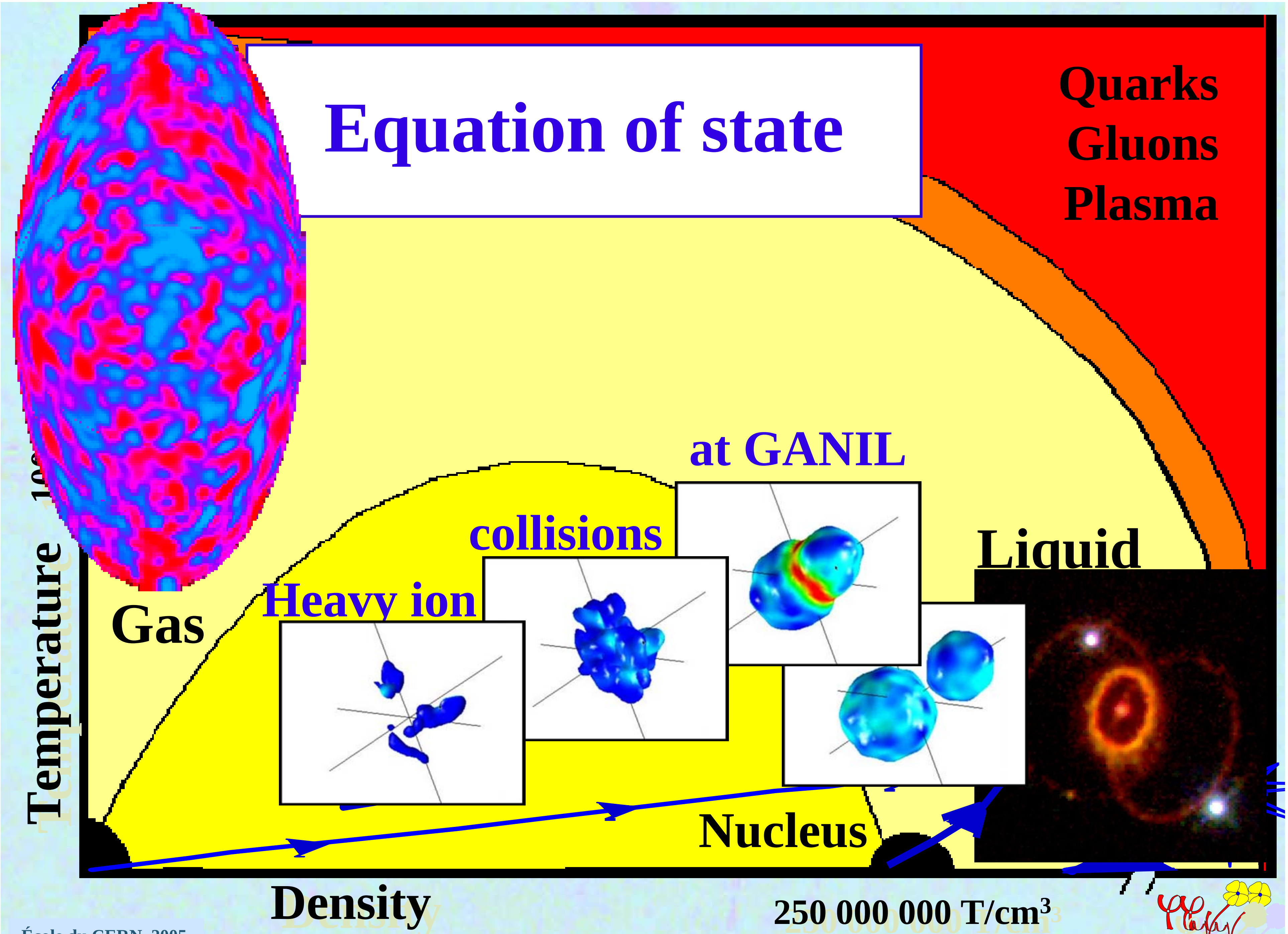


Heavy ion collisions

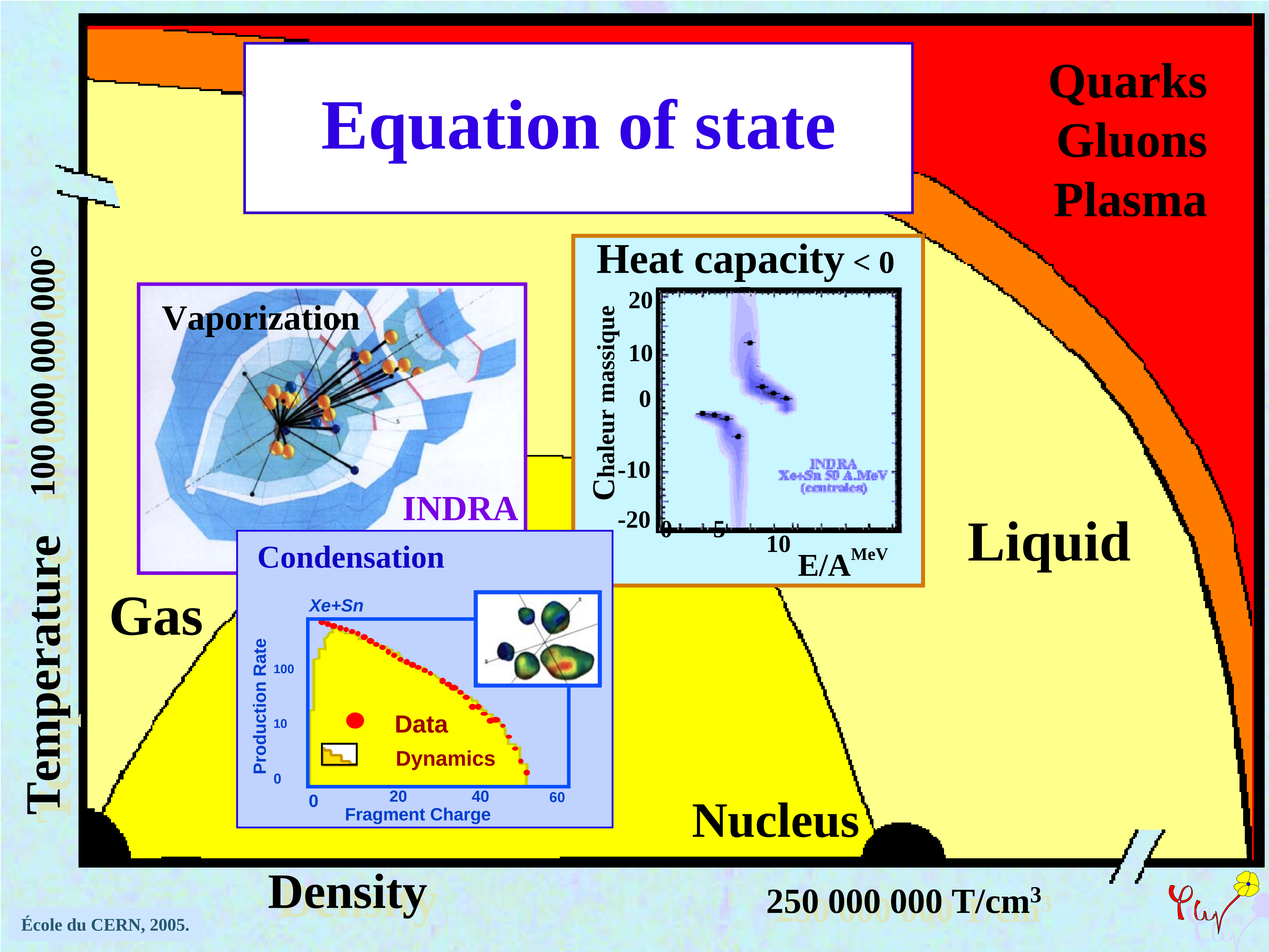
Fragmentation of nuclei



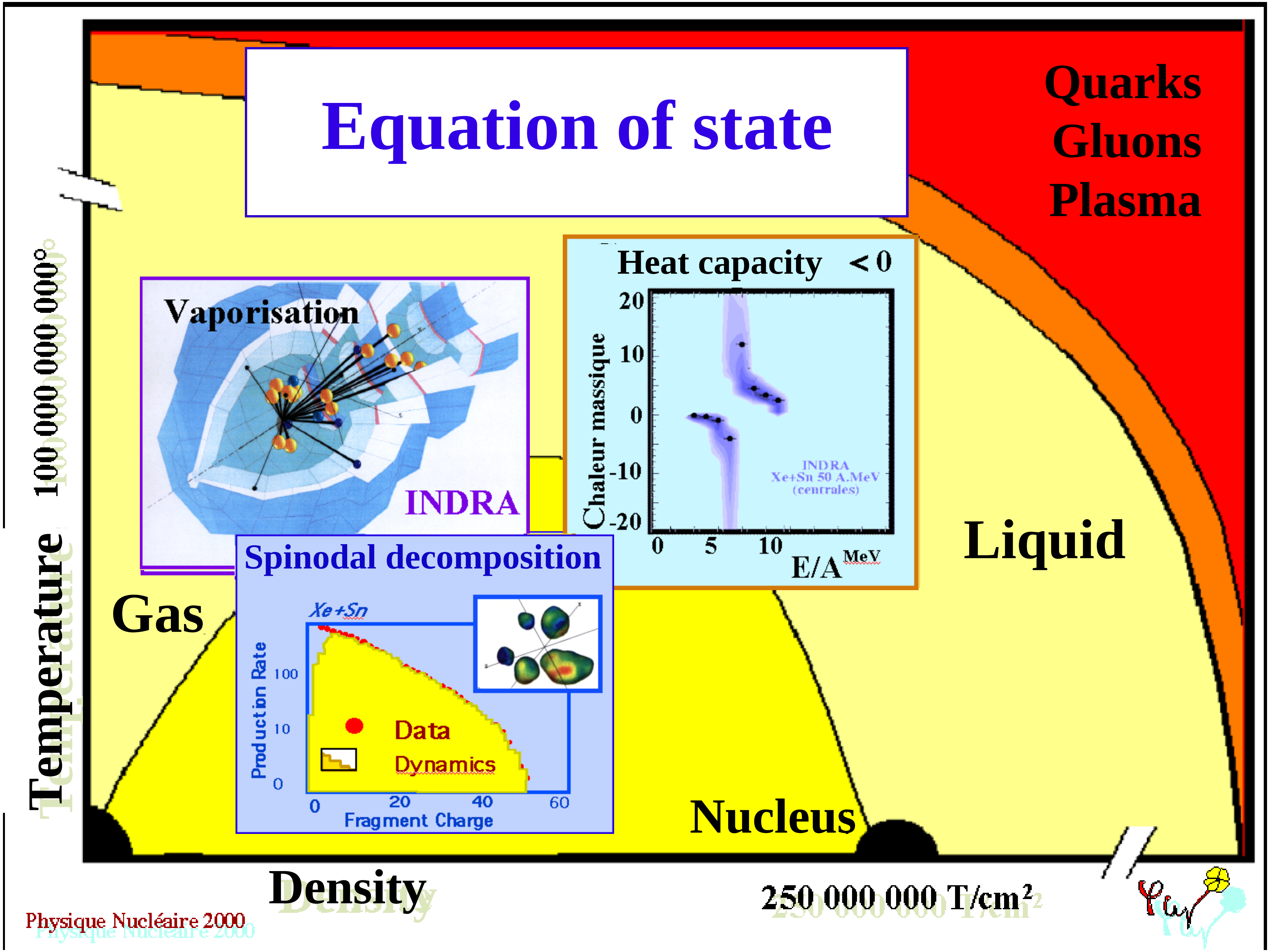
Caen
INDRA
Multidetector



École du CERN, 2005.



Equation of state
Quarks
Gluons
Plasma
Heat capacity < 0
Chaleur massique
20
10
0
-10
-20
0
5
10
E/A MeV
INDRA
Xe+Sn 50 A.MeV
(centrales)
Vaporization
INDRA
Condensation
Xe+Sn
Production Rate
100
10
0
Data
Dynamics
0
20
40
60
Fragment Charge
Liquid
Gas
Nucleus
Temperature 100 000 000 000°
Density
250 000 000 T/cm3



Equation of state
Quarks
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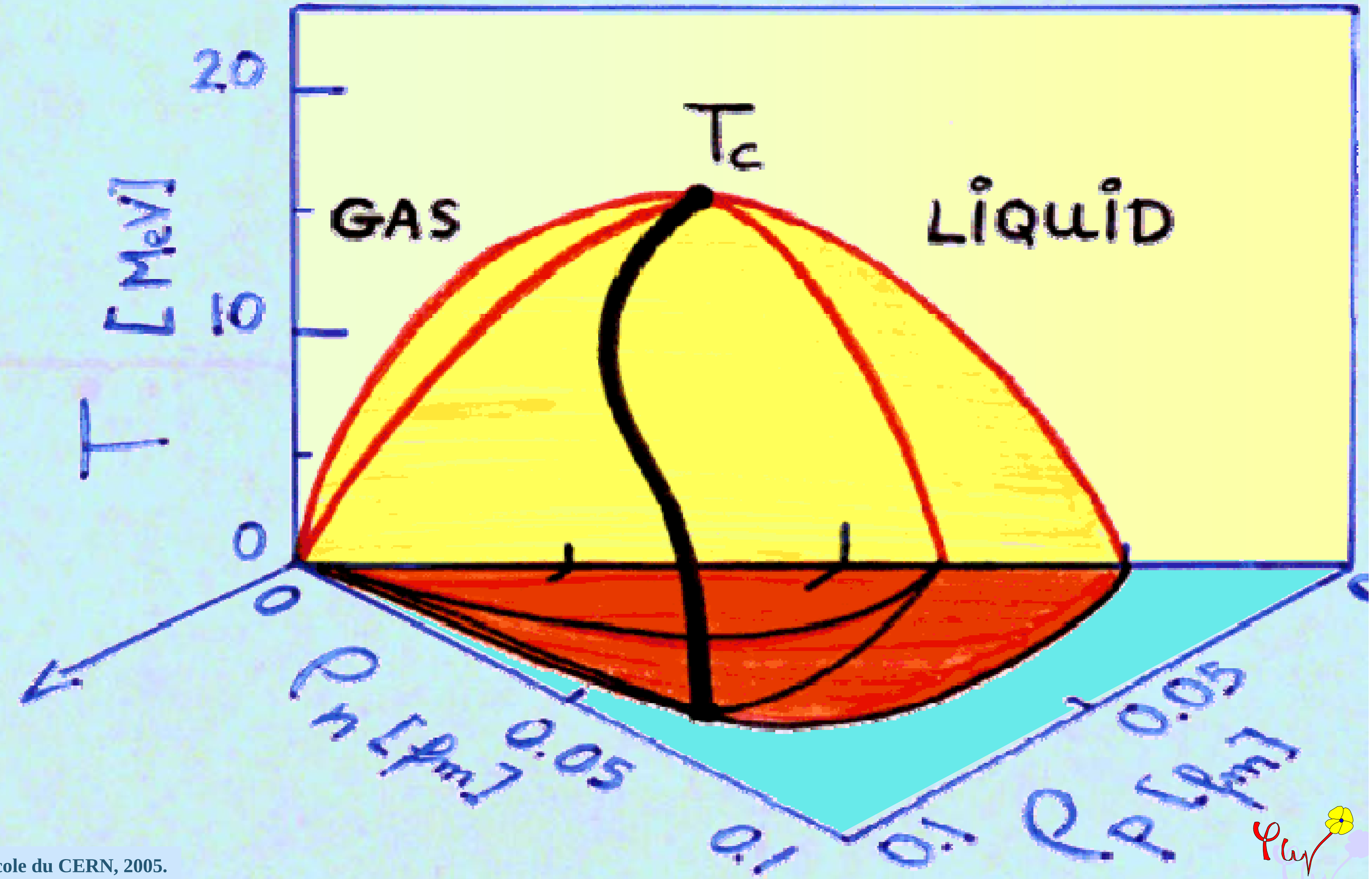
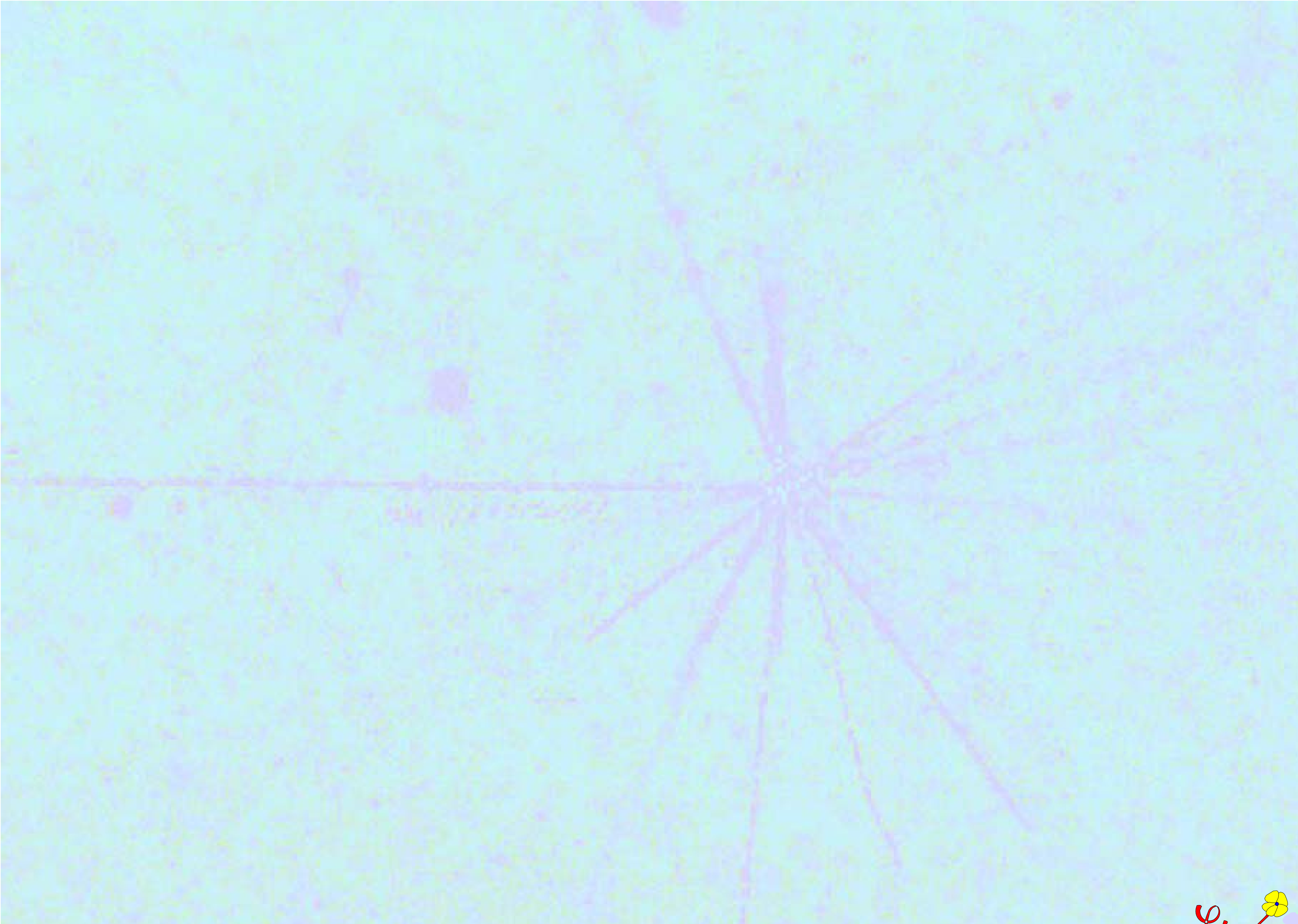
Xe+Sn 50 A.MeV
(centrales)
Vaporisation
INDRA
Spinodal decomposition
Xe+Sn
Production Rate
100
10
0
Data
Dynamics
0
20
40
60
Fragment Charge
Liquid
Gas
Nucleus
Temperature
100 000 000 000°
Density
250 000 000 T/cm²
Physique Nucléaire 2000

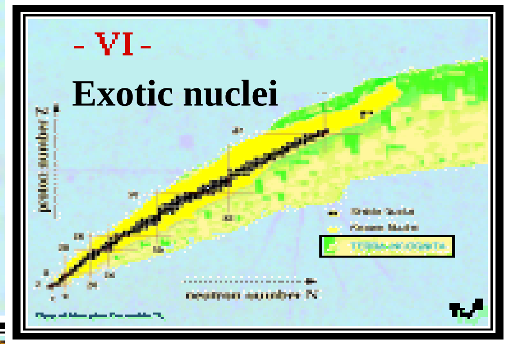
Isospin dependence of EOS?

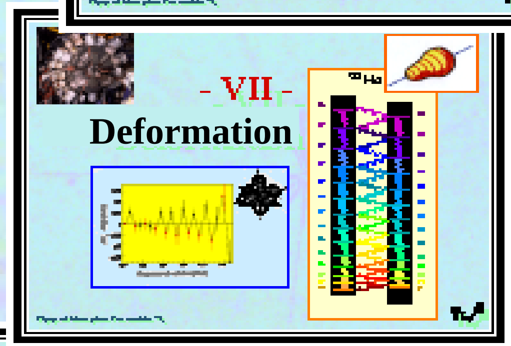


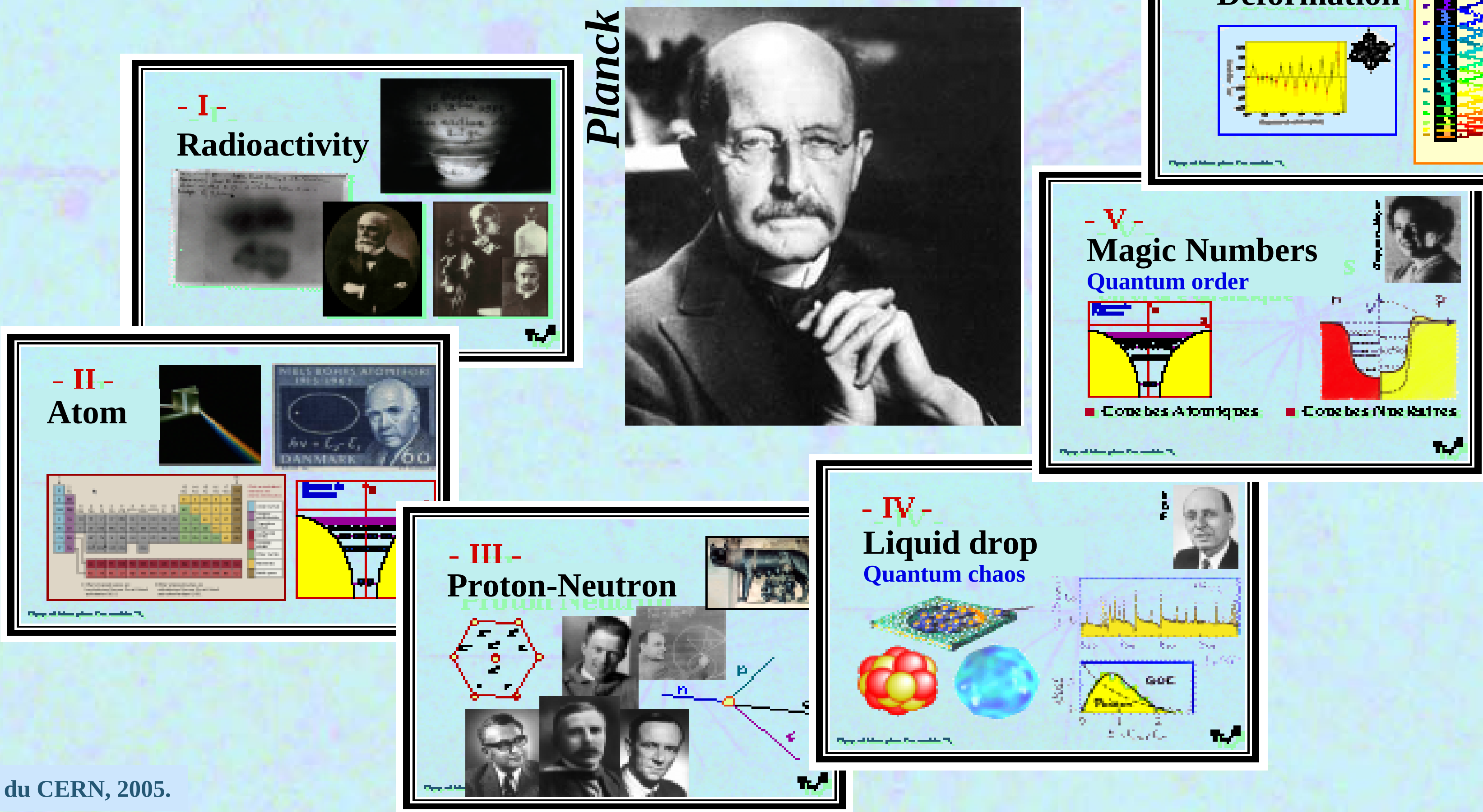


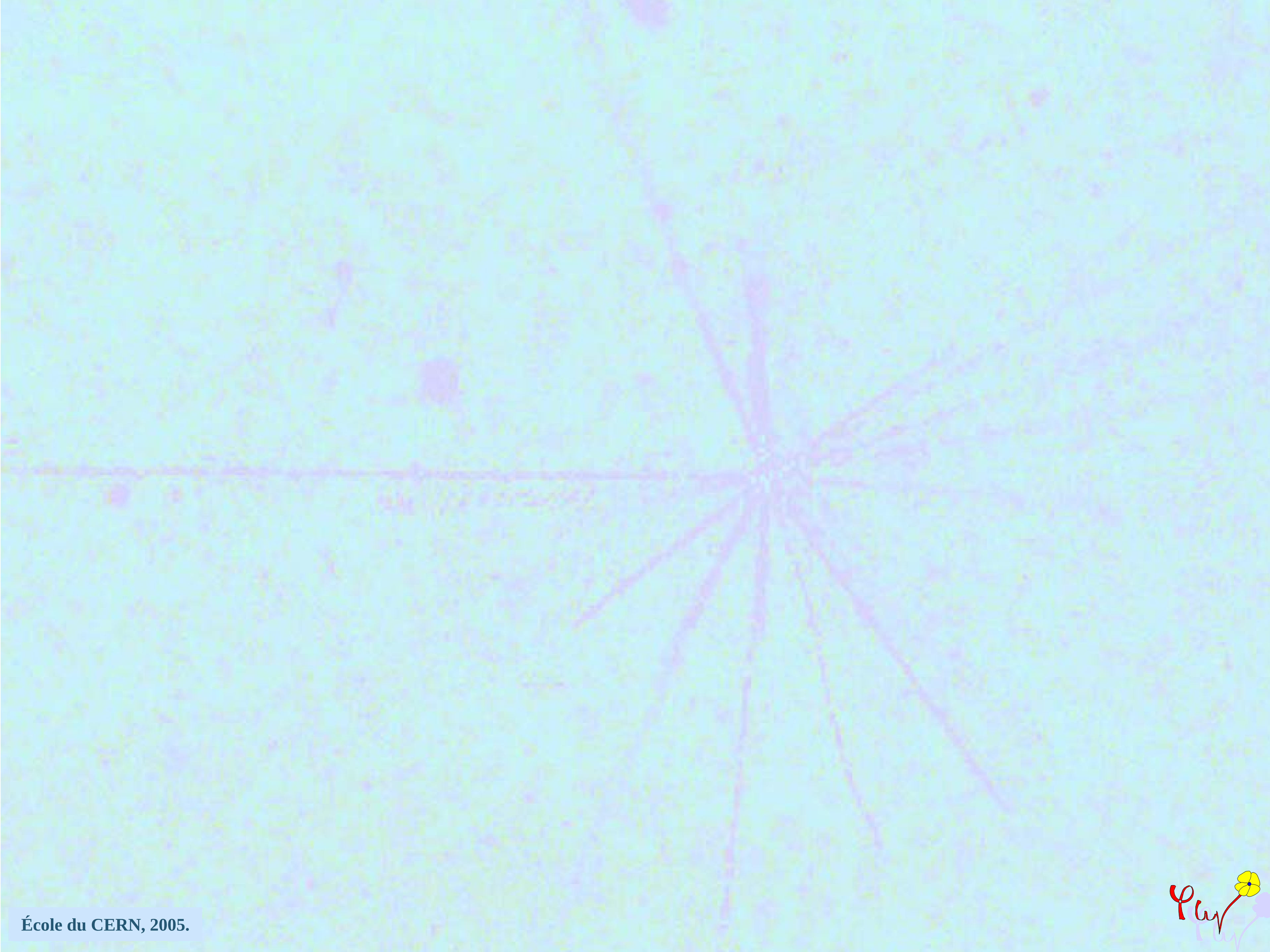
Atomic Nuclei

Complex quantum systems

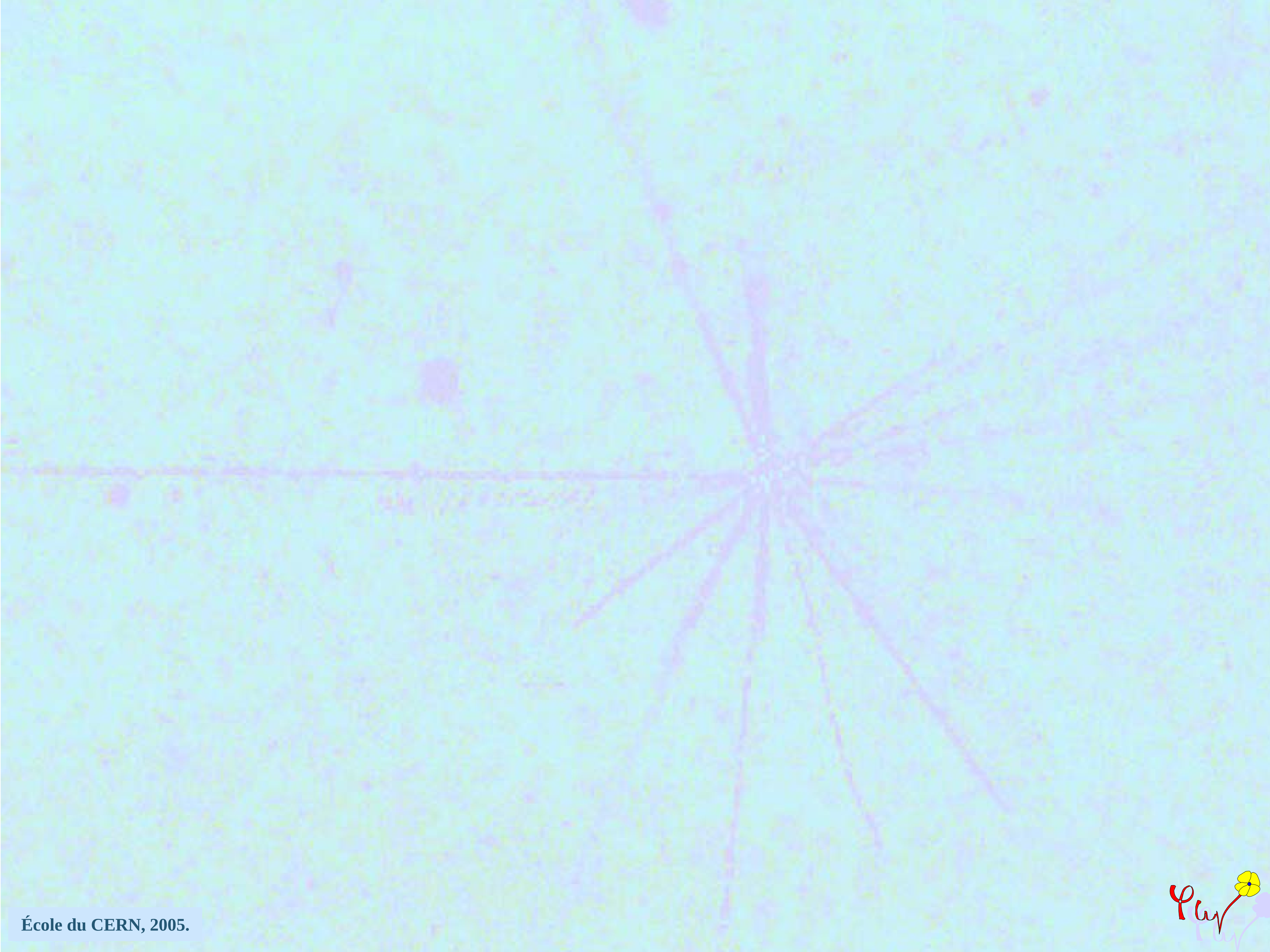




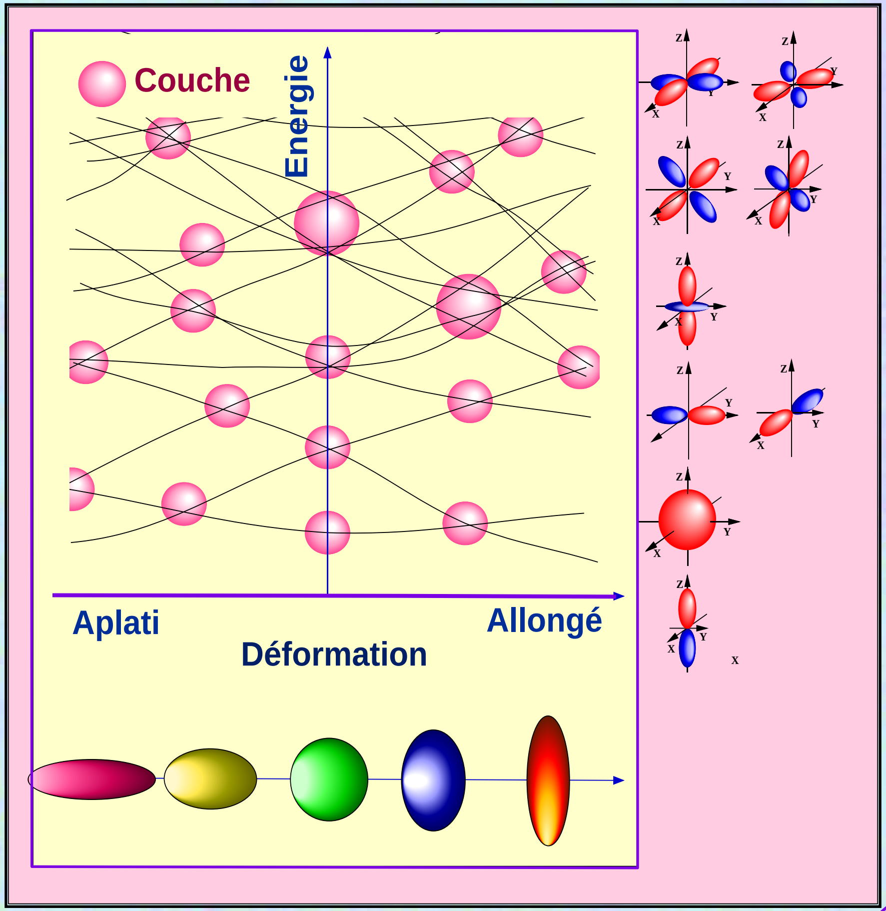




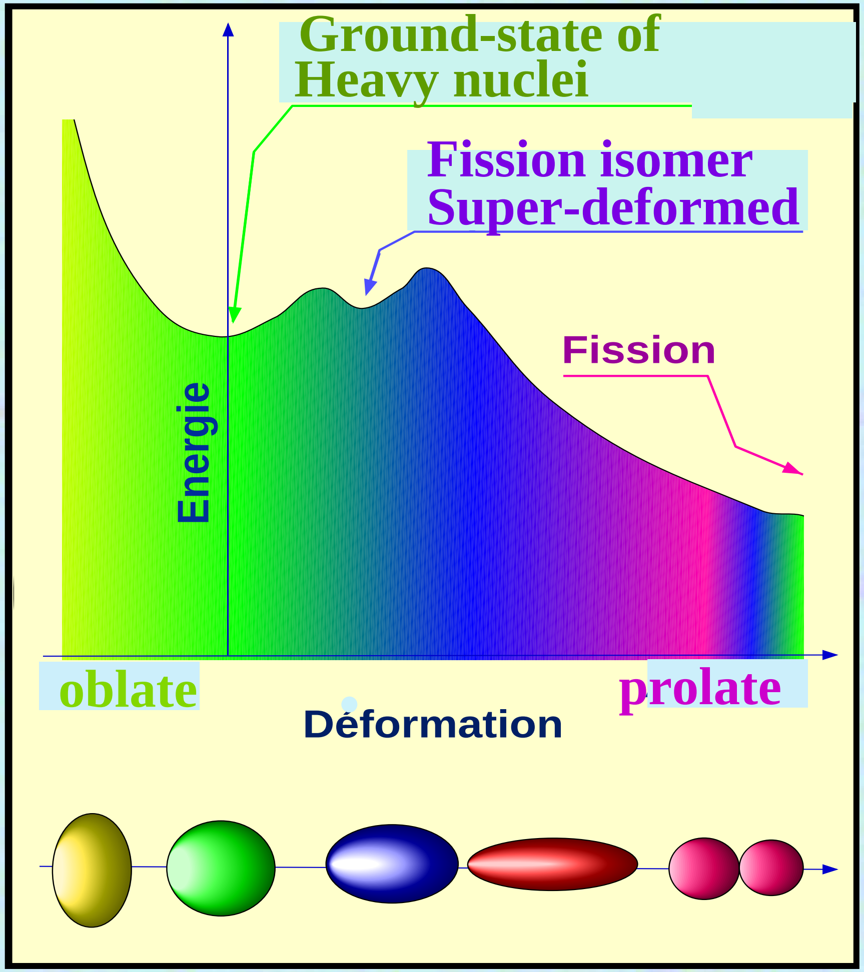
- VII -
Spontaneous deformation
Quantum top



The nucleus is auto-organized

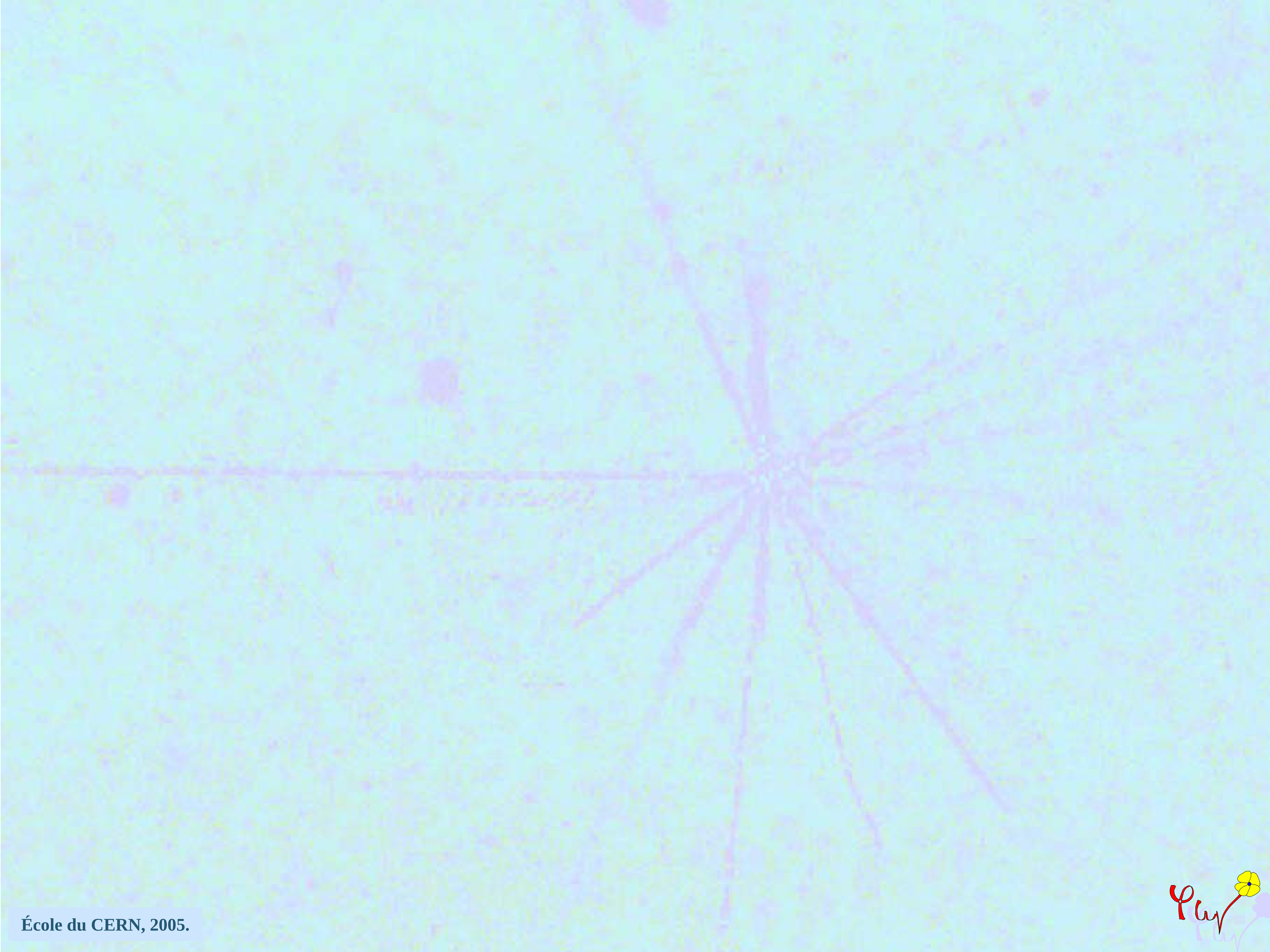


- Orbitals have shapes and deform the nucleus
- This deformation favors specific orbitals



Deformed until breaking : Fission

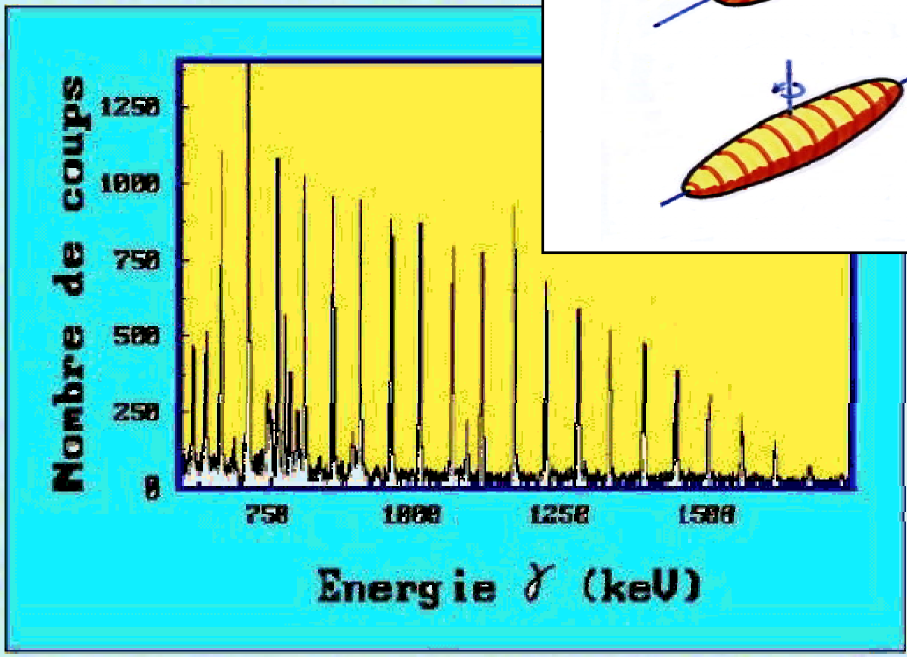
- Spontaneous symmetry breaking
- Superdeformed nuclei

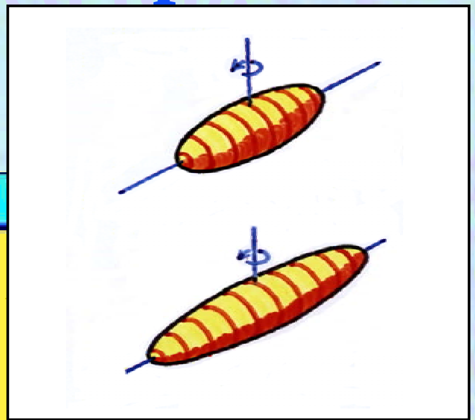


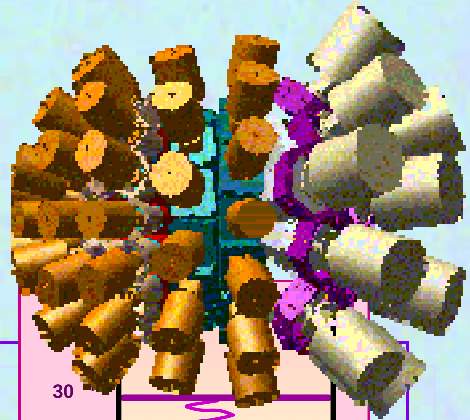
Quantum order

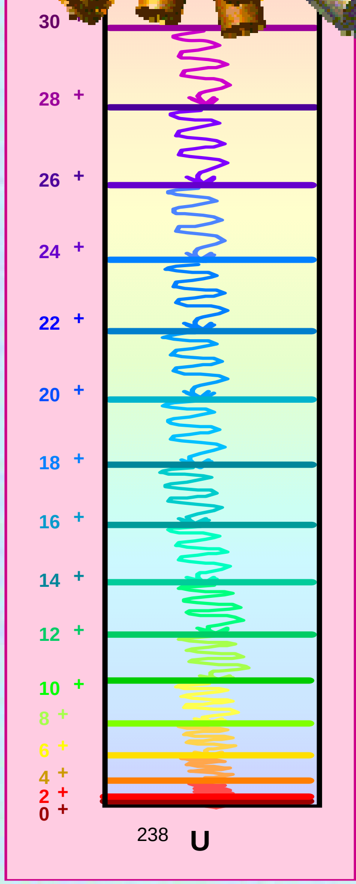
- **Super-deformed top:**

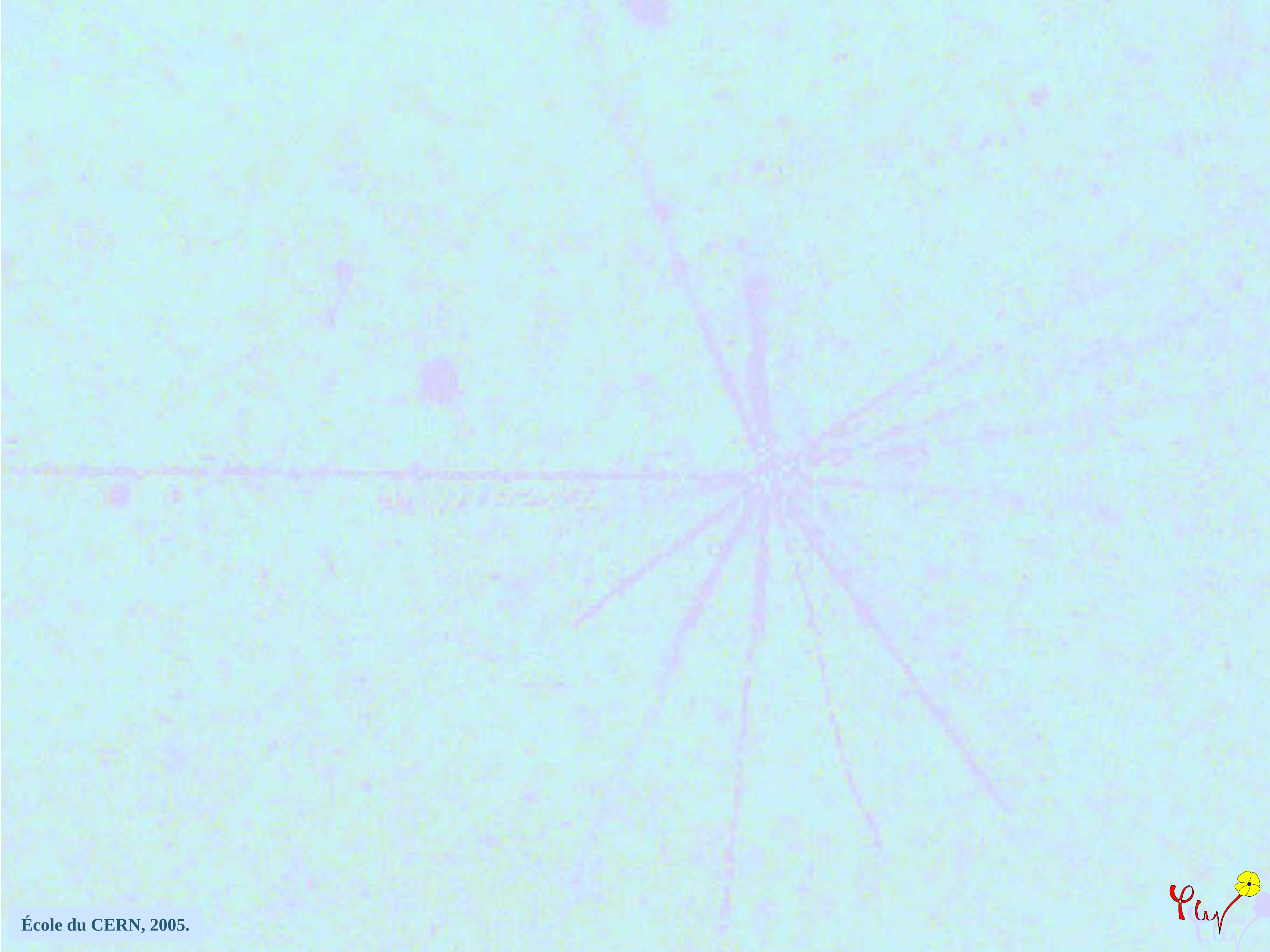
$$E = \frac{J^2}{2I} = \frac{j(j+1)\hbar^2}{2I}$$

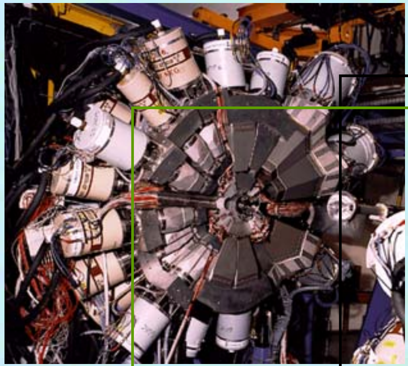










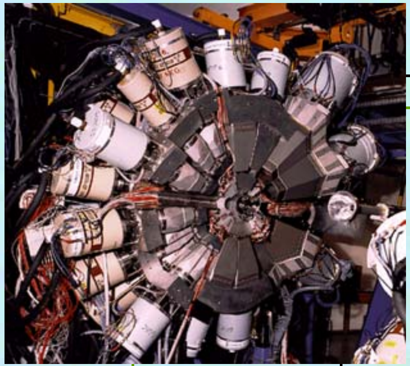


Eurogam

Symmetry Breaking

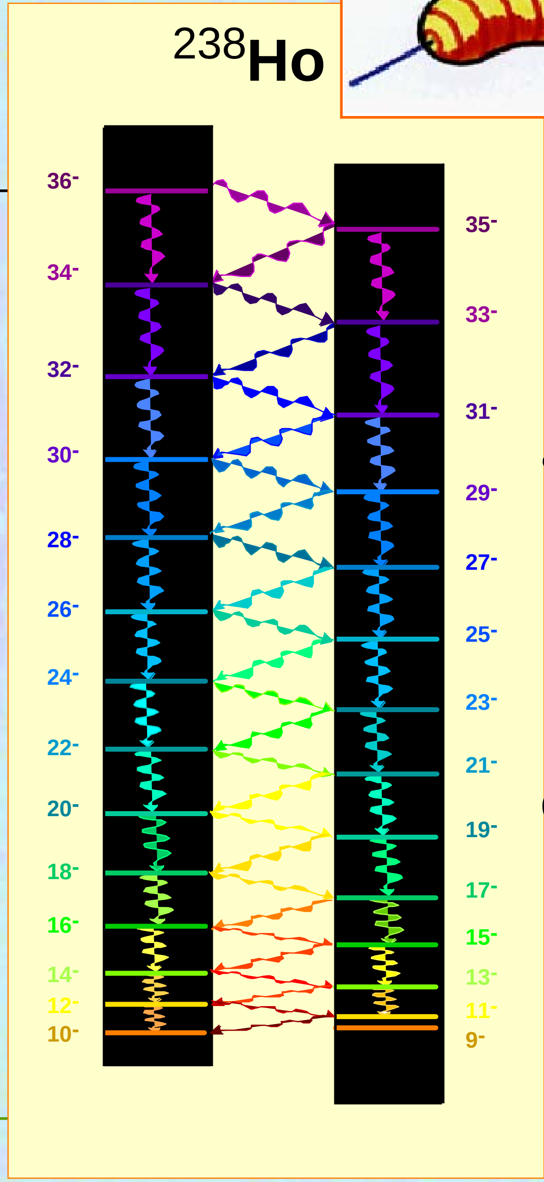
- More complex shapes

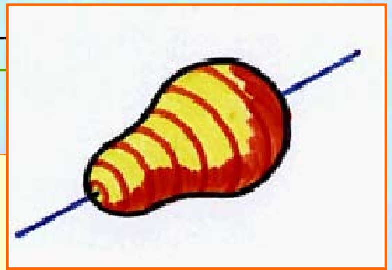
Symmetry Breaking



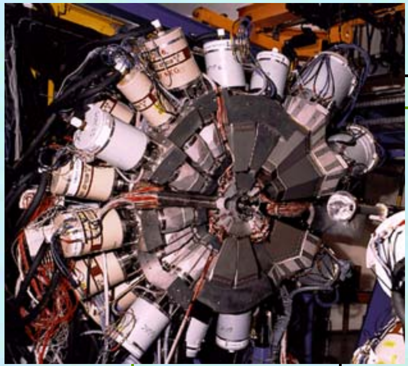
Eurogam

- More complex shapes





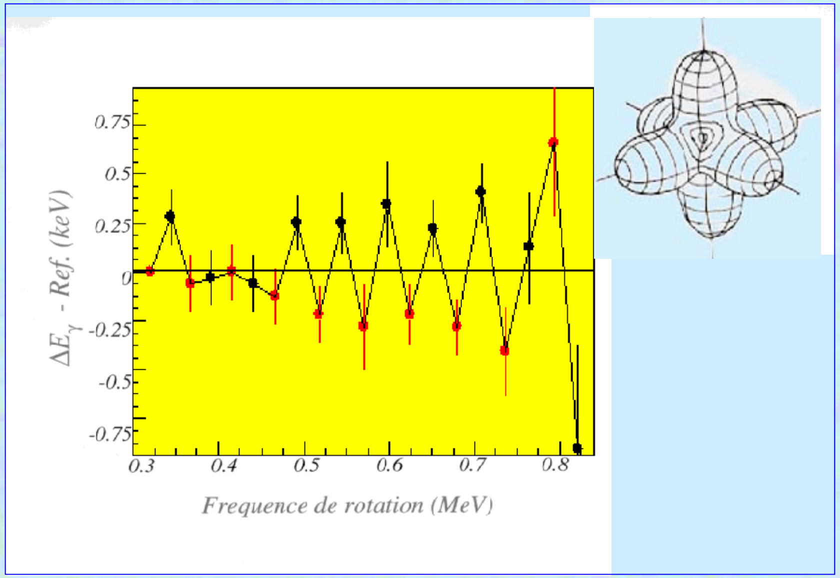
Brisure de la symétrie droite gauche



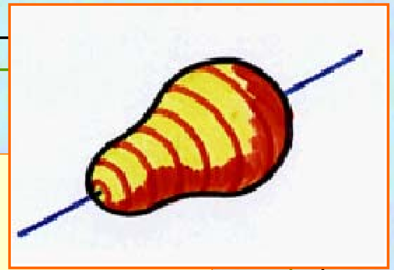
Eurogam

Symmetry Breaking

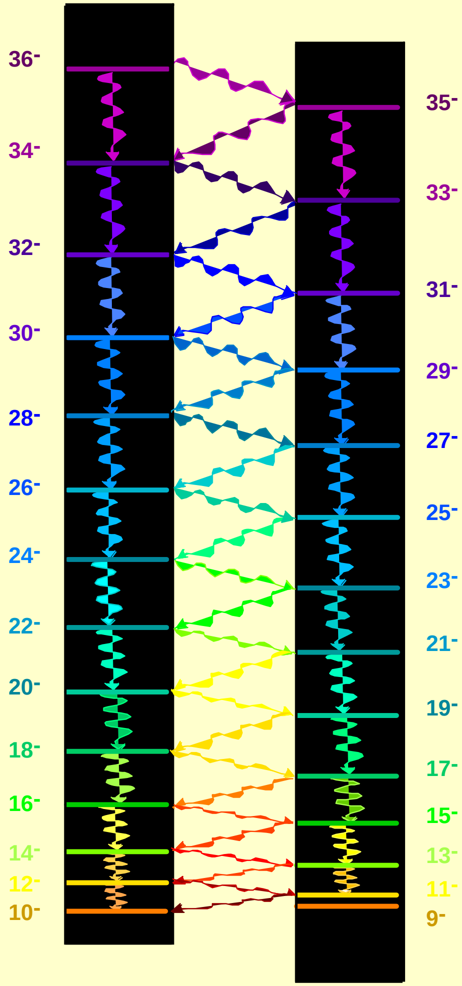
- **More complex shapes**



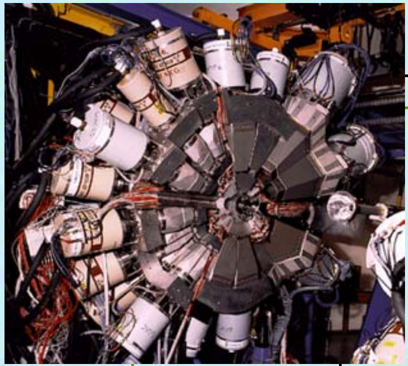
C4 shape



^{238}Ho

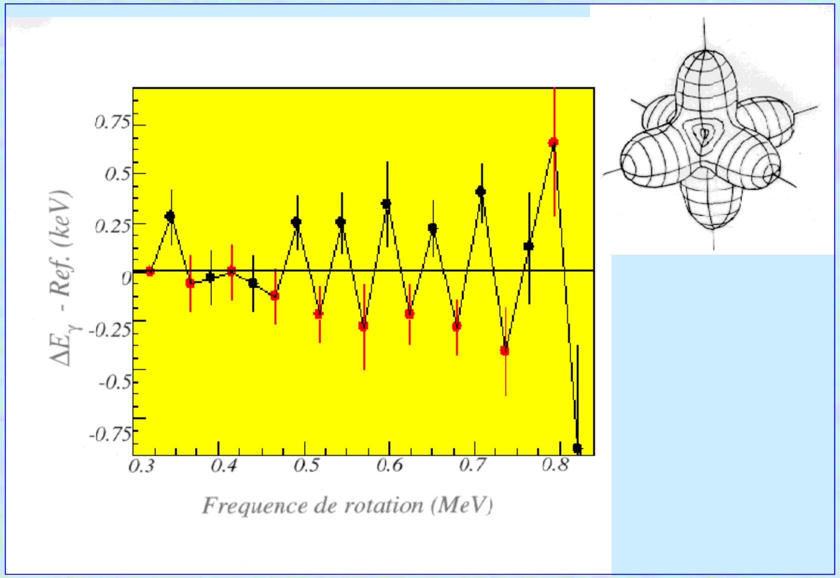


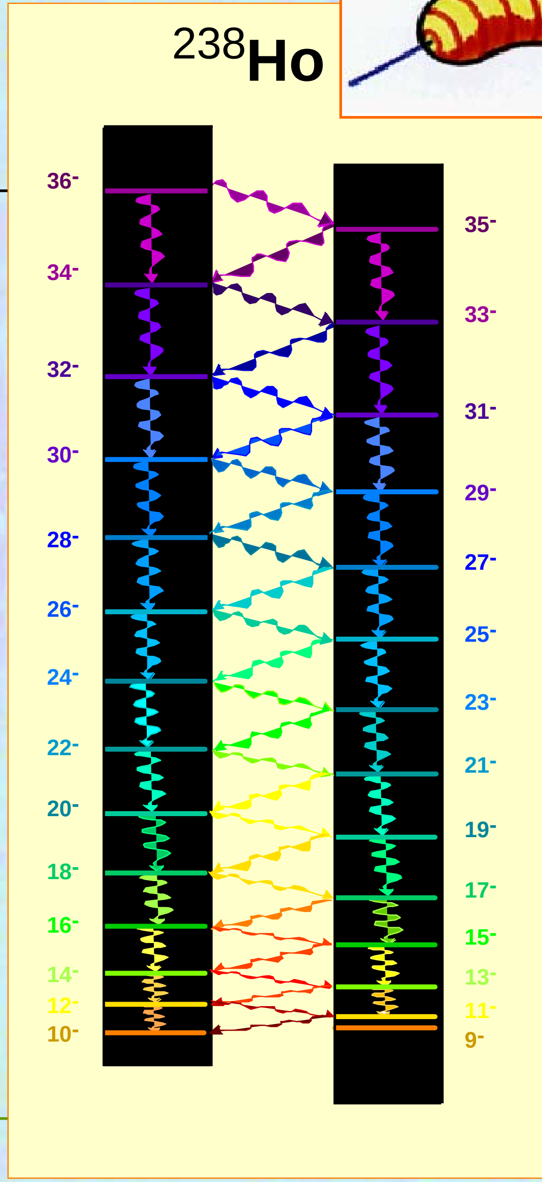
Breaking of the left-right symmetry

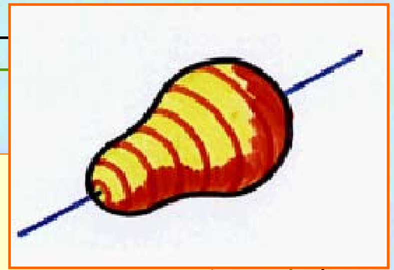


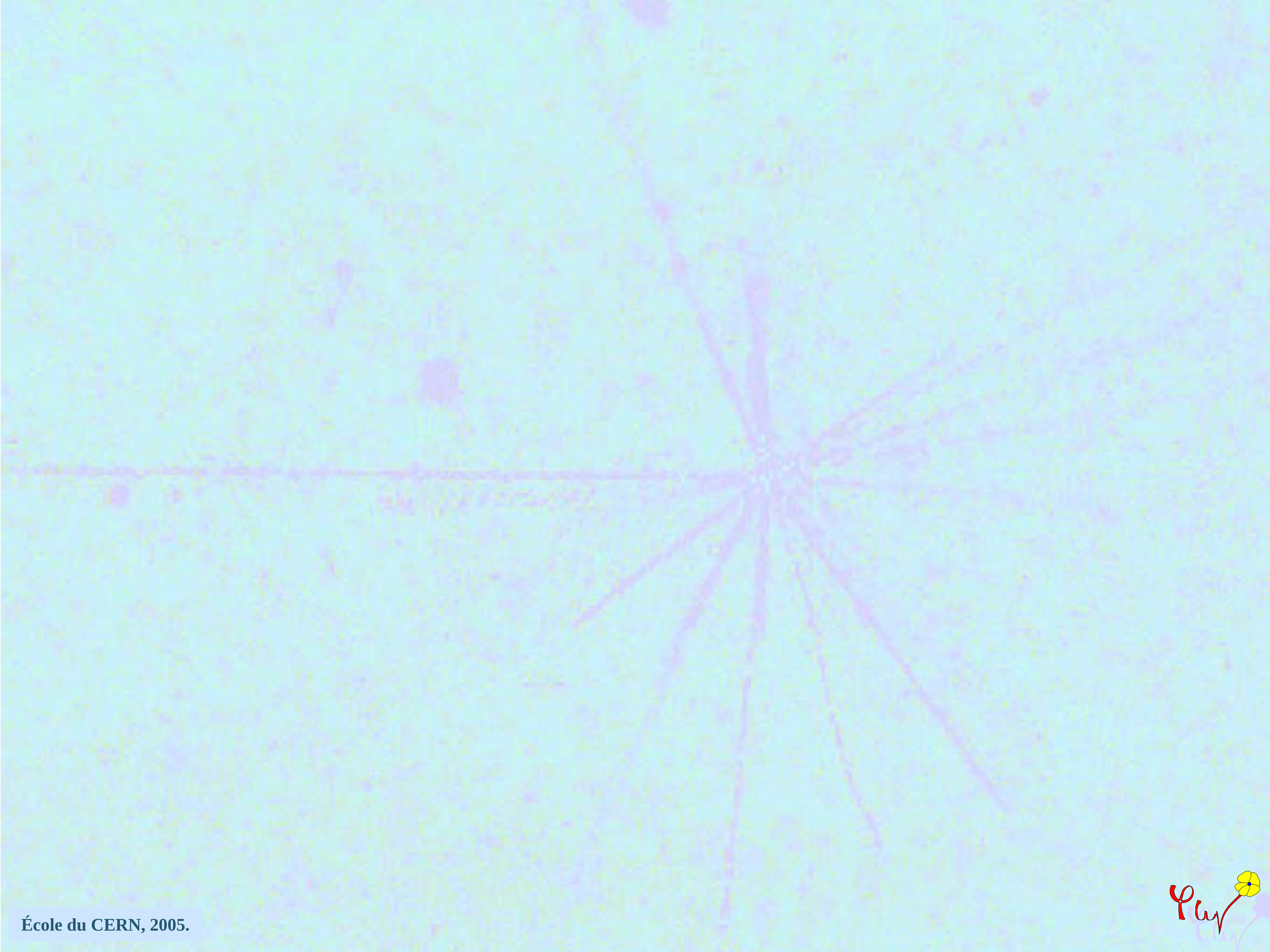
Symmetry Breaking

- Spectra signals symmetries.



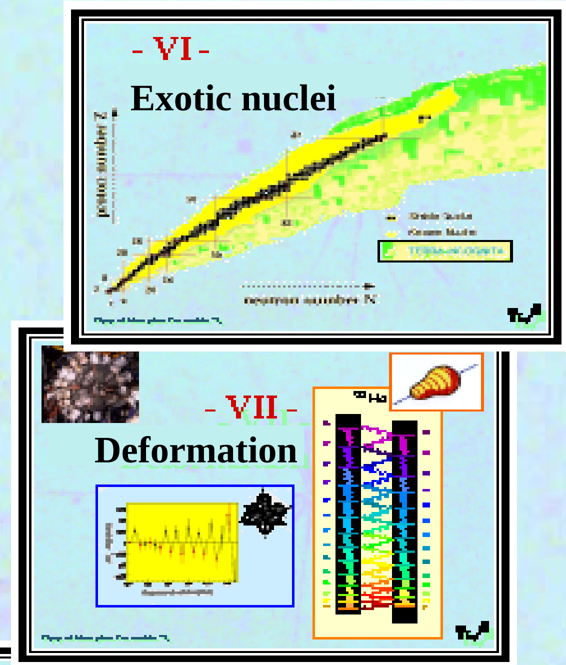


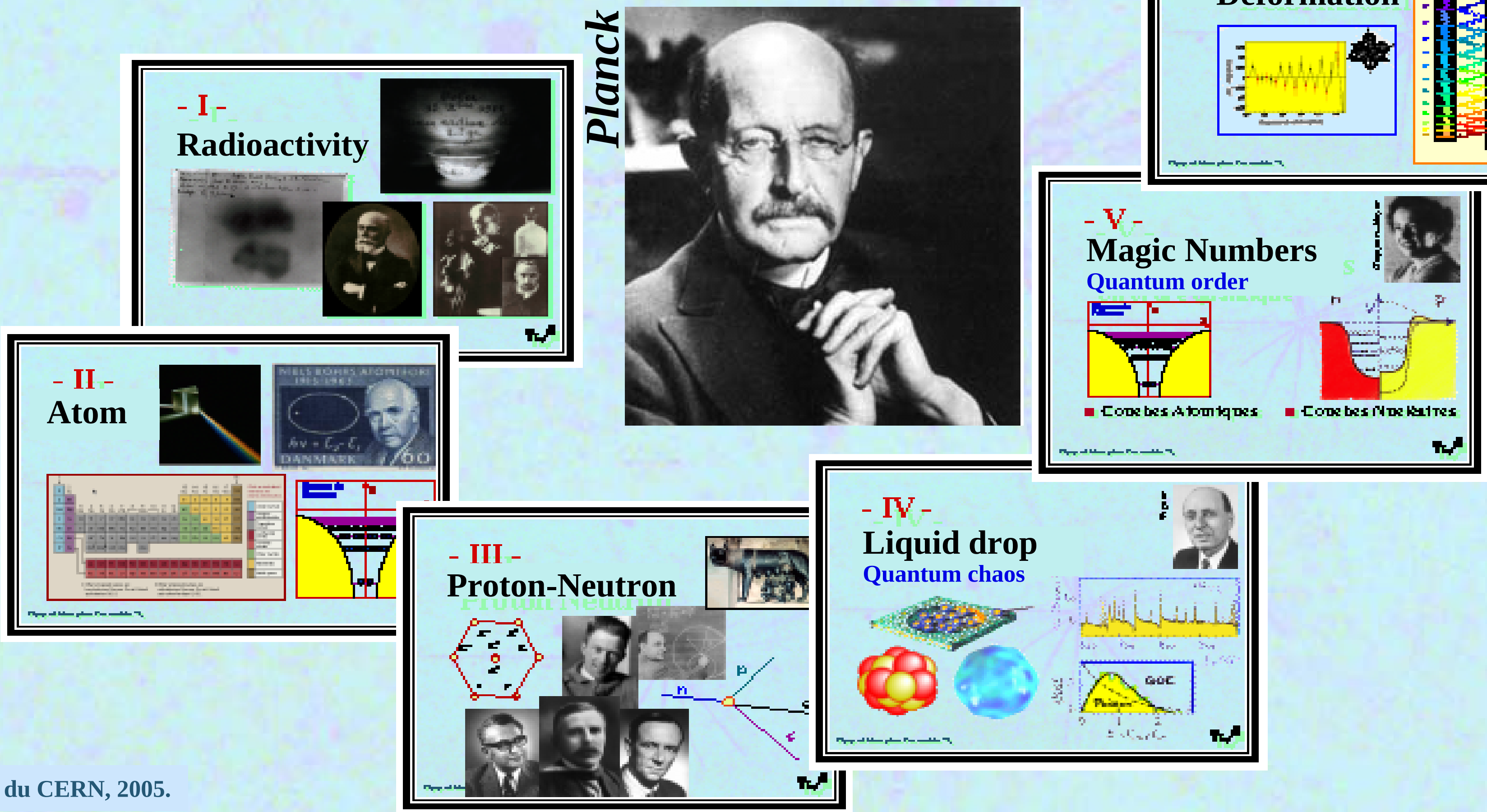




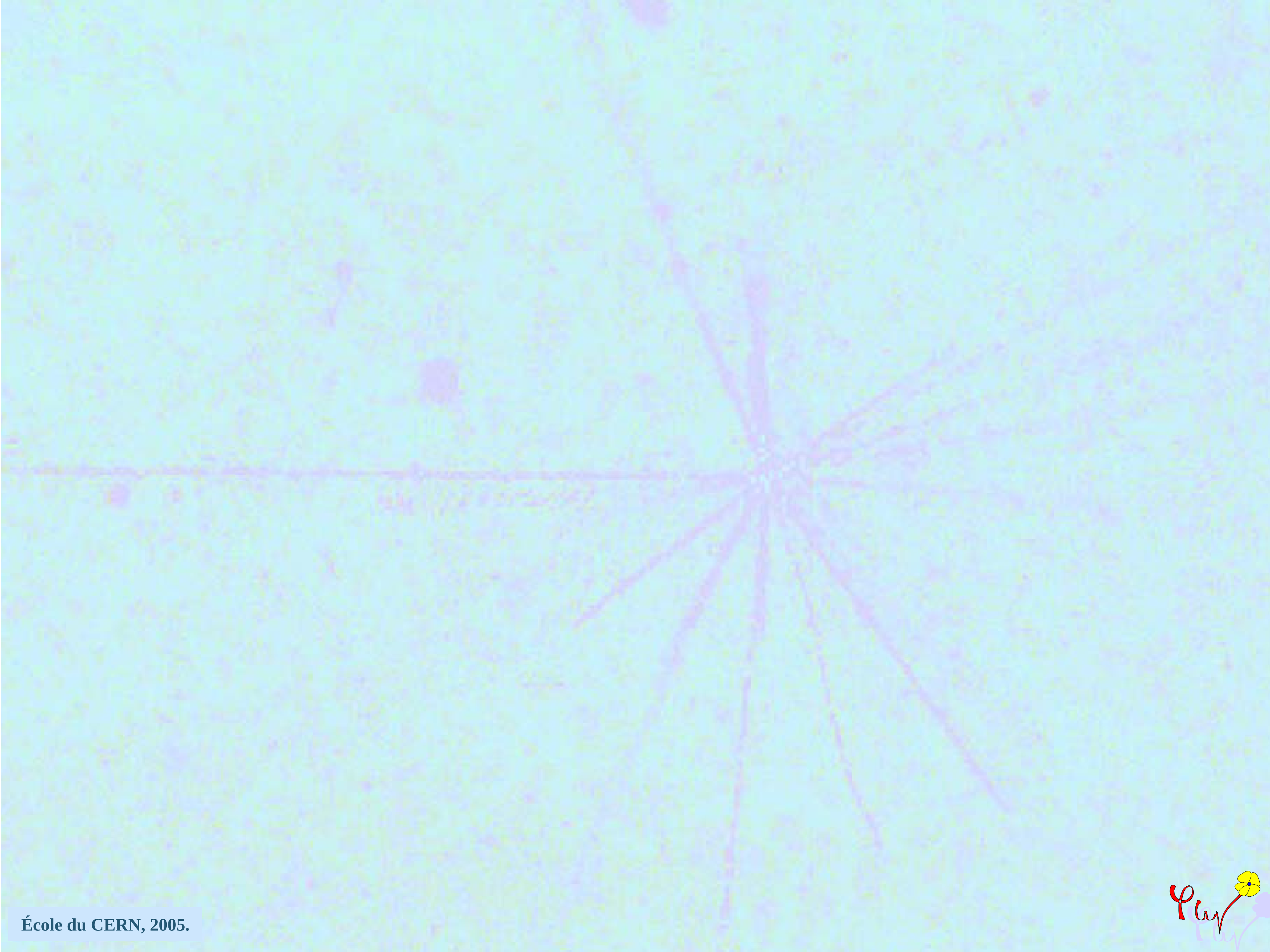
Atomic Nuclei

Complex quantum systems

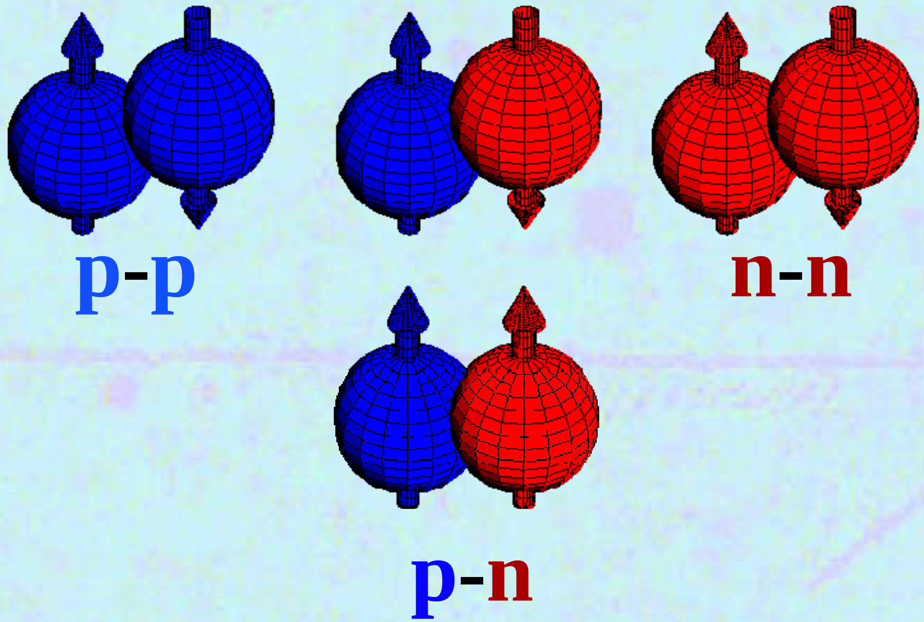




École du CERN, 2005.



Bosons (pairs, quartets) in Nuclei

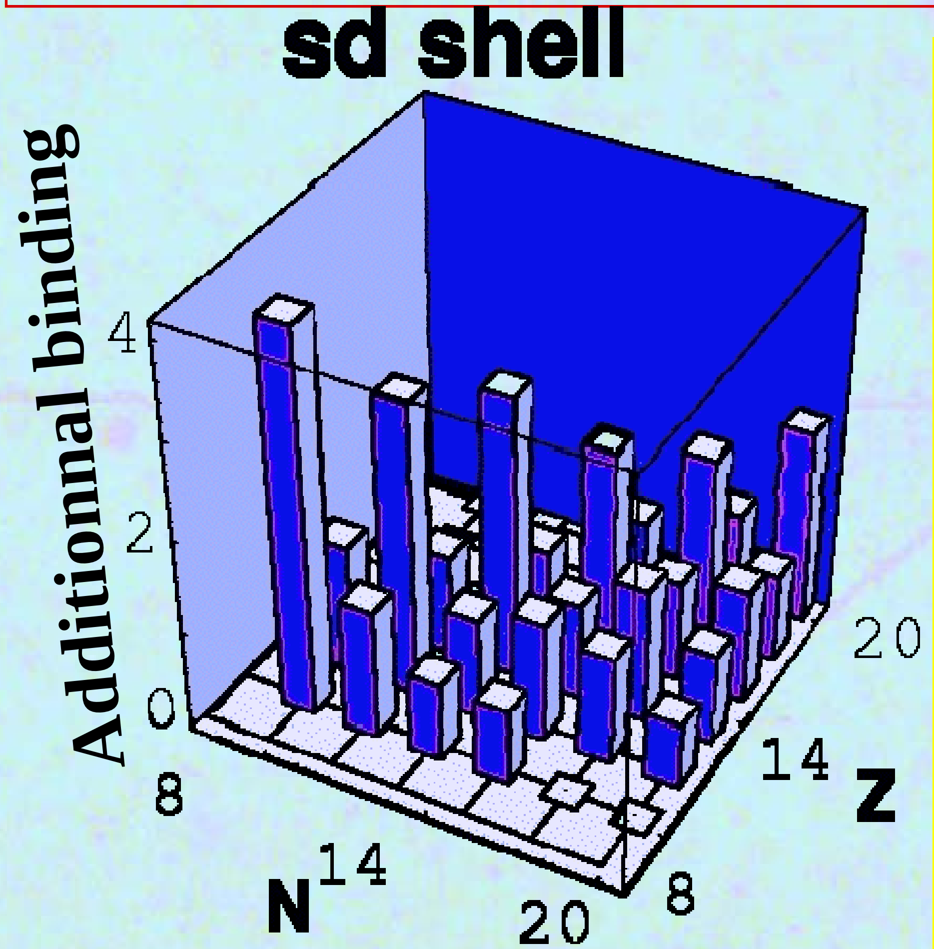


- Normal superfluidity
  - ☞ Opposite spins
- New superfluidity

  N=Z nuclei
  - ☞ Parallel spins
  - ☞ T=0 (n-p) pairs
  - ☞ Additionnal binding

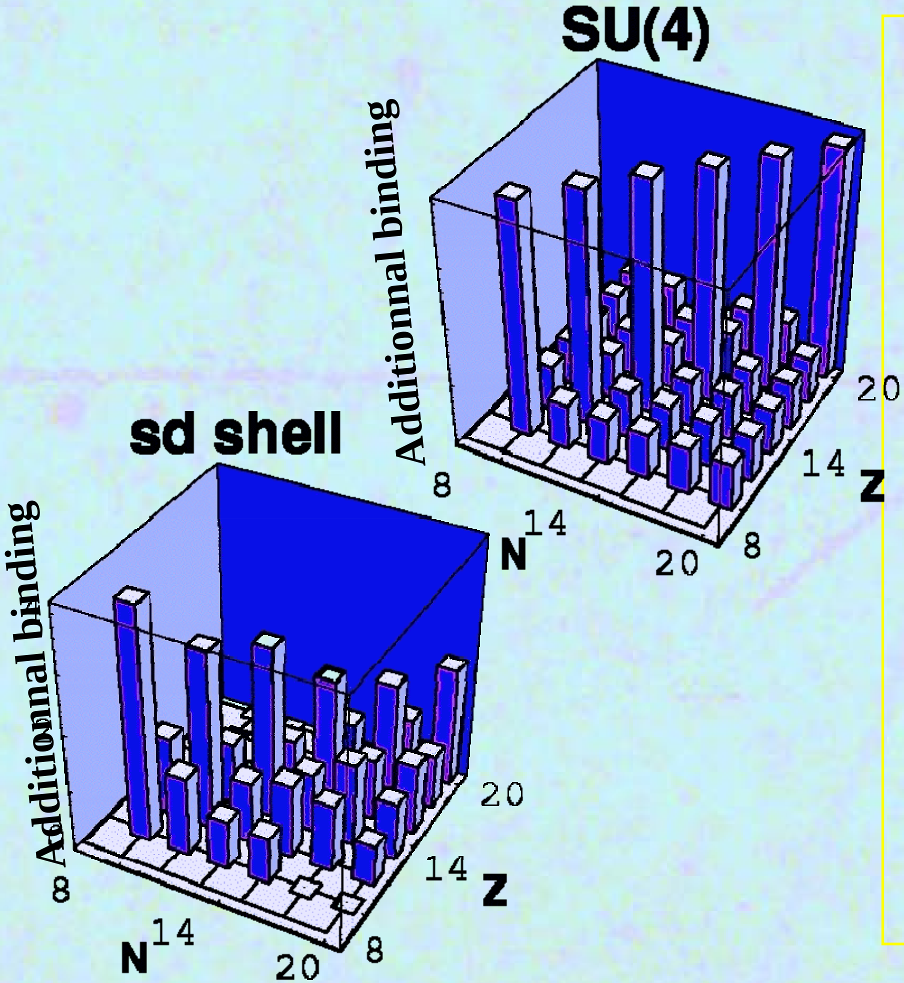
    N=Z Nuclei

Bosons (pairs, quartets) in Nuclei



- Normal superfluidity
  - Opposite spins
- New superfluidity
  N=Z nuclei
  - Parallel spins
  - T=0 (n-p) pairs
  - Additionnal binding
    N=Z Nuclei

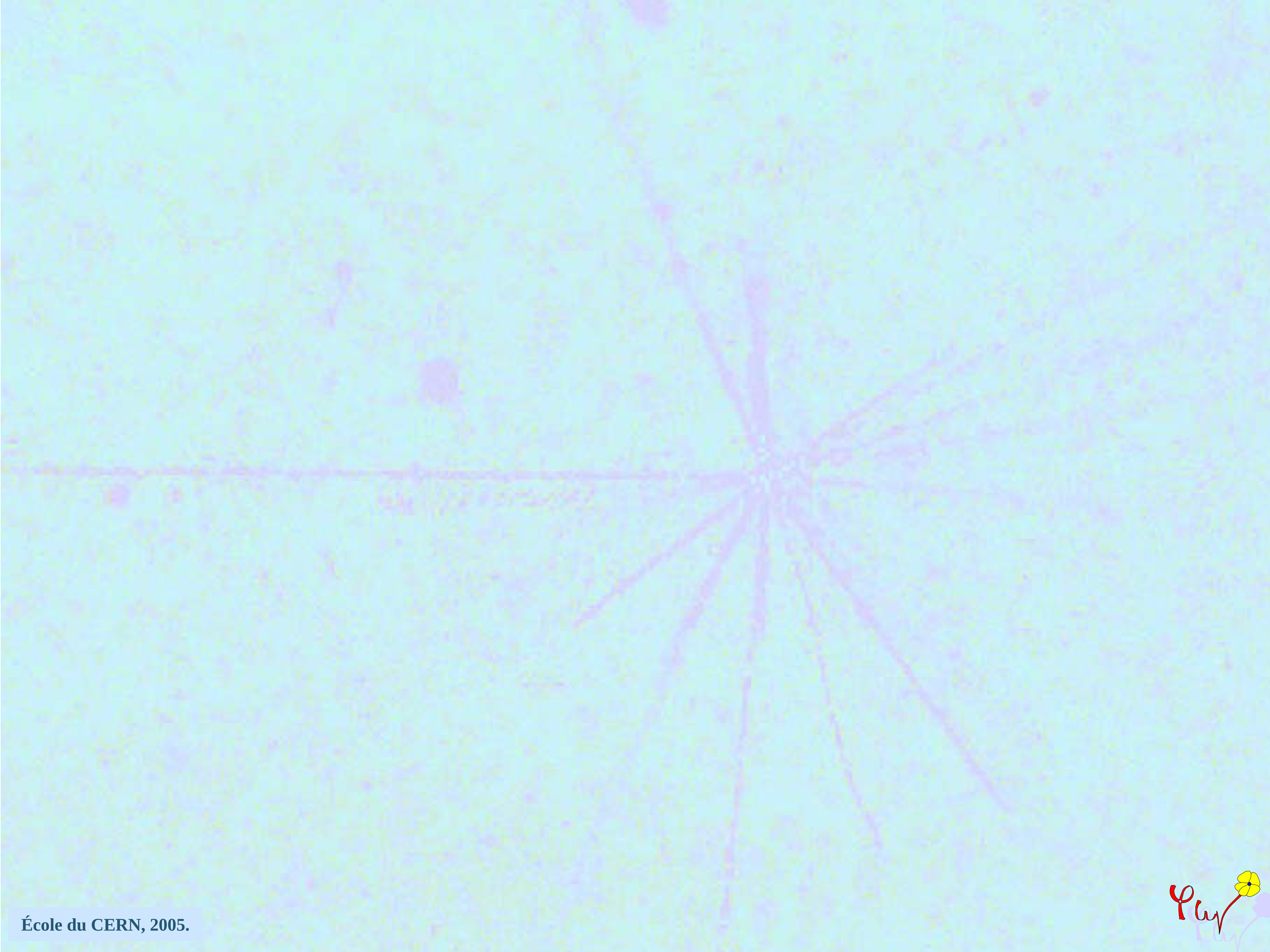
Bosons (pairs, quartets) in Nuclei



- Quartet condensate?
  - ☞ Spin-isospin (α)
  - ☞ Pseudo-spin (new)
- New superfluidity

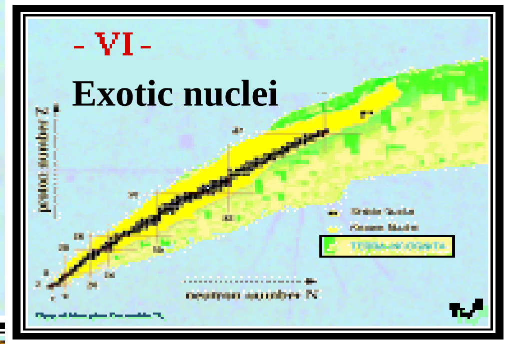
  N=Z nuclei
  - ☞ Parallel spins
  - ☞ T=0 (n-p) pairs
  - ☞ Additional binding

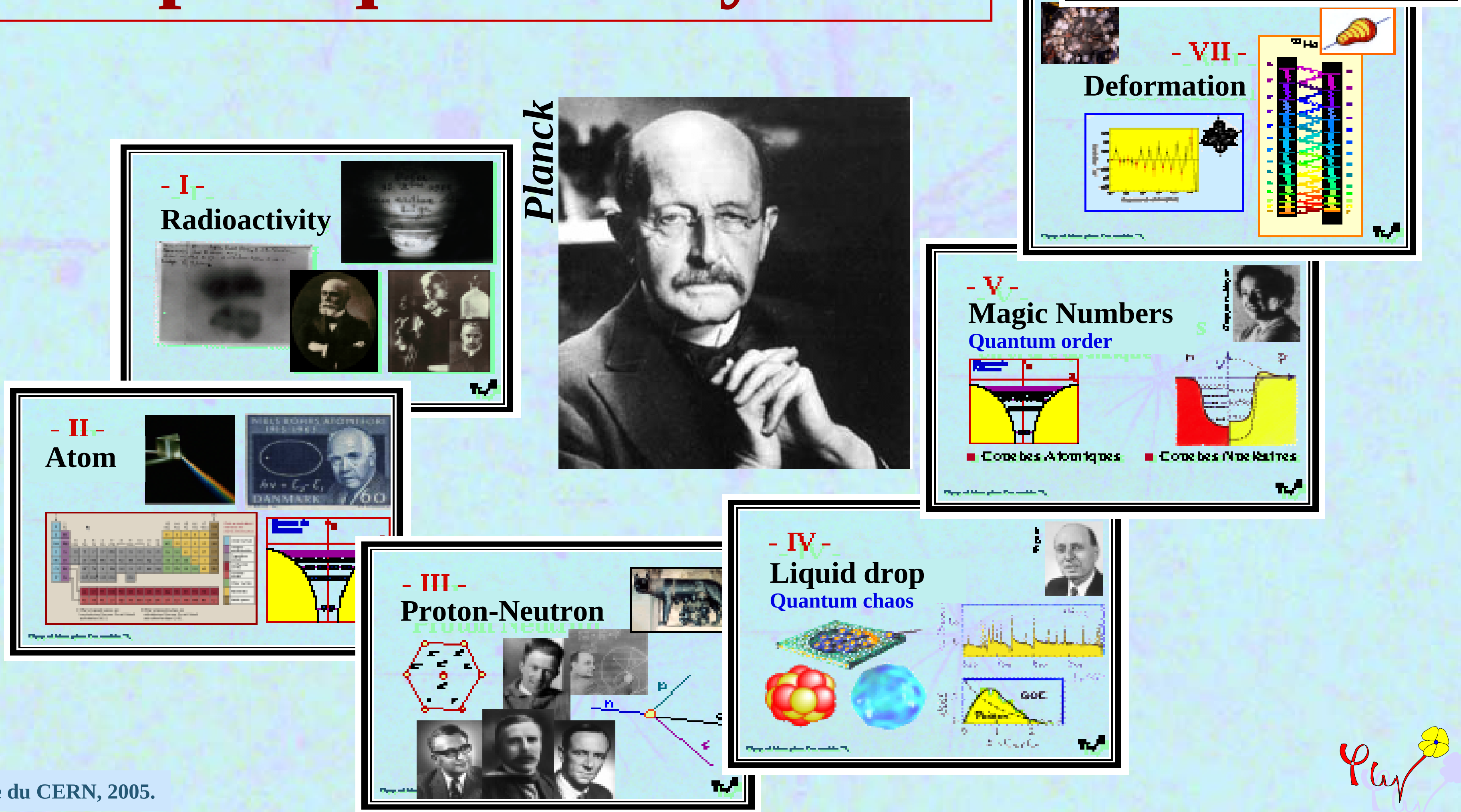
    N=Z Nuclei



Atomic Nuclei

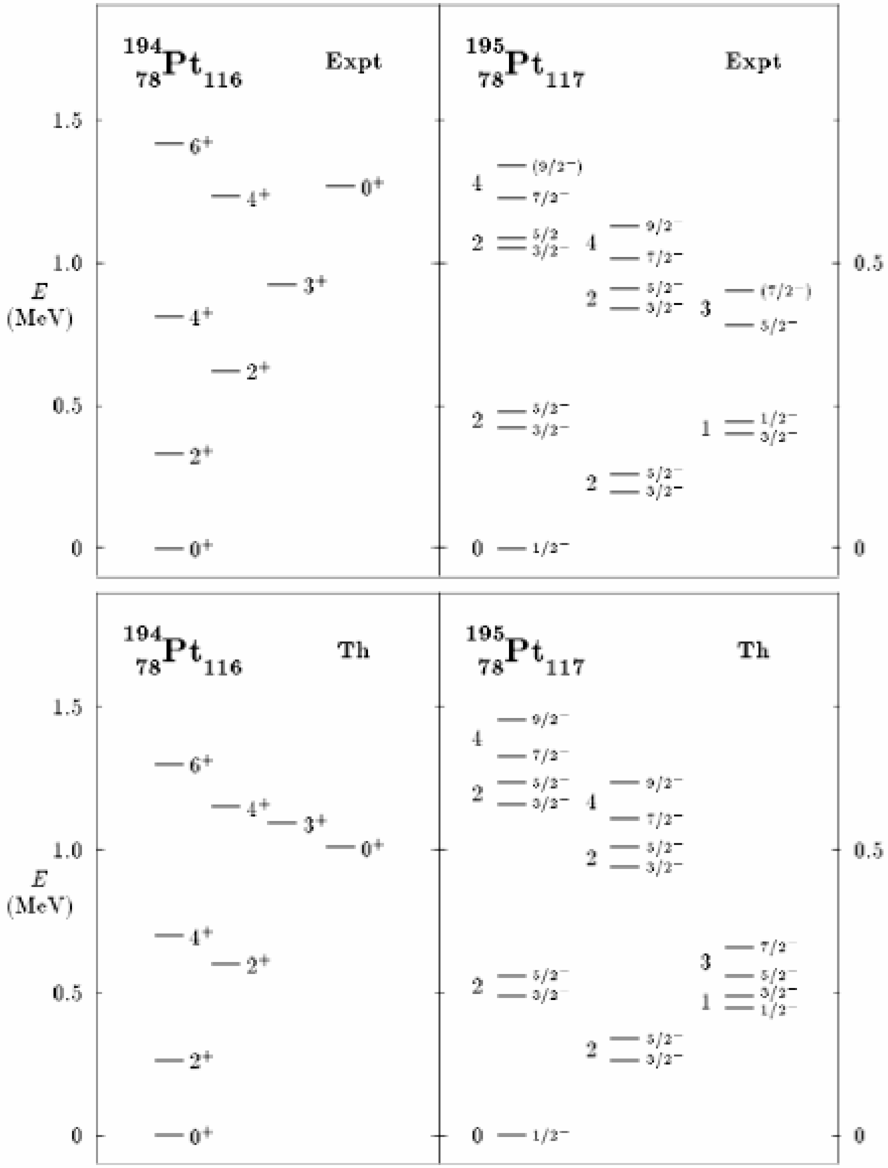
Complex quantum systems



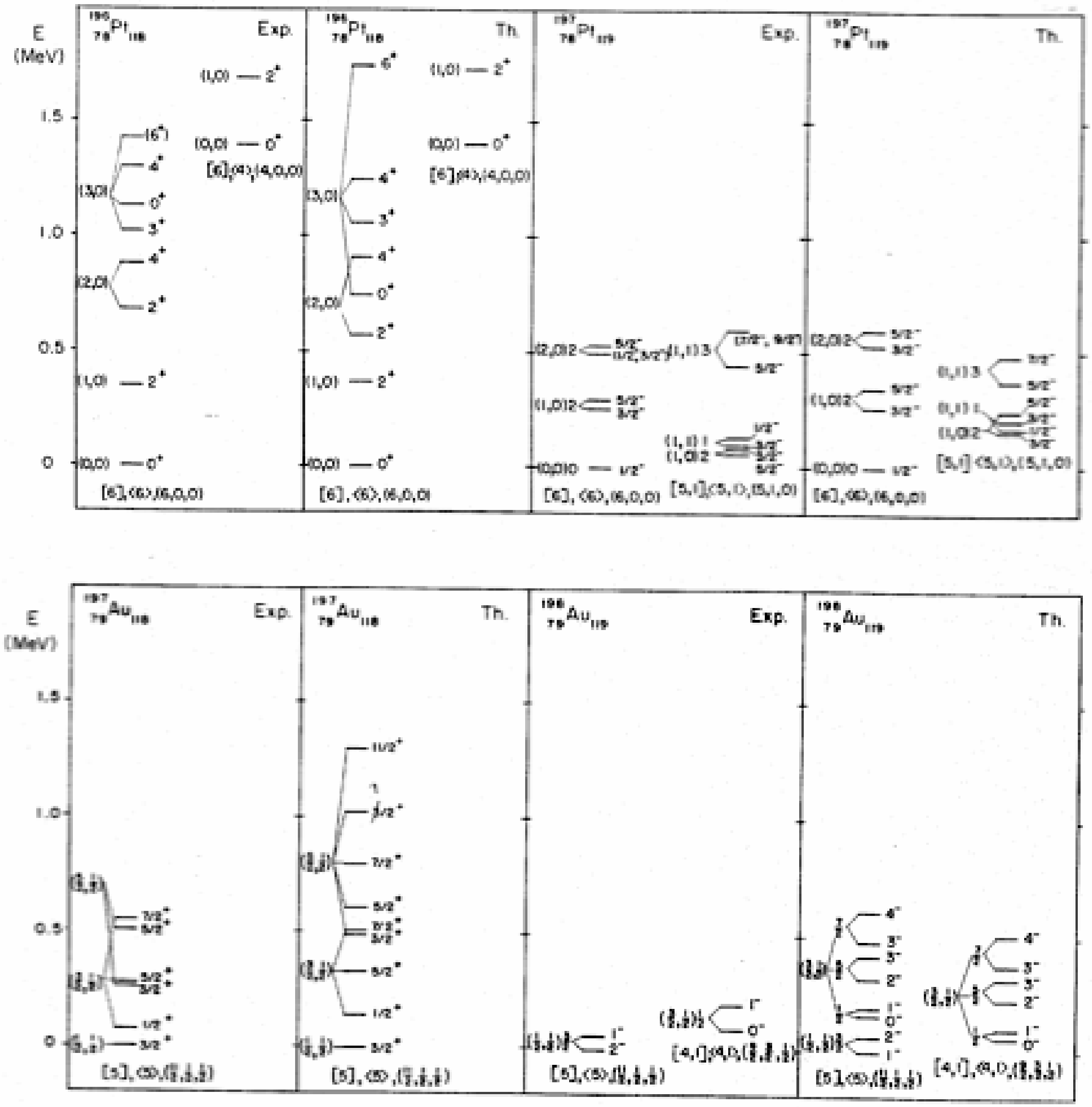


Super-symmetry

- Example: The ^{194}Pt - ^{195}Pt doublet.



- Example: The ^{196}Pt - ^{197}Pt - ^{197}Au - ^{198}Au quartet.



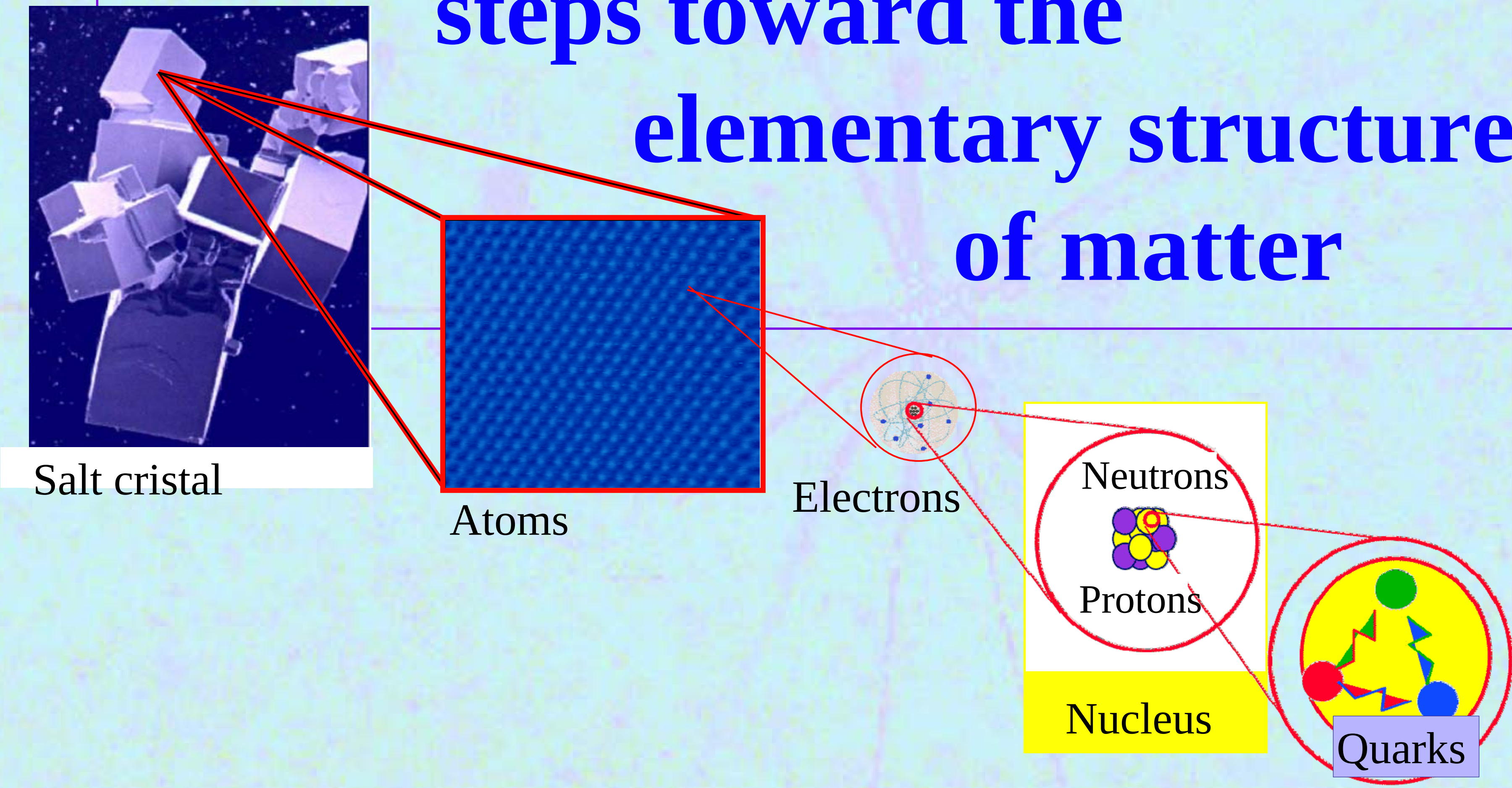
Nuclear Physics

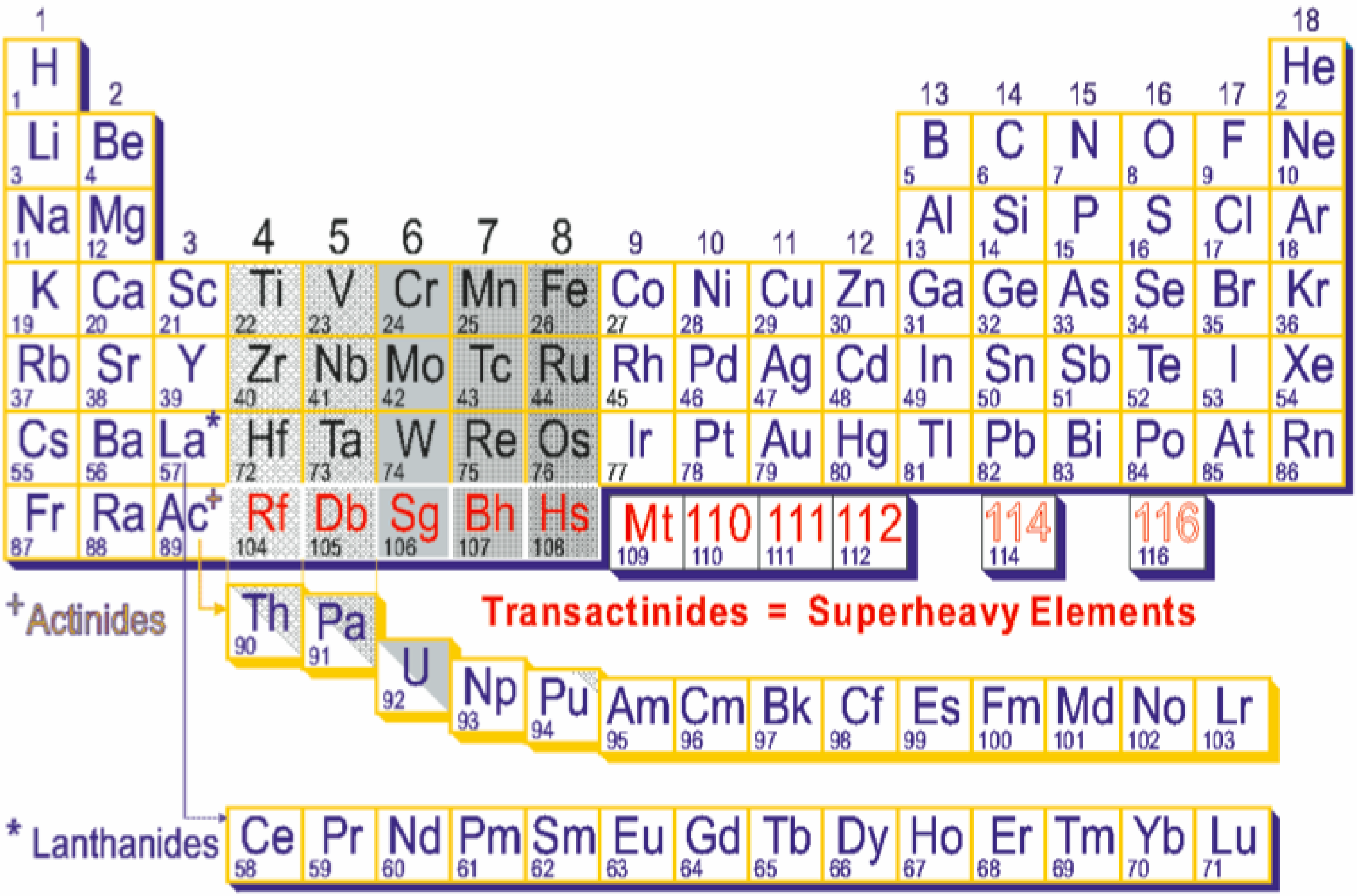
an Introduction

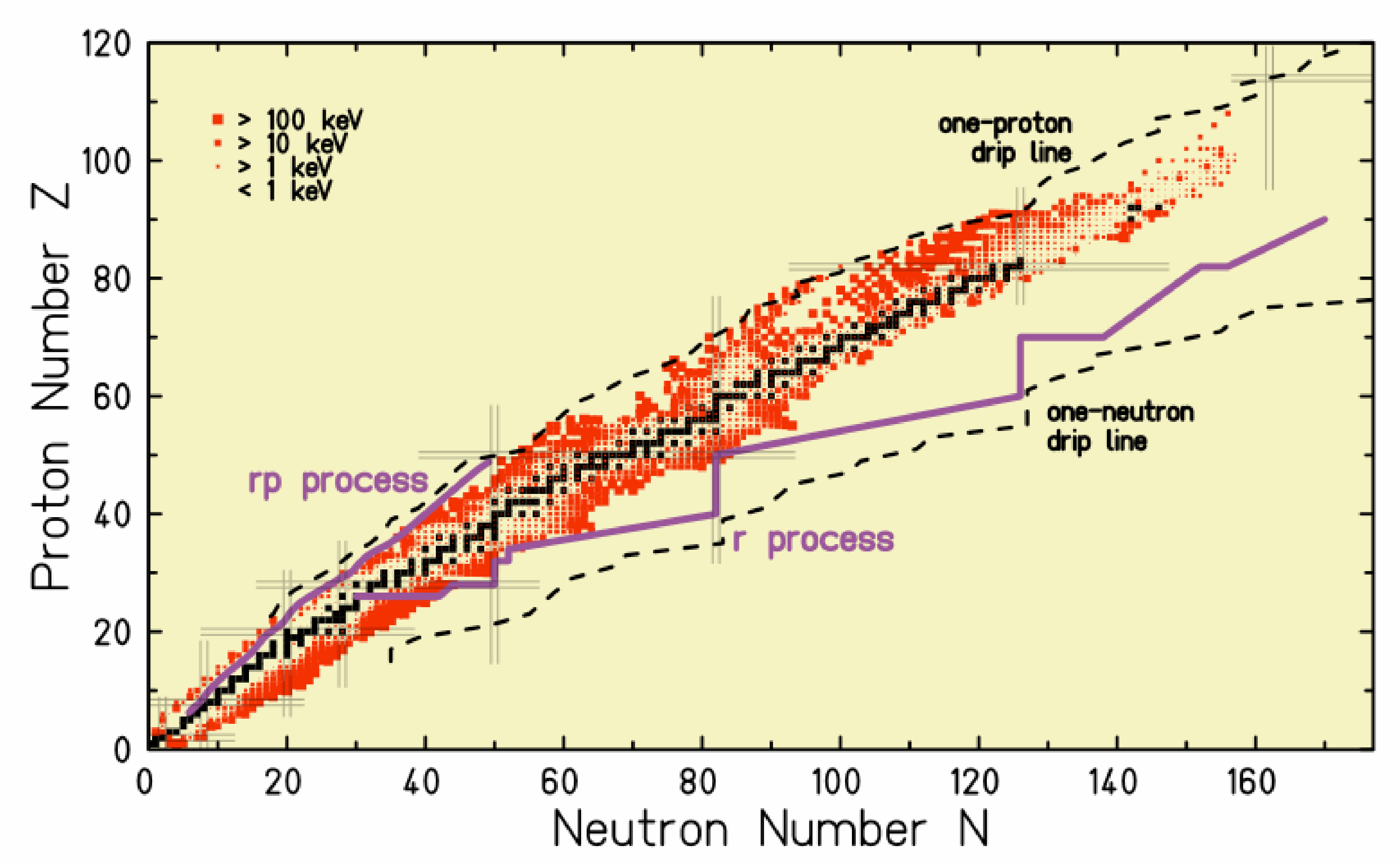
Philippe CHOMAZ
GANIL-CAEN

Nucleons and nuclei:

steps toward the elementary structure of matter




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



> 100 keV
> 10 keV
> 1 keV
< 1 keV
one-proton drip line
one-neutron drip line
rp process
r process
Proton Number Z
Neutron Number N
0
20
40
60
80
100
120
140
160

Definition of symmetry

- A hamiltonian H has symmetry G (is invariant under G) if

$$\forall g \in G: \quad [H, g] = 0$$

- The transformations g are assumed to form a Lie algebra.

Consequences of symmetry

- Degeneracy:

$$H|\Gamma\rangle = E|\Gamma\rangle \quad \Rightarrow \quad Hg|\Gamma\rangle = Eg|\Gamma\rangle$$

- State labelling:

$$H|\Gamma\gamma\rangle = E(\Gamma)|\Gamma\gamma\rangle$$

- Action of transformations g:

$$g|\Gamma\gamma\rangle = \sum_{\gamma'} a^{\Gamma}_{\gamma\gamma'}(g)|\Gamma\gamma'\rangle$$

- The a-matrices constitute a representation of the elements g of G.

Definition of a group

- A set of elements G and a multiplication operation.
- Axioms:
  - Closure

$$g \in G \wedge g' \in G \Rightarrow g \circ g' \in G$$

  - Associativity

$$g \circ (g' \circ g'') = (g \circ g') \circ g''$$

  - Existence of an identity element e

$$e \circ g = g \circ e = g$$

  - Existence of unique inverse for every element g

$$g \circ g^{-1} = g^{-1} \circ g = e$$

- Commutativity is not required.

Definition of a Lie algebra

- A Lie group contains an infinite number of elements that depend on a set of continuous variables.

- The corresponding Lie algebra is obtained from (a finite number of) infinitesimal operators, called generators.

- An algebraic structure over the generators is defined through commutation relations in terms of structure constants:

$$\left[g_i, g_j\right] \equiv g_i \circ g_j - g_j \circ g_i = \sum_k c_{ij}^k g_k$$

- Structure constants are antisymmetric in i and j.

- Generators satisfy the Jacobi identity:

$$\left[g_i, \left[g_j, g_k\right]\right] + \left[g_j, \left[g_k, g_i\right]\right] + \left[g_k, \left[g_i, g_j\right]\right] = 0$$

Casimir operators

- An operator that commutes with all generators of G is called a Casimir operator and denoted as (n is the order of the operator in the generators)

$$C_n[G]$$

- Thus:

$$H = \sum_n \kappa_n C_n[G] \quad \Rightarrow \quad H \text{ has symmetry } G$$

- Example: Rotations in three dimensions, SO(3).

  - Second-order Casimir operator of SO(3):

$$C_2[SO(3)] = j_x^2 + j_y^2 + j_z^2 \equiv j^2$$

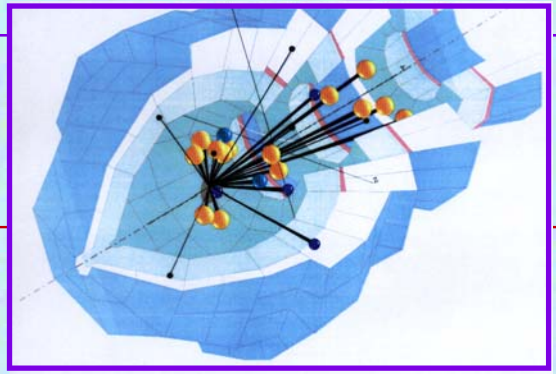
  - SO(3) symmetry:

$$H = j^2 \quad \Rightarrow \quad H \text{ has } SO(3) \text{ symmetry}$$

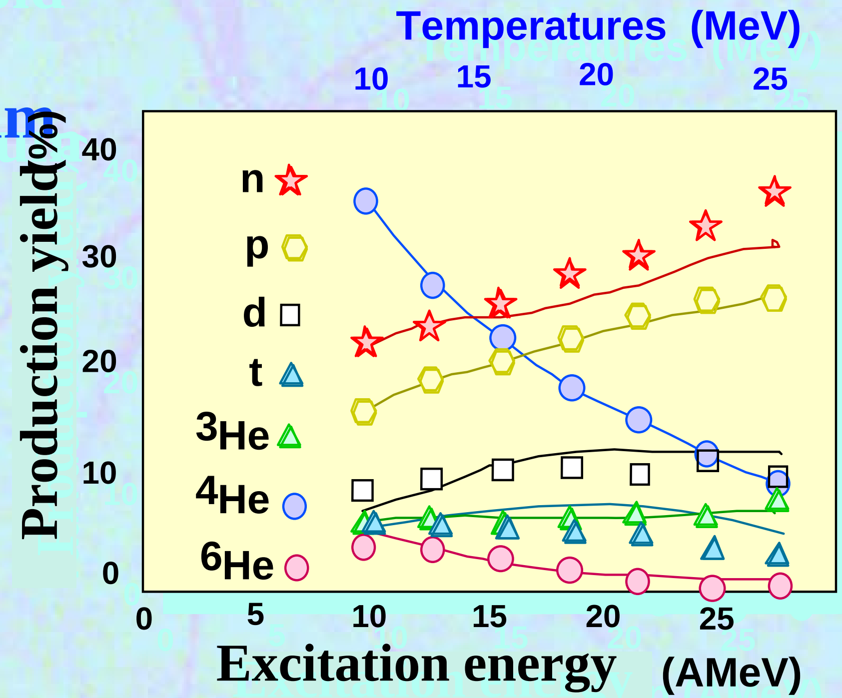
  - Degeneracy and state labelling:

$$C_2[SO(3)]|jm_j\rangle = j(j+1)|jm_j\rangle$$

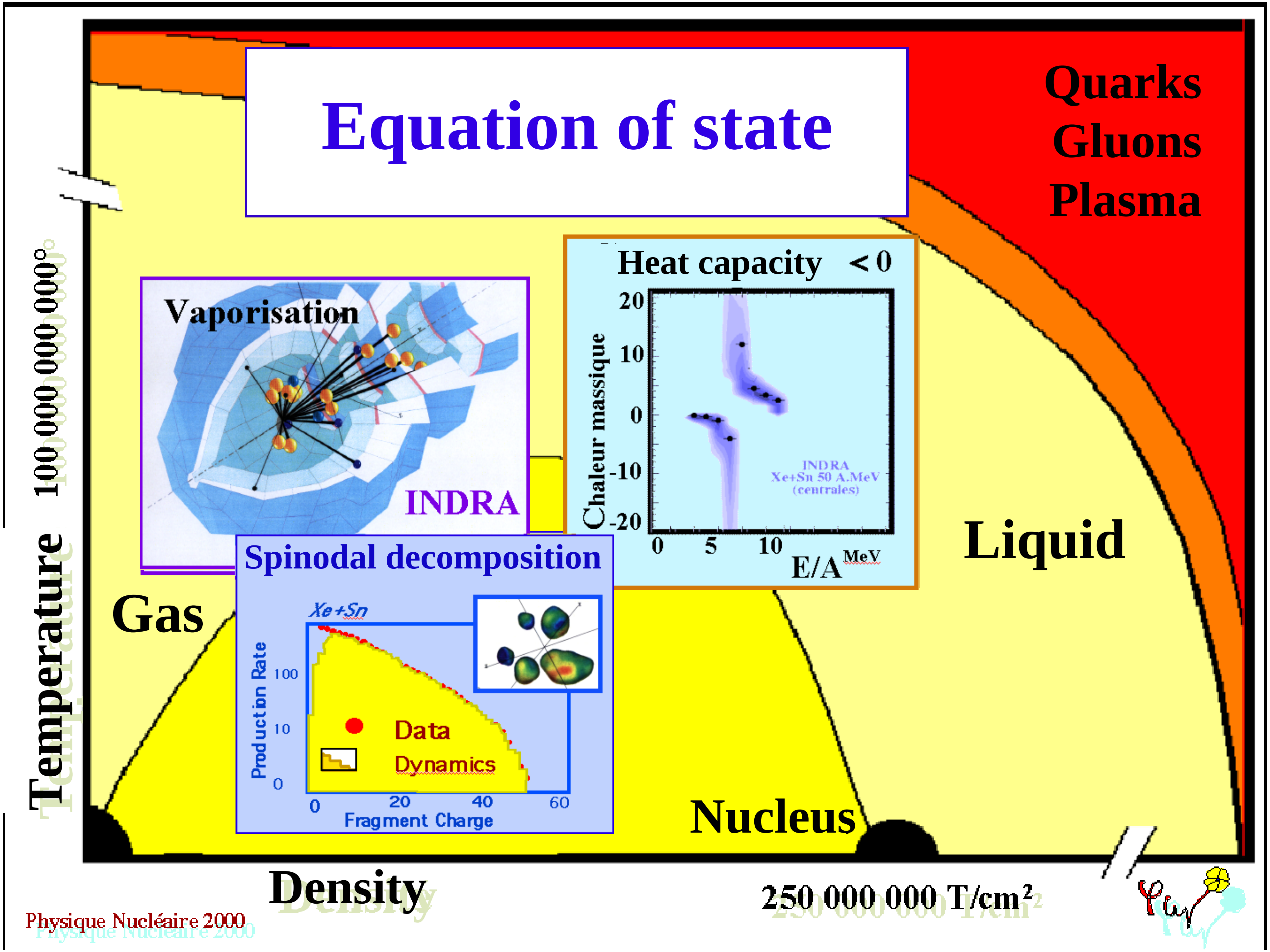
Vaporization



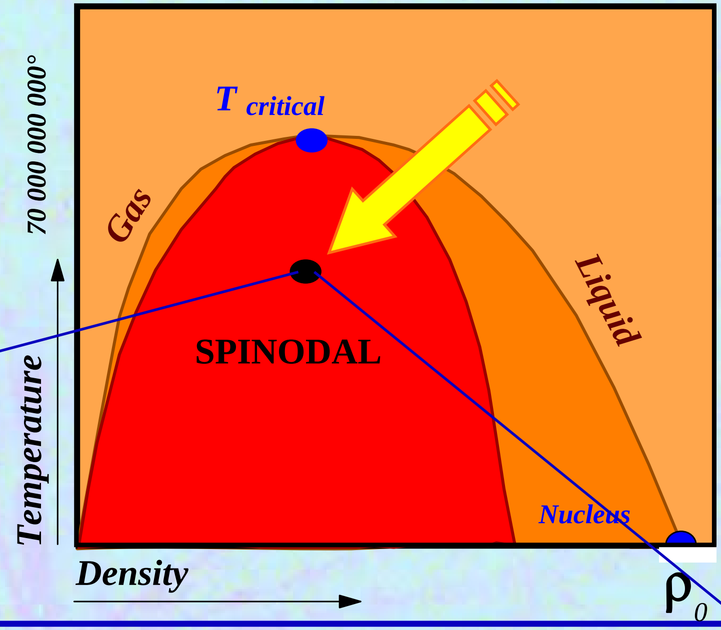
- Determination of vaporization threshold
- Real gas at equilibrium
- T > 100 000 000 000°.

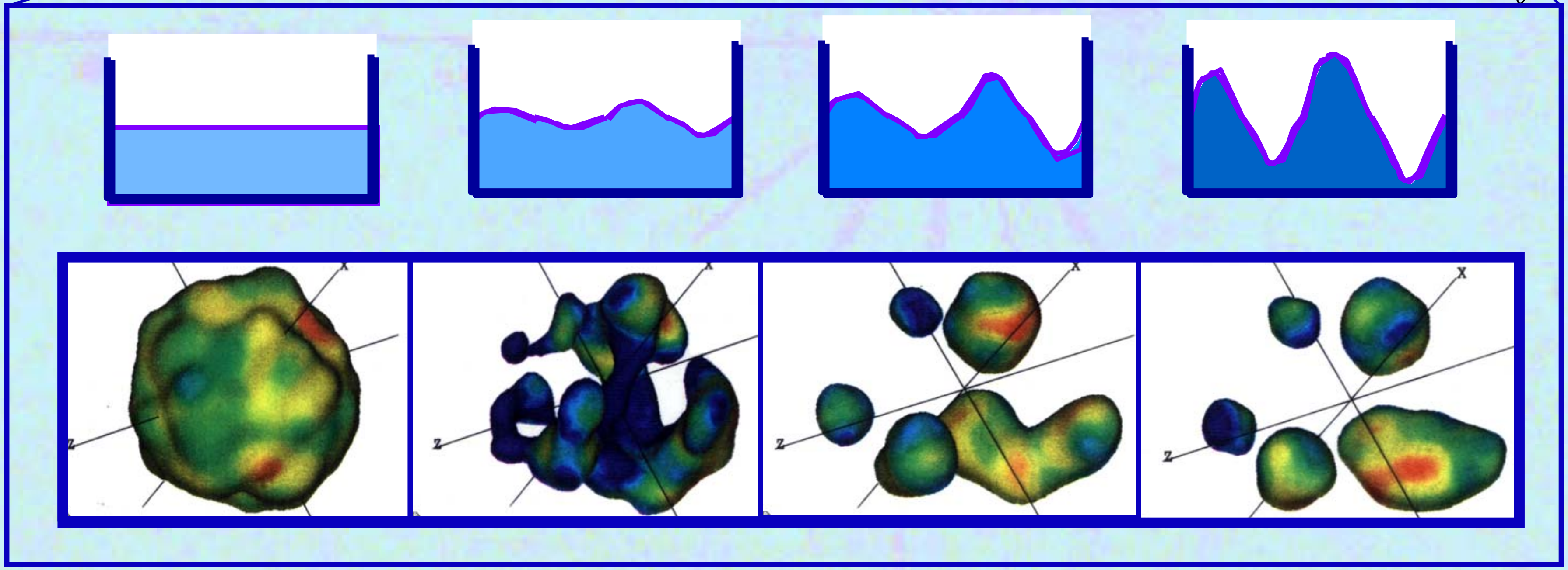


Gulminelli and INDRA collaboration

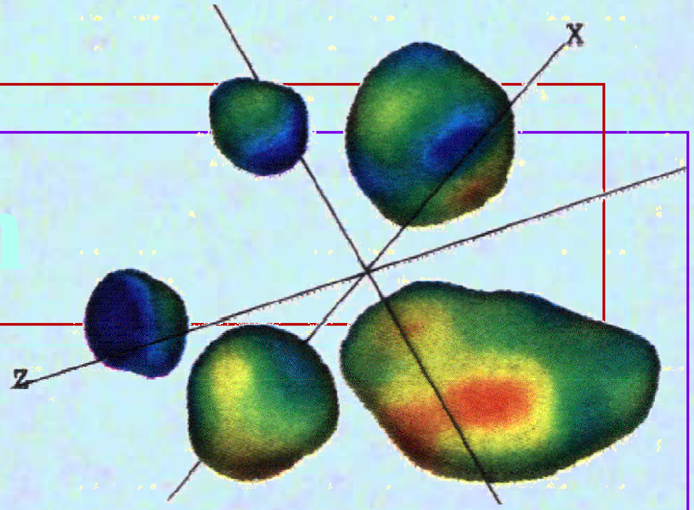

Equation of state
Quarks
Gluons
Plasma
Heat capacity < 0
Chaleur massique
20
10
0
-10
-20
0
5
10
E/A MeV
INDRA
Xe+Sn 50 A.MeV
(centrales)
Vaporisation
INDRA
Spinodal decomposition
Xe+Sn
Production Rate
100
10
0
Data
Dynamics
0
20
40
60
Fragment Charge
Liquid
Gas
Nucleus
Temperature
100 000 000 000°
Density
250 000 000 T/cm²
Physique Nucléaire 2000

Condensation after a rapid **Expansion**



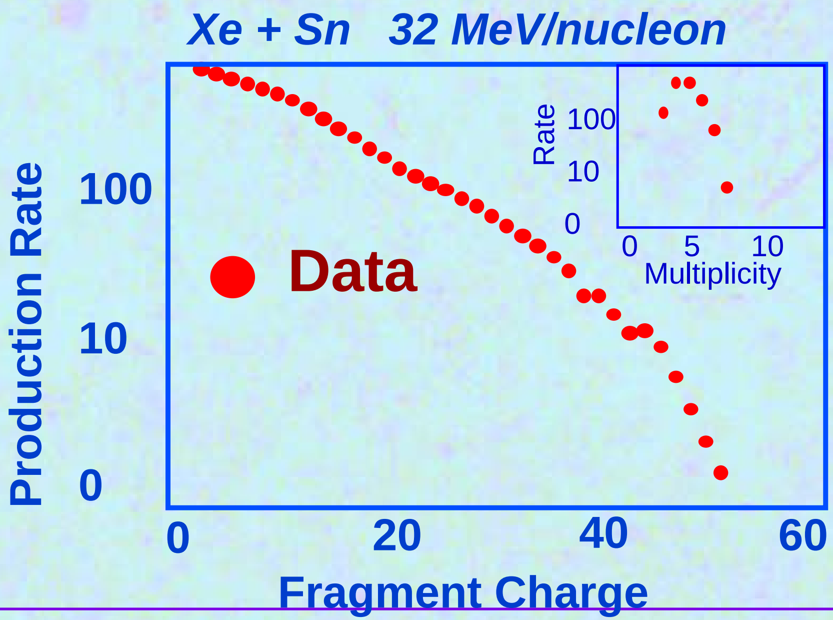


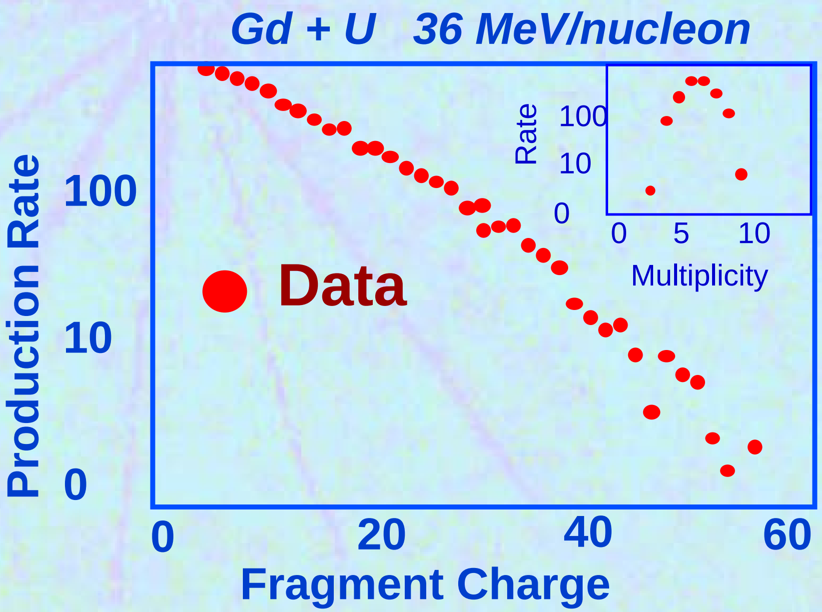
Multifragmentation



- Volume effect

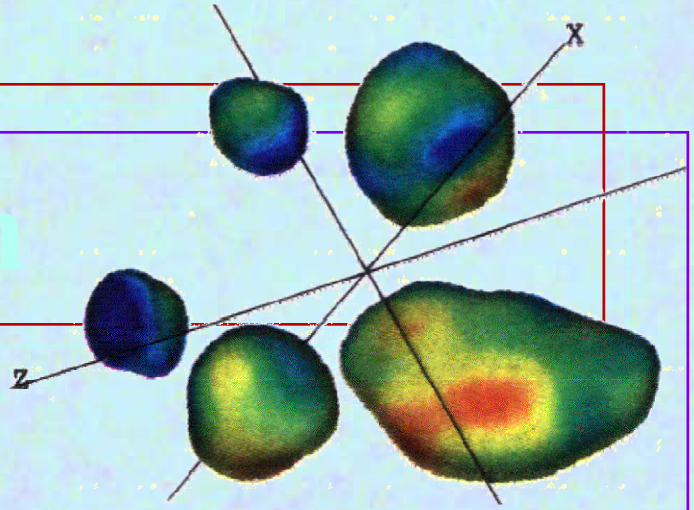
Dynamics of a phase transition





Frankland et al

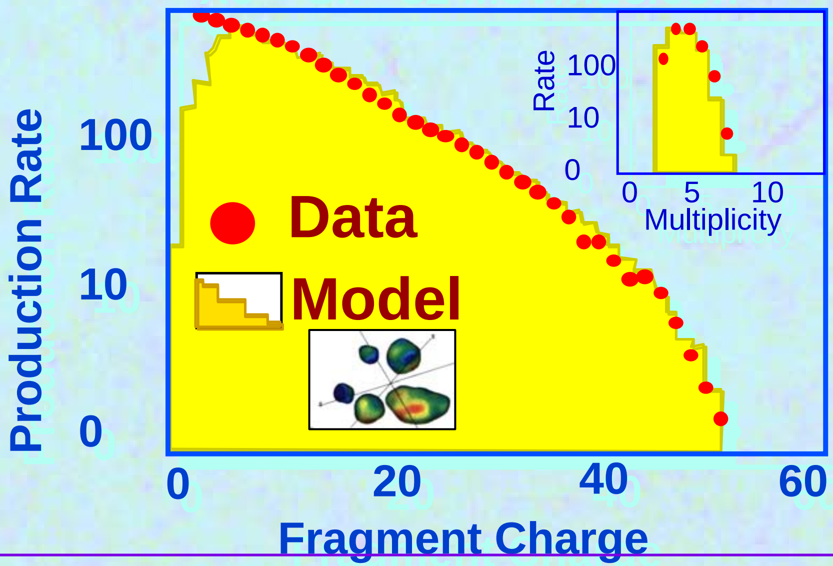
Multifragmentation



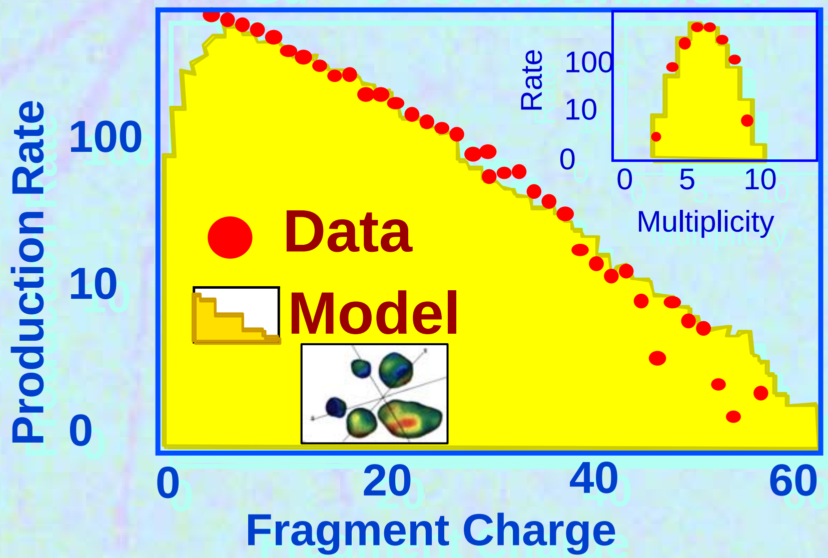
- **Volume effect**

Dynamics of a phase transition

Xe + Sn 32 MeV/nucleon

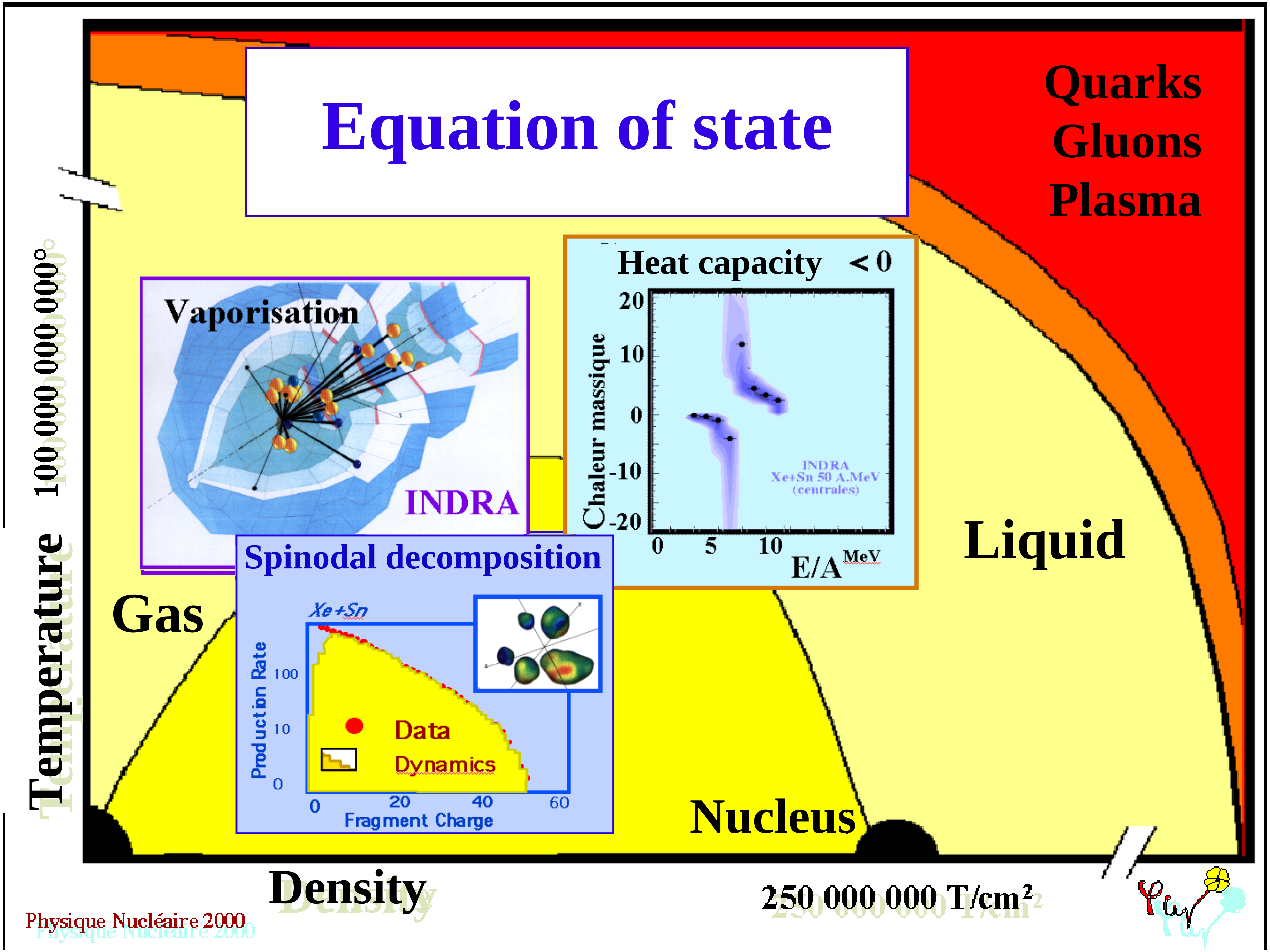


Gd + U 36 MeV/nucleon



Frankland et al

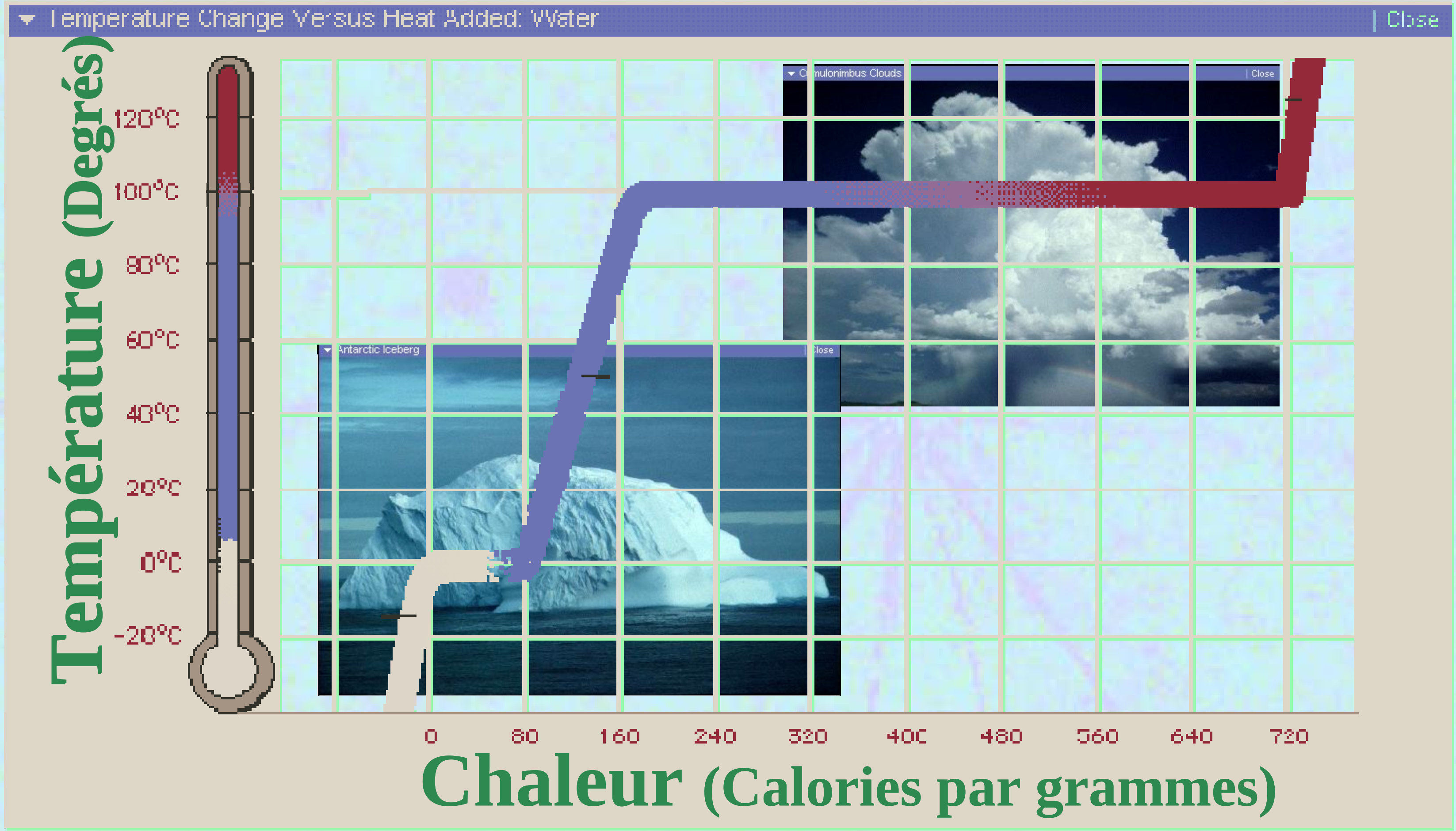
Equation of state



Phase Transition

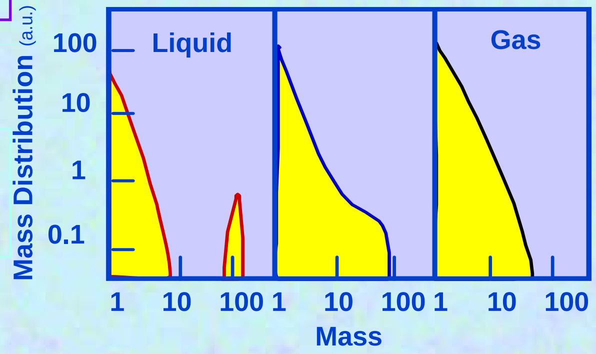
Phase Transition

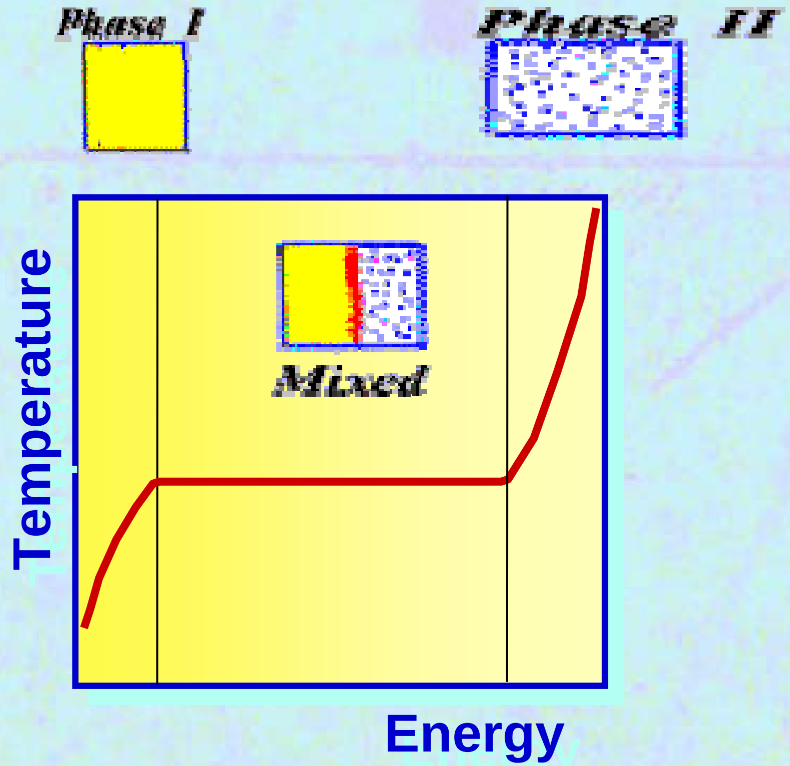
Phase Transition

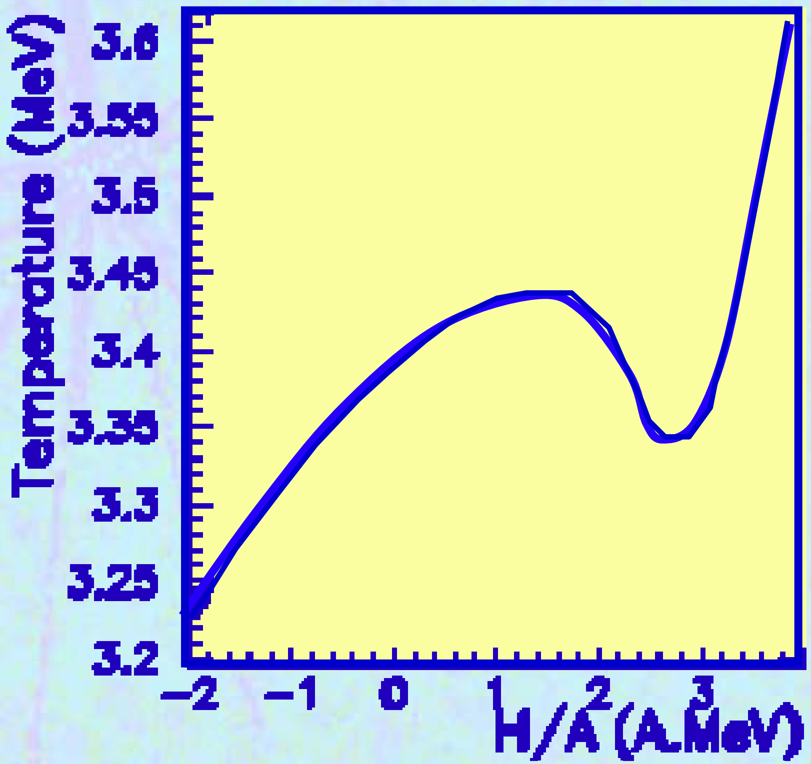


Phase Transition

In small systems



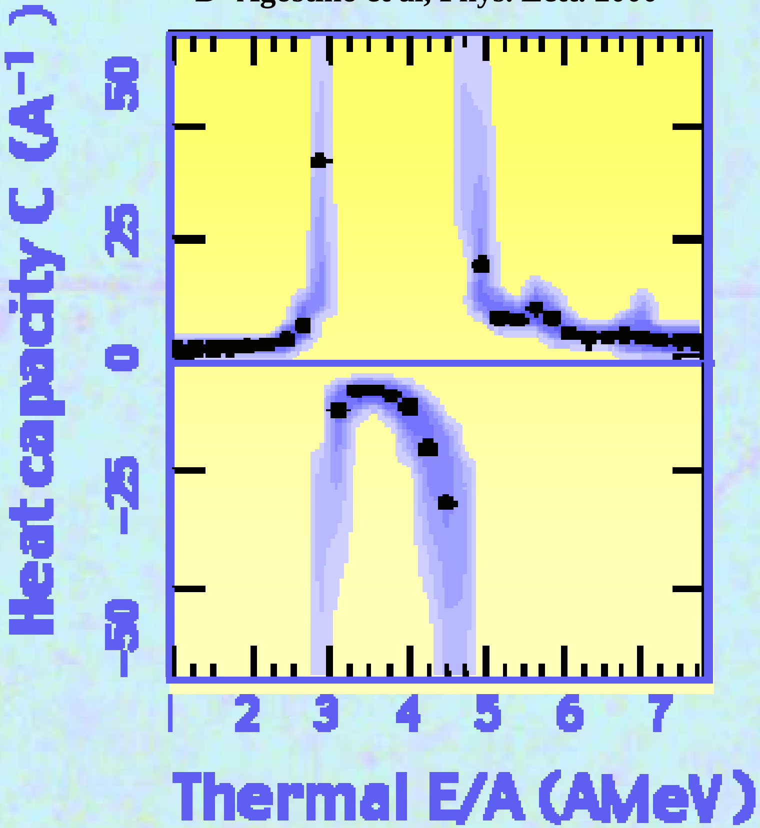




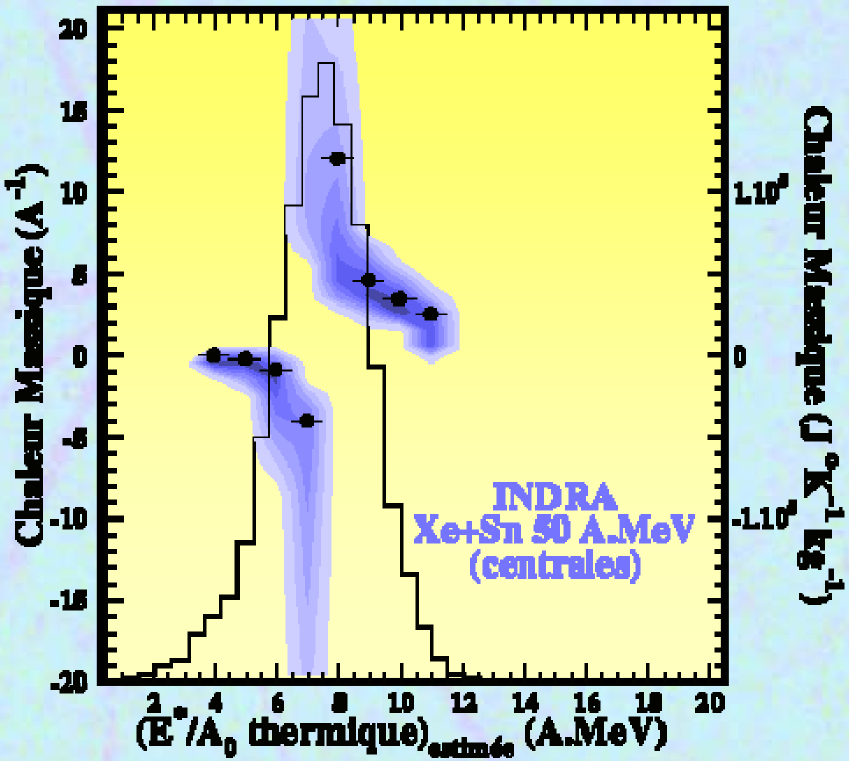
Chomaz,Gulminelli, Duflot

First Observations

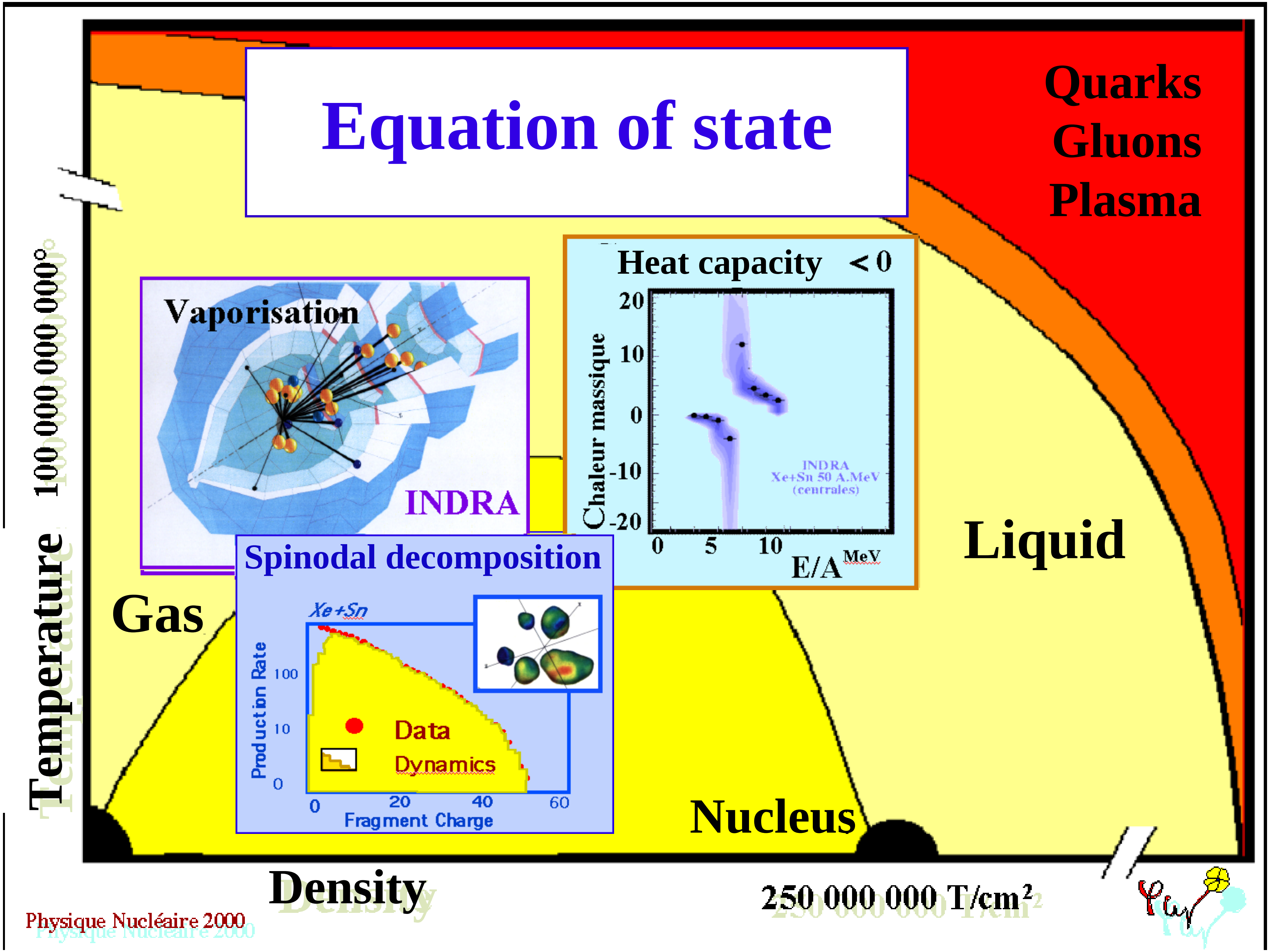
D 'Agostino et al, Phys. Lett. 2000



Bougault et al



Equation of state



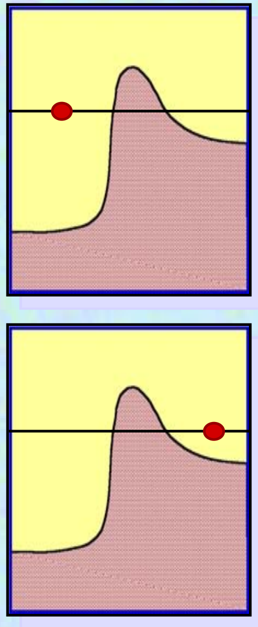
- I -

Radioactivity

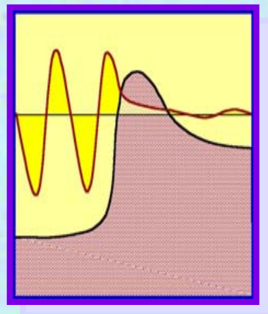
Quantum property

- **Exponential decay**
  $dN/dt = -N/T_{life}$
- **Finite life time**
  but always young
- **Transmutation**

« In »
Or
« Out »



« In »
And
« Out »



Schrödinger Cat

- I -

Radioactivity

Quantum property

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Schrödinger cat