

Principes fondamentaux de l'interaction forte et phénoménologie

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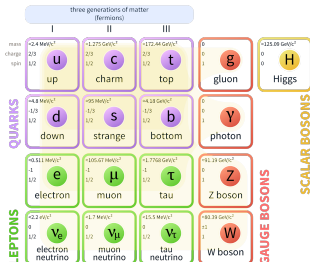


Introduction



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	$W^+ W^- z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons

Standard Model of Elementary Particles



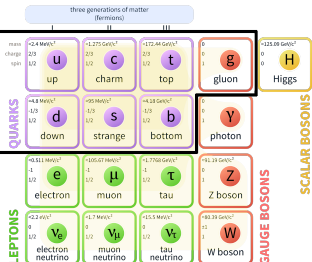
Introduction



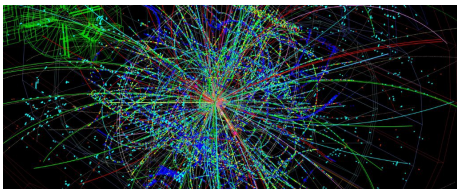
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Strong sector

Standard Model of Elementary Particles



Quantum ChromoDynamics

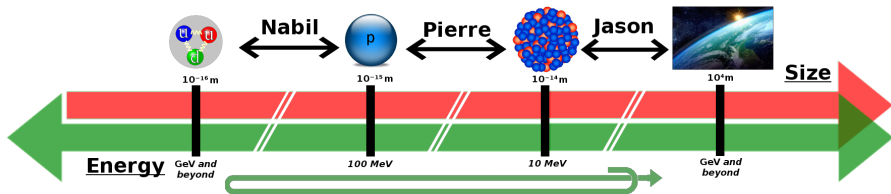


Quantum ChromoDynamics (QCD) solvable at high energy but extremely complex at low energy: We understand easily what happens in proton-proton collision at CERN but we don't understand the proton itself.



Outline

1 Introduction



2 Nucleon tomography

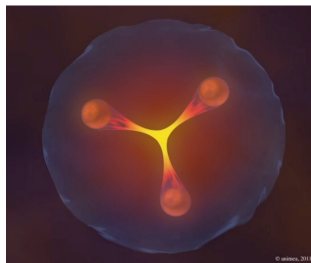
3 Nuclear structure

4 Nucleon-Nucleus collision

5 Conclusion

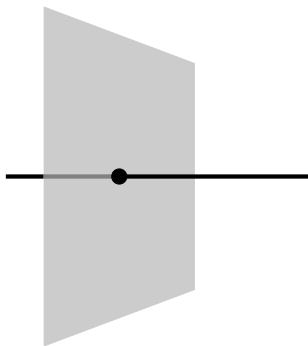
What does the nucleon look like?

- Imaging the nucleon?



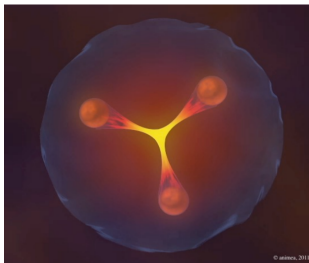
Nucleon with
three valence quarks

What does the nucleon look like?



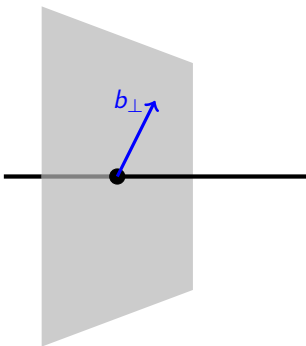
Transverse plane
of the nucleon

- Imaging the nucleon?
 - ▶ Quantum relativistic description!



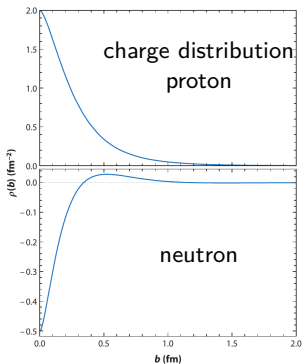
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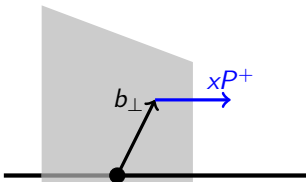


Transverse plane
of the nucleon

- Imaging the nucleon?
 - ▶ Quantum relativistic description!
 - ▶ Spatial distribution: **F**orm **F**actors.

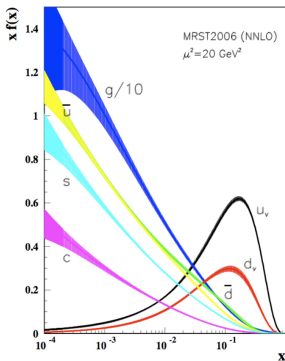


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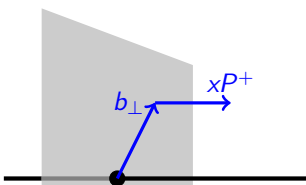


Transverse plane
of the nucleon

- Imaging the nucleon?
 - ▶ Quantum relativistic description!
 - ▶ Spatial distribution: **F**orm **F**actors.
 - ▶ Longitudinal momentum distribution: **P**arton **D**istribution **F**unctions.



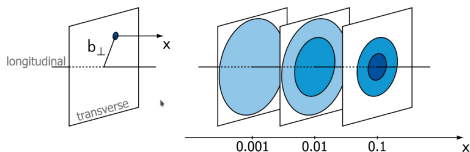
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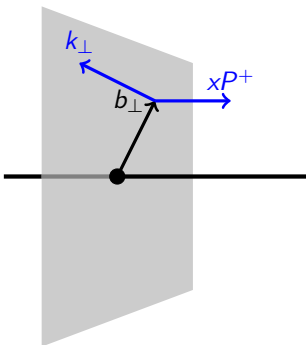
Transverse plane
of the nucleon

- Imaging the nucleon?

- ▶ Quantum relativistic description!
- ▶ Spatial distribution: **Form Factors**.
- ▶ Longitudinal momentum distribution: **Parton Distribution Functions**.
- ▶ **Generalized Parton Distributions**: correlation between b_{\perp} and x .



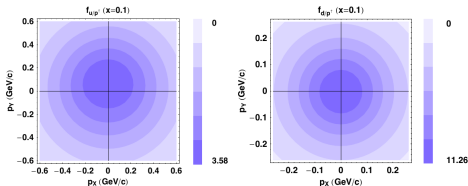
What does the nucleon look like?



Transverse plane
of the nucleon

- Imaging the nucleon?

- ▶ Quantum relativistic description!
- ▶ Spatial distribution: **F**orm **F**actors.
- ▶ Longitudinal momentum distribution: **P**arton **D**istribution **F**unctions.
- ▶ **G**eneralized **P**arton **D**istributions: correlation between b_{\perp} and x .
- ▶ **T**ransverse **M**omentum **D**ependent PDFs: correlation between k_{\perp} and x .

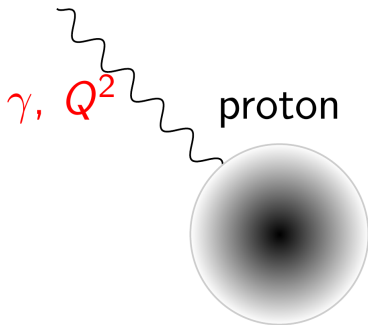


Probing the nucleon

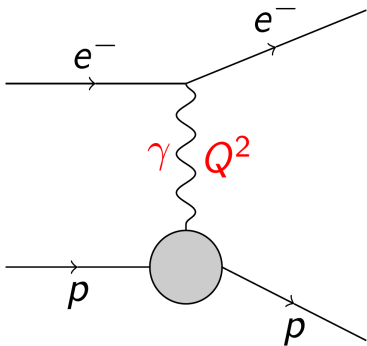
proton



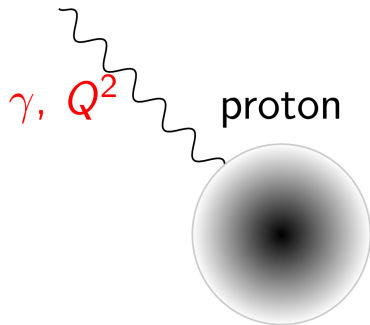
Probing the nucleon



Probing the nucleon

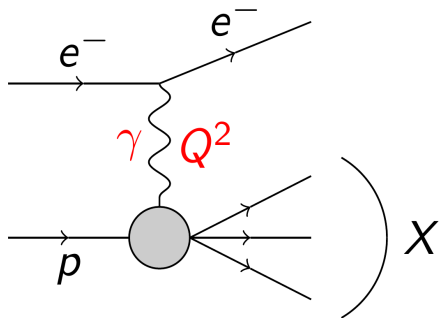


Elastic scattering

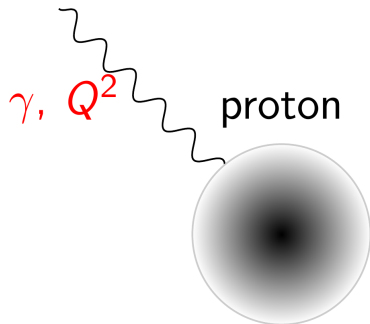


- Electromagnetic Form Factors
 - ▶ Spatial distribution.
 - ▶ Momentum distribution.

Probing the nucleon

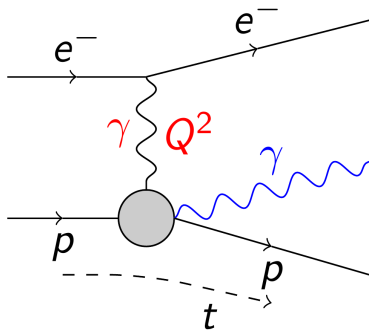


Deep Inelastic Scattering

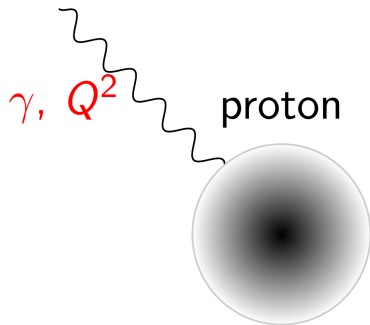


- PDFs
 - ▶ Spatial distribution.
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Probing the nucleon

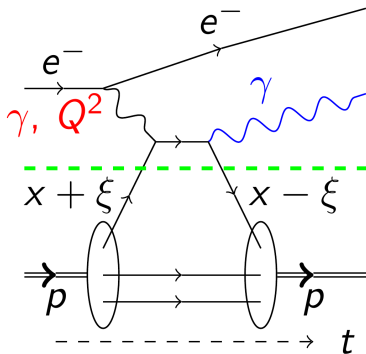


Deeply Virtual Compton Scattering

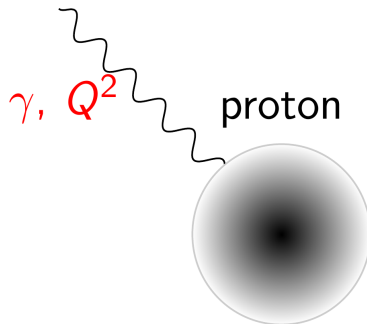


- GPDs
 - ▶ Spatial distribution.
 - ▶ Momentum distribution.

Probing the nucleon



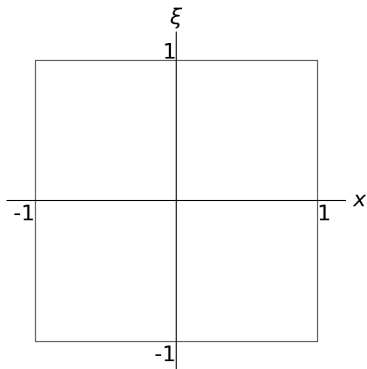
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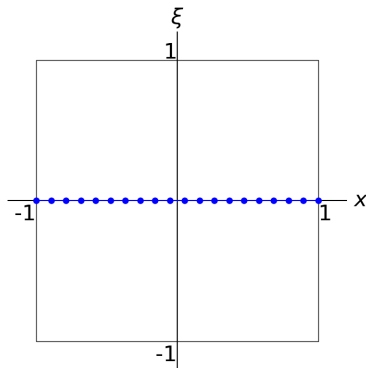
Modeling GPDs

- What do we want?



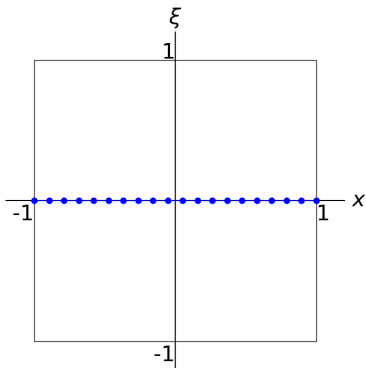
Modeling GPDs

- What do we want?
 - ▶ GPD at $\xi = 0$.



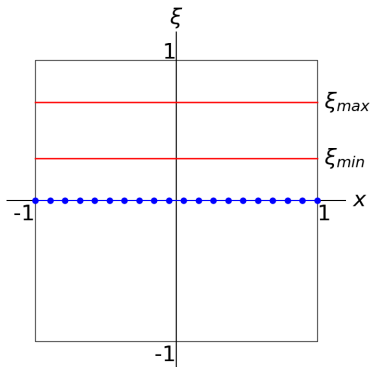
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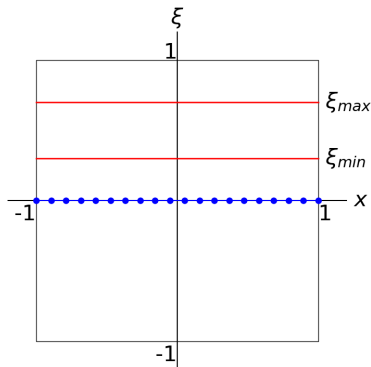
Modeling GPDs

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 - ▶ Experimental access: integrals over x of GPD at $\xi > 0$.



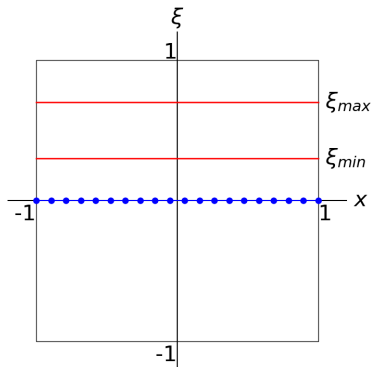
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- Link to first principles through **Light cone wave functions**:



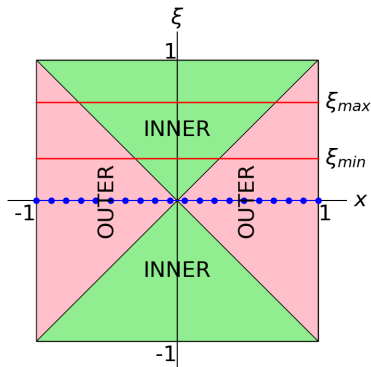
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- Link to first principles through **Light cone wave functions**:
 - ▶ Derive all partons distributions!



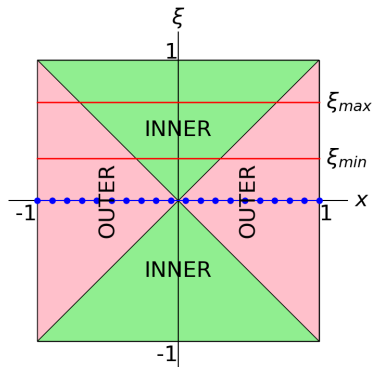
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 - ▶ **But GPD limited to the outer region.**



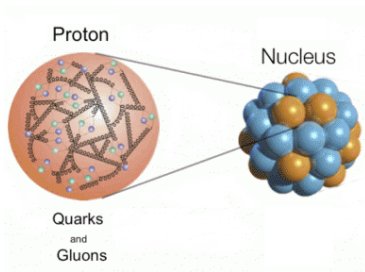
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- Link to first principles through **Light cone wave functions**:
 - ▶ Derive all partons distributions!
 - ▶ But GPD limited to the outer region.
- **Use Lorentz invariance to extend it!**



From nucleons to the nucleus

We move at higher length scale



- Nucleons are point-like particles
- Nuclear interaction is the resultant of the strong force felt by quarks

The nucleus as a system

What is a nucleus?

(Quasi) Bound or resonant state of N neutrons and Z protons (and Y hyperons)

- 80 stable elements ($Z \leq 82$)
- 254 nuclides stable vs α , γ and β decays, fission...
- ~ 2500 nuclides synthesized
- Heaviest synthesized element is $Z = 118$



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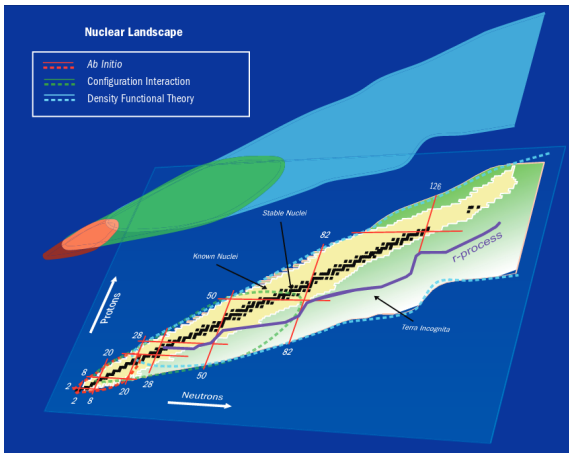


Huge diversity of nuclear phenomena

- Ground state properties: Mass, deformation, superfluidity, size...
- Spectroscopy: Excitation modes
- Radioactive decays: $(2)\beta$, α , $(2)p$, fission...
- Reaction processes: Fusion, transfer, knock-out...
- Limits: Drip lines, mass, clusters, halos...

Methods in nuclear structure theory

Different methods to treat the whole nuclear chart:

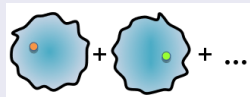


- Different reaches
- Different drawbacks

How we treat the nucleus

First order approximation: Particles in a mean field

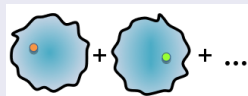
- Mean field produced by the nucleons
- Set up the orbitals that the nucleons occupy
- Nucleons interact with the mean field, not each other



How we treat the nucleus

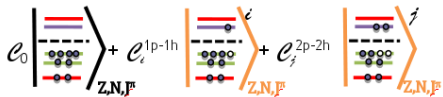
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Dynamical correlations

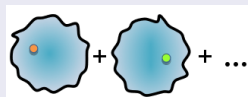
- Do not change the structure
- Needed for a precise description
- Included through particle excitation



How we treat the nucleus

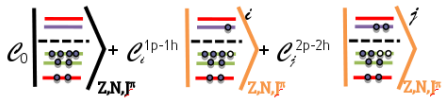
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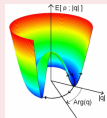
Dynamical correlations

- Do not change the structure
- Needed for a precise description
- Included through particle excitation



Non-dynamical correlations

- Linked to physical properties of nuclei: superfluidity, deformation...
- Needed for a qualitatively correct description
- Included through symmetry breaking



On *ab initio* methods

How to proceed

- 1 Consider point-like nucleons as appropriate degrees of freedom
- 2 Use interactions rooted in underlying theory (i.e. QCD)
- 3 Expand the many-body Schrödinger equation solution systematically
- 4 Truncate at a given order and solve using computational methods

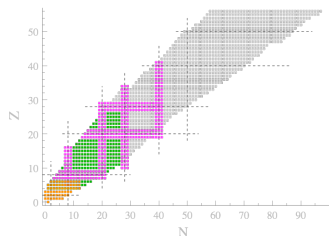
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Pros and cons

- ✓ Rigorous formalism
- ✓ Allow a precise error estimation
- ✗ Computationally intensive
- ✗ Restricted to light- and medium-mass nuclei



Bogoliubov MBPT: Why?

Based on Many-Body Perturbation Theory

- Rigorous *ab initio* formalism
- Include dynamical correlations from the start
- Computationally friendlier

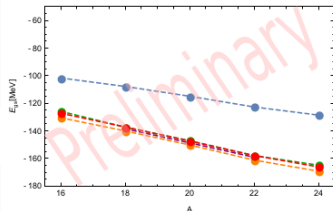
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Break particle-number symmetry

- Incorporate correlations linked to superfluidity
- Access to open-shell nuclei



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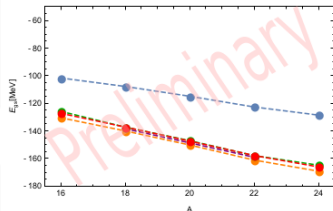
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Link to Energy Density Functionals

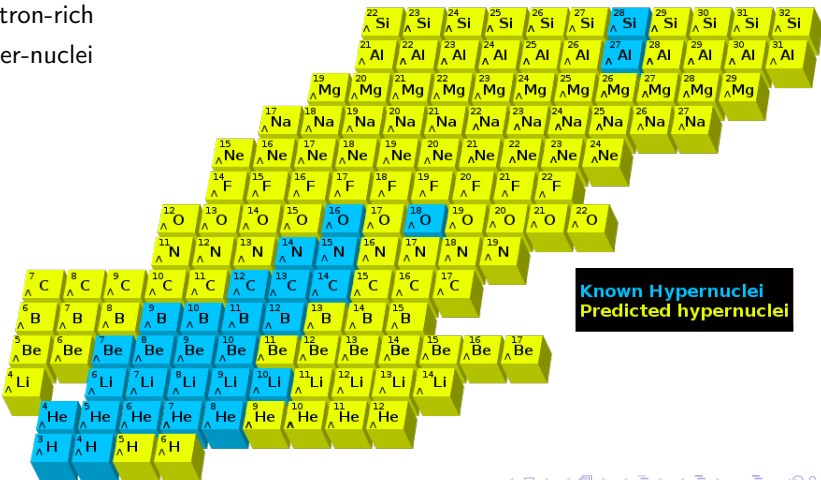
- Put formally rigorous constraints on the functional
- Access to the whole nuclear chart



From nuclear structure theory... to its application

Nuclear structure calculations access so-called exotic nuclei:

- proton-rich
- neutron-rich
- hyper-nuclei

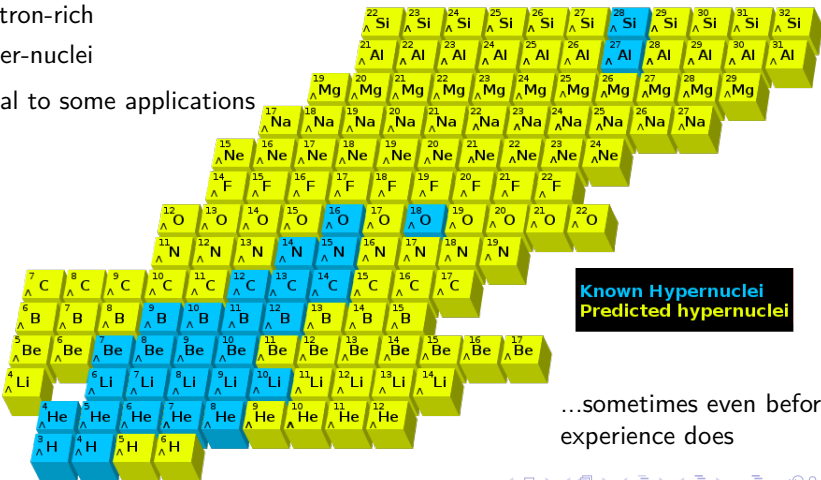


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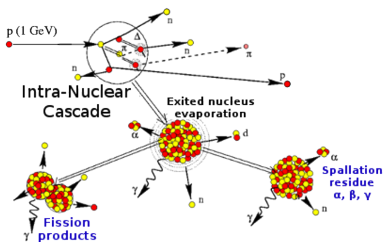
→ Crucial to some applications



...sometimes even before experience does

Jason - The Alchemist

Spallation reaction or How to transmute lead into gold

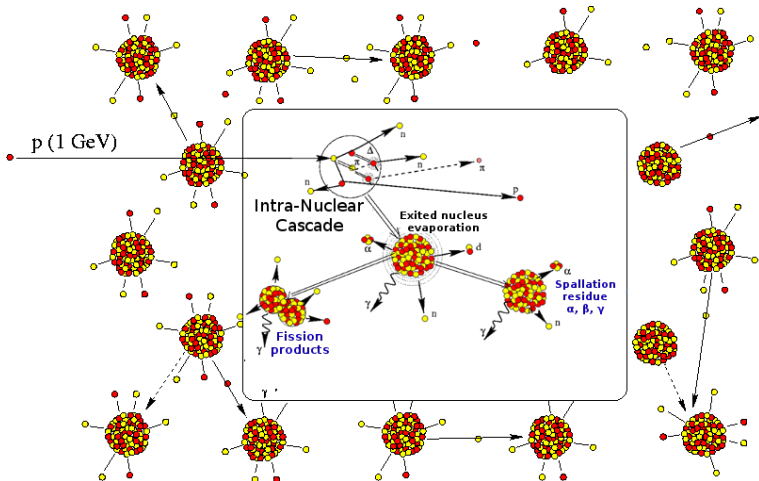


The spallation with numbers

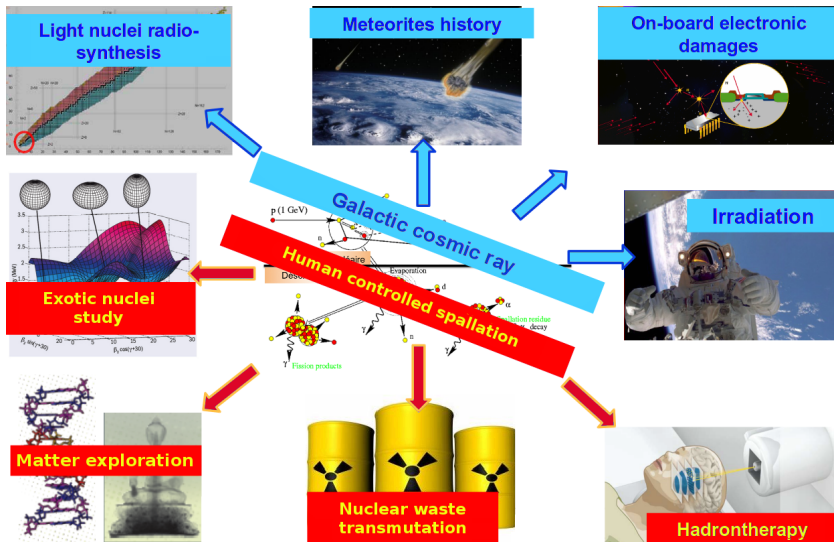
- Light projectile (p, π, α, \dots)
- Heavy target ($^{12}\text{C}, ^{208}\text{Pb}, \dots$)
- Kinetic energy around the GeV
- Time scale: $\sim 10^{-22} - 10^{-20}$ s

Jason - The Alchemist

Macroscopic spallation reaction



Spallation application

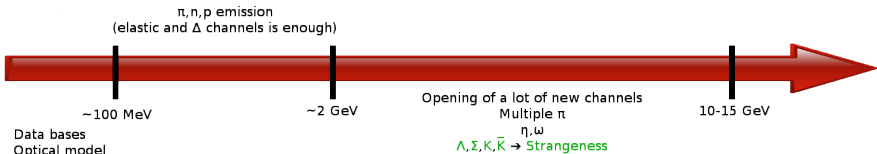
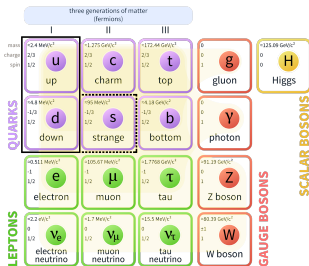


INCL improvement

This subject: Improvement of the intra-nuclear cascade simulation code at high energy through a new degree of freedom:

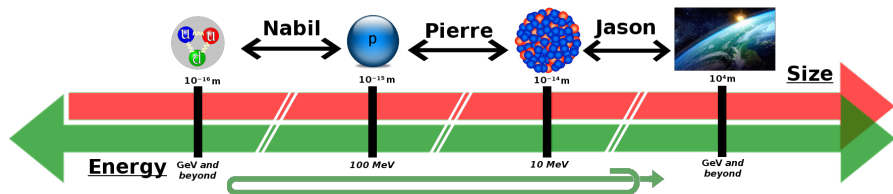
Strangeness

Standard Model of Elementary Particles



Conclusion

Research on theory and phenomenology is very active...



Strong interaction implications go...

- from quarks to astrophysical systems
- from fundamental research to everyday-life applications

Thank you for you attention