The atomic nucleus : A natural laboratory of complexity

Raphaël-David Lasseri

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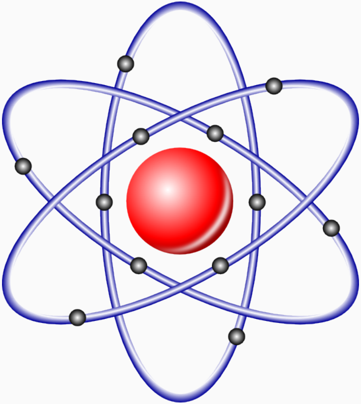
Definitions

Is it a nucleus ?

A **building** block of matter



- Small and dense region at the center of the Atom
- Inferred by Rutherford
- "Made" of protons and neutrons

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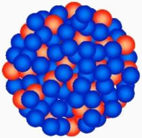

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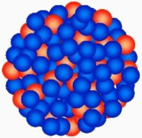

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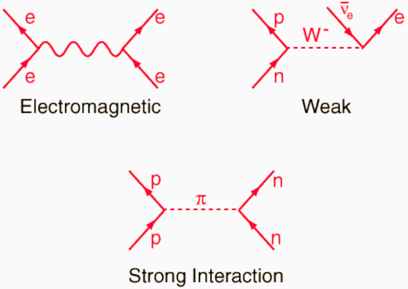
$\boxed{\text{What are the correct d.o.f to describe it ?}}$

What is a nucleus ?

A quantum-many-body system:

- Sensitive to 3 fundamental interactions (EM,W,S)
- Composed of non-elementary fermions
- Strongly correlated system of finite size



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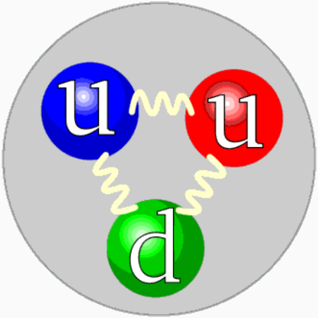

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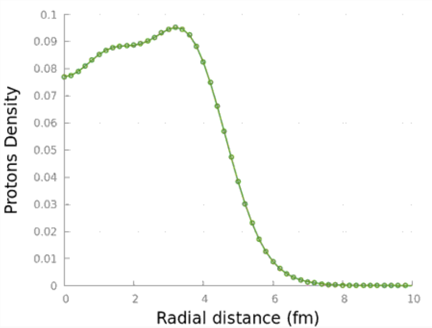

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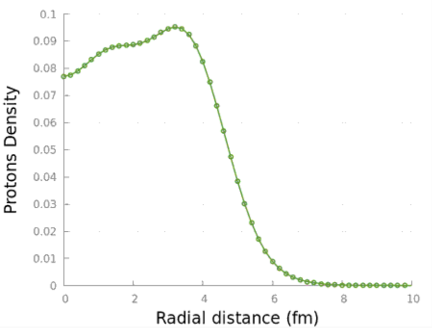

The nucleus is a complex system

Complexity – A challenging description

Consequences:

- No systematic analytical treatment of the problem.
- A wide variety of phenomena.

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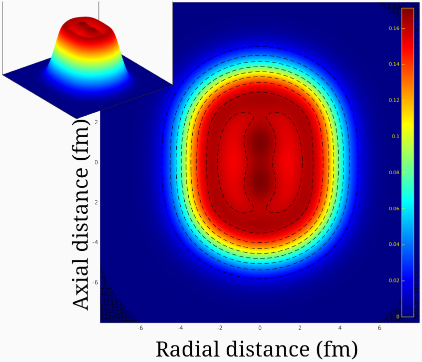
Deformation:



Complexity – A challenging description

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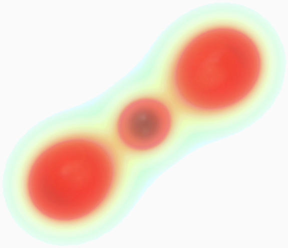
Clustering:



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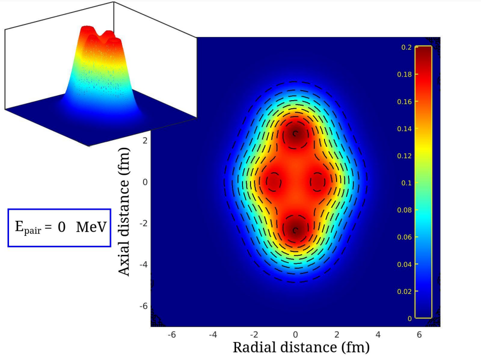
Superfluidity:

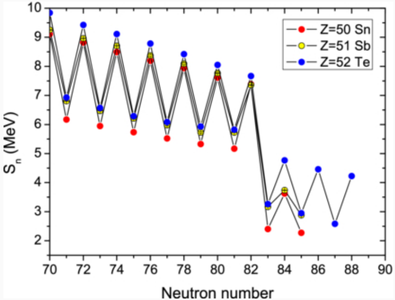


What can one measure ?

Some observables

Ground-State:

- Energy (Separation)
- Radii



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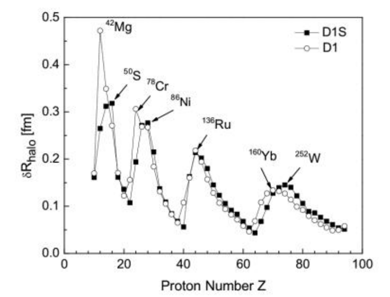
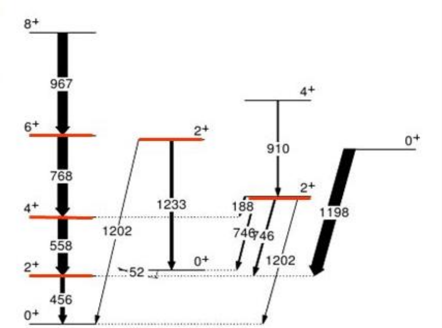


Some observables

Excited-states:

- Energies (Spectroscopy)
- Electric moments



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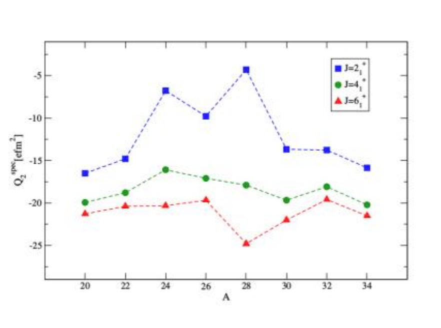
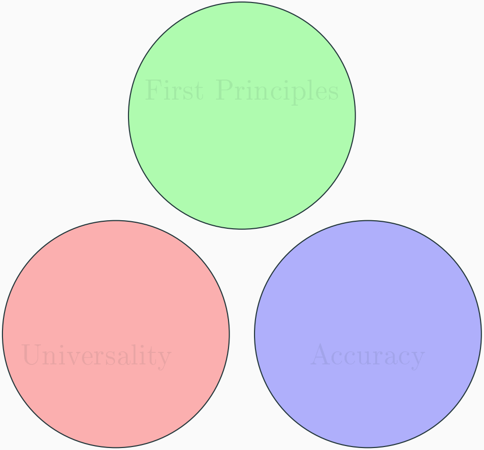


Description(s)

Nuclear "Philosophy" – A complicated compromise



- A scaling problem
- Treatment of the many-body problem
- Description of the interaction

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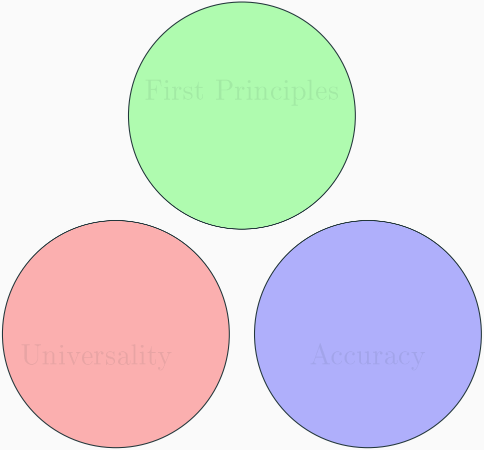

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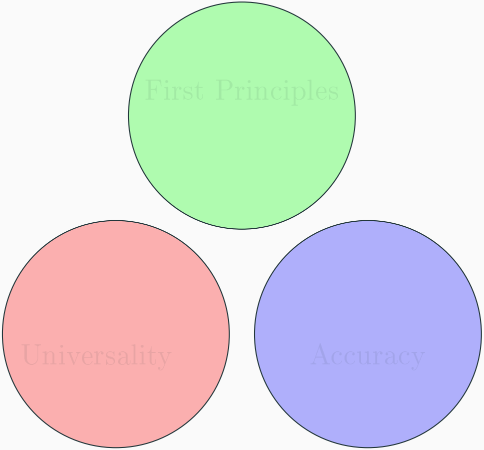

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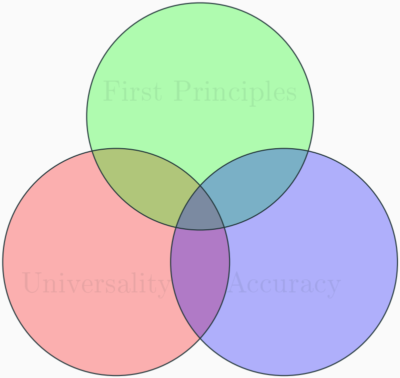

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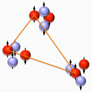
We need a compromise !

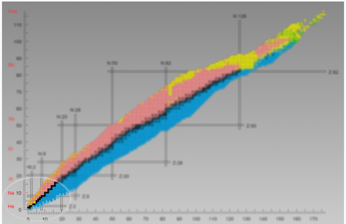
The quantum Many-body problem

- Exact
- Ab-initio
- EDF



Summary: Explicit treatment of the total wave-function

- $\hat{H}\Psi = E\Psi$
- Very accurate with a true interaction.
- Extremly coastly and heavy (Power-law scaling)



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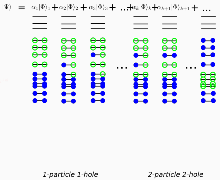
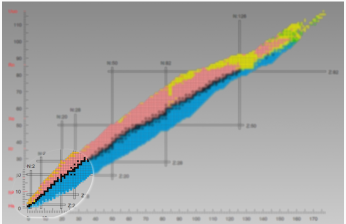


Summary: Explicit treatment of truncated total wave-function

- $\Psi = \sum_I c_I \Phi_I$
- Predictive with an effective interaction
- Very coastly and heavy (Combinatorial scaling)



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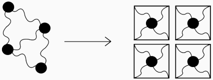
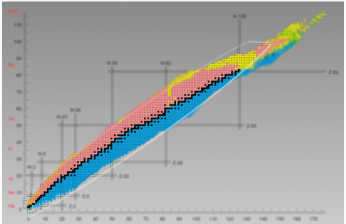


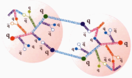
<u>Summary:</u> Mean-field like treatment of the wave-function

- $[\hat{H}, \hat{\rho}] = 0$
- Almost universal, but uses a phenomenological interaction
- Quite computationaly easy (Polynomial scaling)



From QCD to strong-force

From the "true" non-abelian gauge theory...



$$\mathcal{L} = -\frac{1}{4}F^{A}_{\alpha\beta}F^{\alpha\beta}_{A} + \sum_f \bar{q}_A(i\gamma^\mu D_\mu - m)_{AB}\, q_B + \mathcal{L}_{gauge-fixing} + \mathcal{L}_{ghost}$$

From QCD to strong-force

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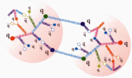
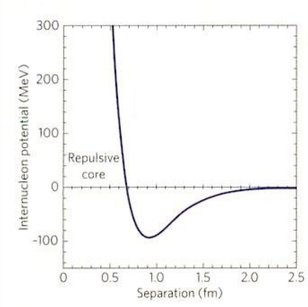
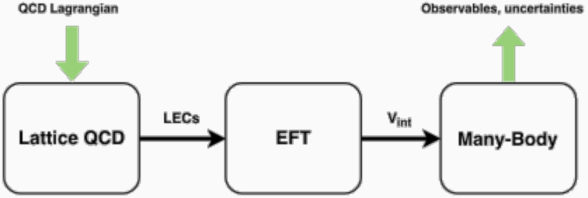


To a realistic N-N interaction



Establish a direct link between QCD and an effective strong force



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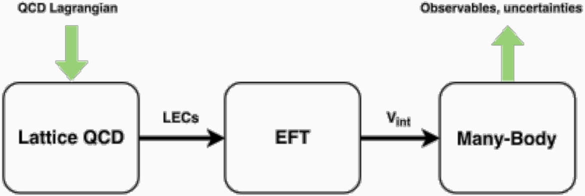
The Holy Grail

Establish a direct link between QCD and an effective strong force

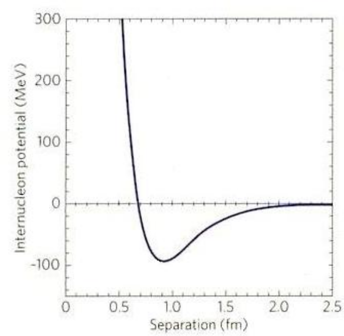


Courtesy M. Drissi

Still a lot of work...

Energy Functionals – A Phenomenological approach

An example Relativistic Mean Field Theory (RMF)



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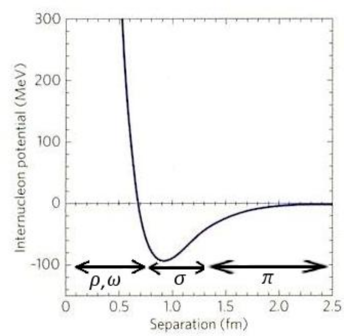
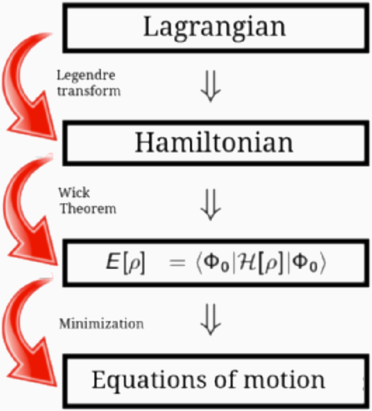


Interpretation in term of mesons exchange

A brief summary



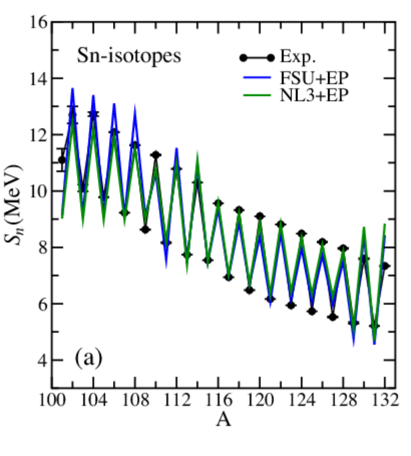
$$\mathcal{L}_{int} = g_\sigma \overline{\psi} \sigma \psi + g_\omega \overline{\psi} \gamma_\mu \omega^\mu \psi + g_\rho \overline{\psi} \gamma_\mu \vec{\rho^\mu} \cdot \vec{\tau} \psi + g_\pi \overline{\psi} \gamma_5 \vec{\pi} \cdot \vec{\tau} \psi$$

$$\mathcal{H} = \hat{T}_{i,j} + \hat{V}_{eff}$$

- Mesons : $(\partial_\mu \partial^\mu + M^2)\phi^\nu = j^\nu$
- Nucleons :$(\not{p} - m_{eff} + \Sigma)\psi = 0$

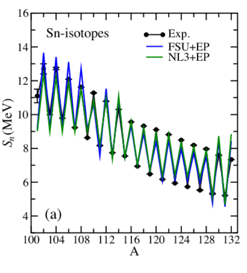
State-of-the-art descriptions

Some "observable" problems

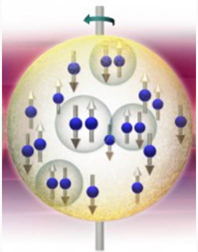


Correlations

Some "observable" problems

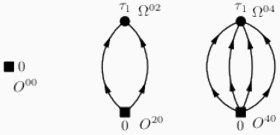


Odd-even staggering ⇒ Pairing correlations



Correlations (1)

Explicit fields expansion truncated at a given order



Bogoliubov-Many-Body-Perturbation-Theory (BMBPT) diagrams

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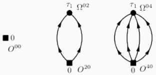
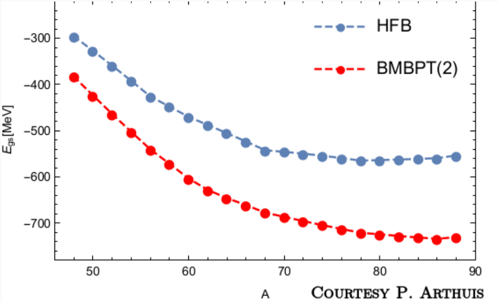


<u>Results:</u>



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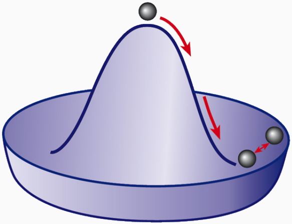
Correlations (2)

Symmetry breaking:



- Capture additional correlations
- For any sym. group. (U(1),O(3),etc...)

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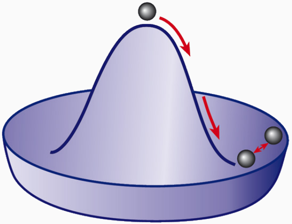

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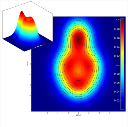
And restoration:
Generator **C**oordinate **M**ethod

- Pick a generating coordinate
- Sum over symmetry broken states



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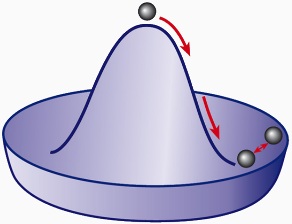

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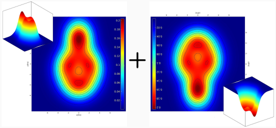

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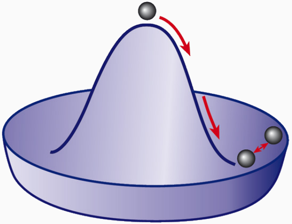

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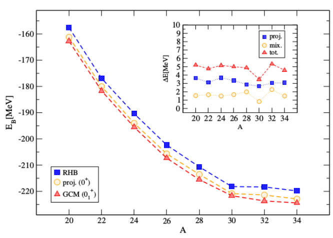

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Conclusions

A dynamic field

Nuclear physics is an active research field !

Major intrinsic open subjects:

- Theoretical link between QCD and N-N Interaction
- Systematic and simultaneous restorations
- New (non-spurious) many-body techniques.
- Hybrid approaches (EDF/EFT, EDF/CI,...)

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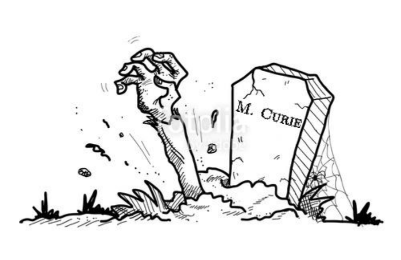
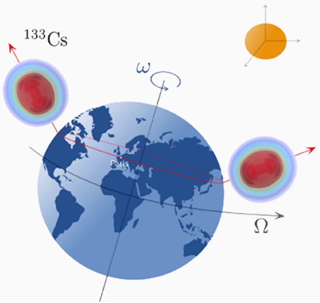


Detection of Majorana neutrinos

- Precise study of double-beta decays
- Dependence on nuclear reactions knowledge

Cross-fertilizing topics

Lorentz-symmetry breaking[1]



- Very strong dependance on nuclear structure knowledge
- Major cosmological impact

[1] H.Pians-Le Bars, C. Guerlin, R-D.L, J-P. Ebran, Q.G. Baily, S.Bize, E.Khan, P.Wolf **Phys.Rev.D 95,075026**

Questions

Thank you !