Nuclear structure and α radioactivity

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PhyNet

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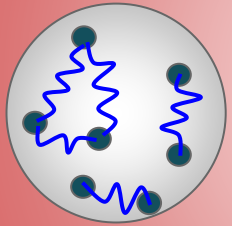
I. The nuclear many body problem
II. Building an interaction
III. Many body interacting problem
IV. Alpha and cluster radioactivity

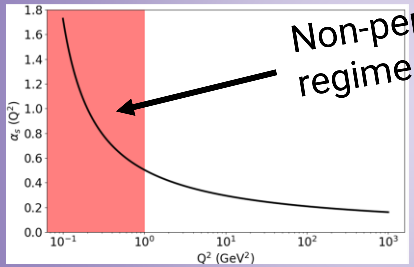
Tackling the nuclear many body problem

Quantum many body interacting problem !



Many (strongly) interacting particles but not enough for statistical approximation TOOOOO hard to be solved exactly

Interaction coming from (non-perturbative) QCD !

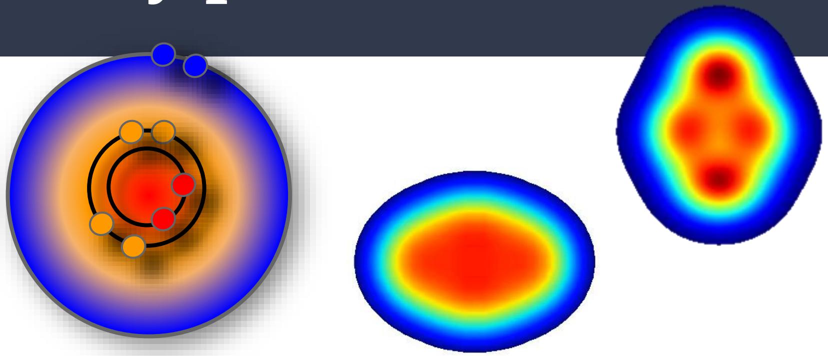


Non-perturbative regime at low energy !

EFT

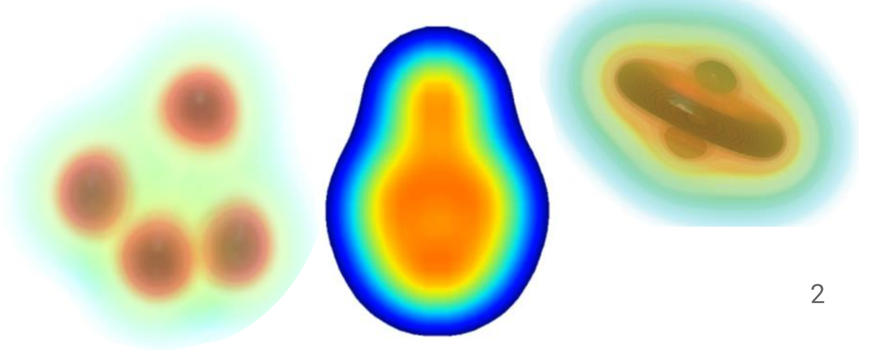
2N, 3N, 4N, ... interactions

Relevant degrees of freedom ?



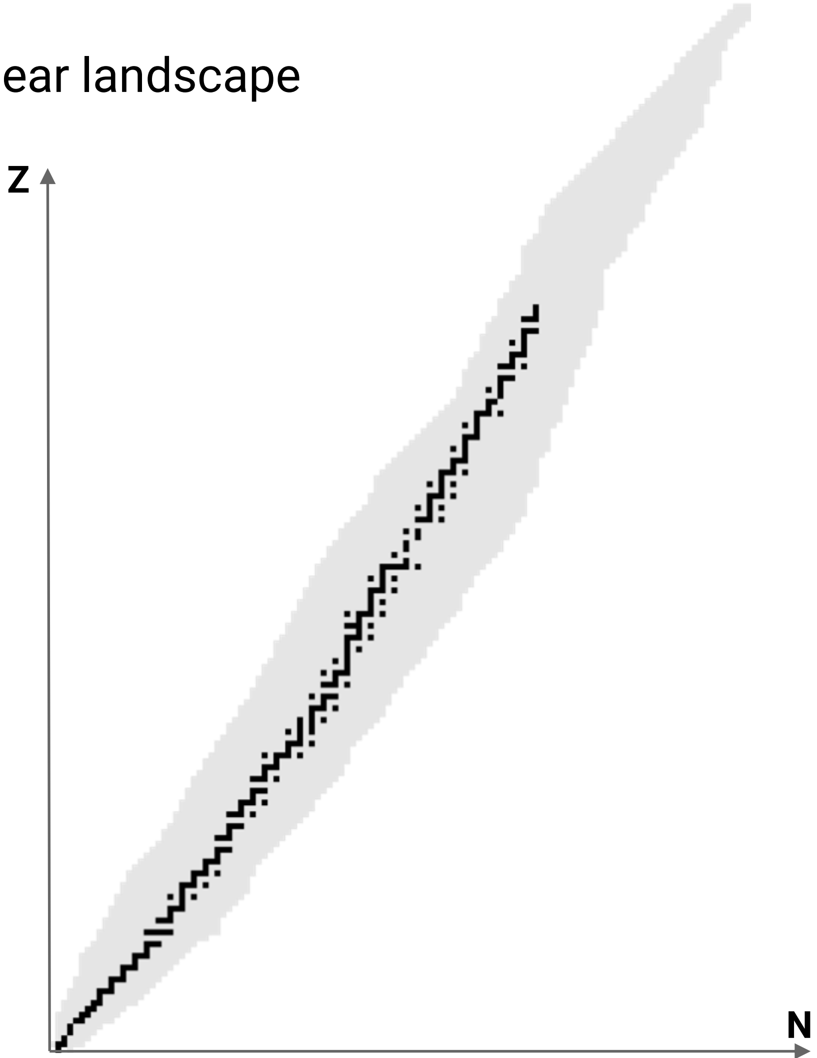
Huge phenomenology !

Many emerging properties : deformation, radioactivity, halo, neutron skin, superfluidity, clustering, excitations, ...



The different methods to deal with nuclear system

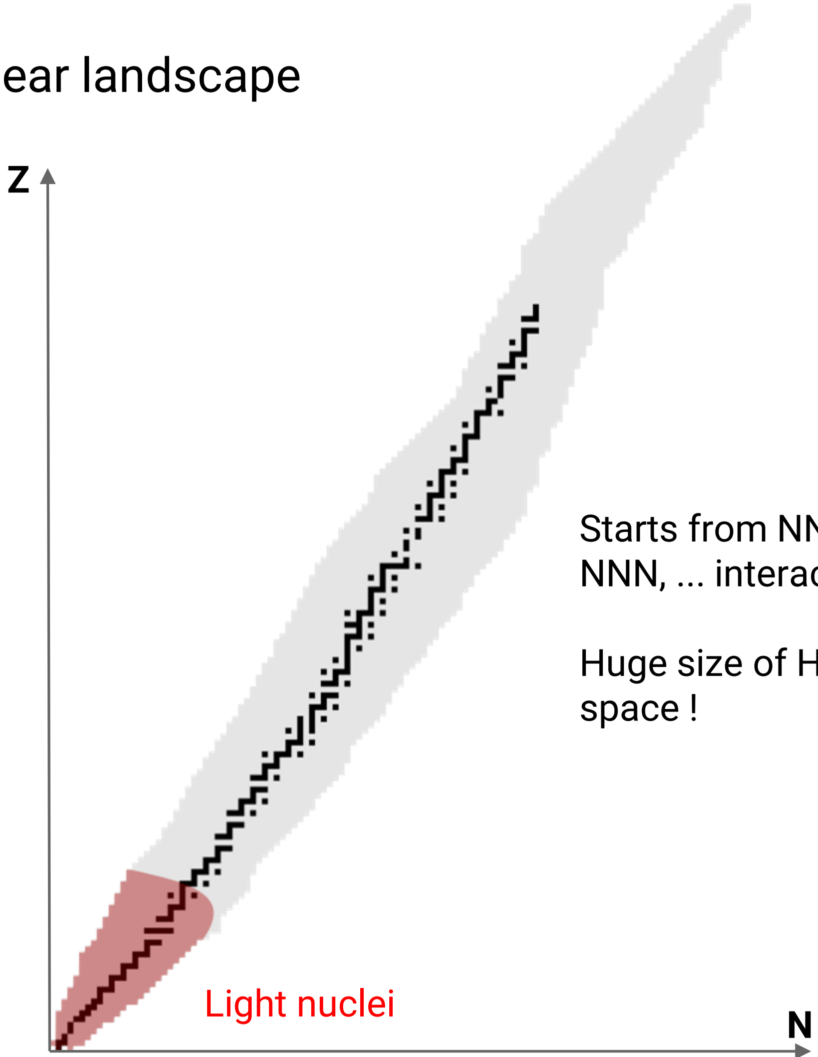
Nuclear landscape



The different methods to deal with nuclear system

- Ab Initio

Nuclear landscape



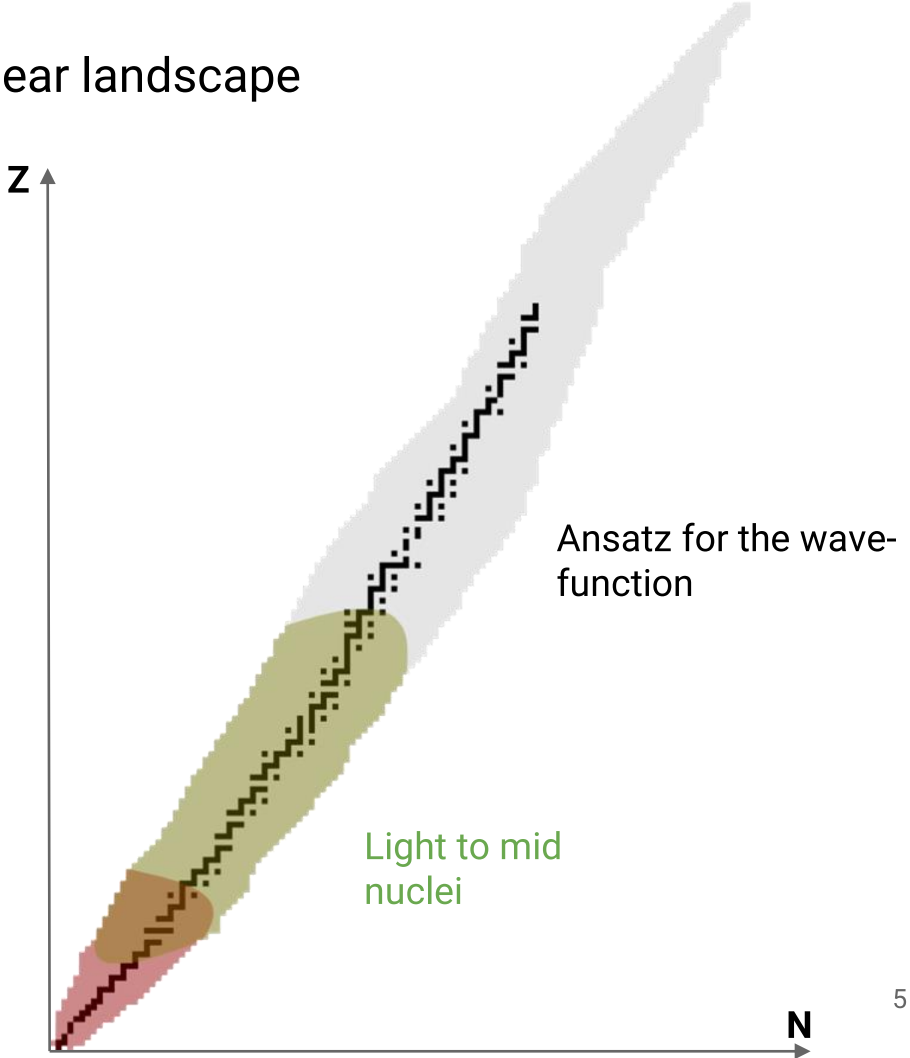
Starts from NN, NNN, ... interaction

Huge size of Hilbert space !

The different methods to deal with nuclear system

- Ab Initio
- Configuration interaction

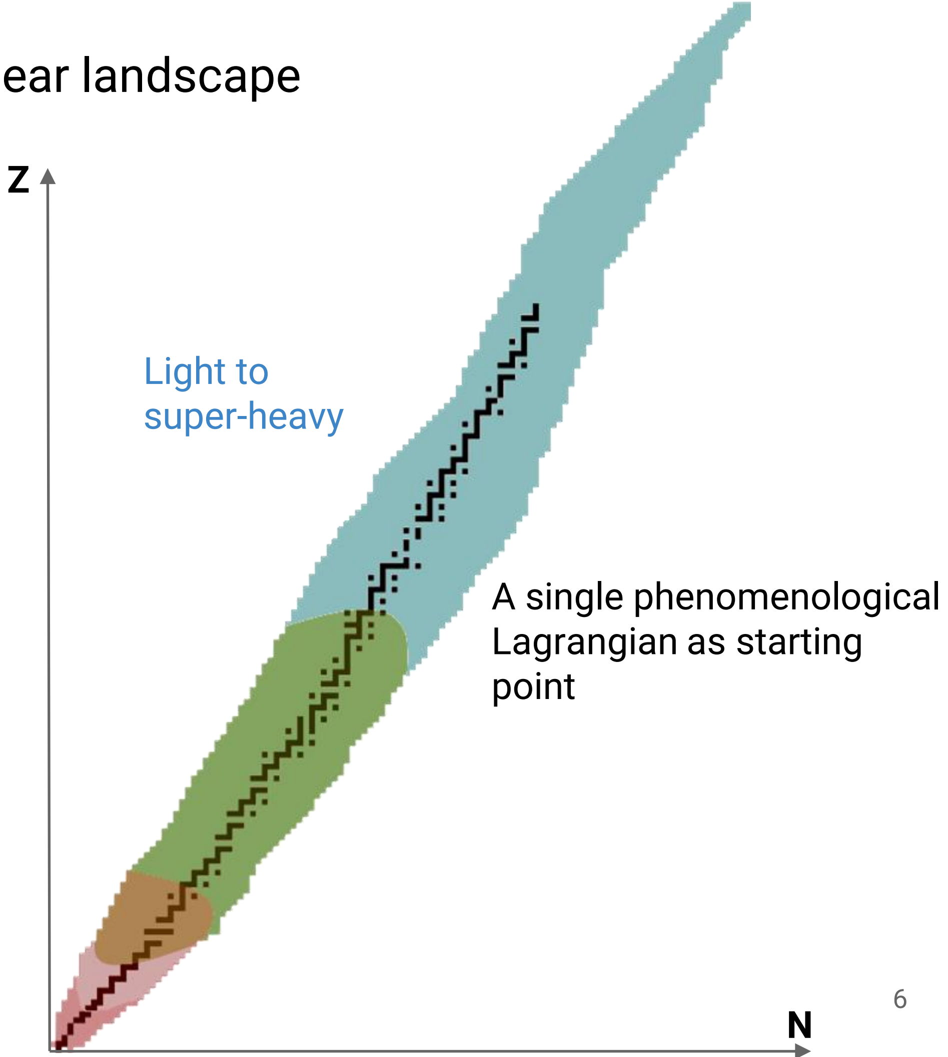
Nuclear landscape



The different methods to deal with nuclear system

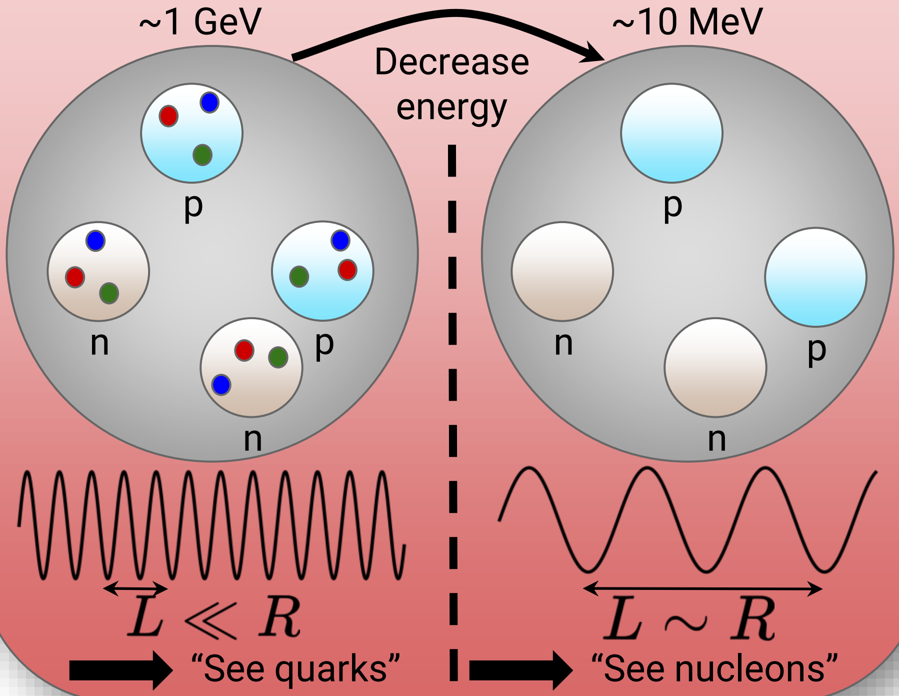
- Ab Initio
- Configuration interaction
- Energy density functional

Nuclear landscape

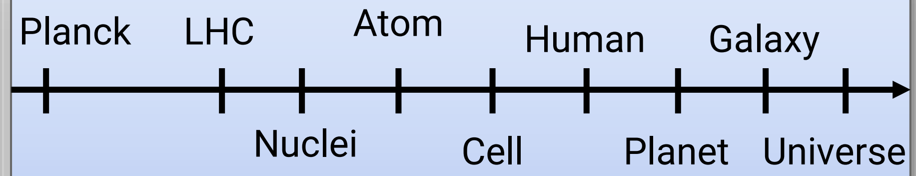


Building an interaction : what is the idea ?

Relevant degrees of freedom ?



Effective field theory

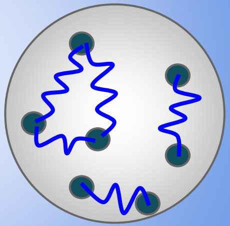


- Scale separation is the key ingredient
- Zooming out (decreasing energy, increasing scale) leads to different theories !
- Allows a scale by scale study in Science !

Many body interacting problem

Strongly **interacting many body** system

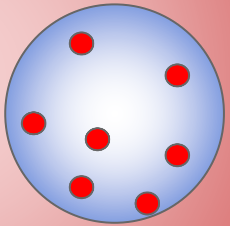
VERY HARD



Mapping → **Fermi liquid**

One-body problem involving **independent quasi-particles**

Mean-field



Idea :

$$H = \left[\sum_i \frac{p_i^2}{2m}\right] + \left[\sum_{ij} V_{ij} + \sum_{i<j<k} V_{ijk} + \ldots\right]$$

$$= \left[\sum_i \frac{p_i^2}{2m} + U_i\right] + \left[\sum_{ij} V_{ij} + \sum_{i<j<k} V_{ijk} + \ldots - \sum_i U_i\right]$$

$$= H_0 + \mathcal{V}_{res}$$

Such that $|H_0| \gg |\mathcal{V}_{res}|$

One body term

Find the "best" U_i

As much physics as possible ↔ Justify perturbative approach

Hartree-Fock theory

Symmetries

$H = H_0 + \mathcal{V}_{res}$ with a certain U_i

We know that the Hamiltonian *H* possesses some symmetries

$[H, N] = 0$ Particle number conservation

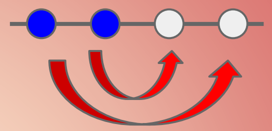
$[H, J] = 0$ Invariance under rotation

Let us choose the same symmetries for H_0

$[H_0, N] = 0 \quad [H_0, J] = 0$

Problem

Perturbation theory



Improvement by going at higher order

$$E = \mathcal{E} + \sum_{n>0} \underbrace{\frac{|\langle \phi_n | \mathcal{V}_{res} | \phi_0 \rangle|^2}{\mathcal{E} - \mathcal{E}_n}}_{\gg 1} + \dots$$

For (quasi-) degenerate state

We are missing an essential ingredient in $\mathcal{V}_{res}$!

Change U_i to change the physical content

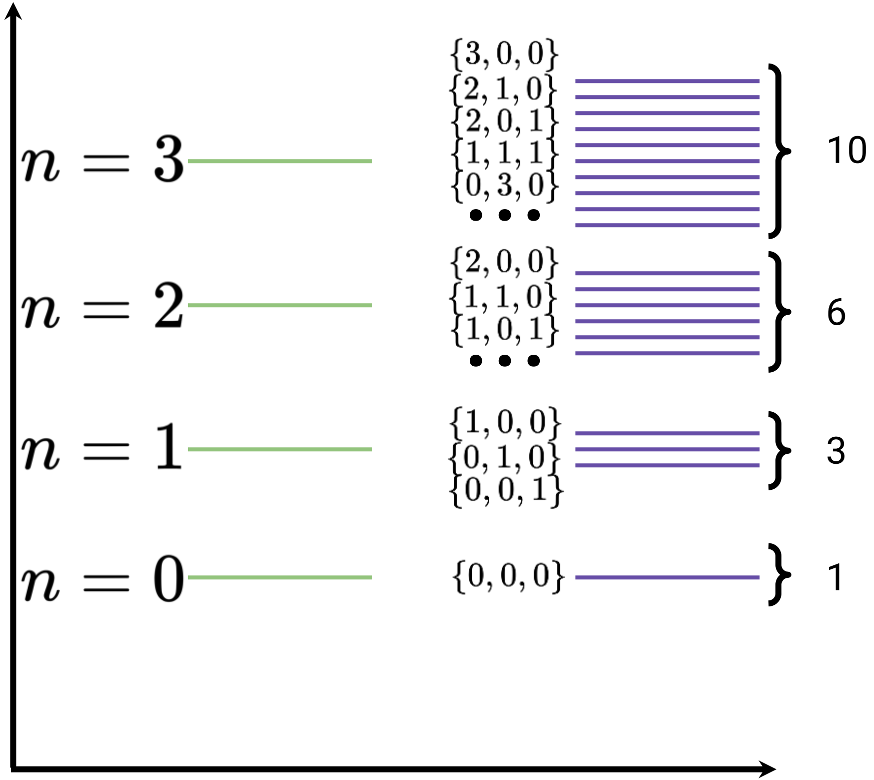
How to raise degeneracies ?

The isotropic (symmetric) harmonic oscillator

$$E_n^{sym} = \hbar\omega(n_x + n_y + n_z + 3/2)$$
$$= \hbar\omega(n + 3/2)$$

The anisotropic (asymmetric) harmonic oscillator

$$E_{n_x n_y n_z}^{asym} = \hbar(\omega_x n_x + 1/2) + \hbar(\omega_y n_y + 1/2)$$
$$+\hbar(\omega_z n_z + 1/2)$$



→ Breaking symmetries seems to raise degeneracies !!

Hartree-Fock-Bogoliubov theory

Symmetries

$H = H_0 + \mathcal{V}_{res}$ with a certain U_i

We know that the Hamiltonian *H* possesses some symmetries

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Let us choose the same symmetries for H_0

$$[H_0, N] = 0 \qquad [H_0, J] = 0$$

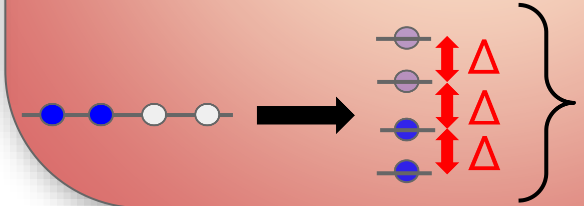
~~Problem~~ Solution

Assume $[H'_0, N] \neq 0$ → Particle number not conserved anymore !

Particles can create pairs which behave as single degree of freedom

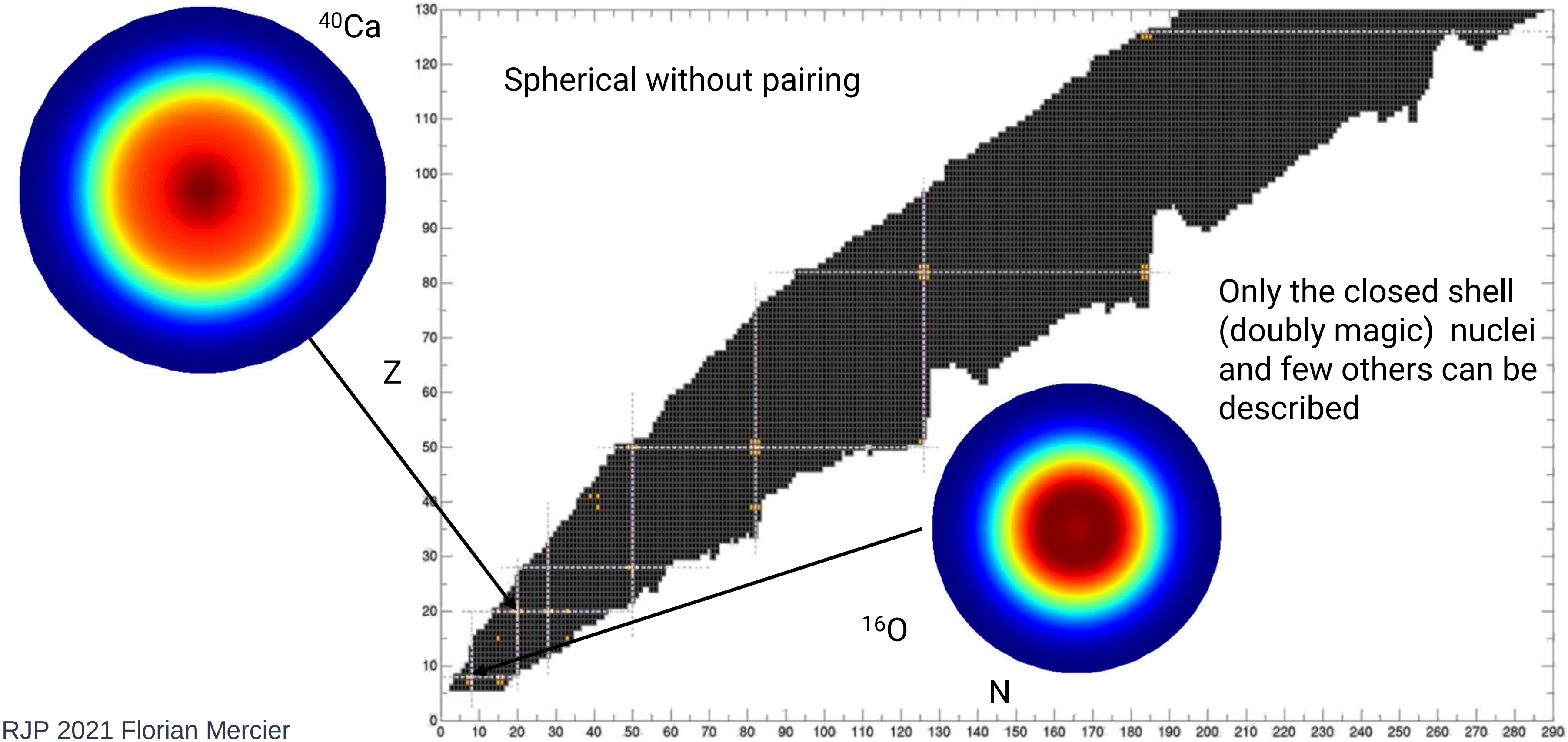
As for spin pairing, it leads to a splitting of the energy and a new minimum energy configuration !

$$E = \epsilon \pm \Delta$$



Non degenerate anymore !

Impact of symmetry breaking : no breaking



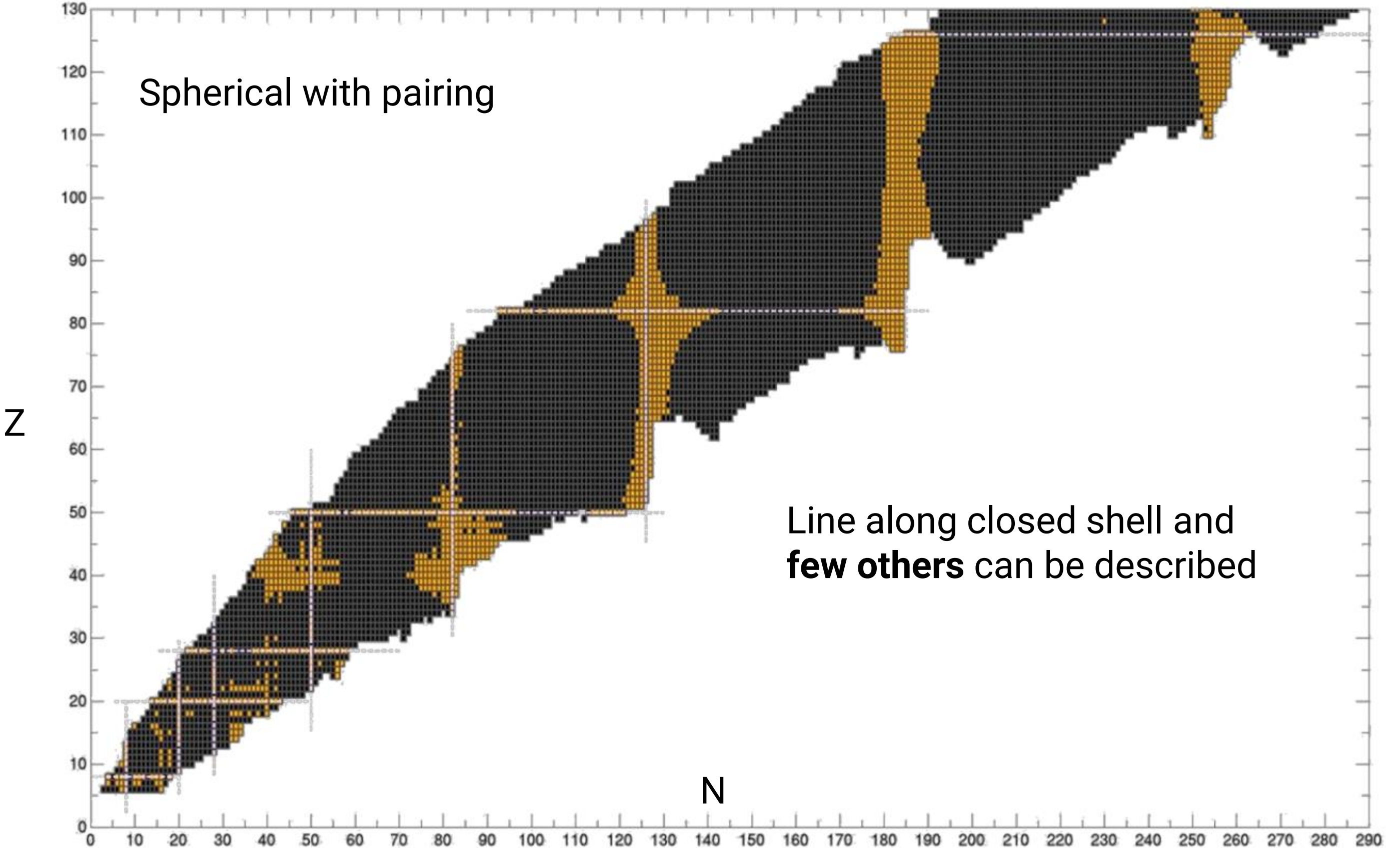
Impact of symmetry breaking : U(1) breaking

What are we missing then ?

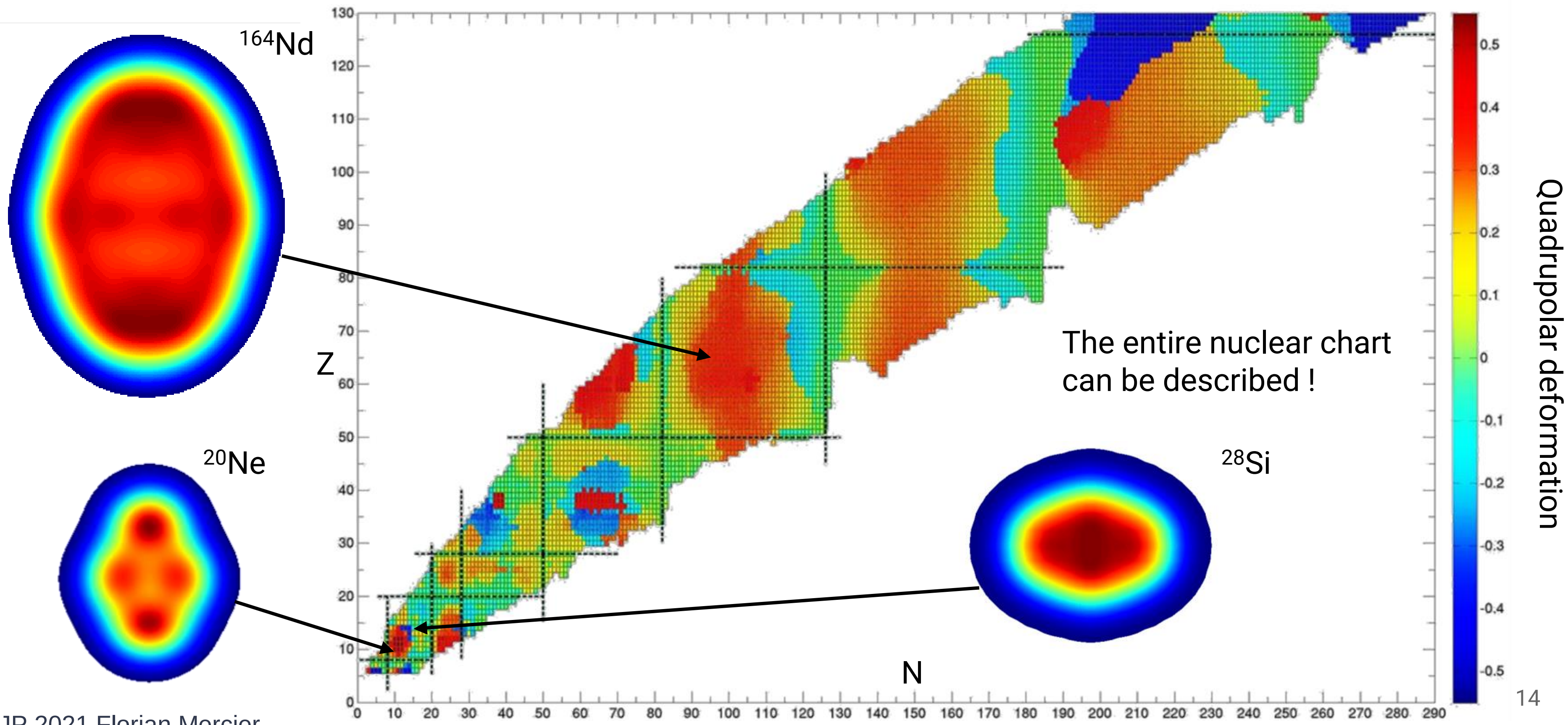
Let us break other symmetries !

$$[H_0 , J] \neq 0$$

Nuclei can now be deformed



Impact of symmetry breaking : U(1) and SO(3)

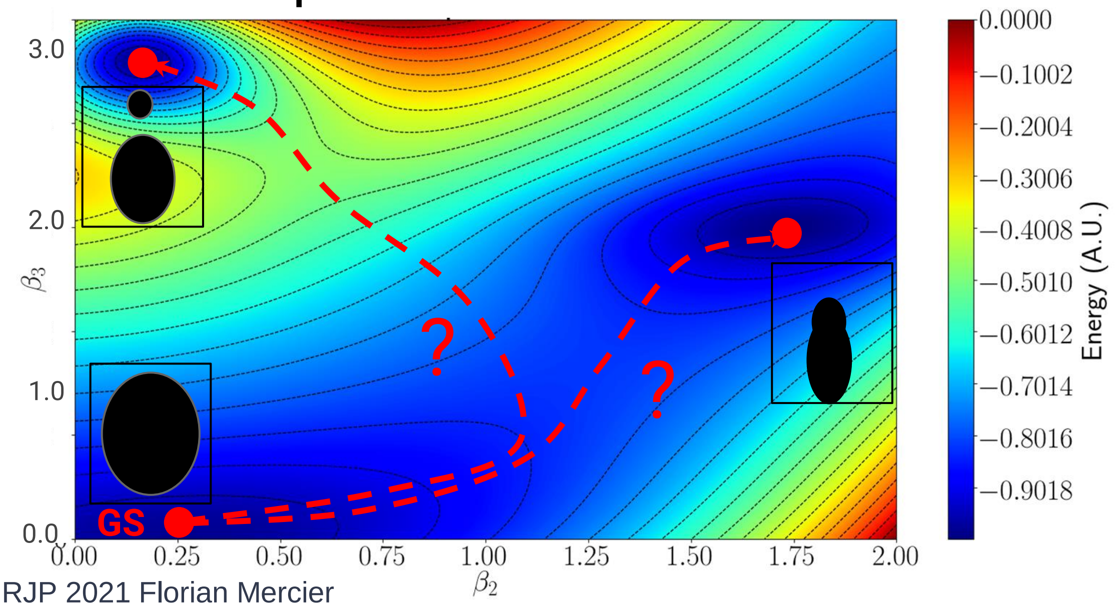


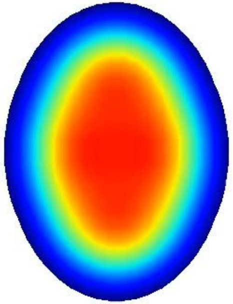
Deformations and Potential Energy Surface

Impose the deformation in quadrupolar/octupolar shapes and compute E

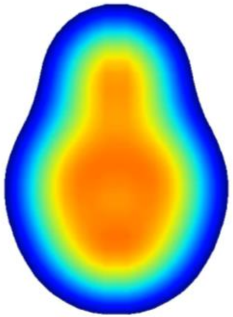
It will give $E(\beta_2, \beta_3) \geq E_{min}$

Example of what could be a PES





Quadrupolar β_2



Octupolar β_3

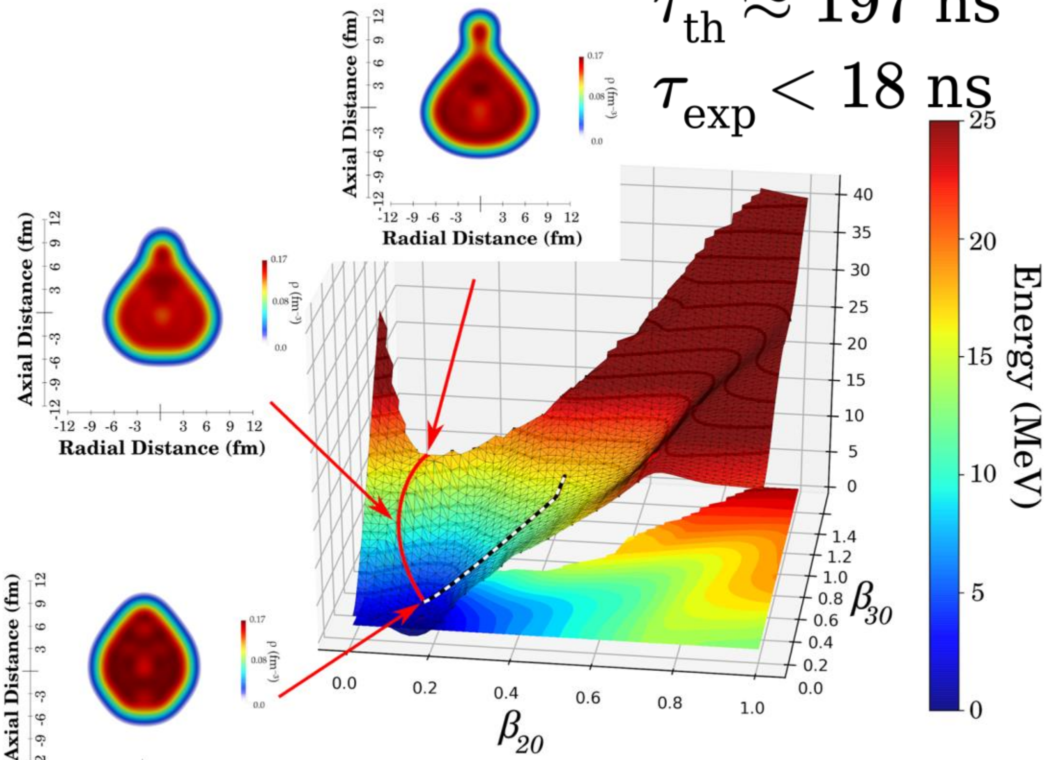
- Can shapes evolve from GS to α emission ?
- Is it possible to compute the associated probability ?

Alpha decay chain $^{108}\text{Xe} \rightarrow {}^{104}\text{Te} \rightarrow {}^{100}\text{Sn}$

F. Mercier and al., Phys. Rev. C 102, 011301(R) (2020)

$\tau_{\text{th}} \approx 197$ ns

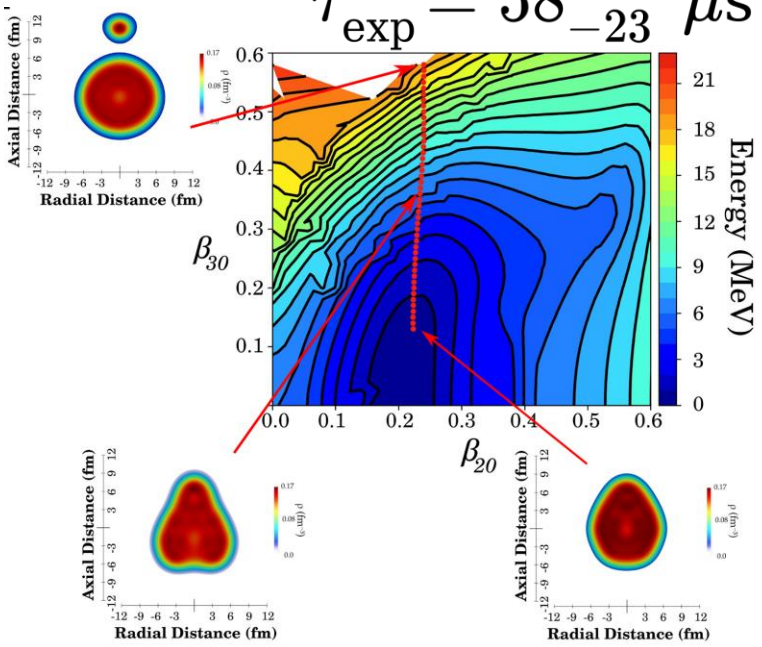
$\tau_{\text{exp}} < 18$ ns



$^{104}\text{Te} \rightarrow \alpha + {}^{100}\text{Sn}$

$\tau_{\text{th}} = 50\mu s$

$\tau_{\text{exp}} = 58^{+106}_{-23}\ \mu s$

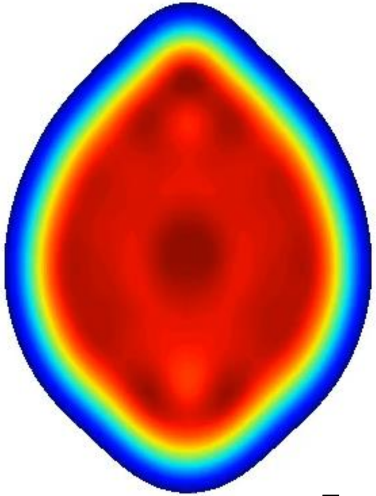


$^{108}\text{Xe} \rightarrow \alpha + {}^{104}\text{Te}$

Other results for heavier nuclei

F. Mercier and al., to be published

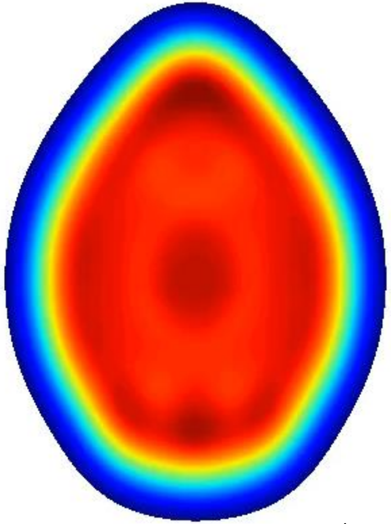
$^{212}Po \rightarrow \ ^{208}Pb + \alpha$



$\tau_{th} \approx 6 \times 10^{-7} s$

$\tau_{exp} \approx 3 \times 10^{-7} s$

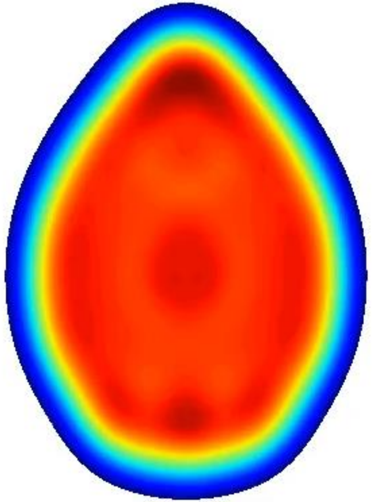
$^{224}Ra \rightarrow \ ^{220}Rn + \alpha$



$\tau_{th} \approx 8 \times 10^{5} s$

$\tau_{exp} \approx 3 \times 10^{5} s$

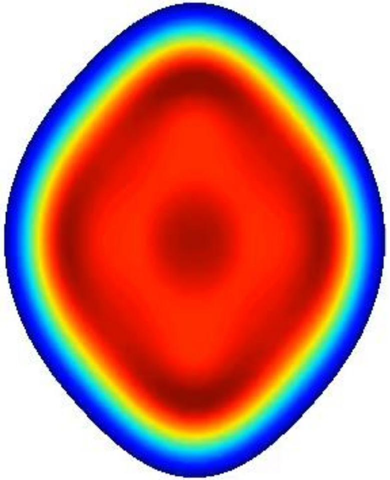
$^{224}Ra \rightarrow \ ^{210}Pb +^{14} C$



$\tau_{th} \approx 3 \times 10^{17} s$

$\tau_{exp} \approx 7 \times 10^{15} s$

$^{224}Ra \rightarrow \ ^{216}Po + 2\alpha$



$\tau_{th} \approx 10^{14} s$

$\tau_{exp} =??$