Theory of nuclear fission: a guided tour through 80 years of research

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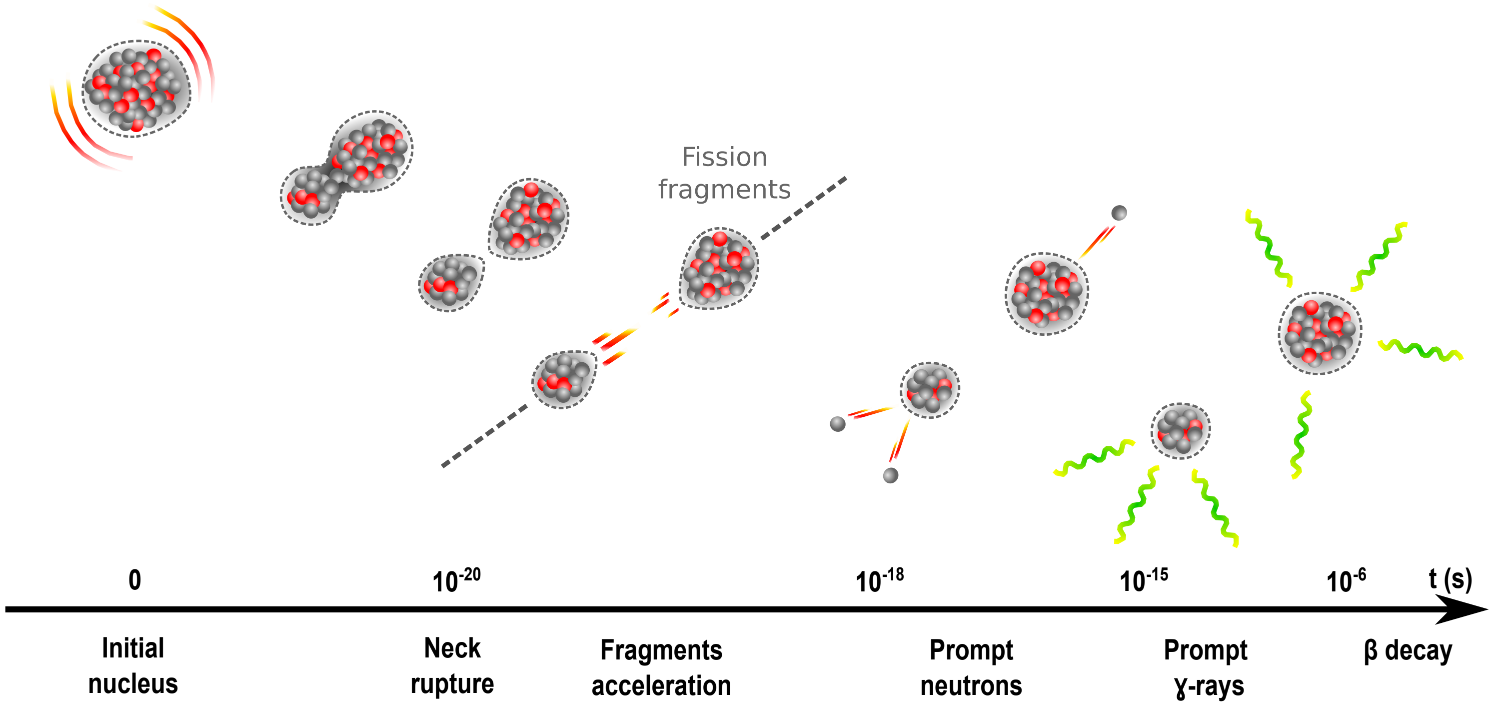
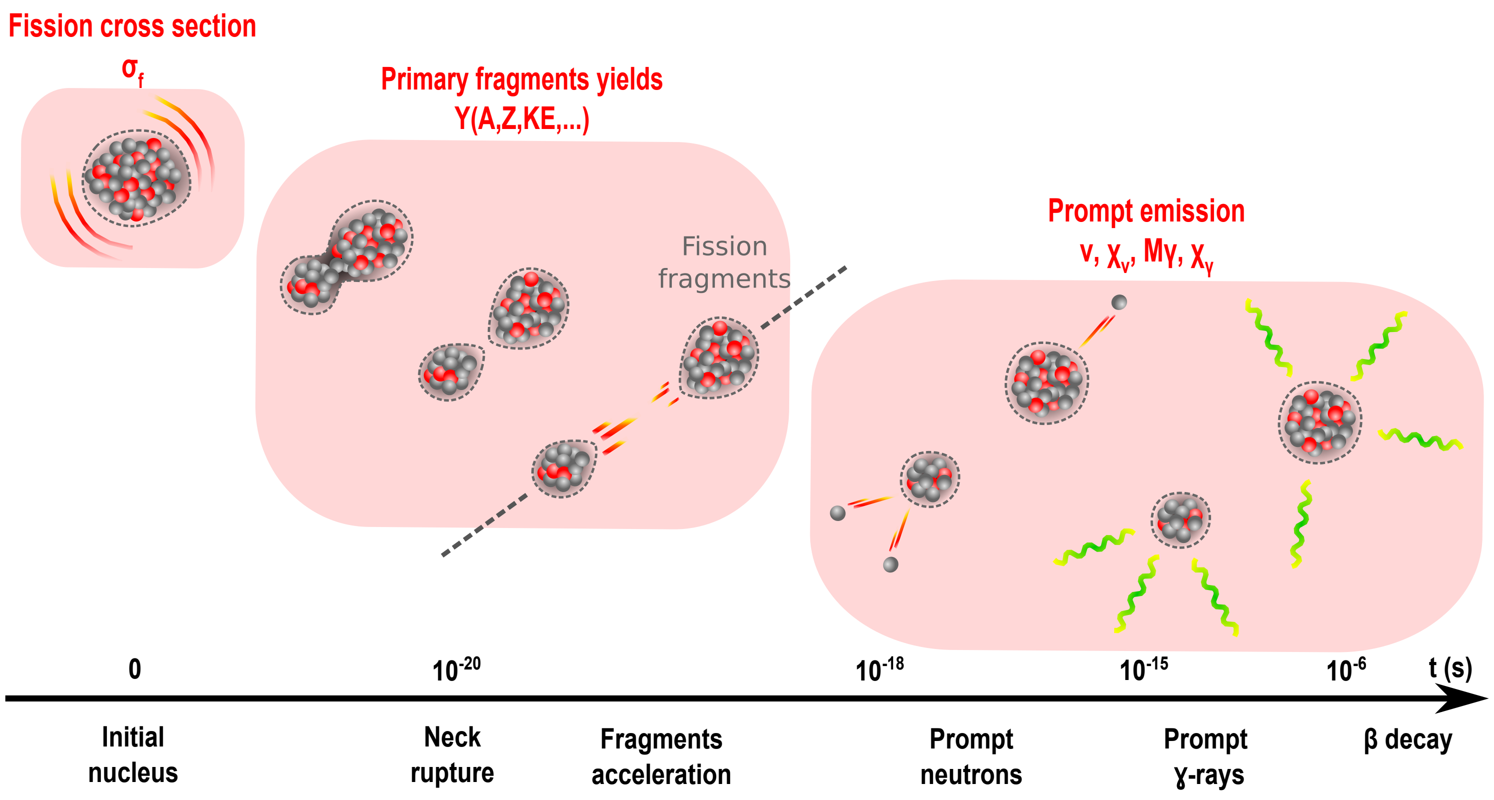
Fission of an atomic nuclei



A theoretical challenge:

- Quantum many-body problem: more than 10^{200} **Bytes** to store the wavefunction
- **Dynamical process** with a large number of possible reaction outcomes

Reducing the theoretical difficulty



- σ_f: 'One channel' reaction theory
- Y(A, Z, KE...): Scission point models, many-body dynamics (this talk)
- $\nu, \chi_\nu, M_\gamma, \chi_\nu$: Statistical deexcitation models V. Piau (talk)

Different theoretical approaches for different needs

Fission cross section
σ_f

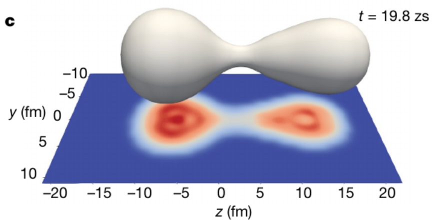
~1%
U, Pu

— Precision required

Primary fragments yields
Y(A,Z,KE,...)

~1% on Y(A,Z)
U, Pu

Actinides
Super-heavy
exotic nuclei

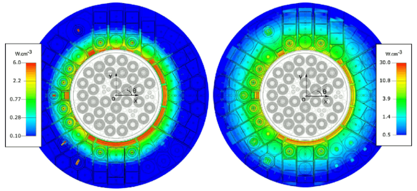


Hundreds of
heavy neutron-rich
nuclei

Prompt emission
ν, χ_ν, $M\gamma$, χ_γ

0.1% on ν
U, Pu

~7% on E_γ
U, Pu



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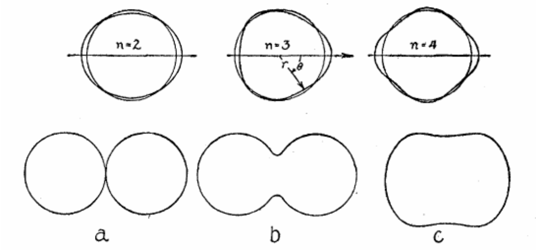
Theoretical predictions of the fragments properties

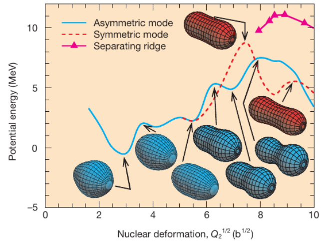
Formation of Primary Fission Fragments

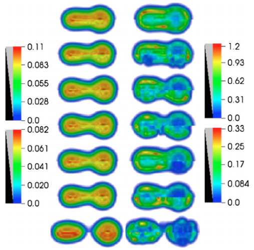
1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010 | 2020

- Liquid drop picture
- Explanation of asymmetric Y(A) from shell effects
- Y(A) from scission point model
- Axially- and reflection-symmetric TDHF dynamics
- Y(A) from 2D Langevin dynamics
- Y(Z) from 5D Brownian motion
- Y(A) from TDGCM
- Symmetry-unrestricted TDHF, TDBCS, TDHFB dynamics

N. Schunck *et al.* Prog. Part. Nucl. Phys. **125** (2022)

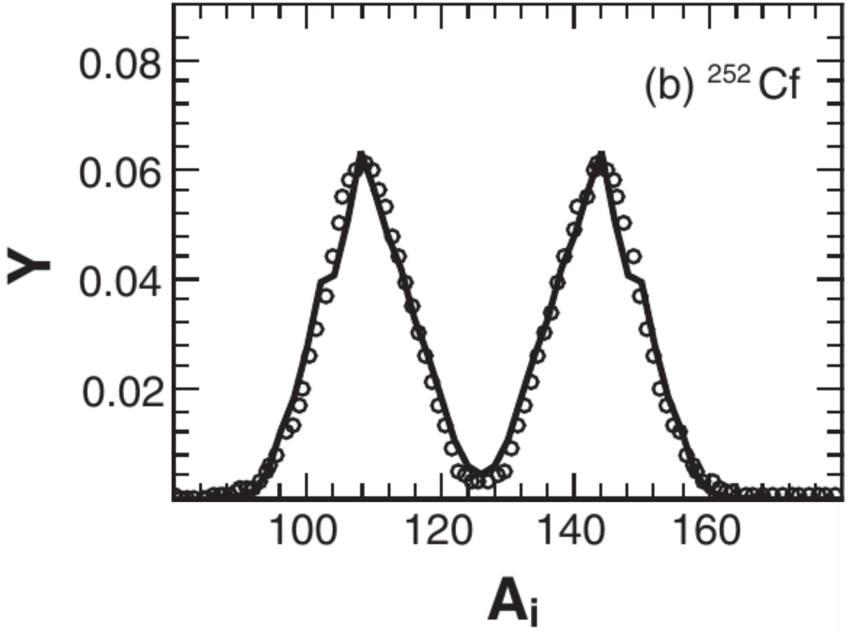




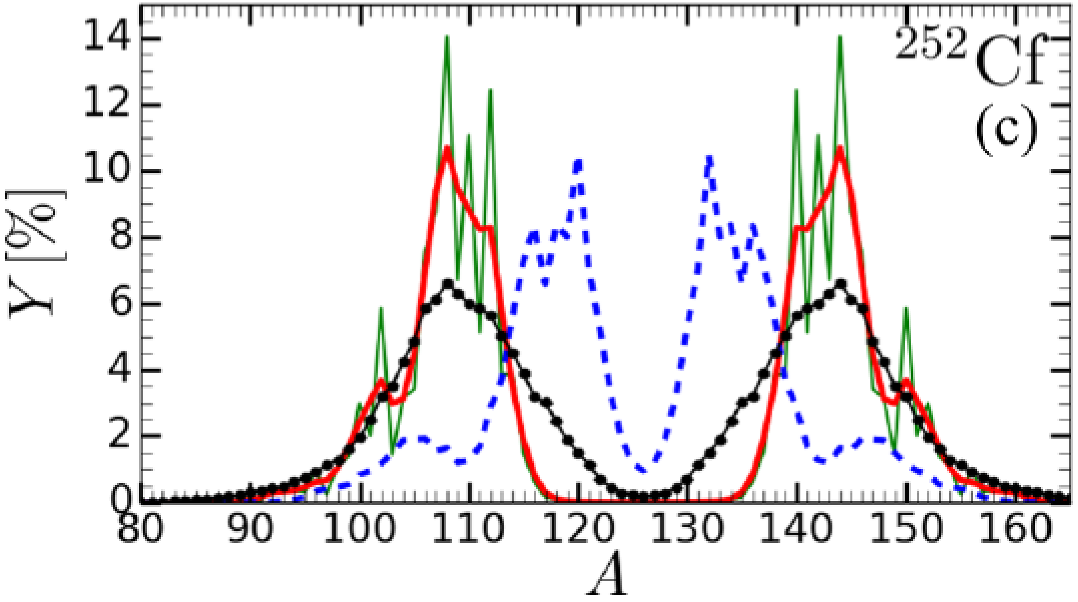


Scission point models

- **Statistical** distribution of states close to scission



H. Pasca *et al.* PRC **99** (2019)



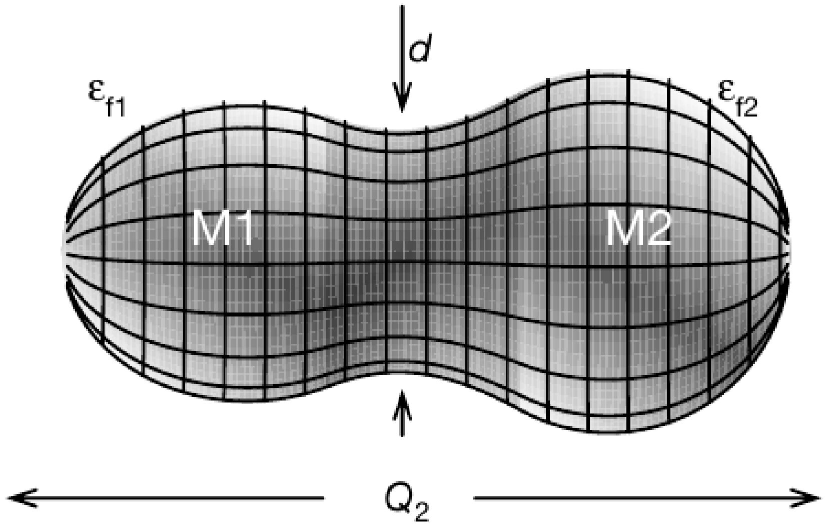
J.-F. Lemaitre *et al.* PRC **99** (2019)

✅ Fast calculations
❌ High dependency to the phase-space considered

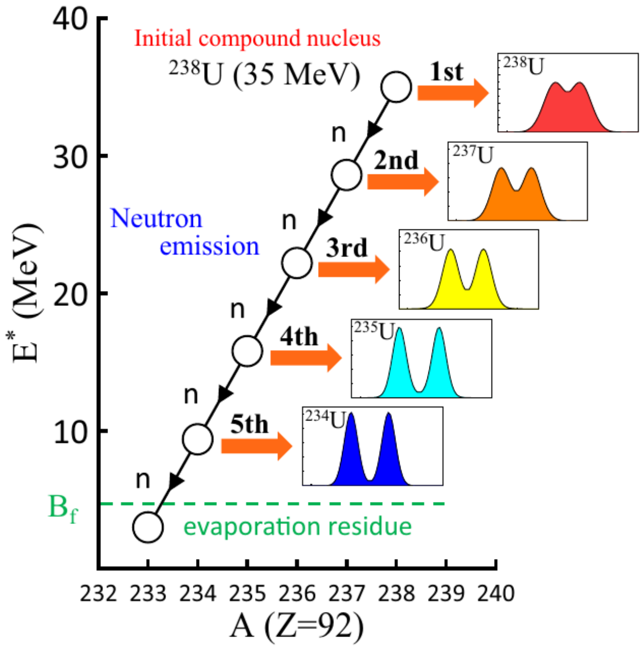
Langevin dynamics

- **Classical statistical** approach
- Shape degrees of freedom coupled to a thermal bath

$$P(r_1, p_1, \cdots, r_N, p_N, t) \simeq P(\text{shape}, t) \times P_{\text{Boltzmann}}(\text{internal})$$



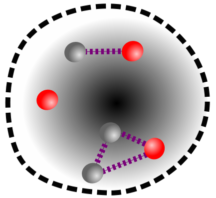
P. Möller et al., Nature **409** (2001)



S. Tanaka *et al.* PRC **100** (2021)

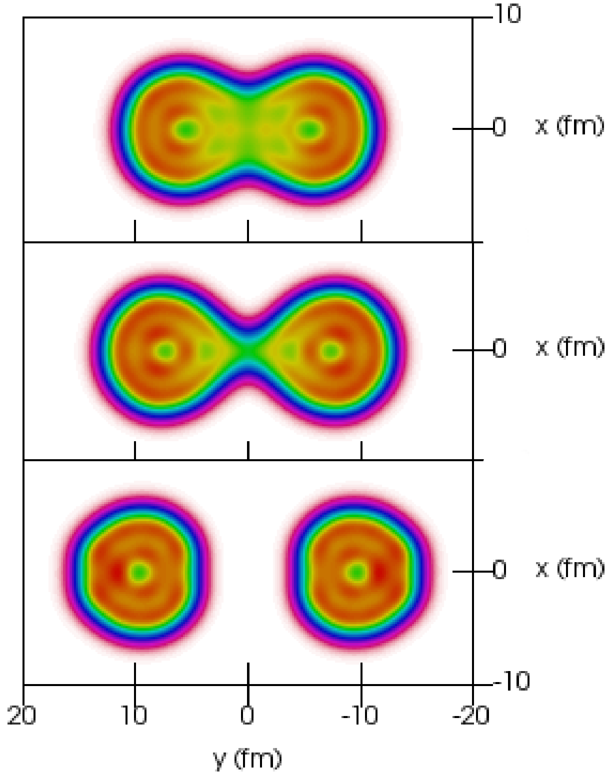
✅ Particle evaporation (neutron, gamma rays)
❌ No information on internal fragments characteristics (e.g. spins)

Time dependent mean-field approaches



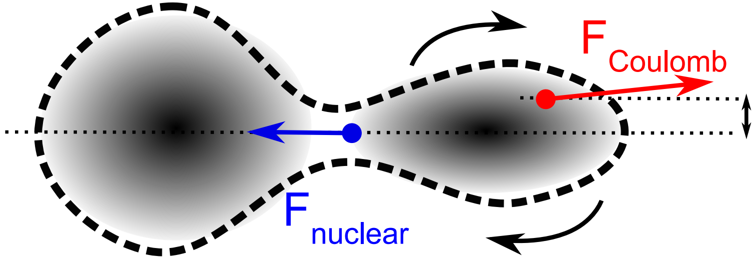
$|\psi(t)\rangle = |\ (t)\rangle$

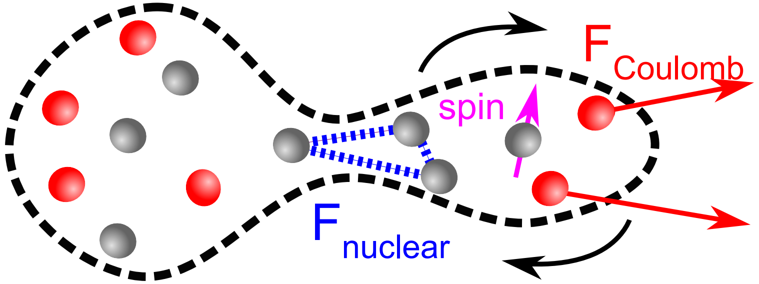
2014: Fission of ^{258}Fm, ^{264}Fm (no pairing)
C. Simenel *et al.*, PRC **89** (2014)
2015: ^{258}Fm with pairing (TDBCS)
G. Scamps *et al.*, PRC **92** (2015)
2016: ^{240}Pu with pairing (full TDHFB)
A. Bulgac *et al.*, PRL **11** (2016)
2021-2022: Fragments spins
A. Bulgac *et al.*, PRL **126** (2021)
A. Bulgac *et al.*, PRL **128** (2022)



✅ Dynamics through scission, good prediction of the **energy balance**
❌ No fragments mass yields (lack one-body fluctuations)

Fragments spin





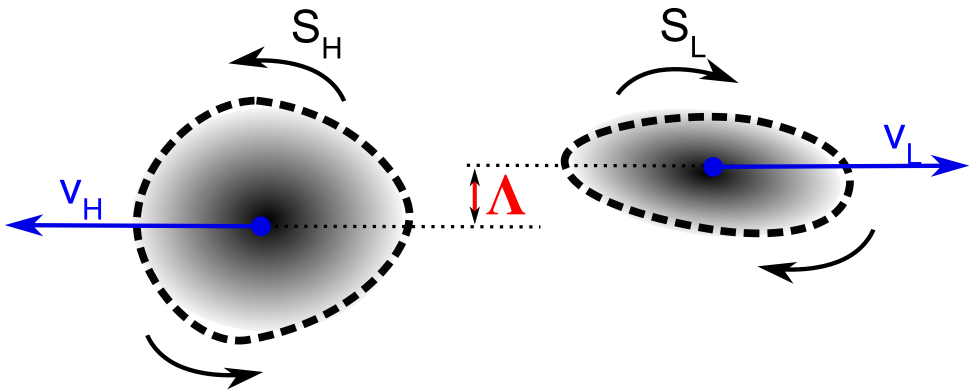
- What is the **distribution of primary fragments spins** ?
- How does it vary with the mass/charge of the fragments ?
- What mechanisms produce these spins ?

➡️ Crucial input for the **prompt gamma emission** (cf. V. Piau (talk))

Two recent experimental inputs

- J. N. Wilson *et al.* Nature **590** (2021)
- M. Travar *et al.* Phys. Let. B **817** (2021)

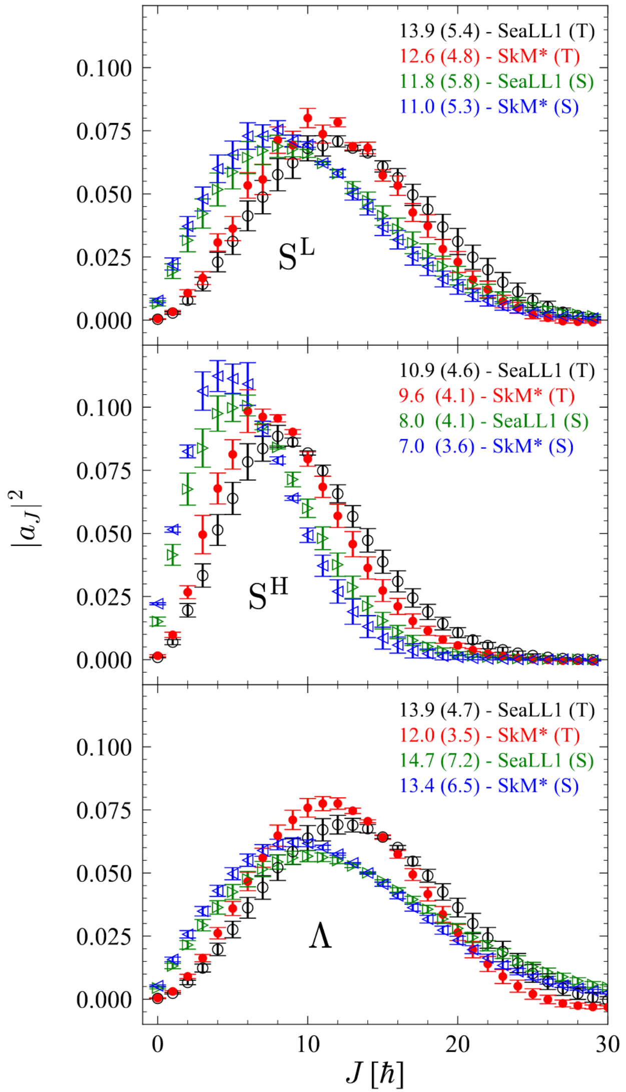
Insight from time dependent mean-field



$$\vec{S}_L + \vec{S}_R + \vec{\Lambda} = 0$$

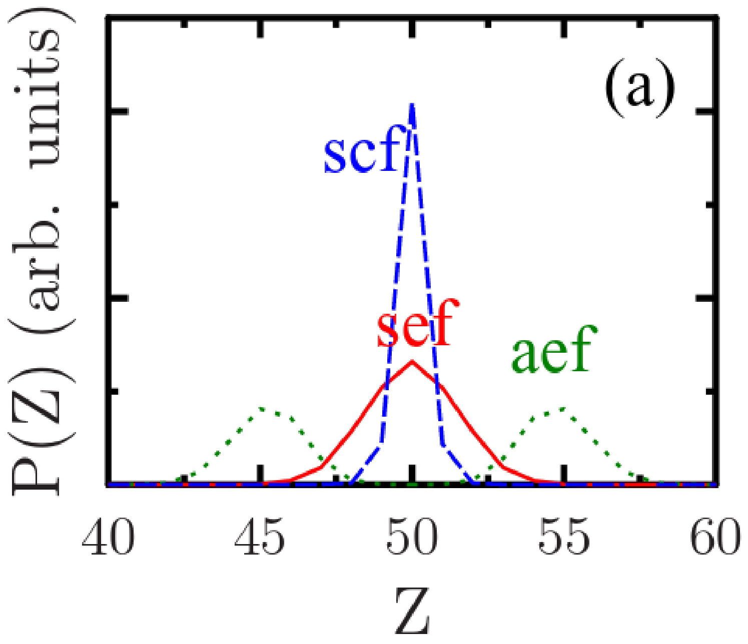
A. Bulgac *et al.*, PRL **128** (2022)

- $S_L \simeq 11\hbar > S_H \simeq 7\hbar$
- Λ **is large** ($\simeq 11\hbar$)



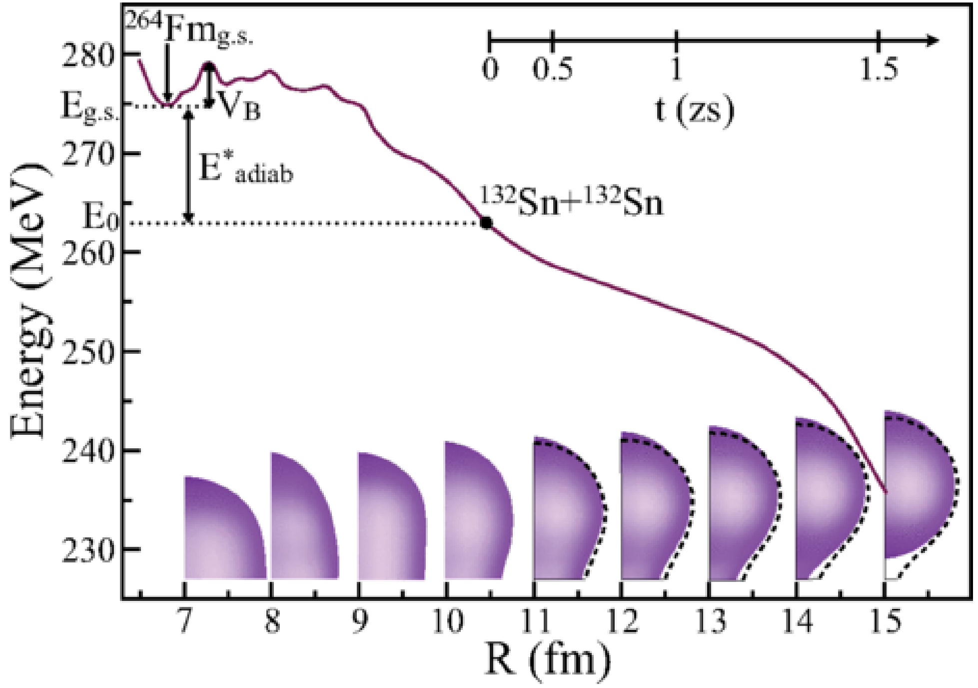
Limitations of the time dependent mean-field picture

Too sharp charge yields



Charge distribution in one fragment.
Three TDBCS simulations of ^{258}Fm fission
G. Scamps *et al.*, PRC **92** (2015)

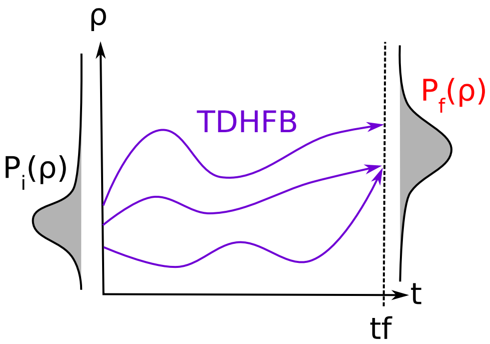
No collective tunneling



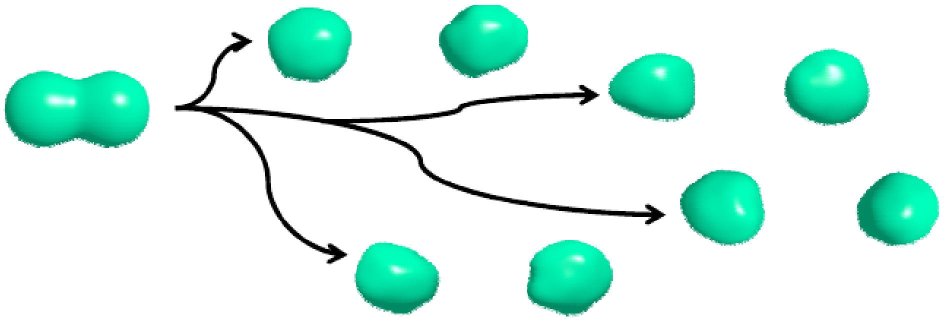
C. Simenel *et al.*, PRC **89** (2014)

Statistical ensemble of mean-field like trajectories

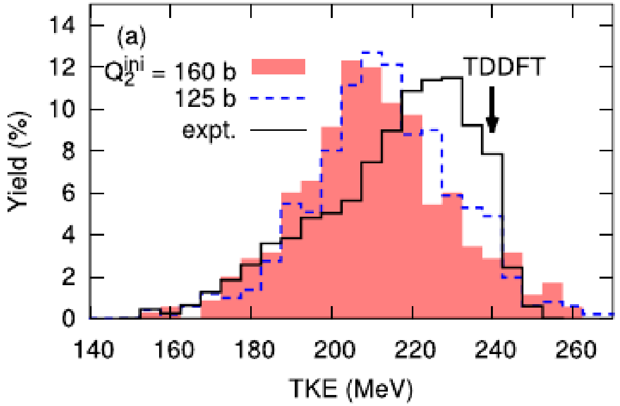
- **Statistical** distribution of initial **quantum** states
- Average to predict observables



Example: Stochastic Mean Field



D. Lacroix *et al.* EPJA **50** (2014)



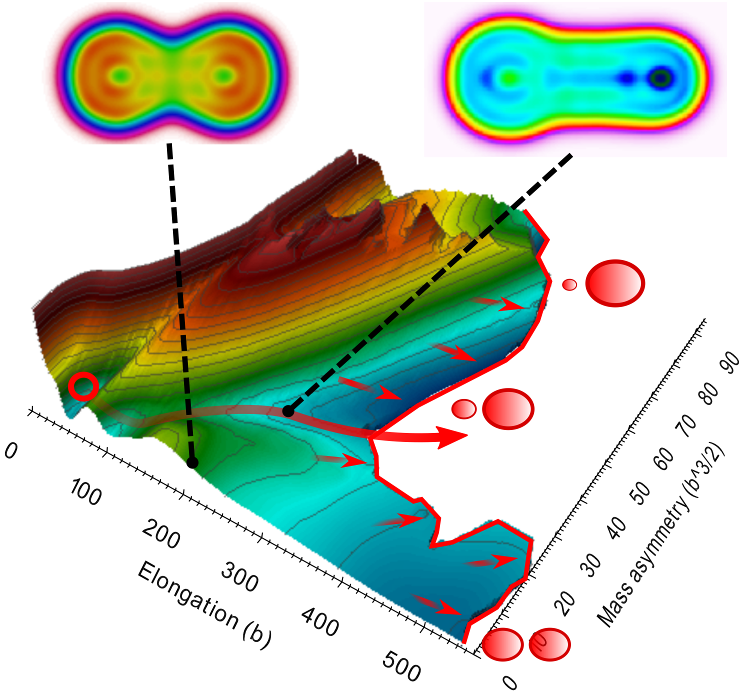
Y. Tanimura *et al.* PRL **118** (2017)

✅ Fragment kinetic energy distribution (fluctuations + energetic)
❌ No tunnelling through fission barrier (no quantum interferences)

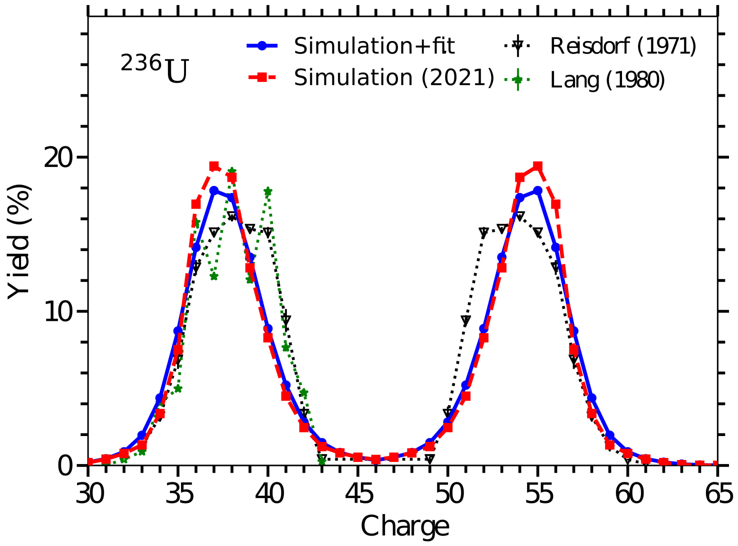
Quantum mixing of mean-field states

$$|\psi(t)\rangle = f_1(t)|\ \rangle + f_2(t)|\ \rangle + \cdots$$

Constrained HFB states with ≠ shapes



- Set of parameterized states
- Dynamics in a **collective coordinates** space

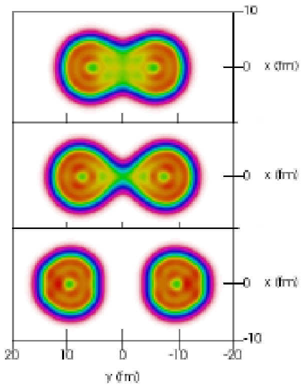


M. Verriere *et al.* PRC **103** (2021)

✅ Quantum tunnelling through fission barrier
❌ Dynamics through scission (diabatic aspect)

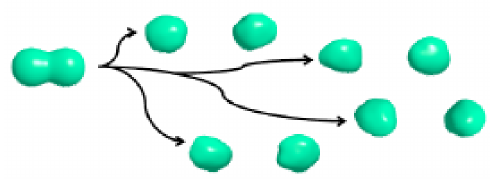
Overview

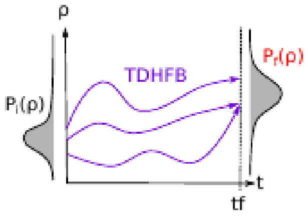
Single reference



- Diabatic dynamics
- Misses collective fluctuations
- Breaks symmetries
- No collective tunnelling

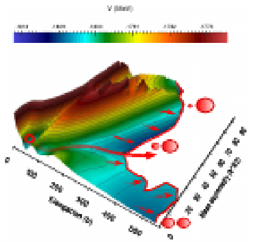
Semi-classical ensemble

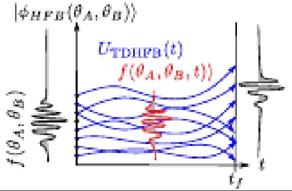




- More collective fluctuations (standard deviation of 1-body observables)
- Low cost, parallel algorithms
- Misses quantum interferences

Multi-configuration





- Quantum fluctuations, probability distribution
- Difficulty to get both fluctuations and diabatic motion
- High cost, parallel algorithms in some cases
- Issue with EDF kernels

One method $\simeq$ one type of observables

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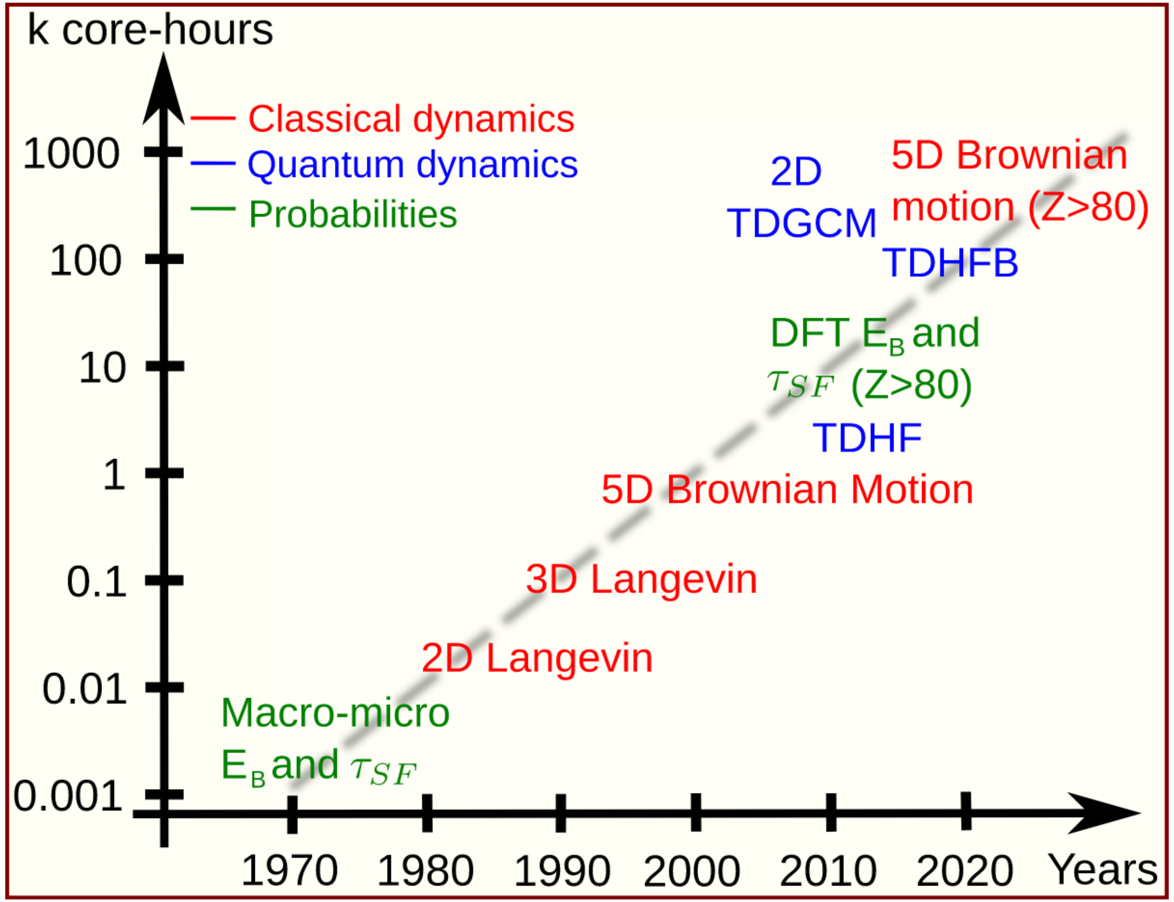
Moore's law in nuclear theory

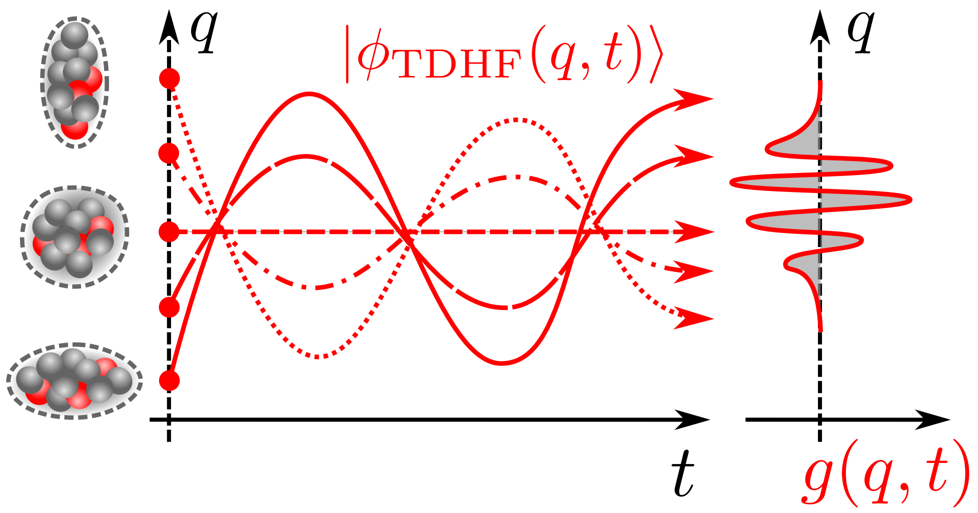


N. Schunck *et al.* Prog. Part. Nucl. Phys. **125** (2022)

Toward richer trial wavefunctions

Quantum mixing TD mean field states

$$|\psi(t)\rangle = \int_q f(q,t)|\phi(q,t)\rangle$$

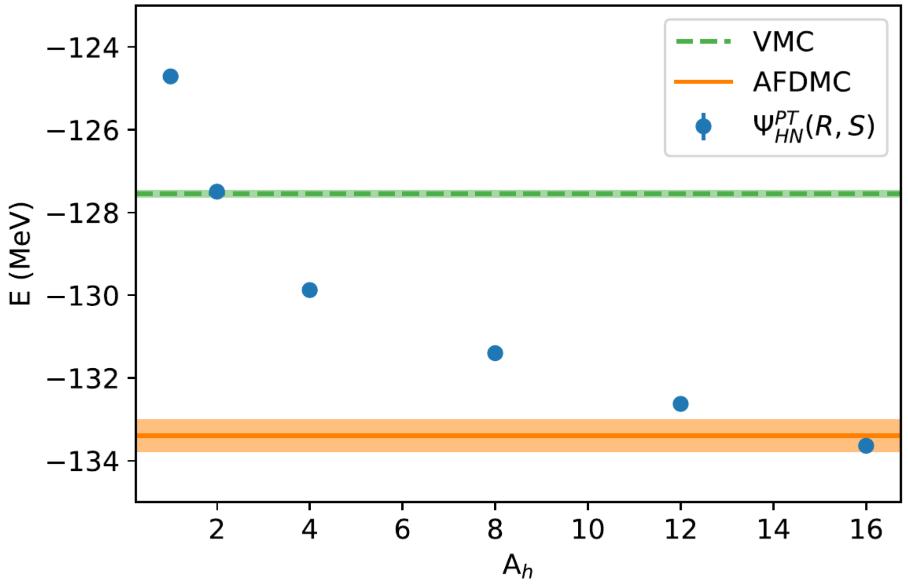


Multi-phonons in 40Ca

P. Marevic *et al.* arXiv:2304.07380 (2023)

Neural network wave functions

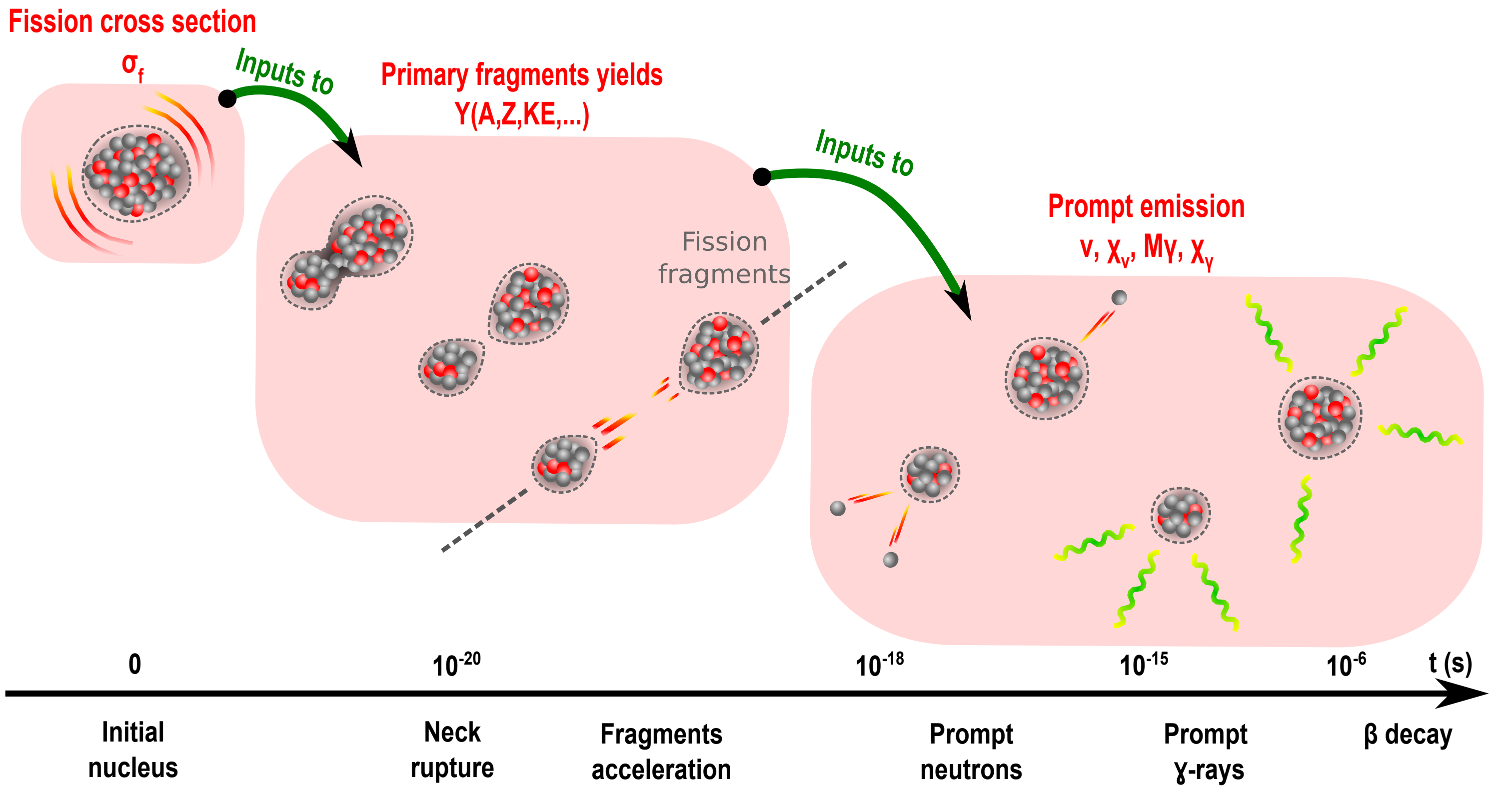
$$\psi(r_1\sigma_1,\cdots r_N\sigma_N) = \mathrm{NN}(r_1\sigma_1,\cdots r_N\sigma_N)$$



Ab-initio ground state energy of ^{16}O

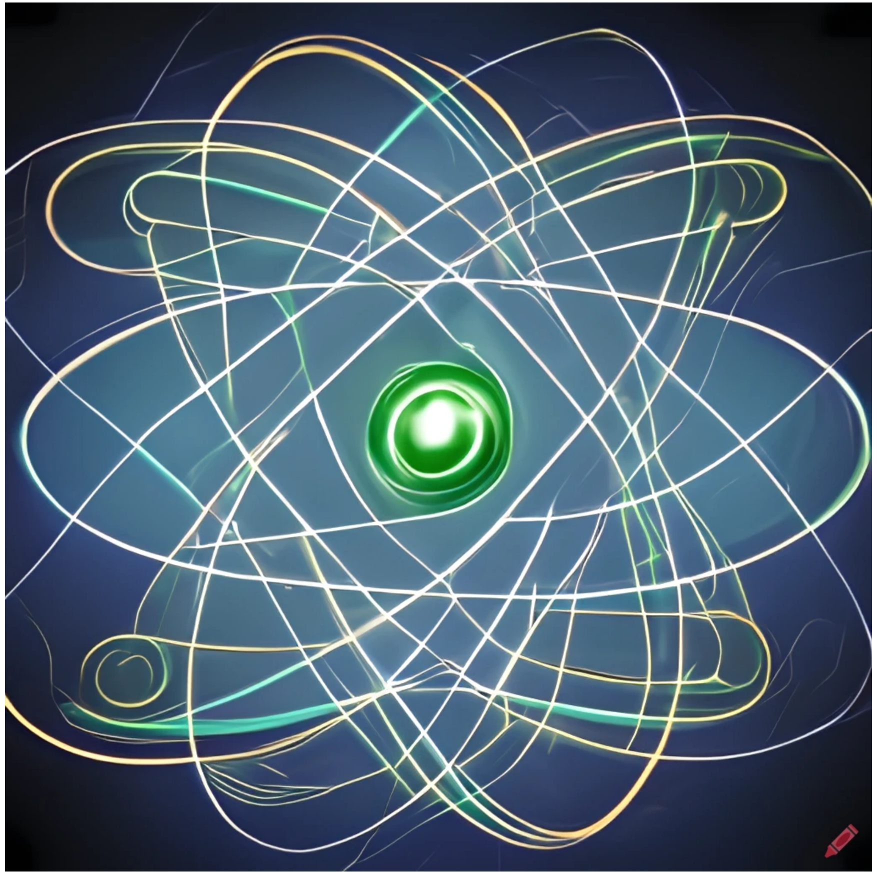
A. Lovato *et al.* PRR **4** (2022)

Ultimate goal: bridging the steps of the fission process



Observables of interest

- Prompt emission of exotic fissioning systems
- Impact of the input channel on fission yields



CRAIYON: 'Atomic nucleus in the quantum realm'

Thank you for your attention !