Impact of pairing correlations on binding energies and other observables

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Superfluidity in nuclear matter, finite nuclei and ultra-cold fermion gases

Outline

- PNP correlation energies with Gogny D1M and binding energies
- Coulomb antipairing in fission
- Fission barriers and collective inertias with PNP
- Pairing strength and fission lifetimes

PNP correlation energies

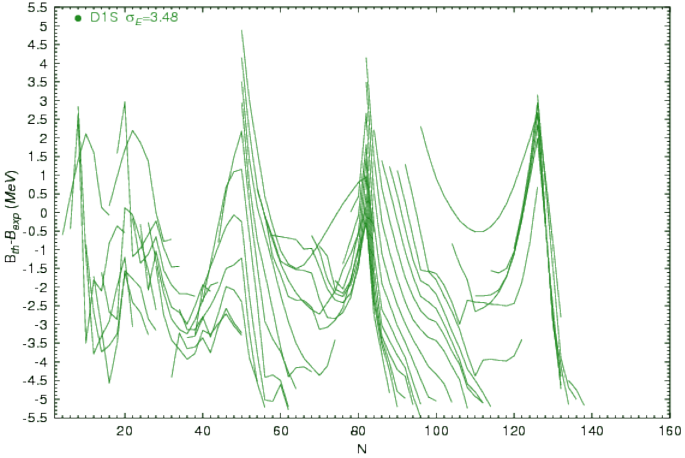
Mass table binding energy evaluation is important in many applications like the understanding of nuclear reactions in stellar processes.

As many nuclei are not experimentally accesible, theoretical predictions are important, specially near neutron drip line.

Theorerical predictions

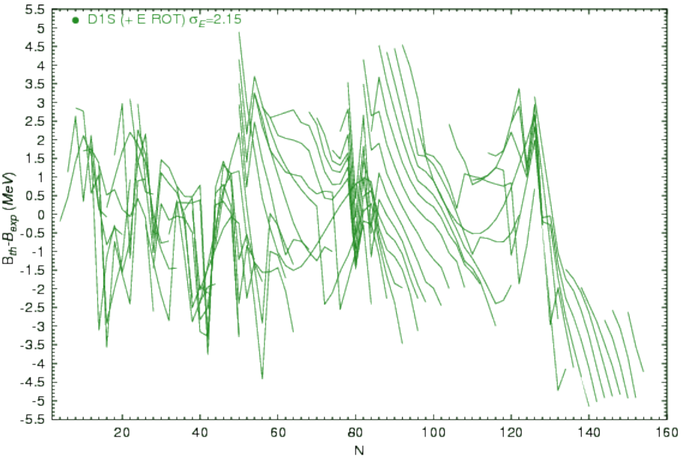
- Based on mean field theories
- Phenomelogical global interactions (Gogny, Skyrme, Relativistic)

Gogny D1S binding in e-e nuclei



HFB energies ; $\sigma_E^2 = \sum_{i=1}^{579}(E_{Exp}(i) - E_{th}(i))^2$

Gogny D1S+E_{ROT}



Gogny D1M

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First Gogny-Hartree-Fock-Bogoliubov Nuclear Mass Model

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We present the first Gogny-Hartree-Fock-Bogoliubov (HFB) model which reproduces nuclear masses with an accuracy comparable with the best mass formulas. In contrast with the Skyrme-HFB nuclear-mass models, an explicit and self-consistent account of all the quadrupole correlation energies are included within the 5D collective Hamiltonian approach. The final rms deviation with respect to the 2149 measured masses is 798 keV. In addition, the new Gogny force is shown to predict nuclear and neutron matter properties in agreement with microscopic calculations based on realistic two- and three-body forces.

DOI: 10.1103/PhysRevLett.102.242501 PACS numbers: 21.10.Dr, 21.30.−x, 21.60.Ev, 21.60.Jz

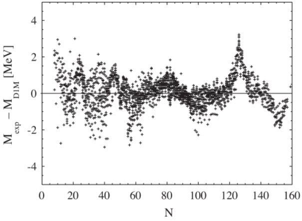
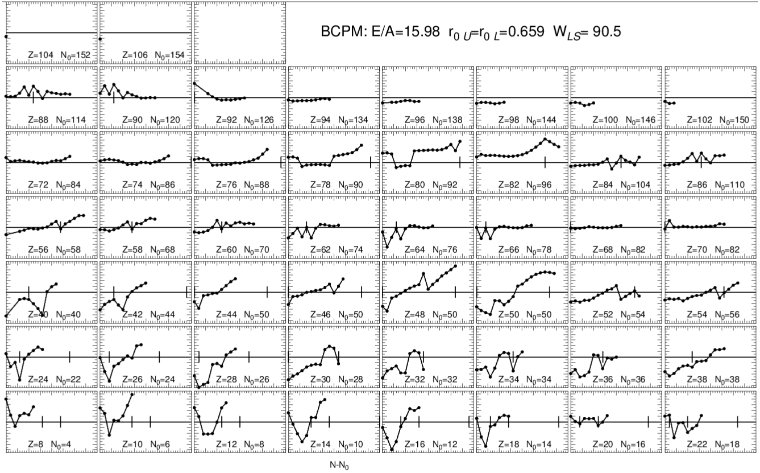


FIG. 1. Differences between measured [4] and D1M masses, as a function of the neutron number N.

Beyond mean field correlation energies included in the fit

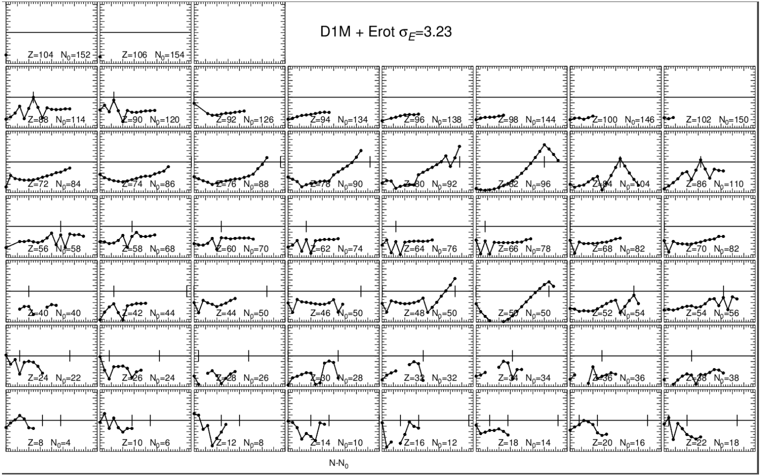
Rot + quadrupole fluctuation

BCPM



Most of the discrepancies associated to magic numbers
Missing ingredient: functional or correlations ?

Results: D1M + E_{Rot}



Shift because no $\epsilon_0(\beta, \gamma)$ is considered

Similar behavior to BCPM, we conclude correlations are missing

Beyond mean field correlation energies

Symmetry restoration $\epsilon_{CORR} = \langle H \rangle - \langle H P^J \rangle$
often computed in the *large deformation limit*

- Rotations (large def, $\epsilon_{CORR} = \langle \Delta \vec{J}^2 \rangle / (2\mathcal{J})$)
- Particle number $\epsilon_{CORR} = \lambda_2 \langle \Delta N^2 \rangle$
- Parity breaking

Fluctuations $|\Psi\rangle = \int dQ\, f(Q) |\varphi(Q)\rangle$

- β and γ (Bohr Hamiltonian)
- $\langle \Delta N^2 \rangle$
- β_3 (Octupole)

Particle number restoration

- $E^N = \langle\phi|HP^N|\phi\rangle/\langle\phi|P^N|\phi\rangle$
- $P^N = \frac{1}{2\pi}\int d\varphi e^{i\varphi(\hat{N}-N)}$

- $\epsilon_{CORR} = \langle H\rangle - E^N$
- (large pairing corr, $\epsilon_{CORR} = \lambda_2\langle\Delta N^2\rangle$)

Intrinsic wave function $|\phi\rangle$ can be determined

- Minimizing $\langle H\rangle$ (E^N computed afterwards) (PAV) . Misses correlations when the intrinsic state is not deformed.
- Minimizing E^N (VAP). Intrinsic states usually differ from the HFB ones, and are deformed.

Problems specific to PNP

- Weak pairing regime in atomic nuclei implies $\epsilon_{CORR} = \lambda_2 \langle \Delta N^2 \rangle$ is not a good approximation.

Exact projection is also plagued with inconsistencies

- Divergences (when some of direct, exchange or pairing contribs are neglected, as in Coulomb)
- Self-energies and self-pairing of EDF
- Prescription for "density dependences" of the interaction
- Complex "density dependent" terms

Our approach

- Particle number Projected energy computed exactly
- Gogny force with all terms included (D1S)
- *Projected density* prescription

$$H[\rho] = H[\rho_N] = t_3 \delta(\vec{r}_1 - \vec{r}_2)\rho_N^{\alpha}$$

with ρ_N the projected density (real). (to be tested !)

RVAP

Instead of full variation after projection (VAP) we determine $|\phi\rangle$ by minimizing the projected energy with respect to the relevant degrees of freedom, namely $\langle \Delta N^2 \rangle$ for protons and neutrons. Lipkin-Nogami is RVAP with $\langle \Delta N^2 \rangle$ but the projected energy is

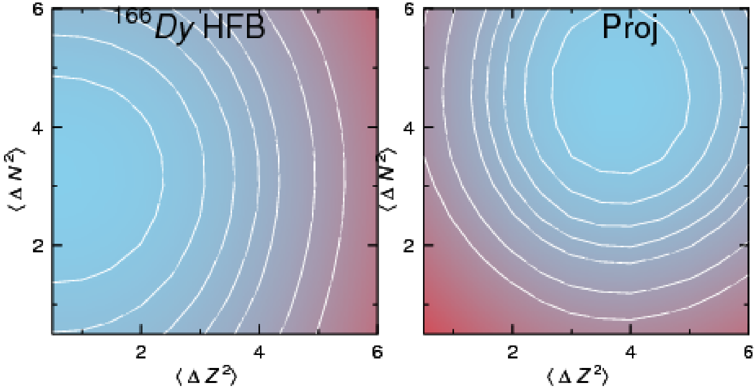
computed approximately $\epsilon_{CORR} = \lambda_2 \langle \Delta N^2 \rangle$

Advantages of RVAP

- Computational cost substantially reduced
  Mass table runs on a personal computer
- Prevents spuriosities to spoil the calculations
  Robust, as required for large scale calculations
- Compares well with full VAP (model and realistic hamiltonians*)
- Starting point for GCM
  The intrinsic wave functions can be used as generating wf

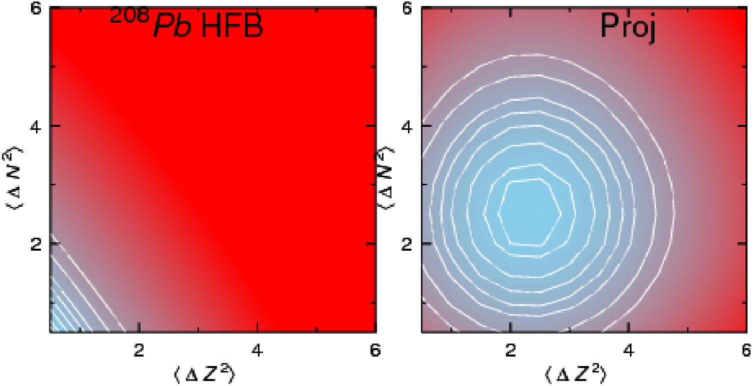
* *PRC 72, 064303; PL B545, 62*

Example



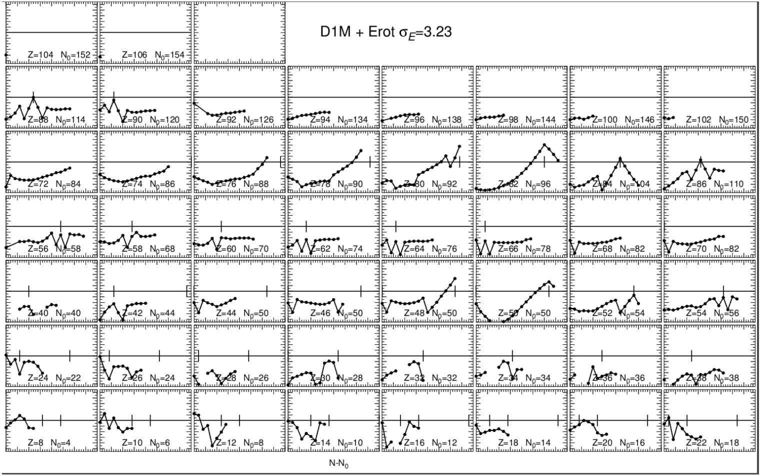
$|\phi(\Delta Z^2, \Delta N^2)\rangle$

Magic numbers



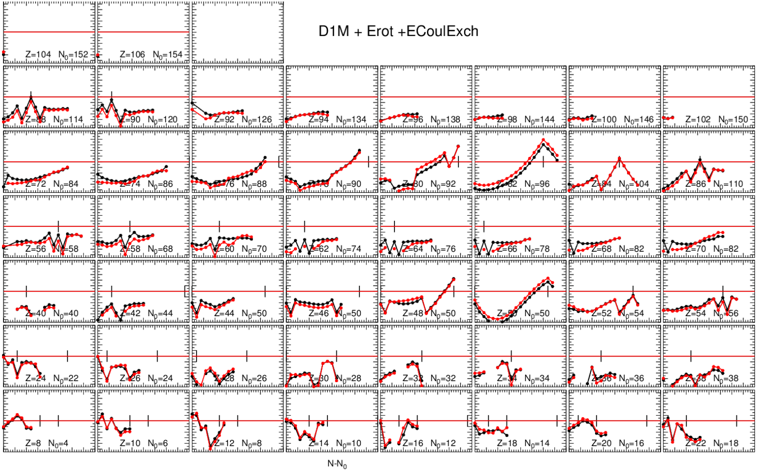
$|\phi(\Delta Z^2, \Delta N^2)\rangle$

Results: D1M + E_{Rot}

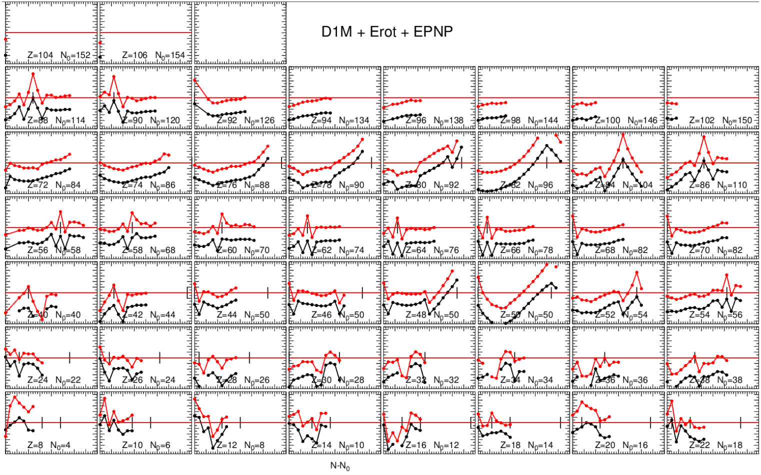


Shift because no $\epsilon_0(\beta,\gamma)$ is considered

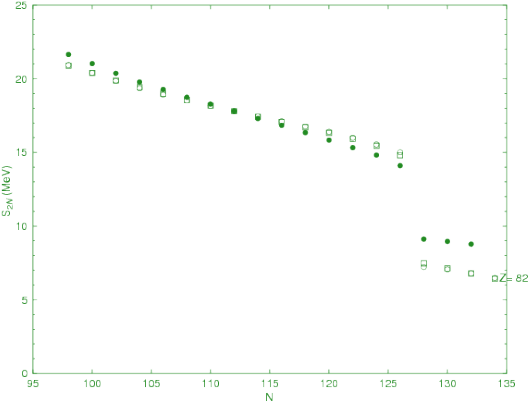
Results: D1M + E_{Rot} + Coul Exch



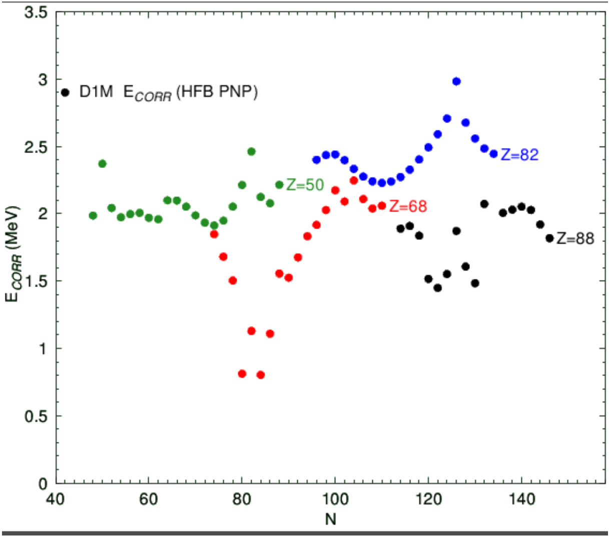
Results: D1M + E_{Rot} + E_{PNP} (RVAP)



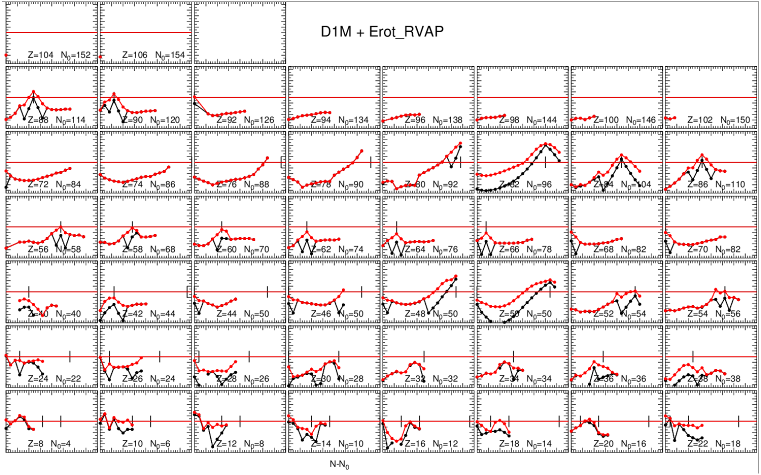
Results: S_{2N} Z=82



Results: PNP Corr E: Even-even nuclei

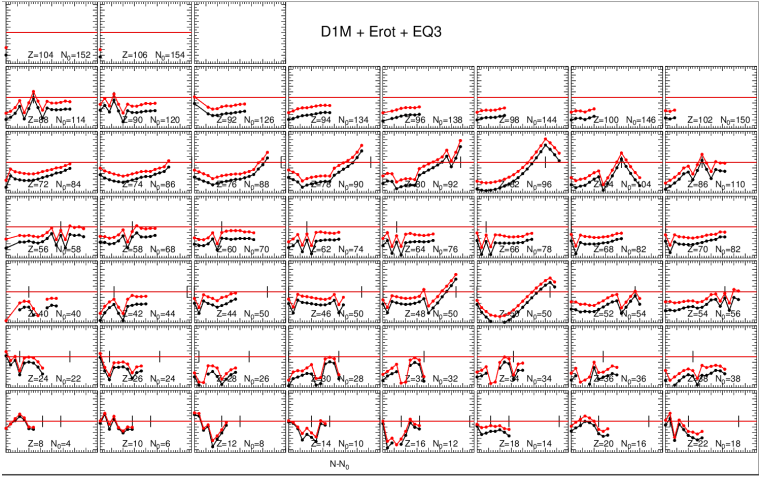


D1M + E_{Rot} (RVAP)



Compute approximate projected energy $E^{J=0}(Q_{20})$ and look for the minimum

D1M + E_{Rot} + $\epsilon_0(Q_{30})$



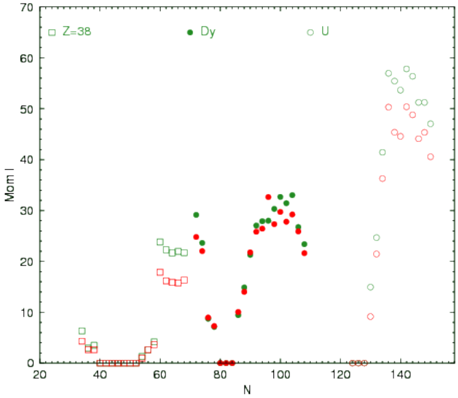
Work to include $\epsilon_0(Q_{20})$ is in progress.

Conclusions

- Reasonable alternative to Lipkin-Nogami
- Valid near or at semimagic Z and N
- Reasonable computational resources required (include in fit ?)
- Correlation energies are almost "structureless"
- Not a strong impact in σ_E, S_{2N}, etc
- Posible to consider together with other correlation energies like E_{ROT} (VAP) ?

What about other observables ?

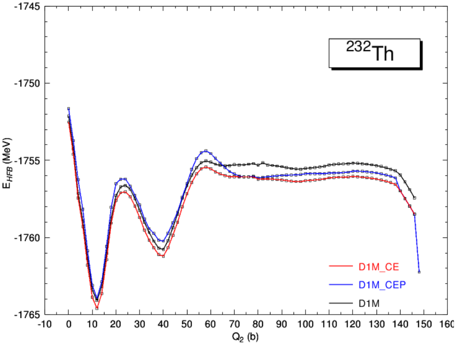
Thouless-Valatin moment of inertia

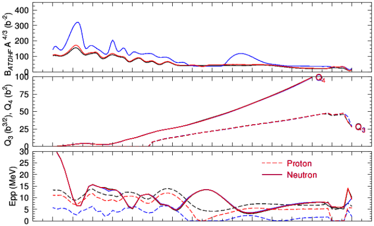


Computed in the cranking approximation from the intrinsic wf minimizing E_{PNP}

Up to a 20 % impact on rotational 2^+ energies

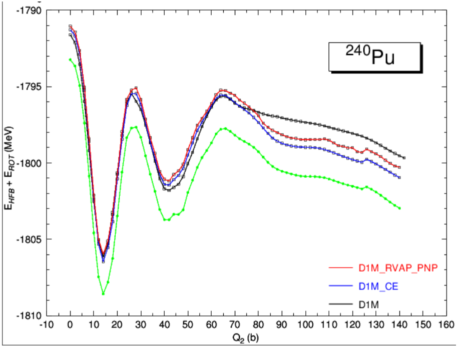
Coulomb antipairing in fission

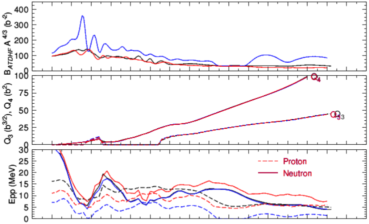




- Third fission barrier linked to Coulomb antipairing ?
- Large impact on collective inertias
- Is the experimental procedure to extract fission barrier heights correct ?

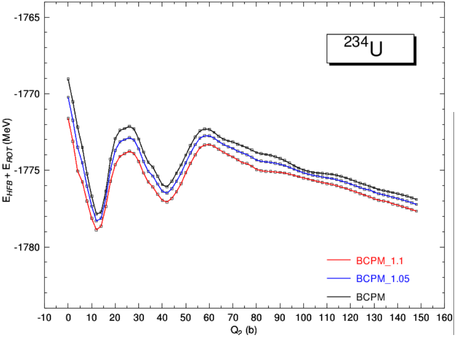
PNP correlations in fission

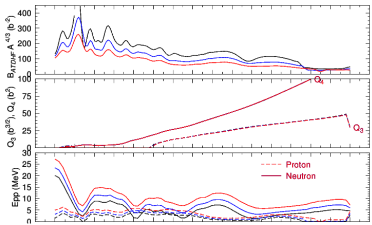




- Just a parallel shift in energies (Green E_{PNP} (RVAP)
- Large impact on collective inertias
- Large correlation energy gain (around 2 MeV)

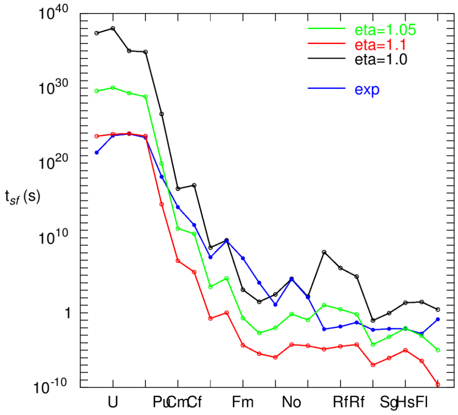
Pairing strengths





- Δ multiplied by $\eta = 1.05$ and 1.10
- Large impact in collective inertias
- Correlation energy gain in between 1-2 MeV (Reduction of barrier height)

Pairing strengths and fission lifetimes



- Large variability in t_{sf} predictions depending on pairing strengths
- Use fission data to constrain pairing ?

Thanks to ...

- G.F. Bertsch
- S.A. Giuliani
- and the BCPM team (M. Baldo, P. Schuck, and X. Viñas)