# Self-consistent single-particle approximation to nuclear state densities at high excitation energy

**Paolo Finelli**

**University of Bologna and INFN**

**Contacts:**

**paolo.finelli@unibo.it**

**www.fisicanucleare.it**

**in collaboration with A. Ventura (INFN) and B. V. Carlson (Sao José dos Campos, ITA, Brazil)**

# Introduction

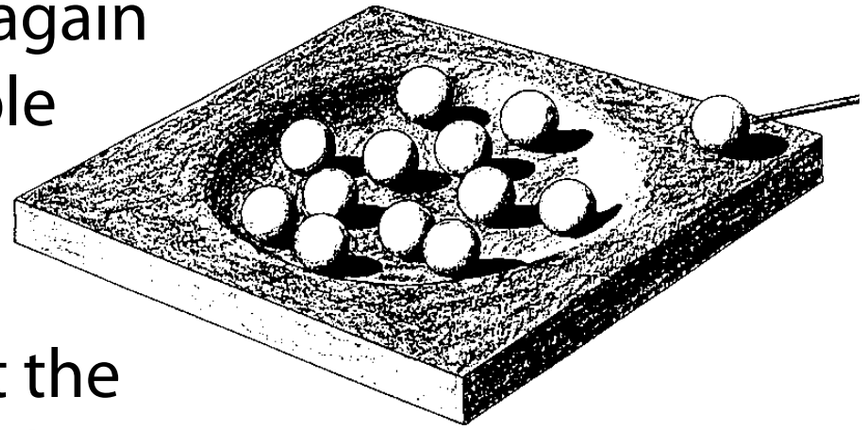
- The **nuclear level density *ρ(E)*** is a characteristic property of every nucleus and it is defined as the number of levels per unit energy at a certain excitation energy.

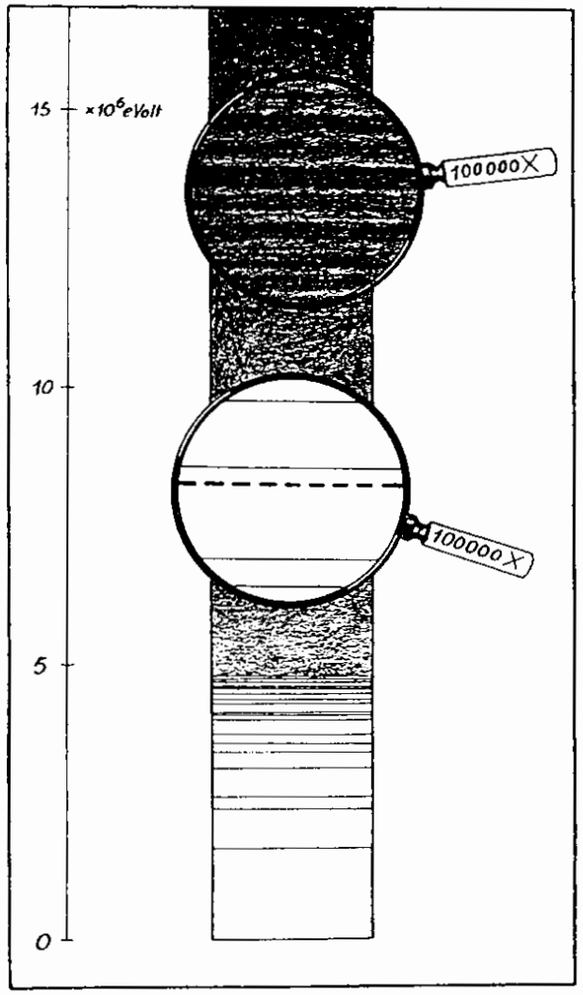
$$\rho(E) = \mathrm{d}N/\mathrm{d}E$$

- It is the number of different ways in which individual nucleons can be placed in the various single particle orbitals such that the excitation energy lies in the range *E* to *E*+*dE*. It increases rapidly with excitation energy.
- In the independent-particle model, the nuclear level density is determined from the neutron and proton single-particle level densities. This single-particle level density can be subdivided into **compound-nucleus and gas components**.
- The **nuclear level density ρ is an essential ingredient** in calculating the statistical decay of a compound nucleus by particle evaporation, γ -ray emission, or fission.

# Introduction - compound nucleus

The "compound nucleus" is a state in which **the excitation energy is distributed statistically among all the available degrees of freedom**. Only as the result of a very rare fluctuation, all the excitation energy could be again concentrated on a single particle, which will then be able to leave the nucleus, which has **no memory** of the original reaction






It was known experimentally that the lowest excited states in heavy nuclei had energies of order a few hundred keV above the ground state. Bohr expected these low-lying states to reflect the normal modes of motion (surface, compressive modes, and collection rotation) of the nuclear substance.

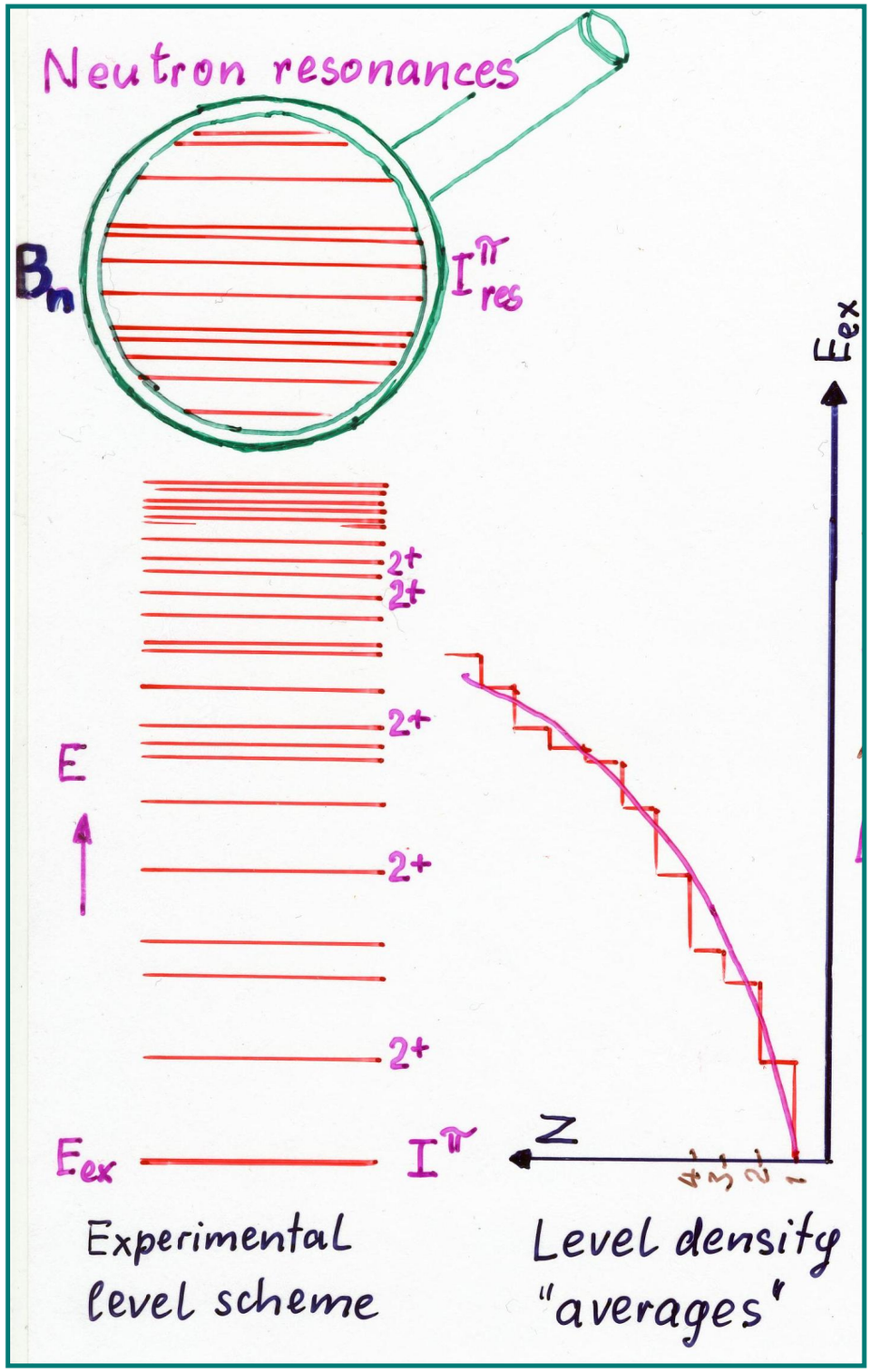
With increasing excitation energy, the number of ways in which the total energy can be divided among these different modes increase exponentially and therefore the level density of the quantum states of the compound nucleus will increase

N. Bohr, Nature **137**, 344 (1936)

# Introduction - compound nucleus

The levels of a nucleus can be divided into two regions. This division arises naturally from the different approaches employed for their analysis: the spectroscopical approach for the low energy levels and the statistical approach for the high energy levels. The **low-lying nuclear excited levels** are small in number, well separated, and rather simple in structure.

With increasing excitation energy, the spacing between the levels is progressively reduced. The existence of such complex levels is illustrated by the **neutron-capture resonances**. Their average spacing is about $10^6$ times smaller than the average single-particle level spacing, and their widths are also $10^6$ times smaller than expected for a single particle excitation.



# Introduction (a simple derivation)

A simple result can be obtained within the independent-particle model. It starts with sets of single-particle levels for both neutrons and protons. **The determination of the nuclear level density is essentially a combinatorial problem**, i.e., determining how many ways these single-particle levels can be occupied to give the desired total excitation energy.

$$\rho(E^*) = \frac{\exp S}{2\pi\sqrt{D}}$$

Nucleon number $$A = \frac{\partial \ln Z}{\partial \alpha} = \sum_i f_i$$

Total energy $$E = E_{\rm gs} + E^* = -\frac{\partial \ln Z}{\partial \beta} = \sum_i \varepsilon_i \, f_i$$

where **f** are the average occupancy of a single particle level

$$f_i = \frac{1}{[1 + \exp(\beta\epsilon_i - \alpha)]}$$

Entropy $$S = \beta E - \alpha N + \ln Z(\alpha, \beta)$$

$$S = \sum_i s_i$$

$$s_i = -f_i \ln f_i - (1 - f_i)\ln(1 - f_i)$$

Charity and Sobotka, PRC **71,** 024310 (2005)

# Introduction (a simple derivation)

A simple result can be obtained within the independent-particle model. It starts with sets of single-particle levels for both neutrons and protons. **The determination of the nuclear level density is essentially a combinatorial problem**, i.e., determining how many ways these single-particle levels can be occupied to give the desired total excitation energy.

$$\rho(E^*) = \frac{\exp S}{2\pi\sqrt{D}}$$

Entropy

$$S = \beta E - \alpha N + \ln Z(\alpha, \beta)$$

$$S = \sum_i s_i$$

$$s_i = -f_i \ln f_i - (1 - f_i)\ln(1 - f_i)$$

At the saddle point

$$\ln Z = \sum_i \ln[1 + \exp(\alpha - \beta\epsilon_i)]$$

$$D = \begin{vmatrix} \frac{\partial^2 \ln Z}{\partial\alpha^2} & \frac{\partial^2 \ln Z}{\partial\alpha\partial\beta} \\ \frac{\partial^2 \ln Z}{\partial\beta\partial\alpha} & \frac{\partial^2 \ln Z}{\partial\beta^2} \end{vmatrix}$$

$$g(\epsilon) = \sum_i \delta(\epsilon - \epsilon_i)$$

$$\rho(E^*) = \frac{\exp S}{\sqrt{48}E^*}$$

$$S = 2\sqrt{aE^*} = 2aT$$

**level-density parameter**

Charity and Sobotka, PRC **71,** 024310 (2005)

# Introduction (general definition)

AUGUST 15, 1936 PHYSICAL REVIEW VOLUME 50

**An Attempt to Calculate the Number of Energy Levels of a Heavy Nucleus**

H. A. BETHE, *Cornell University*

(Received June 5, 1936)

Although the previous formula can be derived without recourse to statistical mechanics, Bethe realized there is a close analogy to the problem of a Fermi gas in contact with a heat bath of temperature $T = 1/\beta$ and with chemical potential $\mu$. ***Z is the grand partition function***, *S* is the entropy, and thus $1/T = dS/dE^*$.

$$Z_{\mathrm{GC}}(\beta,\alpha) = \mathrm{Tr}\exp[-\beta\hat{H} + \alpha\hat{N}]$$

$$Z_{\mathrm{GC}}(\beta,\alpha) = \sum_N \int_{E_0}^{\infty} \rho(E,N) e^{-\beta E + \alpha N} dE$$

$$\rho(E,N) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_0^{2\pi} Z_{\mathrm{GC}}(\beta+is,\alpha+i\phi) \times e^{-(\alpha+i\phi)N+(\beta+is)E} d\phi ds.$$

$$\rho(E,N) \approx \frac{Z_{\mathrm{GC}}(\beta,\alpha)e^{\beta E-\alpha N}}{[(2\pi)^2 \mathrm{Det}(\frac{\partial^2 \ln Z_{\mathrm{GC}}}{\partial\eta_i \partial\eta_j})]^{1/2}}$$

# Introduction (a common approach)

The Fermi gas model in its various modifications is widely used for calculation of the nuclear level density. This model enables simple systematics to be established based on normalization of the energy dependence of the nuclear level density to data on the cumulative numbers of low-lying levels and the average spacings between S-wave neutron resonances at the neutron binding energy ($B_n$) in the nucleus.

However, the level density parameter ***a*** and excitation energy shift $\delta_{eff}$, caused by even-odd differences in the nuclei, are considered free parameters. Since the $\delta_{eff}$ values obtained for odd-odd nuclei are negative, this approximation has been termed the **back-shifted Fermi gas model**.

**total level density**

$$\rho(U) = \frac{1}{12\sqrt{2}} \frac{1}{\sigma a^{1/4}} \frac{\exp\left[2\sqrt{a(U-\delta_{eff})}\right]}{(U-\delta_{eff})^{5/4}}$$

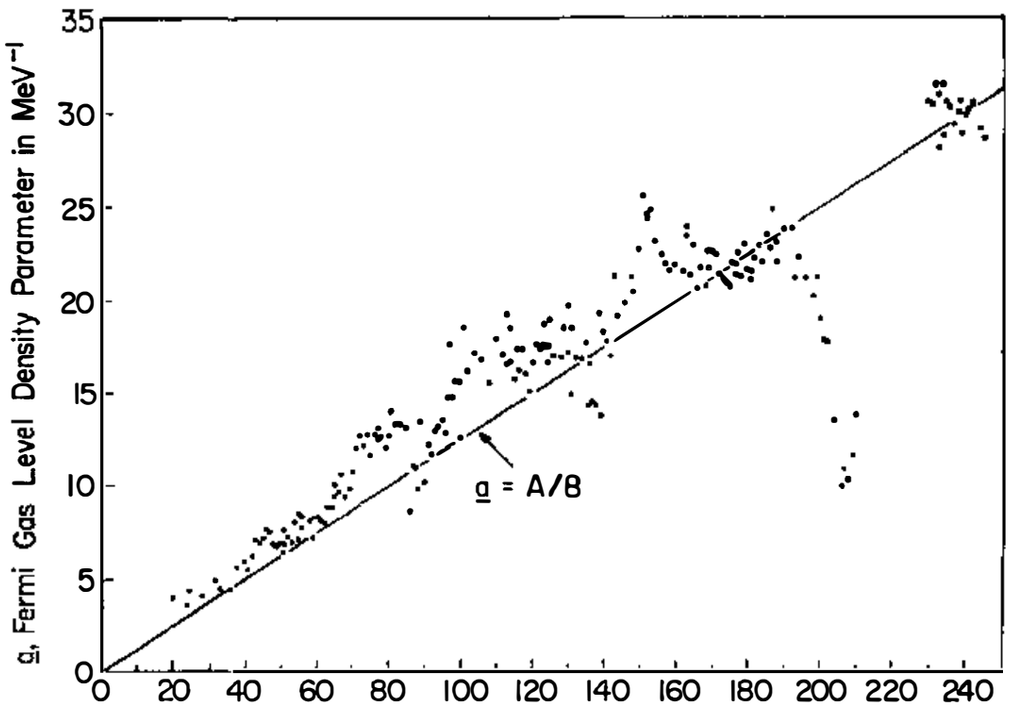
***a*** is the level density parameter associated with the density of single particle states near the Fermi energy;

the excitation energy shift $\delta_{eff}$ is caused by even-odd differences in the nuclei

# Introduction (experimental sources)

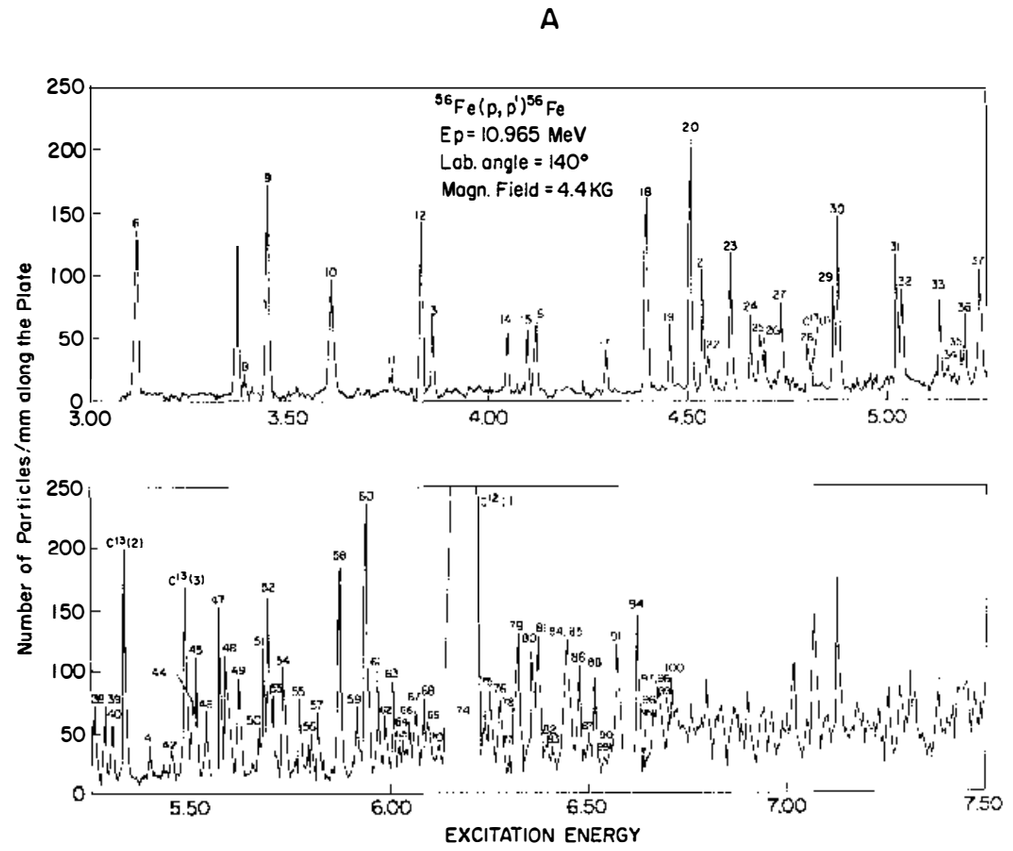
## Neutron resonances

In this type of experiment the nuclear energy levels are observed at an energy just exceeding the neutron binding energy, and the number of levels is obtained by counting the resonances in a particular neutron energy interval. It is necessary in such experiments that the width $\Gamma$ of each level be less than the level spacing $\Delta$ and that the experimental resolution be good enough to resolve individual levels.




## Inelastic scattering and nuclear reactions to resolved levels

The resolution obtained in these experiments is orders of magnitude poorer than that achieved with s-wave neutron spectroscopy. With such experiments, it is possible to study isolated levels up to an excitation energy of approximately 5 to 6 MeV for a nucleus with atomic mass around 60. Typical nuclear reactions are the ($p$, $p'$), ($n$, $n'$), ($\alpha$, $\alpha'$) and ($p$, $\alpha$) reactions.




## and others…

# Our project

**Relativistic mean field**

input

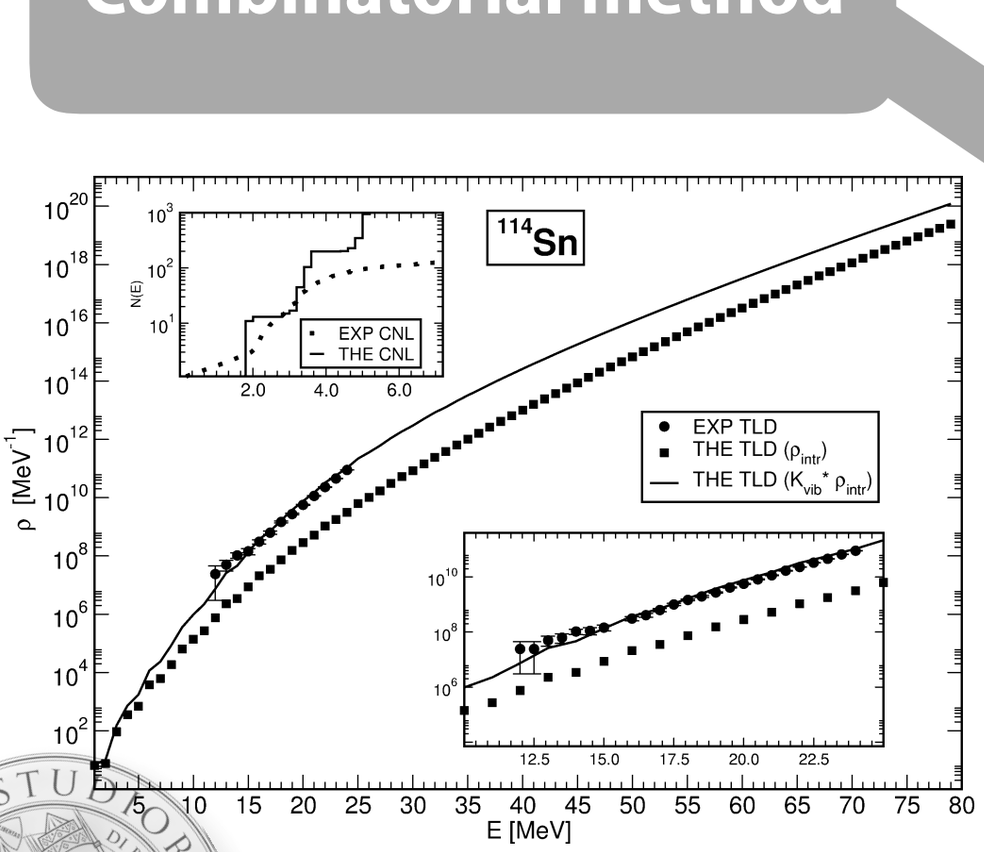
**Frozen bound states**

input

input

**Subtraction method**

**Combinatorial method**

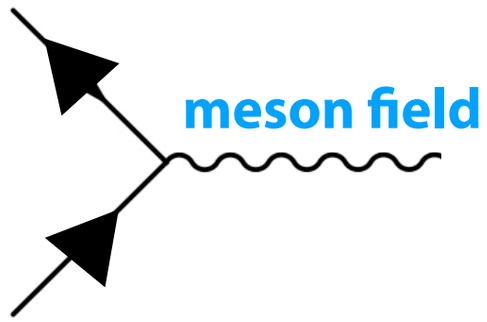



Pezer, **Ventura** and Vretenar, NPA **717** (2003) 21-43

$\rho$

# Relativistic mean field (I)

**Finelli** et al., PRC **66**, 024306 (2002)




## Lagrangian density

$$\mathcal{L} = \bar{\psi}\left[i\gamma^\mu\partial_\mu - M - g_\sigma\sigma - g_\omega\gamma^\mu\omega_\mu - g_\rho\gamma^\mu\vec{\tau}\cdot\vec{\rho}_\mu - e\gamma^\mu A_\mu\frac{1-\tau_3}{2}\right]\psi$$
$$+\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - U_\sigma(\sigma) - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + U_\omega(\omega_\mu) - \frac{1}{4}\vec{R}^{\mu\nu}\cdot\vec{R}_{\mu\nu} + U_\rho(\vec{\rho}_\mu)$$
$$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu},$$

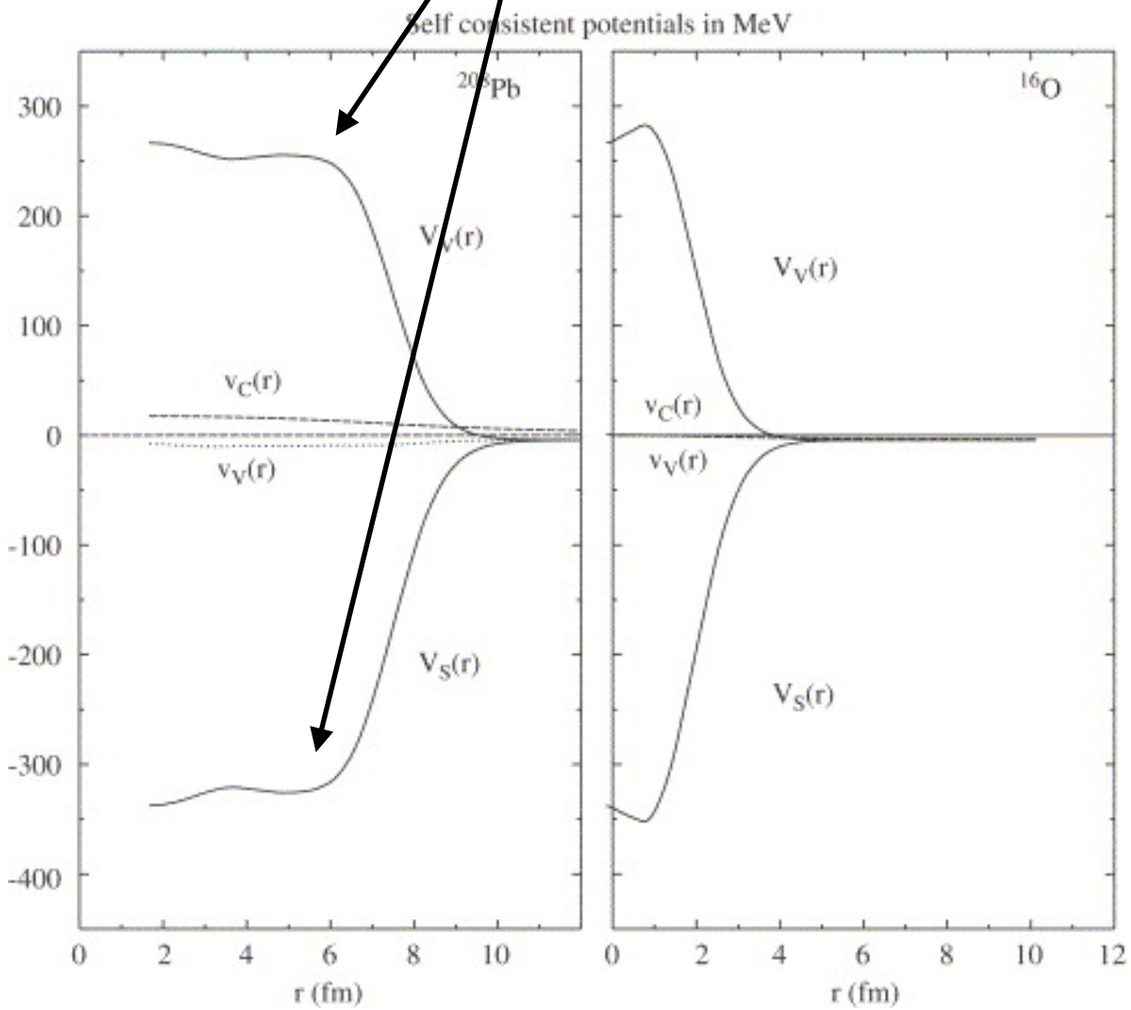
## Meson fields

$$\begin{aligned}
-\boldsymbol{\nabla}^2\sigma + U'_\sigma(\sigma) &= -g_\sigma\rho_s,\\
-\boldsymbol{\nabla}^2\omega_0 + U'_\omega(\omega_0) &= g_\omega\rho_v,\\
-\boldsymbol{\nabla}^2\rho_0^3 + U'_\rho(\rho_0^3) &= g_\rho\rho_3,\\
-\boldsymbol{\nabla}^2 A_0 &= e\rho_c.
\end{aligned}$$

**non linear terms**

$$\begin{aligned}
U_\sigma(\sigma) &= \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4,\\
U_\omega(\omega_\mu) &= \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu + \frac{1}{4}c_3\left(\omega^\mu\omega_\mu\right)^2,\\
U_\rho(\vec{\rho}_\mu) &= \frac{1}{2}m_\rho^2\vec{\rho}^{\,\mu}\cdot\vec{\rho}_\mu + \frac{1}{4}d_3\left[\vec{\rho}^{\,\mu}\cdot\vec{\rho}_\mu\right]^2.
\end{aligned}$$

**sigma and omega fields have opposite signs**



# Relativistic mean field (II)

**Finelli** et al., PRC **66**, 024306 (2002)

## Mean field

$$|\Phi\rangle = \prod_{i=1}^{A} c_i^\dagger |0\rangle \qquad \langle\Phi|\Phi\rangle = 1$$

$$\begin{aligned} E_{\mathrm{RMF}}(\rho,\phi) =& \langle\Phi|\mathcal{H}|\Phi\rangle \\ =& \int d^3x \mathrm{Tr}\left[\beta\left(\boldsymbol{\gamma}\cdot\mathbf{p} + M + g_\sigma\sigma + g_\omega\omega^\mu\gamma_\mu + g_\rho\vec{\tau}\cdot\vec{\rho}_\mu\gamma^\mu + \frac{1}{2}e(1-\tau_3)A_\mu\gamma^\mu\right)\rho\right] \\ &+ \int d^3x\left\{-\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma + U_\sigma(\sigma) + \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} - U_\omega(\omega_\nu) + \frac{1}{4}\vec{R}^{\mu\nu}\cdot\vec{R}_{\mu\nu} - U_\rho(\vec{\rho}_\nu) + \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\right\} \end{aligned}$$

## Spinor wave function for spherical symmetry

$$\psi_{\alpha\kappa m}(\mathbf{r},t) = \begin{pmatrix} i\dfrac{G_\alpha^\kappa(r)}{r} \\ \dfrac{F_\alpha^\kappa(r)}{r}\boldsymbol{\sigma}\cdot\hat{\mathbf{r}} \end{pmatrix} Y_{jm}^l(\theta,\phi)\chi_{t_\alpha}(t)$$

**central potential**

$$\begin{aligned} \epsilon_\alpha G_\alpha^\kappa &= \left(-\frac{d}{dr} + \frac{\kappa}{r}\right) F_\alpha^\kappa + (M + S(r) + V(r))\, G_\alpha^\kappa, \\ \epsilon_\alpha F_\alpha^\kappa &= \left(+\frac{d}{dr} + \frac{\kappa}{r}\right) G_\alpha^\kappa - (M + S(r) - V(r))\, F_\alpha^\kappa, \end{aligned}$$

**spin-orbit potential**

$$\begin{aligned} S(r) &= g_\sigma\sigma, \\ V(r) &= g_\omega\omega_0 + g_\rho\tau_3\rho_0^3 + \frac{1}{2}e(1-\tau_3)A_0. \end{aligned}$$

# Relativistic mean field (III)

**Finelli** et al., PRC **66**, 024306 (2002)

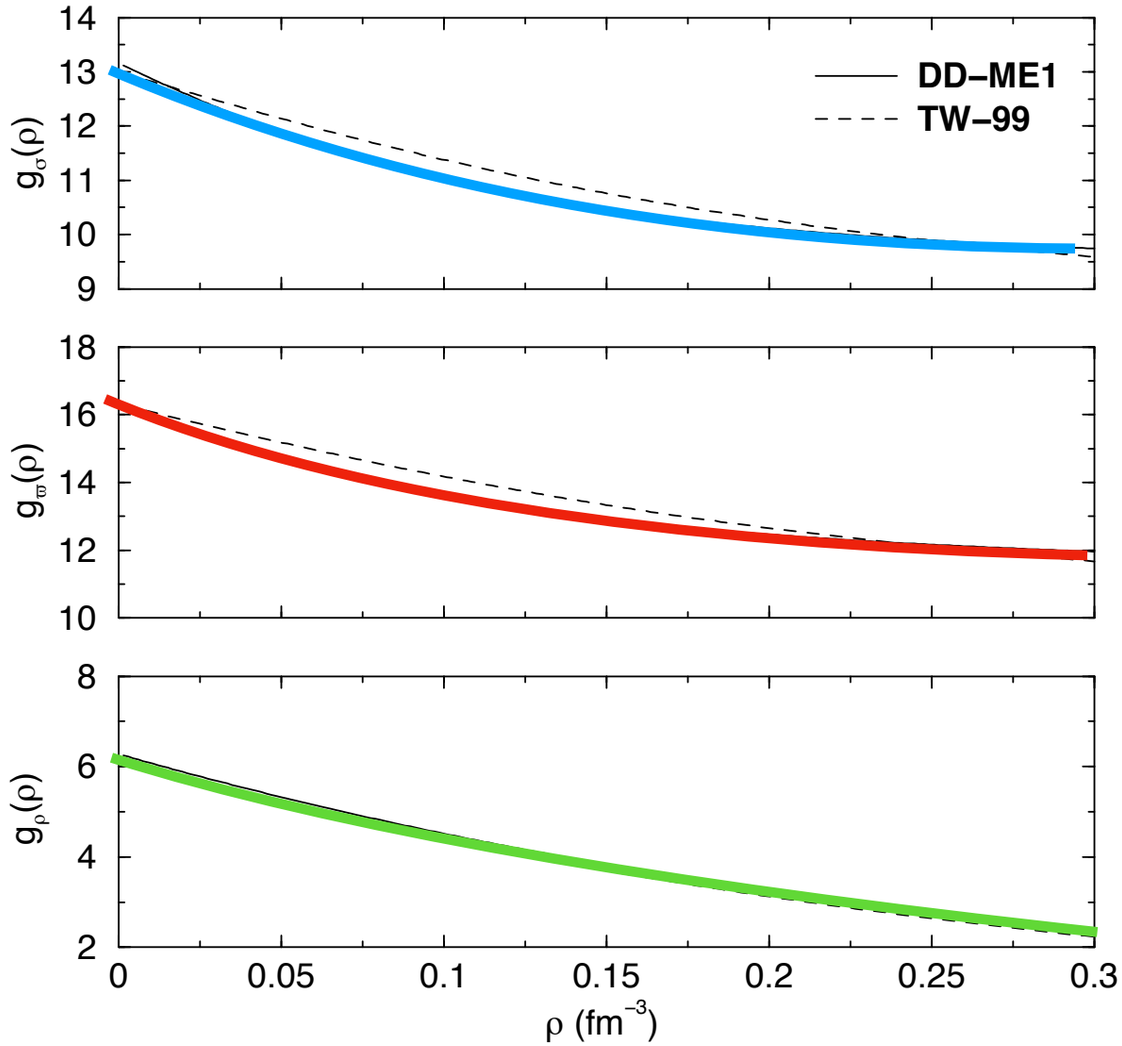
## Density-dependent extension

$$g_i(\rho_v) = g_i(\rho_{\rm sat}) f_i(x)$$

$$f_i(x) = a_i \frac{1 + b_i(x + d_i)^2}{1 + c_i(x + d_i)^2} \qquad x = \rho/\rho_{sat}$$

$$g_\rho = g_\rho(\rho_{\rm sat}) \exp[-a_\rho(x - 1)]$$

| | E/A (MeV) | $r_{ch}$ (fm) | $r_n - r_p$ (fm) |
|---|---|---|---|
| $^{16}$O | -7.974 (-7.976) | 2.730 (2.730) | -0.03 |
| $^{40}$Ca | -8.576 (-8.551) | 3.464 (3.485) | -0.05 |
| $^{48}$Ca | -8.631 (-8.667) | 3.482 (3.484) | 0.19 |
| $^{90}$Zr | -8.704 (-8.710) | 4.294 (4.272) | 0.06 |
| $^{112}$Sn | -8.501 (-8.514) | 4.586 (4.596) | 0.11 |
| $^{116}$Sn | -8.516 (-8.523) | 4.616 (4.626) | 0.15 (0.12) |
| $^{124}$Sn | -8.462 (-8.467) | 4.671 (4.674) | 0.25 (0.19) |
| $^{132}$Sn | -8.352 (-8.355) | 4.720 | 0.27 |
| $^{204}$Pb | -7.885 (-7.880) | 5.500 (5.486) | 0.18 |
| $^{208}$Pb | -7.884 (-7.868) | 5.518 (5.505) | 0.20 (0.20) |
| $^{214}$Pb | -7.764 (-7.772) | 5.568 (5.562) | 0.27 |
| $^{210}$Po | -7.857 (-7.834) | 5.553 | 0.18 |



# Relativistic mean field (finite T)

The temperature dependent equations are derived by the minimization of the thermodynamical potential ***Ω***,

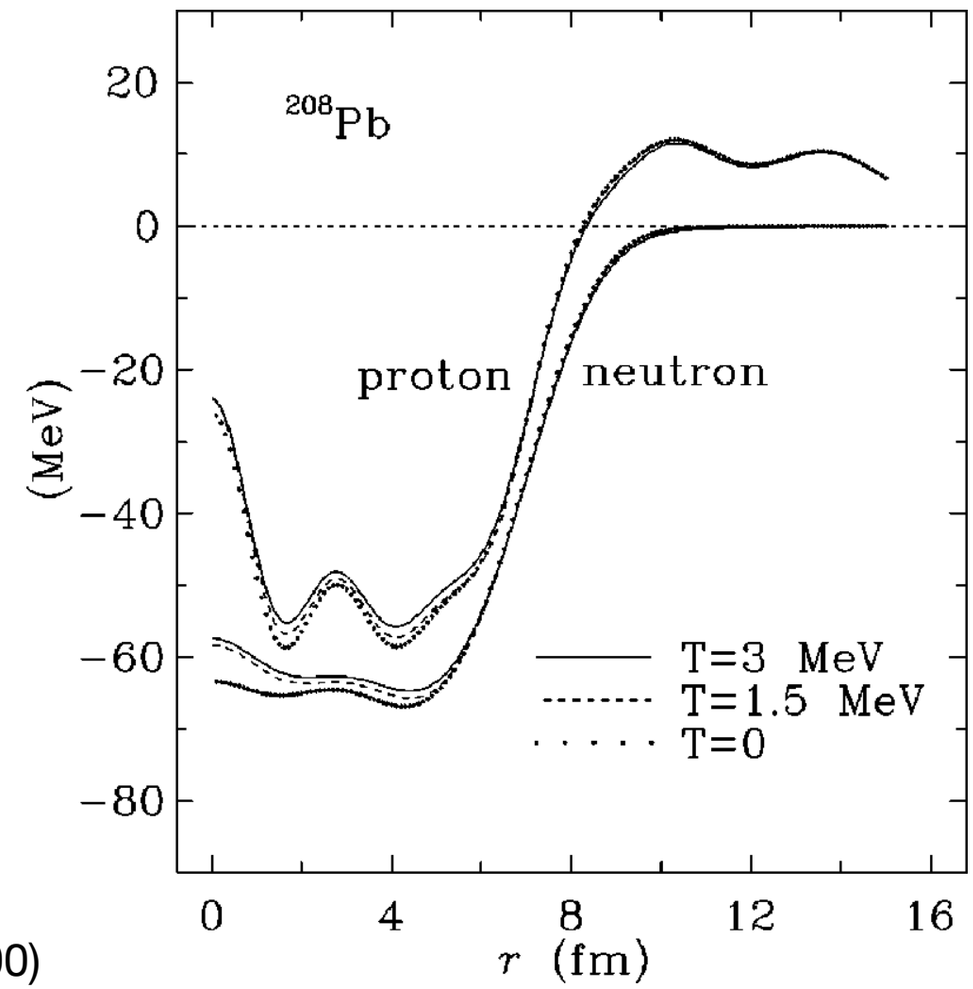
$$\Omega = E - TS - \mu N$$

where ***E*** being the energy, ***T*** is the thermodynamic temperature which is introduced through the statistical Fermi occupation probabilities $n_i$

$$n_i = \left[ 1 + \exp\left( \frac{\varepsilon_i - \mu}{kT} \right) \right]^{-1}$$

$$S = -\sum_i \left[ n_i \ln n_i + (1 - n_i) \ln (1 - n_i) \right]$$

$$E^*(T) = E(T) - E(T=0)$$

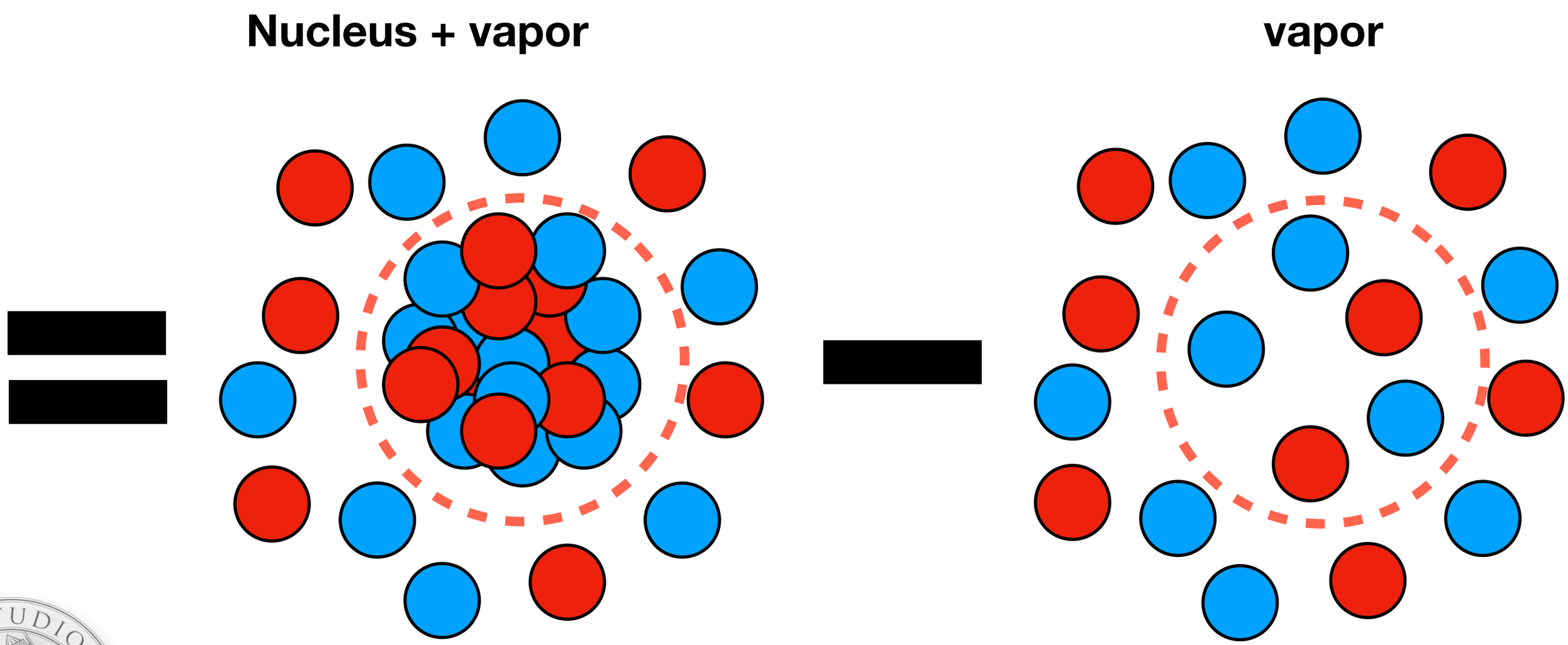



Gambhir, Maharana, Lalazissis, Panos, and P. Ring, PRC **62** 054610 (2000)

# Subtraction method

## Bonche-Levit-Vautherin procedure

A vapor subtraction procedure is used to account for unbound states and to remove long range Coulomb repulsion between the hot nucleus and the gas as well as the contribution of the external nucleon gas.




Bonche, Levit, and Vautherin, NPA **427**, 278 (1984); **436**, 265 (1985)

# Subtraction method

## Bonche-Levit-Vautherin procedure

They observed that the mean field equations have two solutions for a given chemical potential and temperature. One of these can be associated with a **nucleus in equilibrium with the evaporated nucleons (nucleus+gas)** while the other consists of a **gas of nucleons alone**.

They determined the properties of the hot nucleus in terms of the difference between quantities associated with the the nucleus+gas and those of the gas.

Formally, this is done by defining a subtracted thermodynamic potential as the difference between that of the nucleus+gas and that of the gas, with the exception of the Coulomb contribution. In particular, the baryon and proton numbers of the hot nucleus are then

$$A = \int d^3r \, [\rho_{B,n+g}(\vec{r}) - \rho_{B,g}(\vec{r})],$$

$$Z = \int d^3r \, [\rho_{p,n+g}(\vec{r}) - \rho_{p,g}(\vec{r})],$$

Bonche, Levit, and Vautherin, NPA **427**, 278 (1984); **436**, 265 (1985)

# Subtraction method

## Bonche-Levit-Vautherin procedure

The Coulomb contribution to the thermodynamic potential must be treated differently due to its long range. **The Coulomb term must be modified in order that the only contribution is from protons in the hot nucleus**. This is done by replacing the difference between the two Coulomb contributions in the thermodynamic potential by a term taking into account only the contribution of those protons,

$$\frac{1}{2}\int d^3r[\rho_{p,n+g}(\vec{r})V_C\rho_{p,n+g}(\vec{r}\,') - \rho_{p,g}(\vec{r})V_C\rho_{p,g}(\vec{r}\,')]$$

$$\rightarrow \frac{1}{2}\int d^3r\{[\rho_{p,n+g}(\vec{r}) - \rho_{p,g}(\vec{r})]V_C$$

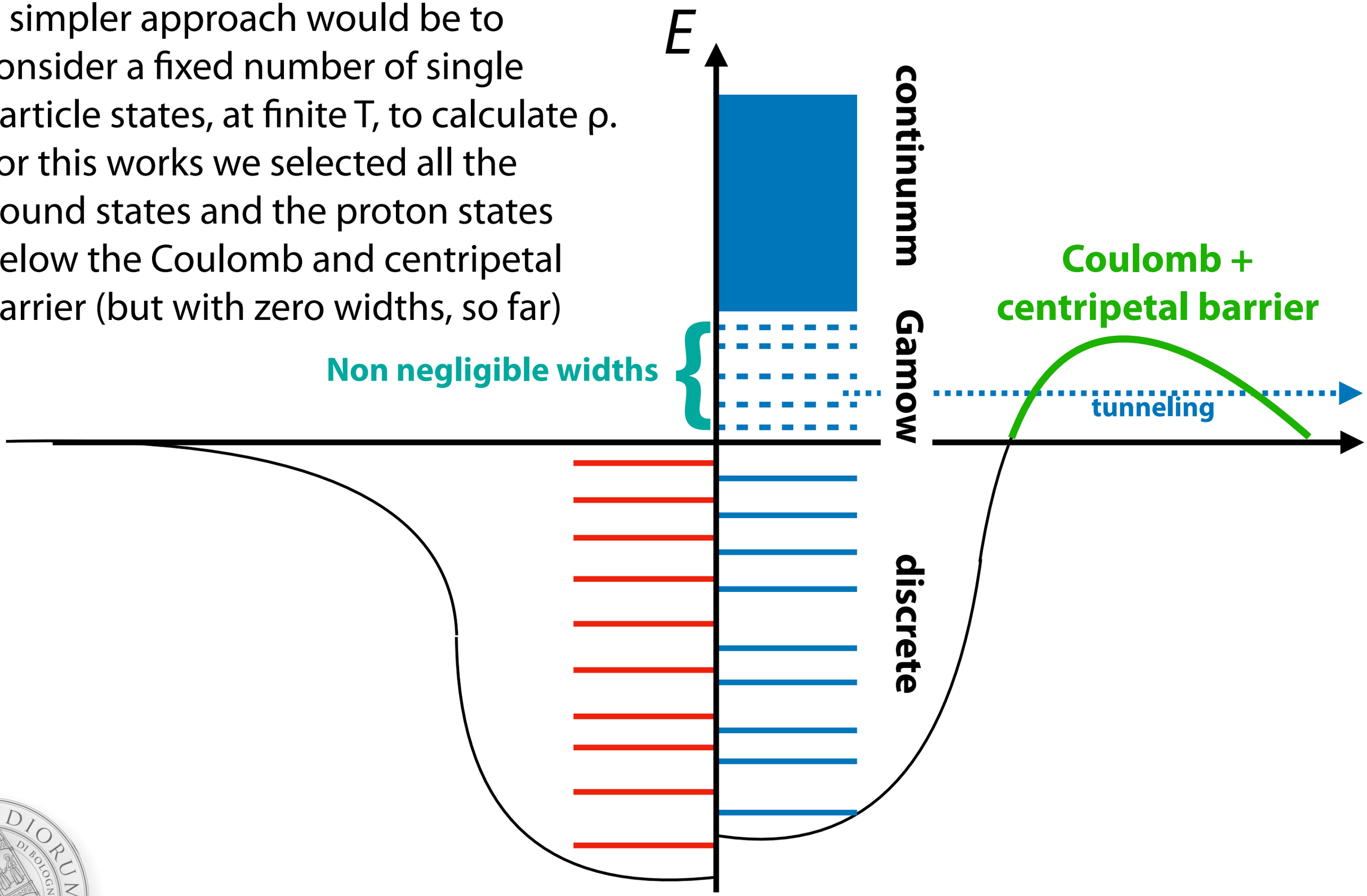
$$\times [\rho_{p,n+g}(\vec{r}\,') - \rho_{p,g}(\vec{r}\,')]\}.$$

Note that, with this substitution, the evaporated protons of the nucleon+gas and gas solutions are still subject to the Coulomb repulsion of the hot nucleus, as would be expected for protons leaving the hot system.

Bonche, Levit, and Vautherin, NPA **427**, 278 (1984); **436**, 265 (1985).

# Bound-state method

A simpler approach would be to consider a fixed number of single particle states, at finite T, to calculate ρ. For this works we selected all the bound states and the proton states below the Coulomb and centripetal barrier (but with zero widths, so far)



# Preliminary results

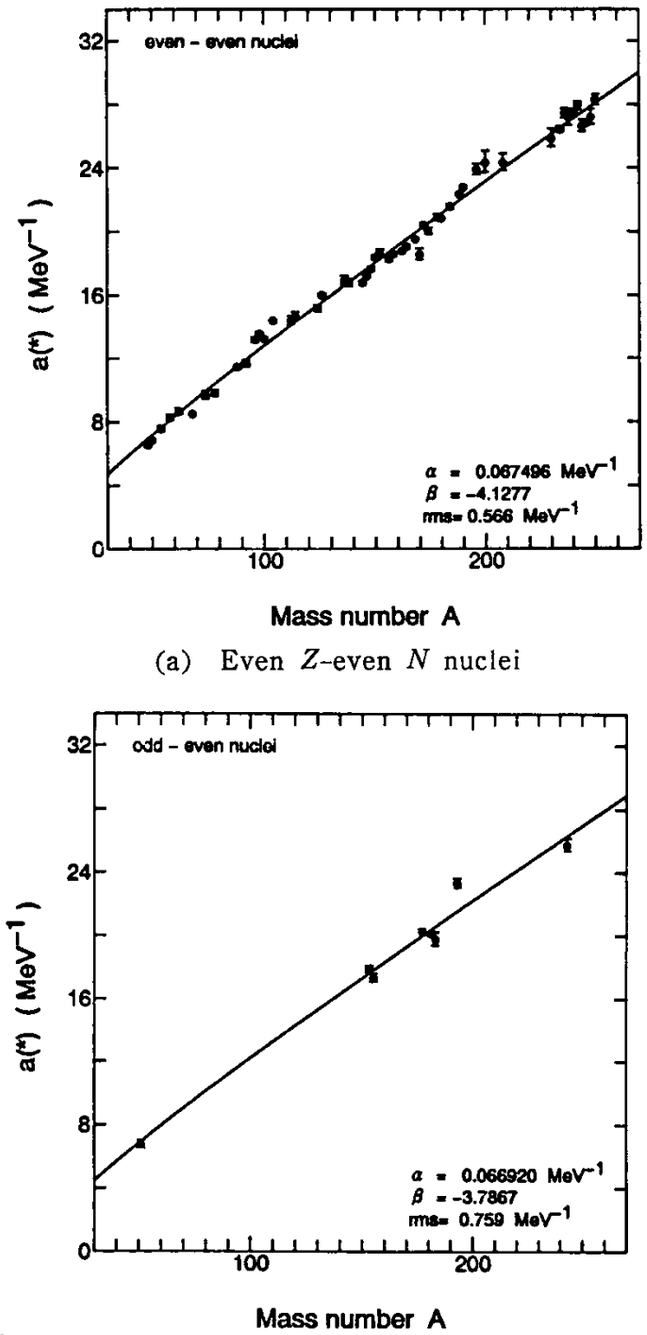
# $^{16}$O, $^{40}$Ca, $^{60}$Ni, $^{90}$Zr, $^{114}$Sn, and $^{208}$Pb

# Benchmark

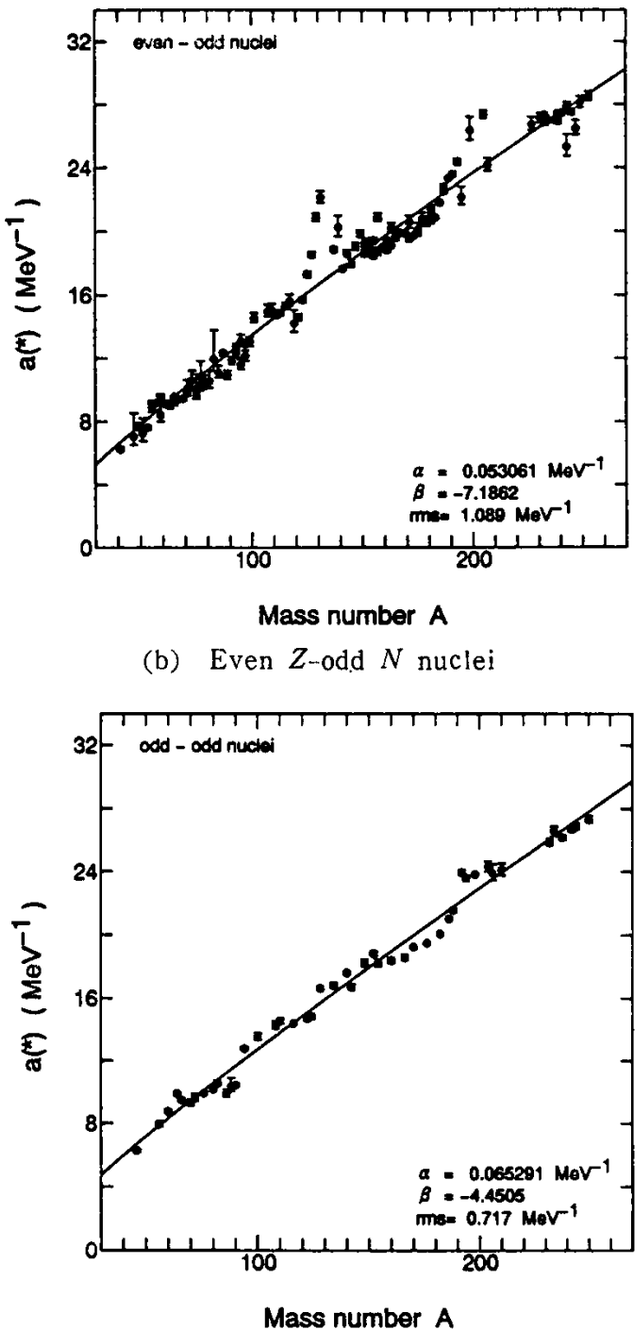
## Fermi-Gas Model Parametrization of Nuclear Level Density

Alberto MENGONI† and Yutaka NAKAJIMA

Journal of Nuclear Science and Technology, **31:2**, 151-162 (1994)




(a) Even $Z$-even $N$ nuclei




(b) Even $Z$-odd $N$ nuclei







## Pairing correction

$$U \rightarrow U - \delta \begin{cases} = 2\delta & \text{even} - \text{even} \\ = \delta & \text{odd} \\ = 0 & \text{odd} - \text{odd} \end{cases}$$

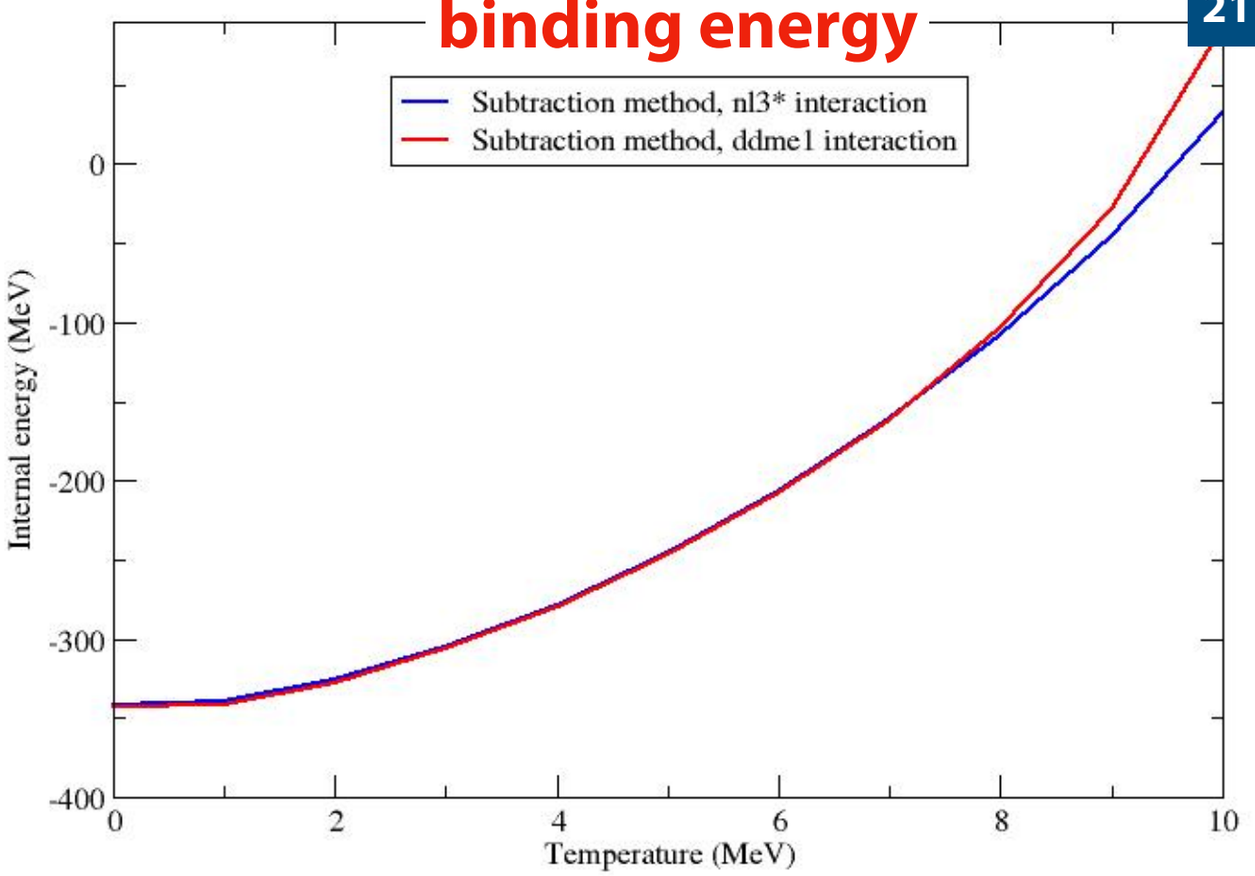
## Shell correction

$$a(U) = a(*)\left[1 + \frac{E_{sh}}{U}(1 - e^{-\gamma U})\right]$$

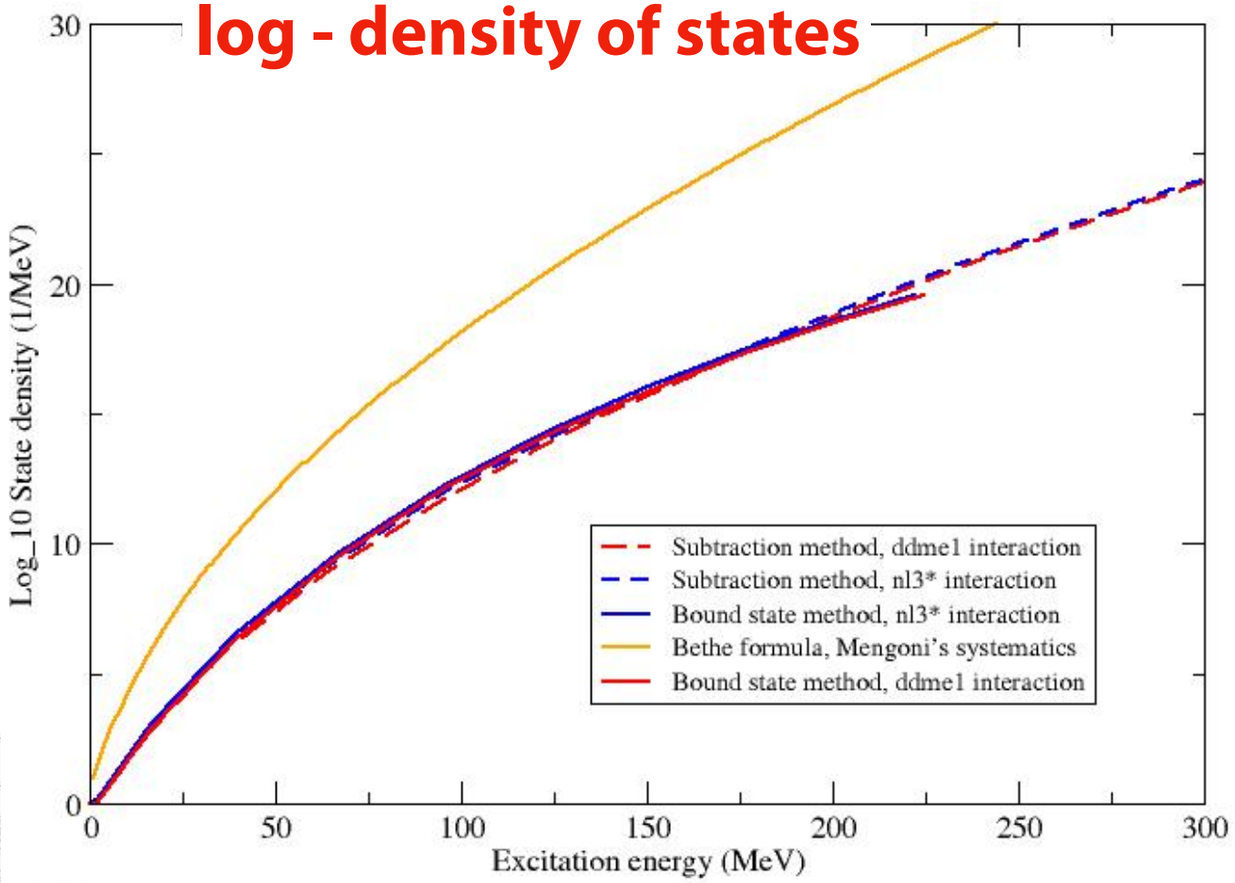
# $^{40}Ca$

- weak dependence on the interaction (non-linear vs. density dependent)
- $\log_{10}$ density of states substantially underestimated respect to phenomenological approaches
- no appreciable differences between the two methods

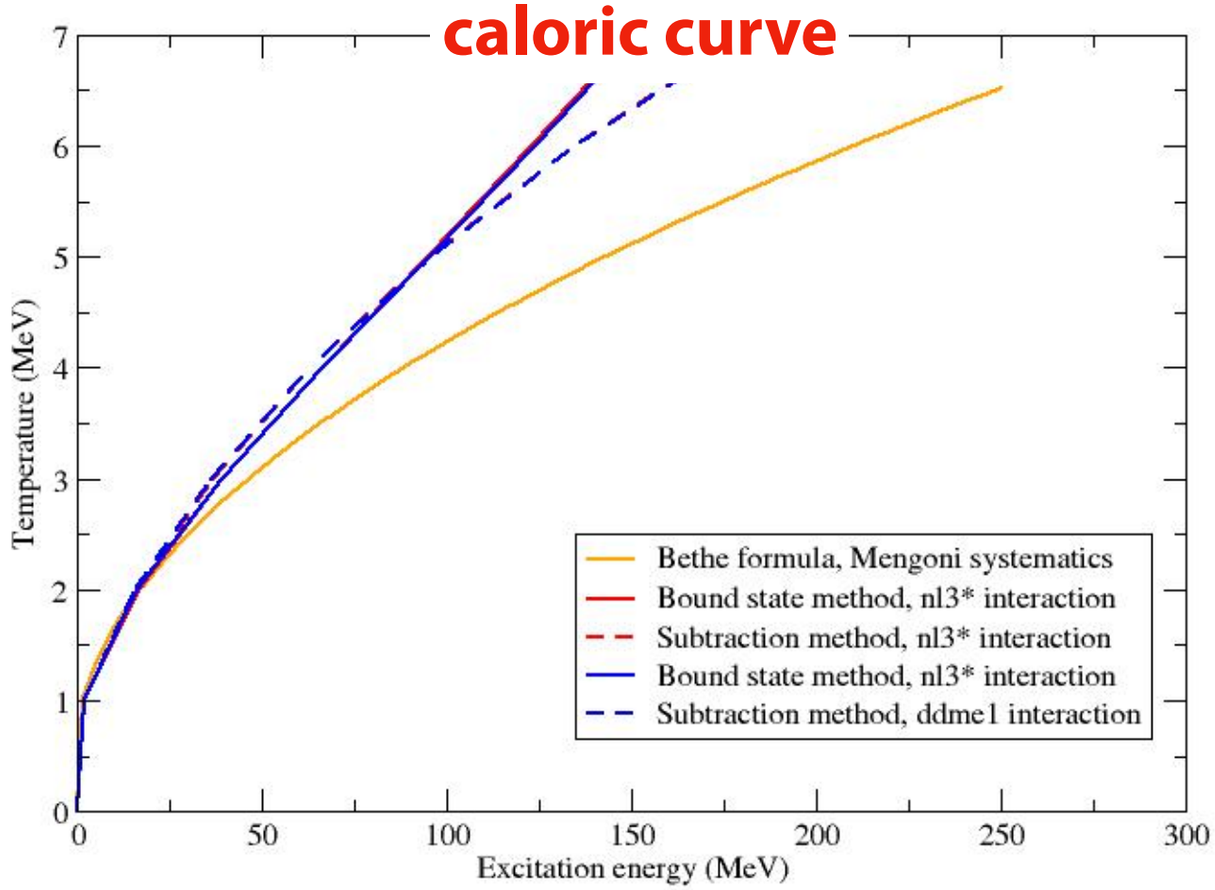
## binding energy




## log - density of states



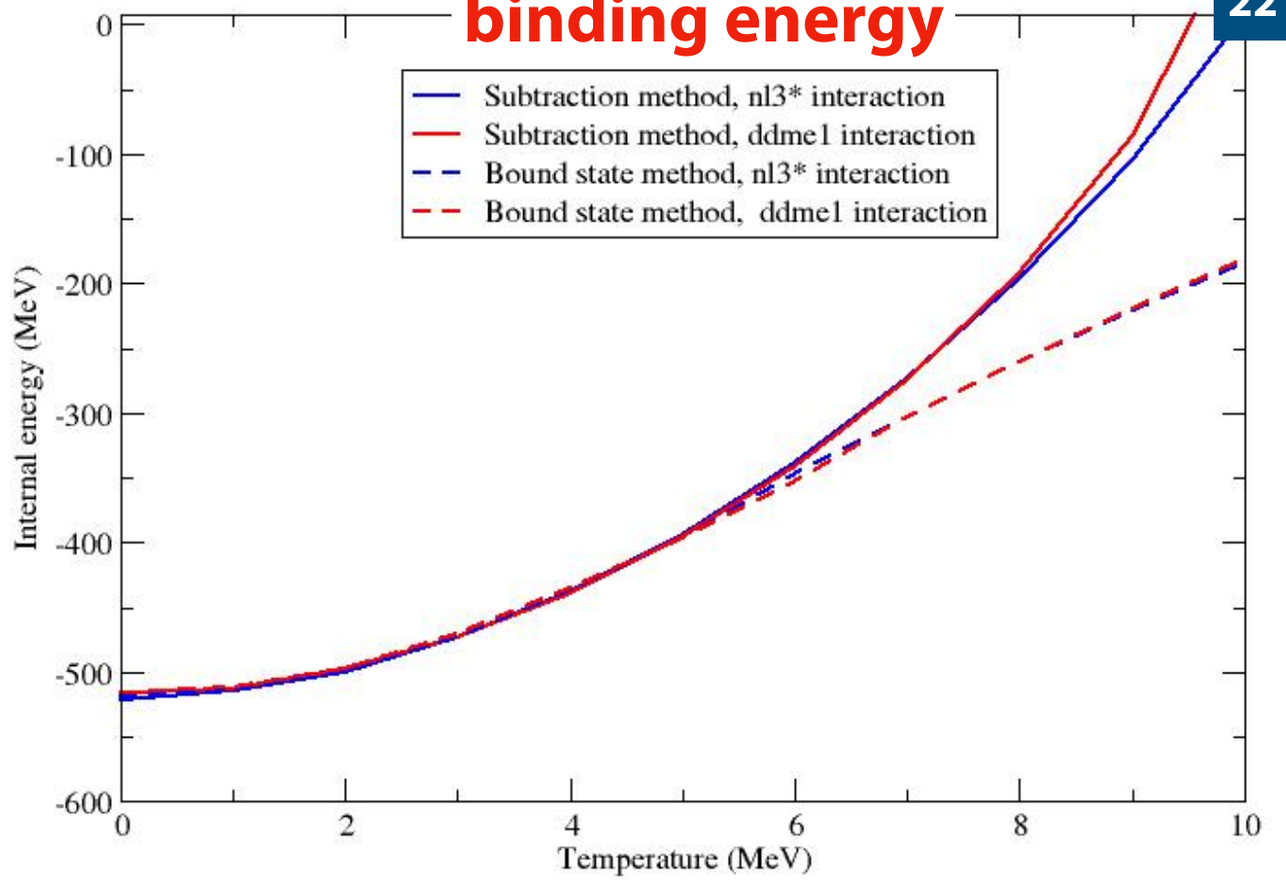

## caloric curve



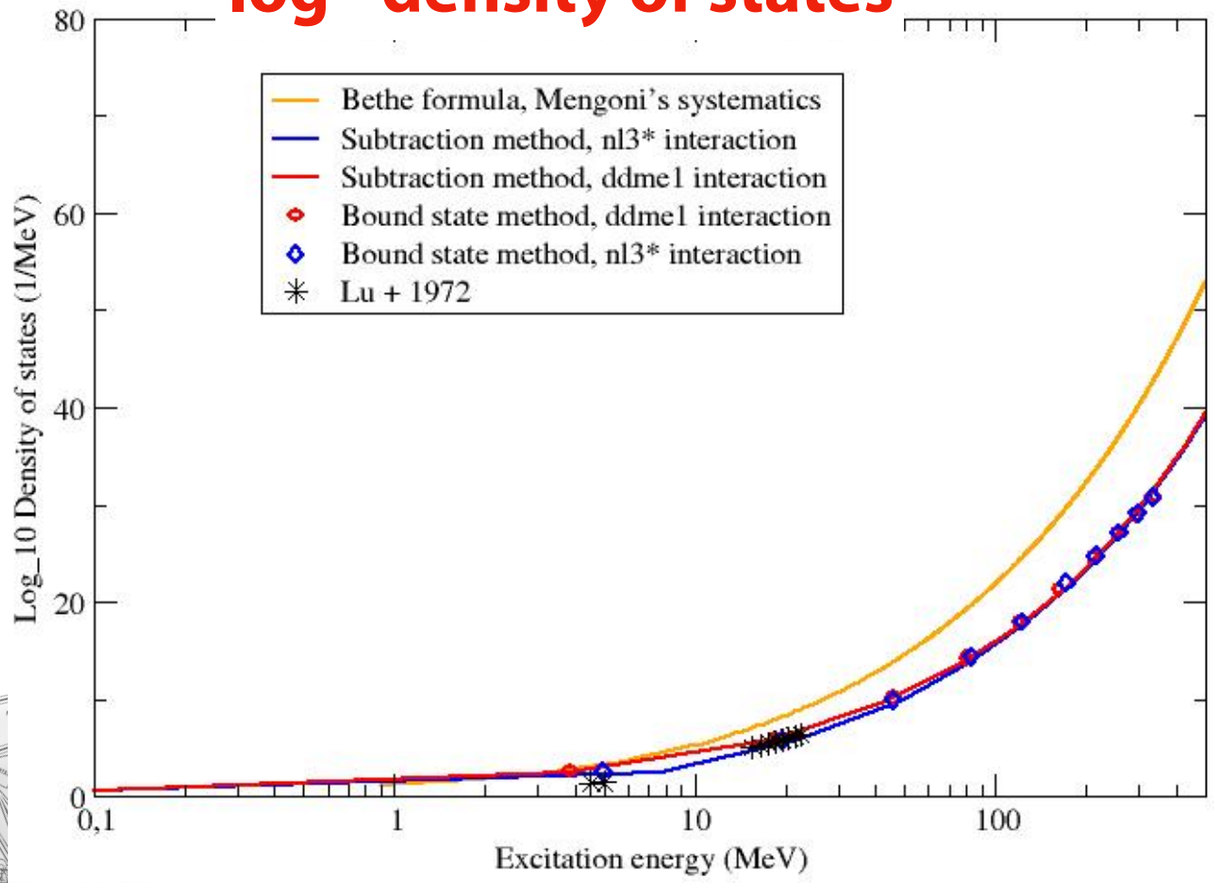
# $^{60}$Ni

- weak dependence on the interaction (non-linear vs. density dependent)
- $\log_{10}$ density of states closer to phenomenological estimates
- appreciable differences between the two methods for higher excitation energies

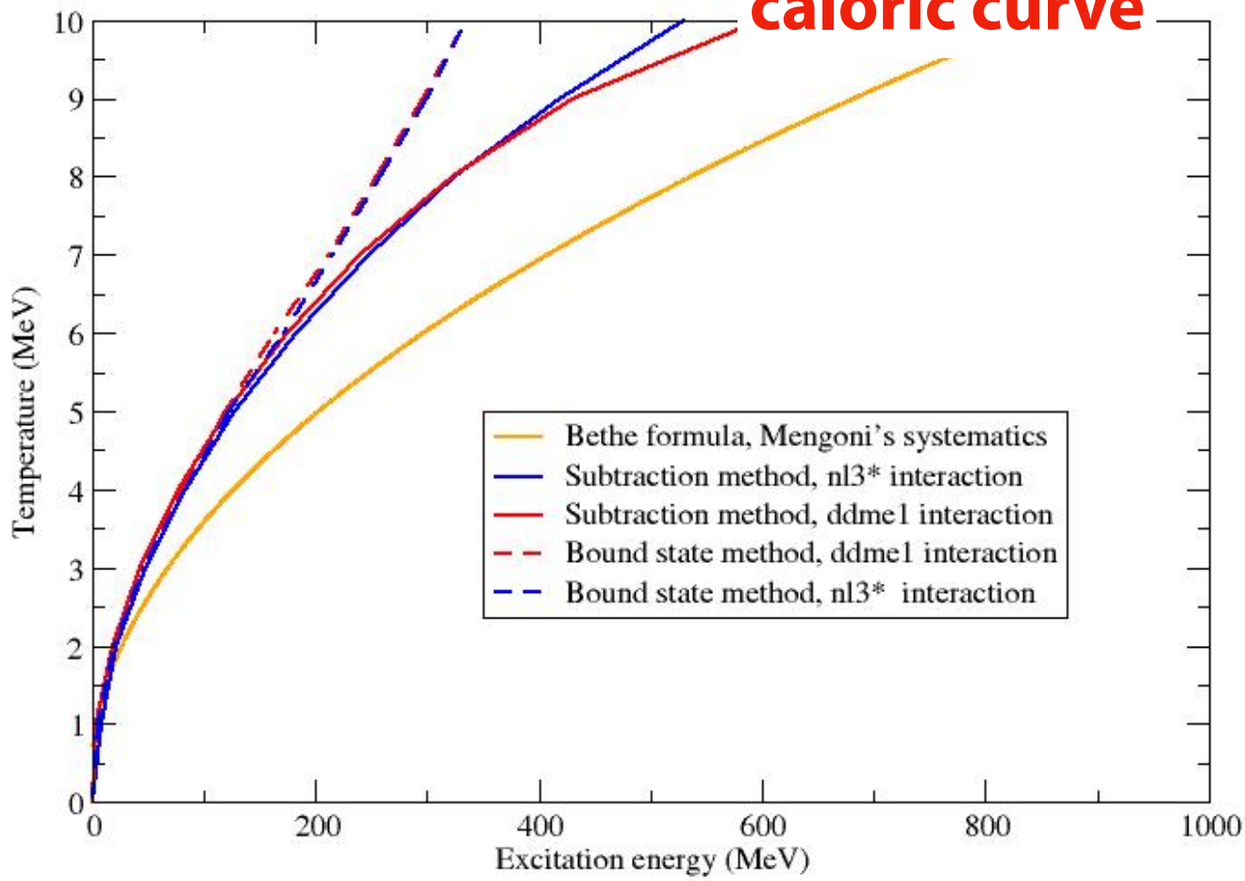
## binding energy



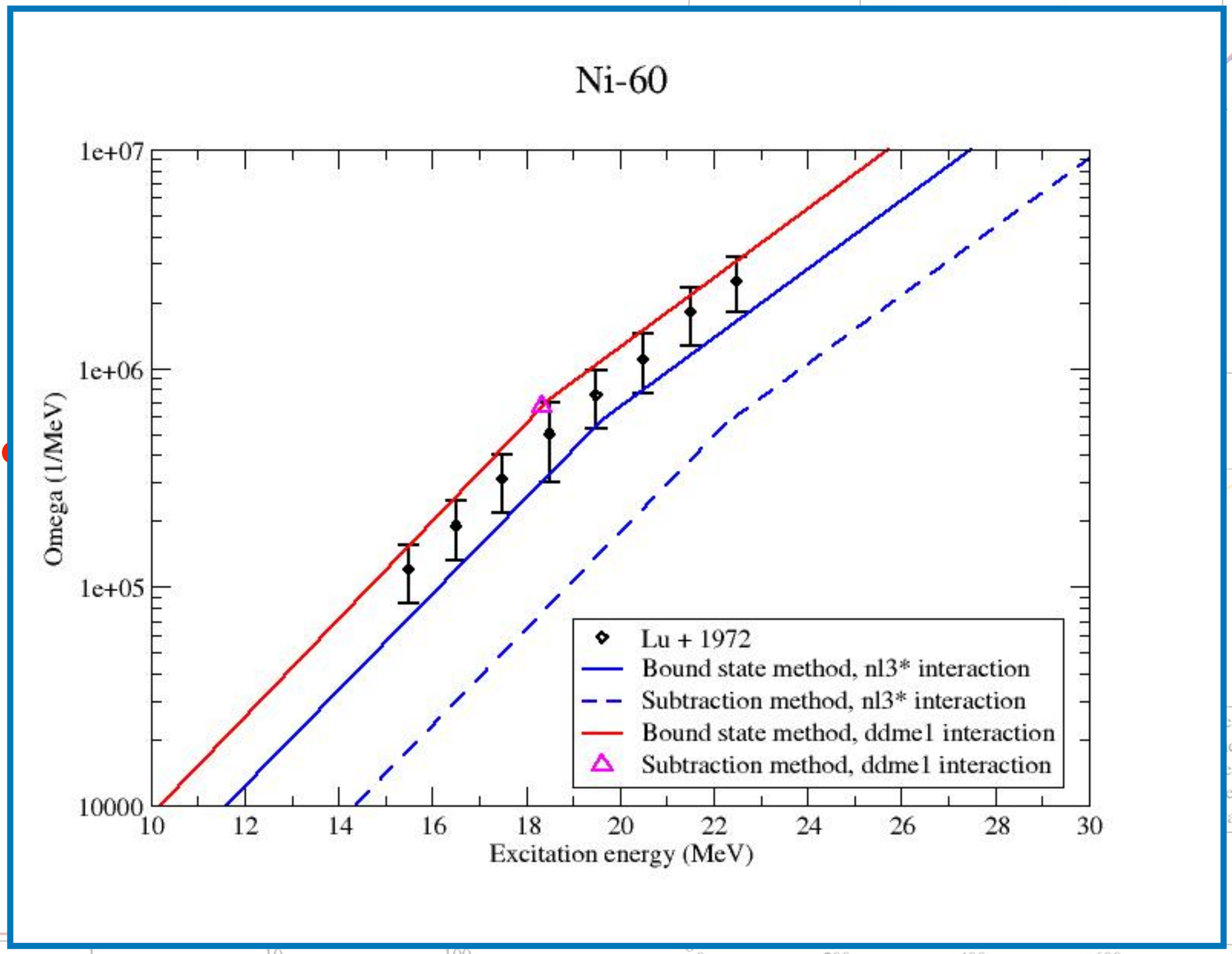

## log - density of states




## caloric curve

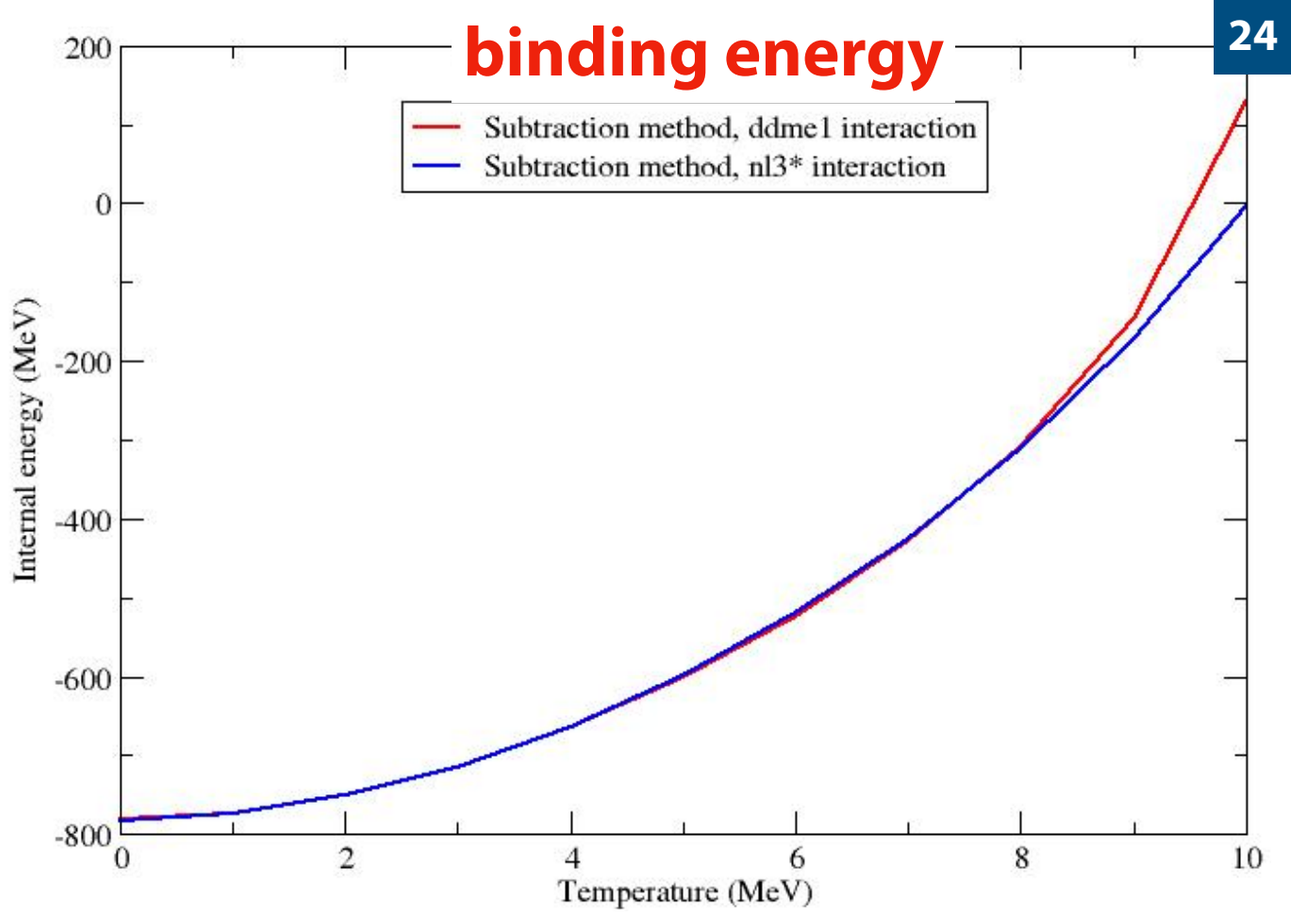


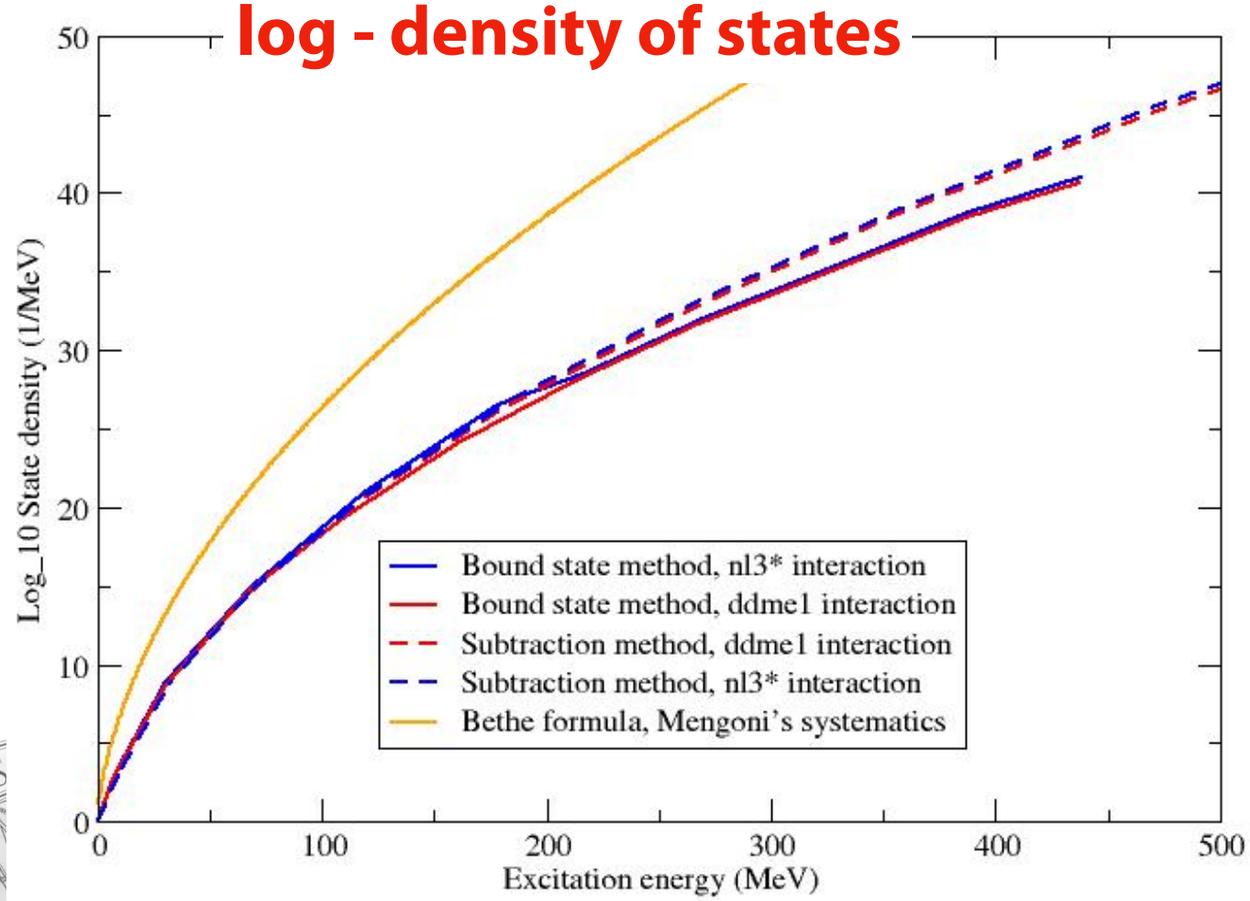
# $^{60}$Ni

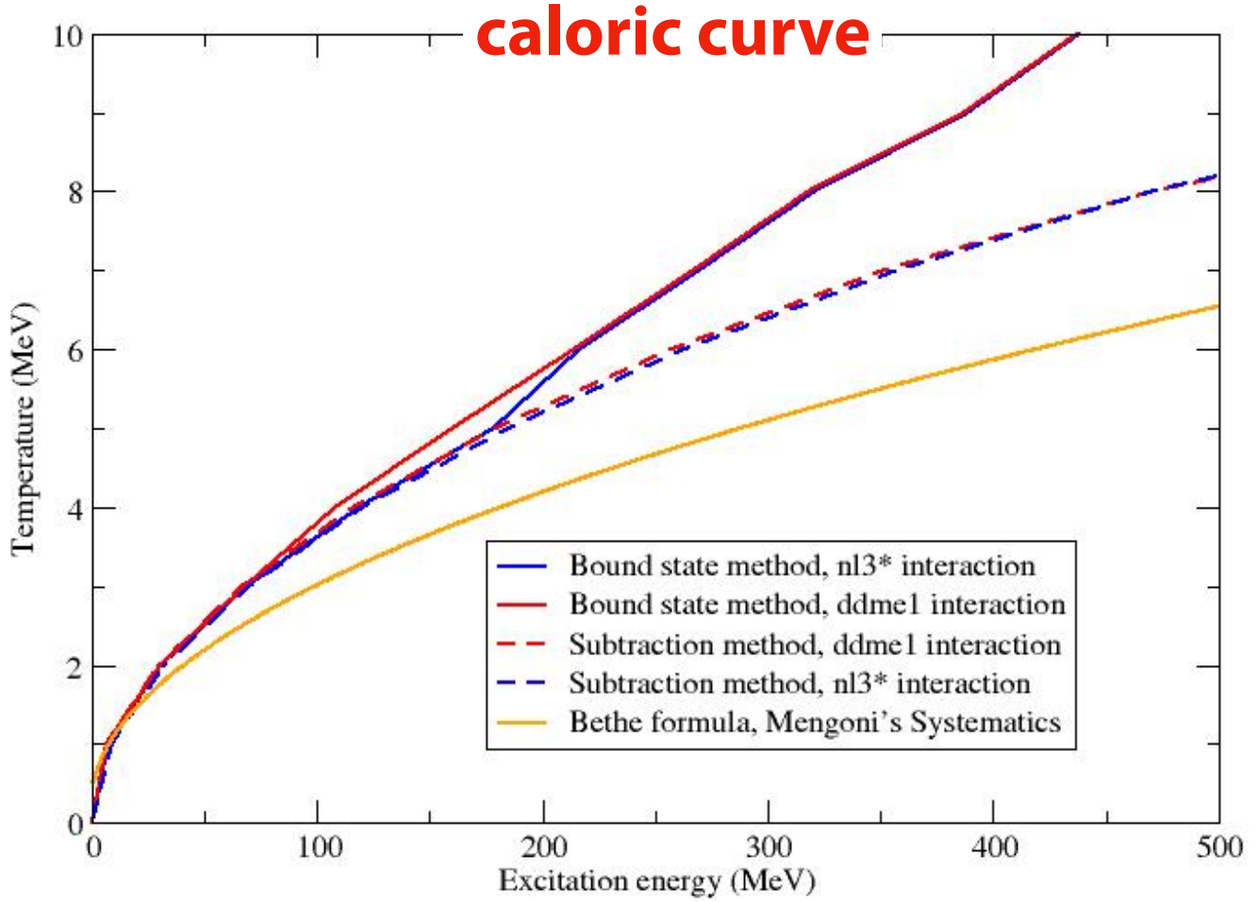

Ni-60
Omega (1/MeV)
1e+07
1e+06
1e+05
10000
10
12
14
16
18
20
22
24
26
28
30
Excitation energy (MeV)
Lu + 1972
Bound state method, nl3* interaction
Subtraction method, nl3* interaction
Bound state method, ddme1 interaction
Subtraction method, ddme1 interaction

# $^{90}Zr$

- weak dependence on the interaction (non-linear vs. density dependent)
- $\log_{10}$ density of states substantially underestimated respect to phenomenological approaches
- appreciable differences between the two methods for higher excitation energies

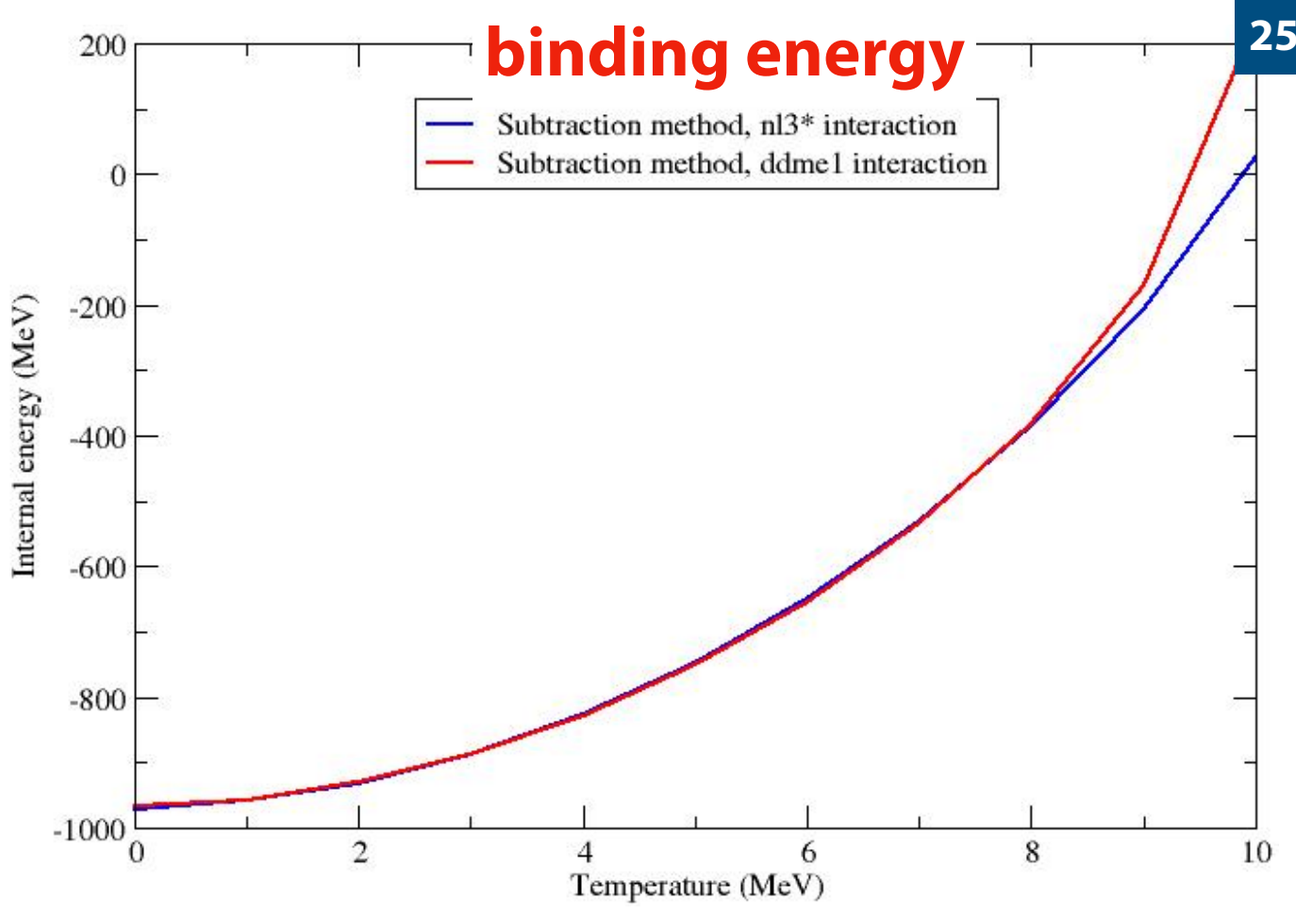


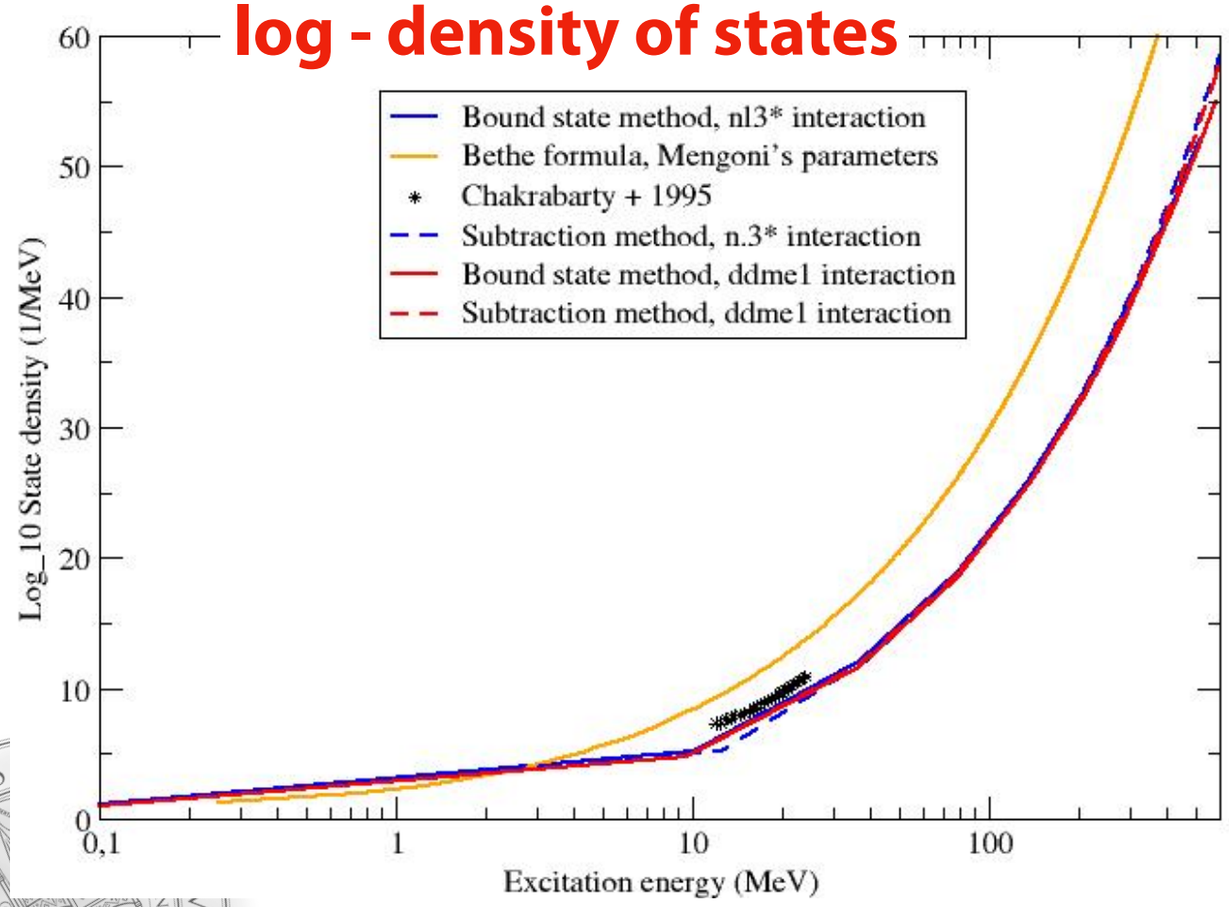



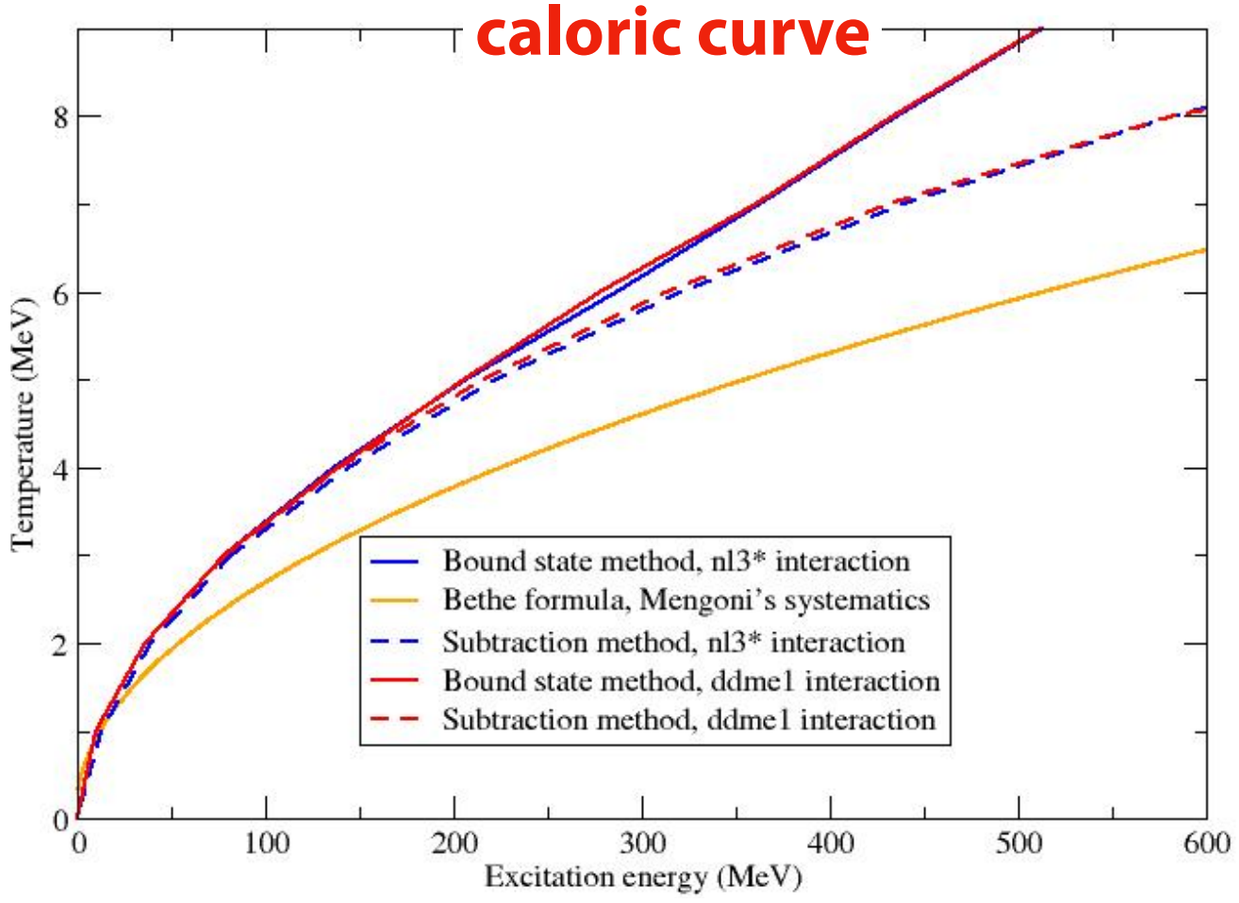



# $^{114}$Sn

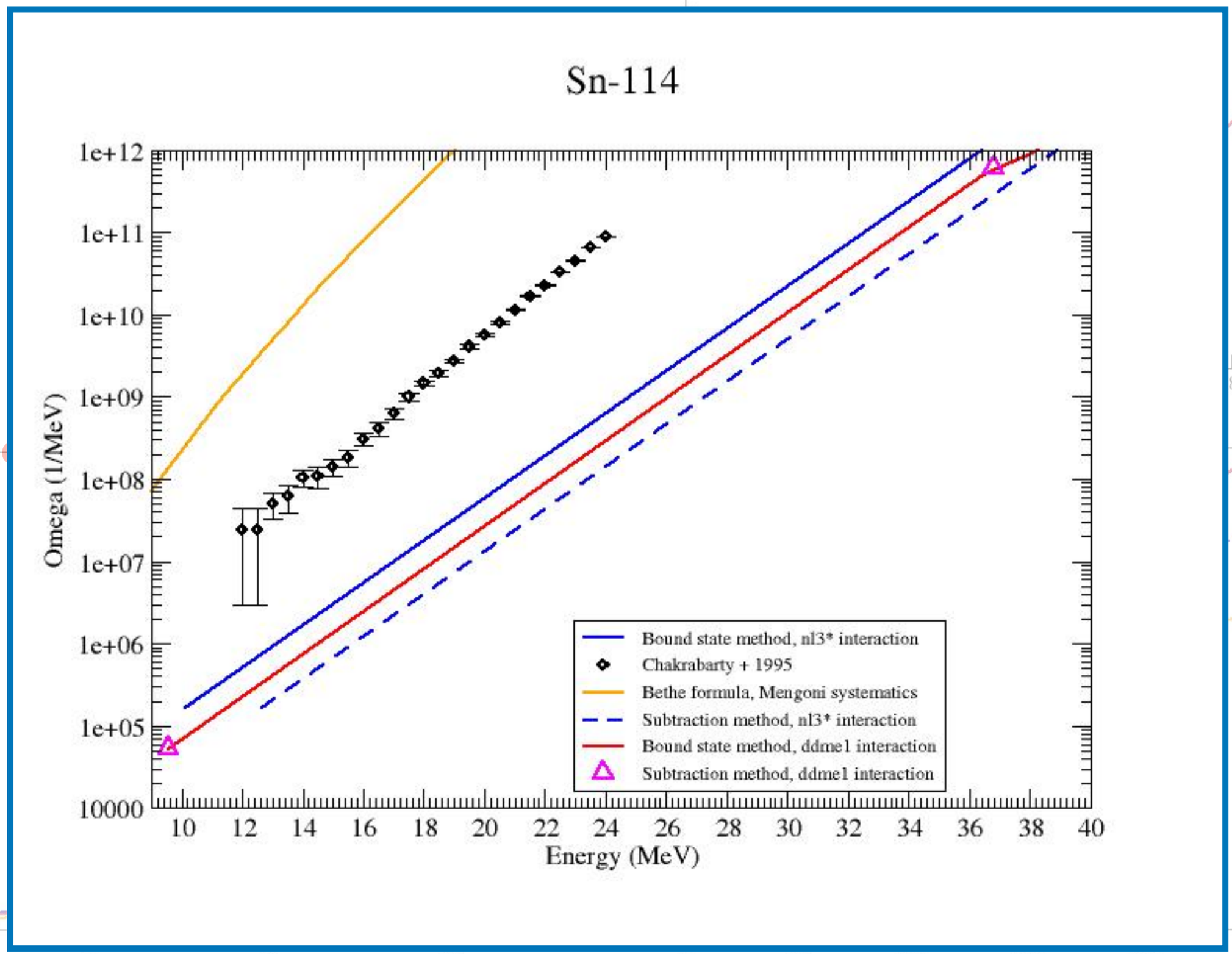
- weak dependence on the interaction (non-linear vs. density dependent)
- $\log_{10}$ density of states closer to phenomenological estimates
- appreciable differences between the two methods for higher excitation energies



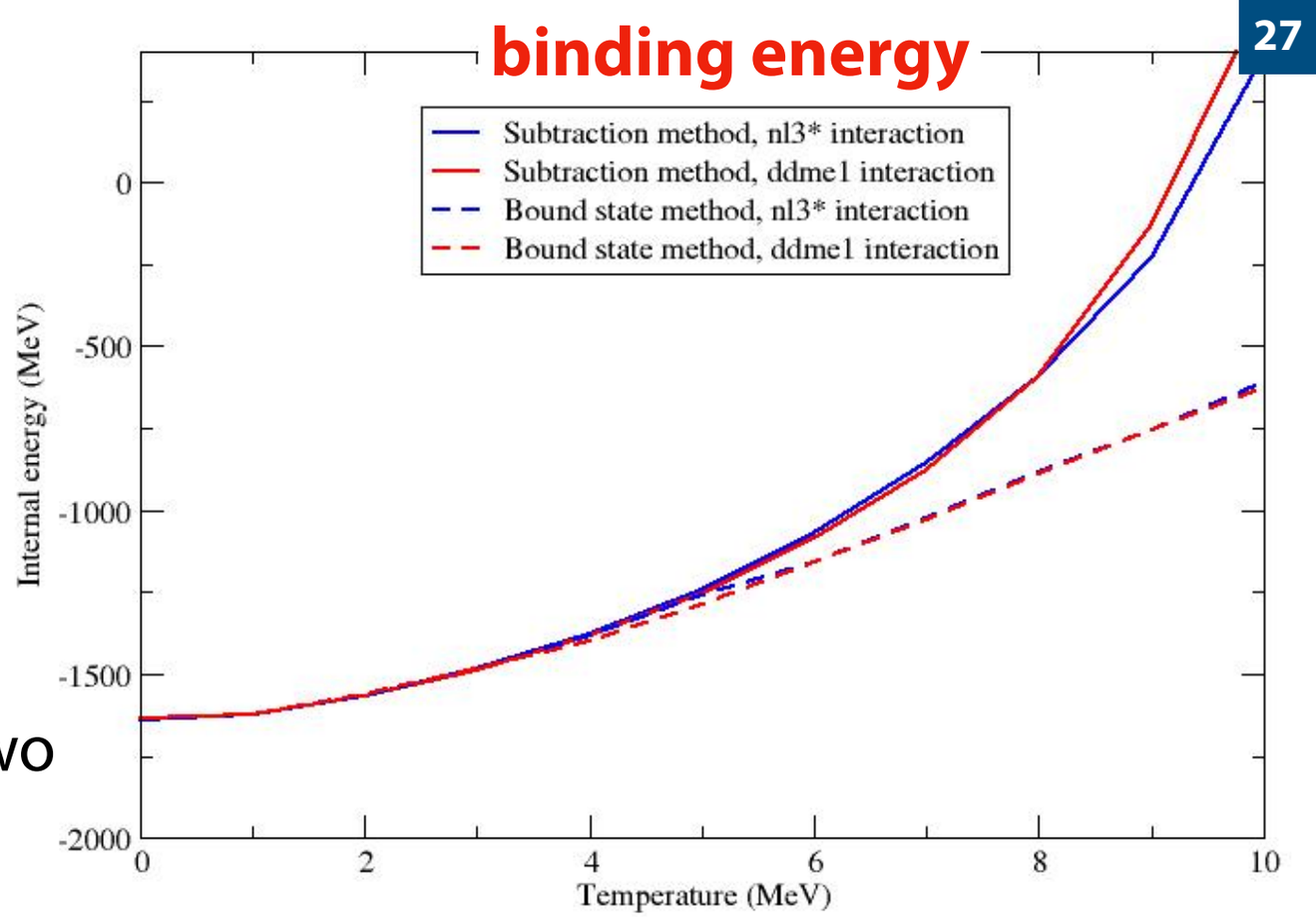



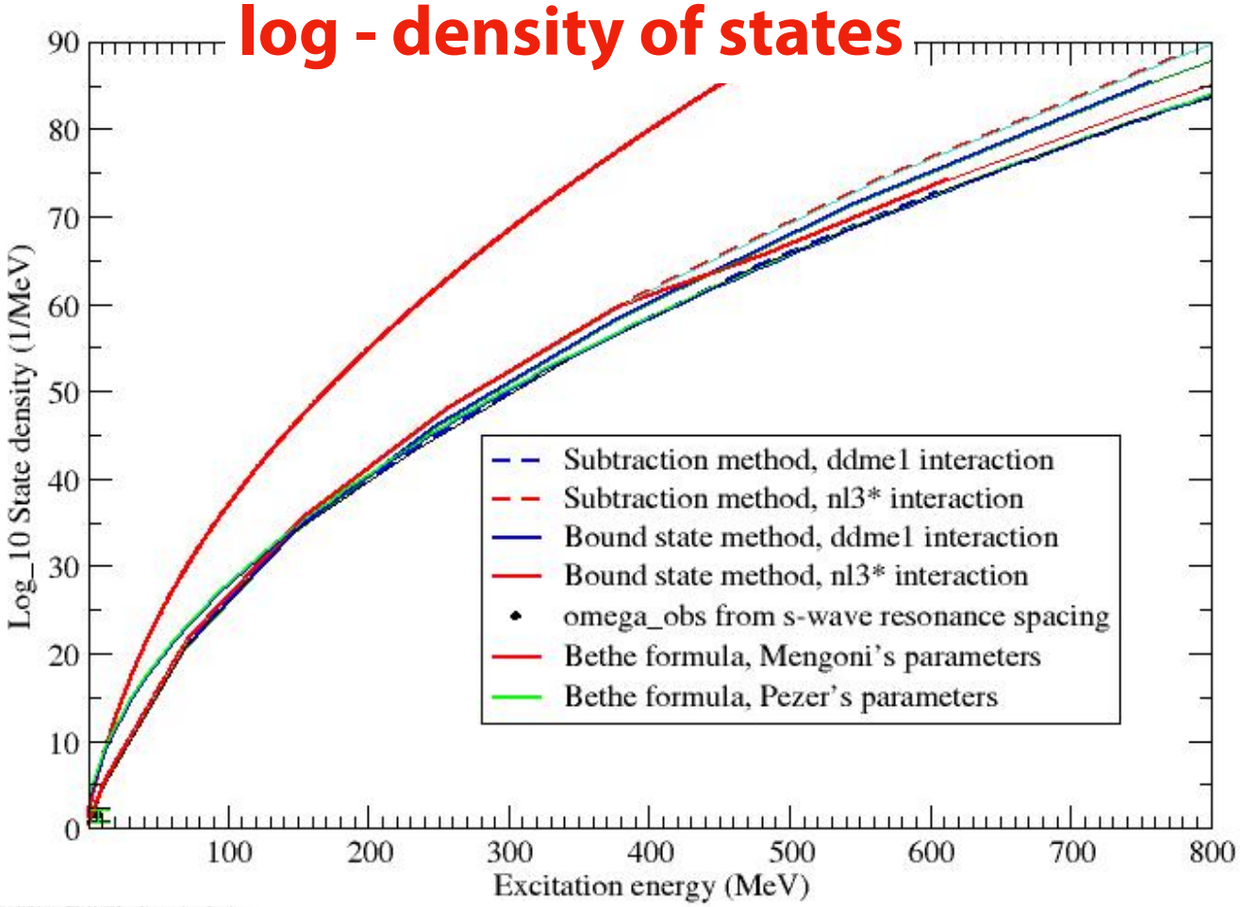
# $^{114}$Sn

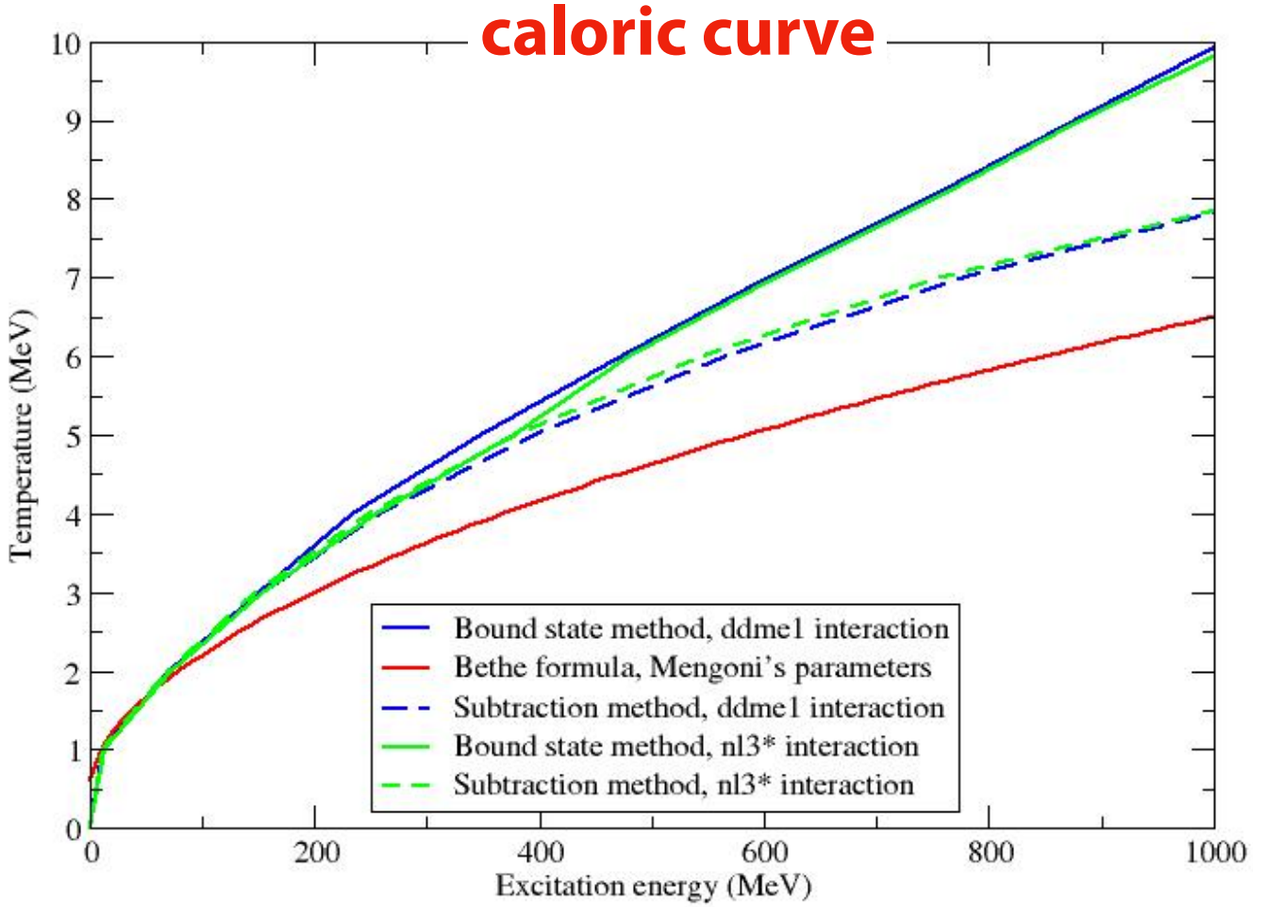

Sn-114
Omega (1/MeV)
1e+12
1e+11
1e+10
1e+09
1e+08
1e+07
1e+06
1e+05
10000
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
Energy (MeV)
Bound state method, nl3* interaction
Chakrabarty + 1995
Bethe formula, Mengoni systematics
Subtraction method, nl3* interaction
Bound state method, ddme1 interaction
Subtraction method, ddme1 interaction

# $^{208}$Pb

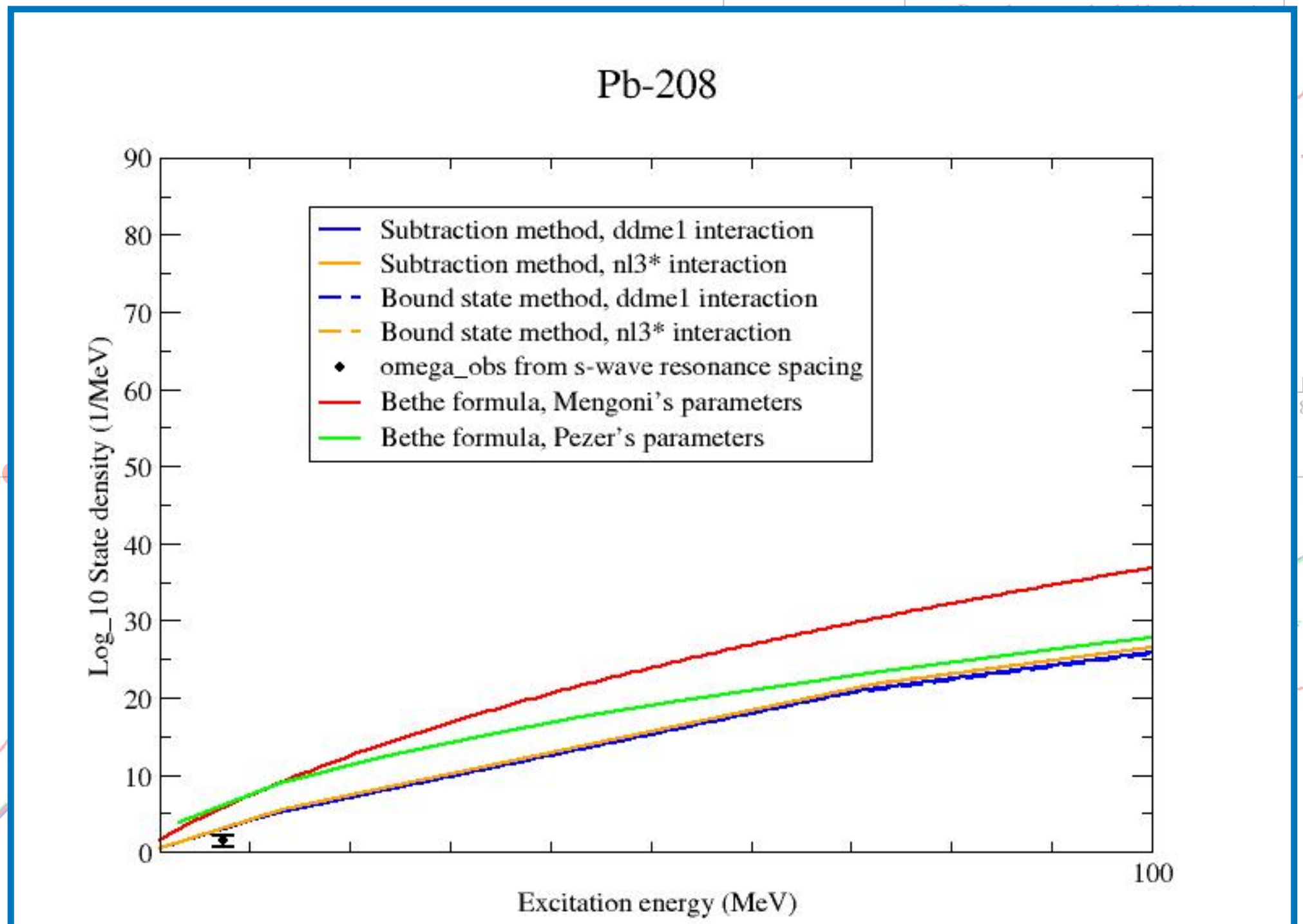
- mild dependence on the interaction (non-linear vs. density dependent)
- $\log_{10}$ density of states substantially underestimated respect to phenomenological approaches (Mengoni but not Pezer)
- appreciable differences between the two methods for higher excitation energies



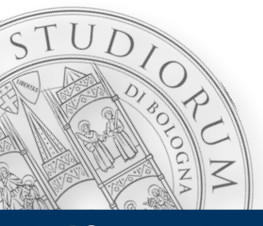



# $^{208}$Pb

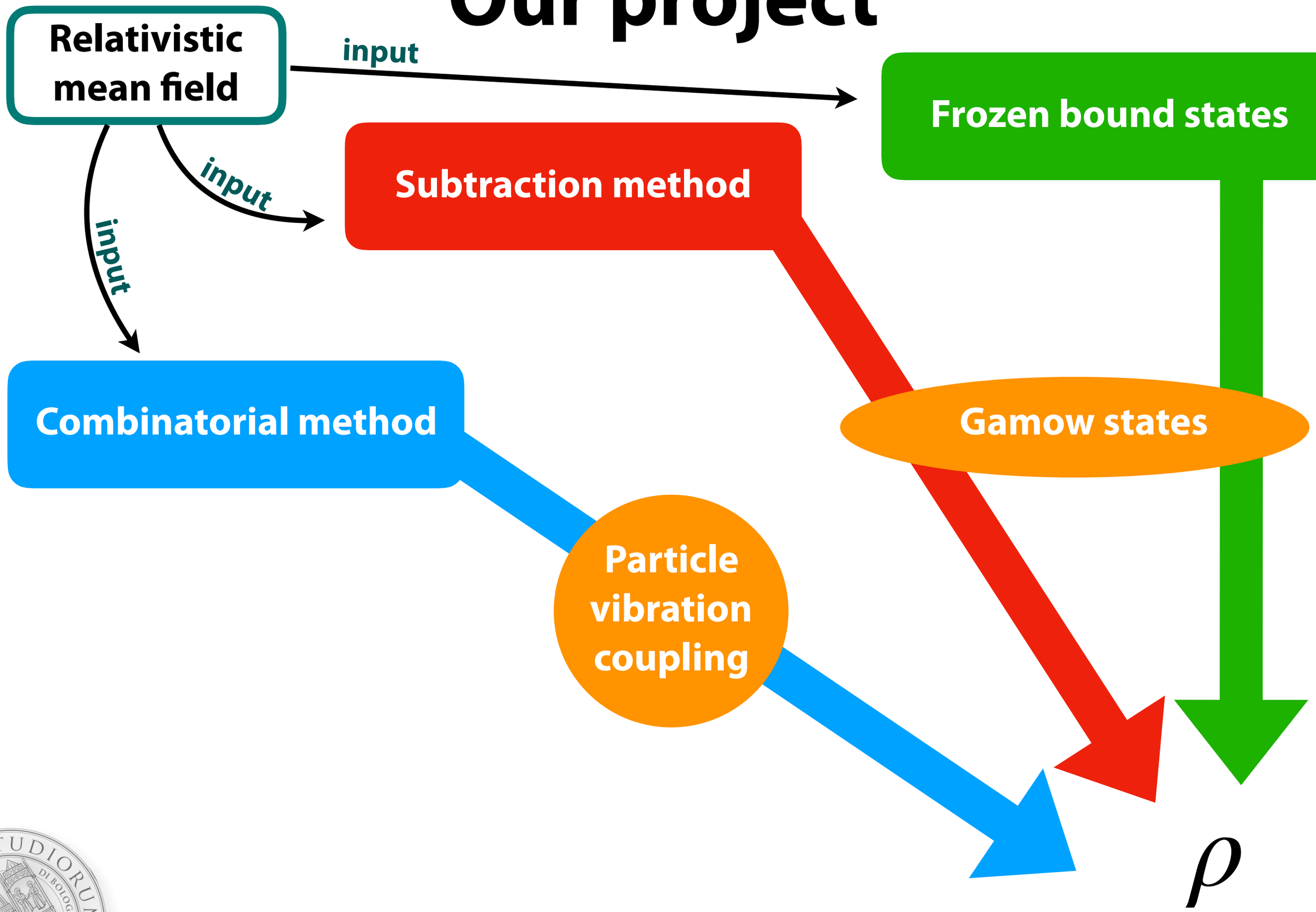

Pb-208
Subtraction method, ddme1 interaction
Subtraction method, nl3* interaction
Bound state method, ddme1 interaction
Bound state method, nl3* interaction
omega_obs from s-wave resonance spacing
Bethe formula, Mengoni's parameters
Bethe formula, Pezer's parameters
Log_10 State density (1/MeV)
Excitation energy (MeV)
0
10
20
30
40
50
60
70
80
90
100

# Open issues

1. Importance of the **effective mass**
2. **Non negligible widths** for resonance states
3. Corrections for low excitation energies
4. Extension of the combinatorial approach to higher energies



# Our project


Relativistic mean field
input
input
input
Frozen bound states
Subtraction method
Combinatorial method
Gamow states
Particle vibration coupling
$\rho$

# Extensions - CSM (work in progress)

## Complex scaling method

Y. K. Ho, Phys. Rep. **99**, 1 (1983); A. T. Kruppa et al., Phys. Rev. C **37**, 383 (1988); Guo et al., CPC **181**, 500 (2010), Guo et al., PRC **82**, 034318 (2010)

The starting point of the CSM is a transformation of the Hamiltonian ***H***. First one defines the unbounded non-unitary scaling operator ***U(θ)*** where ***θ*** is real

$$U(\theta) = \begin{pmatrix} e^{i\theta\hat{S}} & 0 \\ 0 & e^{i\theta\hat{S}} \end{pmatrix} \qquad \hat{S} = r\frac{\partial}{\partial r}$$

The transformed complex scaled Hamiltonian is of the form

$$H_\theta = \begin{pmatrix} V(re^{i\theta}) + S(re^{i\theta}) + M & e^{-i\theta}(-\frac{d}{dr} - \frac{1}{r} + \frac{\kappa}{r}) \\ e^{-i\theta}(\frac{d}{dr} + \frac{1}{r} + \frac{\kappa}{r}) & V(re^{i\theta}) - S(re^{i\theta}) - M \end{pmatrix}$$

The corresponding complex scaled equation is

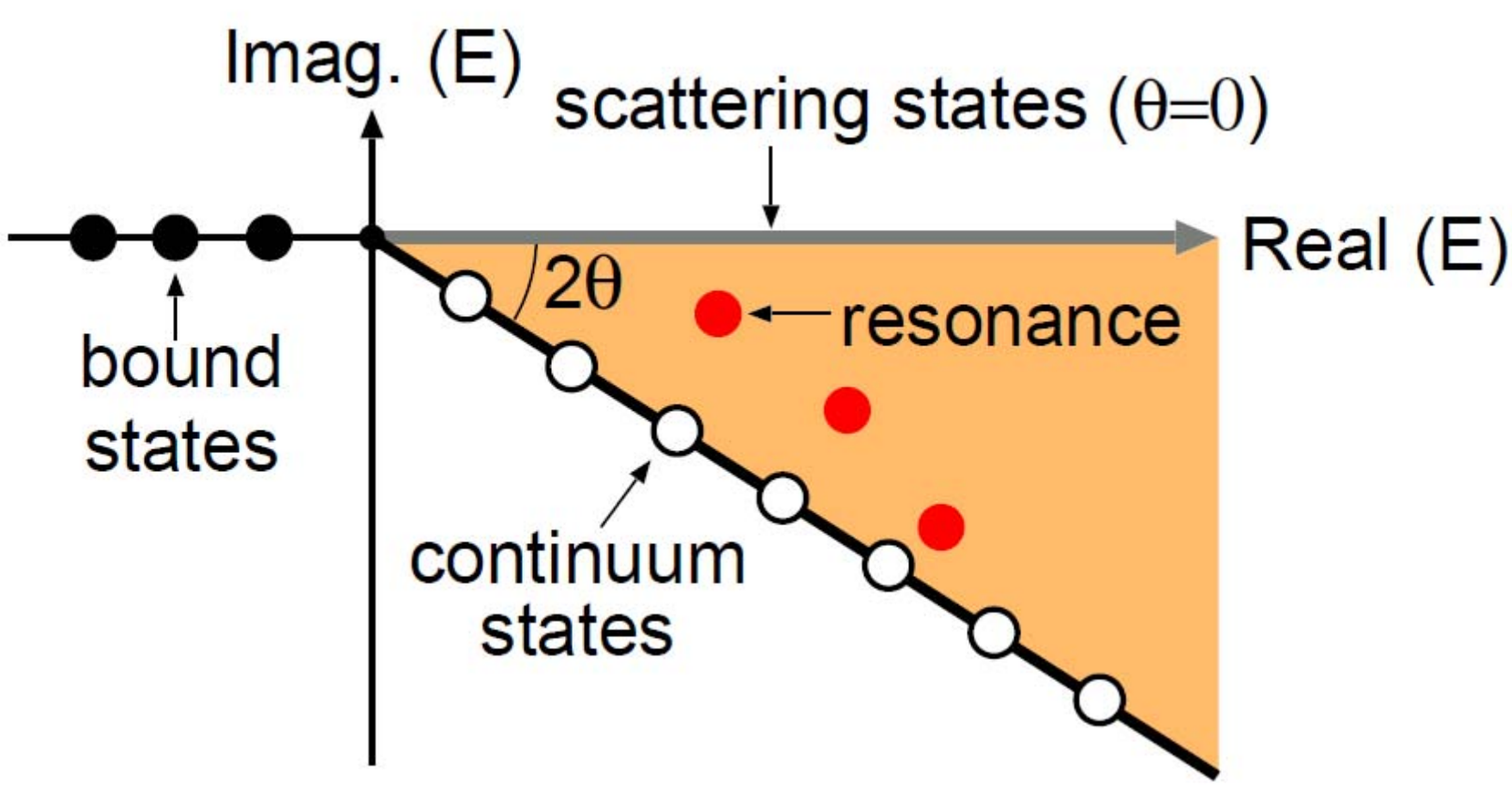
$$H_\theta\psi_\theta = \epsilon_\theta\psi_\theta$$

# Extensions - CSM (work in progress)

## Complex scaling method

Y. K. Ho, Phys. Rep. **99**, 1 (1983); A. T. Kruppa et al., Phys. Rev. C **37**, 383 (1988); Guo et al., CPC **181**, 500 (2010), Guo et al., PRC **82**, 034318 (2010)

- A bound state eigenvalue of $H$ remains also an eigenvalue of $H_\Theta$
- A **resonance pole $\varepsilon = E - i\Gamma/2$** of the Green-operator of H is an eigenvalue of $H_\Theta$
- The continuous part of the spectrum of $H_\Theta$ is rotated down into the complex energy plane by the angle $\theta$

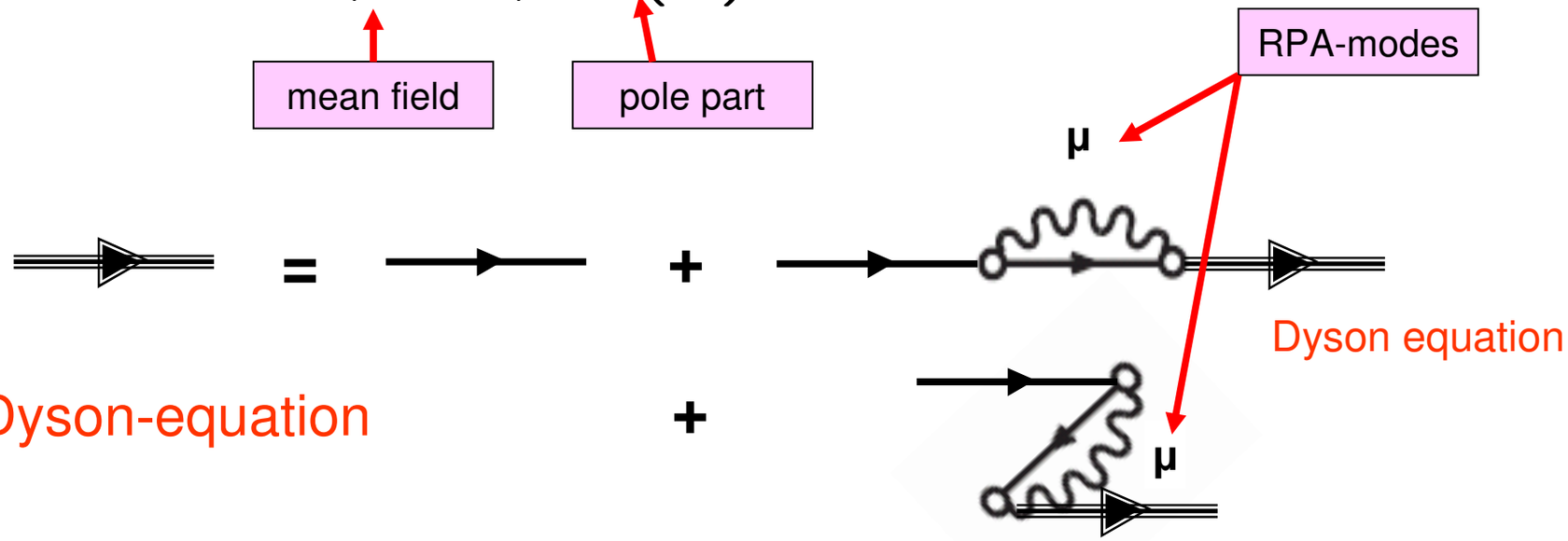


# Extensions - PVC (work in progress)

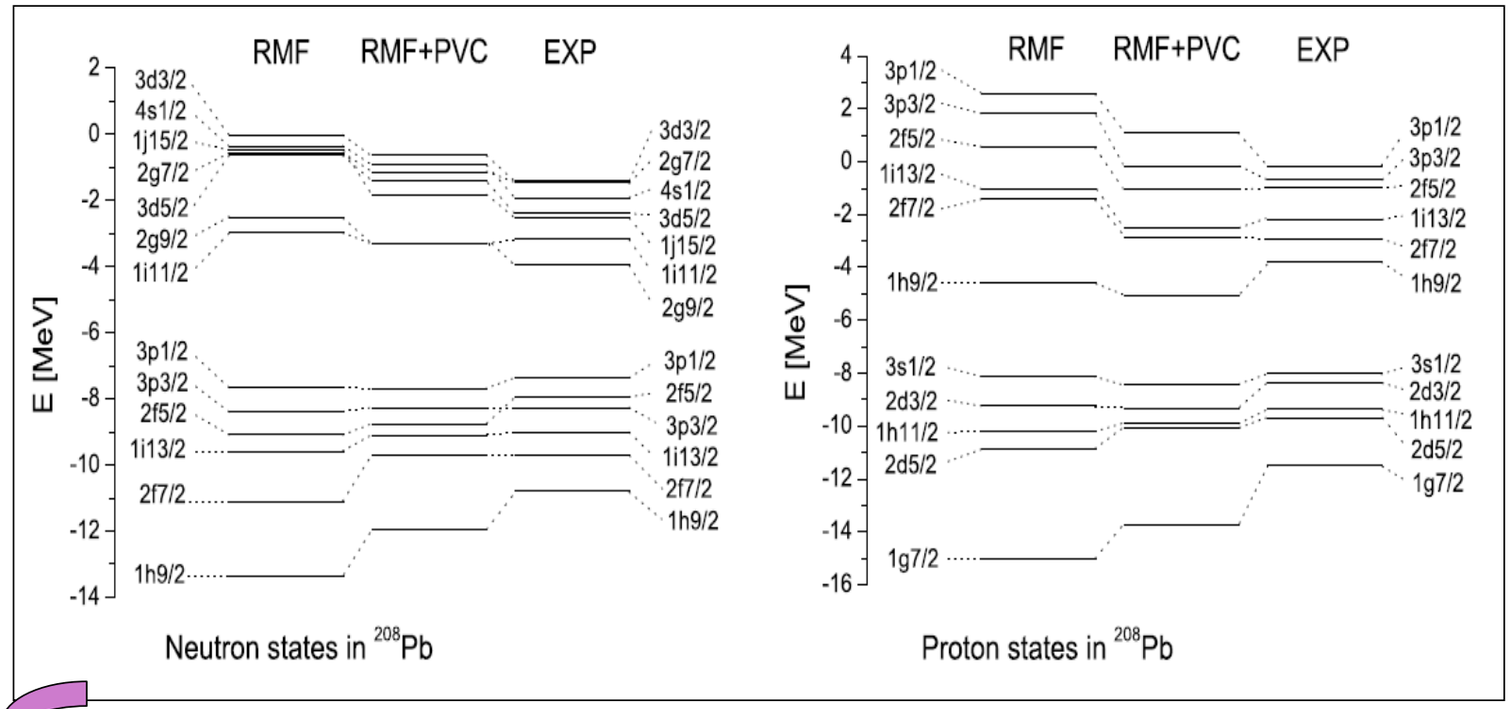
Litvinova and Ring, PRC **73**, 44328 (2006), Ring talk @ 2011 KLFTP-BLTP Joint Workshop

$$\Sigma = S + V + \Sigma(\omega)$$

mean field | pole part




The density of states above and below the Fermi surface is increased




$m_{eff}$ 0.76 0.92 1.0 0.71 0.85 1.0

# *Thank you very much*