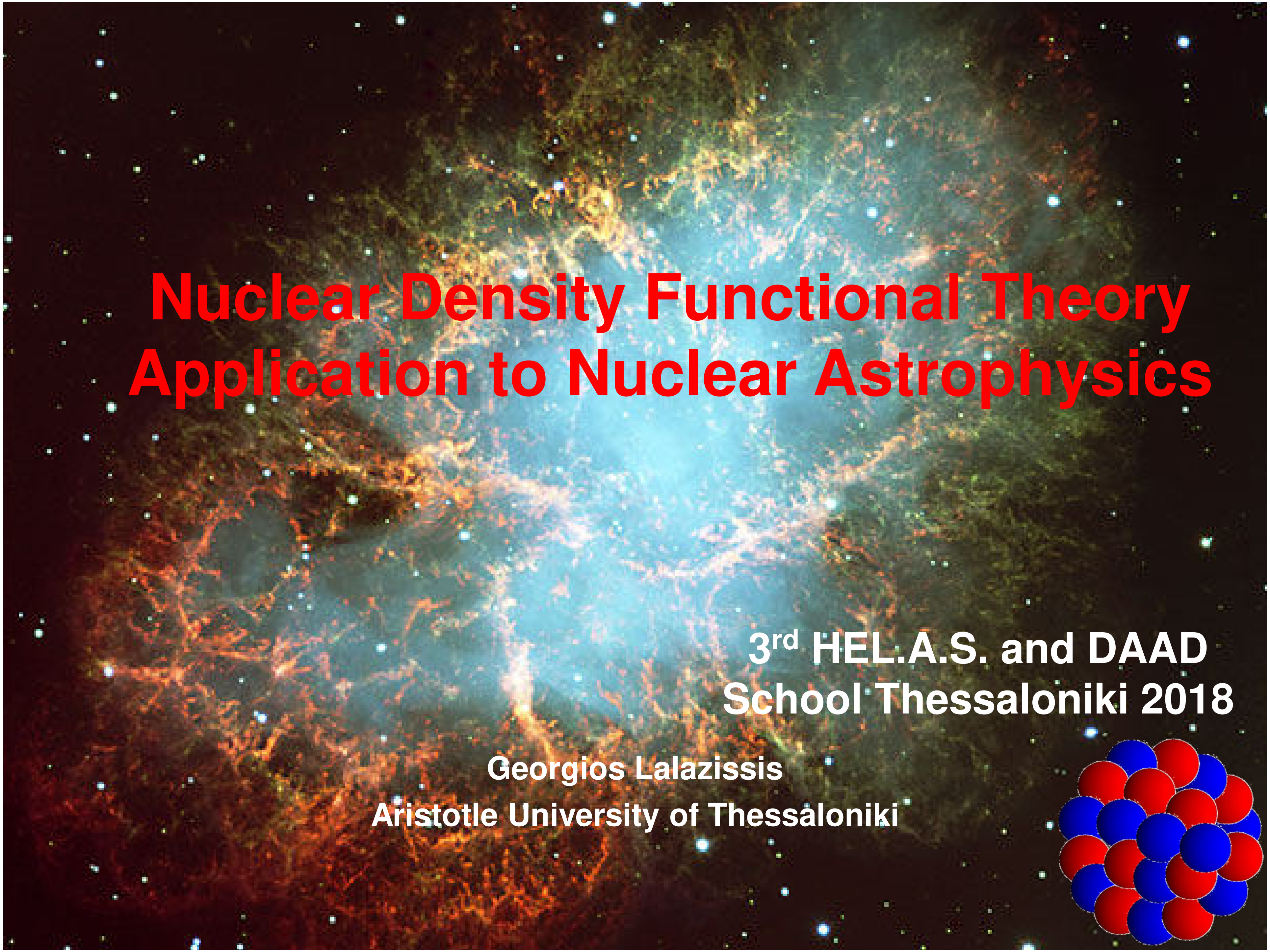
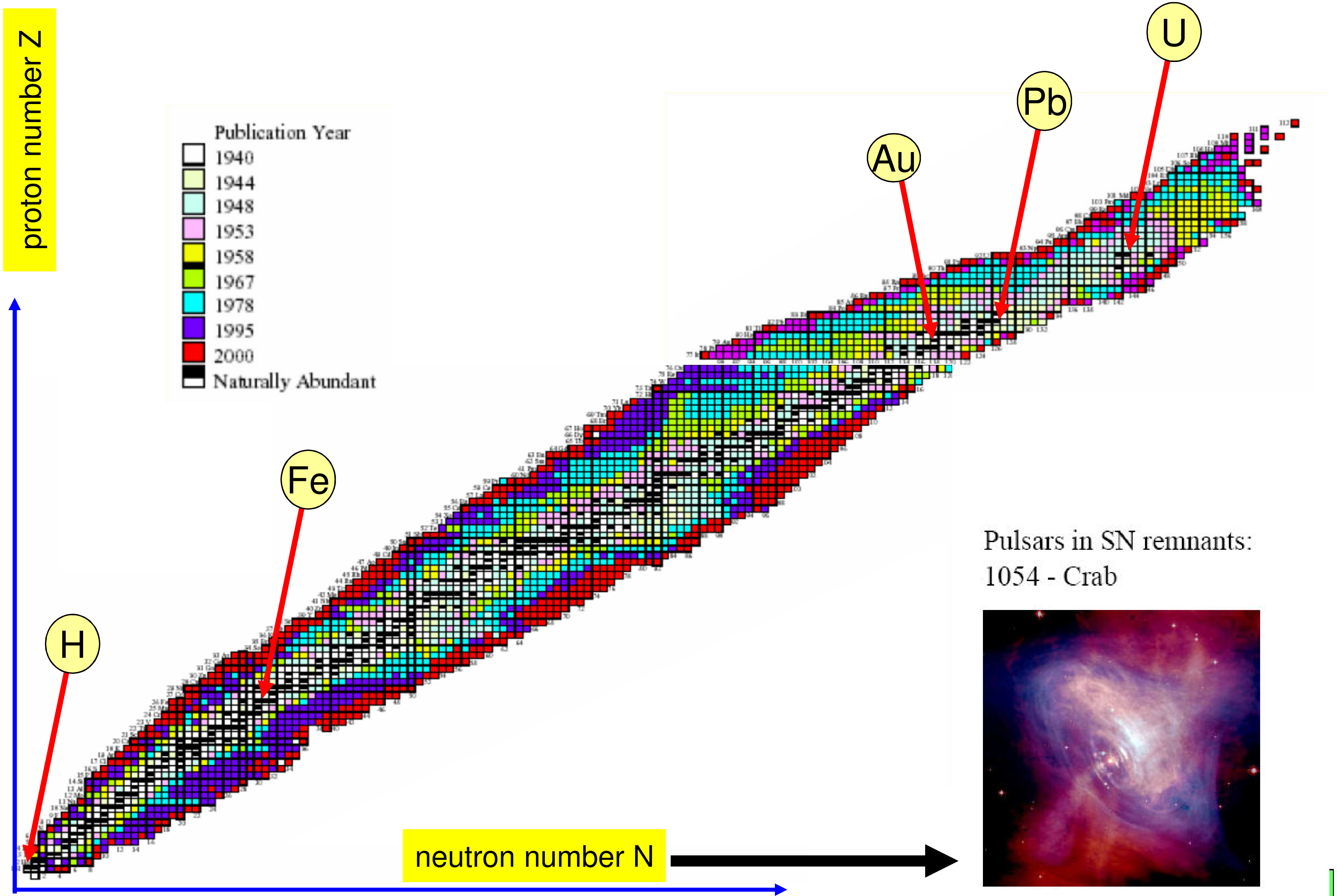


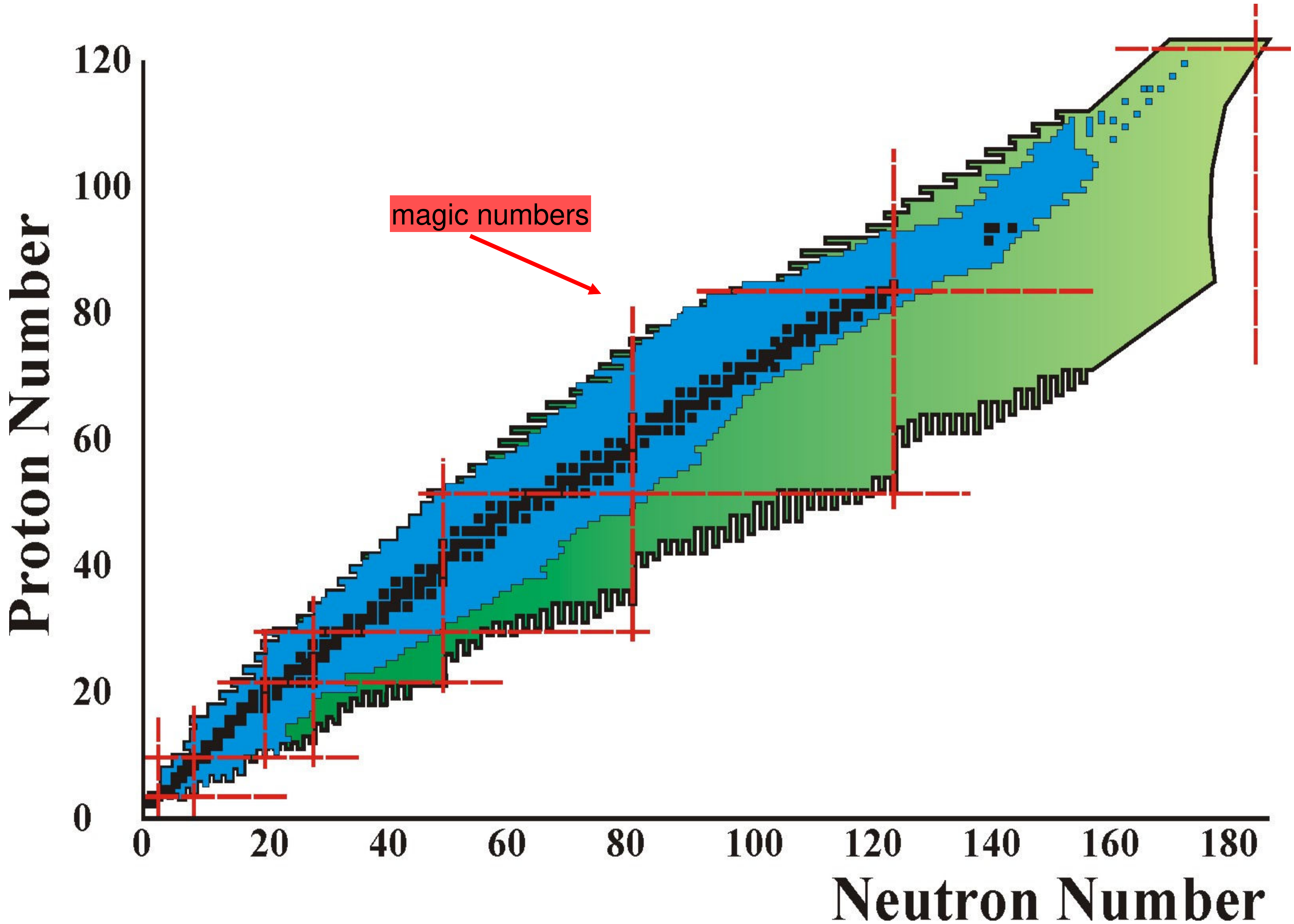
Nuclear Density Functional Theory
Application to Nuclear Astrophysics

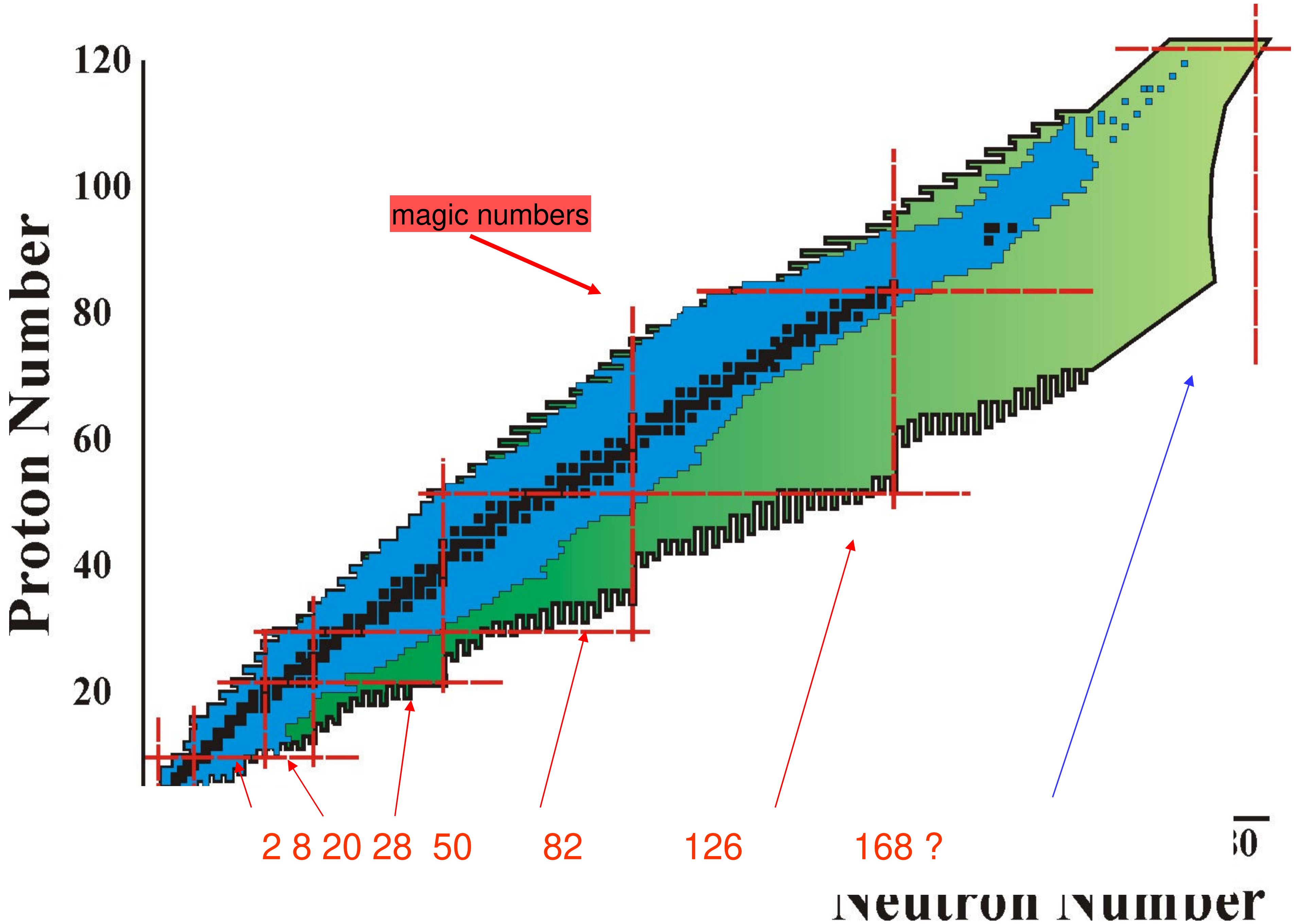
3rd HEL.A.S. and DAAD
School Thessaloniki 2018

Georgios Lalazissis
Aristotle University of Thessaloniki

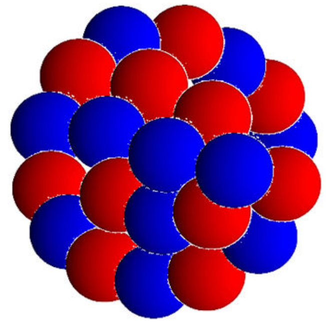


Pulsars in SN remnants:
1054 - Crab


magic numbers
Proton Number
Neutron Number
0
20
40
60
80
100
120
0
20
40
60
80
100
120
140
160
180


120
100
80
60
40
20
Proton Number
magic numbers
2 8 20 28 50 82 126 168 ?
Neutron Number

Forces acting in the nucleus:

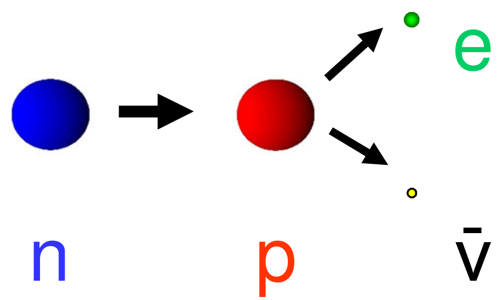


the **Coulomb force** repels the protons

the **strong interaction** ("nuclear force") causes binding
is stronger for pn-systems than nn-systems

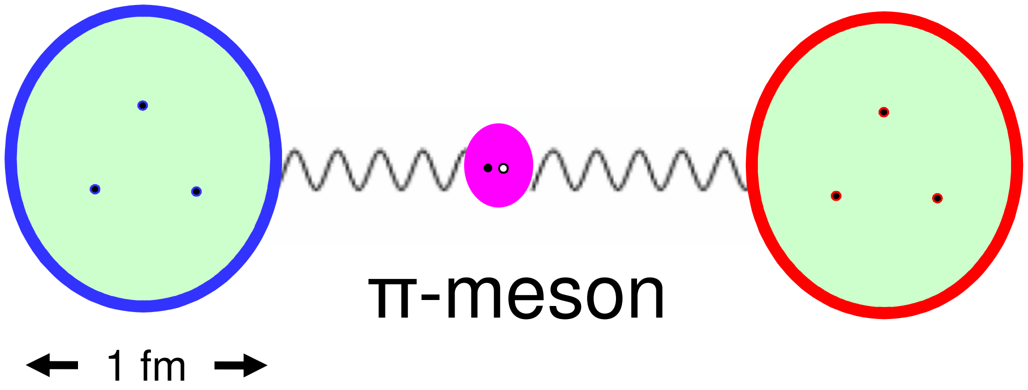
neutrons alone form no bound states
exception: neutron stars (**gravitation**!)

the **weak interaction** causes β-decay:

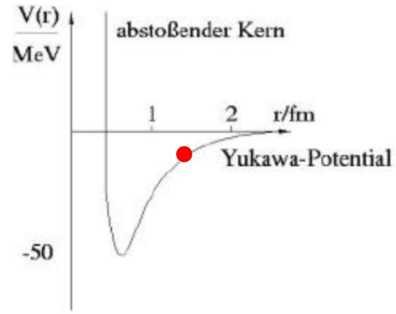


the nucleon-nucleon interaction:

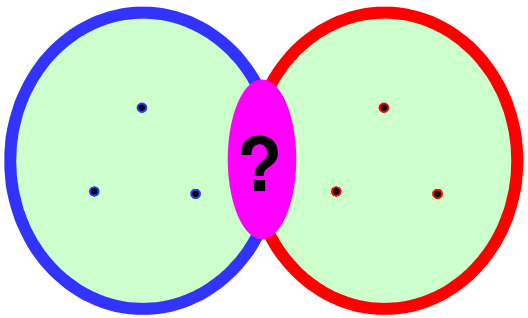
distance > 1 fm



attractive

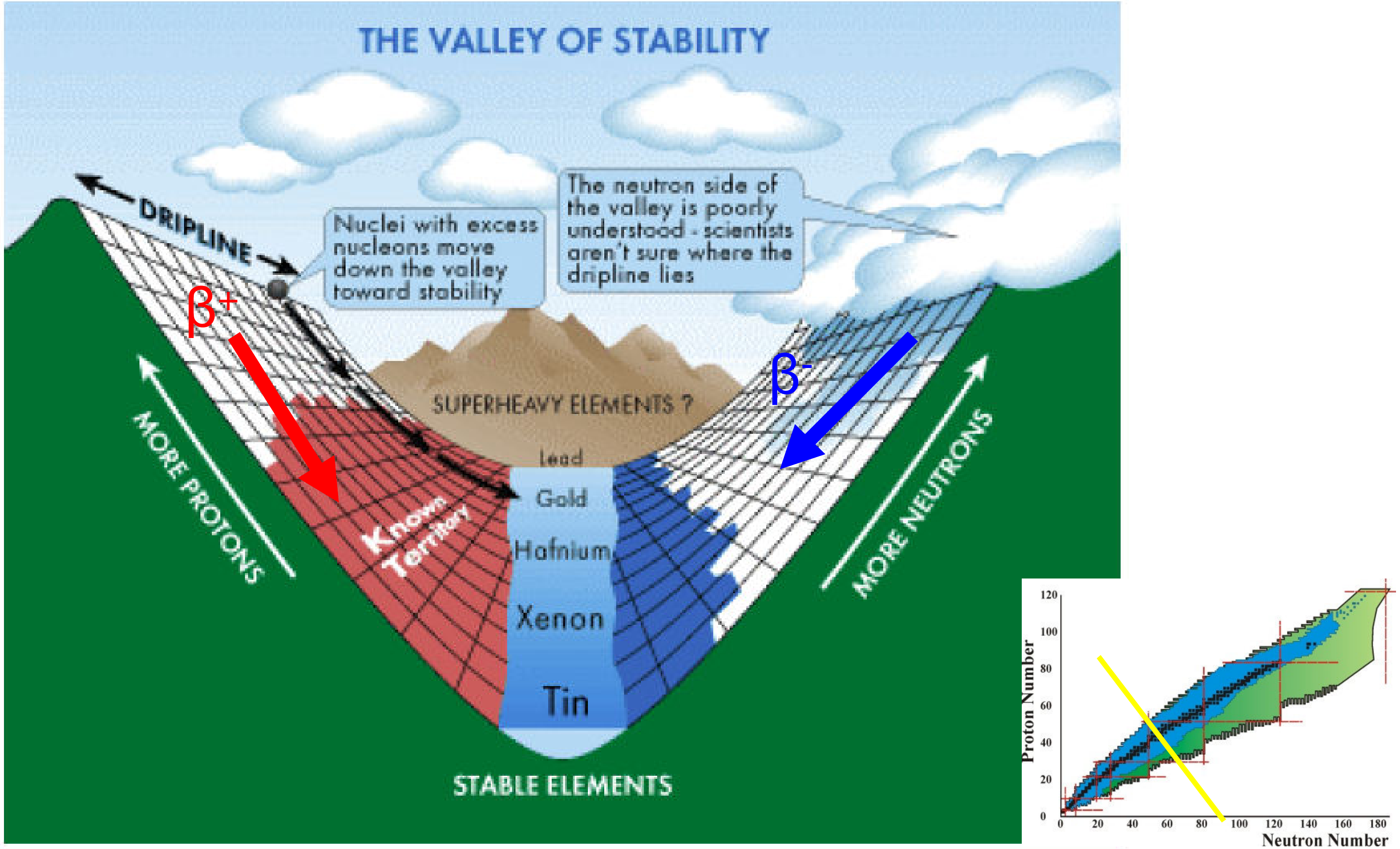


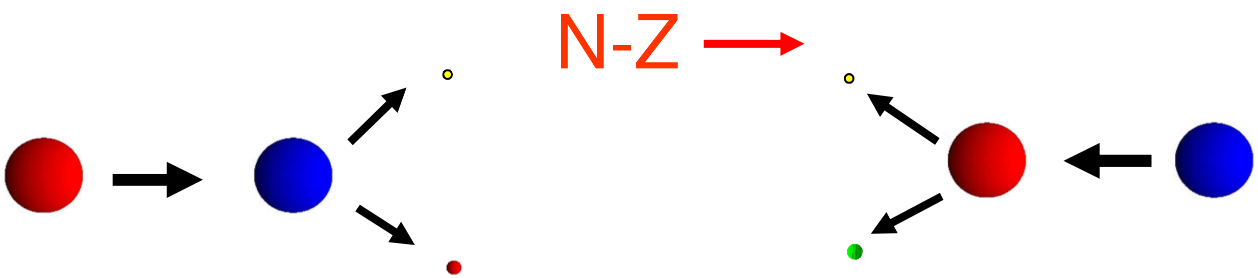
distance < 0.5 fm



repulsive

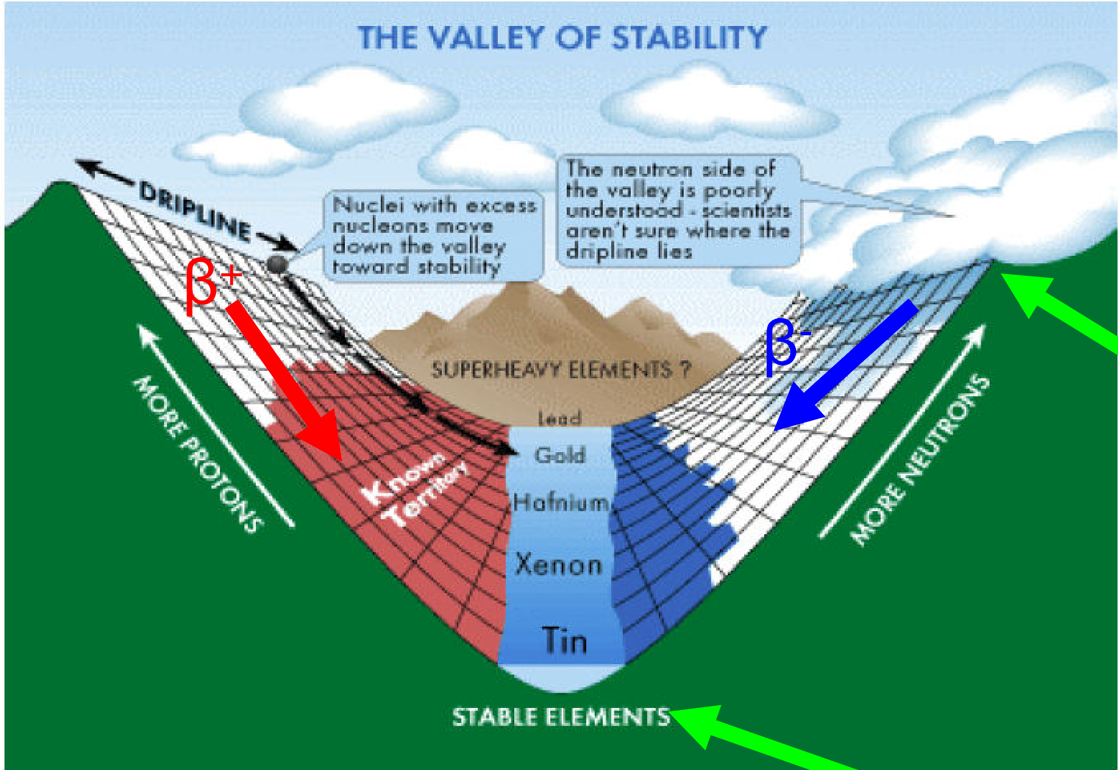
three-body forces ?

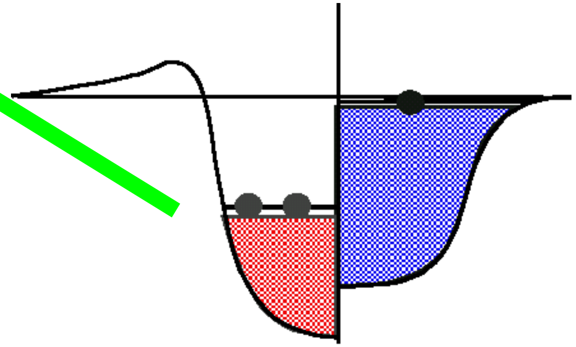




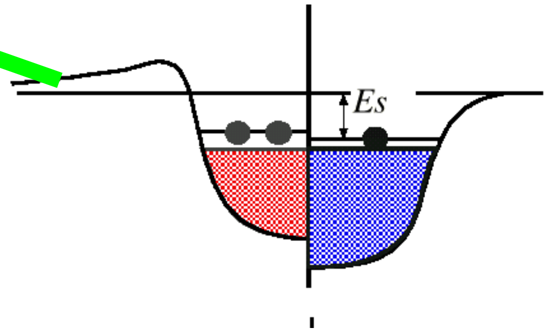
β^+ decay

β^- decay

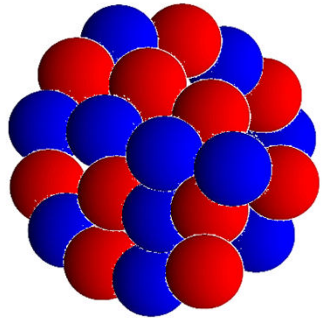

THE VALLEY OF STABILITY
DRIPLINE
Nuclei with excess nucleons move down the valley toward stability
The neutron side of the valley is poorly understood - scientists aren't sure where the dripline lies
β+
β-
SUPERHEAVY ELEMENTS ?
Lead
Gold
Hafnium
Xenon
Tin
Known Territory
MORE PROTONS
MORE NEUTRONS
STABLE ELEMENTS

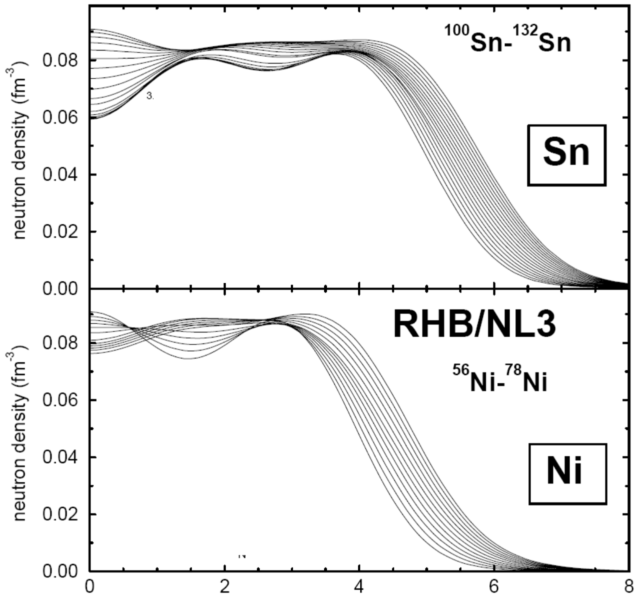


N-Z →

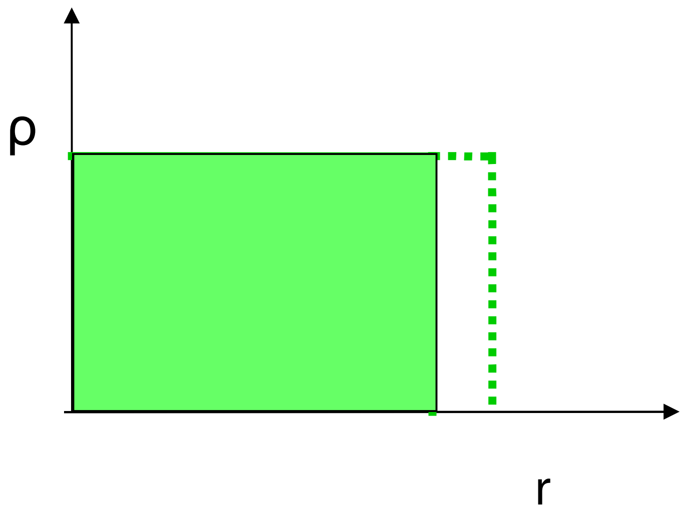

Es

the nuclear density: ρ(r)



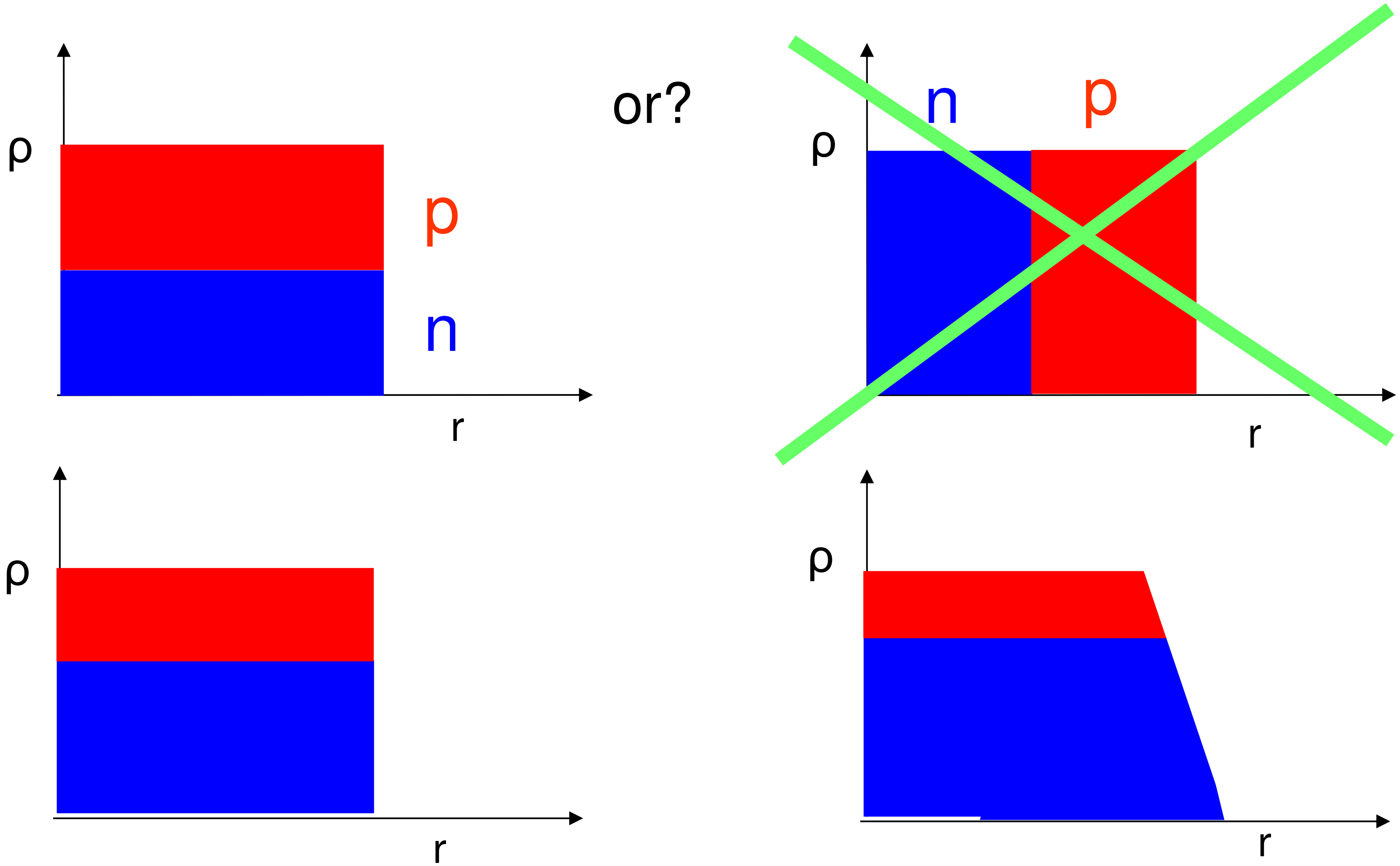


simplified representation:



ρ=1.6 nucleons/fm^3

proton and neutron densities



small neutron excess

large neutron excess

Nuclei far from stability: what can we learn?

- the origin of more than half of the elements with Z>30

- constraints on effective nuclear interactions

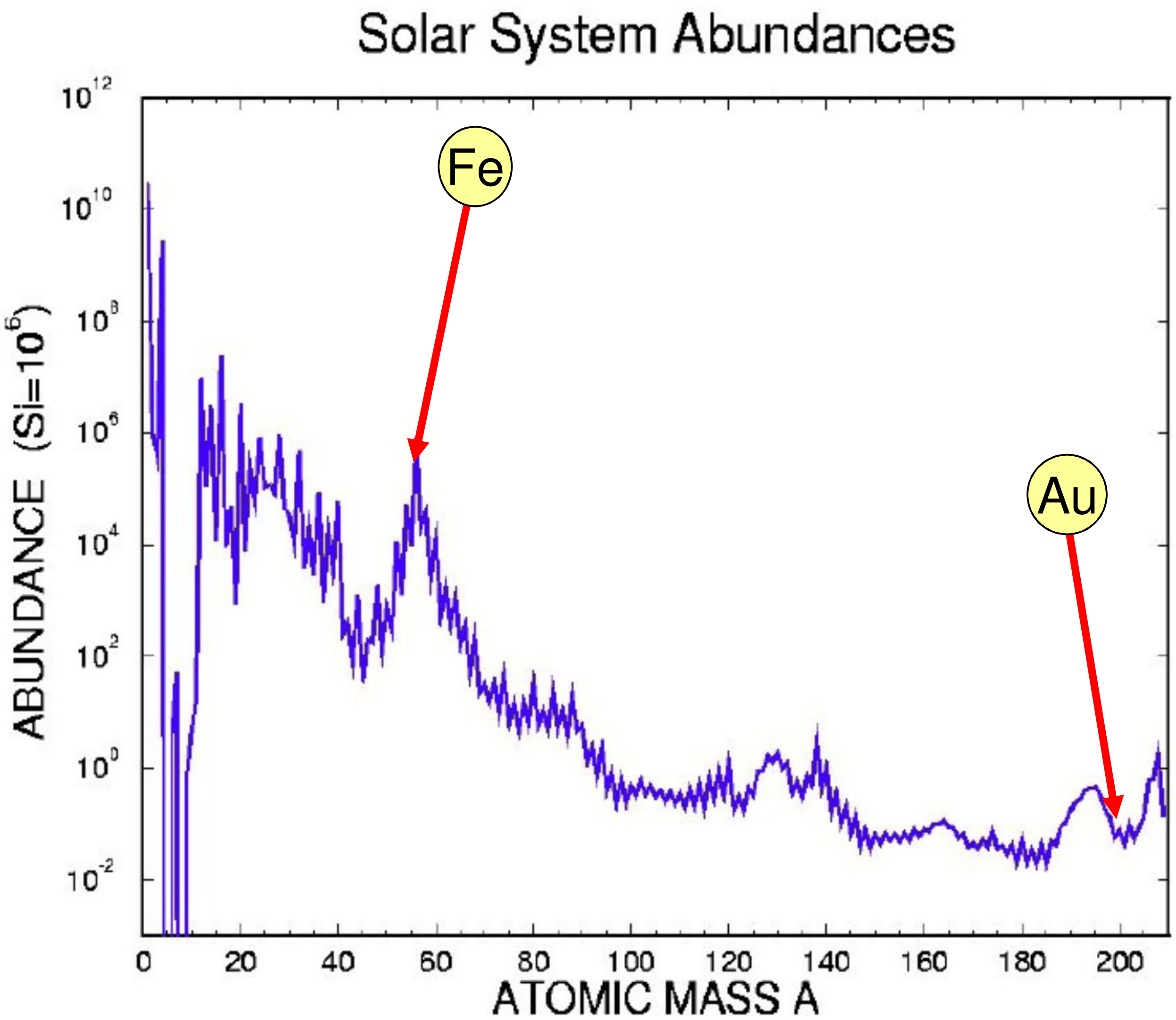
- evolution of shell structure

- reduction of the spin-orbit interaction

- properties of weakly-bound and open quantum systems

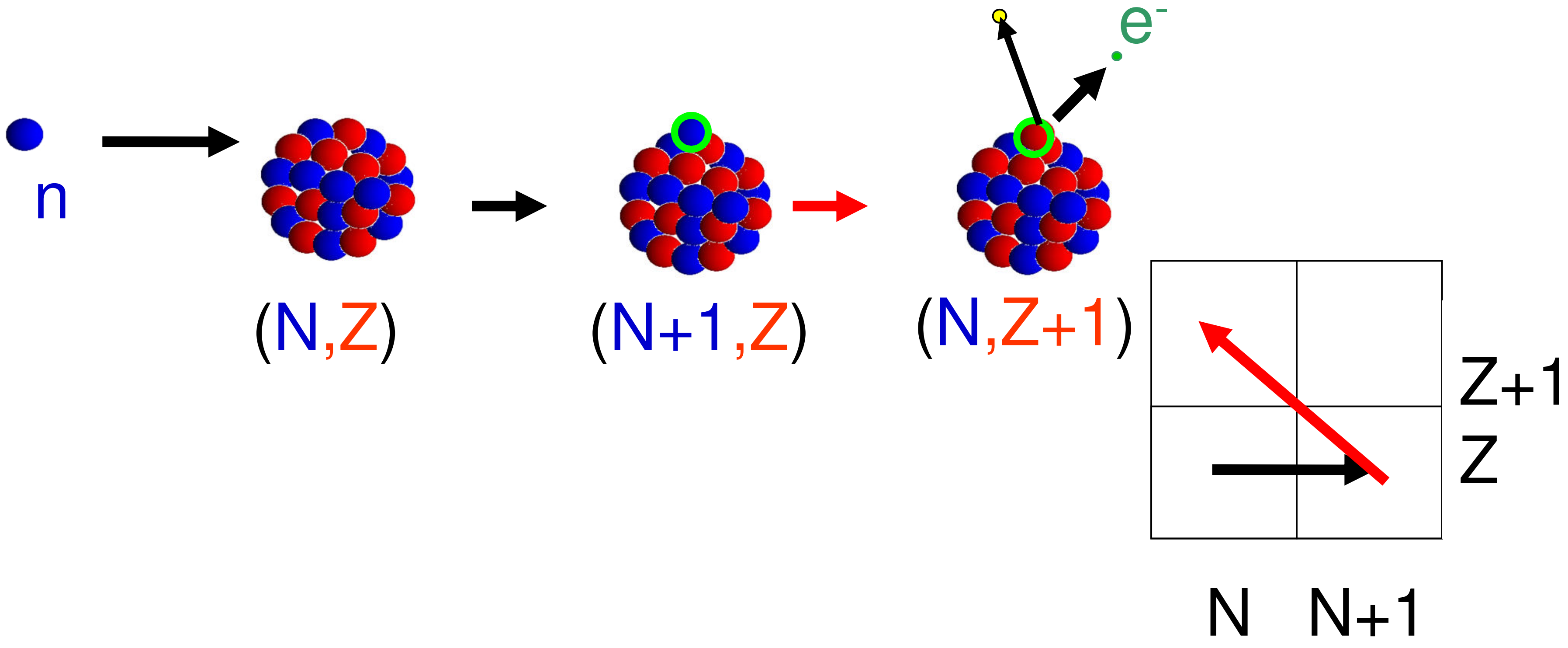
- exotic modes of collective excitations
  (pygmy, toroidal resonances)
- possible new forms of nuclei (molecular states,
  bubble nuclei, neutron droplets...)
- asymmetric nuclear matter equation of state and
  the link to neutron stars
- applications in astrophysics

Abundancies of elements in the solar system

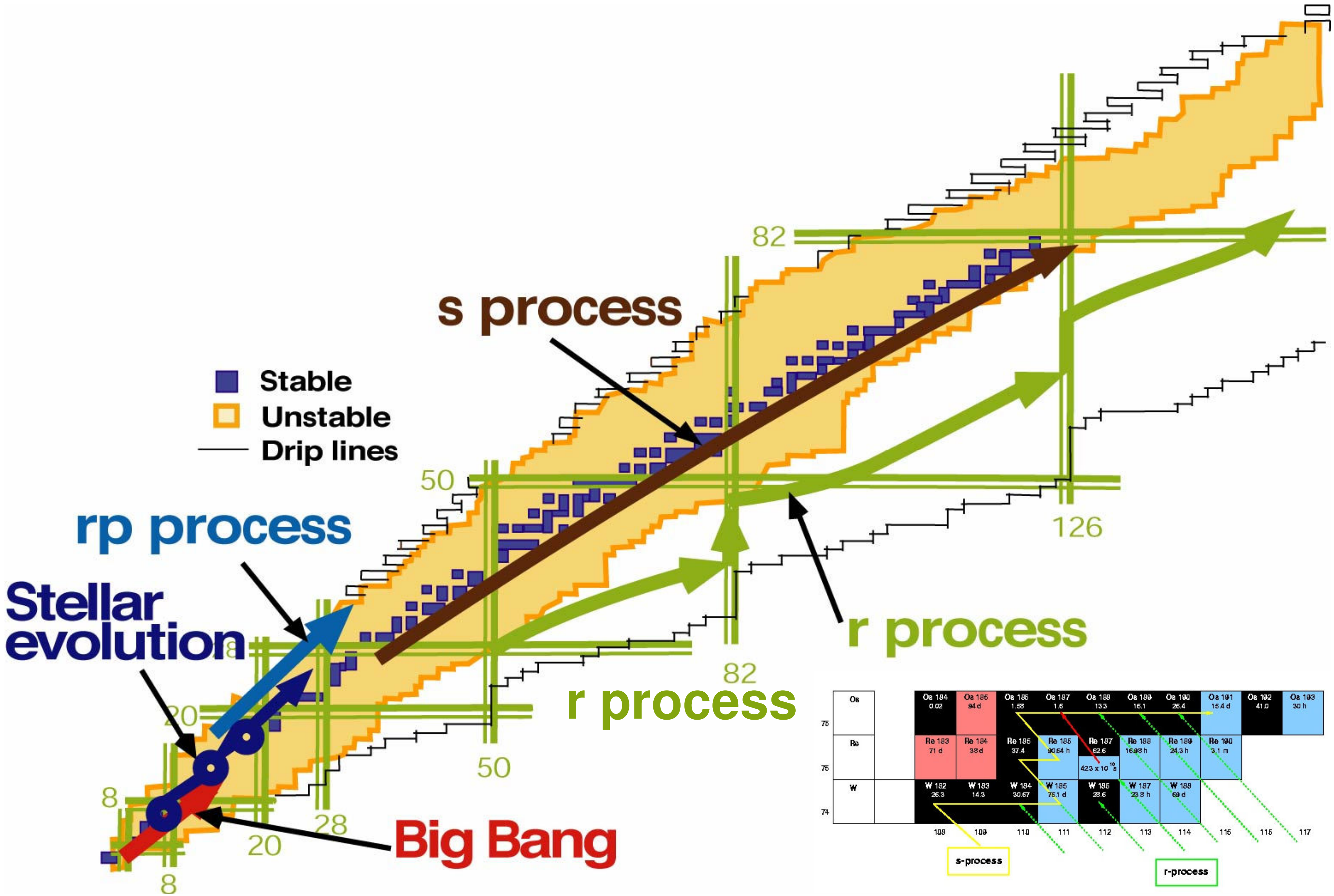


synthesis of heavy elements beyond Fe

neutron capture and successive β⁻decay:



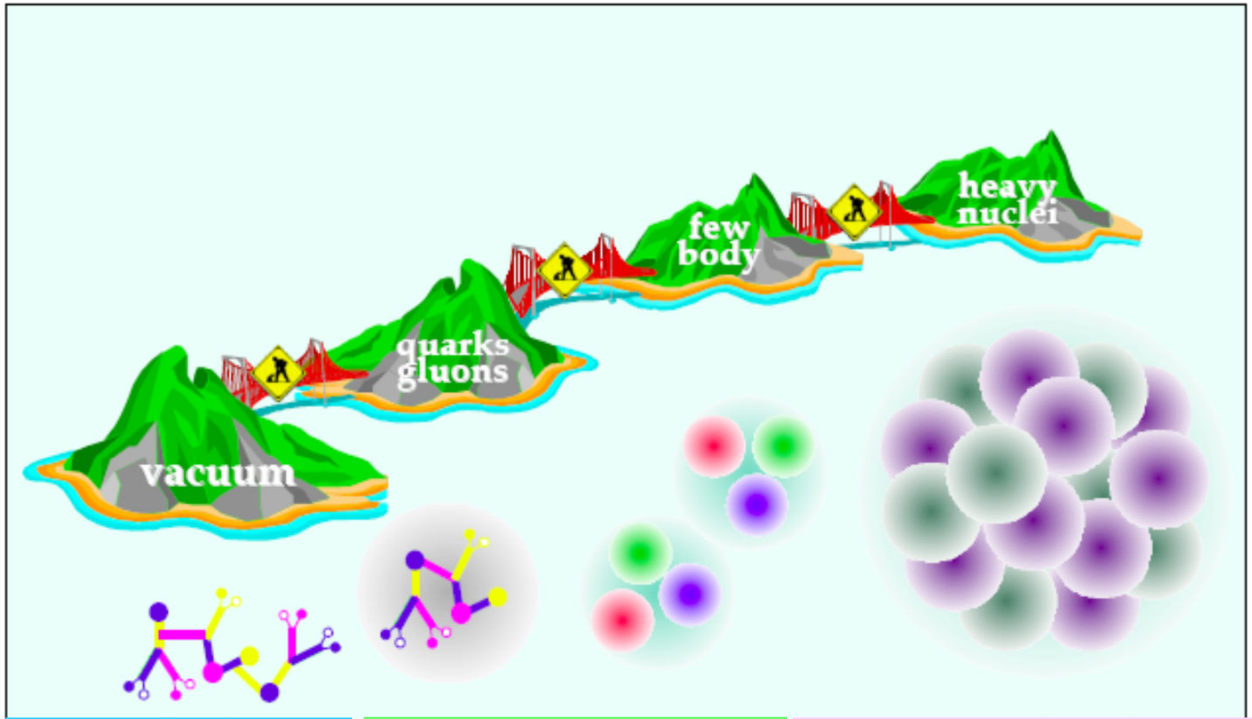
Study of Nucleosynthesis



What do the astrophysicists need ?

- nuclear masses (bindung energies – Q-values)
- equation of state (EOS) of nuclear matter: $E(\rho)$
- isospin dependence $E(\rho_p, \rho_n)$
- nuclear matrix elements (life times of β-decay ..)
- cross section for neutron or electron capture ….
- fission probabilities
- cross sections for neutrino reactions
- …..
- …..

nuclei and QCD?



QCD	NN- forces in the vacuum	effective forces in the nucleus

Scales: 1 GeV 100 keV

density functional theory:

theorem of Hohenberg und Kohn:

The exact energy of a quantum mechanical many body

system is a functional of the local density $\rho(\mathbf{r})$

$$E[\rho] = \langle \Psi | H | \Psi \rangle$$

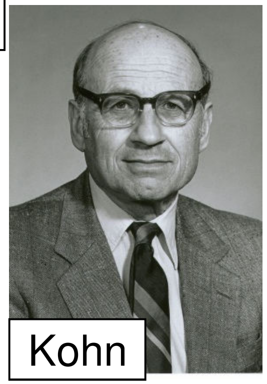
This functional is universal. It does not depend on the system, only on the interaction.

One obtains the exact density $\rho(\mathbf{r})$ by a variation of the functional with respect to the density

note:

$\rho(\mathbf{r})$ is a function of 3 variables.

$\Psi(\mathbf{r}_1 \ldots \mathbf{r}_N)$ is a function of $3N$ variables.



Kohn-Sham theory:

In order to reproduce shell structure Kohn and Sham introduced a single particle potential $V_{eff}(r)$, which is defined by the condition, that after the solution of the single particle eigenvalue problem

$$\left\{-\frac{\hbar^2}{2\mathrm{m}}\Delta + V_{eff}(r)\right\}\phi_k(r) = \varepsilon_k \phi_k(r)$$

the density obtained as $\rho(r) = \sum_{i=1}^{A} |\phi_i(r)|^2$ is the exact density

Obviously to each density $\rho(r)$ there exist such a potential $V_{eff}(r)$.

The non interacting part of the energy functional is given by:

$$E_{ni}[\rho] = \int \frac{\hbar^2}{2m}\tau(r)d^3r = \int \frac{\hbar^2}{2m}\sum_{i=1}^{A}|\nabla\phi_i(r)|^2 d^3r = \sum_{i=1}^{A}\varepsilon_i - \int \rho(r)V_{eff}(r)d^3r$$

and obviously we have:

$$V_{eff}(r) = -\frac{\delta}{\delta\rho}E_{ni}[\rho] = -\frac{\delta}{\delta\rho}(E_{HK} - E_H - E_{xc})$$

limitations of exact density functionals:

formally exact | in practice

Hohenberg-Kohn: $E[\rho(\mathbf{r})]$ — no shell effects

Kohn-Sham: $E[\rho(\mathbf{r}),\tau(\mathbf{r})]$ — no l·s,

Skyrme: $E[\rho(\mathbf{r}),\tau(\mathbf{r}),J(\mathbf{r})]$ — no pairing

Gogny: $E[\rho(\mathbf{r}),\tau(\mathbf{r}),J(\mathbf{r}),\kappa(\mathbf{r})]$ — no config.mixing

generalized mean field: **no configuration mixing,**
no two-body correlations

local density: $\rho(\mathbf{r}) = \langle a^\dagger(\mathbf{r})a(\mathbf{r})\rangle = \sum_i^A |\varphi_i(\mathbf{r})\rangle\langle\varphi_i(\mathbf{r})|$

kinetic energy density: $\tau(\mathbf{r}) = \sum_i^A |\nabla\varphi_i(\mathbf{r})\rangle\langle\nabla\varphi_i(\mathbf{r})|$

pairing density: $\kappa(\mathbf{r}) = \langle a^\dagger(\mathbf{r},s)a^\dagger(\mathbf{r},-s)\rangle$

twobody density: $\rho(\mathbf{r},\mathbf{r}') = \langle a^\dagger(\mathbf{r})a(\mathbf{r})a^\dagger(\mathbf{r}')a(\mathbf{r}')\rangle$

Density functional theory in nuclei

- In nuclei DFT has been introduced by **effective Hamiltonians**:
  by Vautherin and Brink (1972)

$$E = \langle \Psi | H | \Psi \rangle \approx \langle \Phi | \hat{H}_{eff}(\hat{\rho}) | \Phi \rangle \overset{?}{=} E[\hat{\rho}]$$

Skyrme
Gogny
Rel. MF

- Nuclei are **self-bound systems**.
  The exact density is a constant. $\rho(r) = \text{const}$
  Hohenberg-Kohn theorem is true, but useless
  $\rho(r)$ has to be replaced by the intrinsic density:

$$\rho_I(\vec{r}) = \rho(\vec{r} + \vec{R}_{CM}) \quad \text{with} \quad \vec{R}_{CM} = \frac{1}{A}\sum_i \vec{r}_i$$

- Density functional theory in nuclei is probably **not exact**,
  but it is a very good approximation.

General properties of self-consistent mean field theories:

- the nuclear energy functional is so far **phenomenological** and not connected to any NN-interaction.
- it is expressed in terms of powers and gradients of the nuclear ground state density using the principles of **symmetry** and **simplicity**
- The remaining parameters are adjusted to characteristic properties of **nuclear matter** and **finite nuclei**

Virtues:

(i) the intuitive interpretation of mean fields results in terms of **intrinsic shapes** and of shells with **single particle states**

(ii) the **full model space** is used: no distinction between core and valence nucleons, **no need for effective charges**

(iii) the functional is **universal**: it can be applied to all nuclei throughout the periodic chart, light and heavy, spherical and deformed

Why covariant ?

– no relativistic kinematic necessary: $\sqrt{p_F^2 + m_N^2} = m_N \sqrt{1 + 0.075}$

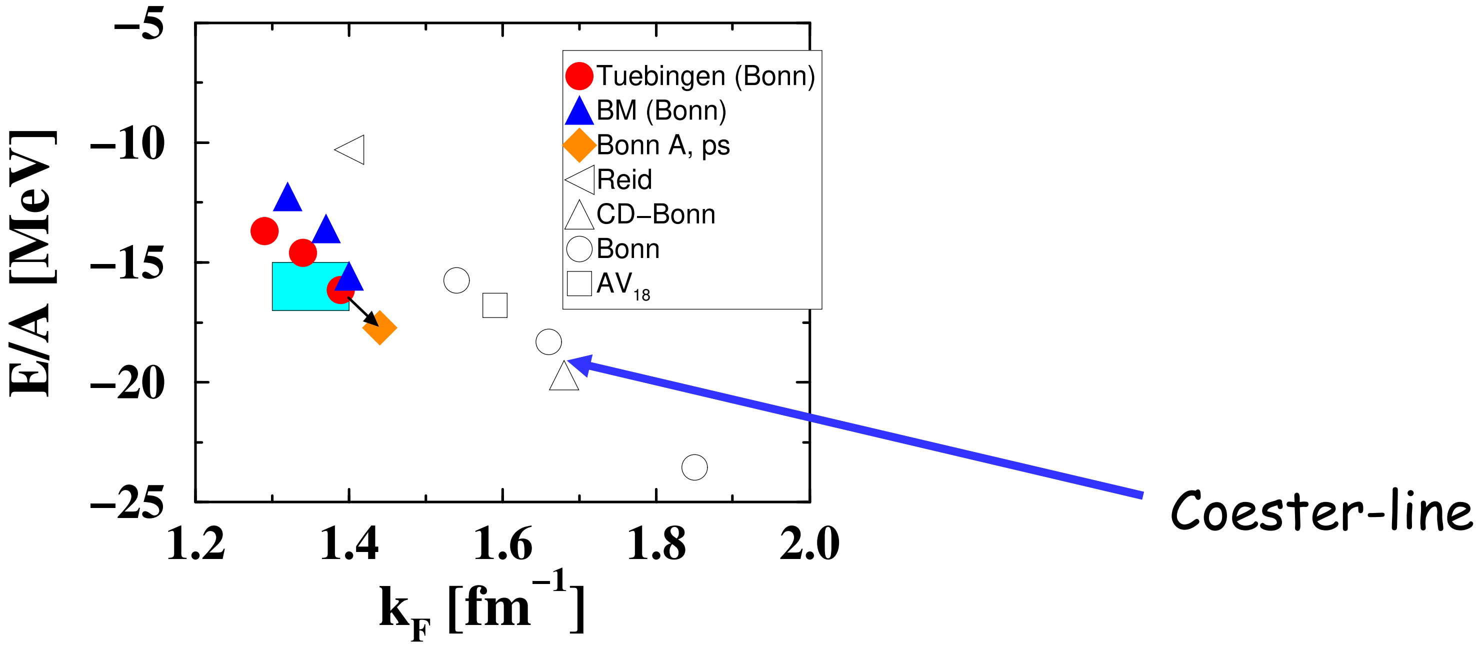
– non-relativistic DFT works well

– technical problems:
  no harmonic oscillator
  no exact soluble models
  double dimension
  huge cancellations V-S
  no variational method

– conceptual problems:
  treatment of Dirac sea
  no well defined many-body theory

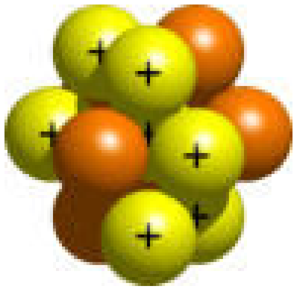
Why covariant?

1) Large spin-orbit splitting in nuclei
2) Large fields V≈350 MeV , S≈-400 MeV
3) Success of Relativistic Brueckner
4) Success of intermediate energy proton scatt.
5) relativistic saturation mechanism
6) consistent treatment of time-odd fields
7) Pseudo-spin Symmetry
8) Connection to underlying theories ?
9) As many symmetries as possible

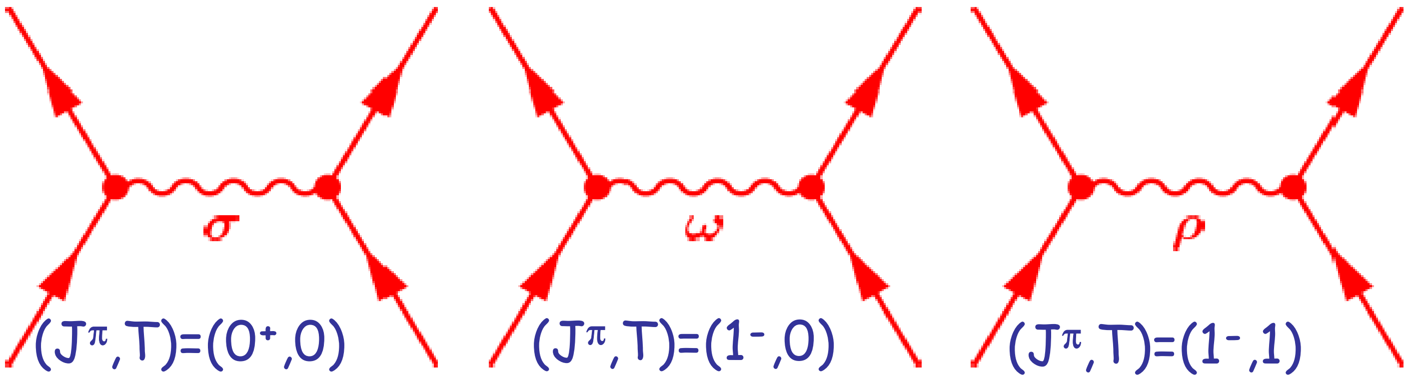


Walecka model

$$E[\hat{\rho}]$$



Nucleons are coupled by exchange of mesons through an effective Lagrangian (EFT)



$$S(r) = g_\sigma \sigma(r) \qquad V(r) = g_\omega \omega(r) + g_\rho \vec{\tau}\vec{\rho}(r) + eA(r)$$

Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive

Rho-meson: isovector field

Lagrangian density

free Dirac particle

free meson fields

free photon field

$$\mathcal{L} = \bar{\psi}(i\gamma\cdot\partial - m)\psi + \frac{1}{2}(\partial\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2$$
$$- \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^{\,2} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$- g_\sigma\bar{\psi}\sigma\psi - g_\omega\bar{\psi}\gamma\cdot\omega\psi - g_\rho\bar{\psi}\gamma\cdot\vec{\rho}\vec{\tau}\psi - e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi$$

interaction terms

Parameter:

meson masses: m_σ, m_ω, m_ρ

meson couplings: g_σ, g_ω, g_ρ

$$\mathcal{L} = \mathcal{L}(\psi, \sigma, \omega, \rho, A)$$

Equations of motion

$$\partial_\mu \frac{\partial L}{\partial(\partial_\mu q_k)} - \frac{\partial L}{\partial q_k} = 0.$$

for the nucleons we find the Dirac equation

$$\left(\gamma^\mu (i\partial_\mu - V_\mu) - m + S\right)\psi_i = 0.$$

No-sea approxim. !

for the mesons we find the Klein-Gordon equation

$$\begin{aligned}
(\partial^\nu \partial_\nu + m_\sigma^2)\sigma &= -g_\sigma \rho_s \\
(\partial^\nu \partial_\nu + m_\omega^2)\omega_\mu &= g_\omega j_\mu \\
(\partial^\mu \partial_\mu + m_\rho^2)\vec{\rho}_\mu &= g_\rho \vec{j}_\mu \\
\partial^\nu \partial_\nu A_\mu &= e j_\mu^{(em)}
\end{aligned}$$

$$\begin{aligned}
\rho_s(x) &= \sum_{i=1}^{A} \bar{\psi}_i(x)\psi_i(x) \\
j_\mu(x) &= \sum_{i=1}^{A} \bar{\psi}_i(x)\gamma_\mu \psi_i(x) \\
\vec{j}_\mu(x) &= \sum_{i=1}^{A} \bar{\psi}_i(x)\vec{\tau}\gamma_\mu \psi_i(x) \\
j_\mu^{(em)}(x) &= \sum_{i=1}^{A} \bar{\psi}_i(x)\frac{1}{2}(1-\tau_3)\gamma_\mu \psi_i(x)
\end{aligned}$$

Static limit (with time reversal invariance)

for the nucleons we find the static Dirac equation

$$\left(\vec{\alpha}\,\vec{p}+V+\beta\left(m-S\right)\right)\psi_i=\varepsilon_i\psi_i\,.$$

$$S=-g_s\sigma,\qquad V=g_\omega\omega_0+g_\rho\rho_0+eA_0$$

for the mesons we find the Helmholtz equations

No-sea approxim. !

$$\left(-\Delta+m_\sigma^2\right)\sigma=-g_\sigma\rho_s \qquad \rho_s=\sum_{i=1}^{A}\bar{\psi}_i\psi_i$$

$$\left(-\Delta+m_\omega^2\right)\omega_0=g_\omega\rho_B \qquad \rho_B=\sum_{i=1}^{A}\psi_i^+\psi_i$$

$$\left(-\Delta+m_\rho^2\right)\rho_0^3=g_\rho\rho^3 \qquad \rho^3=\sum_{i=1}^{A}\psi_i^+\tau_3\psi_i$$

$$-\Delta A_0=e\rho^{(em)} \qquad \rho^{(em)}=\sum_{i=1}^{A}\psi_i^+\frac{1}{2}\left(1-\tau_3\right)\psi_i$$

Relativistic saturation mechanism:

We consider only the σ-field, the origin of attraction its source is the scalar density

$$m_\sigma^2 \sigma = -g_\sigma \sum_{i=1}^{A} \bar{\psi}_i \psi_i = -g_\sigma \sum_{i=1}^{A} \left(g_i^+ g_i - f_i^+ f_i \right)$$

for high densities, when the collapse is close, the Dirac gap ≈2m* decreases, the small components f_i of the wave functions increase and reduce the scalar density, i.e. the source of the σ-field, and therefore also scalar attraction.

$$f_i(r) = \frac{1}{\varepsilon_i + 2\tilde{m}} \vec{\sigma}\vec{k} g_i(r)$$

$$m_\sigma^2 \sigma \approx -g_\sigma \rho_B - 2\sum_{i=1}^{A} f_i^+ f_i = -g_\sigma \rho_B + \frac{1}{\tilde{m}} \sum_{i=1}^{A} \nabla g_i^+ \nabla g_i$$

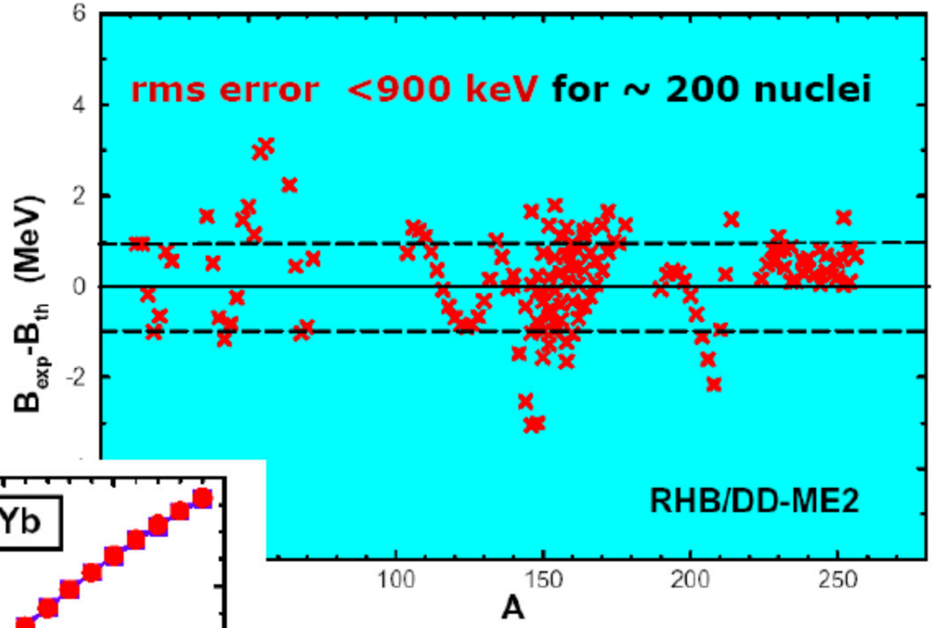
In the non-relativistic case, Hartree with Yukawa forces would lead to collapse

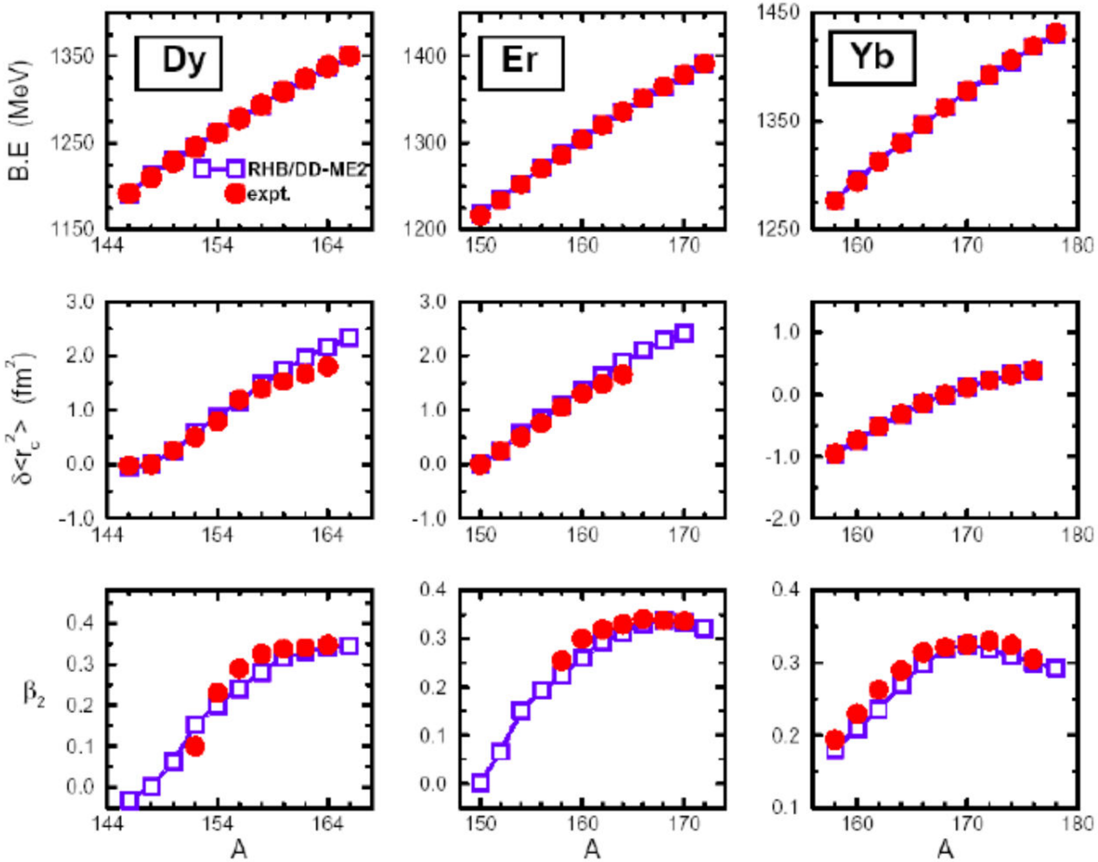
Successes of relativistic investigations:

- Masses and radii
- Isotope shifts
- Neutron halo‘s
- Proton emitters
- Collective vibrations
- Pygmy modes
- Beyond mean field: transitional nuclei
- Beyond mean field: complex configurations

Relativistic Hartree-Bogoliubov calculations: DD-ME2 + Gogny D1S pairing

Absolute deviations of the calculated binding energies from experimental values:





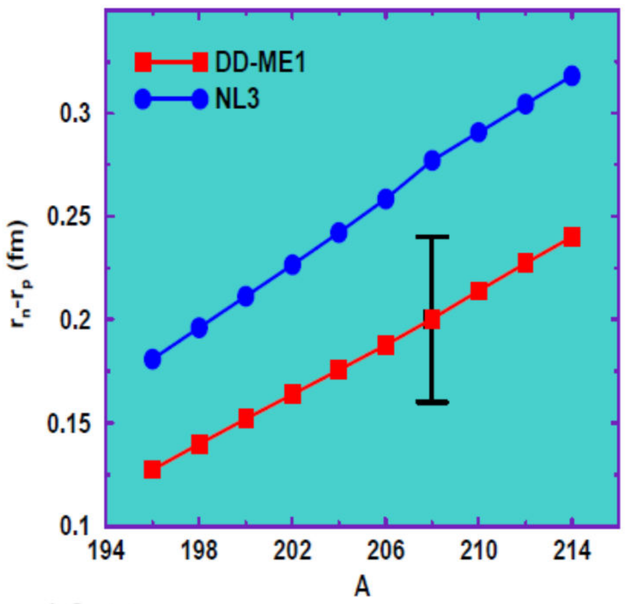
Binding energies, charge isotope shifts and quadrupole deformations of isotopic chains in the rare-earth region.

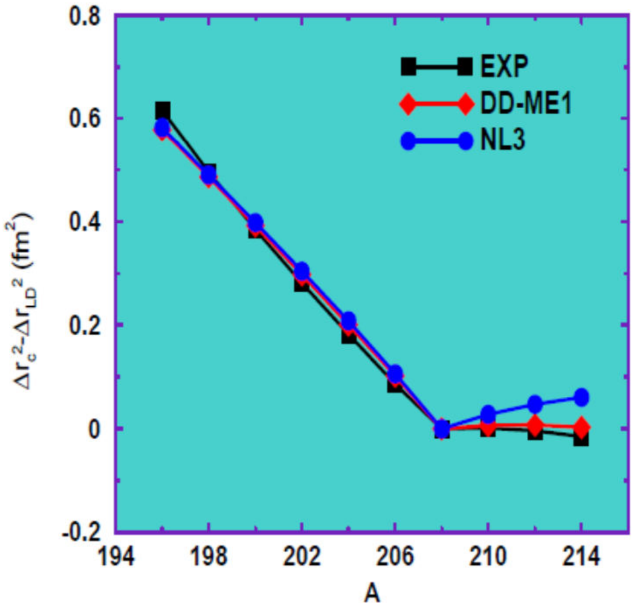
Phys. Rev. C **71**, 024312 (2005)

Kink in the isotopic shifts of radii: relativistic

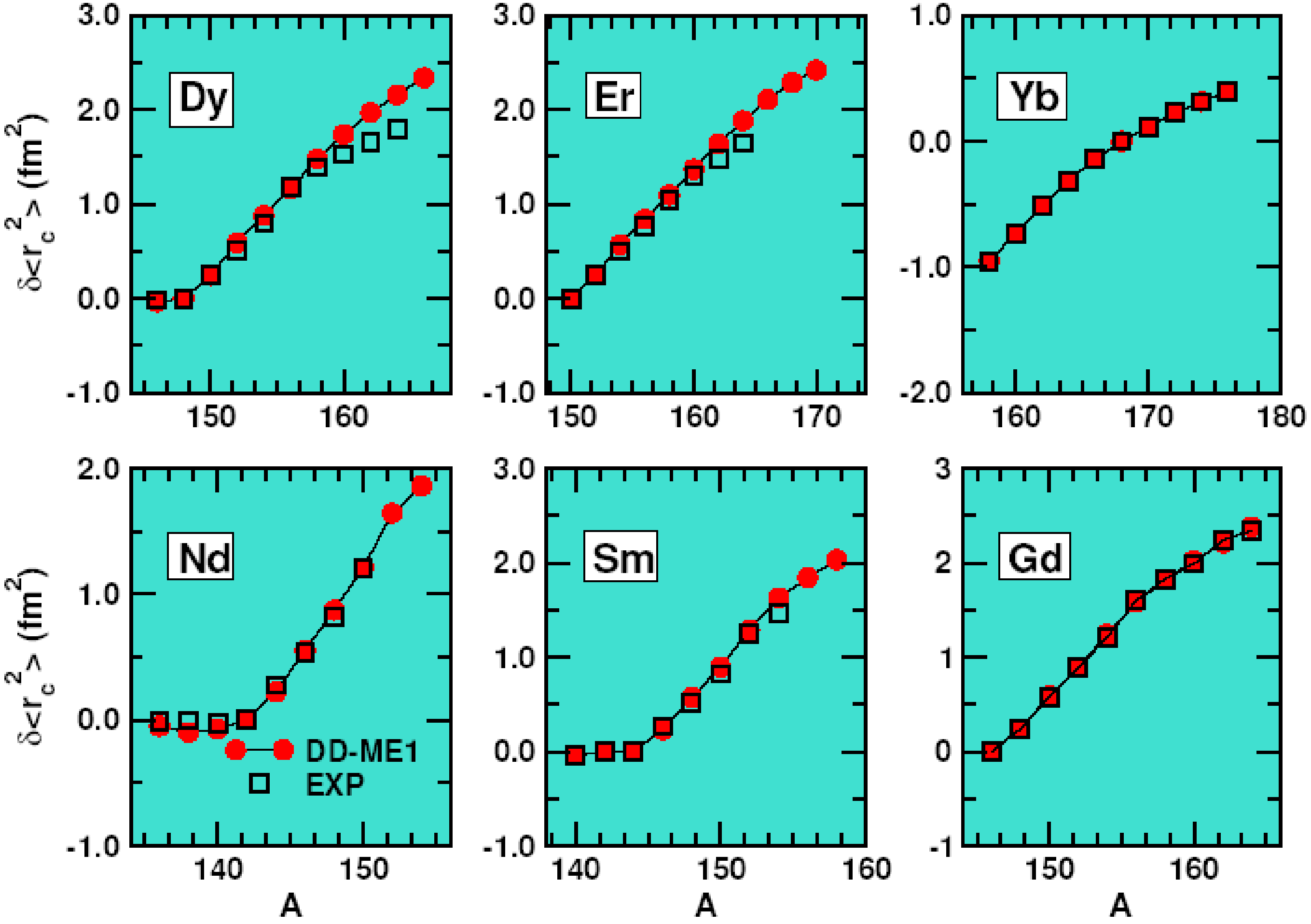
Pb isotopes

- differences between neutron and proton radii
- charge isotope shifts





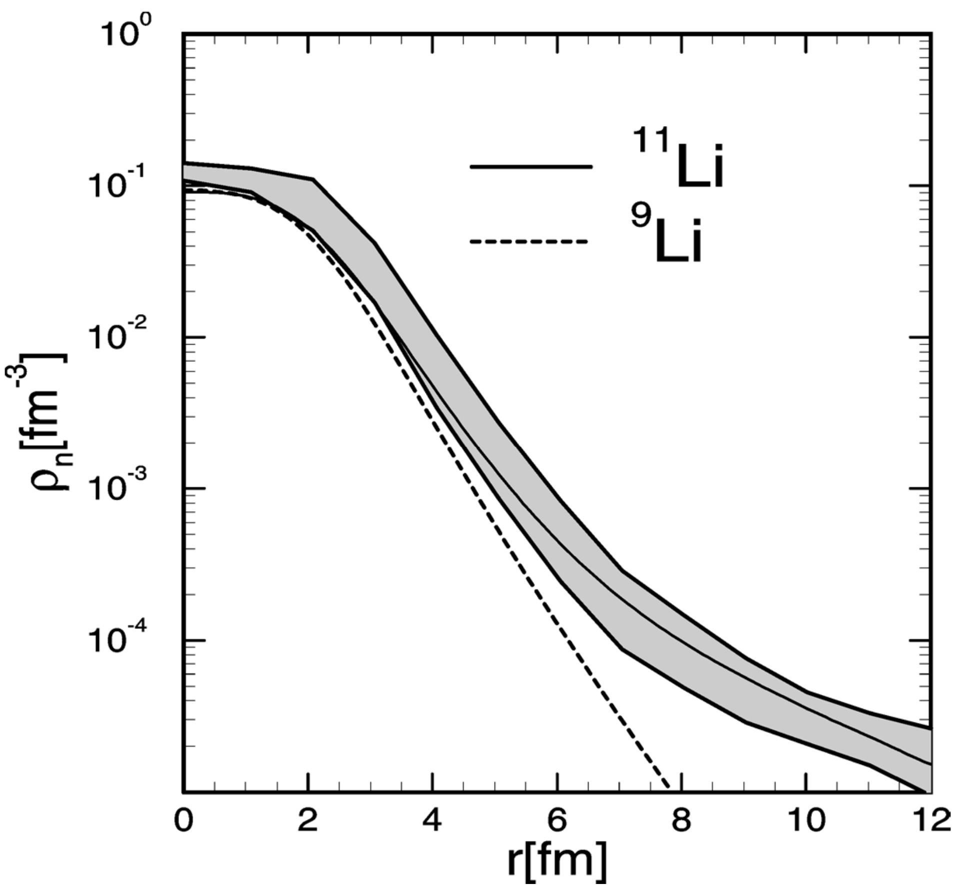
NL3: Isotope shifts in deformed nuclei:

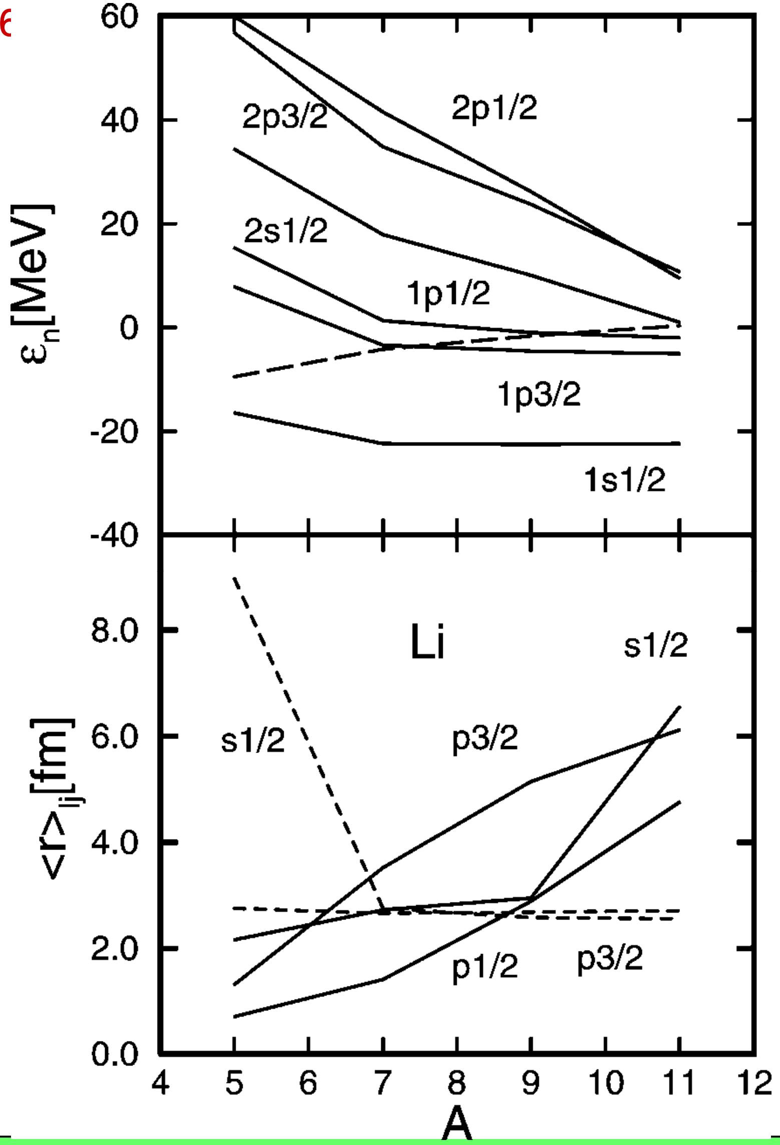


Empirical data: E.G. Nadjakov et al., At. Data Nucl. Data Tables 56, 133(1994)

Density distribution in Li-nuclei

J. Meng and P. Ring , PRL 77, 3963 (1996

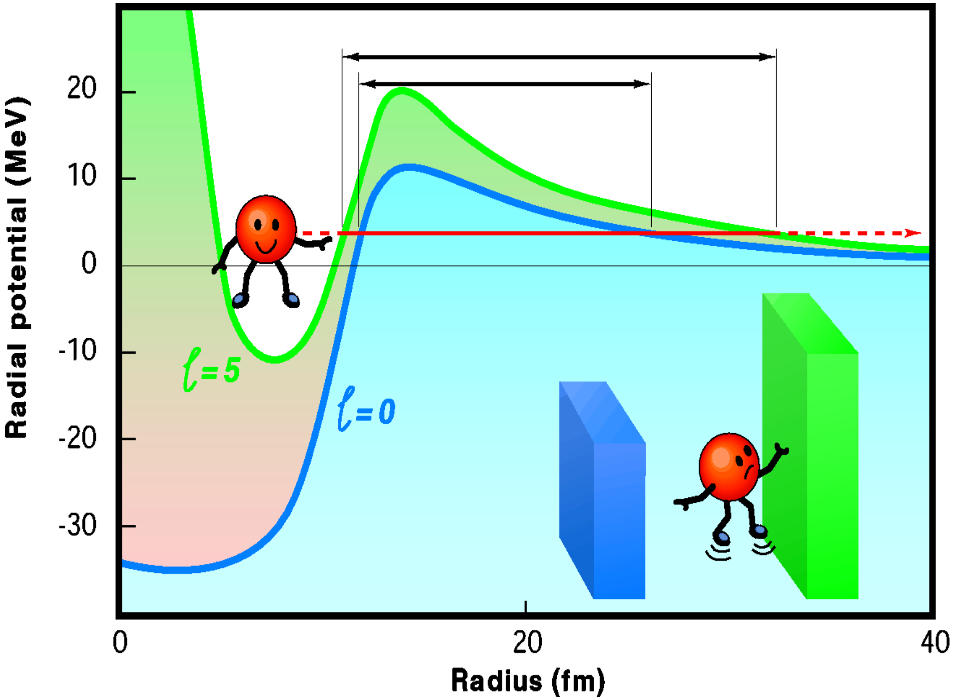




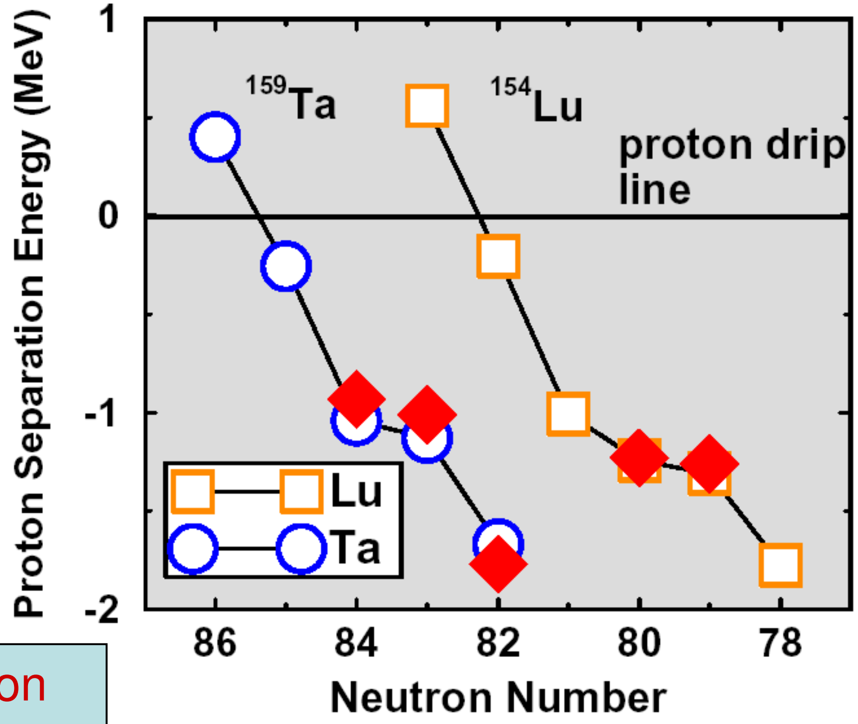
Proton emitters at the proton dripline

Vretenar, Lalazissis, Ring, Phys.Rev.Lett. 82, 4595 (1999)

characterized by exotic ground-state decay modes such as the direct emission of charged particles and β -decays with large Q-values.



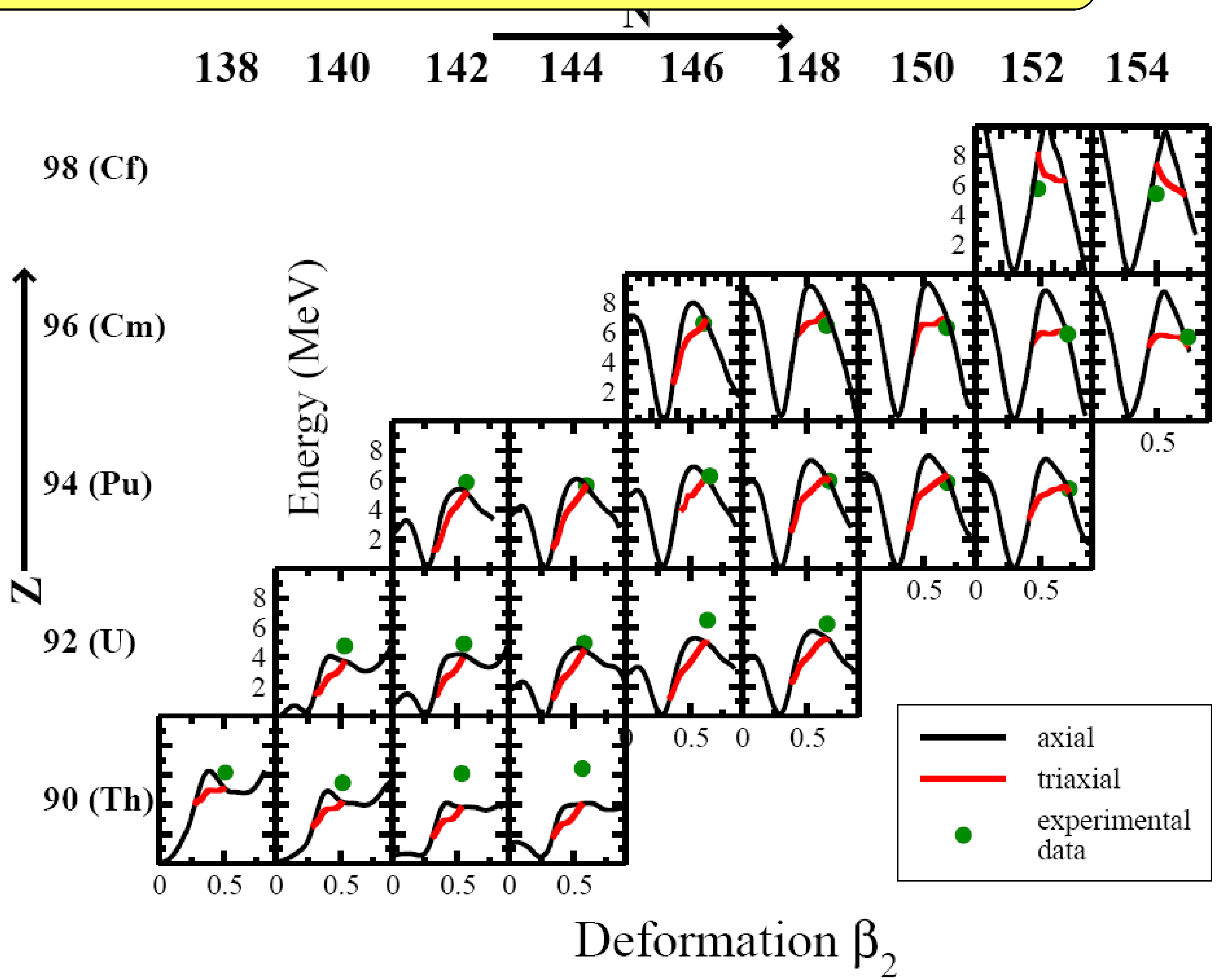
Ground-state proton emitters



Lalazissis, Vretenar, Ring
Phys.Rev. C60, 051302 (1999)

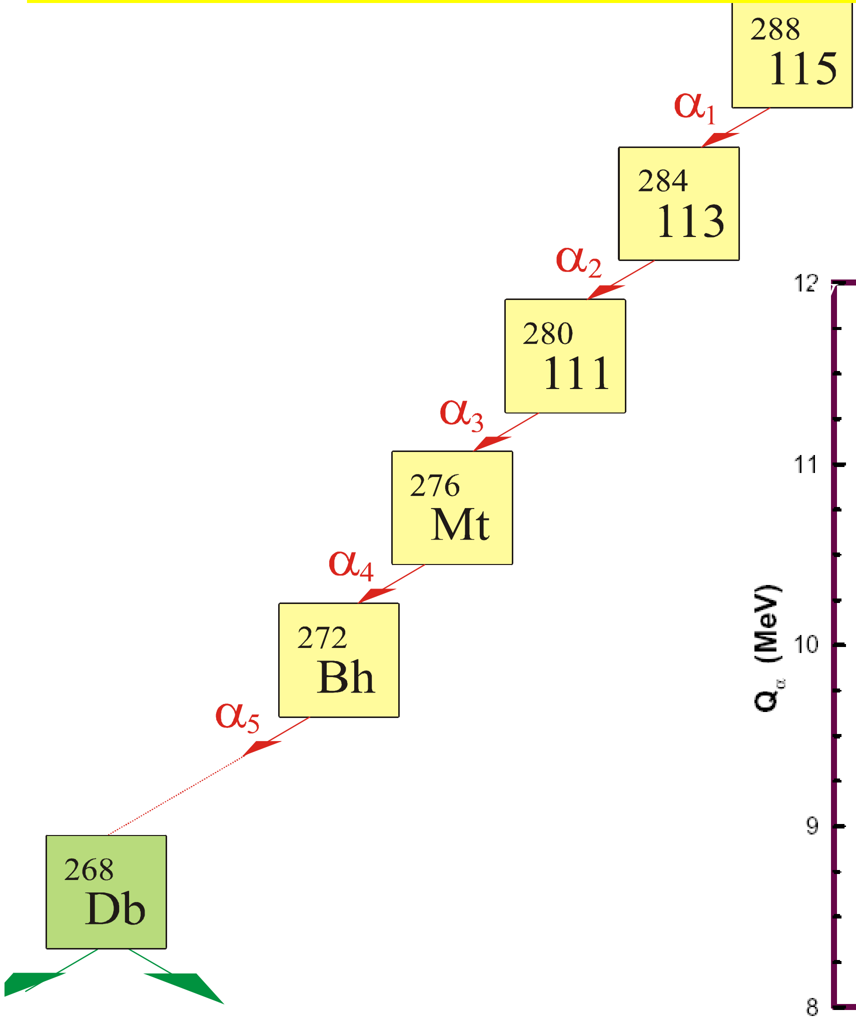
Self-consistent RHB calculations -> separation energies, quadrupole deformations, odd-proton orbitals, spectroscopic factors

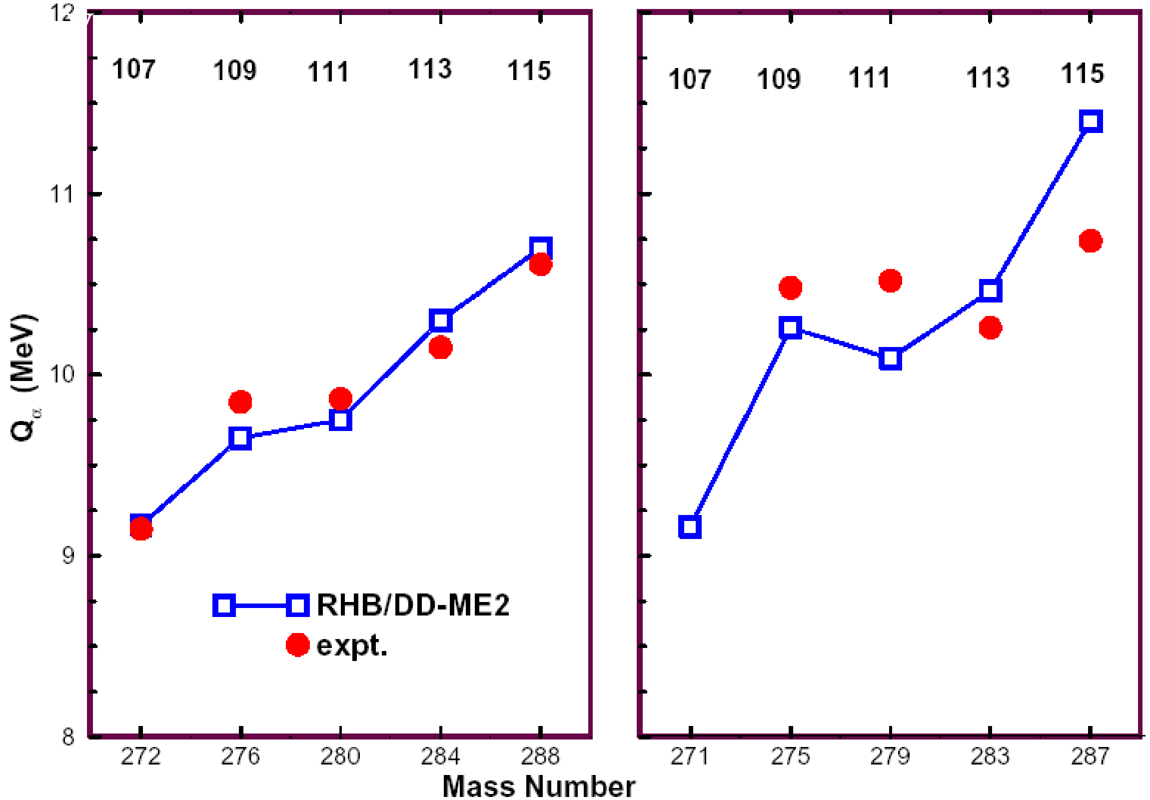
Fission barriers for triaxially deformed shapes:



Nucleus	B.E (MeV)	r_c (fm)	r_n (fm)	Q_p (b)	H_p (b^2)
^{224}Ra	1720.47 (1720.31)	5.71	5.85	4.93 (6.33)	0.45
^{226}Ra	1731.13 (1731.61)	5.74	5.88	6.22 (7.19)	0.65
^{228}Ra	1741.67 (1742.49)	5.76	5.92	7.44 (7.76)	0.79
^{230}Ra	1751.94 (1753.05)	5.79	5.95	8.39	0.86
^{228}Th	1743.04 (1742.49)	5.78	5.90	7.64 (8.42)	0.88
^{230}Th	1751.94 (1753.05)	5.80	5.93	8.57 (8.99)	0.97 (1.09)
^{232}Th	1766.10 (1766.92)	5.82	5.96	9.28 (9.66)	1.00 (1.22)
^{234}Th	1776.80 (1777.68)	5.84	5.99	9.78 (8.96)	0.96
^{232}U	1766.39 (1765.97)	5.83	5.94	9.57 (10.00)	1.10
^{234}U	1778.66 (1778.57)	5.85	5.97	10.10 (10.35)	1.10 (1.40)
^{236}U	1790.29 (1790.42)	5.87	6.00	10.46 (10.80)	1.03 (1.30)
^{238}U	1801.38 (1801.69)	5.88	6.02	10.74 (11.02)	0.94 (0.83)
^{240}U	1811.82 (1812.44)	5.90	6.05	11.03	0.86
^{238}Pu	1801.85 (1801.27)	5.89	6.01	11.09 (11.26)	1.00 (1.38)
^{240}Pu	1813.84 (1813.46)	5.91	6.03	11.32 (11.44)	1.00 (1.15)
^{242}Pu	1825.26 (1825.01)	5.92	6.05	11.55 (11.61)	0.90
^{244}Pu	1836.00 (1836.06)	5.94	6.08	11.61 (11.73)	0.79
^{246}Pu	1845.97 (1846.66)	5.95	6.10	11.52 (11.52)	0.66

Superheavy Elements: Q_α-values



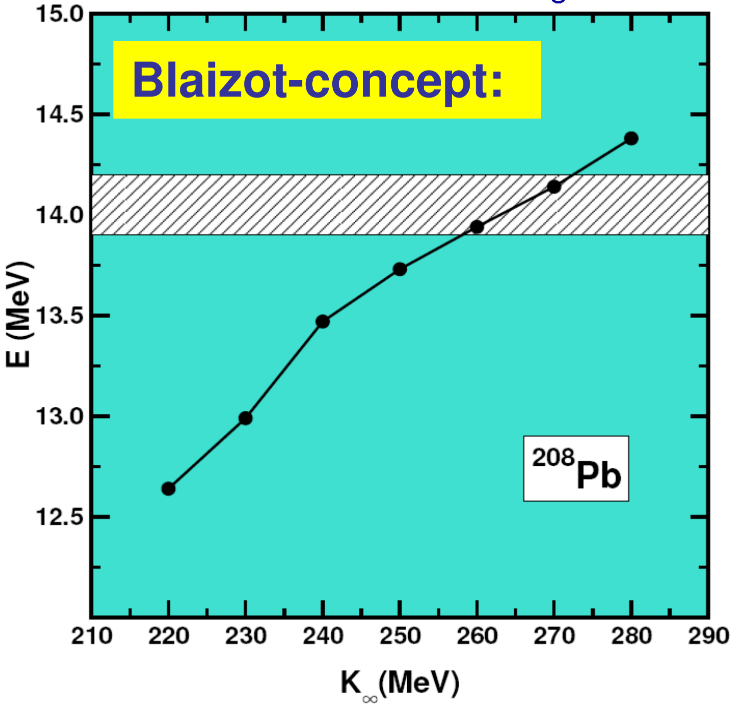


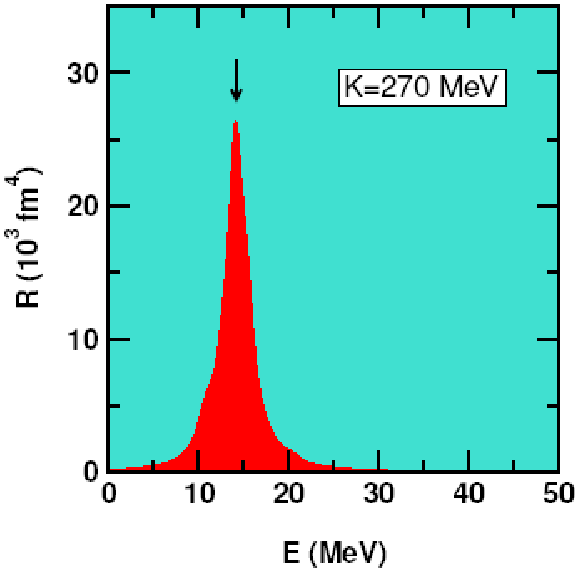
● Exp: Yu.Ts.Oganessian *et al*, PRC 69, 021601(R) (2004) ◻ Lalzissis

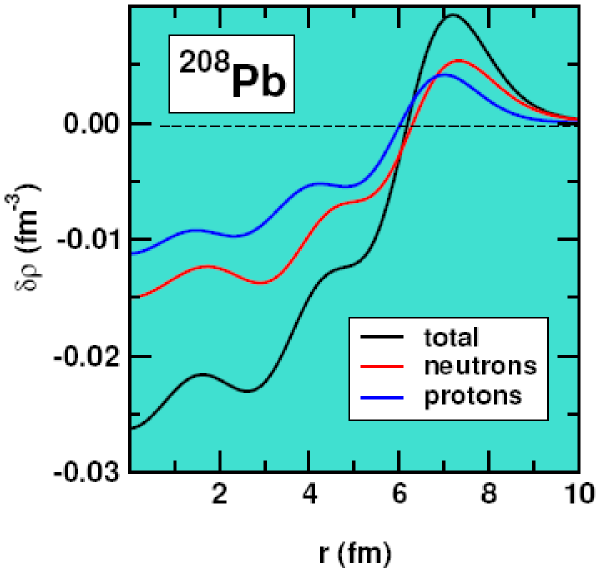
Isoscalar Giant Monopole: IS-GMR

The ISGMR represents the essential source of experimental information on the nuclear incompressibility

$$K_0 = p_f^2 \frac{d^2 E/A}{dp_f^2}\bigg|_{p_{f0}}$$







constraining the nuclear matter compressibility

$\rho(t) = \rho_0 + \delta\rho(t)$

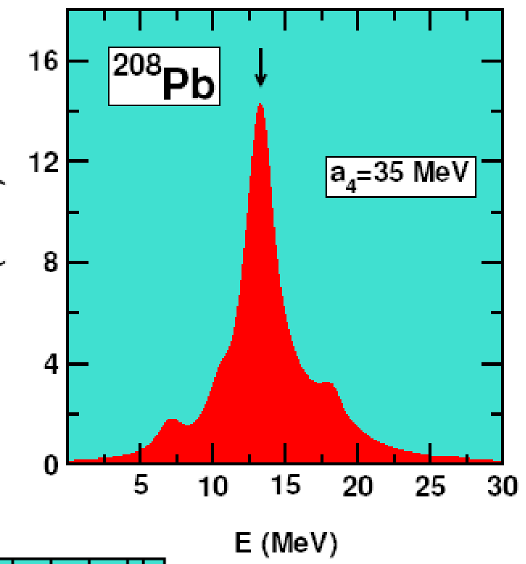
RMF models reproduce the experimental data only if

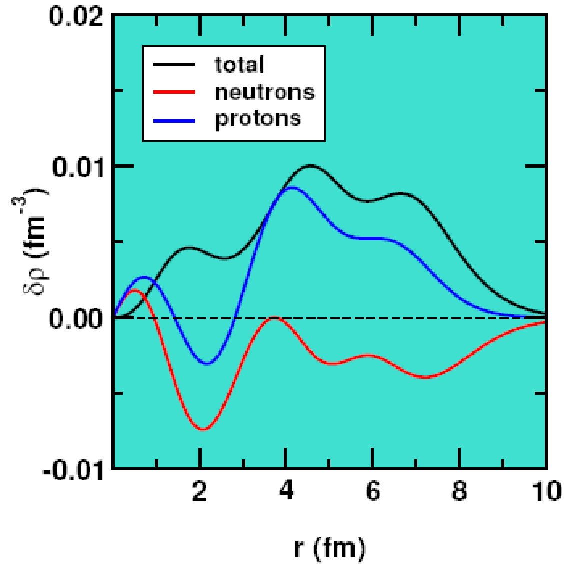
$250 \text{ MeV} \leq K_0 \leq 270 \text{ MeV}$

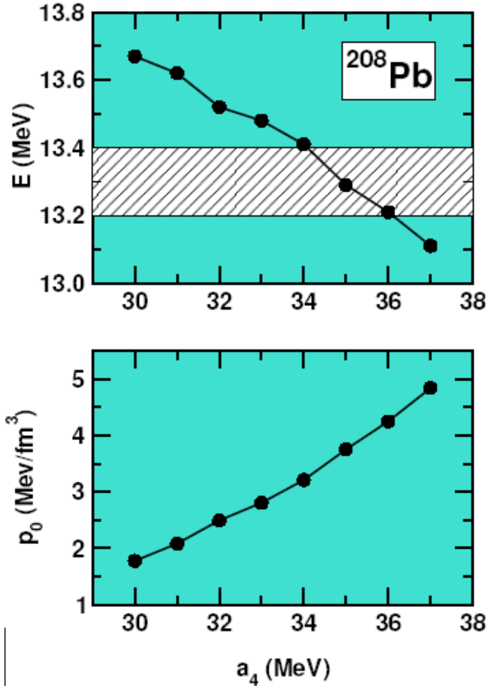
T. Niksic et al., PRC 66 (2002) 024306

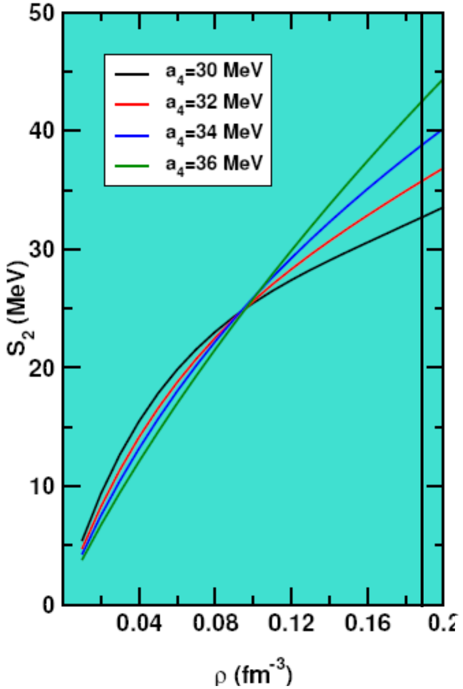
Isovector Giant Dipole: IV-GDR

the IV-GDR represents one of the sources of experimental informations on the nuclear matter symmetry energy









constraining the nuclear matter symmetry energy

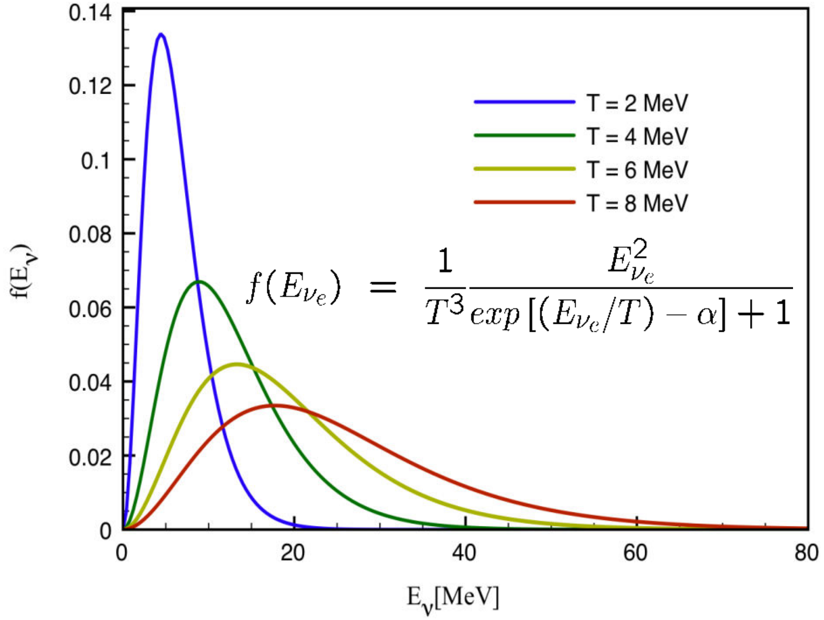
the position of IV-GDR is reproduced if

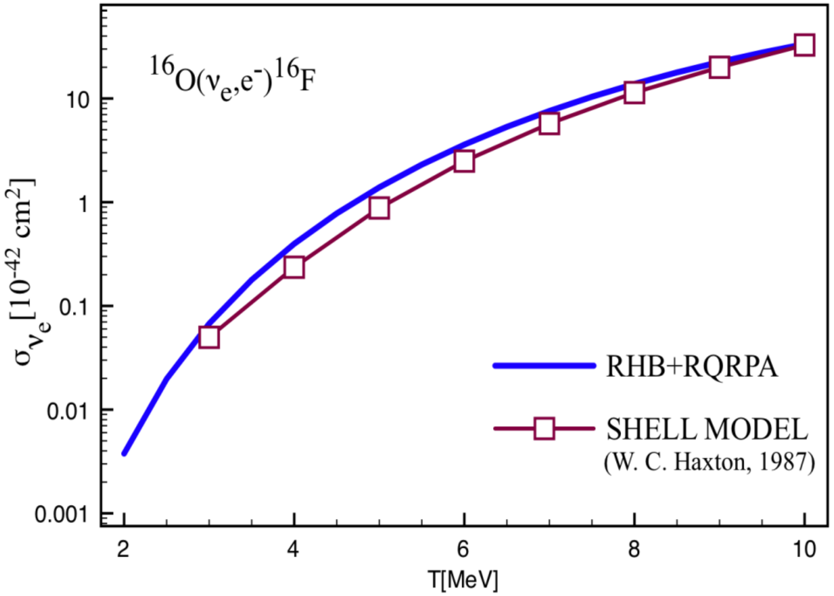
$$32 \text{ MeV} \leq a_4 \leq 36 \text{ MeV}$$

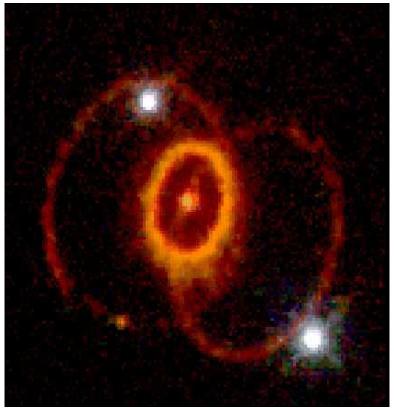
T. Niksic et al., PRC 66 (2002) 024306

Cross section averaged over supernova neutrino flux

Supernova neutrino flux is
given by Fermi-Dirac spectrum

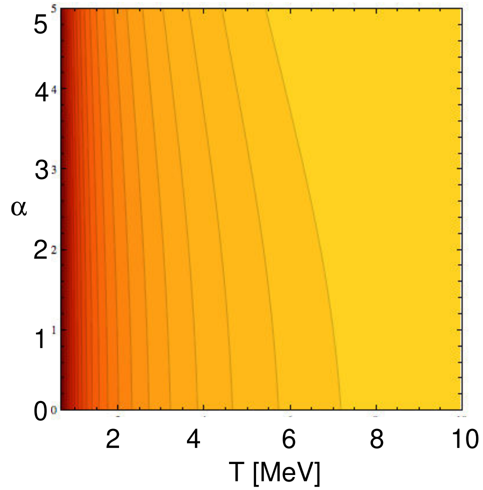






Cross section averaged over
Supernova neutrino flux

$$\langle \sigma_\nu \rangle = \frac{\int dE_\nu \sigma_\nu(E_\nu) f(E_\nu)}{\int dE'_\nu f(E'_\nu)}$$



How many parameters ?

4 + 3 parameters

symmetric nuclear matter: E/A, ρ_0 → G_σ G_ω

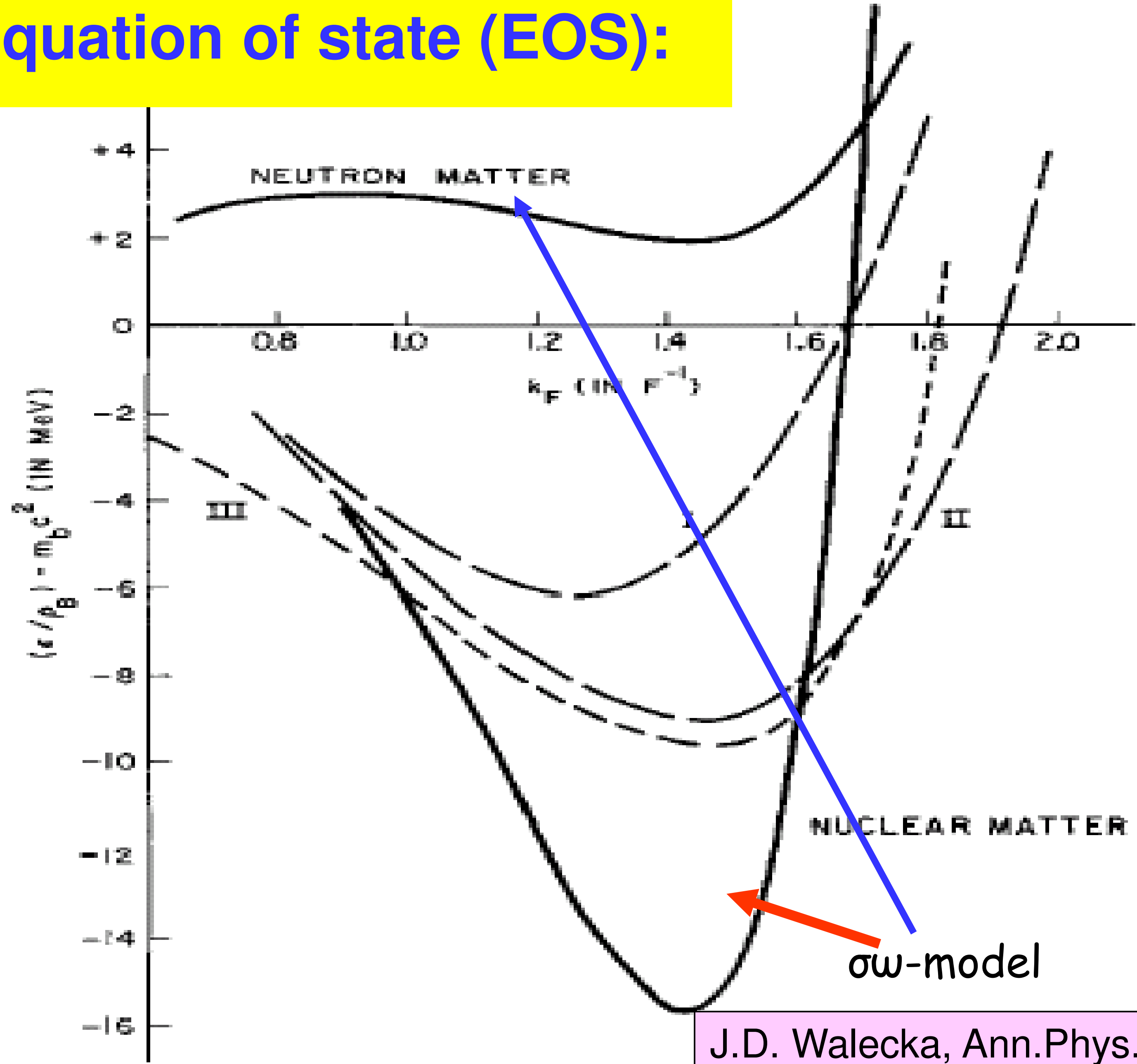
finite nuclei (N=Z): E/A, radii, spinorbit for free → m_σ

Coulomb (N≠Z): a_4 → G_ρ

density dependence: T=0 K_∞ → g_2 g_3

T=1 r_n - r_p → a_ρ

Equation of state (EOS):



J.D. Walecka, Ann.Phys. (NY) 83, (1974) 491

Effective density dependence:

non-linear potential:

NL1,NL3..

Boguta and Bodmer, NPA 431, 3408 (1977)

$$\frac{1}{2}m_\sigma^2\sigma^2 \quad \Rightarrow \quad U(\sigma)=\frac{1}{2}m_\sigma^2\sigma^2+\frac{1}{3}g_2\sigma^3+\frac{1}{4}g_3\sigma^4$$

density dependent coupling constants:

R.Brockmann and H.Toki, PRL 68, 3408 (1992)
S.Typel and H.H.Wolter, NPA 656, 331 (1999)
T. Niksic, D. Vretenar, P. Finelli, and P. Ring, PRC 56 (2002) 024306

$$g_o, g_\omega, g_\rho \Rightarrow g_o(\rho), g_\omega(\rho), g_\rho(\rho)$$

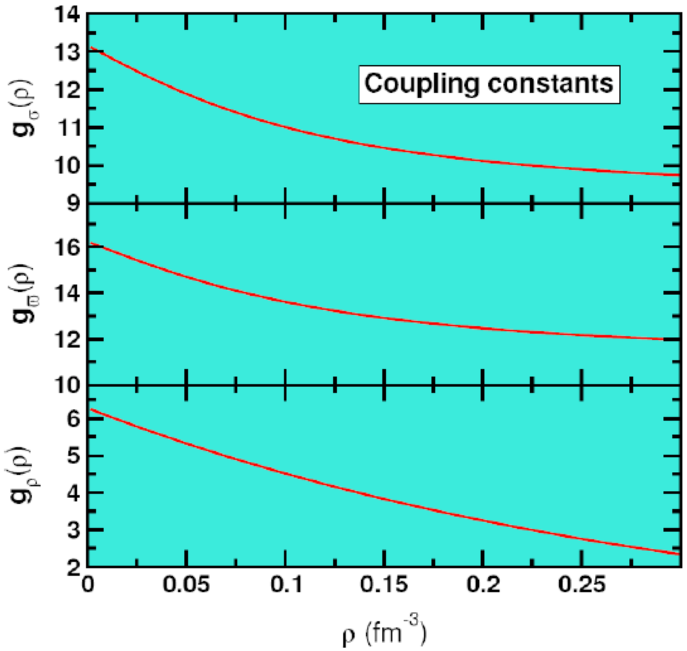
g $\rightarrow$ **g(ρ(r))**

DD-ME1,DD-ME2

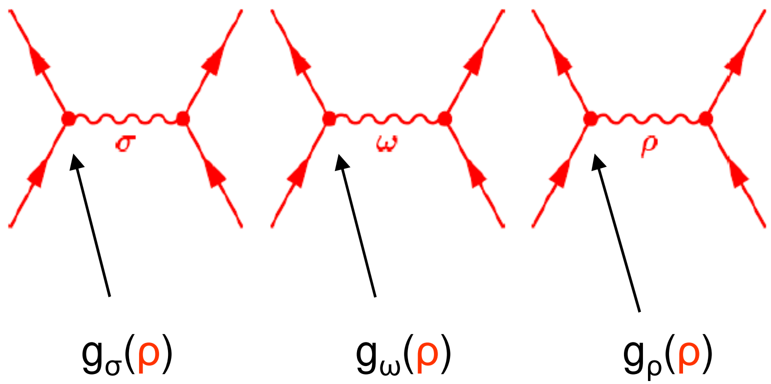
Effective density dependence:

The basic idea comes from ab initio calculations
density dependent coupling constants include Brueckner correlations
and threebody forces

non-linear meson coupling: **NL3**



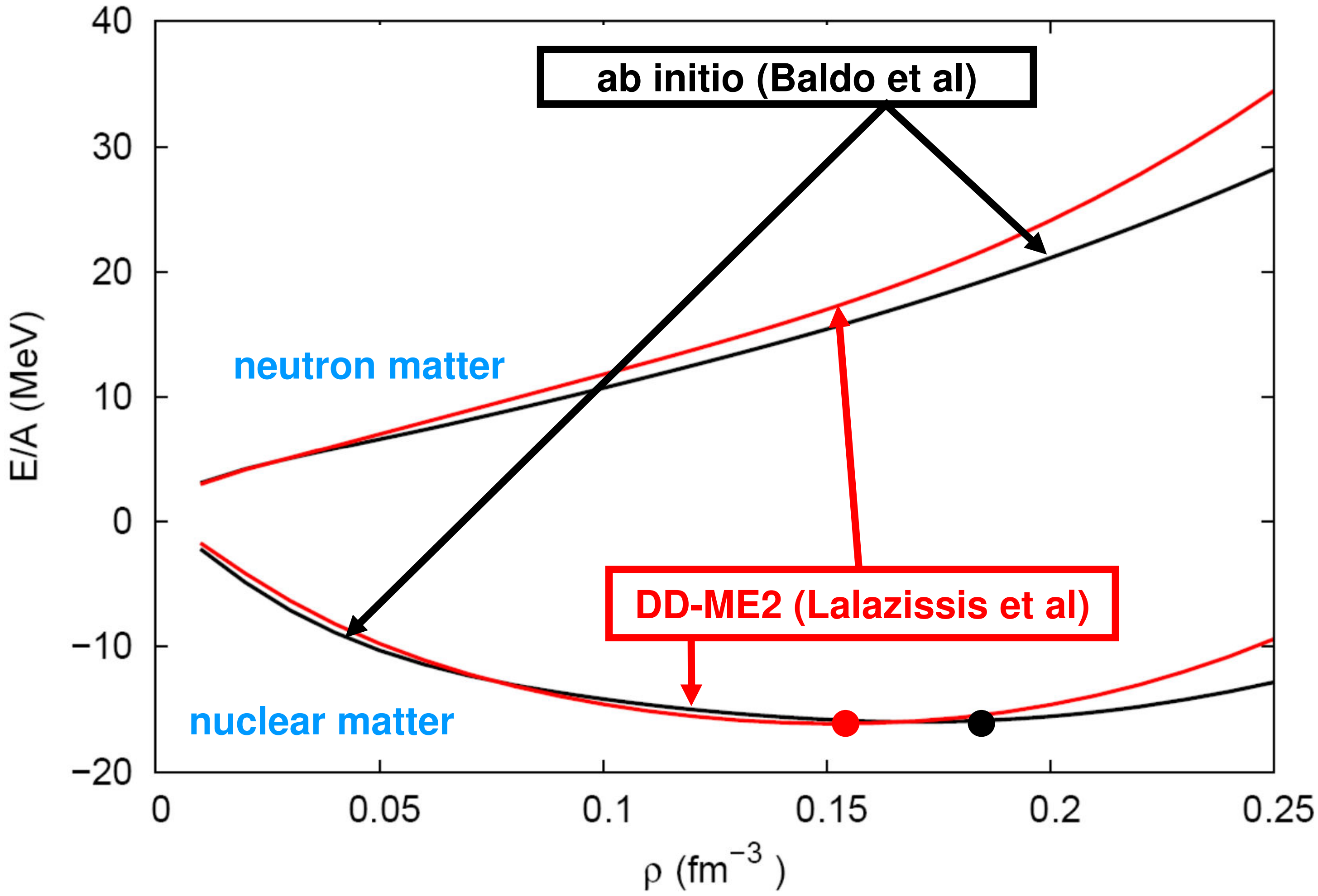
Effective interactions with medium-dependent couplings:



adjusted to ground state properties of finite nuclei

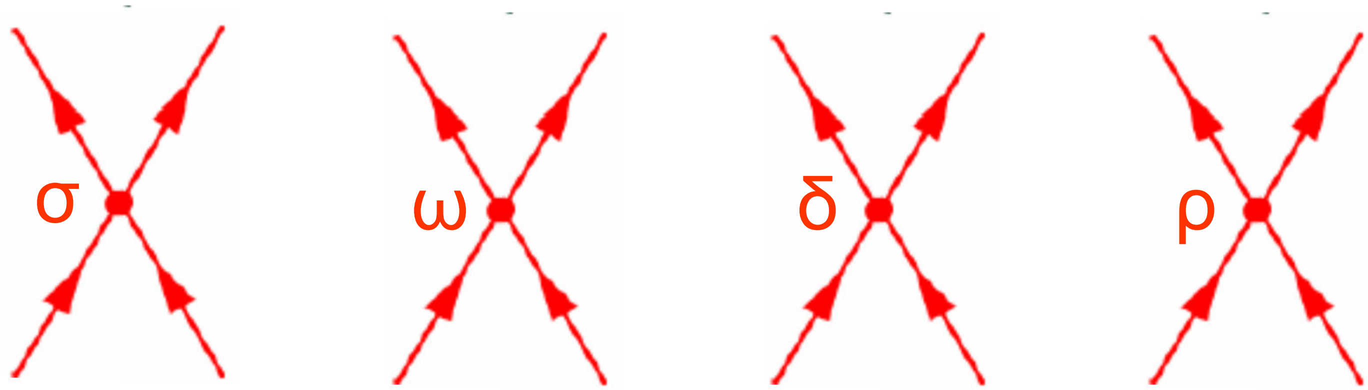
Typel, Wolter, NPA **656**, 331 (1999)
Niksic, Vretenar, Finelli, P.R., PRC **66**, 024306 (2002): **DD-ME1**
Lalazissis, Niksic, Vretenar, P.R., PRC 78, 034318 (2008): **DD-ME2**

Comparison with ab initio calculations:



we find excellent agreement with ab initio calculations of Baldo et al.

Point-Coupling Models



J=0, T=0   J=1, T=0   J=0, T=1   J=1, T=1

$$G_\sigma = \frac{g_\sigma^2}{m_\sigma^2} \qquad G_\omega = \frac{g_\omega^2}{m_\omega^2} \qquad G_\delta = \frac{g_\delta^2}{m_\delta^2} \qquad G_\rho = \frac{g_\rho^2}{m_\rho^2}$$

Manakos and Mannel, Z.Phys. **330**, 223 (1988)
Bürvenich, Madland, Maruhn, Reinhard, PRC **65**, 044308 (2002)

Lagrangian density for point coupling

free Dirac particle

$$
\begin{aligned}
\mathcal{L} \;=\;& \bar{\psi}\,(i\gamma\cdot\boldsymbol{\partial} - m)\,\psi \\
&+ G_\sigma(\bar{\psi}\psi)(\bar{\psi}\psi) \quad + \; G_\omega(\bar{\psi}\gamma^\mu\psi)(\bar{\psi}\gamma_\mu\psi) \\
&+ G_\delta(\bar{\psi}\vec{\tau}\psi)(\bar{\psi}\vec{\tau}\psi) \; + \; G_\rho(\bar{\psi}\gamma^\mu\vec{\tau}\psi)(\bar{\psi}\gamma_\mu\vec{\tau}\psi) \\
&+ D_\sigma(\bar{\psi}\partial^\mu\psi)(\bar{\psi}\partial_\mu\psi) \\
&- \frac{1}{4}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} \; + \; e^2\bar{\psi}\gamma^\mu A_\mu\frac{(1-\tau_3)}{2}\psi \qquad (1)
\end{aligned}
$$

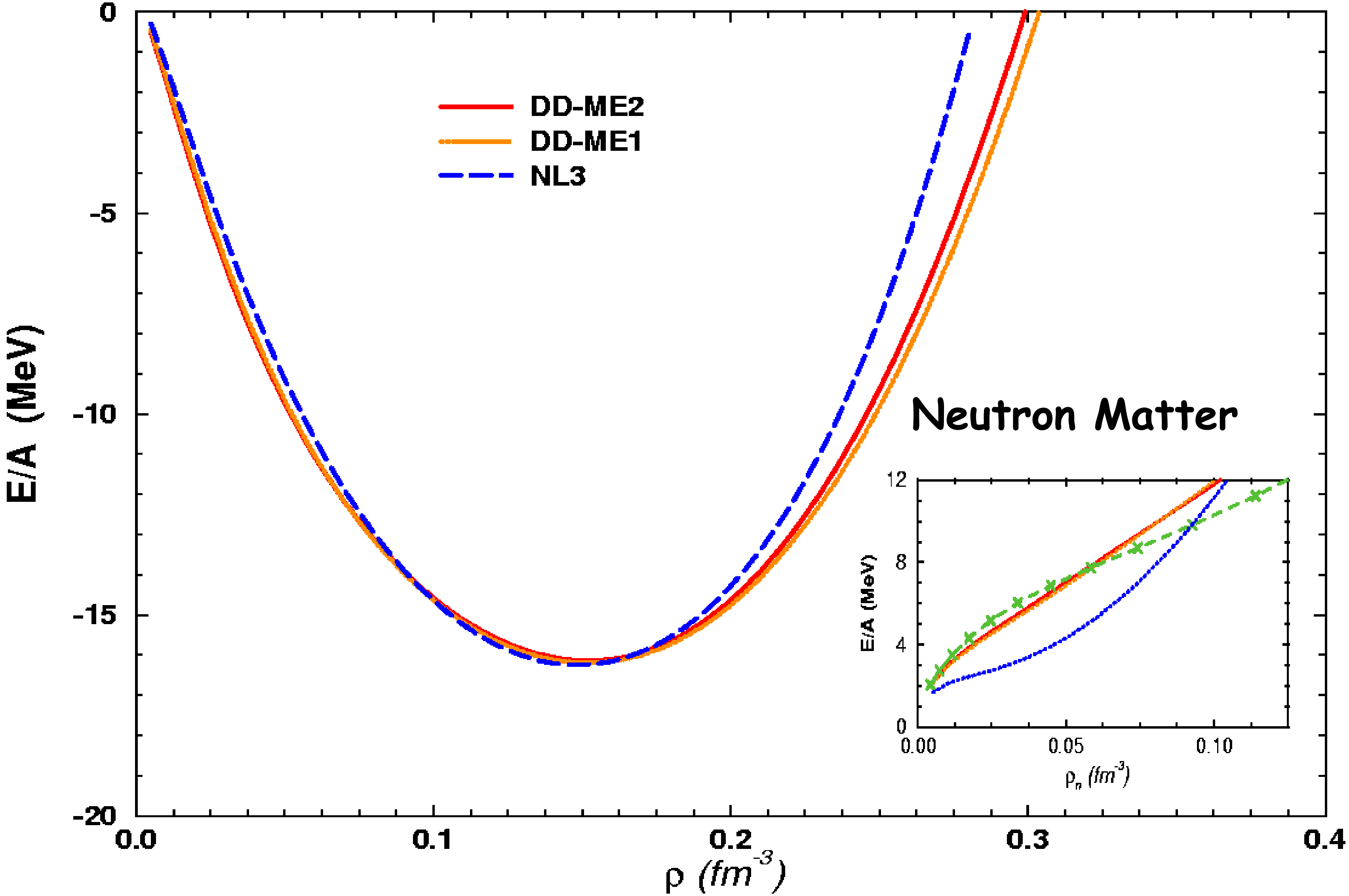
Parameter:

photon field

point couplings: G_σ, G_ω, G_δ, G_ρ, $\quad G_i = \left(\frac{g_i}{m_i}\right)^2$

derivative terms: D_σ

Nuclear matter equation of state



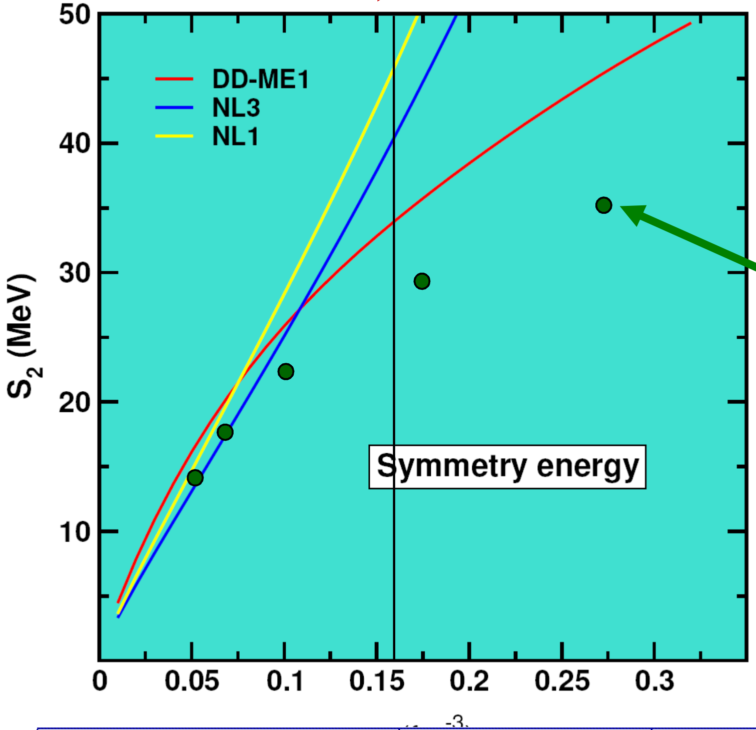
Symmetry energy

$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + S_4(\rho)\alpha^4 + \cdots$$

$$S_2(\rho) = a_4 + \frac{p_0}{\rho_{sat}^2}(\rho - \rho_{sat}) + \frac{\Delta K_0}{18\rho_{sat}^2}(\rho - \rho_{sat})^2 + \cdots$$

$$\alpha \equiv \frac{N-Z}{N+Z}$$

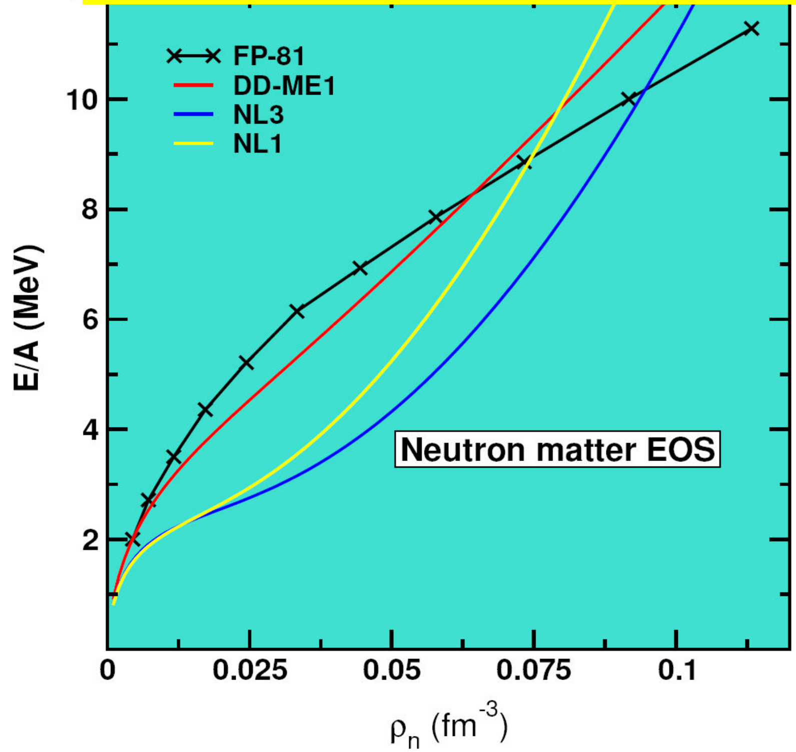
saturation density



Lombardo

empirical values:

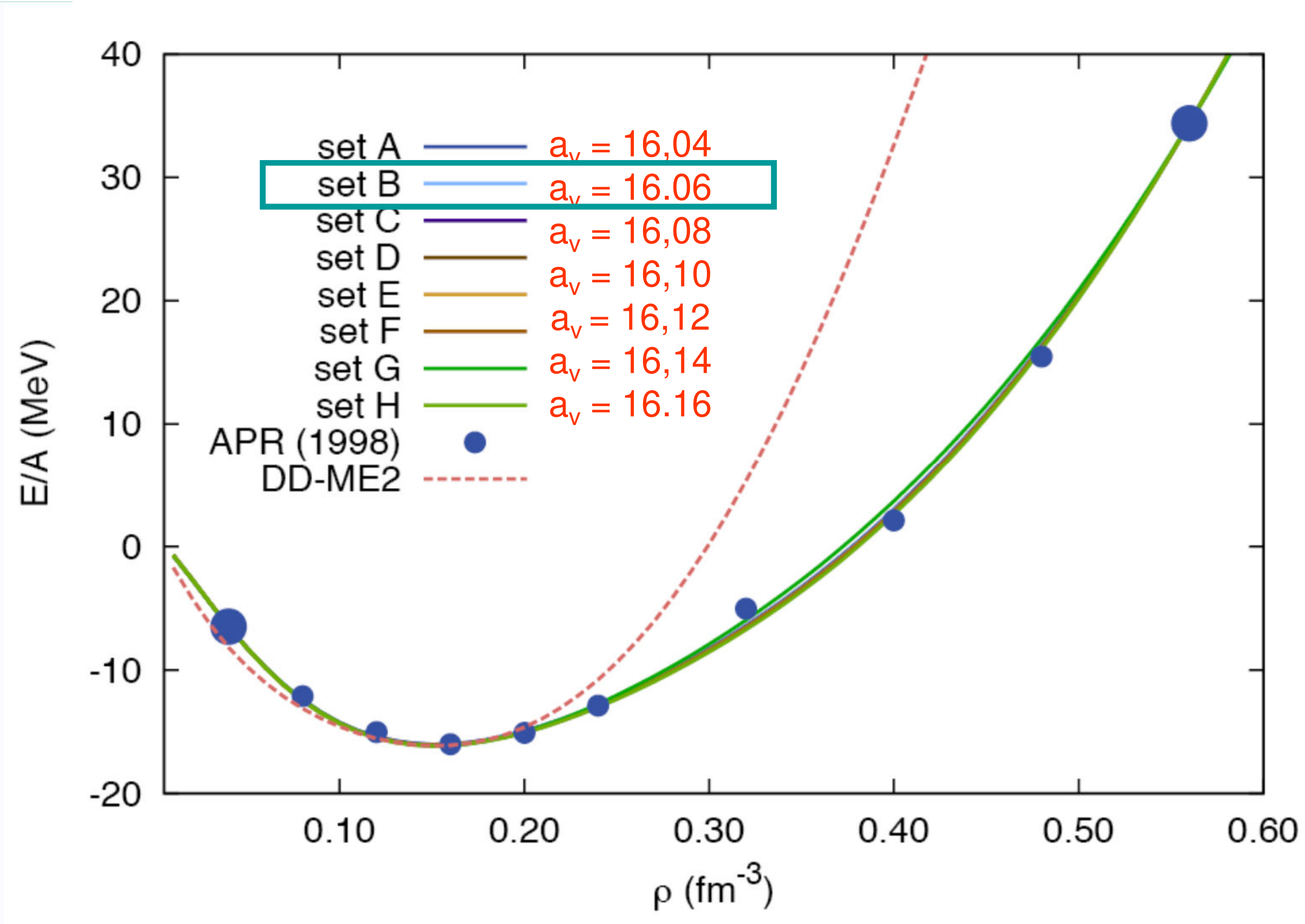
30 MeV $\le a_4 \le$ 34 MeV
2 MeV/fm³ < p_0 < 4 MeV/fm³
-200 MeV < ΔK_0 < -50 MeV



	DD-ME1	NL3	NL1
$a_4(MeV)$	33.1	37.9	43.7
$p_0(MeV/fm^3)$	3.26	5.92	7.0
$\Delta K_0(MeV)$	-128.5	52.1	67.3

Using ab initio data for the fit

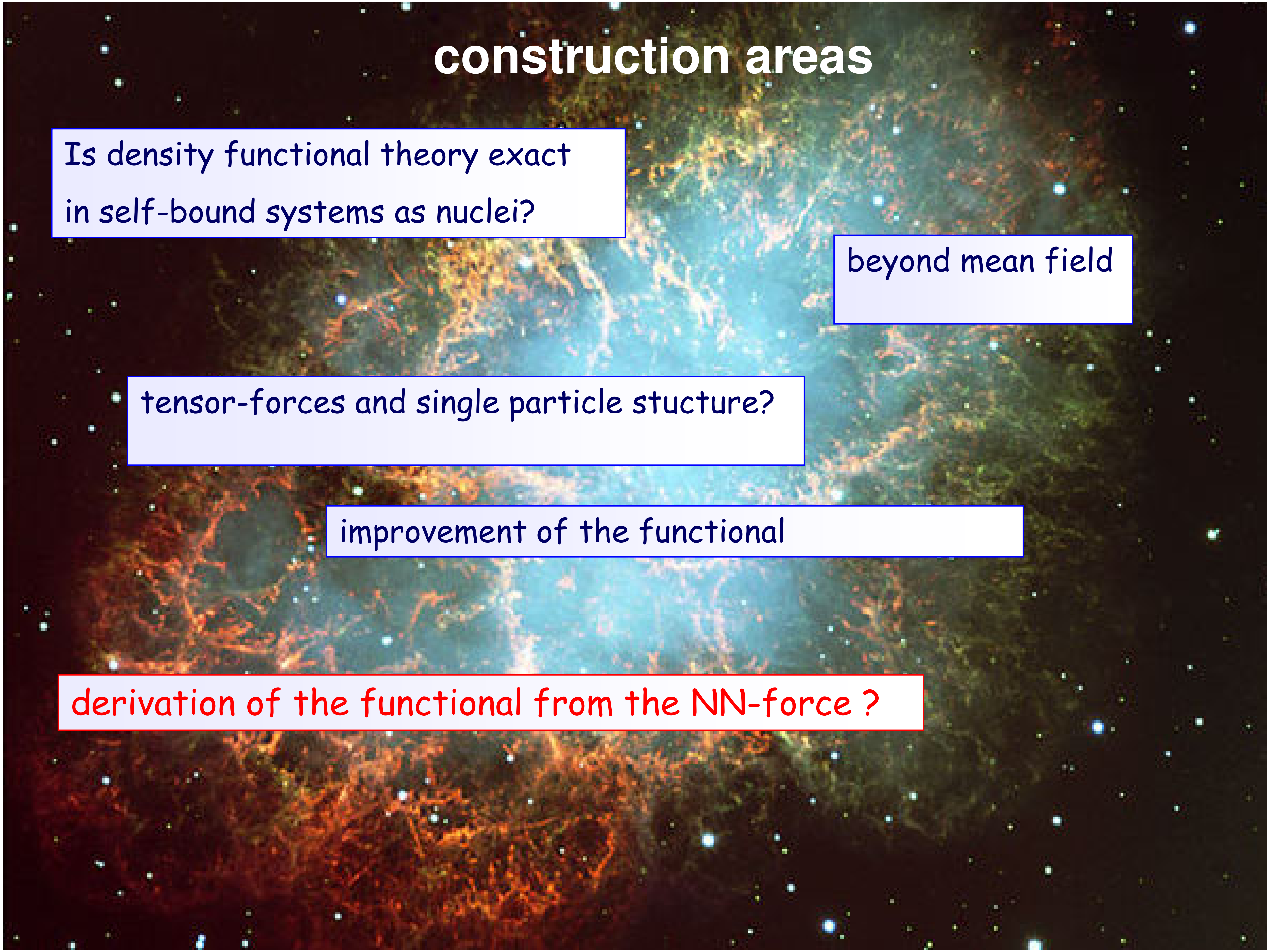
point coupling model is fitted to microscopic nuclear matter
and to masses of 64 deformed nuclei:



ρ_{sat} = 0.152 fm^{-3}
m^* = 0.58m
K_{nm} = 230 MeV
a_4 = 33 MeV

DD-PC1

A. Akmal, V.R. Pandharipande, and D.G. Ravenhall, PRC. 58, 1804 (1998).



construction areas

Is density functional theory exact
in self-bound systems as nuclei?

beyond mean field

tensor-forces and single particle stucture?

improvement of the functional

derivation of the functional from the NN-force ?

Literature:

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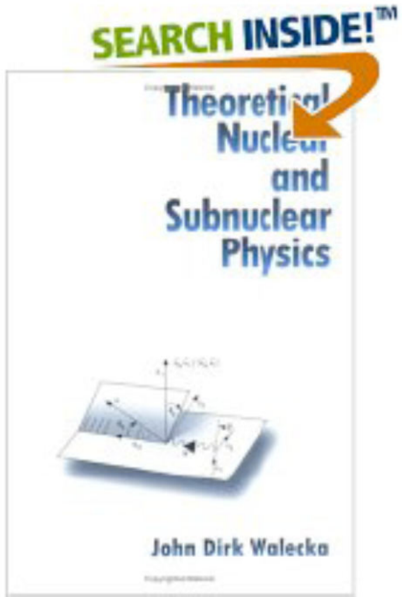

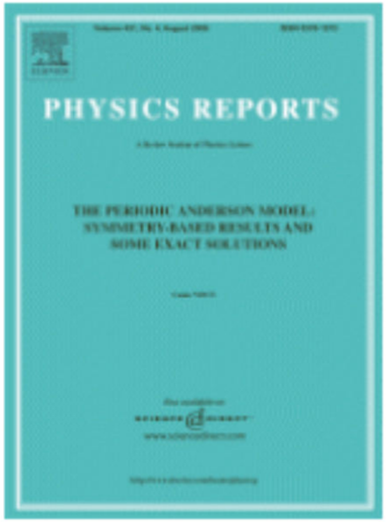

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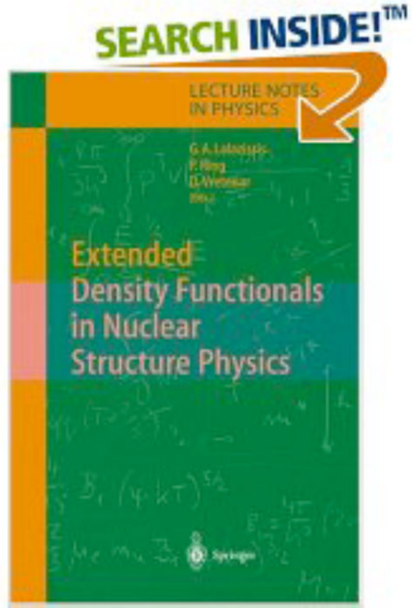

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- W. Pöschl et al, Comp. Phys. Comm. **101**, 295 (1997), "*Application of the Finite Element Method in RMF theory: the spherical Nucleus.*"
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- P. Ring, Y.K. Gambhir and G.A. Lalazissis, **105**, 77 (1997), "*Computer Program for the RMF Description of Ground State Properties of Even-Even Axially Deformed Nuclei .*"