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French–Italian–Polish Collaborations on

Nuclear Structure and Reactions

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Tailoring interactions for beyond-mean-field models in EDF theories

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

cnrs dépasser les frontières

Collaborators

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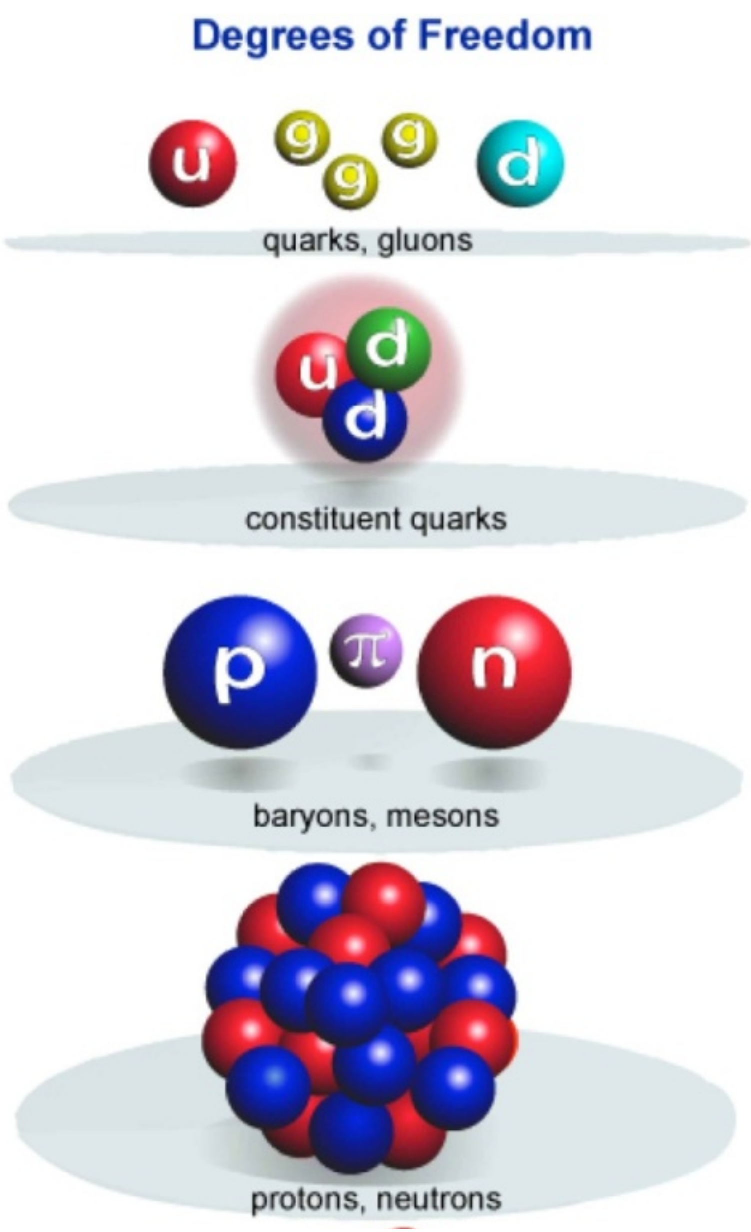
From quarks to nuclei



From quarks to hadrons (baryons and mesons)

From hadrons to nuclei

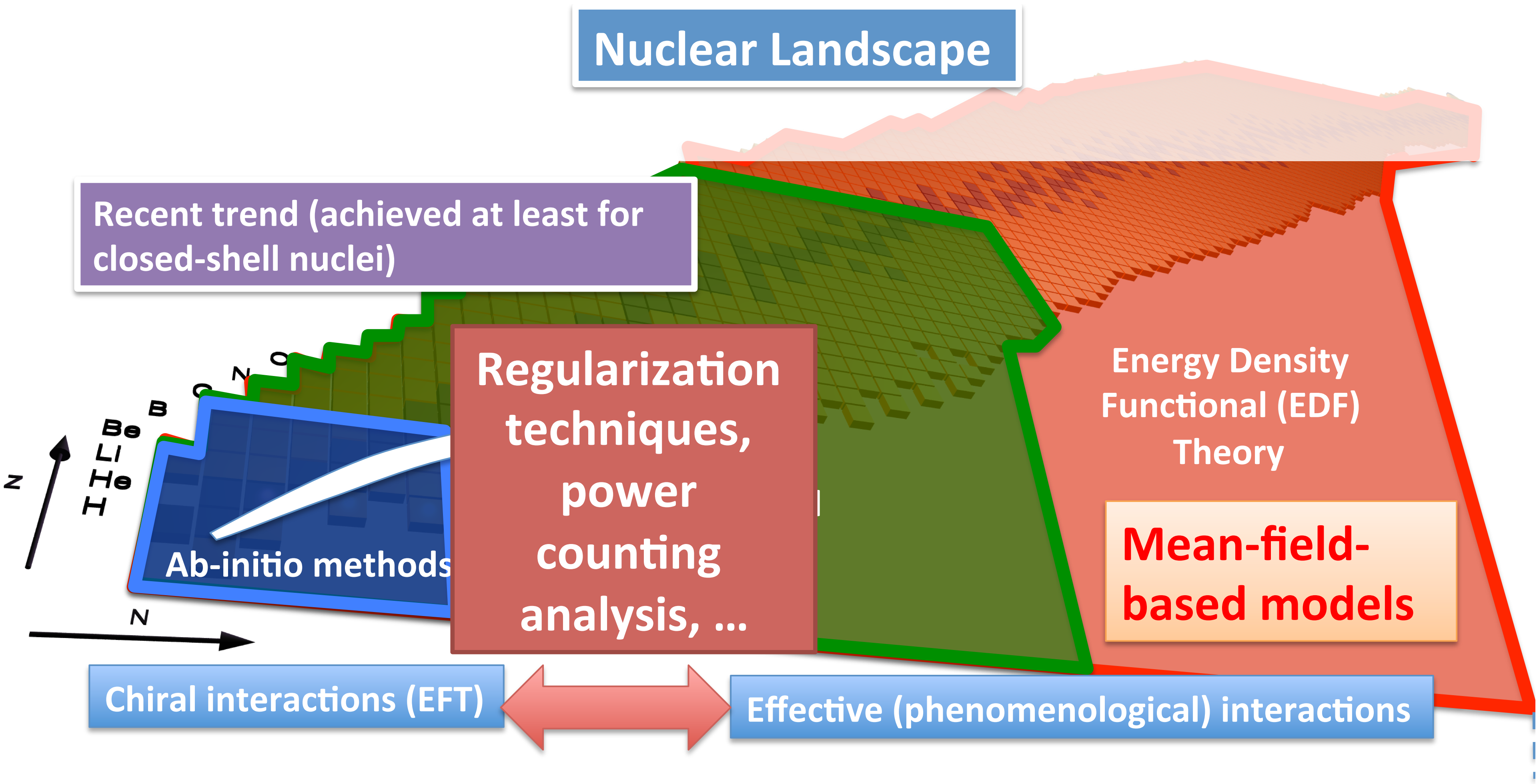
Modern trends: constructing interfaces

Chiral EFT

↕

Effective nucleon-nucleon interaction and many-body techniques

Energy Density Functional (EDF) and traditional shell model: structure and reactions



- More sophisticated beyond-mean-field models : improving predictive power, describing complex phenomena

- Numerical complexity, divergences, double counting

EDF: models currently employ Skyrme and Gogny phenomenological forces adjusted at the mean-field level

- Beyond Mean Field: Double counting and ultraviolet divergences –> some specific solutions exist (SRPA)

GENERAL OBJECTIVE

Within the EDF: designing interactions adapted for beyond mean-field models (cancellation of double counting and regularization of divergences)

Outline

- One example of beyond-mean-field model: the **SRPA model with a subtraction procedure**
- Low-lying states and giant resonances in ^{16}O

- **More in general, beyond the mean field: Which interaction to use?**
- Focus on the second-order EOS of nuclear matter

1) Regularization and adjustment of parameters

2) Description of the low-density limit in neutron matter

- Conclusions and Perspectives

SRPA with subtraction

The SRPA model

$$Q_\nu^\dagger = \sum_{ph} (X^\nu_{ph} a^\dagger_p a_h - Y^\nu_{ph} a^\dagger_h a_p)$$
$$+ \sum_{p<p',h<h'} (X^\nu_{php'h'} a^\dagger_p a_h a^\dagger_{p'} a_{h'} - Y^\nu_{php'h'} a^\dagger_h a_p a^\dagger_{h'} a_{p'})$$

Excitation operators

$$\begin{pmatrix} \mathcal{A} & \mathcal{B} \\ -\mathcal{B}^* & -\mathcal{A}^* \end{pmatrix} \begin{pmatrix} \mathcal{X}^\nu \\ \mathcal{Y}^\nu \end{pmatrix} = \omega_\nu \begin{pmatrix} \mathcal{X}^\nu \\ \mathcal{Y}^\nu \end{pmatrix}$$

RPA-type eqs.

$$\mathcal{A} = \begin{pmatrix} \boxed{A_{11}} & A_{12} \\ A_{21} & \boxed{A_{22}} \end{pmatrix}, \quad \mathcal{B} = \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$$

$$\mathcal{X}^\nu = \begin{pmatrix} X_1^\nu \\ X_2^\nu \end{pmatrix}, \quad \mathcal{Y}^\nu = \begin{pmatrix} Y_1^\nu \\ Y_2^\nu \end{pmatrix}$$

1 and 2:

short-hand notation for 1p1h and 2p2h

No cut in the matrix elements and large cutoff values

- Papakonstantinou and Roth, Phys. Lett. B 671, 356 (2009)
- Papakonstantinou and Roth, Phys. Rev. C 81, 024317 (2010)

Interaction derived from Argonne V18

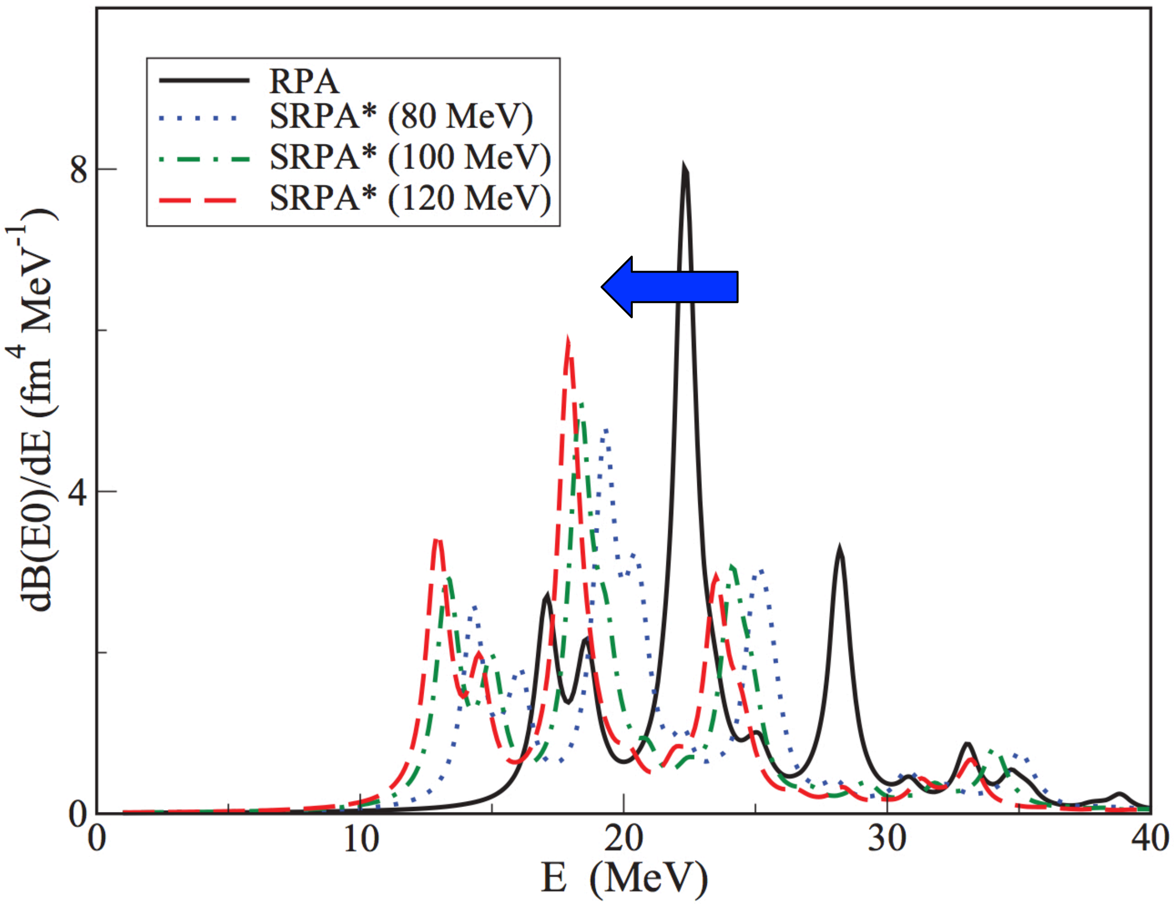
- Gambacurta, Grasso, and Catara, Phys. Rev. C 81, 054312 (2010)
- Gambacurta, Grasso, and Catara, J. Phys. G 38, 035103 (2011)
- Gambacurta, Grasso, and Catara, Phys. Rev. C 84, 034301 (2011)
- Gambacurta, Grasso, De Donno, Co', and Catara, Phys. Rev. C 86, 021304(R) (2012)

Phenomen. Skyrme and Gogny interactions

With the Gogny force (density-dependent contact term in the construction of the residual interaction) - ^{16}O

Isoscalar monopole response. The cutoff is in 2p2h configurations (in parentheses)

Shift and cutoff dependence



Gambacurta, Grasso, et al., Phys. Rev. C 86, 021304 (R) (2012)

Stability condition in SRPA. Recent formal study:

- Papakonstantinou, Phys. Rev. C 90, 024305 (2014)

- Tselyaev, Phys. Rev. C 88, 054301 (2013) (subtraction method, initially only for double counting)

By following Tselayev 2013 ->

Subtraction applied to SRPA

Rescaling of unperturbed elementary excitations

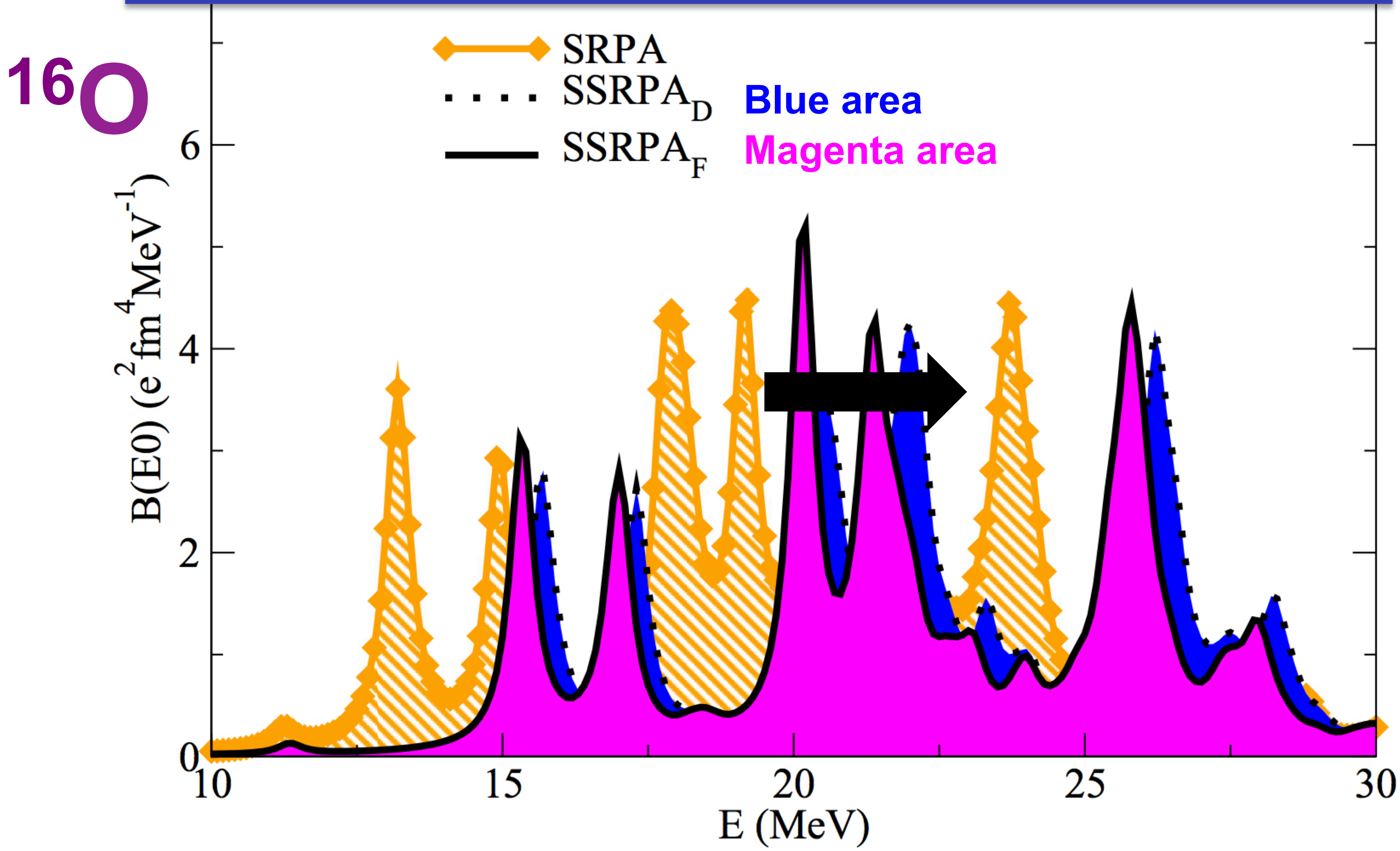
$$\mathcal{A}_F^S = \begin{pmatrix} A_{11'} + \boxed{\sum_2 A_{12}(A_{22'})^{-1}A_{21'} + \sum_2 B_{12}(A_{22'})^{-1}B_{21}} & A_{12} \\ A_{21} & A_{22'} \end{pmatrix}$$

$$\mathcal{B}_F^S = \begin{pmatrix} B_{11'} + \sum_2 A_{12}(A_{22'})^{-1}B_{21'} + \sum_2 B_{12}(A_{22'})^{-1}A_{21'} & B_{12} \\ B_{21} & B_{22'} \end{pmatrix}$$

S -> subtracted

F -> full scheme (inversion of the matrix $A_{22'}$)

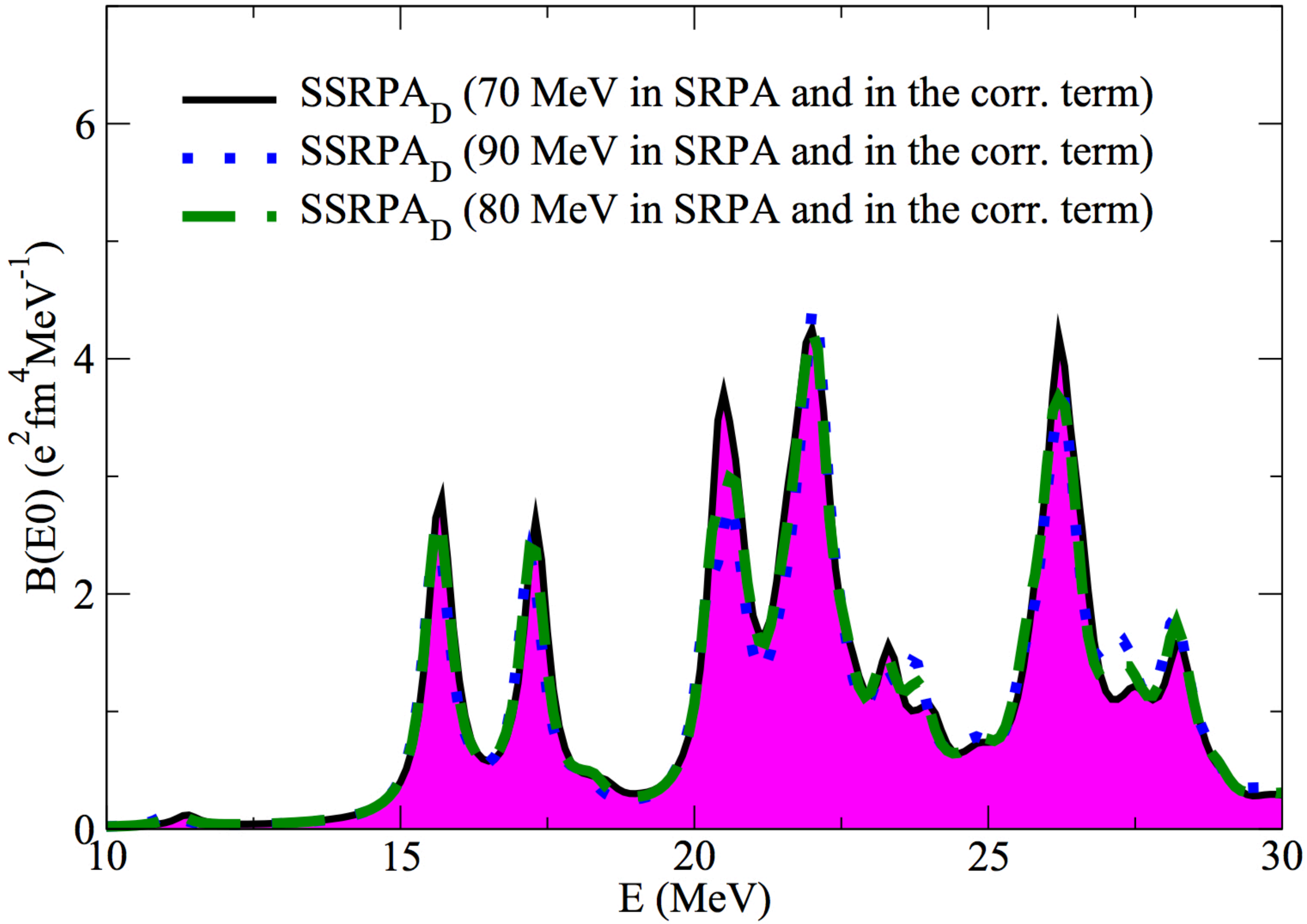
Effect of the subtraction. Isoscalar monopole response



Gambacurta, Grasso, Engel, PRC 92, 034303 (2015)

Robust prediction. No cutoff dependence
Monopole

^{16}O

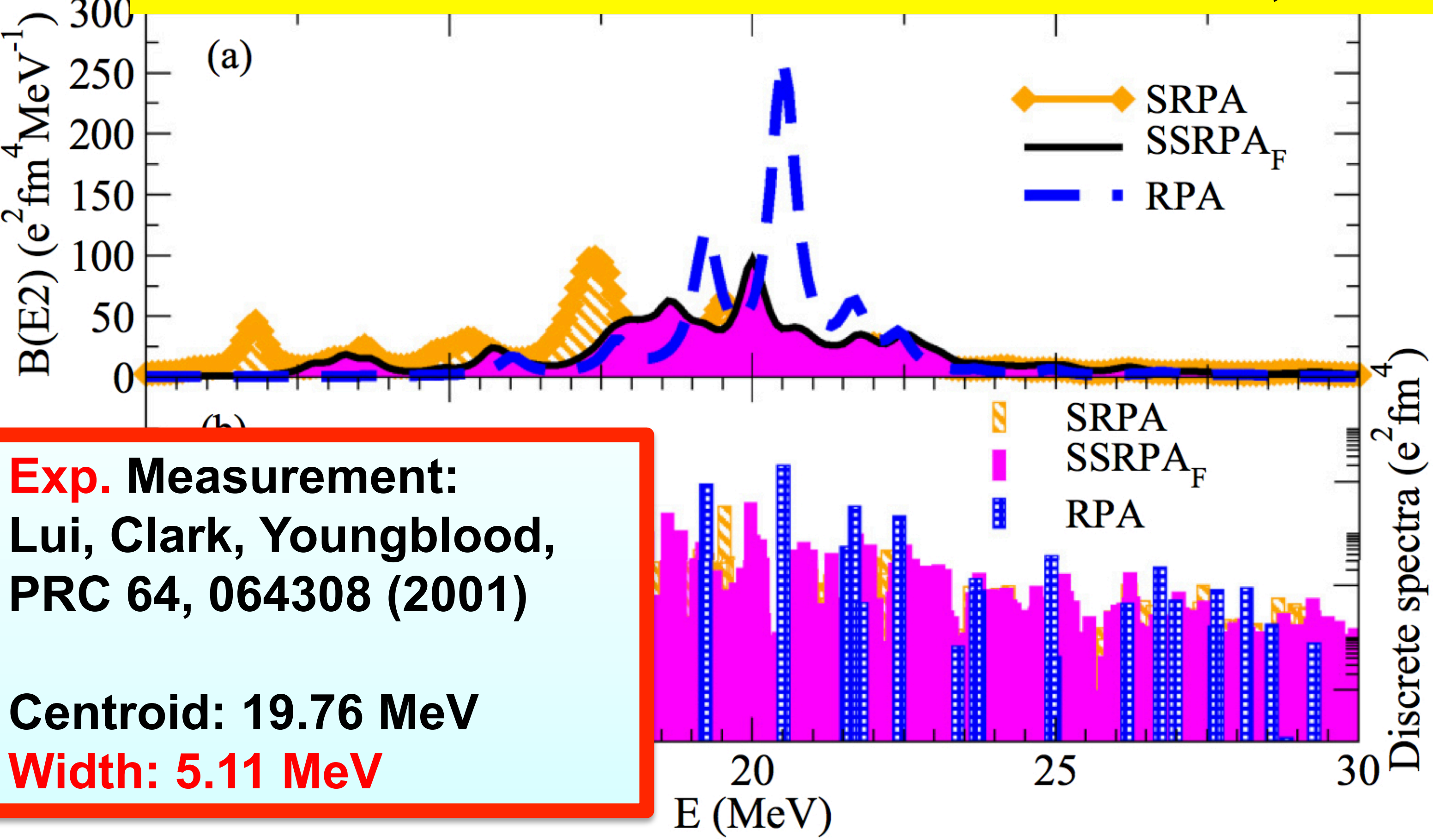


Gambacurta, Grasso, Engel, PRC 92, 034303 (2015)

Comparison with the RPA and with exp. Quadrupole

^{16}O

Centroid and width RPA: 20.73 MeV, 2.42 MeV
Centroid and width subtracted SRPA: 20.21 MeV, 4.05 MeV

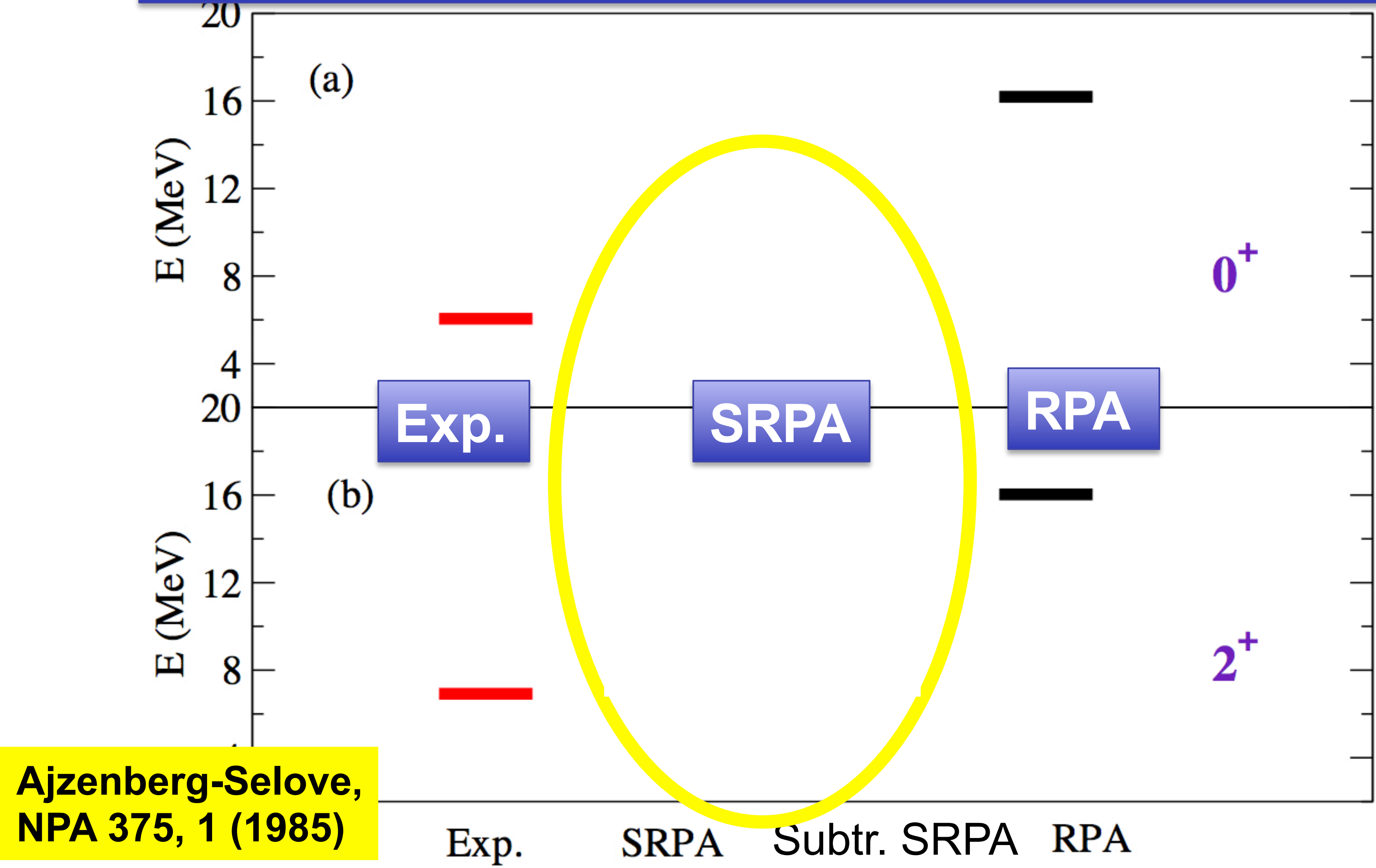


Exp. Measurement:
Lui, Clark, Youngblood, PRC 64, 064308 (2001)

Centroid: 19.76 MeV
Width: 5.11 MeV

Gambacurta, Grasso, Engel, PRC 92, 034303 (2015)

Low-lying states. Two-particle/two-hole states



Gambacurta, Grasso, Engel, PRC 92, 034303 (2015)

Nuclear matter, many-body perturbation theory, regularization, links with Effective Field Theories

1. Nuclear matter. Regularization and adjustment of parameters

(Skyrme interaction)

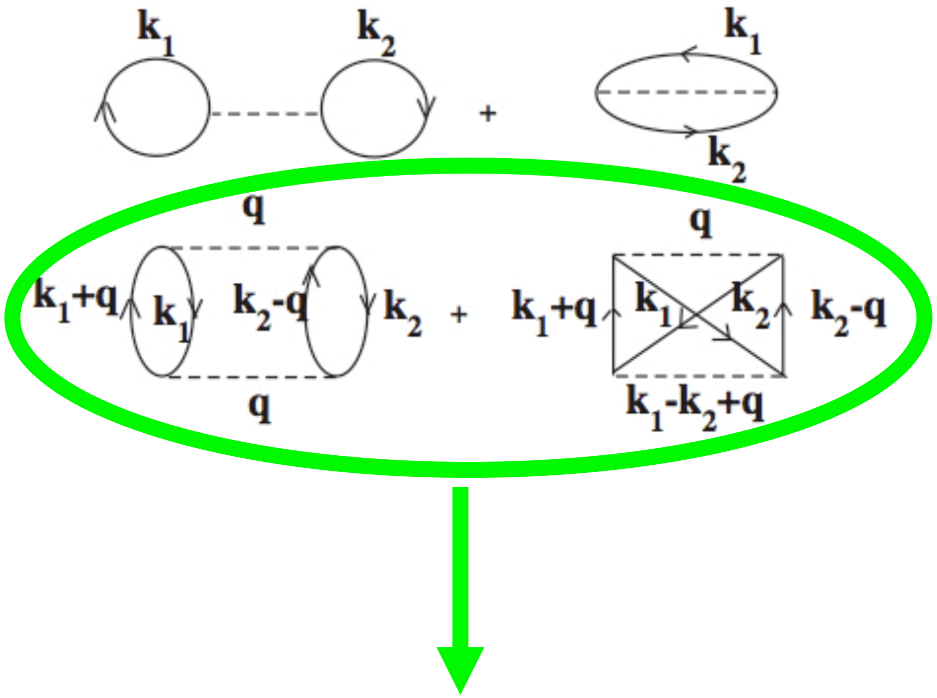
$$v = t_0(1+x_0P_\sigma) + \frac{1}{2}t_1(1+x_1P_\sigma)(\mathbf{k}'^2+\mathbf{k}^2) + t_2(1+x_2P_\sigma)\mathbf{k}'\cdot\mathbf{k} + \frac{1}{6}t_3(1+x_3P_\sigma)\rho^\alpha$$

Spin-exchange operator $\Rightarrow$ $P_\sigma = \frac{1}{2}(1+\sigma_1\cdot\sigma_2)$

Nine parameters to adjust

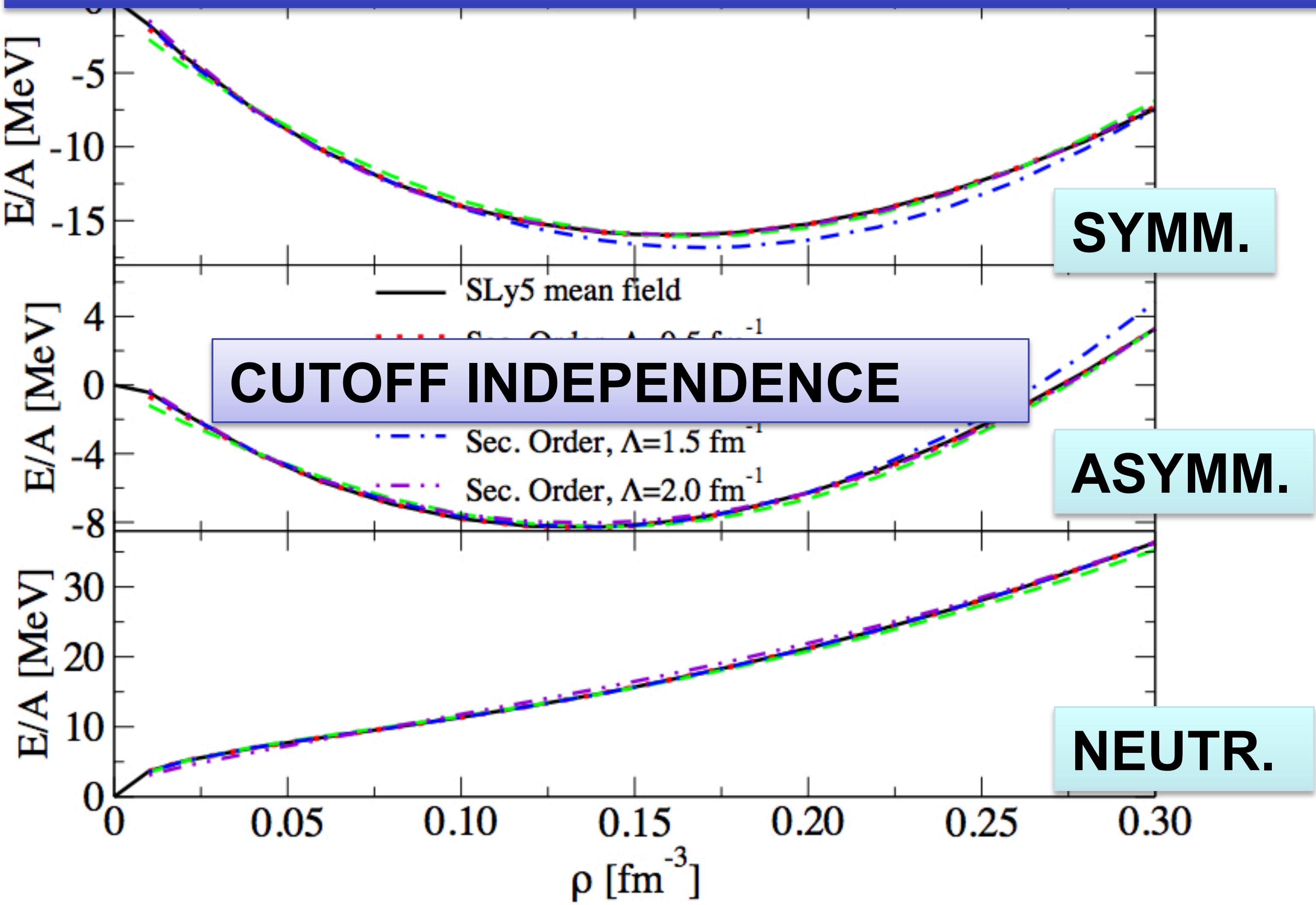
Moghrabi, Grasso, Colo', PRL 105, 262501 (2010)
Yang, Grasso, Roca-Maza, Colo', Moghrabi, arXiv:1604.06278 (nucl-th)

Equation of state of nuclear matter with a Skyrme-type interaction



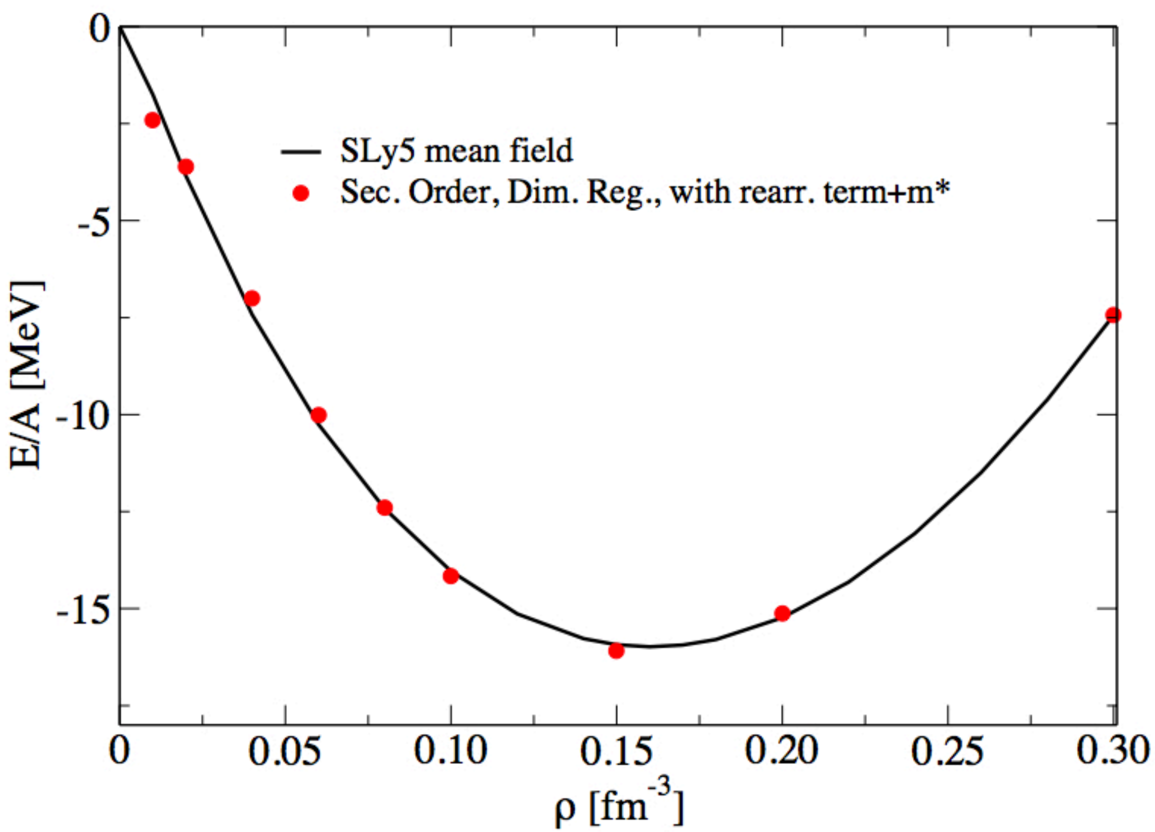
This second-order contribution diverges with a Skyrme-type interaction

Regularized and readjusted EOSs. A unique set of parameters for symmetric, asymmetric and neutron matter



Yang, Grasso, Roca-Maza, Colo', Moghrabi, arXiv:1604.06278 (nucl-th)

DIMENSIONAL REGULARIZATION. IMPORTANCE OF THE DENSITY DEPENDENCE AND OF THE REARRANGEMENT TERMS. SYMM. MATTER



No density

With also rearr. terms

Density dependence. No rearr. terms

Equilibrium point + compressibility

Yang, Grasso, Roca-Maza, Colò, Moghrabi, arXiv:1604.06278 (nucl-th)

Kaiser, J. Phys. G: Nucl. and Part. Phys. 42, 095111 (2015)

2. Nuclear Matter

Low-density for neutron matter. Lee-Yang expansion

Lee and Yang, Phys. Rev. 105, 1119 (1957)

$$\frac{E}{N} = \frac{\hbar^2 k_N^2}{2m}\left[\frac{3}{5} + \frac{2}{3\pi}(k_N a) + \frac{4}{35\pi^2}(11 - 2ln2)(k_N a)^2\right]$$

a -> the scattering length, -18.9 fm

Can we reproduce the low density with the mean field?

- **Lee-Yang expansion (first terms)**

$$\frac{E}{N} = \frac{\hbar^2 k_N^2}{2m}\left[\frac{3}{5} + \frac{2}{3\pi}(k_N a) + \frac{4}{35\pi^2}(11 - 2ln2)(k_N a)^2\right]$$

- **Mean field EOS (t0-t3 model) (first order of Dyson expansion)**

$$\frac{E}{N} = \frac{3}{10}\frac{\hbar^2}{m}k_N^2 + \frac{1}{12\pi^2}t_0(1-x_0)k_N^3 + \frac{1}{24}t_3(1-x_3)\left(\frac{1}{3\pi^2}\right)^{\alpha+1} k_N^{3\alpha+3}$$

?

Yes, for α=1/3

… but to get also a reasonable EOS for neutron matter at usual density scales the scattering length has to be treated as a free parameter (value far from the correct one)

Can we get simultaneously the low-density behavior (with a correct value of the scattering length a) and a reasonable EOS for usual densities ?

The second-order contribution has the k_F^4 term

$$\frac{E_F^{N(2)}}{A} = \boxed{\frac{m k_N^4}{\hbar^2 \pi^4}\left(\frac{1}{280}(11 - 2ln[2])T_0^2\right.} + \frac{1}{1890}(167 - 24ln[2])k_N^2 T_{03} T_1 + \frac{1}{83160}(4943 - 564ln[2])k_N^4 T_1^2$$
$$\left. + \frac{1}{110880}(1033 - 156ln[2])k_N^4 T_2^2\right).$$

Direction: going to higher orders … but only second order is not enough !!!

Yang, Grasso, Lacroix, arXiv:1604.06587 (nucl-th)

Inspired by resumed expressions (resumed functional) (EFT)

EOS for symmetric and

Constrained by the first two terms of Lee Yang formula (scattering length)

$$\frac{E}{A} = K_\beta + \frac{\boxed{B_\beta \rho}}{1 - \boxed{R_\beta \rho^{1/3}} + C_\beta \rho^{2/3}} + D_\beta \rho^{5/3} + F_\beta \rho^{\alpha+1}$$

Resumed expression

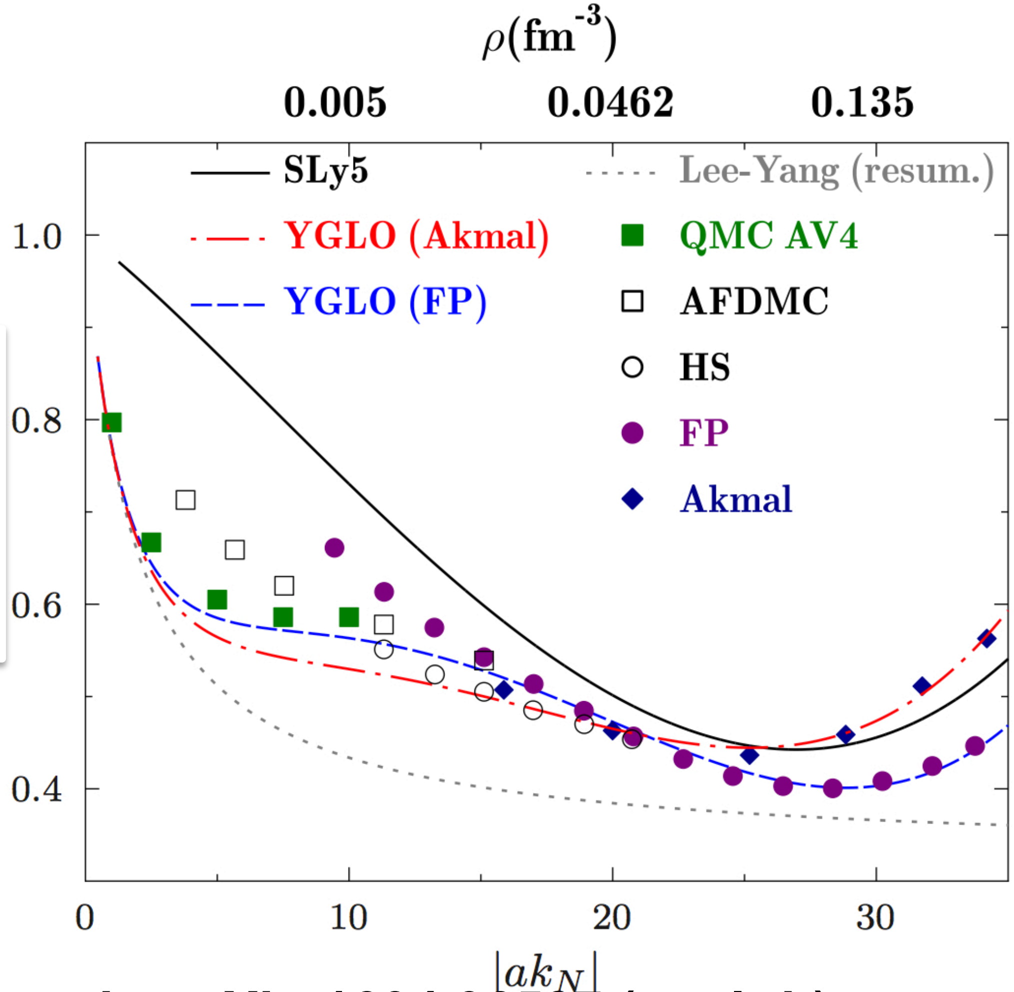
Mimic velocity- and density-dependent terms

Other parameters adjusted on Friedman et al. and Akmal et al. EOSs

Yang, Grasso, Lacroix, arXiv:1604.06587 (nucl-th)

Very low-density behavior of neutron matter

Energy divided by the free gas energy

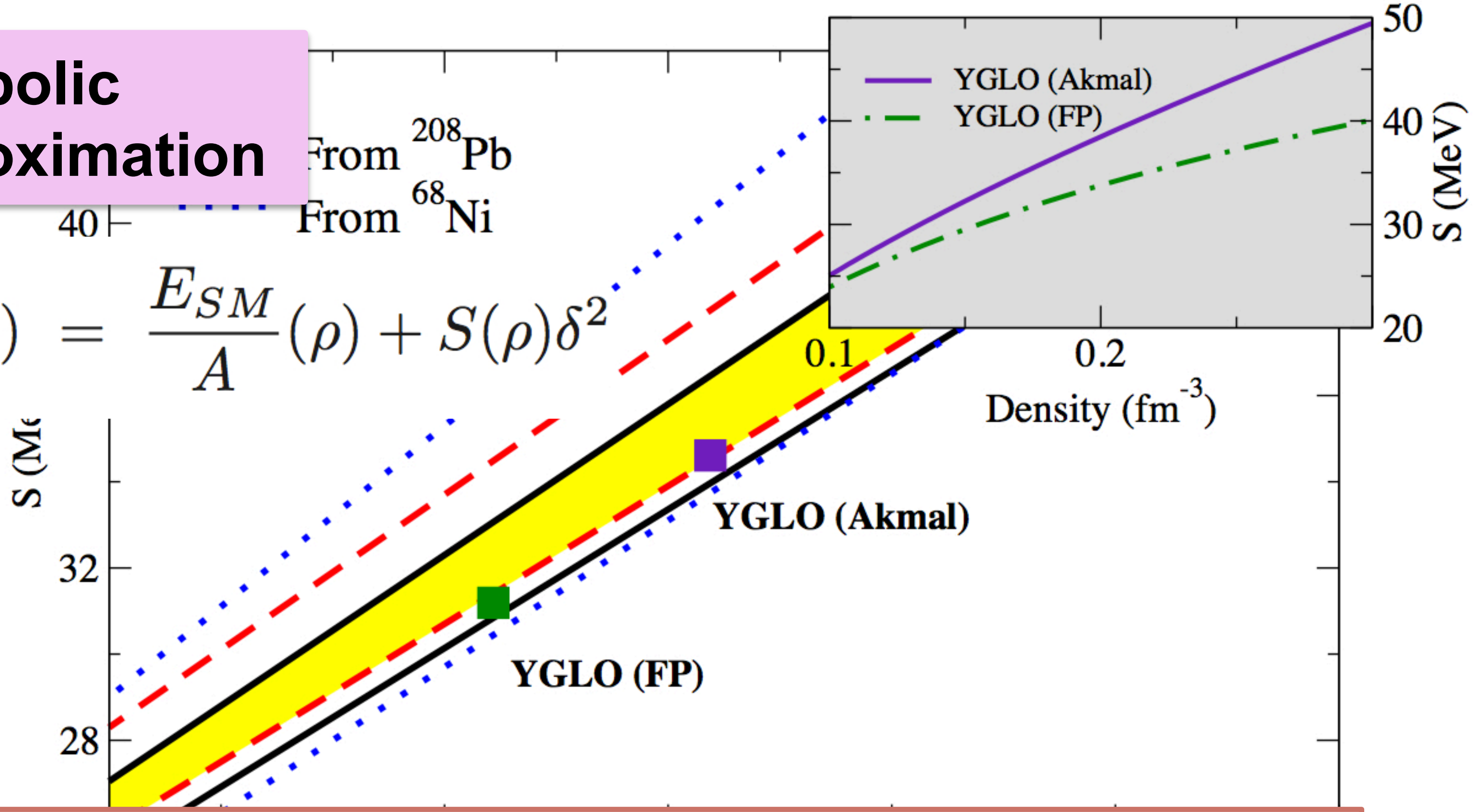


Yang, Grasso, Lacroix, arXiv:1604.06587 (nucl-th)

Symmetry energy and its slope

Parabolic approximation

$$\frac{E_\delta}{A}(\rho) = \frac{E_{SM}}{A}(\rho) + S(\rho)\delta^2$$



Lines delimit the phenomenological areas constrained by the exp. determination of the electric dipole polarizability

Yang, Grasso, Lacroix, arXiv:1604.06587 (nucl-th)

Conclusions and Perspectives

1. SRPA model with a subtraction procedure: double counting and divergences cured.

   A **robust BMF model for describing excitations**

2. Regularization (cutoff and dimensional), and low density in nuclear matter

3. Perspectives: systematics with SRPA, power counting analysis (within EDF) for Many-Body perturbation theory, continuing towards applications to nuclei