iRiS 중이온가속기연구소 Institute for Rare Isotope Science

From nucleons to neutron stars in the unifying framework of energy density functional theory

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Dense Nuclear Matter Equation of State from Theory and Experiments

FRIB, East Lansing MI, USA

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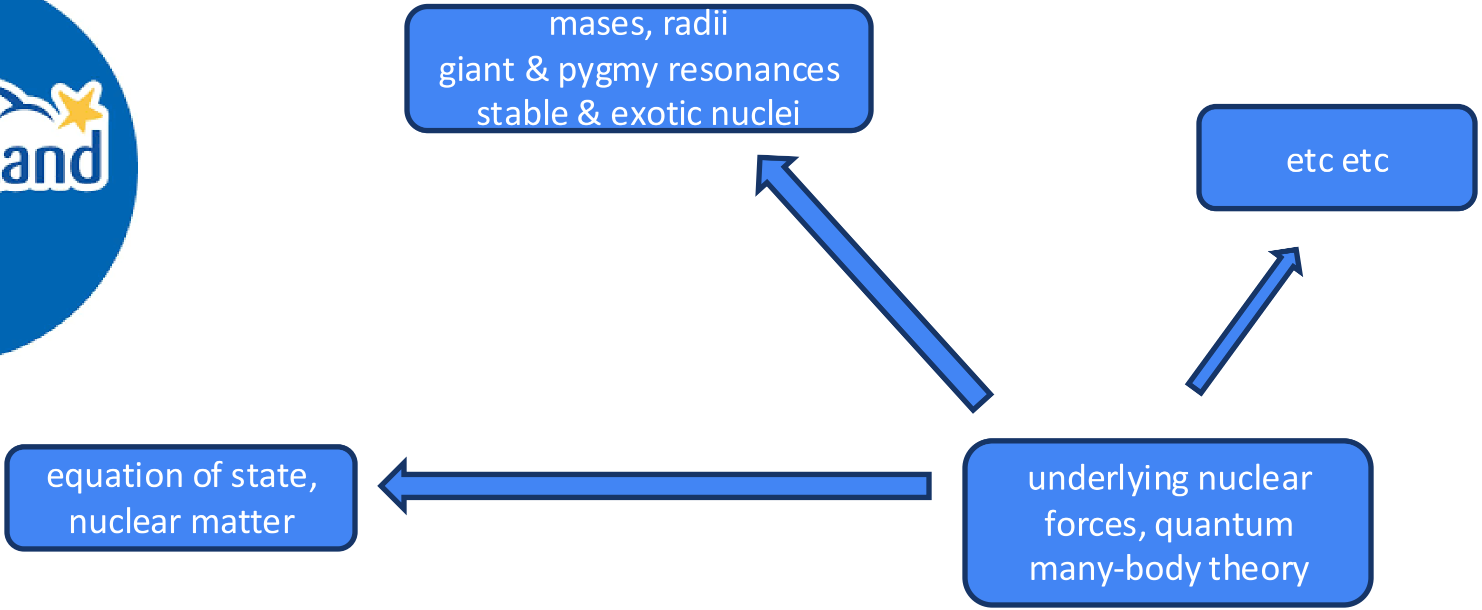
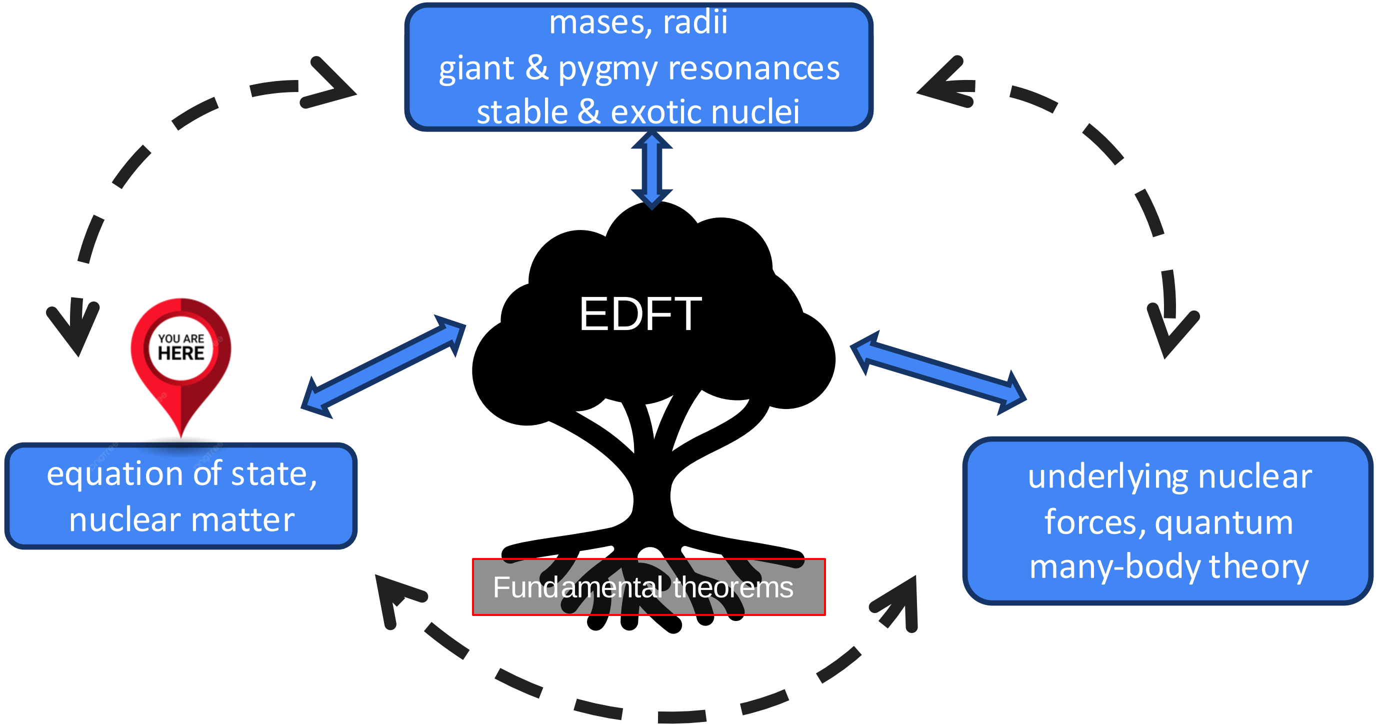
01 Introduction



01 Introduction



01 Introduction

Energy density functional theory boils down to:

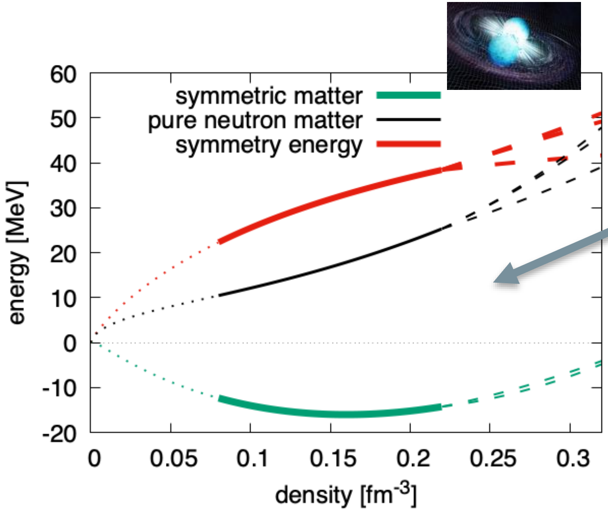
Hohenberg-Kohn and Kohn-Sham theorems

- The energy of a system is a function of the density [distribution].
- One may as well use mean-field theory: Consider non-interacting particles in a single-particle potential such that the energy and density of the non-interacting system are the same as those of the interacting one. One has to make informed guesses as to what this potential looks like.

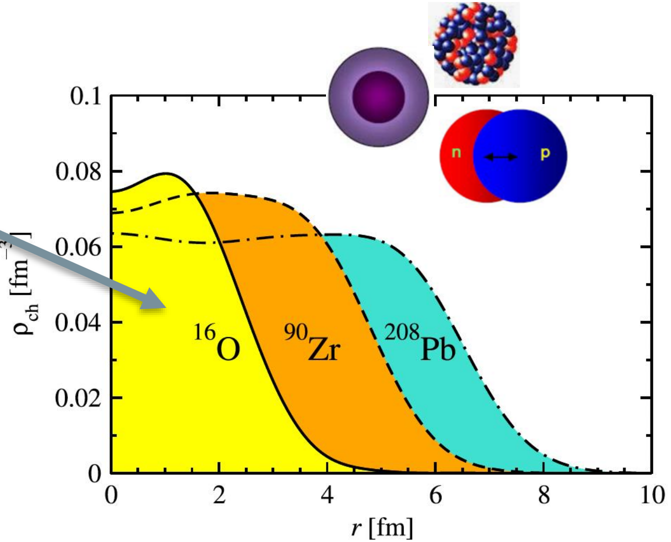
  (here we likely are on less solid ground:)
- But dealing with different numbers of particles, (A,Z), including infinite, and not only at equilibrium density, one needs a way to generate this "mean field" in the same way for all these systems and densities
- Solution: I calculate it self-consistently from some in-medium effective interaction or effective Lagrangian. The guess work reduces to guessing the form of this interaction or Lagrangian.

01 Introduction

"The energy is a function of the density"



- Skyrme (zero-range effective interaction),
- Gogny (finite-range effective interaction),
- RMF (effective Lagrangian)



The fundamental entity is the functional of the density; the effective interactions are auxiliary.

Skyrme effective interaction

$$\hat{v}_{\mathrm{Sk}}(\mathbf{r}_{12}) = t_0\,(1+x_0\hat{P}_\sigma)\,\delta(\mathbf{r}_{12}) + \tfrac{1}{2}\,t_1\,(1+x_1\hat{P}_\sigma)[\hat{\mathbf{k}}^{\dagger 2}\,\delta(\mathbf{r}_{12}) + \delta(\mathbf{r}_{12})\hat{\mathbf{k}}^2] + t_2(1+x_2\hat{P}_\sigma)\,\hat{\mathbf{k}}^\dagger\cdot\delta(\mathbf{r}_{12})\hat{\mathbf{k}}$$

$$+\tfrac{1}{6}\,t_3\,(1+x_3\hat{P}_\sigma)\,\delta(\mathbf{r}_{12})\rho^\alpha\left(\frac{\mathbf{r}_1+\mathbf{r}_2}{2}\right) + iW_0\,(\hat{\boldsymbol{\sigma}}_1+\hat{\boldsymbol{\sigma}}_2)\cdot\hat{\mathbf{k}}^\dagger\,\delta(\mathbf{r}_{12})\hat{\mathbf{k}}$$

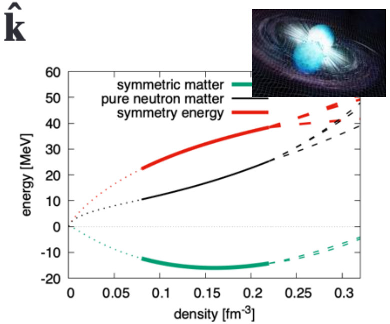
Skyrme energy per particle: density, asymmetry, gradients

$$\mathcal{E}(\rho,\delta) = \frac{\hbar^2}{2m}\tau + \frac{3}{8}t_0\rho + \frac{t_0}{8}(1+2x_0)\rho\delta^2 + \frac{t_3}{16}\rho^{1+\alpha} - \frac{t_3}{48}(1+2x_3)\rho^{1+\alpha}\delta^2$$

$$-\frac{1}{64}(3t_1+6t_1x_1+t_2+2t_2x_2)\frac{(\nabla\rho\delta)^2}{\rho} + \frac{1}{64}(9t_1-5t_2-4t_2x_2)\frac{(\nabla\rho)^2}{\rho}$$

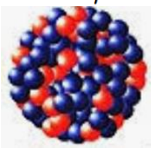
$$+\frac{1}{8}(2t_1+t_1x_1+t_2+t_2x_2)\tau - \frac{1}{8}(t_1+2t_1x_1-t_2-2t_2x_2)\sum_{q=p,n}\frac{\rho_q\tau_q}{\rho} + \frac{1}{2}W_0\left(\frac{\mathbf{J}\cdot\nabla\rho}{\rho} + \sum_{q=p,n}\frac{\mathbf{J}_q\cdot\nabla\rho_q}{\rho}\right)$$

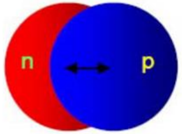
t_0: binding
$t_3\rho^\alpha$: saturation
$t_{1,2}$: kinetic



Skyrme mean field and restoring force for linear response (HF, RPA)

From functional differentiation of the above





- ❑ Now the EDF can mediate a learning process: from nuclei about nuclear matter and vice versa.

Characterization of the nuclear EoS

The Taylor expansion coefficients of the energy per particle $E(\rho)$ at $\delta=0$ around saturation density are conveniently used to characterize the nuclear EoS of isospin-symmetric nuclear matter.

- The most relevant coefficients for nuclei are the saturation density ρ_0 itself, the energy at saturation density E_0, the compression modulus K_0, and the symmetry energy value J (cf. LDM).
- The first derivative at the saturation point vanishes by definition.

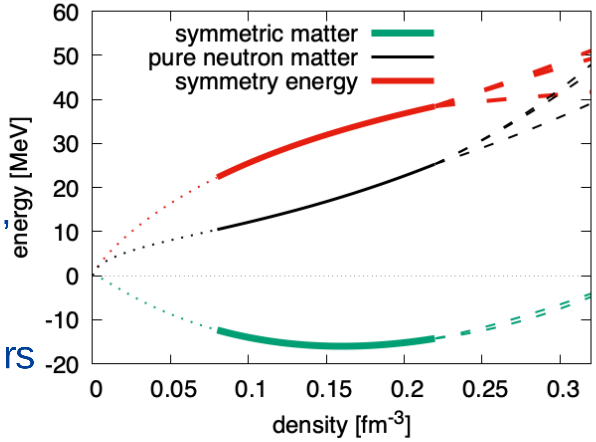
$$E(\rho) = E_0 + \frac{1}{2} K_0 x^2 + \frac{1}{6} Q_0 x^3 + \ldots$$

$$x = (\rho-\rho_0)/3\rho_0$$

- The symmetry energy also is characterized by a Taylor expansion,

$$S(\rho) = J + Lx \; \frac{1}{2} K_{sym} x^2 + \frac{1}{6} Q_{sym} x^3 + \ldots$$

- Extrapolations beyond saturation are controlled by such parameters



Characterization of the nuclear EoS

The Taylor expansion coefficients of the energy per particl
turation density
are conveniently used to characterize the nuclear EoS of i
r matter.

All these parameters have simple analytical forms in the Skyrme framework

- The most relevant coefficients for nuclei are the satura
energy at saturation density E_0, the compression modulus K_0, and the symmetry energy value J (cf. LDM).
- The first derivative at the saturation point vanishes by definition.

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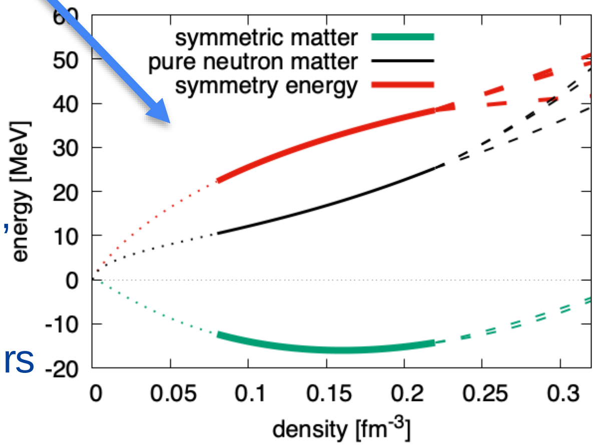
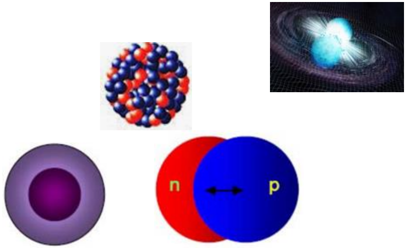


Constraints on the EoS coefficients

- The most accessible nuclear properties are determined by the lower-order EoS coefficients and mostly by those for symmetric matter with the help of liquid drop models and energy density functional theory.
- As a result, the lower-order coefficients and those of symmetric matter are best determined

  $E_0 \approx -16$ MeV , $\rho_0 \approx 0.16$ fm^{-3}, J ≈30-33 MeV, …
- Higher-order ones are important for extrapolations of the nucleonic EoS beyond saturation density
  - – Description of neutron star matter
  - – Neutron skins
  - – Collective vibrations
- Compression modulus $K_0 \approx$ 200-250 MeV, L≈ 40-70MeV, etc.



See also: Roca-Maza&Paar, Prog.Part.Nucl.Phys. 101,96

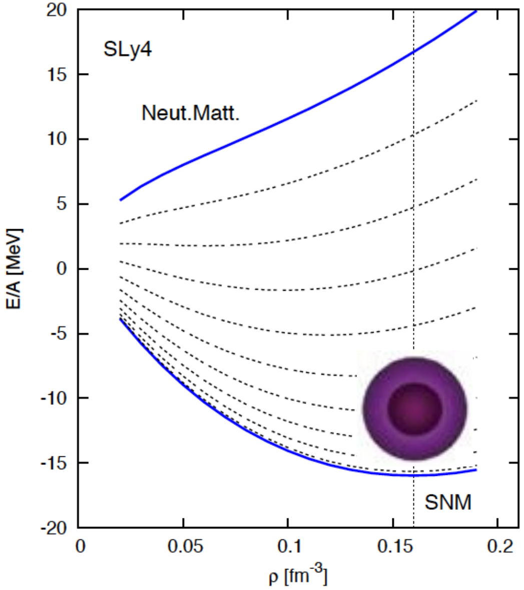
01 Introduction

Constraints on the EoS coefficients from collective excitations

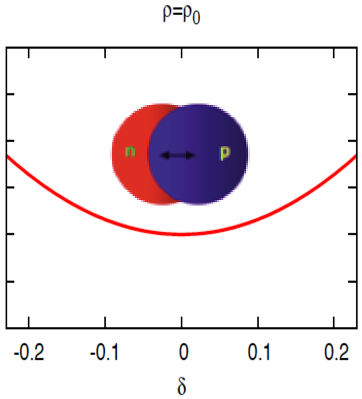
$$\frac{E}{A}(\rho,\delta^2) = \left(\frac{E}{A}\right)_{\rho=\rho_0} + \frac{(\rho-\rho_0)^2}{18}\left(\frac{\partial^2(E/A)}{\partial\rho^2}\right)_{\rho=\rho_0} + \frac{\delta^2}{2}\left(\frac{\partial^2(E/A)}{\partial\delta^2}\right)_{\delta=0}$$

K

J



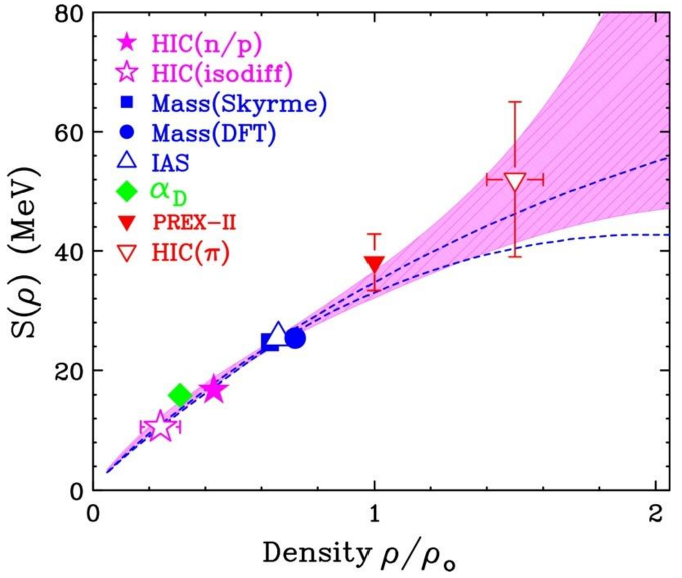
absolute values vs. derivatives



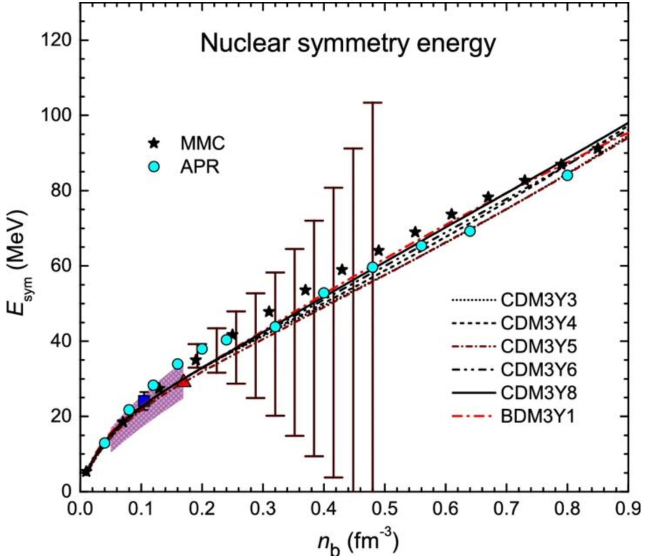
See Garg&Colò, PPNP101(2018)55

Nuclear symmetry energy from various observables and calculations (examples)

Lynch&Tsang, PLB830(2022)137098



Tan et al., EPJA57(2021)153



Some reviews:

- Baldo&Burgio, ProgPartNuclPhys91,203 (2016)
- Oertel et al., Rev.Mod.Phys.89,015007 (2017)
- Roca-Maza&Paar, ProgPartNuclPhys101,96 (2018)

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02 Nuclear EDFT news

KIDS framework
Correlation studies

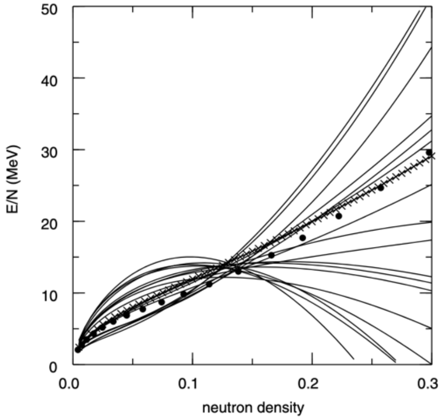
02 Nuclear EDFT news

Phenomenological energy-density functionals

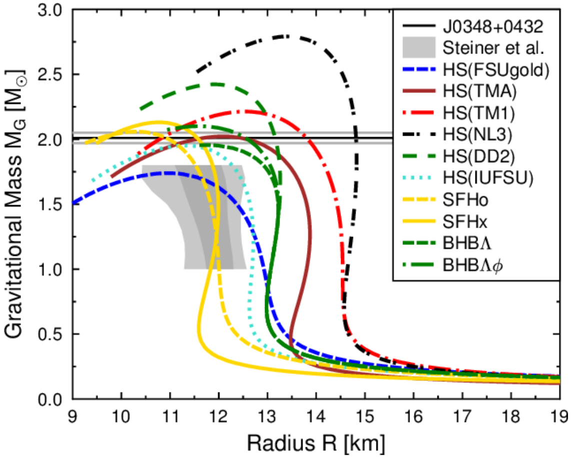
Hundreds of EDF models for nuclei and nuclear matter

- ❑ Typically, ~ten parameters fitted to nuclear properties using different data sets and fitting protocols
- ❑ Very different predictions below and above saturation density
- ❑ Very different predictions at large isospin asymmetries

B.A.Brown, PRL 85(2000)5296



Fischer et al., EPJA50(2014)46



02 Nuclear EDFT news

Phenomenological energy-density functionals

- Only few of the hundreds of EDF models can simultaneously describe nuclear matter and finite nuclei

Dutra et al, PRC85(2012)035201
Stevenson et al., AIP Conf.Proc 1529,262

- Spurious correlations among parameters have been noted; binding energies and seem to radii “prefer” different values for the effective mass

Bender et al., RMP75(2003)121

- Not a satisfactory situation at all:

✕ *“going from successful models in the description of observables to the EoS is a well defined and safe strategy while ensuring reasonable parameters of the EoS do not necessarily lead to a good reproduction of the data on finite nuclei.”*

Roca-Maza&Paar, PPNP101(2018)96

- **Next: How we overcome these problems with *KIDS***

02 Nuclear EDFT news

KIDS: *Korea, IBS,Daegu,SKKU*
Grown-ups: H. Gil, C.H.Hyun (Daegu Univ.) + P.P. (IBS)
Past contributors: T.-S.Park, Y. Lim, Y. Oh, G. Ahn, Y.-M.Kim,J.Xu
Currently collaborating: K.Yoshida, N.Hinohara

KIDS framework for the EoS and EDF

- Analytical form of EoS inspired by Brueckner and effective field theories: expansion in $k_F \sim \rho^{1/3}$

$$\mathcal{E}(\rho,\delta) = \mathcal{T}(\rho,\delta) + \sum_{i=0}^{n} c_i(\delta)\rho^{1+i/3}$$

$$\delta = (\rho_n - \rho_p)/\rho$$

- In quadratic approximation:

$$c_i(\delta) = \alpha_i + \beta_i\delta^2 \text{ and } S(\rho) = \sum_{i=0}^{n} \beta_i \rho^{1+i/3}$$

- Straightforward analytical (linear) relations between standard EoS parameters and KIDS-EoS parameters; freedom to expand to as many EoS parameters as we wish
- **Can be readily transposed to an EDF without altering its parameters**

KIDS framework for the EoS and EDF

- Has the form of an extended Skyrme functional with generalized density dependence. First, we define a Skyrme-like effective interaction

$$
\begin{aligned}
v_{ij} \;=\; & (t_0 + y_0 P_\sigma)\delta(\mathbf{r}_i - \mathbf{r}_j) \\
& + \frac{1}{2}(t_1 + y_1 P_\sigma)[\delta(\mathbf{r}_i - \mathbf{r}_j)\mathbf{k}^2 + \mathbf{k}'^2\delta(\mathbf{r}_i - \mathbf{r}_j)] \\
& + (t_2 + y_2 P_\sigma)\mathbf{k}' \cdot \delta(\mathbf{r}_i - \mathbf{r}_j)\mathbf{k} \\
& + \frac{1}{6}\sum_{n=1}^{N-1}(t_{3n} + y_{3n} P_\sigma)\rho^{n/3}\delta(\mathbf{r}_i - \mathbf{r}_j) \\
& + iW_0\,\mathbf{k}' \times \delta(\mathbf{r}_i - \mathbf{r}_j)\,\mathbf{k} \cdot (\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j),
\end{aligned}
$$

notation:
instead of $t_i x_i$
we write y_i

- **Advantage: standard, efficient Skyrme-nuclear-structure codes can be used**

KIDS framework for the EoS and EDF

$$\mathscr{E} = \frac{\hbar^2}{2m}\tau + \frac{3}{8}t_0\rho - \frac{1}{8}(t_0 + 2y_0)\rho\delta^2 + \frac{1}{16}\sum_{n=1}^{N-1} t_{3n}\rho^{1+n/3} - \frac{1}{48}\sum_{n=1}^{N-1}(t_{3n} + 2y_{3n})\rho^{1+n/3}\delta^2$$

$$+\frac{1}{64}(9t_1 - 5t_2 - 4y_2)\frac{(\nabla\rho)^2}{\rho} - \frac{1}{64}(3t_1 + 6y_1 + t_2 + 2y_2)\frac{(\nabla\rho\delta)^2}{\rho}$$

$$+\frac{1}{8}(2t_1 + y_1 + 2t_2 + y_2)\tau - \frac{1}{8}(t_1 + 2y_1 - t_2 - 2y_2)\sum_q \frac{\rho_q\tau_q}{\rho}$$

$$+\frac{1}{2}W_0\left(\frac{\mathbf{J}\cdot\nabla\rho}{\rho} + \sum_q \frac{\mathbf{J}_q\cdot\nabla\rho_q}{\rho}\right)$$

Gradient and spin-orbit terms for finite nuclei

Correspondence with KIDS EoS for homogeneous matter:

$$\mathscr{T}(\rho,\delta) + \sum_{i=0}^{N-1} c_i(\delta)\rho^{1+i/3}$$

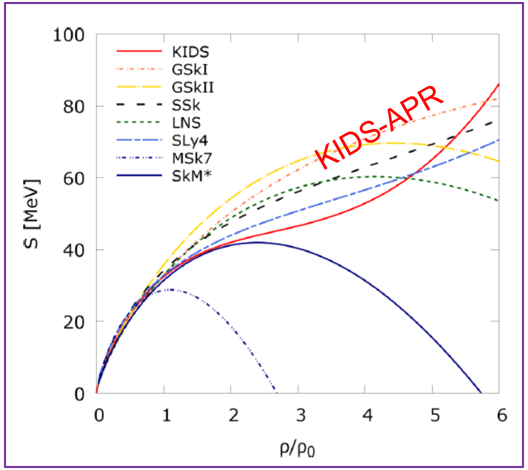
Ambiguity in $\rho^{5/3}$ term:
Freedom to choose m*
[Gil et al., PRC99,064319]

notation:
instead of $t_i x_i$
we write y_i

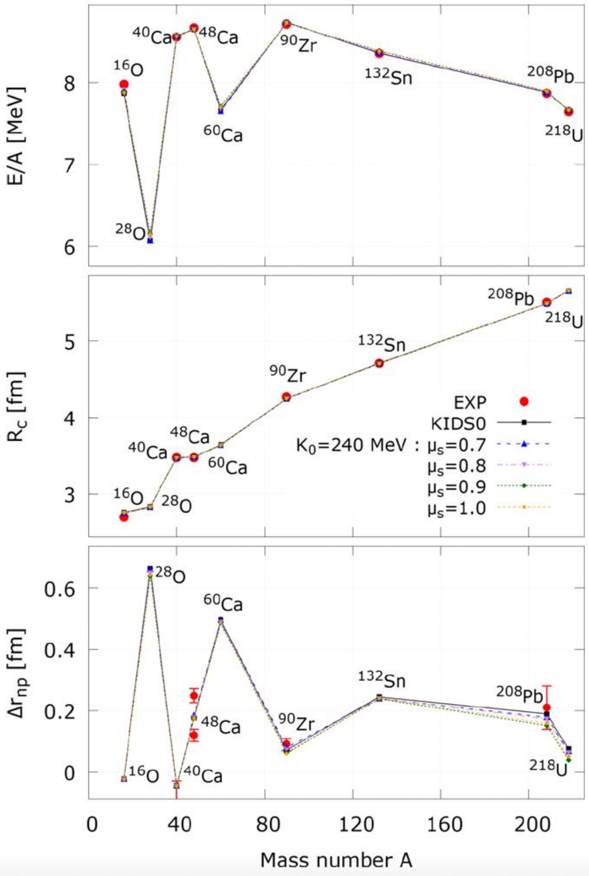
02 Nuclear EDFT news

KIDS framework for the EoS and EDF

- Proof of principle: from the APR EoS straight to nuclei
- EoS parameters taken from fit of analytical KIDS form to APR
- Effective mass can be chosen and the results tested at will



Only fit gradient and spin-orbit terms to a few basic nuclear properties



Gil et al., Phys. Rev. C 99(2019)064319

02 Nuclear EDFT news

Xu&PP, Phys. Rev. C 105,044305
Zhou,Xu,PP, Phys. Rev. C 107, 055803
Gil et al., IJMPE 31, 2250013

Selected results from:

- ❑ Bayesian analysis of nuclear properties; neutron-star properties
- ❑ Combined analyses of nuclear properties and neutron-star properties

Bayesian analysis of nuclear properties

Examined ^{208}Pb and ^{120}Sn

Isovector constraints: Neutron skin thickness, giant dipole resonance, dipole polarizability

	Δr_{np} (fm)	E_{-1} (MeV)	α_D (fm^3)
^{208}Pb	0.283 ± 0.071	13.46 ± 0.10	19.6 ± 0.6
^{120}Sn	0.150 ± 0.017	15.38 ± 0.10	8.59 ± 0.37

Isoscalar constraints: mass, charge radius, energy of the isoscalar monopole resonance

Results for KIDS are compared with standard Skyrme-Hartree-Fock

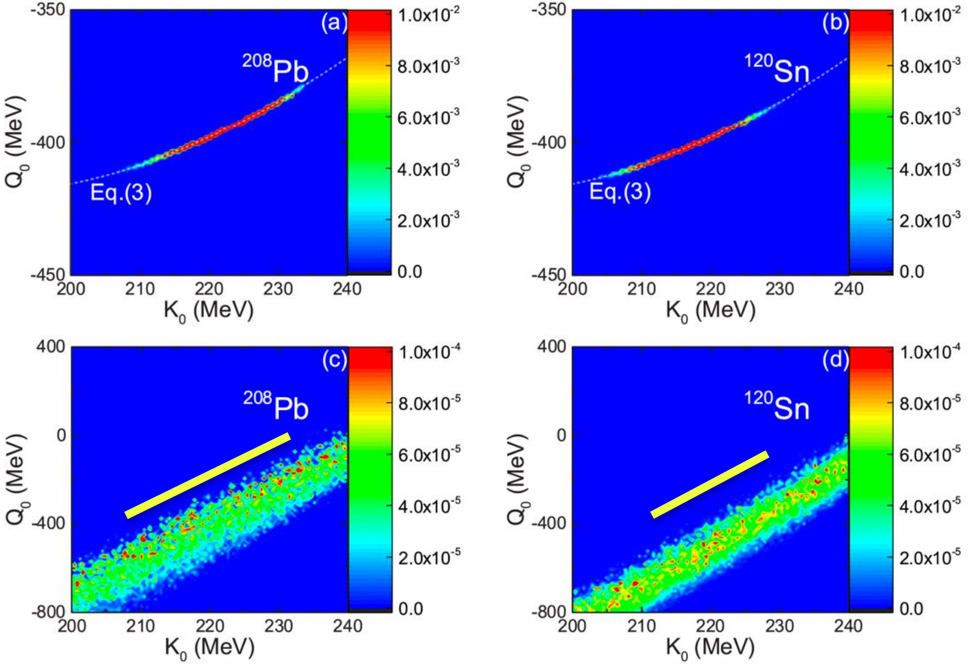
Xu&PP, Phys. Rev. C 105,044305

Bayesian analysis of isoscalar nuclear properties

K_0 vs Q_0

Skyrme:

KIDS :
Much broader PDFs
(notice scale)



Xu&PP, Phys. Rev. C 105,044305

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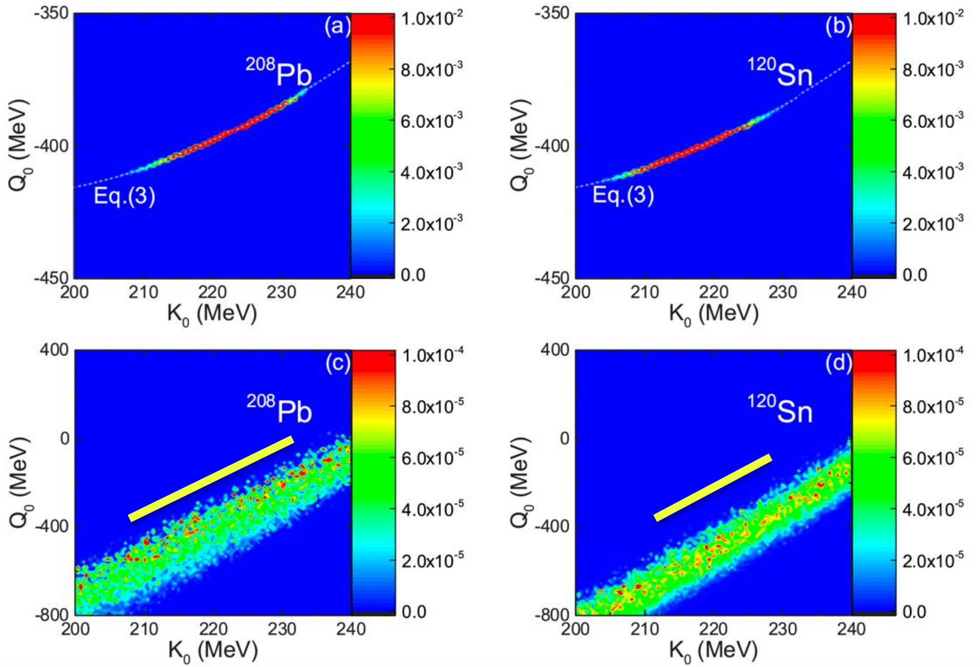


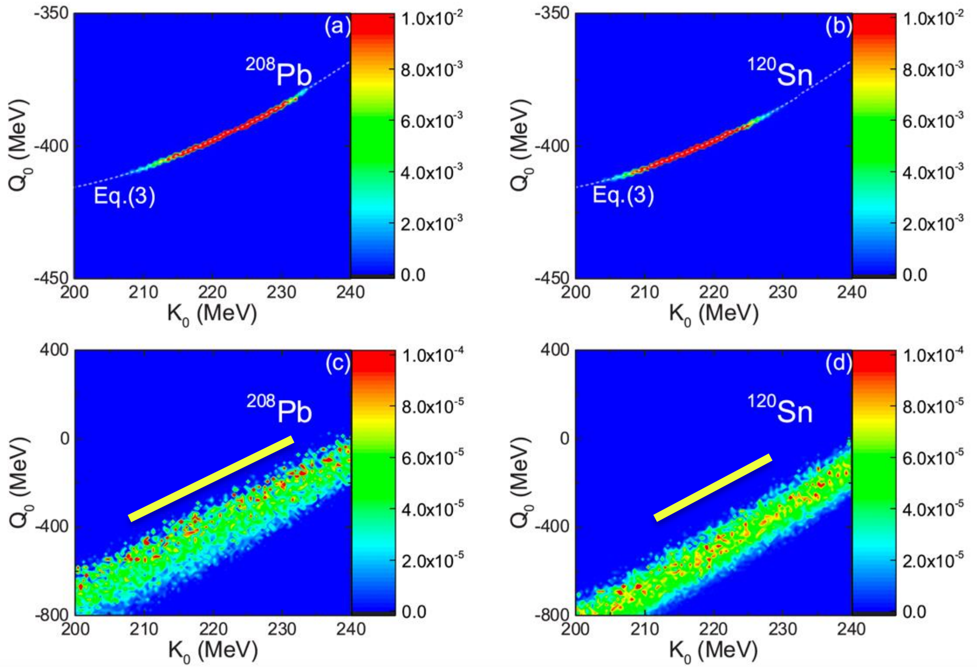
Xu&PP, Phys. Rev. C 105,044305

Bayesian analysis of isoscalar nuclear properties

$$Q_0 = -3(3\alpha+1)\frac{3}{5}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3} + 45(\alpha+1)E_0 + (3\alpha+2)K_0.$$

Skyrme:

KIDS :
Much broader PDFs
(notice scale)

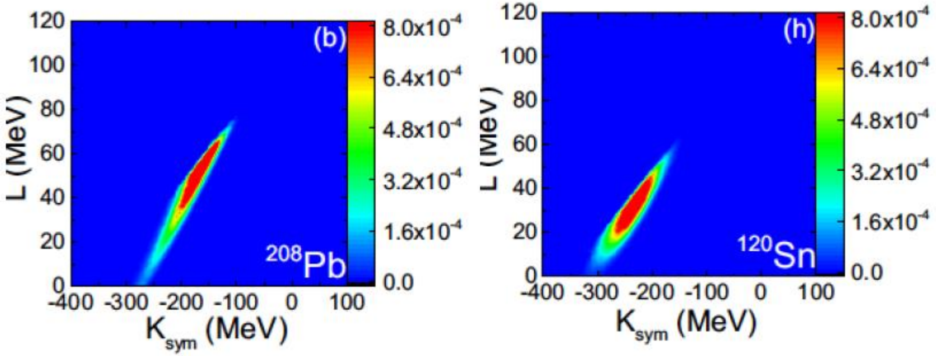


Xu&PP, Phys. Rev. C 105,044305

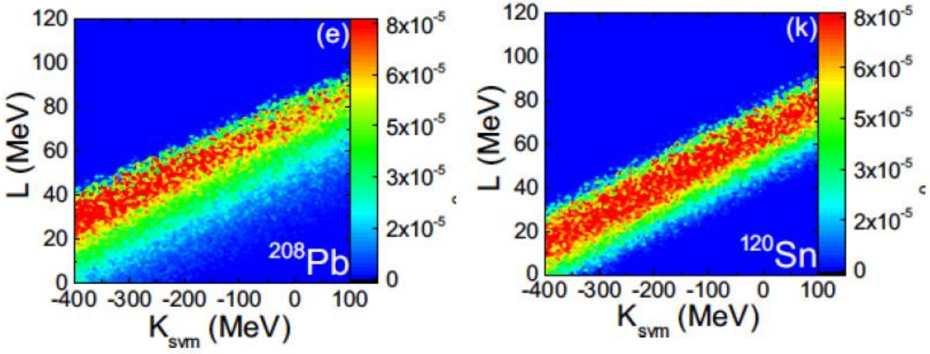
Bayesian analysis of isovector nuclear properties

Ksym vs L

Skyrme:



KIDS :
Broader PDFs
K_{sym} not constrained



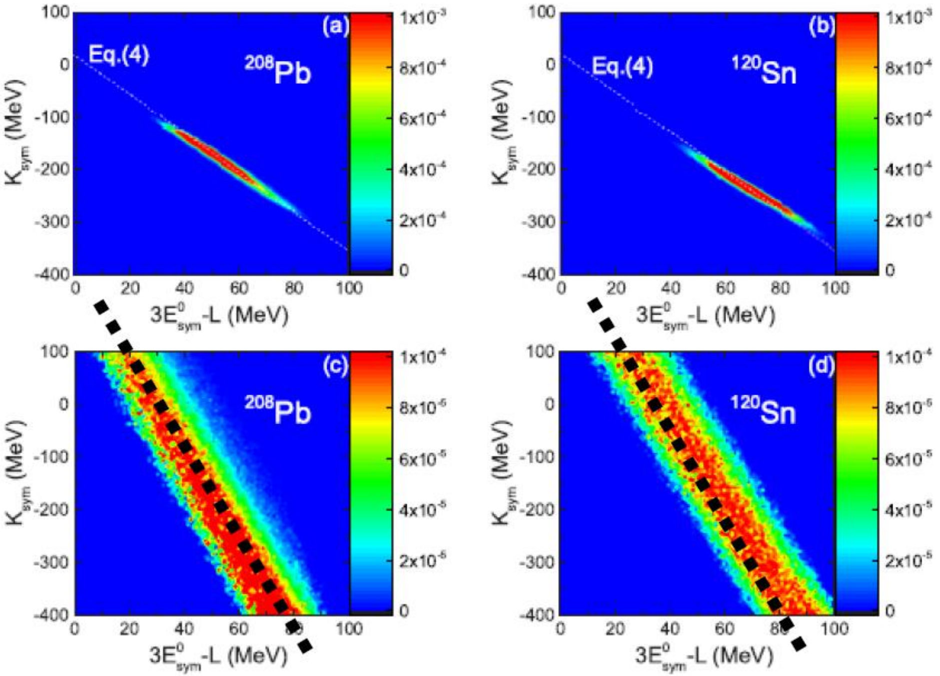
Xu&PP, Phys. Rev. C 105,044305

Bayesian analysis of isovector nuclear properties

Ksym vs 3J-L

Skyrme:

KIDS :
Broader PDFs
K_{sym} not constrained



Xu&PP, Phys. Rev. C 105,044305

02 Nuclear EDFT news

Bayesian analysis of isovector nuclear properties

$$K_{\mathrm{sym}} = (2-3\alpha)\frac{2}{3}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3} \times\left[-3\left(\frac{m}{m_v^\star}-1\right)+4\left(\frac{m}{m_s^\star}-1\right)\right] -3(1+\alpha)\boxed{\left(3E_{\mathrm{sym}}^0-L\right)} +(1+3\alpha)\frac{1}{3}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3}.$$

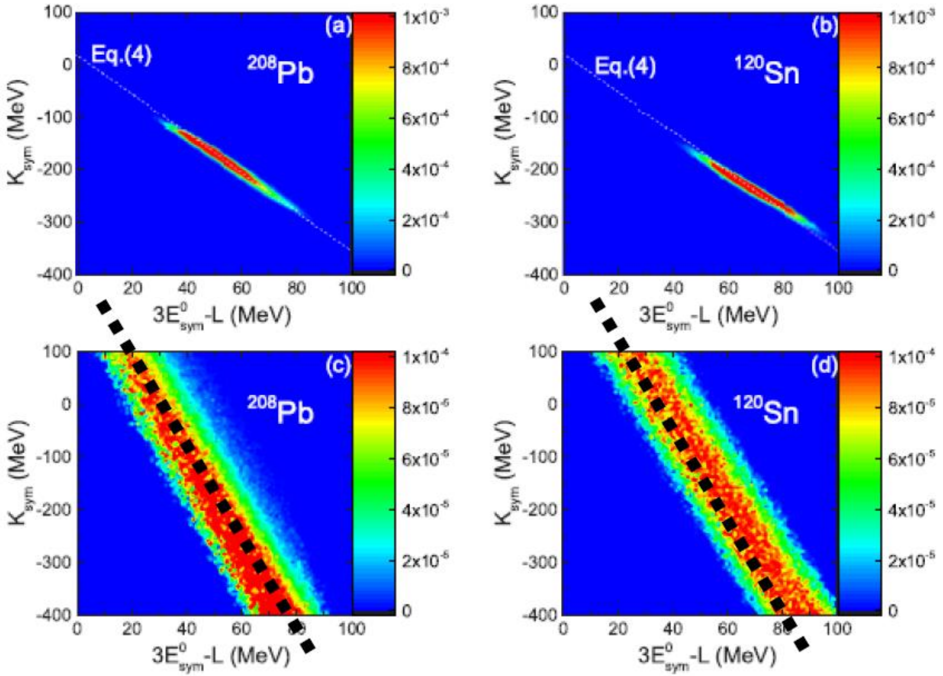
Skyrme:

With line: shown equation for representative ρ_0, α, m^*

KIDS :

Broader PDFs

K_{sym} unconstrained



Xu&PP, Phys. Rev. C 105,044305

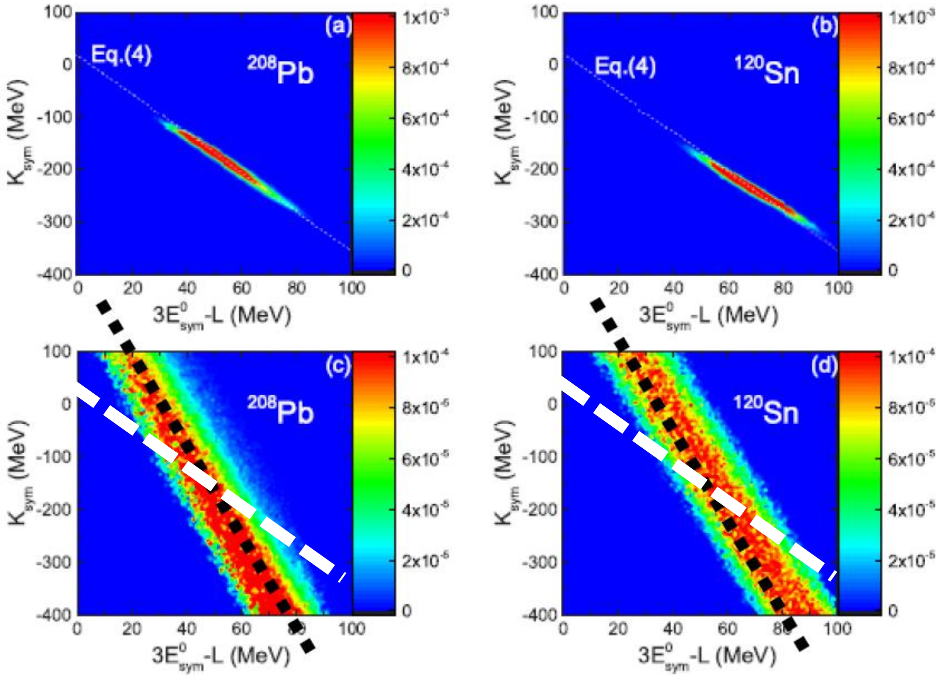
Bayesian analysis of isovector nuclear properties

$$K_{\rm sym} = (2-3\alpha)\frac{2}{3}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3} \times\left[-3\left(\frac{m}{m_v^\star}-1\right)+4\left(\frac{m}{m_s^\star}-1\right)\right] -3(1+\alpha)\left(3E_{\rm sym}^0-L\right) +(1+3\alpha)\frac{1}{3}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3}.$$

Skyrme:

With line: shown equation for representative ρ_0, α, m^*

KIDS :
Broader PDFs
K_{sym} unconstrained



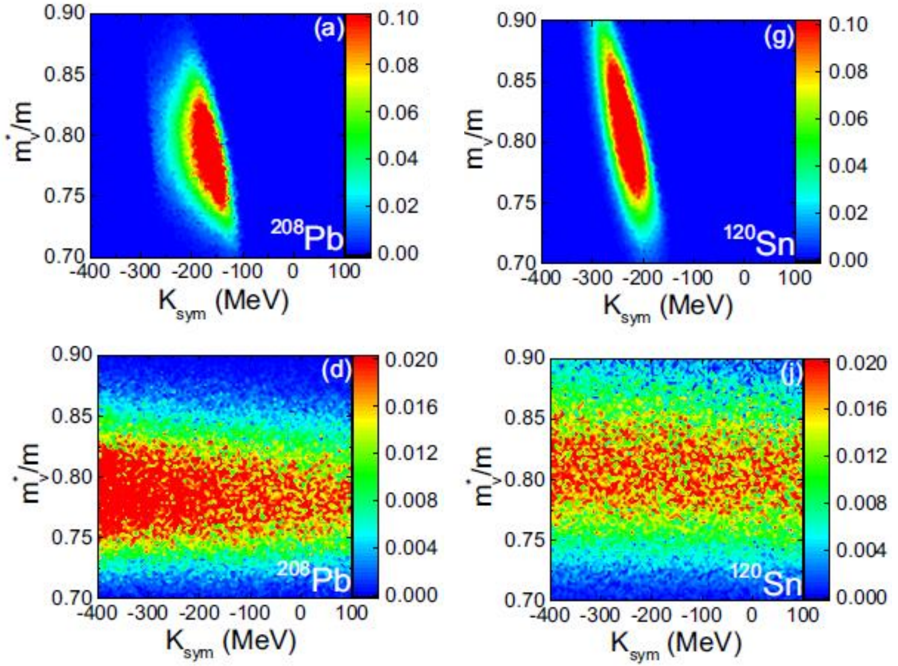
Xu&PP, Phys. Rev. C 105,044305

Bayesian analysis of isovector nuclear properties

Ksym vs IV effective mass

Skyrme:

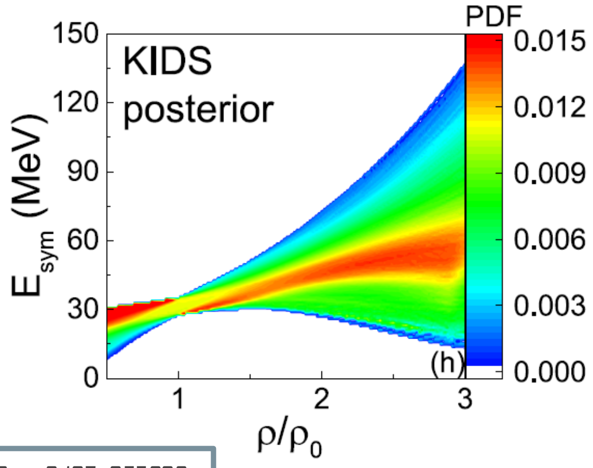
KIDS :
Practically no correlation



Xu&PP, Phys. Rev. C 105,044305

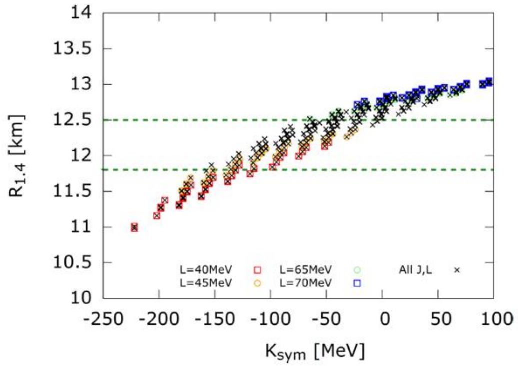
Analyses of astronomical data

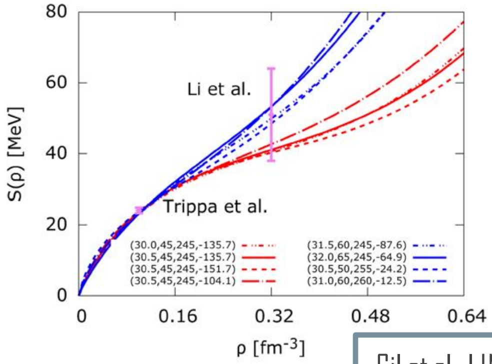
$R_{1.4}$ (km)	11.725 ± 1.105 [15]
$R_{2.08}$ (km)	$13.7^{+2.6}_{-1.5}$ [13] and $12.39^{+1.30}_{-0.98}$ [14]
$\Lambda_{1.4}$	190^{+390}_{-120} [18]
M_{max}	$>2.08 M_{\odot}$ [12]
c_s	<1



Zhou,Xu,PP, Phys. Rev. C 107, 055803

Combined analysis with nuclear data





iRIS 중이온가속기연구소

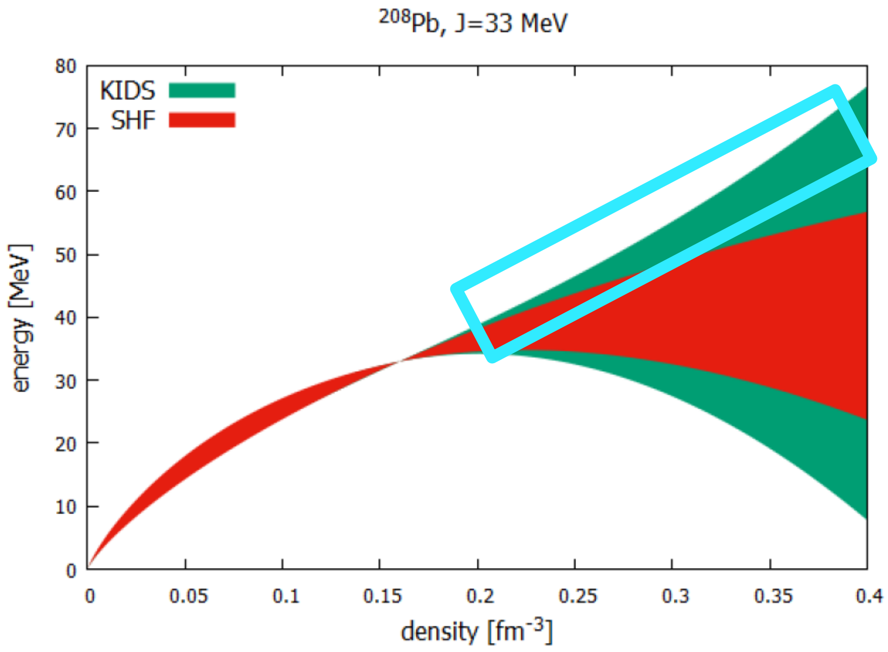
Gil et al., IJMPE 31, 2250013

02 Nuclear EDFT news

Corresponding EoS domains

KIDS model allows for

- ❑ Inflection point: soft-to-stiff transition, important for description of dense matter
- ❑ Decoupling of dilute and dense regimes



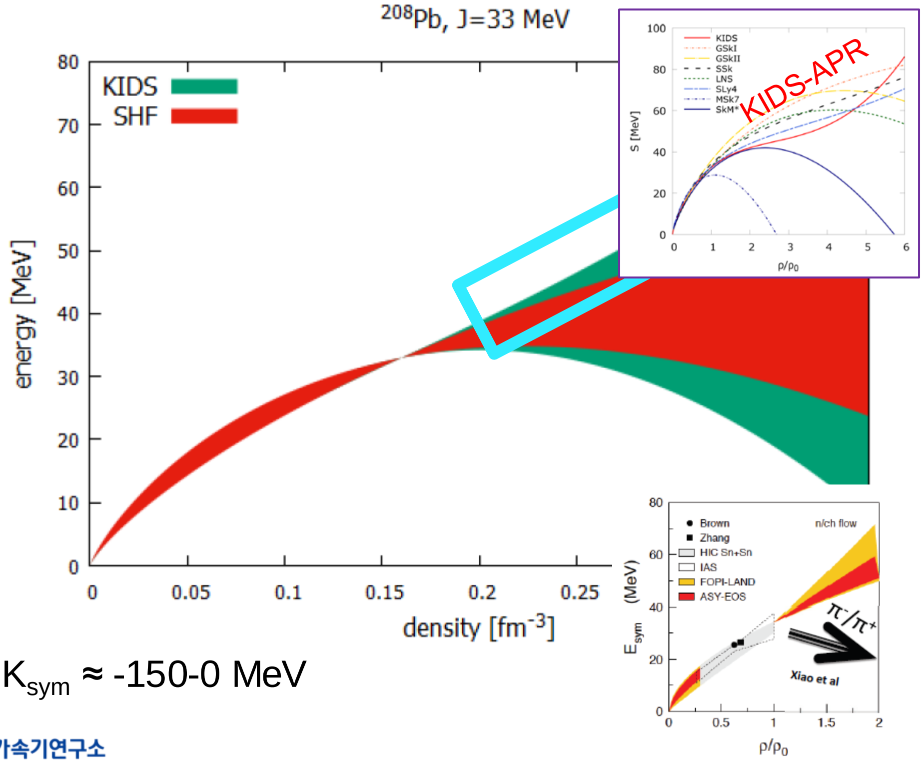
Summary so far: J≈30-33 MeV, L ≈ 45-65 MeV, K_{sym} ≈ -150-0 MeV

02 Nuclear EDFT news

Corresponding EoS domains

KIDS model allows for

- ❑ Inflection point: soft-to-stiff transition, important for description of dense matter
- ❑ Decoupling of dilute and dense regimes

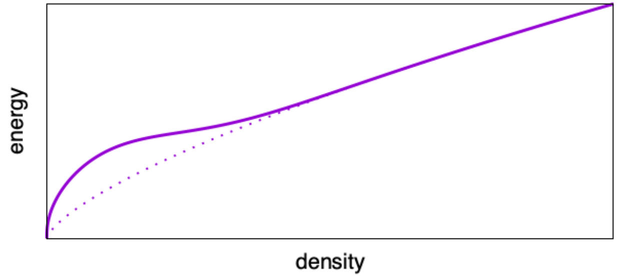


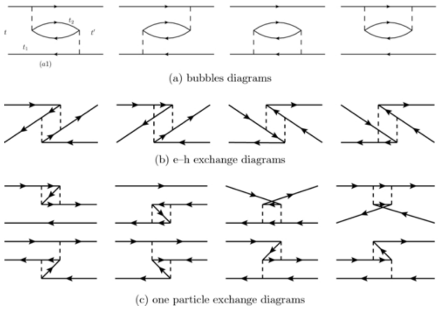
Summary so far: J≈30-33 MeV, L ≈ 45-65 MeV, K_{sym} ≈ -150-0 MeV

Contents

03 Recent developments

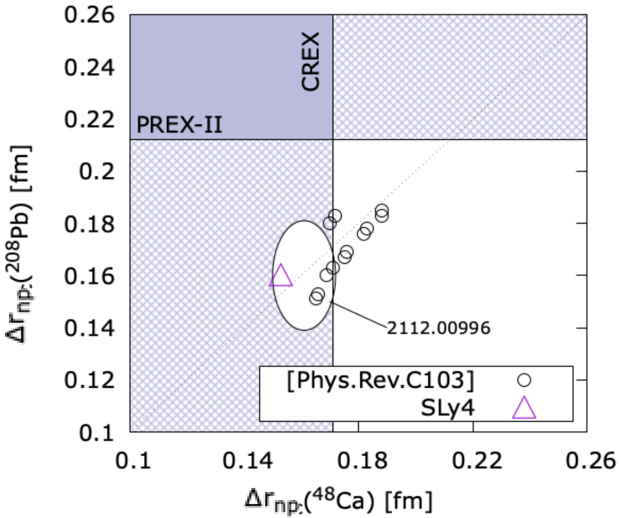
- Distinct density domains in the EoS? (inspired by ongoing work on the PREXII, CREX, dipole polarizability puzzle)
- Beyond mean-field approaches: Fluffiness of Sn isotopes





Predictions for the neutron skin

- KIDS predictions for the neutron skin when the parameters are constrained from gross nuclear properties (masses, charge radii) and neutron star properties, generally agree with CREX and underestimate PREX – see C.H.Hyun, arXiv:2112.00996 *[~300 KIDS EDFs obeying EoS*]
- The tension is similar to other studies, including RMF models



What will it take to reconcile CREX, PREXII, a_D?

- Searching for KIDS parameter sets which reproduce both CREX and PREXII within their respective errors (1σ) and at the same time basic nuclear properties (<1%)
- Extend the formalism to vary freely up to 5+5 EoS parameters: including skewness and kyrtosis of both symmetric matter (Q_0, R_0) and symmetry energy (Q_{sym}, R_{sym}) , as follows:

  ρ_0 = 0.15-0.16 fm^{-3}, E_0 = -16 MeV, K_0 = 200-240 MeV J = 30-36 MeV L = 40-70MeV

  K_{sym} varied widely in steps of 50 MeV

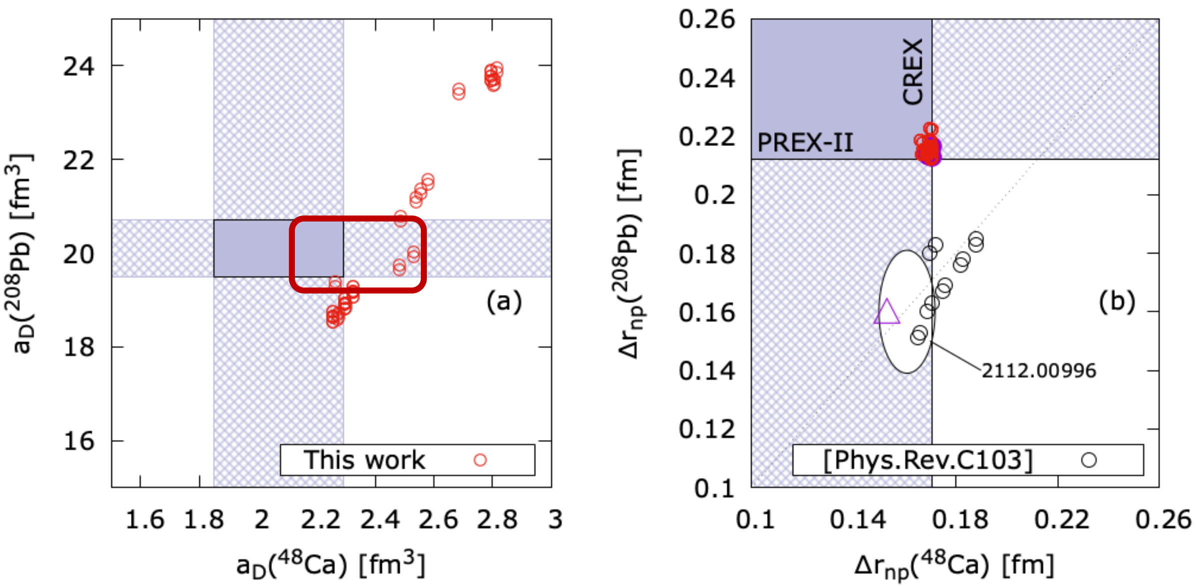
  Q_0, Q_{sym} varied widely in steps of 500MeV

  R_0, R_{sym} varied widely in steps of 2 GeV

  and in addition: C_{12} = -66 MeV fm^5, D_{12} = 2.5 MeV fm^5, m*/m = 0.82, κ = 0.22, W_0 = 133 MeV fm^5

For a first study of CREX-PREX only, see arXiv:2210.02696 (Rila 2022 proceedings)

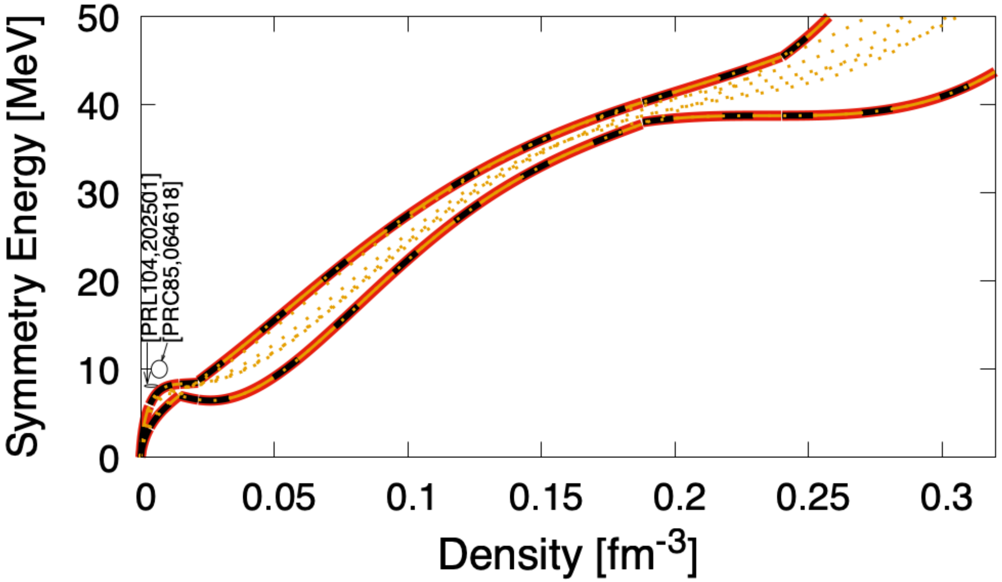
Results for a_D as well as neutron skin



03 Recent developments

Domain with best a_D

- ❑ Unorthodox but not necessarily unphysical behavior at low density
- ❑ Consistent with analyses of heavy-ion collisions



03 Recent developments

Domain with best a_D

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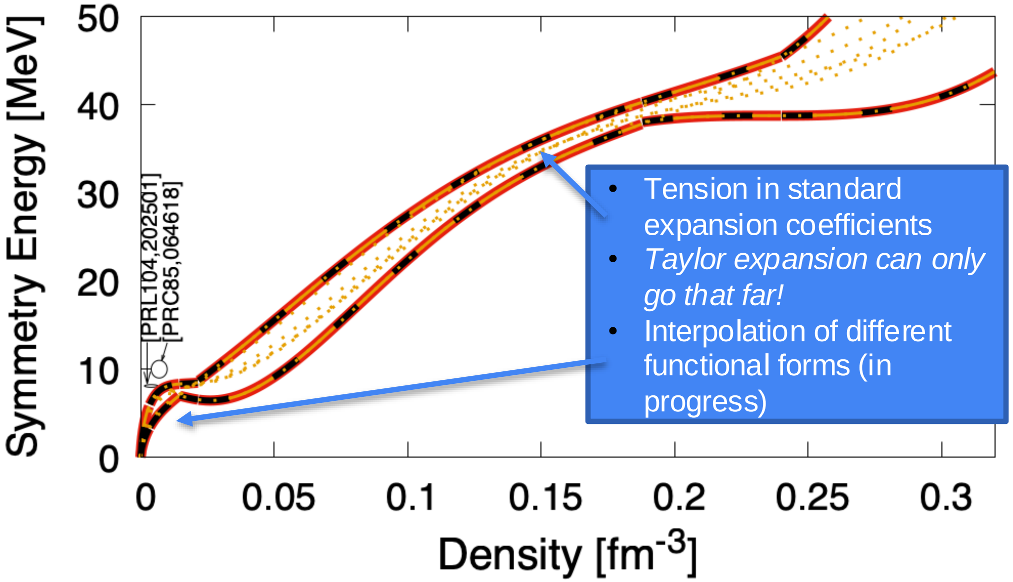
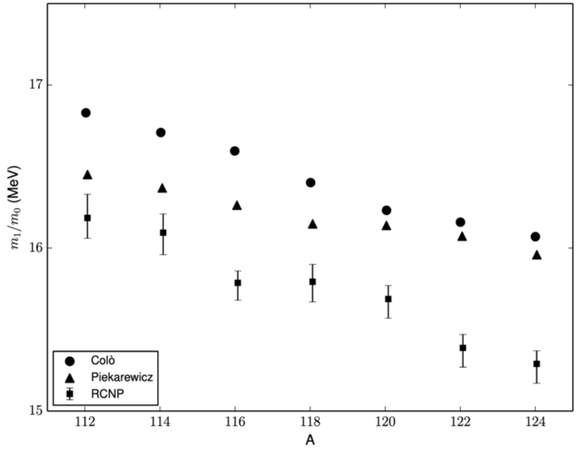
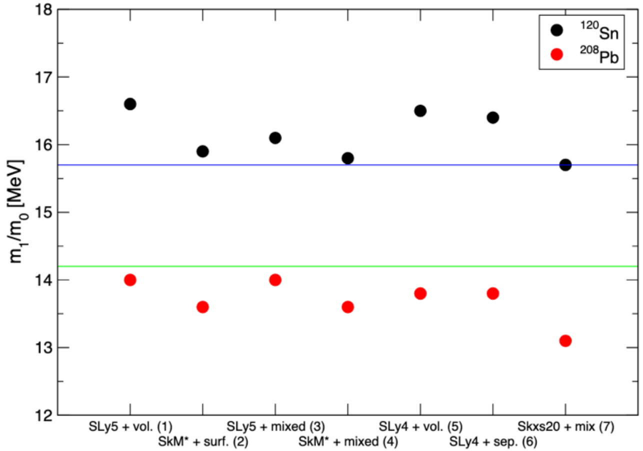


Giant monopole resonance: Why is tin soft?

Garg&Colò, PPNP101(2018)55

- A description of the compression mode of Sn isotopes within self-consistent QRPA cannot be achieved at the same time as ^{208}Pb and other previously studied nuclei; the energy is overestimated.
- In EoS terms, Sn isotopes require a lower model **compression modulus**: they are too “fluffy”

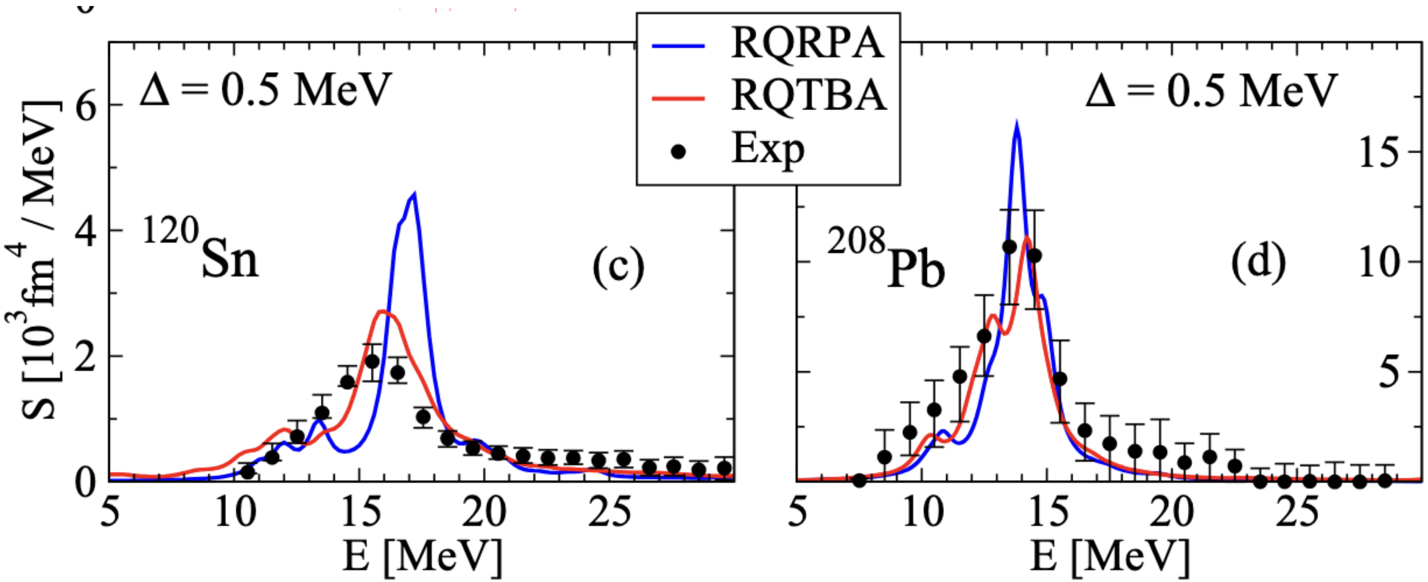




Giant monopole resonance: Why tin is soft

Litvinova, PRC107(2023)L041302

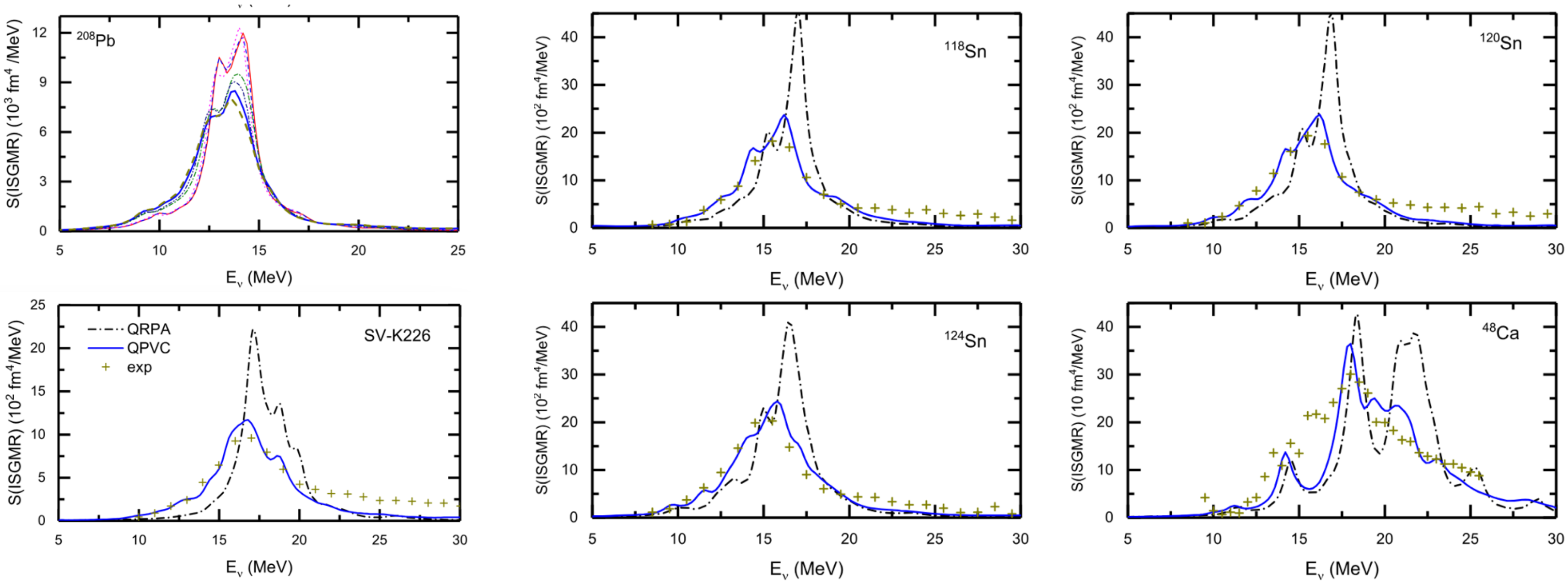
- QRPA+quasiparticle-vibration coupling based on relativistic functionals



Giant monopole resonance: Why tin is soft

Li et al., PRL131(2023)082501

- QRPA+quasiparticle-vibration coupling based on Skyrme HFB



Pondering the domain of orbital-based EDFT

- EDFT and self-consistent RPA as we know them are only expected to describe average single-particle quantities; total sum rules. The detailed strength distribution is known to require beyond-mean-field approaches, correlations, and the like.
- There is no self-consistent geminal-based (based on the two-particle density) response theory. Geminals are in use in quantum chemistry. There are advances for infinite nuclear matter based on the pair distribution function. Such may serve as guides.

Contents

04 Conclusion

Progress in nuclear EDF

- ❑ Optimal number of EoS parameters eliminates spurious correlations btw parameters, observables We saw the examples of K_{sym} vs J,L and of Q_0 vs K_0.
- ❑ The effective mass not an impediment in EDFT: Static, bulk properties of nuclear systems are blind to the in-medium nucleon effective mass. *It may be important in dynamics of course
- ❑ The symmetry energy is predicted to have an inflection point which traditional functionals do not produce. It might be advisable to distinguish between the dilute and dense regimes.

Pondering the domain of orbital-based EDFT

- ❑ EDFT incl. self-consistent RPA are orbital-based and expected to describe average single-particle quantities, total sum rules. Detailed strength distributions are known to require beyond-mean-field approaches. Geminals can encode correlations and are in use in quantum chemistry. There are advances for infinite nuclear matter based on the pair distribution function. Such may serve as guides for approaches for nuclei.

Thank you!

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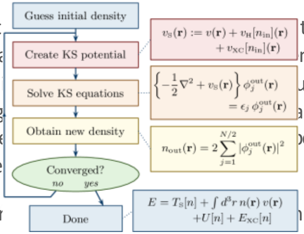
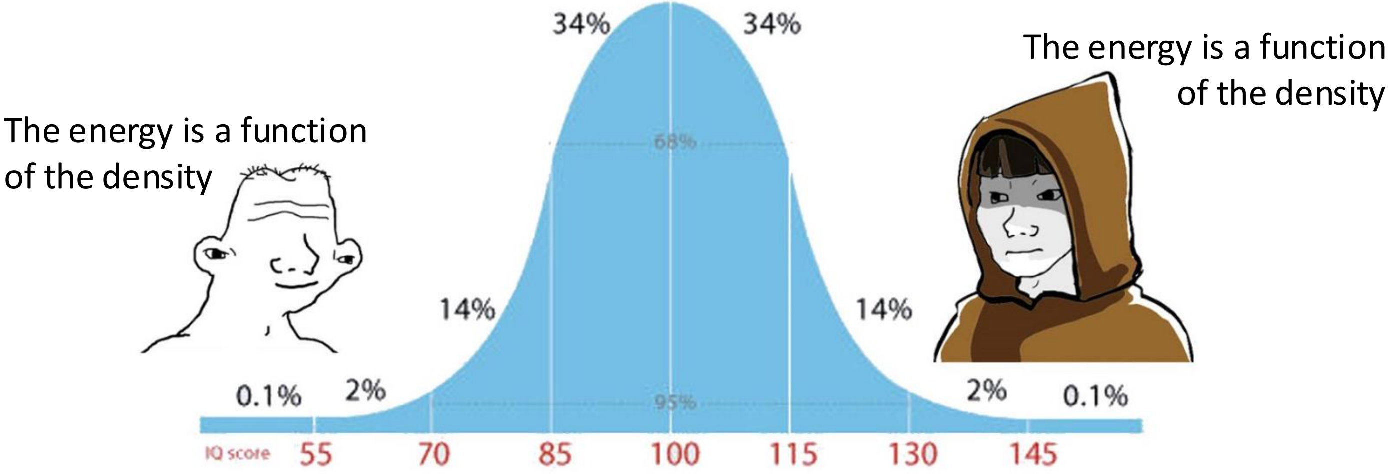
In conclusion

Hohenberg-Kohn Theorem I: "For a system of interact … tial Vext(x), the potential itself is uniquely determined, except for … nsity n(x)." Can also be stated thus: "The total energy E_{Vext}[n] … unctional of the corresponding density n(x)." Generalization: "The g … a physical observable O is a unique functional of the ground state … pecies of particles, we need adjustments: density of protons, ne…

Hohenberg-Kohn Theorem II: For a non-degenerate gr … al potential Vext(x) the energy functional E_Vext[n] assumes its global minimum value E0 varying the density n(x) toward the true ground state density n0(x).



Kohn-Sham Scheme:



01 Nuclear EDFT

Droplet models:

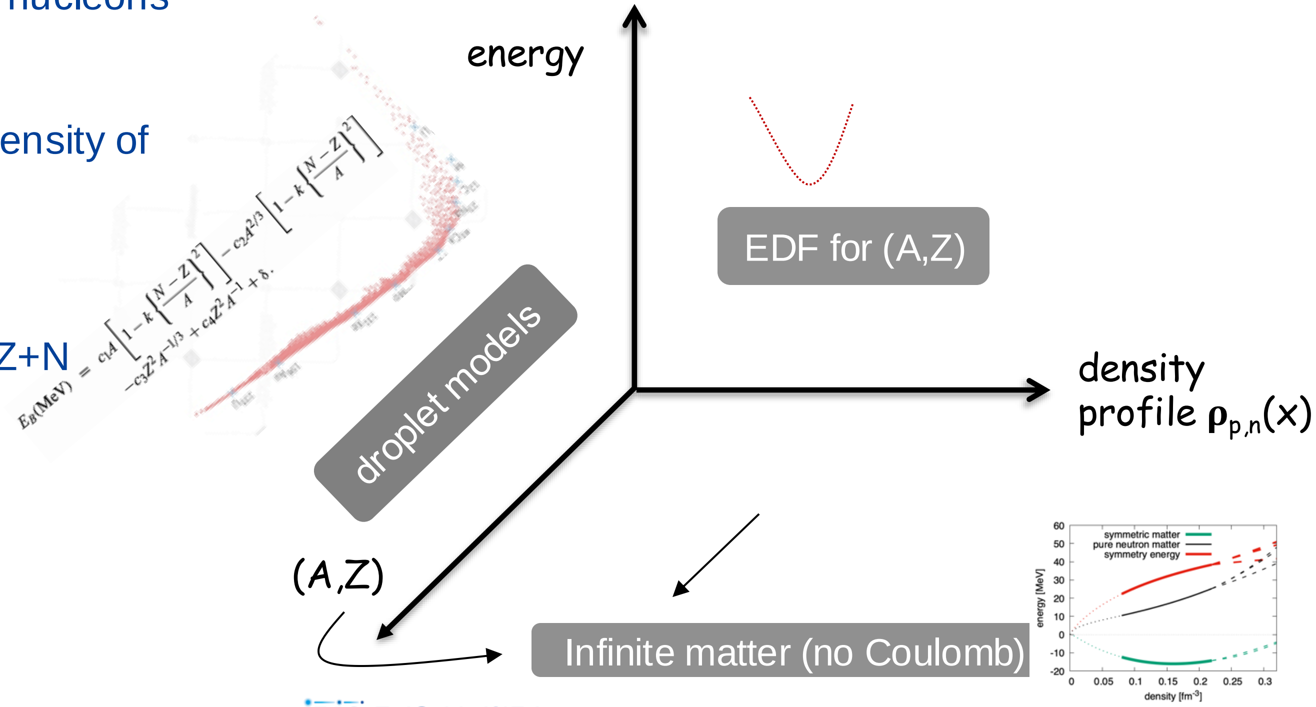
- Ground state of A=Z+N nucleons

Nuclear matter:

- Unique EDF for given density of neutrons, protons

Nuclear EDF:

- Unified EDF for any A=Z+N

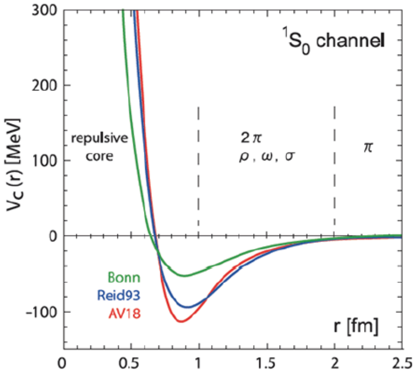


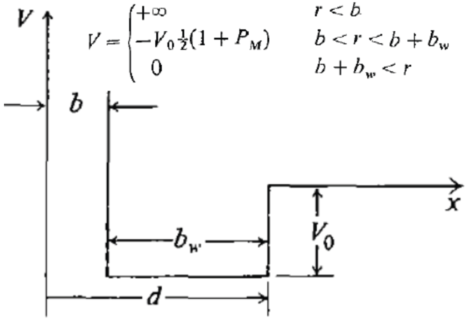
Guessing the EDF form – part I: Brueckner theory

- ❑ Realistic potential: strong repulsive core plus attraction at longer range; apply Brueckner methodology in the calculation of nuclear matter energy
- ❑ Result: converging series of k_F^2, k_F^3, k_F^4 , …

  Even powers: from repulsive part

  Odd powers: from both
- ❑ The relevant variable is k_F, or powers of $\rho^{1/3}$





Fetter&Walecka, Quantum theory of many-particle systems

Guessing the EDF form – part II: effective field theory

- Saturation density is low with respect to (effective) boson exchange range

  One-pion exchange: vanishing expectation value

  Next boson: rho with mass approx. 775 MeV or 4fm^{-1}
- Expansion of E/A in powers of k_F, which means again powers of $\rho^{1/3}$.
- The k_F^3 and k_F^4 are known to be important for saturation

Natural Ansatz: E/A in powers of $\rho^{1/3}$

Hammer&Furnstahl, NPA678(2000)277
Kaiser et al., NPA697(2002)255