Kaonic atoms update

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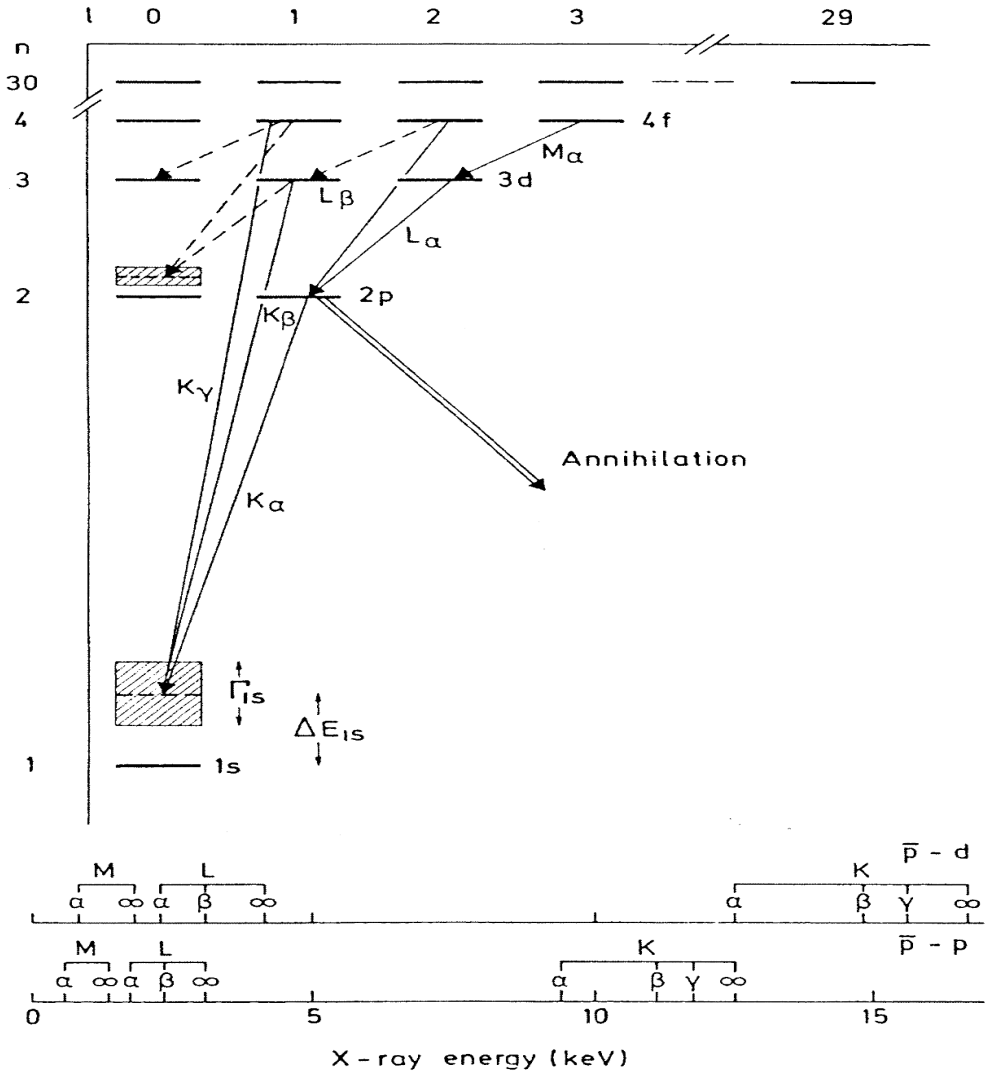
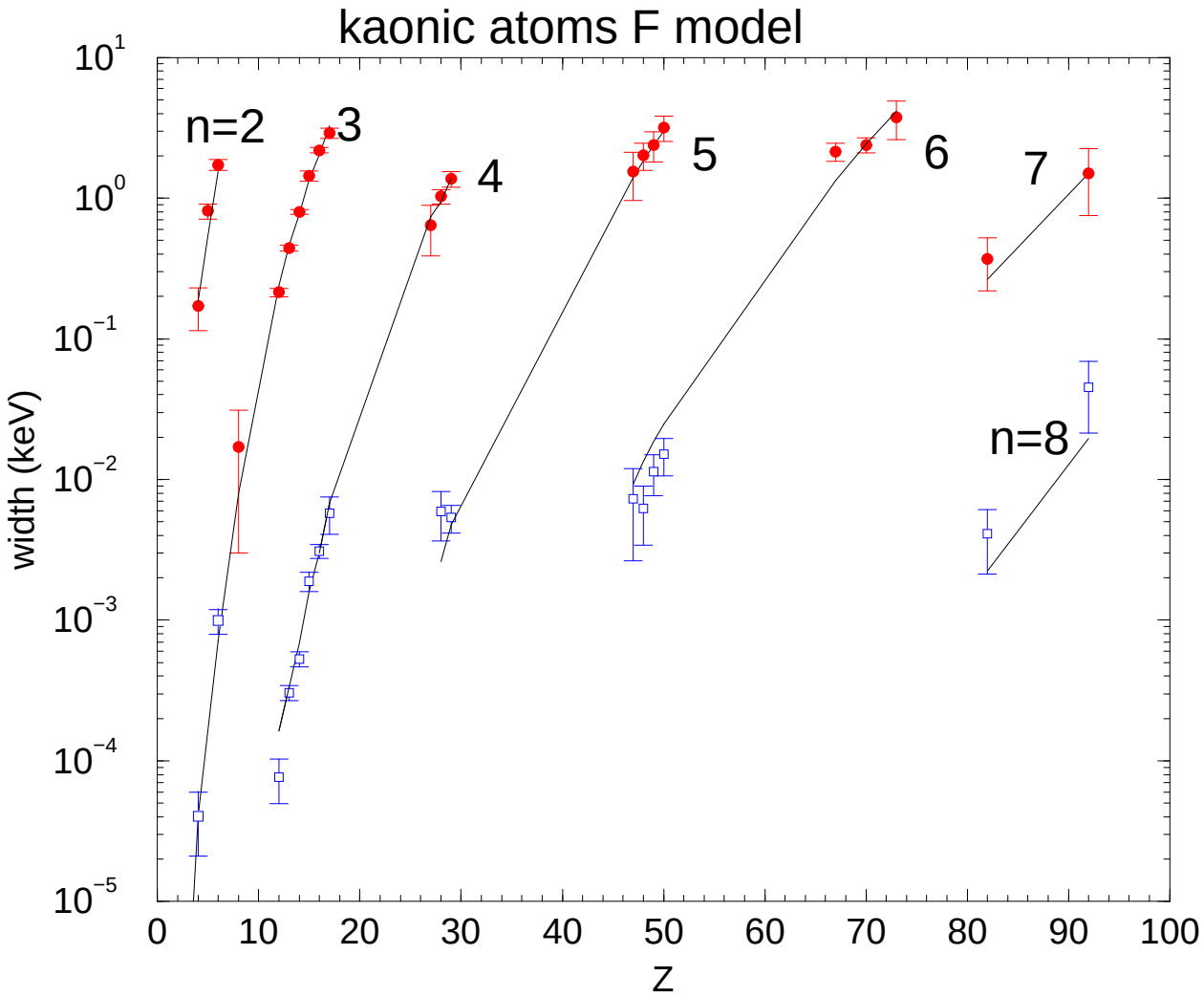
Outline

- A reminder of kaonic atoms as precision science.
- The 'deep or shallow' issue.
- Subthreshold kinematics and $t(\sqrt{s}) \to V(\rho)$ prescription.
- Results of global fits and open problems.
- Summary.

The classical X-ray method





Precision science: quality fits over five orders of magnitude.

Average behaviour from phenomenological analyses:

- Handle large sets of data.
- Could identify characteristic quantities.
- Serve as intermediaries between 'microscopic' theories and experiment (e.g. in reproducing the characteristic quantities).

Tools of the trade: variants of an optical potential.

When analyzing several nuclear species together one must have some model for the nuclear geometry, e.g. make the potential a functional of the nuclear density.

The simplest class of optical potentials $V_{\rm opt}$ is the generic $t\rho(r)$ potential: (isoscalar)

$$2\mu V_{\rm opt}(r) = -4\pi(1 + \frac{A-1}{A}\frac{\mu}{M})b_0[\rho_n(r) + \rho_p(r)]$$

ρ_n and ρ_p are neutron and proton densities normalized to N and Z, respectively, M is the mass of the nucleon.

Results of global fits apply to average behaviour.

Beyond the $t\rho$ model

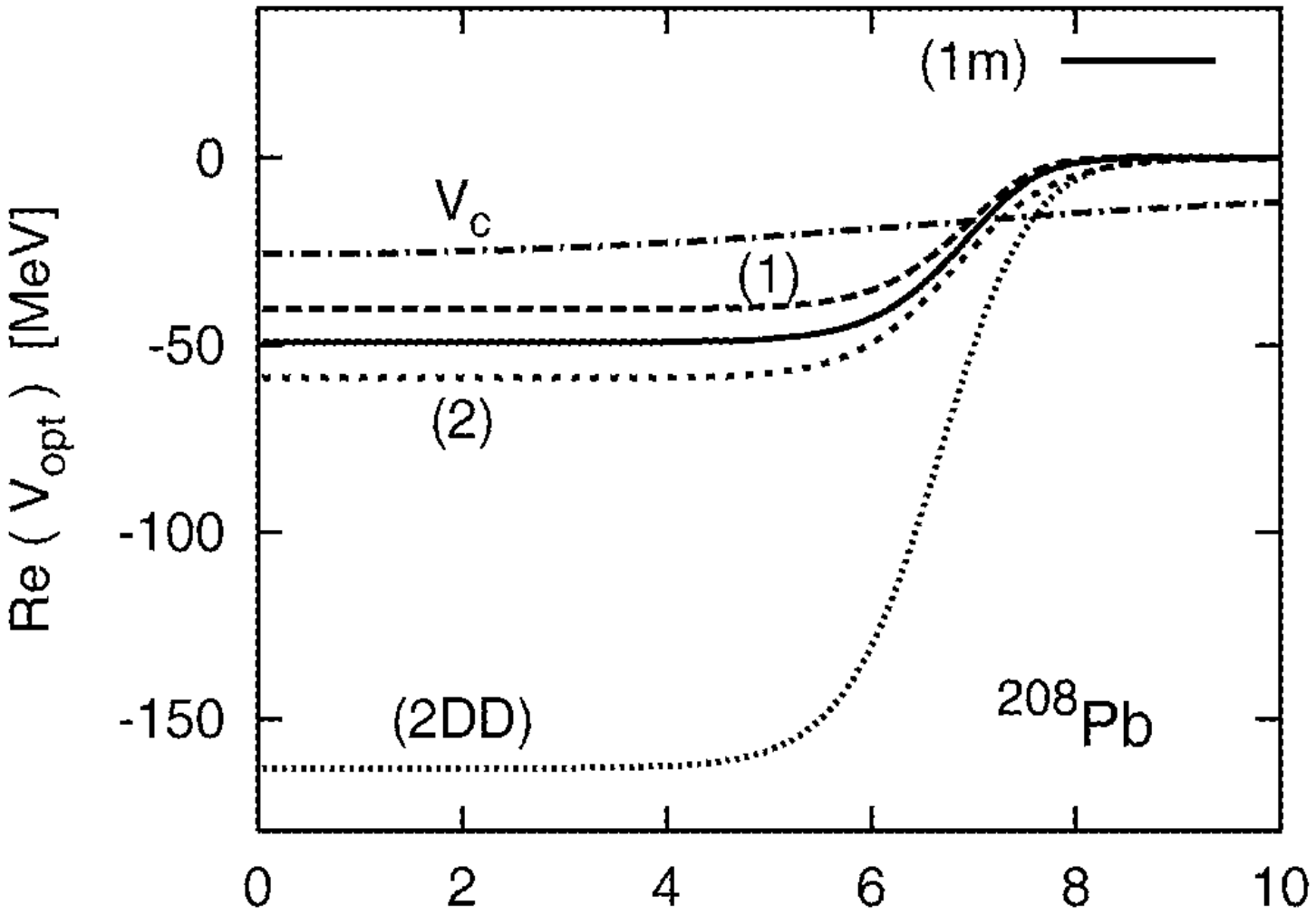
The *empirical* DD form is based on making the effective amplitude density-dependent

$b_0 \rightarrow b_0(\rho)$

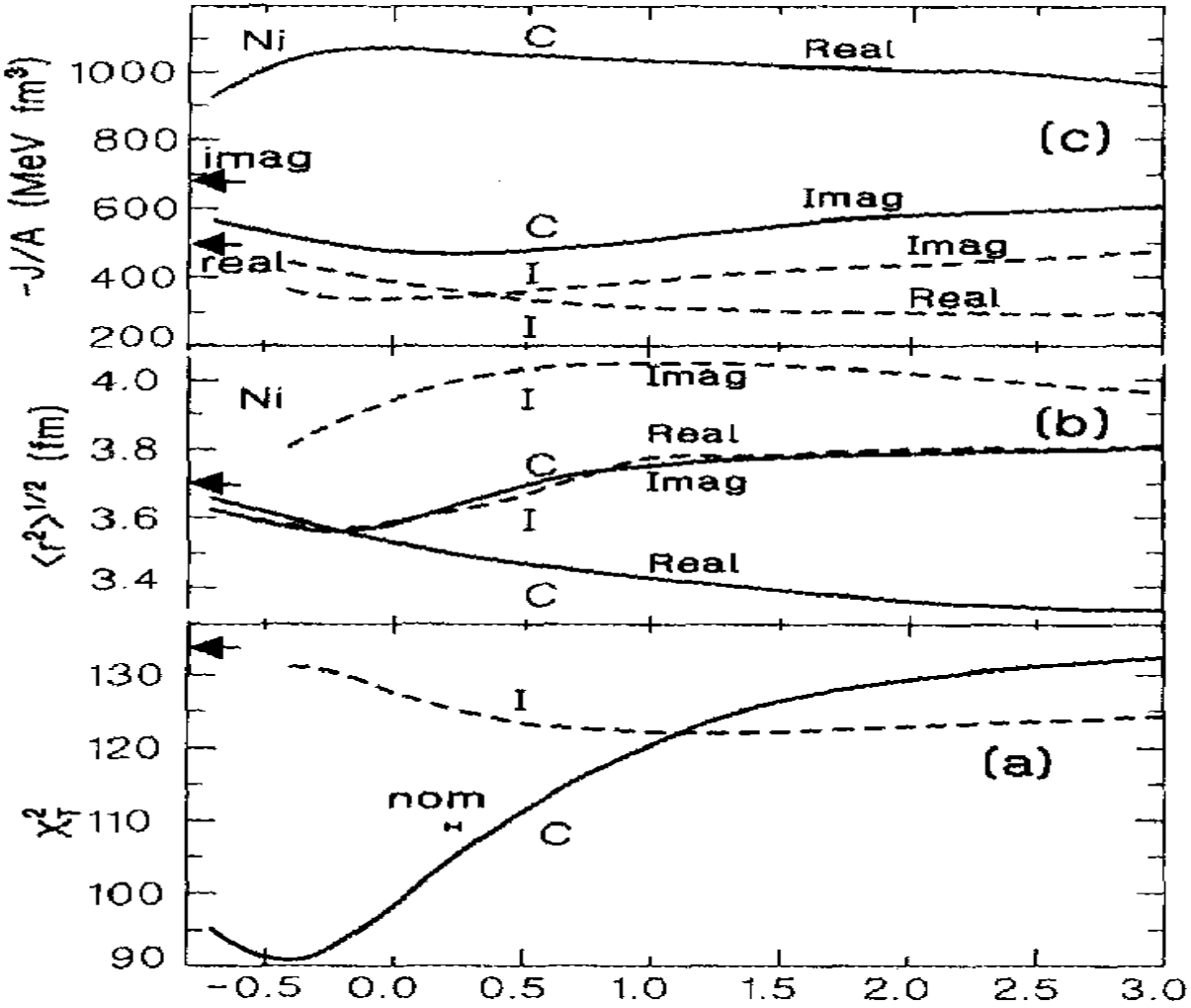
Fixed b_0, χ^2 =130 for 65 points, Re $V_{\rm opt} = -80$ MeV.

For DD, χ^2 =90-100, Re $V_{\rm opt} = -180$ MeV.

Deep potentials have consequences for neutron stars and for K^-NN clusters.


(1m)
0
V_c
(1)
-50
(2)
-100
-150
(2DD)
^{208}Pb
Re (V_{opt}) [MeV]
0
2
4
6
8
10

E.F., A. Gal and C.J. Batty, NPA **579** (1994) 518.



Some comments on geometry (r.m.s. radii)

For fixed-t $t\rho$ potential, $r_{potl} = r_\rho$

(Including finite-range folding, $r_{potl} > r_\rho$)

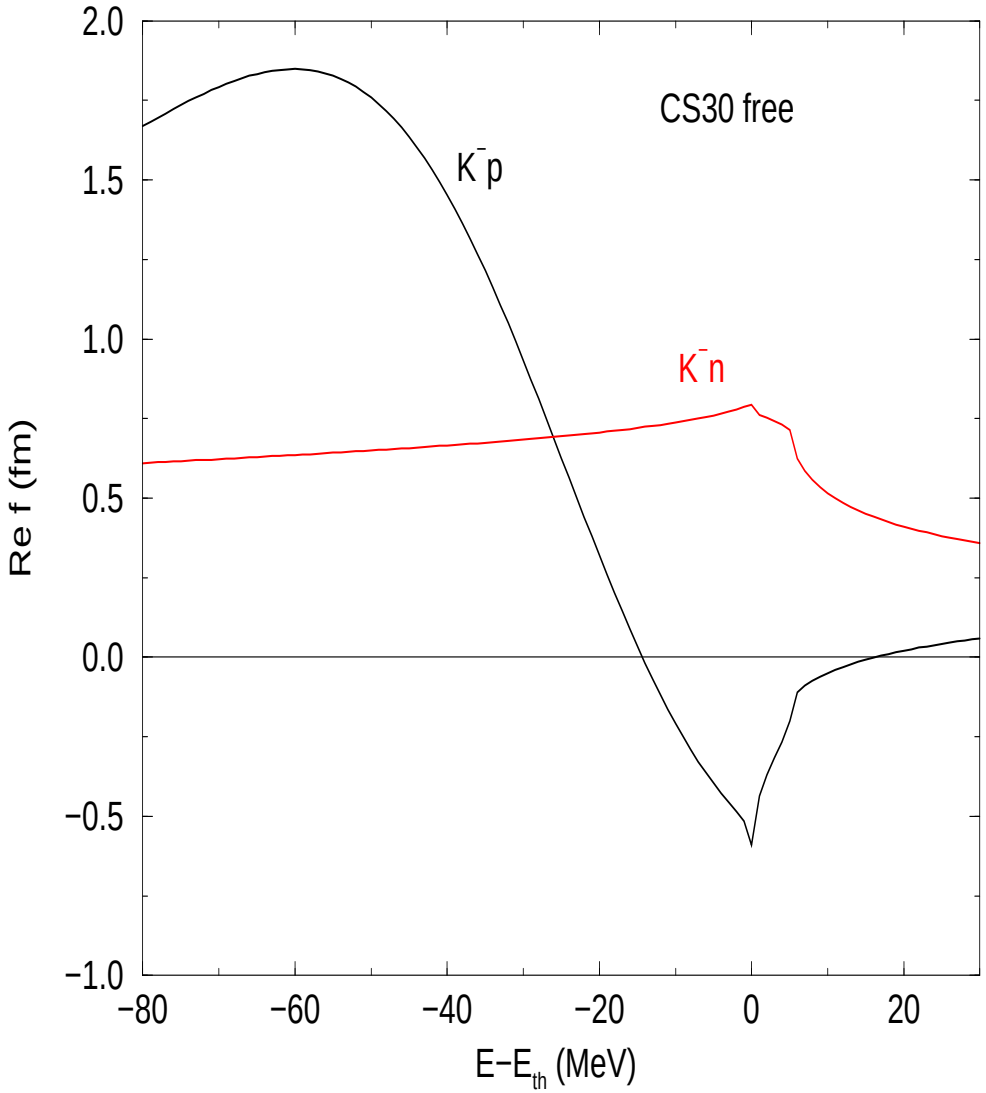
When $t(\rho)$ decreases with increasing ρ, $r_{potl} > r_\rho$

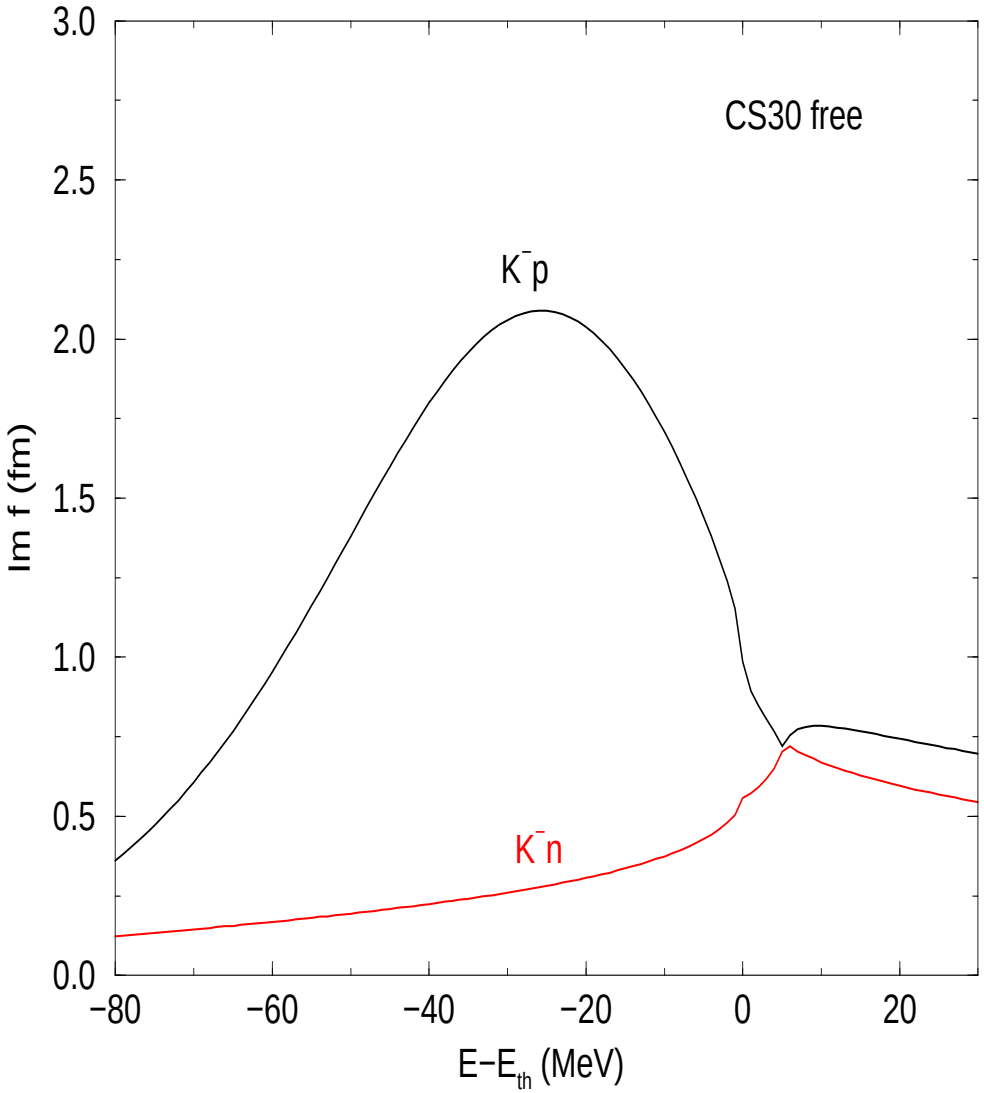
When $t(\rho)$ increases with ρ, $r_{potl} < r_\rho$

Compression of the potential must result from an underlying K^-N interaction that *increases* with density (overshadowing any finite-range effects).

Turn to $t_{K^-N}(\vec{p}, \rho, \sqrt{s})$.

($\sqrt{s} = K^-N$ Mandelstam variable.)





K$^-$p and K$^-$n scattering amplitudes near threshold,
Cieplý and Smejkal, Eur. Phys. J. A **43** 191 (2010).

Going subthreshold: average kinematics

A. Cieplý, E. Friedman, A. Gal, D. Gazda and J. Mareš

PLB **702** (2011) 402;

PRC **84** (2011) 045206.

E. Friedman & A. Gal, NPA **881** (2012) 150.

W. Weise, R. Härtle, Nucl. Phys. A **804** (2008) 173.

D. Gazda and J. Mareš, NPA **881** (2012) 159.

Using the Mandelstam variable s in the nuclear medium

$$s = (E_{K^-} + E_N)^2 - (\vec{p}_{K^-} + \vec{p}_N)^2.$$

Averaging over angles,

$$(\vec{p}_{K^-} + \vec{p}_N)^2 \rightarrow (p_{K^-})^2 + (p_N)^2.$$

Substituting locally

$$\frac{p_K^2}{2m_K} \rightarrow -B_K - \text{Re } V_{\text{opt}} - V_c$$

$$\frac{p_N^2}{2m_N} \rightarrow 23.0(\rho/\rho_0)^{2/3} \text{ (in MeV, Fermi gas model, } \rho_0 = 0.17 fm^{-3}).$$

$$E_K = m_K - B_K, \qquad E_N = m_N - B_N.$$

Keeping only linear terms in B/m:

$$\sqrt{s} \approx E_{th} - B_N - \xi_N B_K - 15.1(\rho/\rho_0)^{2/3} + \xi_K(\mathrm{Re}\ V_{\mathrm{opt}} + V_c). \ (\mathrm{MeV})$$

with

$$E_{th} = m_N + m_K, \quad \xi_N = \frac{m_N}{m_N+m_K}, \quad \xi_K = \frac{m_K}{m_N+m_K}.$$

With V_{opt} proportional to $t_{K^-N}(\vec{p}, \rho, \sqrt{s})$ locally, a self-consistent process is required.

$\approx$ 6 iterations at each radial point for every target.

$$\sqrt{s} \approx E_{th} - B_N - \xi_N B_K - 15.1(\rho/\rho_0)^{2/3} + \xi_K(\mathrm{Re}\ V_{\mathrm{opt}} + V_c).\ (\mathrm{MeV})$$

Subthreshold: for attractive V_{opt}, $\quad \sqrt{s} < E_{th}$.

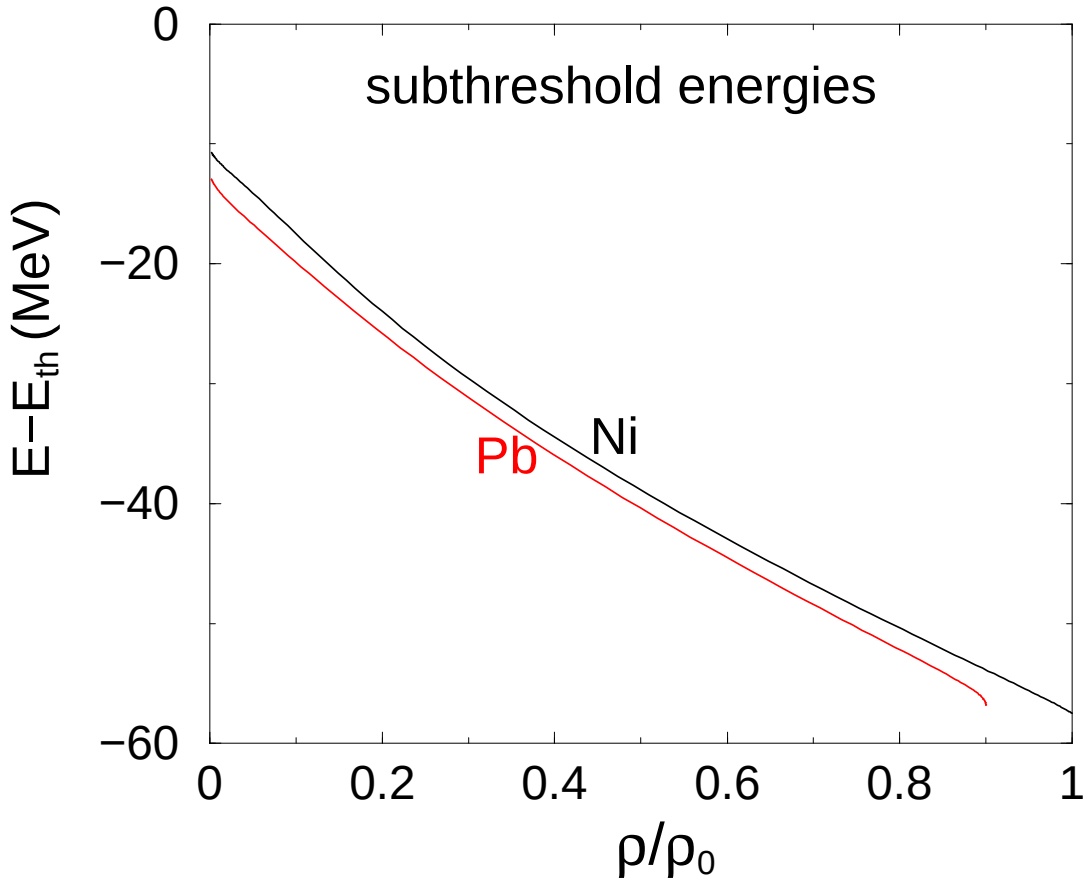
Take $B_N \approx 8$ MeV, weak dependence on precise value.

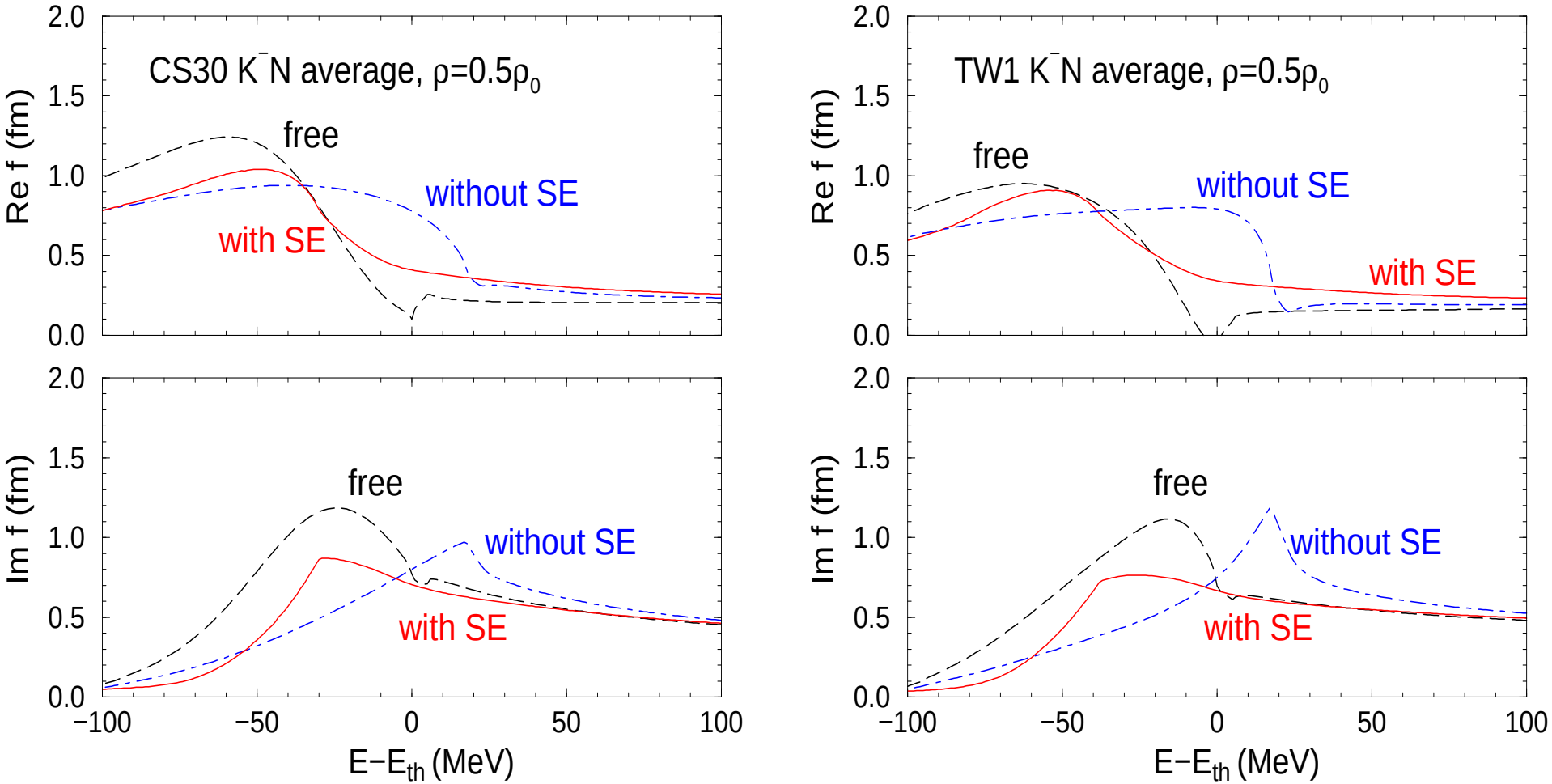
Possible variations:

$\sqrt{s} \rightarrow \sqrt{s} - V_c\ , \qquad B_N \rightarrow B_N\ \rho(r)/\bar{\rho}.$

For a given model for $t_{K^-N}(\vec{p}, \rho, \sqrt{s})$ we have a simple algorithm for constructing V_{opt}.

NLO30 $E(\rho)$ dependence





CS30 and TW1 *average* amplitudes, free and for $0.5\rho_0$,

with and without self energy.

Note sharp drop of Im f towards $\pi\Sigma$ threshold.

Use separate proton and neutron densities and replace

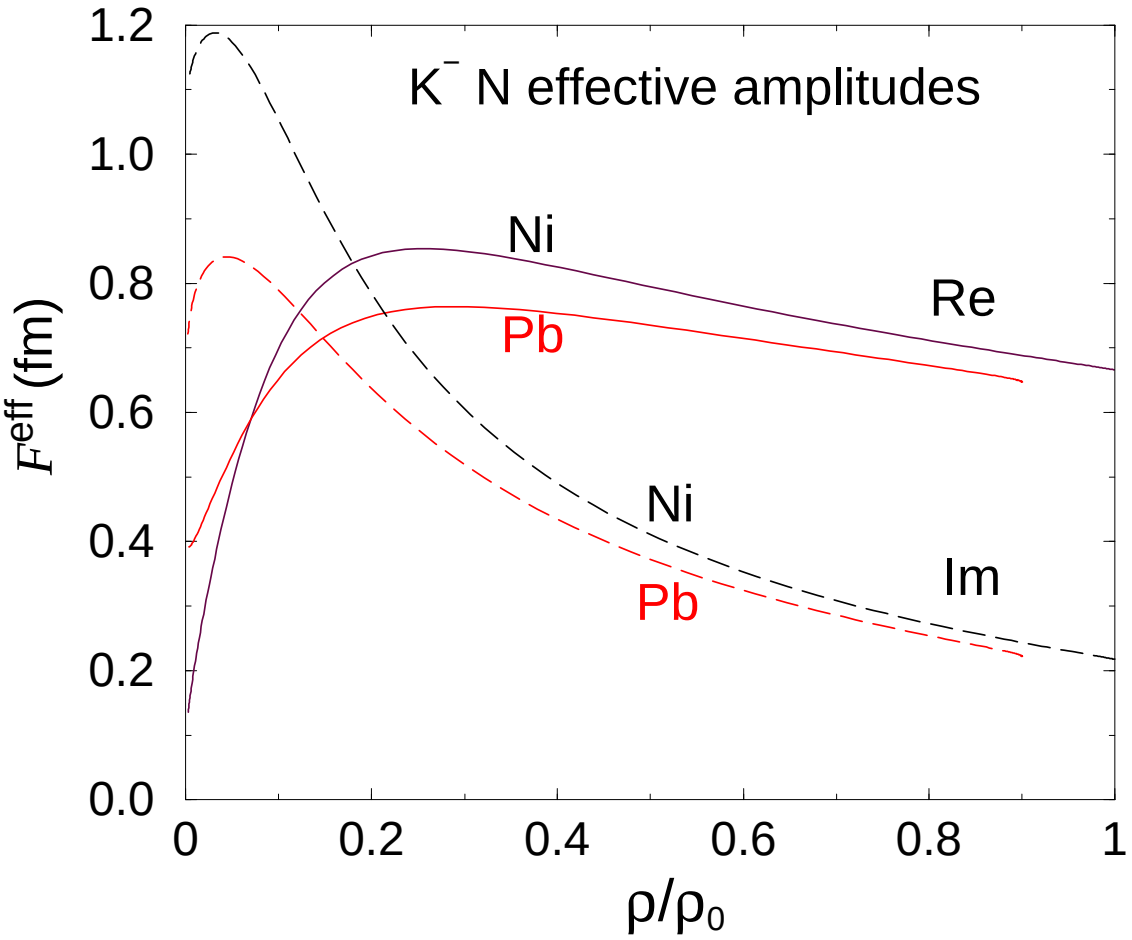
$F_{K^-N}(\sqrt{s},\rho)\rho(r)$ by

$\mathcal{F}^{\rm eff}_{K^-N}(\sqrt{s},\rho)\rho(r) = F_{K^-p}(\sqrt{s},\rho)\rho_p(r) + F_{K^-n}(\sqrt{s},\rho)\rho_n(r)$.

BUT processes beyond K^-N are excluded (K^-NN absorptions etc.)

Additional terms will be required.

Strong interaction effects in kaonic atoms are dominated by absorption.


K⁻ N effective amplitudes
Ni
Re
Pb
Ni
Im
Pb
F^{eff} (fm)
ρ/ρ0
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
1

Results of global fits to 65 data points

Adding a Phenomenological $b\rho + B\rho^2/\rho_0$ term.

No self energy, include $\sqrt{s} \to \sqrt{s} - V_c$

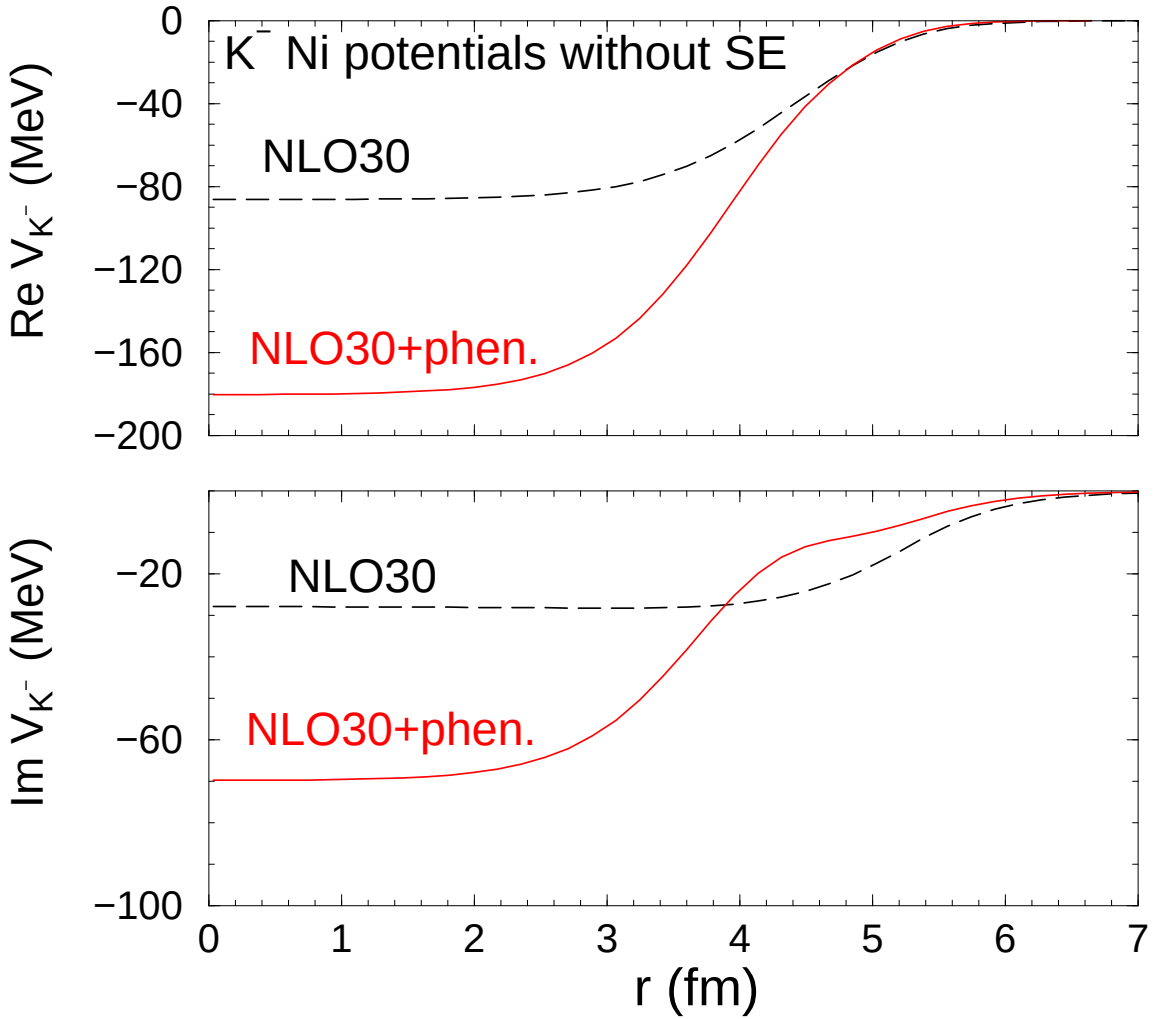
ampl.	χ^2	Reb(fm)	Imb(fm)	ReB(fm)	ImB(fm)
CS30	647	–	–	–	–
	138	-0.10 ± 0.06	-0.39 ± 0.06	0.82 ± 0.13	0.76 ± 0.12
TW1	655	–	–	–	–
	124	-0.06 ± 0.05	-0.41 ± 0.05	0.89 ± 0.23	0.87 ± 0.13

Keeping the amplitudes at threshold, Im$B < 0$ is obtained.

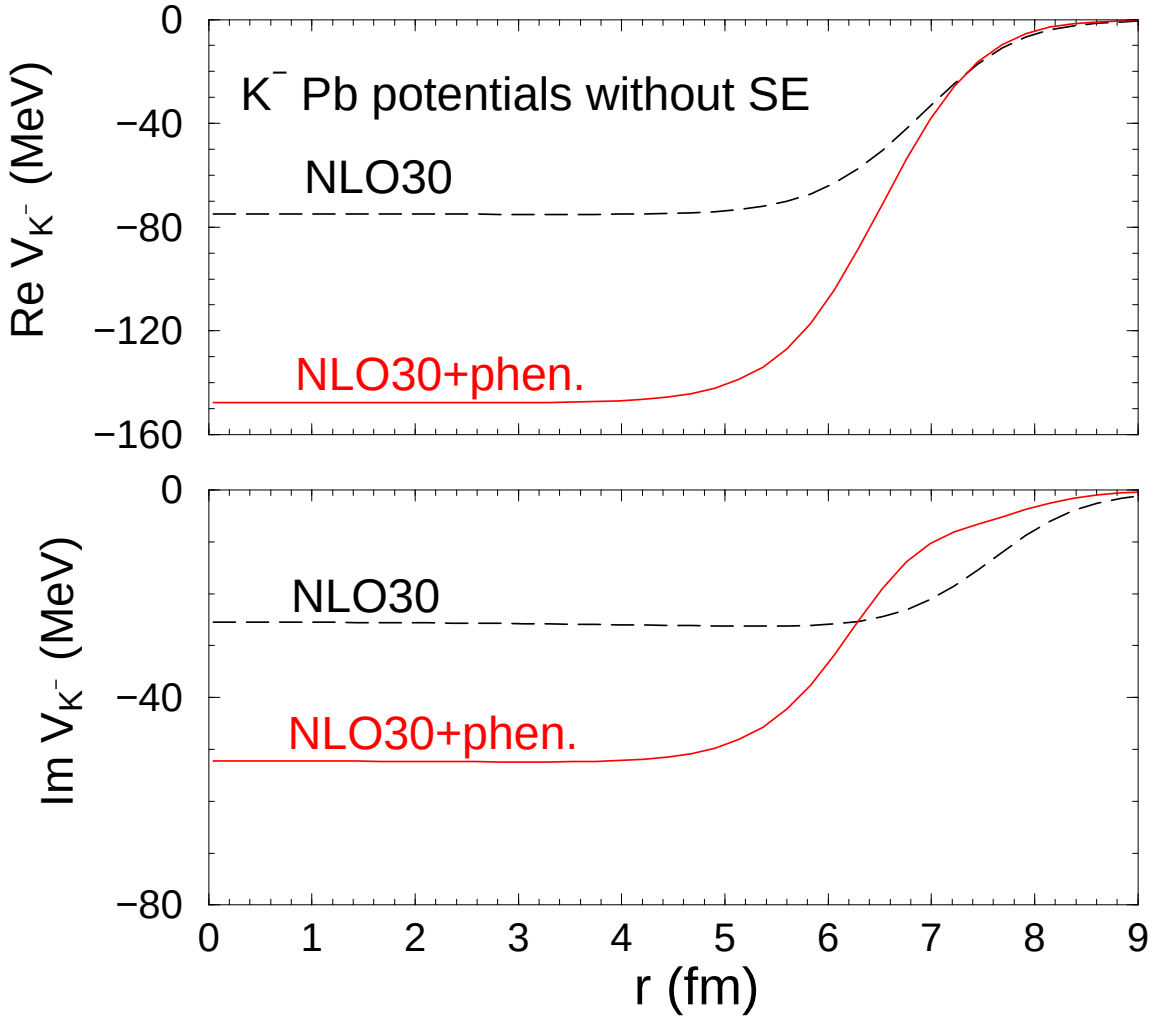
Compression or inflation?

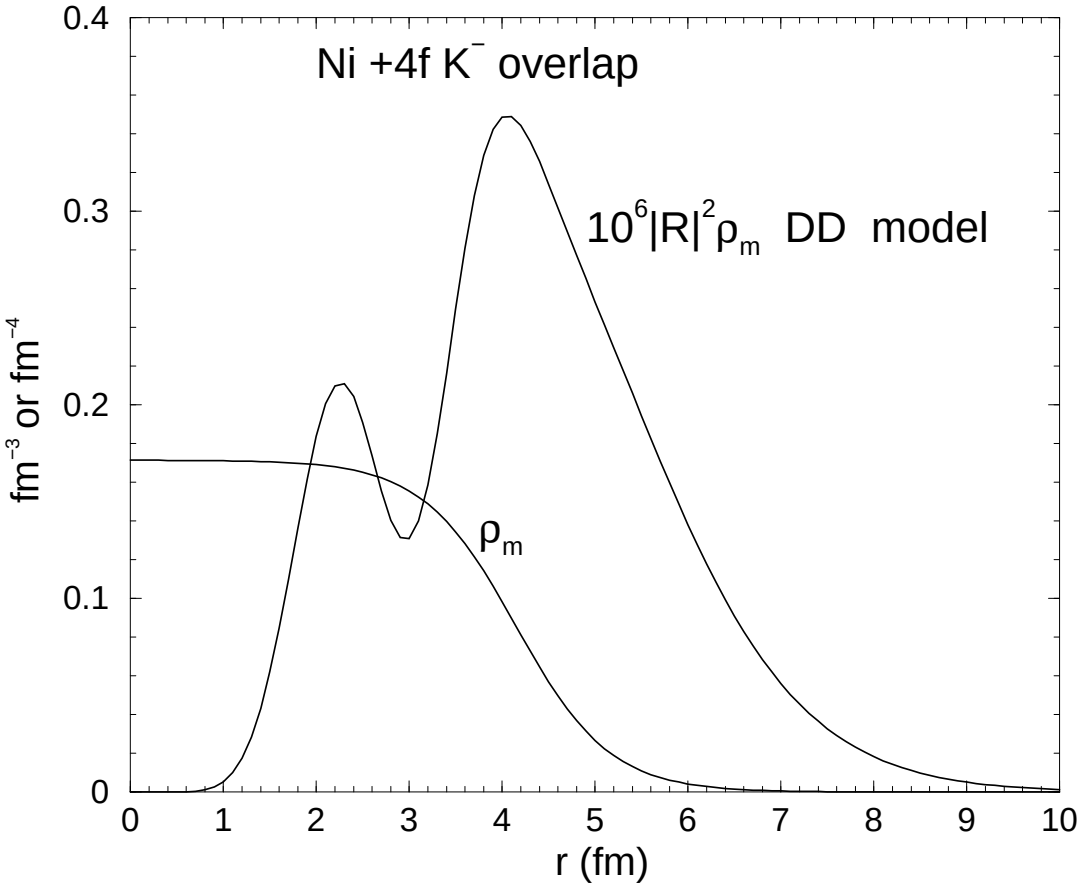
Qualitatively compression of the real part of the potential and inflation of the imaginary part are observed, but these are too mild for the real and too strong for the imaginary, compared to phenomenological potentials.

NLO30 amplitudes fit also recent SIDDHARTA results



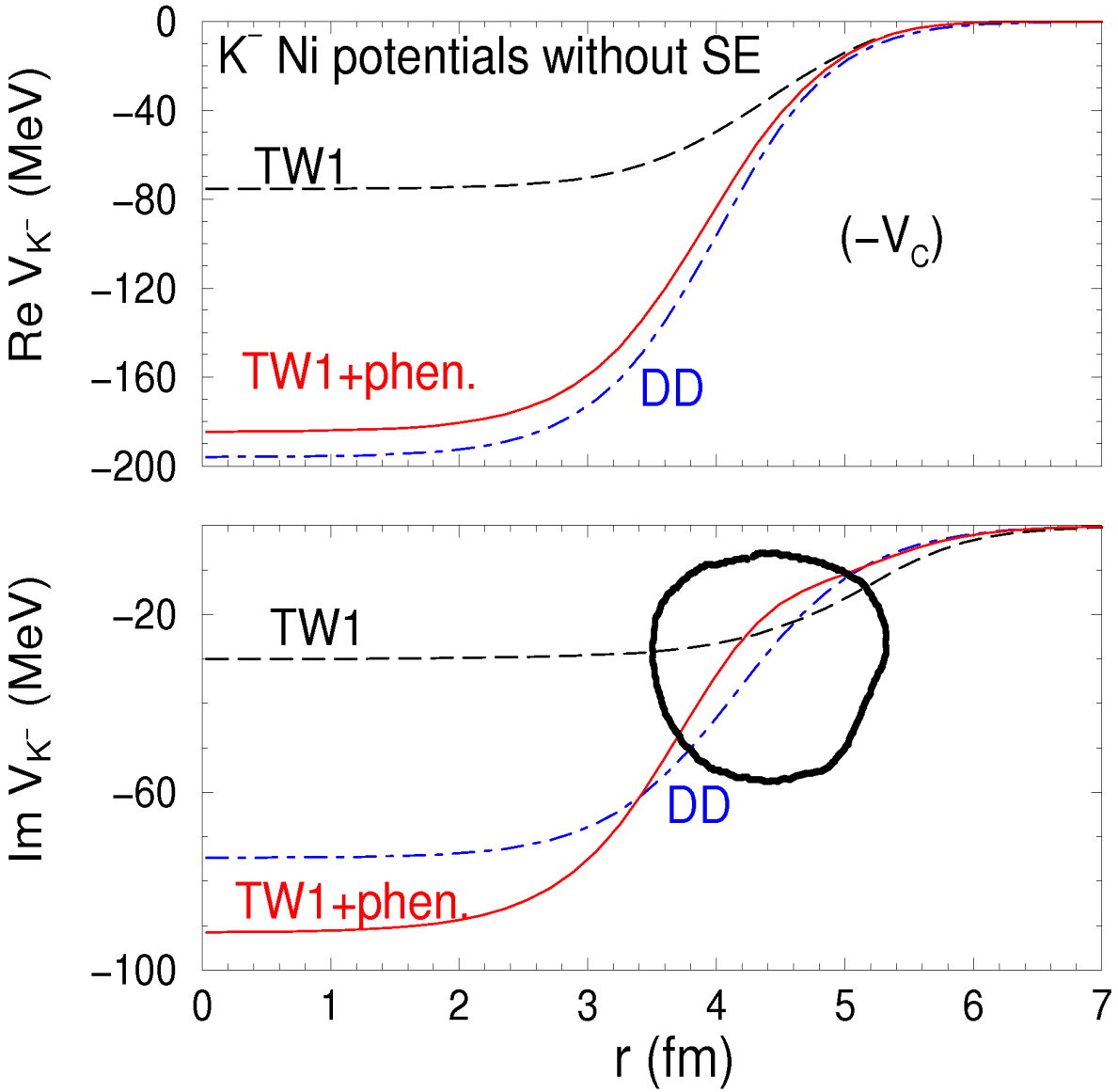
A. Cieplý and J. Smejkal, NPA **881** (2012) 115.


K⁻ Pb potentials without SE
NLO30
NLO30+phen.
Re V_K⁻ (MeV)
Im V_K⁻ (MeV)
0
−40
−80
−120
−160
0
−40
−80
NLO30
NLO30+phen.
0
1
2
3
4
5
6
7
8
9
r (fm)



Overlap of K^- atomic density with the nuclear density.

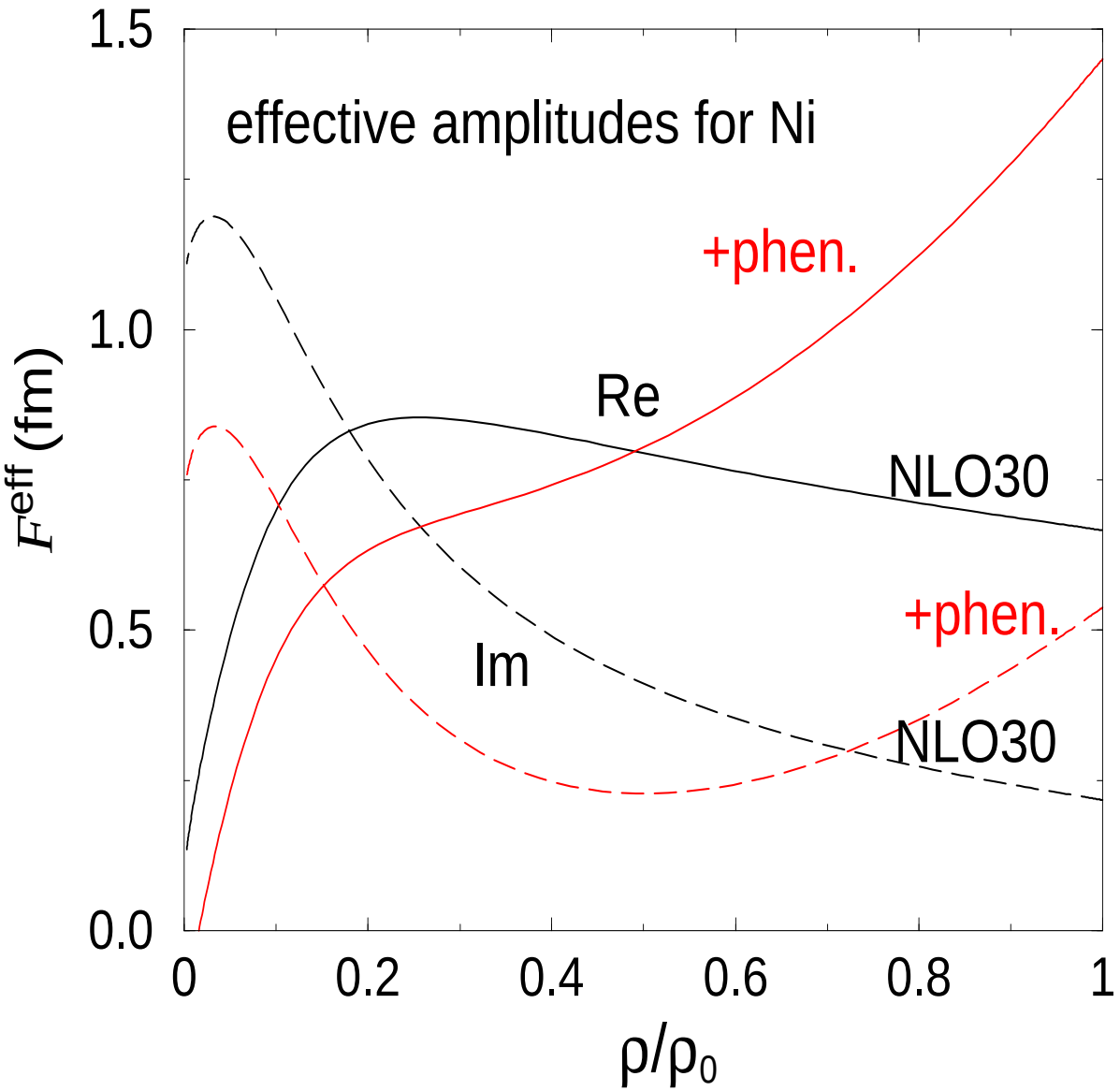
R_B =31.5 fm.

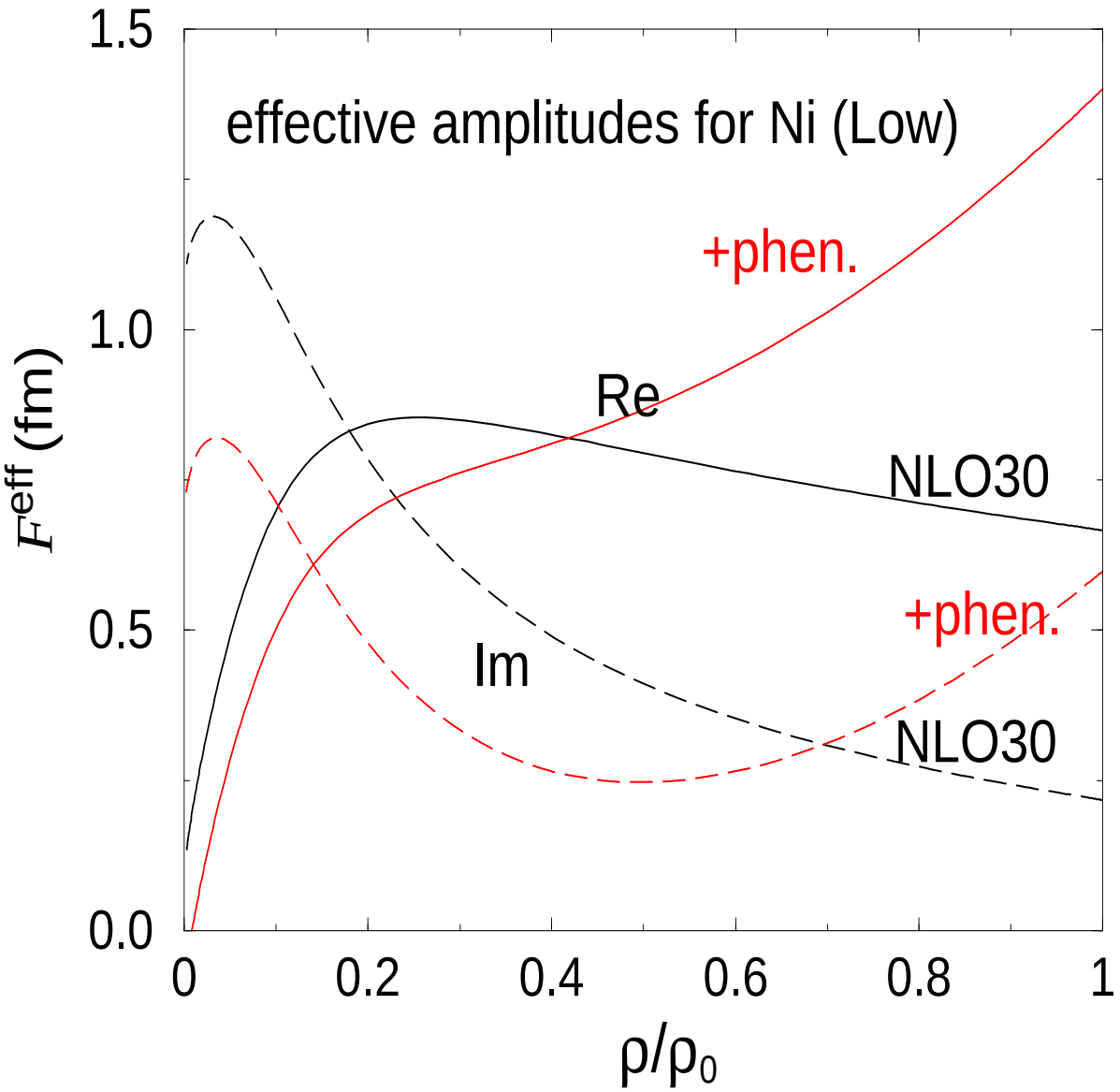

K⁻ Ni potentials without SE
TW1
(−V_C)
TW1+phen.
DD
Re V_K⁻ (MeV)
0
−40
−80
−120
−160
−200
TW1
DD
TW1+phen.
Im V_K⁻ (MeV)
−20
−60
−100
0
1
2
3
4
5
6
7
r (fm)

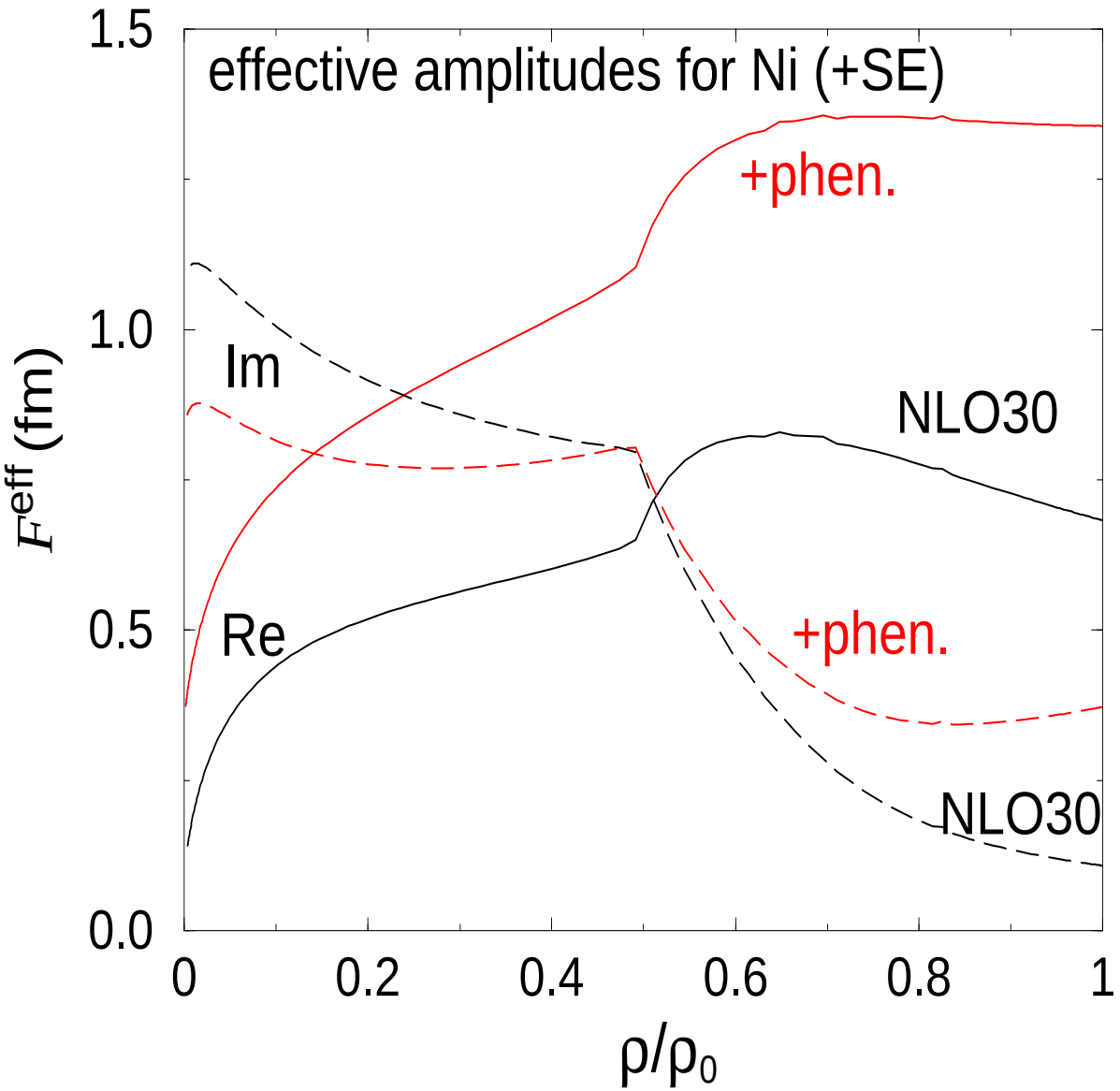
In the sensitive region near the surface the K^-N-based imaginary potential undergoes a *shape* change and is modified by up to 30%, consistent with emulsion data.

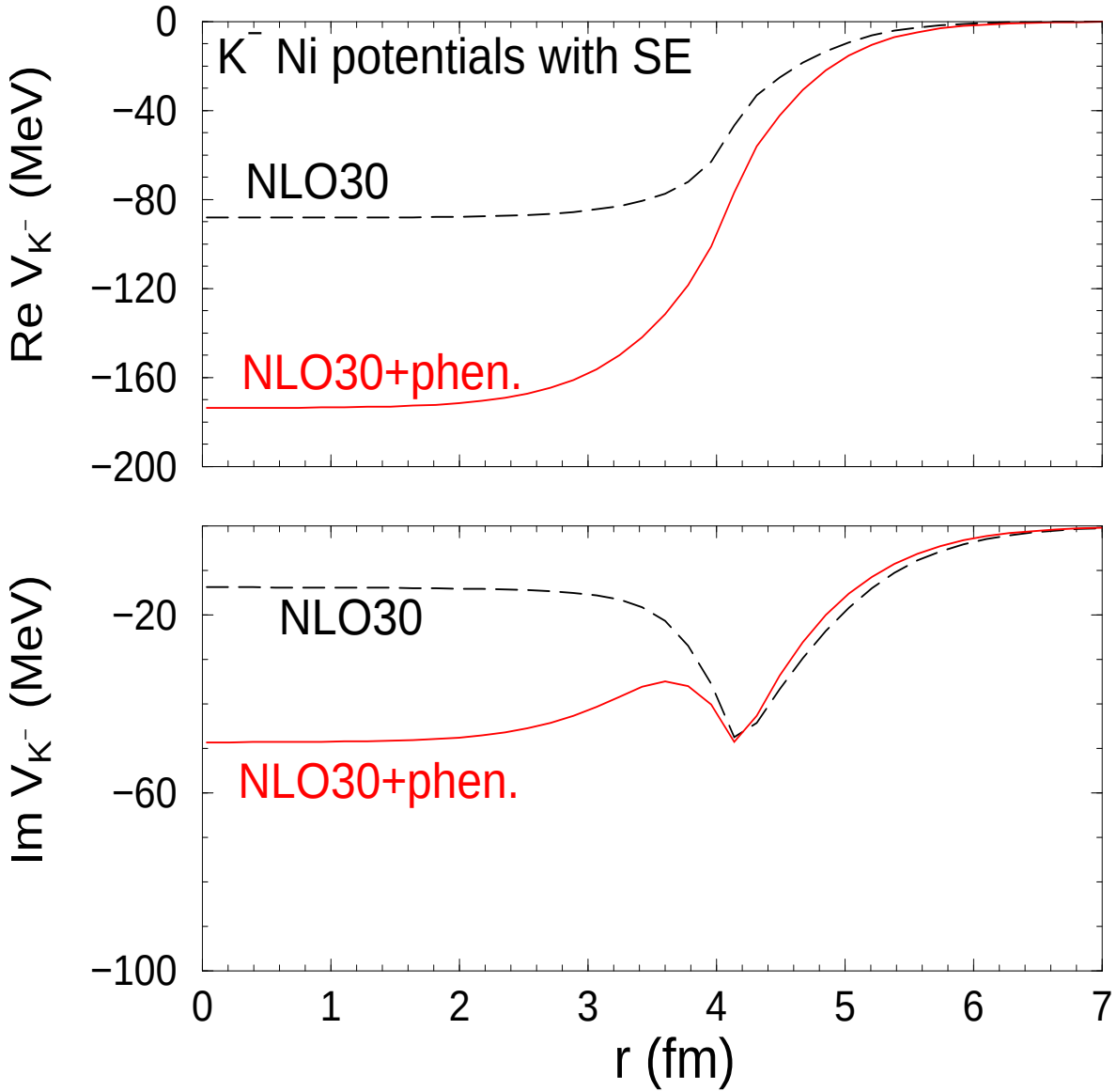
The real potential near the half-density point is 80-90 MeV deep.

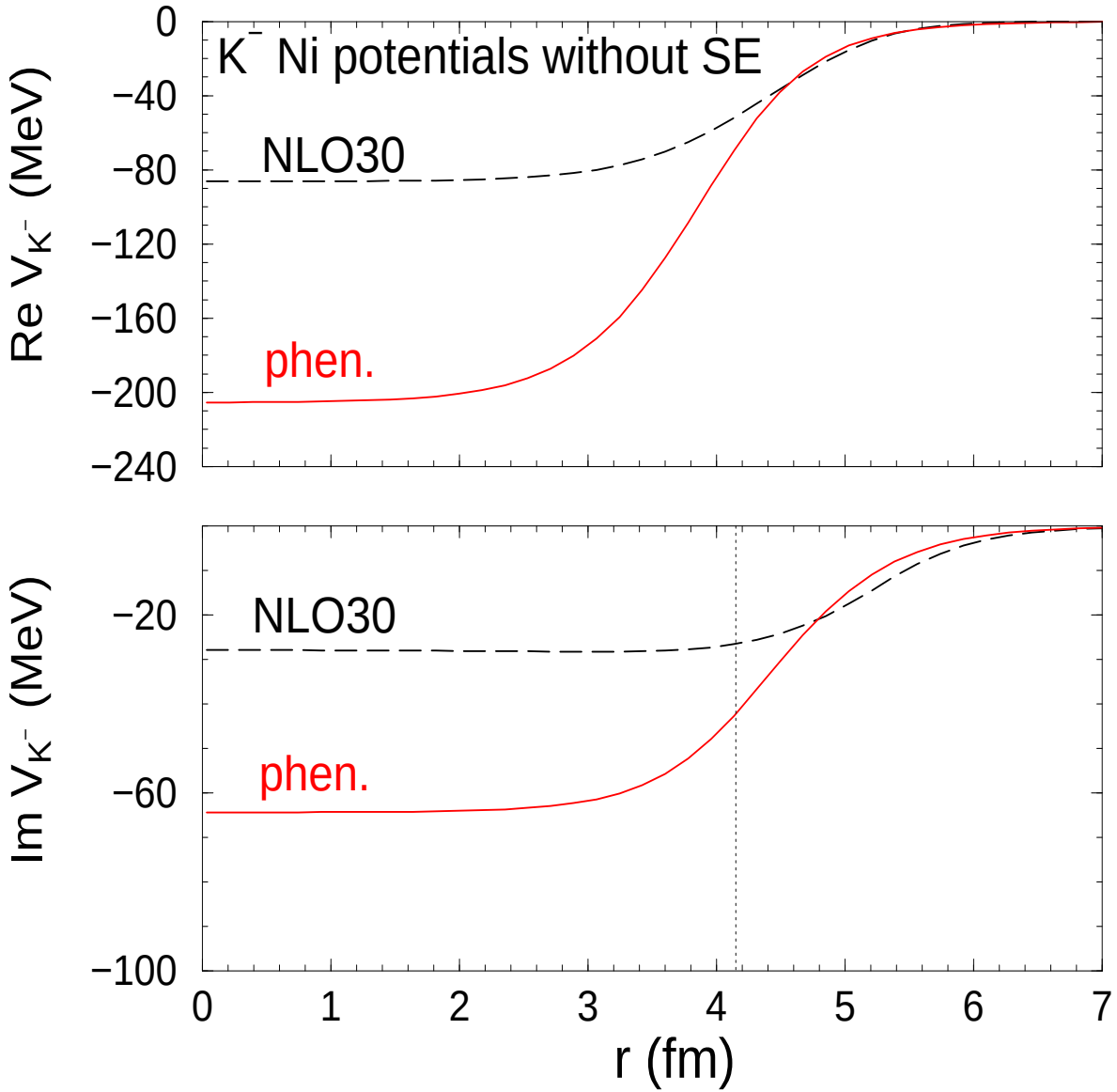
The phenomenology is similar to that for pionic atoms where empirical ρ^2 contributions augment one-nucleon terms.

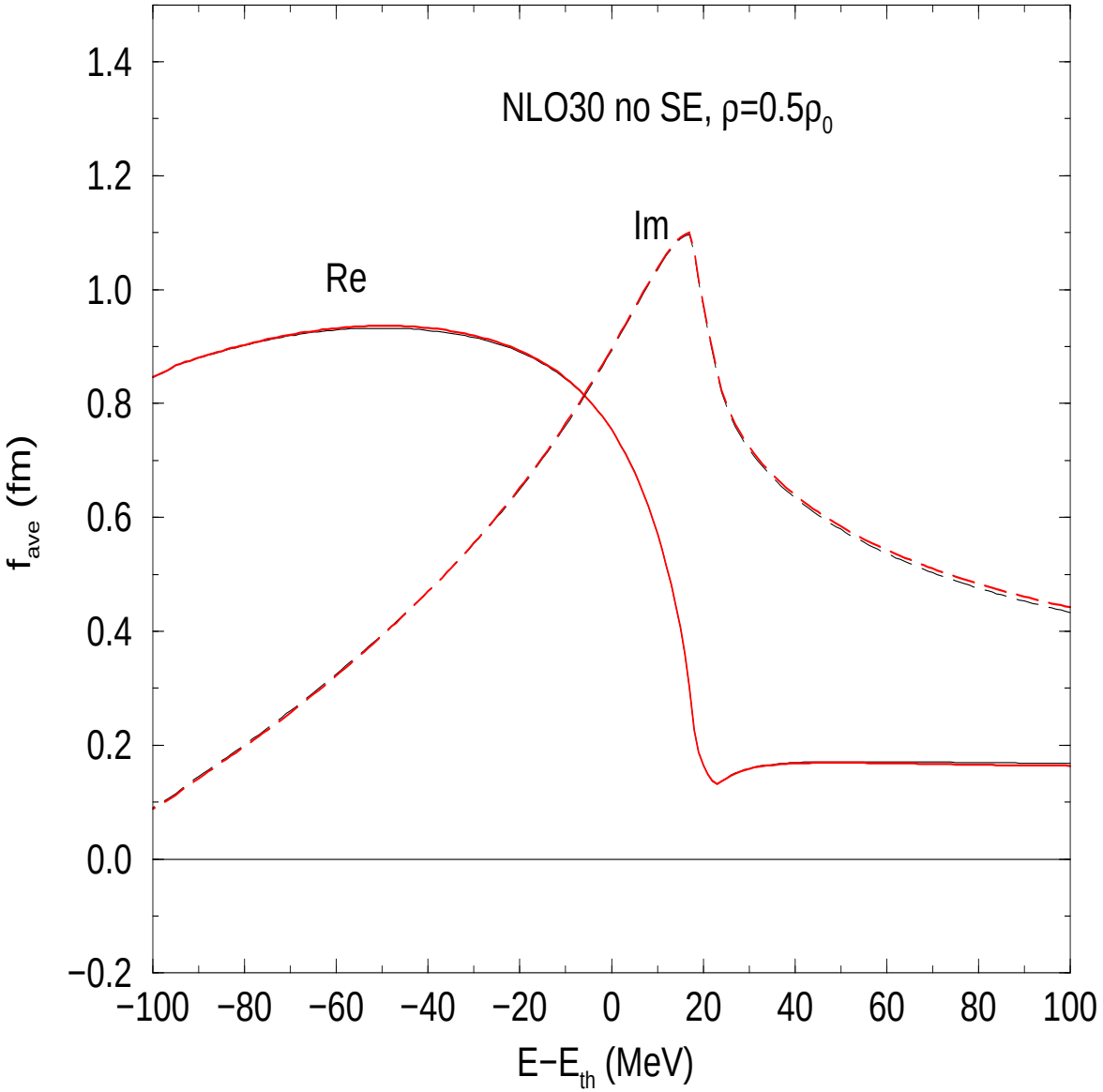

effective amplitudes for Ni
+phen.
Re
NLO30
+phen.
Im
NLO30
F^{eff} (fm)
ρ/ρ_0
1.5
1.0
0.5
0.0
0
0.2
0.4
0.6
0.8
1

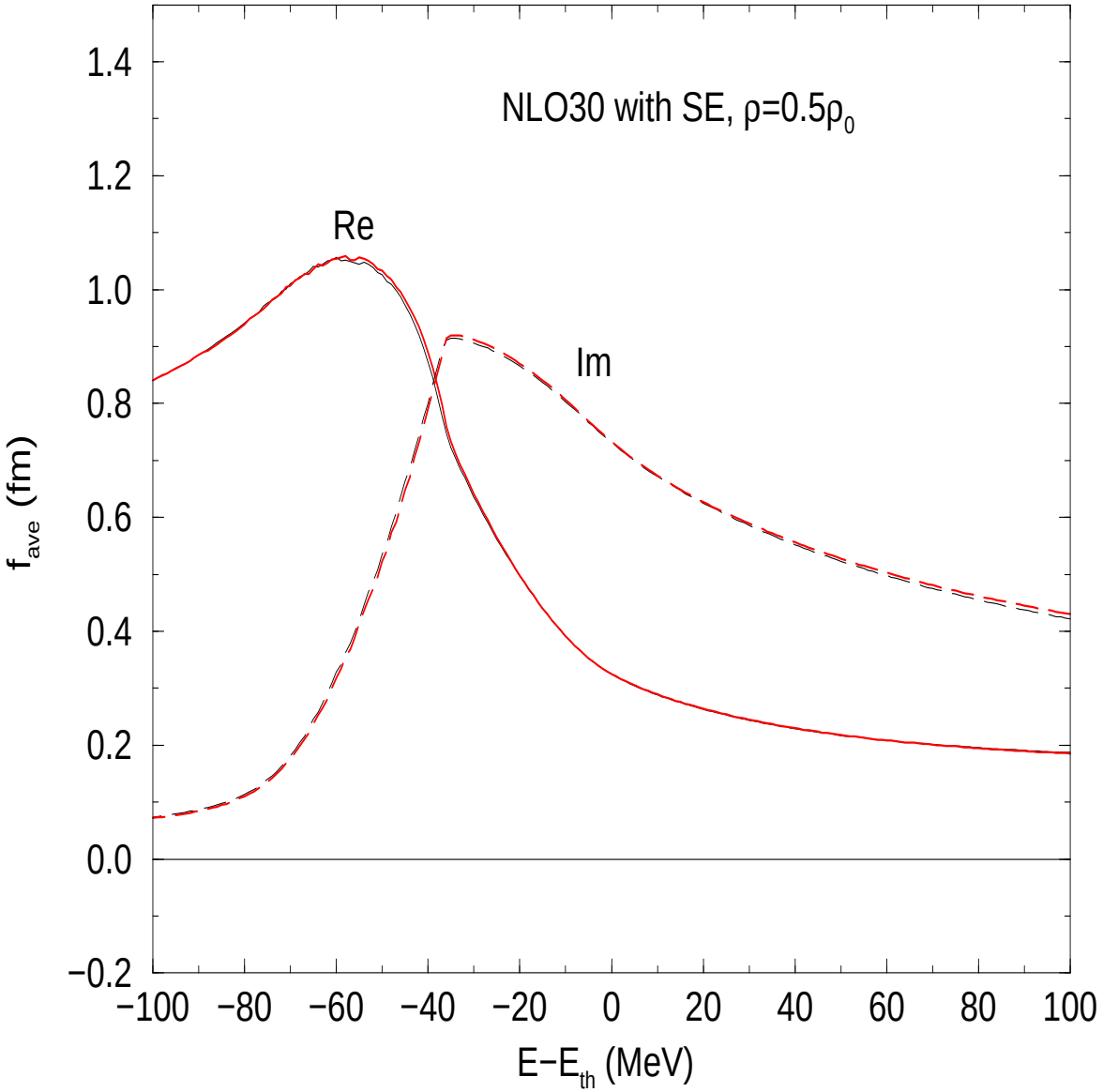

effective amplitudes for Ni (Low)
+phen.
Re
NLO30
+phen.
Im
NLO30
F^{eff} (fm)
ρ/ρ0
1.5
1.0
0.5
0.0
0
0.2
0.4
0.6
0.8
1


effective amplitudes for Ni (+SE)
+phen.
Im
NLO30
Re
+phen.
NLO30
F^{eff} (fm)
1.5
1.0
0.5
0.0
0
0.2
0.4
0.6
0.8
1
ρ/ρ0

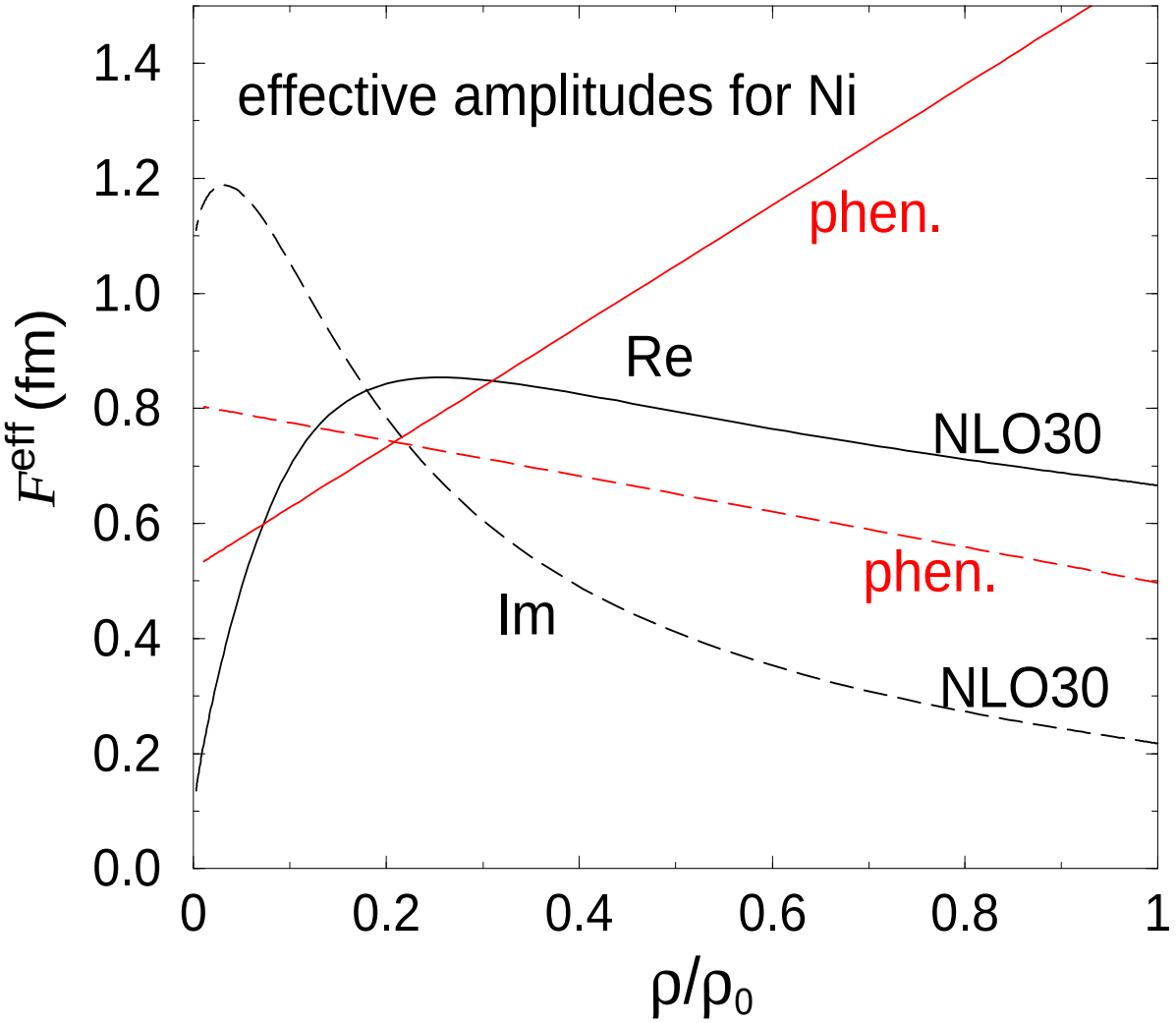

K⁻ Ni potentials with SE
NLO30
NLO30+phen.
Re V_K⁻ (MeV)
0
−40
−80
−120
−160
−200
NLO30
NLO30+phen.
Im V_K⁻ (MeV)
−20
−60
−100
0
1
2
3
4
5
6
7
r (fm)

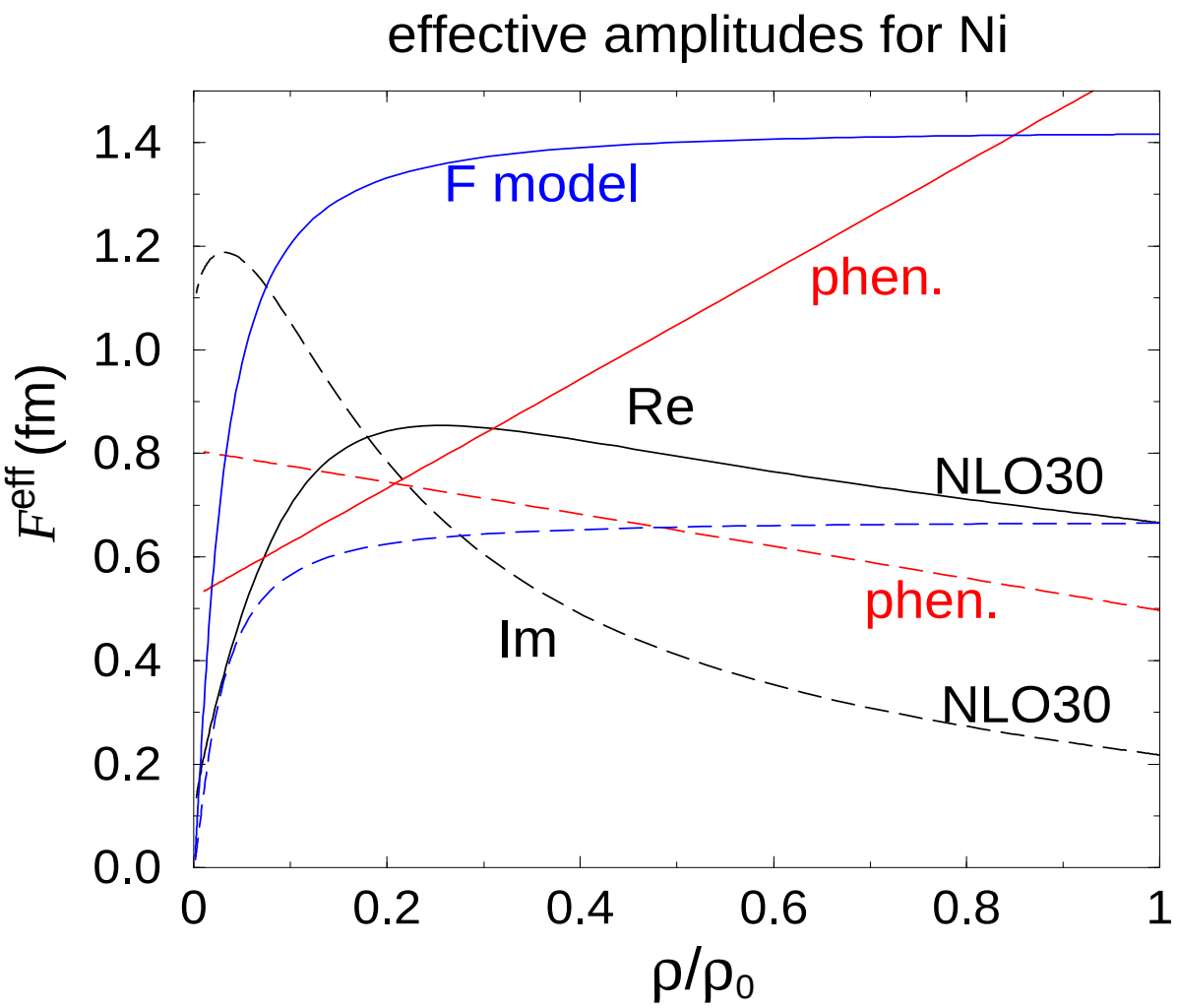

K⁻ Ni potentials without SE
NLO30
phen.
Re V_K⁻ (MeV)
0
−40
−80
−120
−160
−200
−240
NLO30
phen.
Im V_K⁻ (MeV)
−20
−60
−100
0
1
2
3
4
5
6
7
r (fm)


NLO30 no SE, ρ=0.5ρ0
Re
Im
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−100
−80
−60
−40
−20
0
20
40
60
80
100
fave (fm)
E−Eth (MeV)


NLO30 with SE, ρ=0.5ρ0
Re
Im
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−100
−80
−60
−40
−20
0
20
40
60
80
100
fave (fm)
E−Eth (MeV)

Additivity of amplitudes




effective amplitudes for Ni
F model
phen.
Re
NLO30
phen.
Im
NLO30
F^{eff} (fm)
ρ/ρ0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
0.2
0.4
0.6
0.8
1

Summary

- Systematics of r.m.s. radii of optical potentials from global fits to kaonic atom data reflect density dependence of the K^-N amplitudes.
- Density to energy transformation defines the 20-60 MeV below threshold as the relevant region.
- The need for multinucleon absorption processes is clearly observed.
- A multinucleon absorption theory will be most welcome!

Acknowledgements

The ‘subthreshold’ results presented in this talk are due to the long-standing collaboration with
Aleš Cieplý, Avraham Gal, Daniel Gazda and
Jiří Mareš, the Jerusalem-Prague group .