Momentum dependent mean-field dynamics for in-medium Y-interactions

Th. Gaitanos, A. Violaris

ΤΜΗΜΑ ΦΥΣΙΚΗΣ
ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

- Introduction
- Non-Linear Derivative (NLD) model of relativistic hadrodynamics
- RMF approach to infinite nuclear matter & in-medium hyperons
- Saturation properties, EoS, symmetry energy
- In-medium proton & antiproton optical potentials
- In-medium hyperon optical potentials
- Final remarks & outlook

Gaitanos & Kaskulov, Nuclear Physics A 899 (2013) 133
Gaitanos & Kaskulov, Nuclear Physics A 940 (2015) 181
Gaitanos & Violaris,in preparation

Ιωάννινα, 5.5.2017

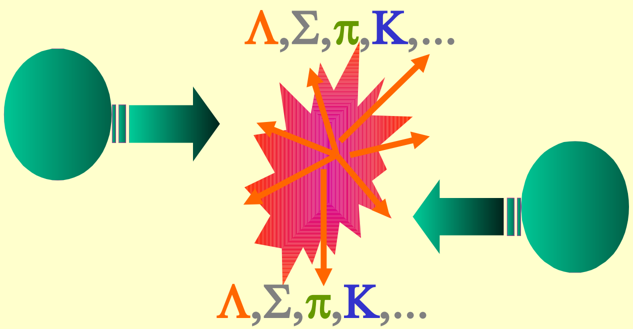
Introduction…

Important for astrophysics

explore EoS beyond saturation, e.g., at high densities

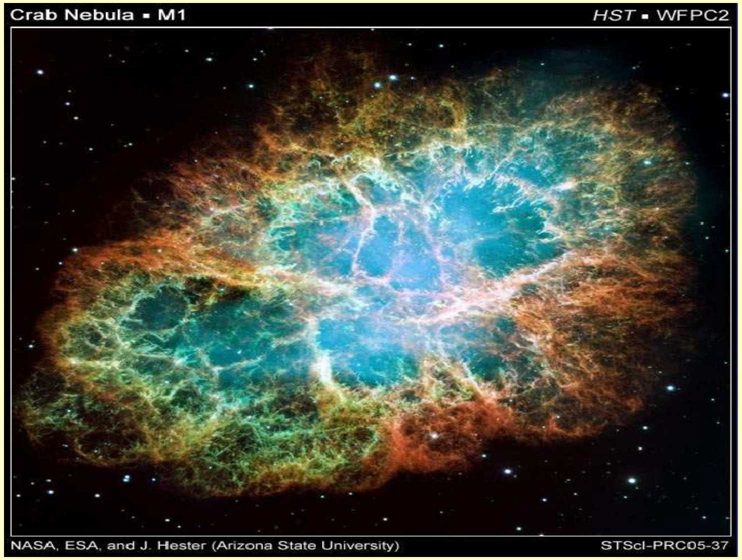
Heavy-ion collisions

(collective flow, meson production)



Densities of fireball for HIC@SIS:
$\rho \sim (2\text{-}3)\rho_0$

Neutron stars (mass & radius)



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- In high-density matter (+kinematics) → particles with high-momenta p
- Not only density dependence, but also momentum dependence (MD) essential

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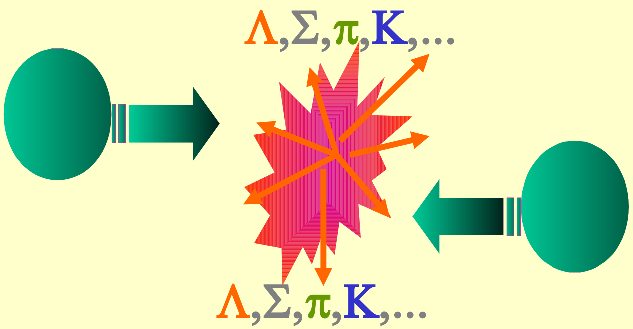

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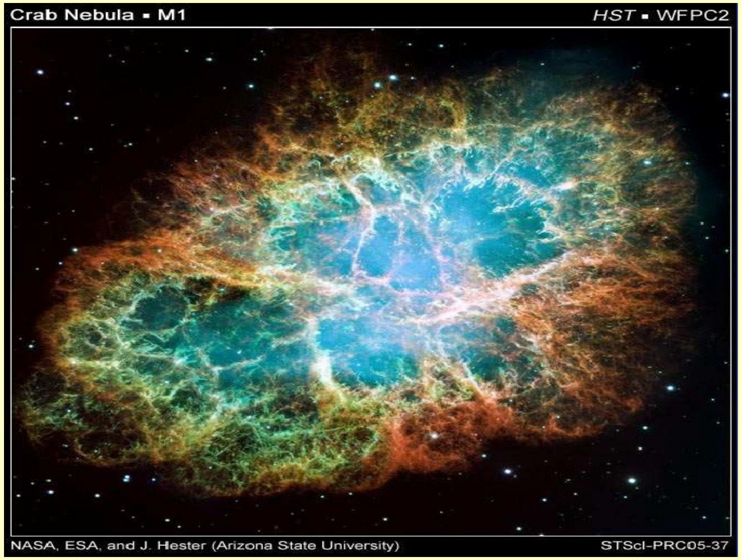

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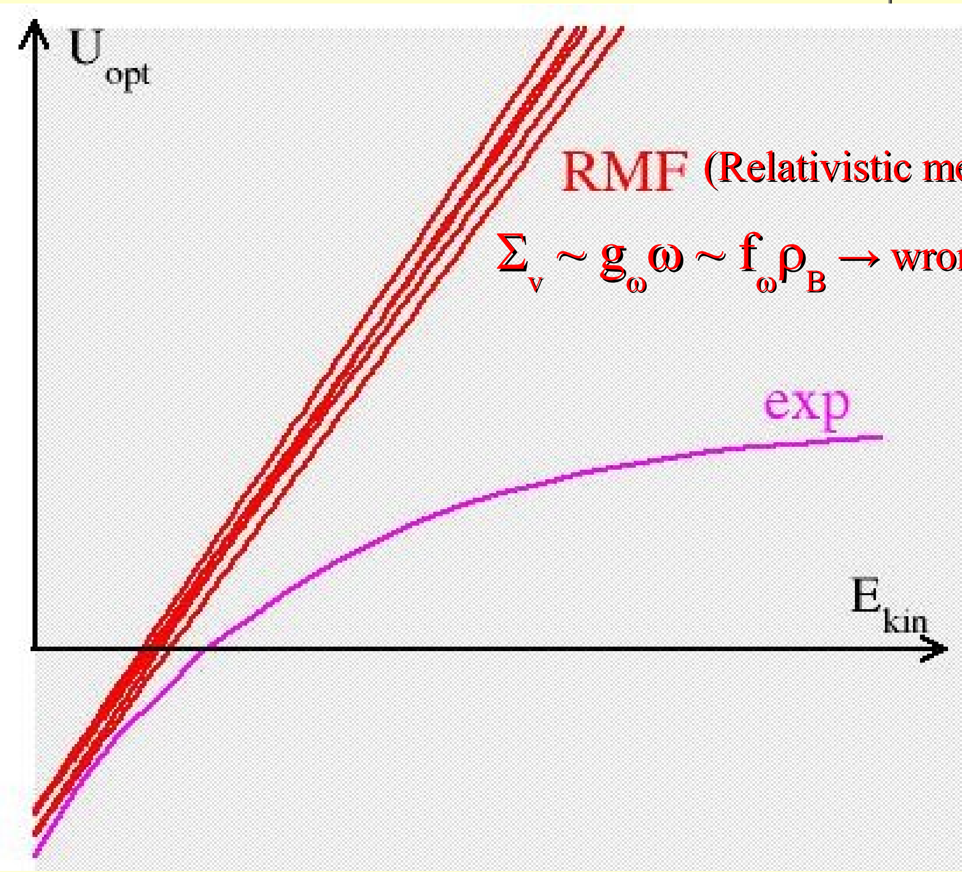
Introduction…

In-medium proton Schrödinger-equivalent $Re(U_{opt})$

$$U_{\text{opt}} = \frac{E}{m}\Sigma_v - \Sigma_s + \frac{1}{2m}\left(\Sigma_s^2 - \Sigma_v^2\right)$$



RMF (Relativistic mean-field)

$\Sigma_v \sim g_\omega \omega \sim f_\omega \rho_B \rightarrow$ wrong divergent MD at high ρ_B rsp. high momenta

DBHF & Dirac-phenomenology:
saturating fields (particular vector) with rising p

Solutions so far:

→ non-local (Hartree-Fock) contributions to RMF (Hartree) mean-field
Weber, Blättel, Cassing et al., Nucl. Phys. A539 (1992) 713

→ first-order derivative coupling terms into the interaction Lagrangian
S. Typel, Phys. Rev. C71, 064301 (2005)

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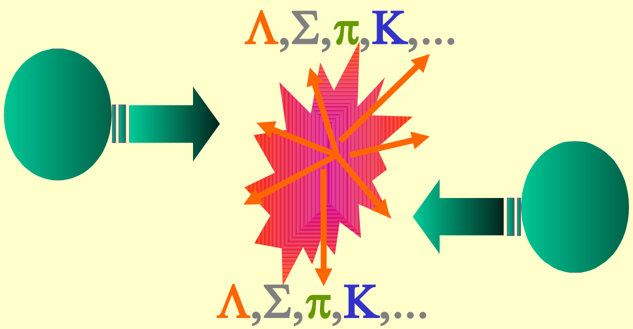

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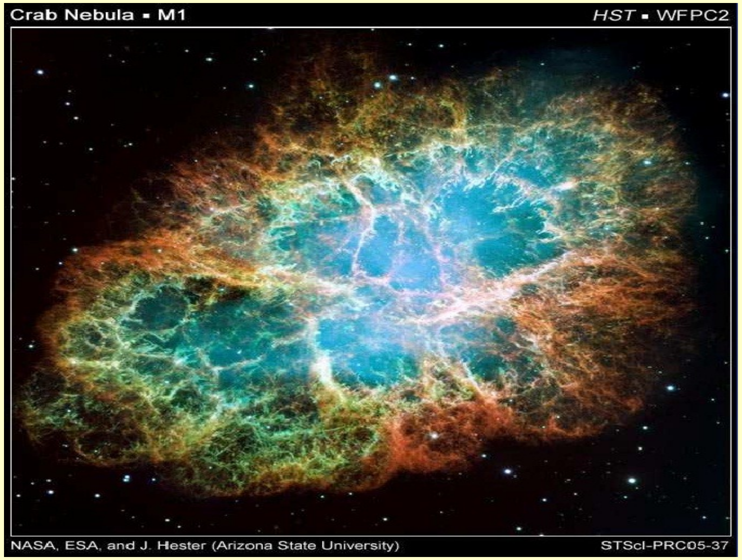

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- In high-density matter(+kinematics) → particles with high-momenta p
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- **Non-Linear Derivative (NLD) model:**
  RMF-based model with regulators for the high-momentum tails of the interaction

The Non-Linear Derivative (NLD) model...

NLD Lagrangian : as in conventional QHD

$$\mathcal{L} = \frac{1}{2}\left[\overline{\Psi}\gamma_\mu i\overrightarrow{\partial}^{\mu}\Psi - \overline{\Psi}i\overleftarrow{\partial}^{\mu}\gamma_\mu\Psi\right] - m\overline{\Psi}\Psi - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma)$$
$$+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^{\,\mu} - \frac{1}{4}\vec{G}_{\mu\nu}\vec{G}^{\,\mu\nu}$$
$$+\mathcal{L}_{int}$$

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$$\mathcal{L}_{int} = \frac{g_\sigma}{2}\left[\overline{\Psi}\Psi\sigma + \sigma\overline{\Psi}\Psi\right] - \frac{g_\omega}{2}\left[\overline{\Psi}\gamma^\mu\Psi\omega_\mu + \omega_\mu\overline{\Psi}\gamma^\mu\Psi\right]$$
$$- \frac{g_\rho}{2}\left[\overline{\Psi}\gamma^\mu\vec{\tau}\Psi\vec{\rho}_\mu + \vec{\rho}_\mu\overline{\Psi}\vec{\tau}\gamma^\mu\Psi\right]$$

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Non-linear derivative operators : Taylor expansion of partial derivatives ξ

$$\overrightarrow{\mathcal{D}} := \mathcal{D}\left(\overrightarrow{\xi}\right) = \sum_{j=0}^{n\to\infty}\frac{\partial^j}{\partial\overrightarrow{\xi}^j}\mathcal{D}|_{\overrightarrow{\xi}\to 0}\frac{\overrightarrow{\xi}^j}{j!} \qquad \overrightarrow{\xi} = -\frac{v^\alpha i\overrightarrow{\partial}_\alpha}{\Lambda}$$

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cut-off, will regulate the high-momentum tail of RMF fields

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NLD: The formalism…

NLD Lagrangian: contains higher field derivatives: $\mathcal{L}\left(\varphi_r,\, \partial_{\alpha_1}\varphi_r,\, \partial_{\alpha_1\alpha_2}\varphi_r, \cdots, \partial_{\alpha_1\cdots\alpha_n}\varphi_r\right)$

→ Generalized Euler-Lagrange equations:

$$\frac{\partial\mathcal{L}}{\partial\varphi_r} + \sum_{i=1}^{n}(-)^i \partial_{\alpha_1\cdots\alpha_i}\frac{\partial\mathcal{L}}{\partial(\partial_{\alpha_1\cdots\alpha_i}\varphi_r)} = 0$$

→ Generalized Noether-Theorem: conserved current

$$J^\mu = -i\left[\mathcal{K}_r^\mu\varphi_r + \mathcal{K}_r^{\mu\sigma_1}\partial_{\sigma_1}\varphi_r + \mathcal{K}_r^{\mu\sigma_1\sigma_2}\partial_{\sigma_1\sigma_2}\varphi_r + \cdots + \mathcal{K}_r^{\mu\sigma_1\cdots\sigma_n}\partial_{\sigma_1\cdots\sigma_n}\varphi_r\right]$$

with the following tensors

$$\mathcal{K}_r^{\mu\sigma_1\cdots\sigma_m} = \sum_{i=1}^{n}(-)^{i+1}\prod_{j=1}^{i-1}\partial_{\alpha_j}\frac{\partial\mathcal{L}}{\partial(\partial_{\mu\alpha_j\sigma_1\cdots\sigma_m}\varphi_r)}\,.$$

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infinite series rsp. to higher-order field derivatives, but...

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All infinite series can be resummed to compact expressions !

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NLD field equations...

→ Dirac equation for nucleons $\left[\gamma_\mu(i\partial^\mu - \Sigma^\mu) - (m - \Sigma_s)\right]\Psi = 0$ with selfenergies

$$\Sigma^\mu = g_\omega \omega^\mu \overrightarrow{\mathcal{D}} + g_\rho \vec{\tau} \cdot \vec{\rho}^{\,\mu} \overrightarrow{\mathcal{D}} + \cdots$$

$$\Sigma_s = g_\sigma \sigma \overrightarrow{\mathcal{D}} + \cdots$$

(up to terms containing derivatives of the meson fields)

→ Meson field equations:

$$\partial_\alpha \partial^\alpha \sigma + m_\sigma^2 \sigma + \frac{\partial U}{\partial \sigma} = \frac{1}{2} g_\sigma \left[\overline{\Psi} \overleftarrow{\mathcal{D}} \Psi + \overline{\Psi} \overrightarrow{\mathcal{D}} \Psi \right] ,$$

$$\partial_\mu F^{\mu\nu} + m_\omega^2 \omega^\nu = \frac{1}{2} g_\omega \left[\overline{\Psi} \overleftarrow{\mathcal{D}} \gamma^\nu \Psi + \overline{\Psi} \gamma^\nu \overrightarrow{\mathcal{D}} \Psi \right] ,$$

$$\partial_\mu \vec{G}^{\,\mu\nu} + m_\rho^2 \vec{\rho}^{\,\nu} = \frac{1}{2} g_\rho \left[\overline{\Psi} \overleftarrow{\mathcal{D}} \gamma^\nu \vec{\tau}\, \Psi + \overline{\Psi} \vec{\tau}\, \gamma^\nu \overrightarrow{\mathcal{D}} \Psi \right]$$

→ Noether current (energy-momentum tensor):

$$J^\mu = \overline{\Psi} \gamma^\mu \Psi - \frac{1}{2}\, g_\sigma \left[\overline{\Psi}\, \overleftarrow{\Omega}^\mu \Psi - \overline{\Psi}\, \overrightarrow{\Omega}^\mu \Psi \right] \sigma + \frac{1}{2}\, g_\omega \left[\overline{\Psi}\, \overleftarrow{\Omega}^\mu \gamma^\alpha \Psi - \overline{\Psi} \gamma^\alpha\, \overrightarrow{\Omega}^\mu \Psi \right] \omega_\alpha$$
$$+ \frac{1}{2}\, g_\rho \left[\overline{\Psi}\, \overleftarrow{\Omega}^\mu \gamma^\alpha \vec{\tau}\, \Psi - \overline{\Psi} \gamma^\alpha\, \overrightarrow{\Omega}^\mu \vec{\tau}\, \Psi \right] \vec{\rho}_\alpha + \cdots$$

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RMF approach to infinite asymmetric nuclear matter…

→ Plane wave *Ansatz* for Ψ and $\overline{\Psi}$ and $\mathcal{D} = \mathcal{D}(\xi)$ with $\xi = -\frac{v_\alpha p^\alpha}{\Lambda}$

$$\Sigma_{vi}^{\mu} = g_\omega \omega^\mu \mathcal{D} + g_\rho \tau_i \rho^\mu \mathcal{D} \ , \ \Sigma_{si} = g_\sigma \sigma \mathcal{D}$$

$$m_\sigma^2 \sigma + \frac{\partial U}{\partial \sigma} = g_\sigma \sum_{i=p,n} \left\langle \overline{\Psi}_i \mathcal{D} \Psi_i \right\rangle = g_\sigma \rho_s$$

$$m_\omega^2 \omega = g_\omega \sum_{i=p,n} \left\langle \overline{\Psi}_i \gamma^0 \mathcal{D} \Psi_i \right\rangle = g_\omega \rho_0$$

$$m_\rho^2 \rho = g_\rho \sum_{i=p,n} \tau_i \left\langle \overline{\Psi}_i \gamma^0 \mathcal{D} \Psi_i \right\rangle = g_\rho \rho_I \ .$$

$$T^{\mu\nu} = \sum_{i=p,n} \frac{\kappa}{(2\pi)^3} \int_{|\vec{p}\,| \leq p_{F_i}} d^3p \, \frac{\Pi_i^\mu p^\nu}{\Pi_i^0} - g^{\mu\nu} \langle \mathcal{L} \rangle$$

$$\Pi_i^\mu = p_i^{*\mu} + m_i^* \left(\partial_p^\mu \Sigma_{si} \right) - \left(\partial_p^\mu \Sigma_{vi}^\beta \right) p_{i\beta}^*$$

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meson-field equations

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Equation of State (EoS)

$$\varepsilon = \sum_{i=p,n} \frac{\kappa}{(2\pi)^3} \int_{|\vec{p}| \le p_{F_i}} d^3p \, E(\vec{p}) - \langle \mathcal{L} \rangle$$

$$P = \frac{1}{3} \sum_{i=p,n} \frac{\kappa}{(2\pi)^3} \int_{|\vec{p}| \le p_{F_i}} d^3p \, \frac{\vec{\Pi}_i \cdot \vec{p}}{\Pi_i^0} + \langle \mathcal{L} \rangle$$

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Features of NLD model...

$$\Sigma^{\mu}_{vi} = g_{\omega}\omega^{\mu}\mathcal{D} + g_{\rho}\tau_i\rho^{\mu}\mathcal{D}\ ,\ \Sigma_{si} = g_{\sigma}\sigma\mathcal{D}$$

cut-off Λ regulates

1) DD & MD of selfenergies

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cut-off Λ regulates

1) DD & MD of selfenergies

2) DD of meson-field sources (particularly for ω-field)

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1) DD & MD of selfenergies

2) DD of meson-field sources (particularly for ω-field)

3) fully thermodynamic consistent (important for neutron stars)

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NLD results: saturation...

Parameters

	$\vec{\mathcal{D}}$	cut-off	Λ_s [GeV]	Λ_v [GeV]	g_σ	g_ω	g_ρ	b [fm^{-1}]	c	m_σ [GeV]	m_ω [GeV]	m_ρ [GeV]
NLD	$\frac{1}{1+\sum_{j=1}^{4}\left(\zeta_j^\alpha i\vec{\partial}_\alpha\right)^2}$	$\frac{\Lambda^2}{\Lambda^2+\vec{p}^2}$	0.95	1.125	10.08	10.13	3.50	15.341	−14.735	0.592	0.782	0.763

Comparison with other models

Model	ρ_{sat} [fm^{-3}]	E_b [MeV/A]	K [MeV]	a_{sym} [MeV]	L [MeV]	K_{sym} [MeV]	K_{asy} [MeV]	
NLD	0.156	−15.30	251	30	81	−28	−514	
NL3*	0.150	−16.31	258	38.68	125.7	104.08	−650.12	→ Lalazissis
DD	0.149	−16.02	240	31.60	56	−95.30	−431.30	→ Typel
D^3C	0.151	−15.98	232.5	31.90	59.30	−74.7	−430.50	
DBHF	0.185	−15.60	290	33.35	71.10	−27.1	−453.70	→ Li, Machleidt, Brockmann
	0.181	−16.15	230	34.20	71	87.36	−340	→ Fuchs
empirical	0.167 ± 0.019	-16 ± 1	230 ± 10	31.1 ± 1.9	88 ± 25	–	-550 ± 100	

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monopole form

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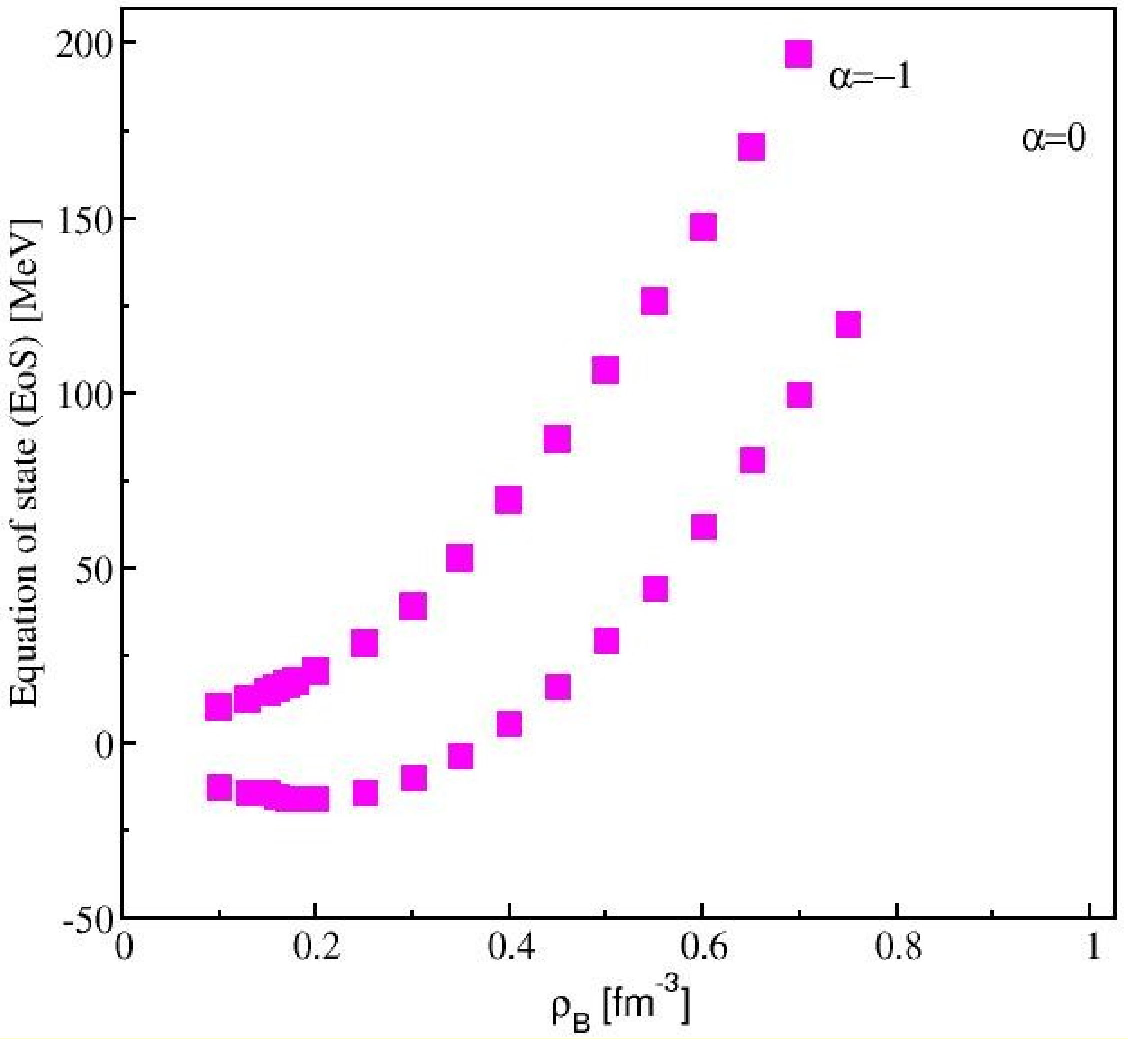
empirical	0.167 ± 0.019	-16 ± 1	230 ± 10	31.1 ± 1.9	88 ± 25	–	-550 ± 100	

soft EoS at ρ_{sat},
but stiff at high ρ relevant for NS!

NLD results: EoS…



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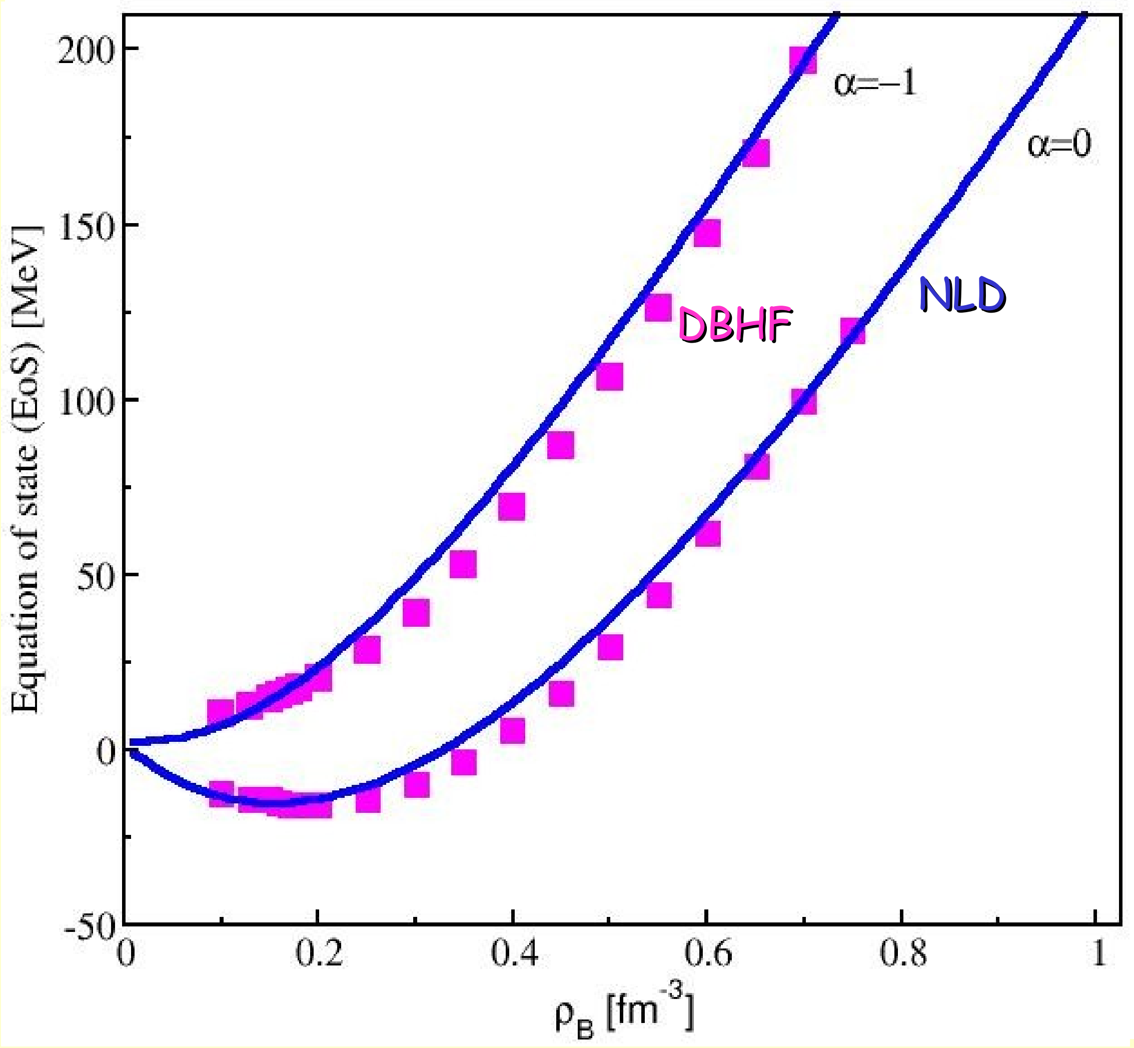
NLD results: EoS...



Remarkable comparison with microscopic DBHF!

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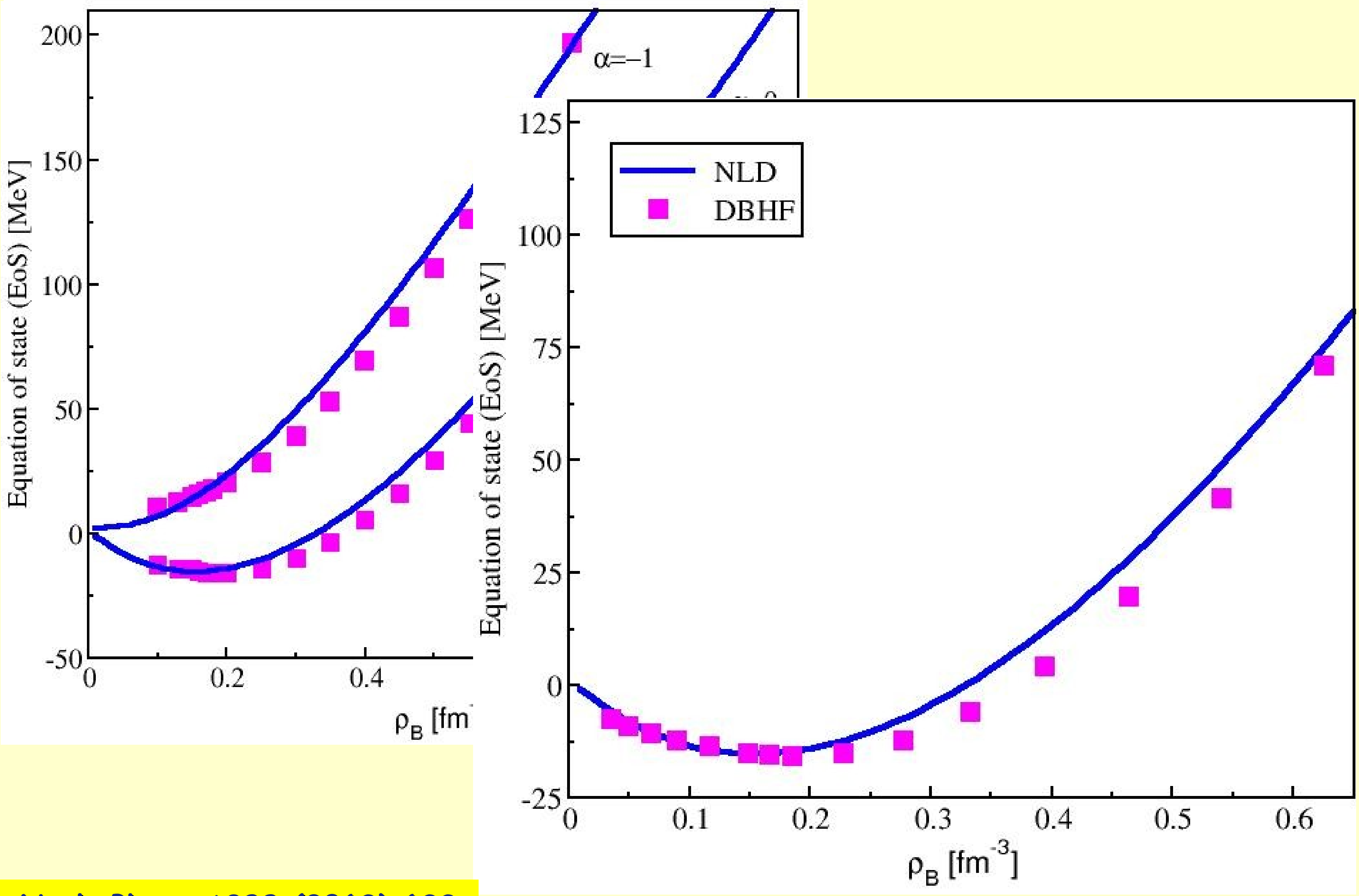
NLD results: EoS...



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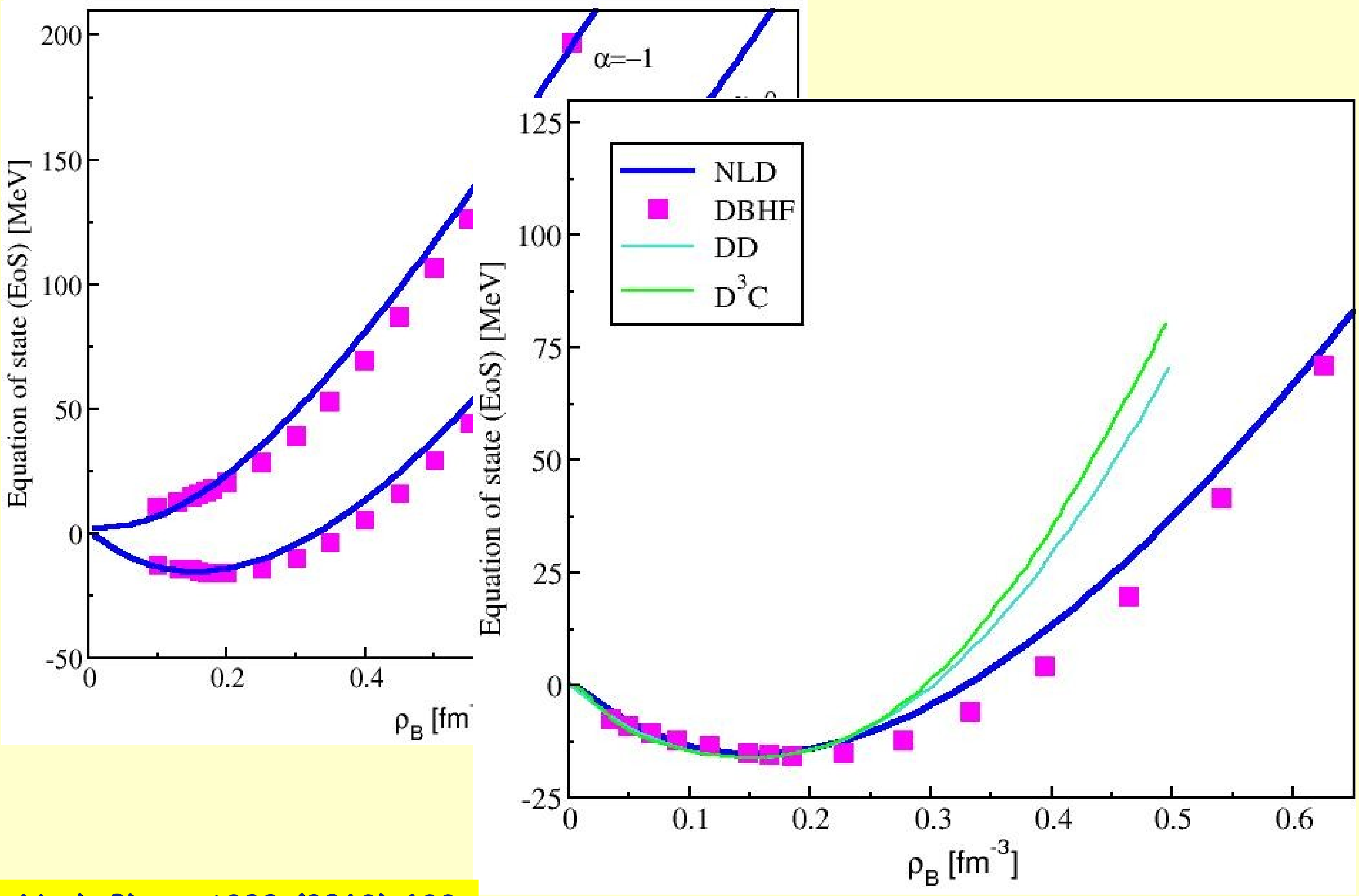
NLD results: EoS…



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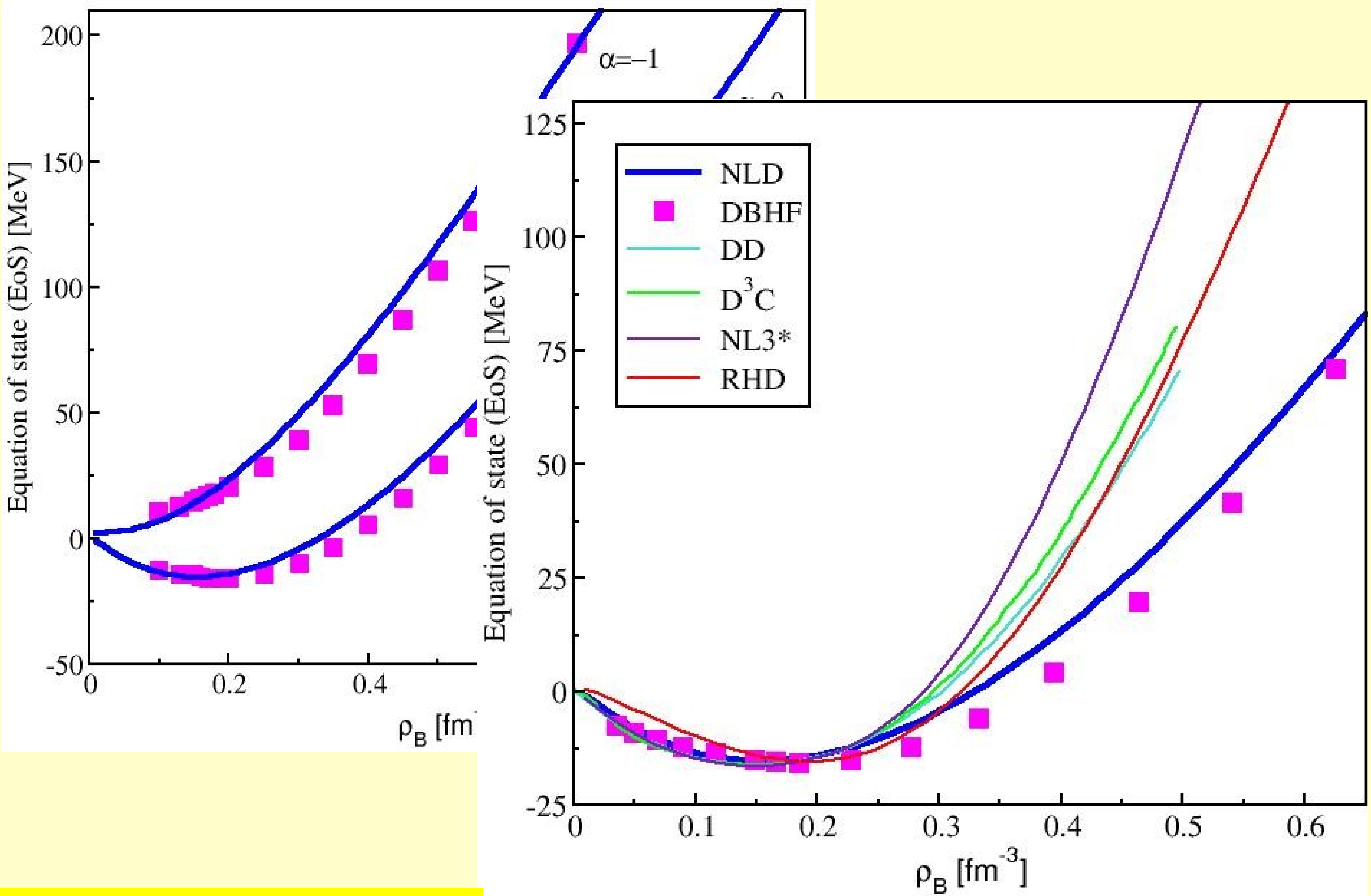
NLD results: EoS…



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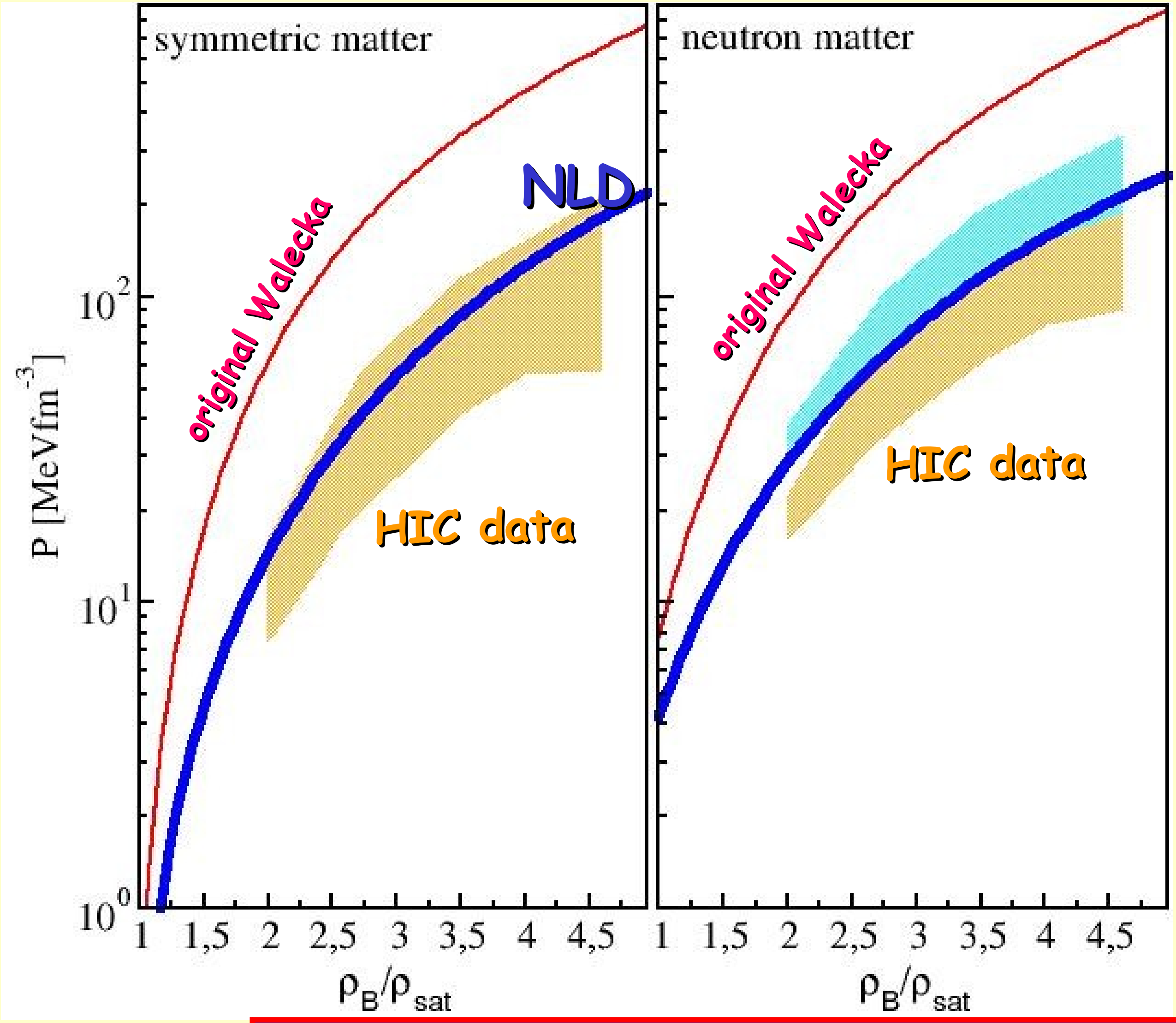
NLD results: EoS...



NLD model is consistent with HIC phenomenology

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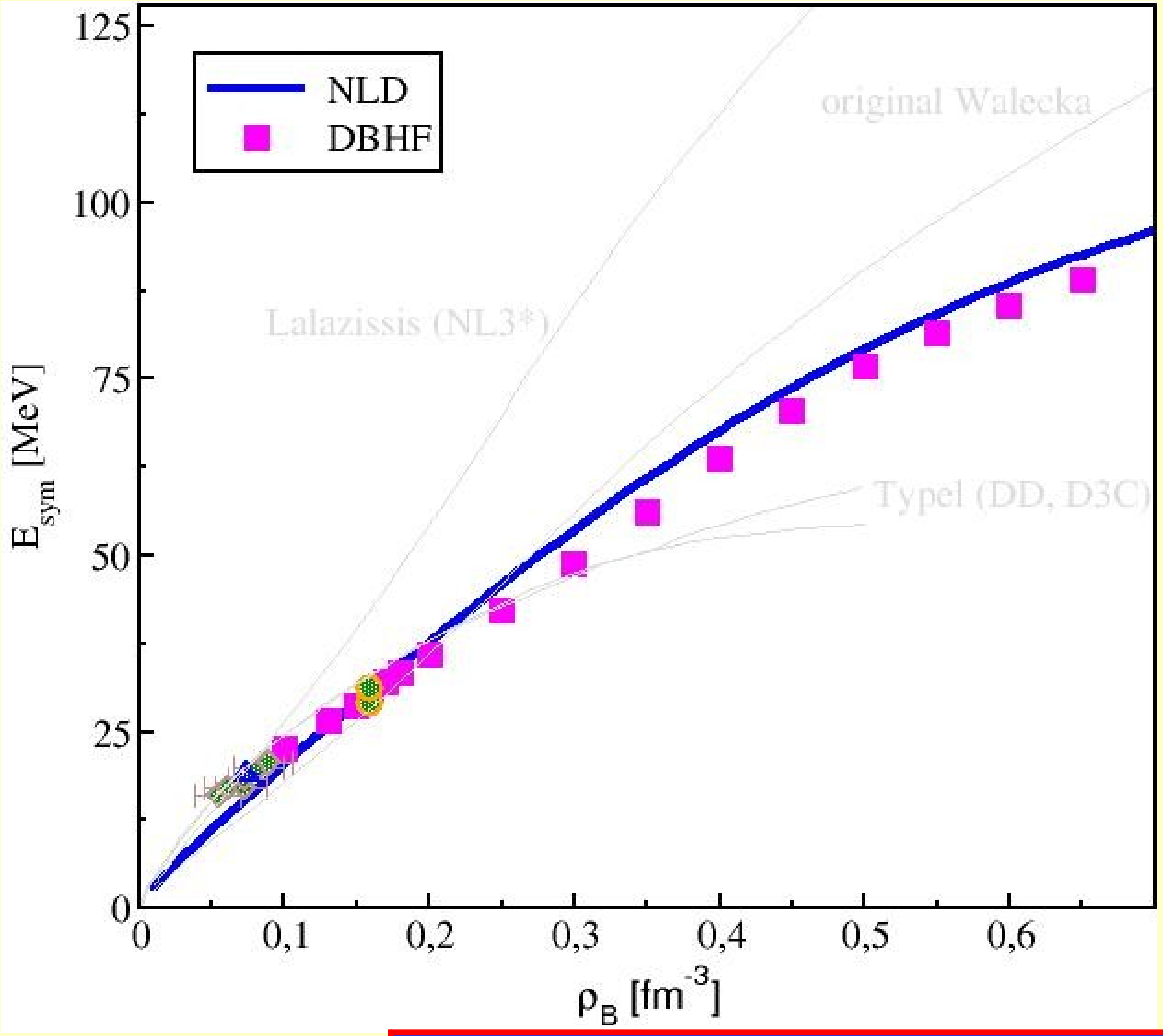
NLD results: symmetry energy...



Remarkable agreement with microscopic DBHF !

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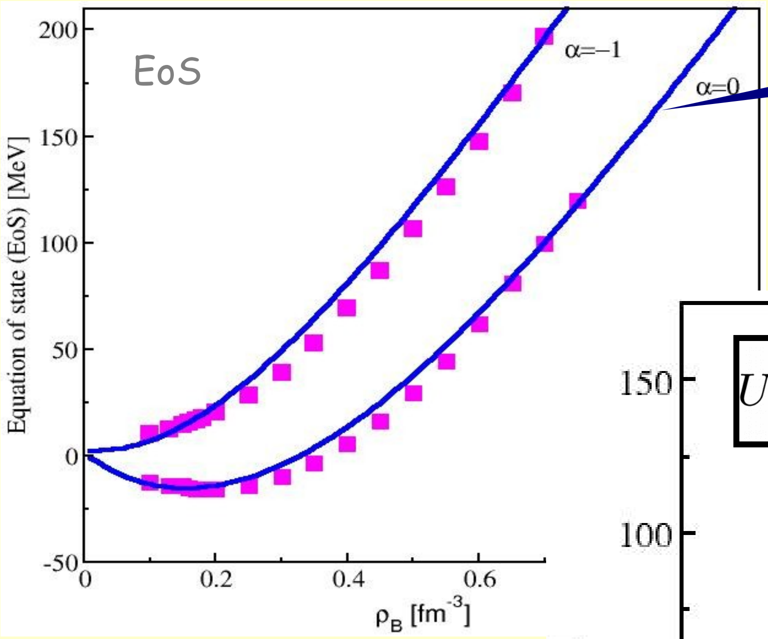
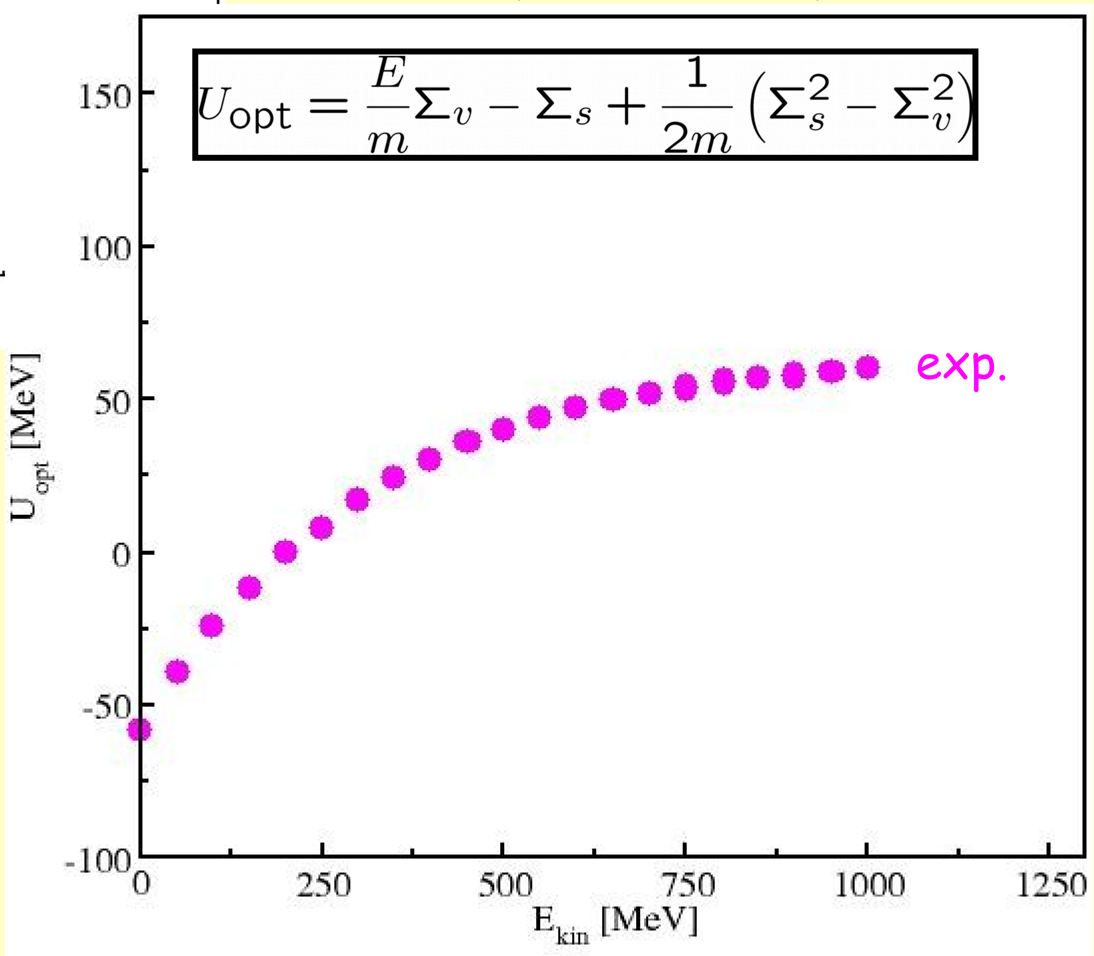
NLD results: MD & optical potentials...



high ρ → high momenta

In-medium proton SEP (real part)



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NLD results: MD & optical potentials...

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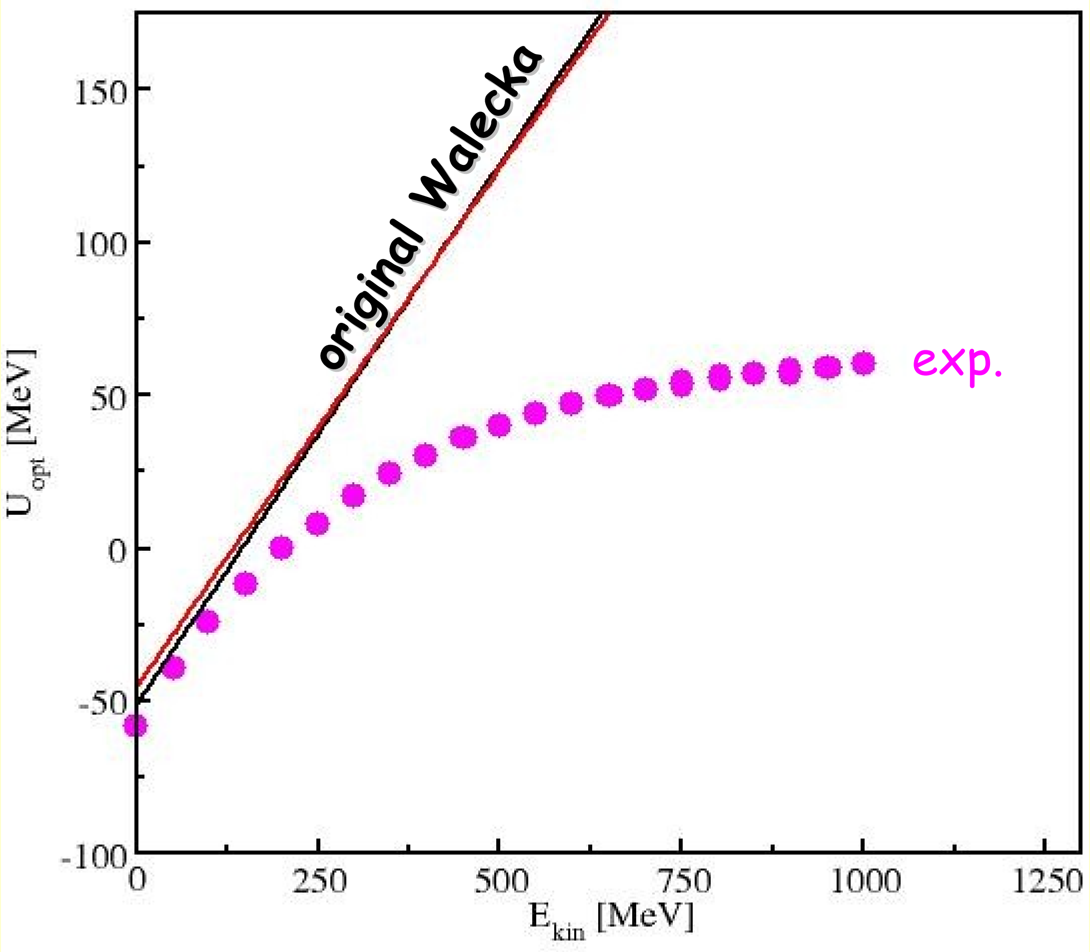

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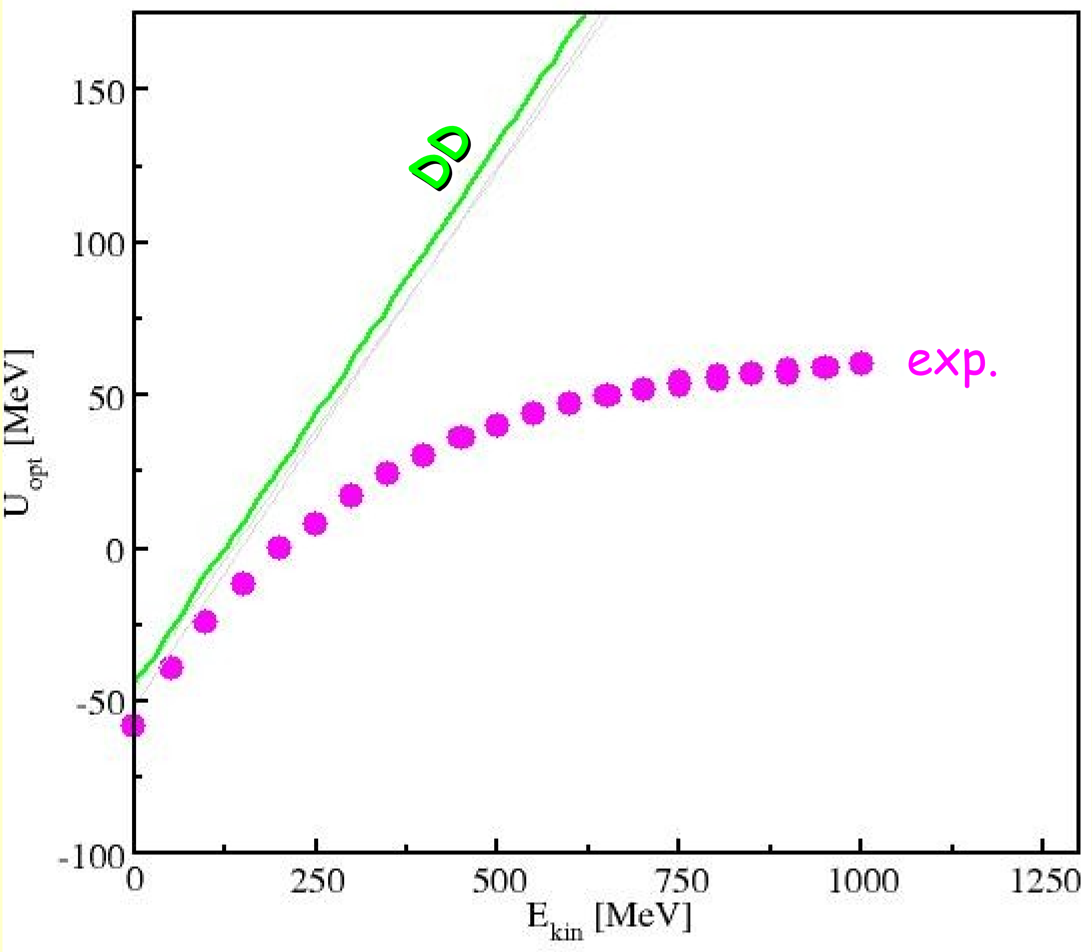

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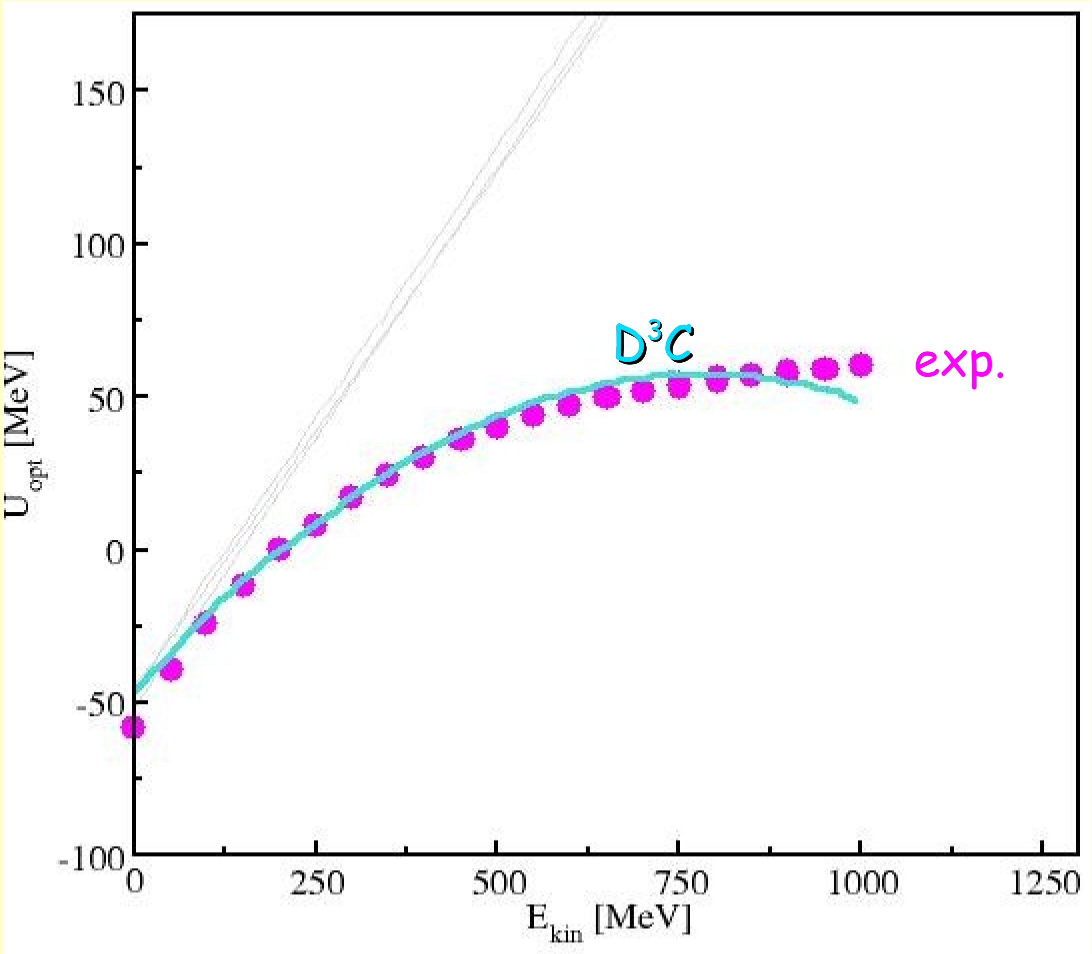

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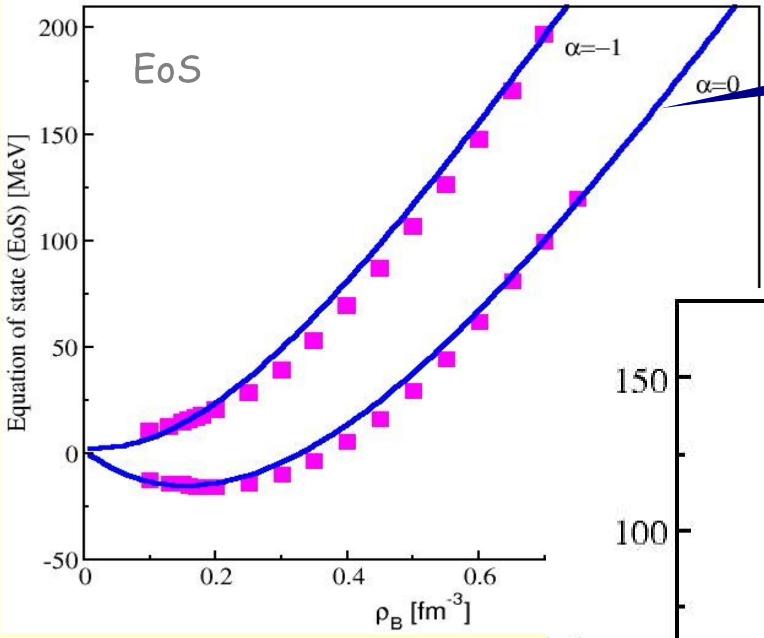
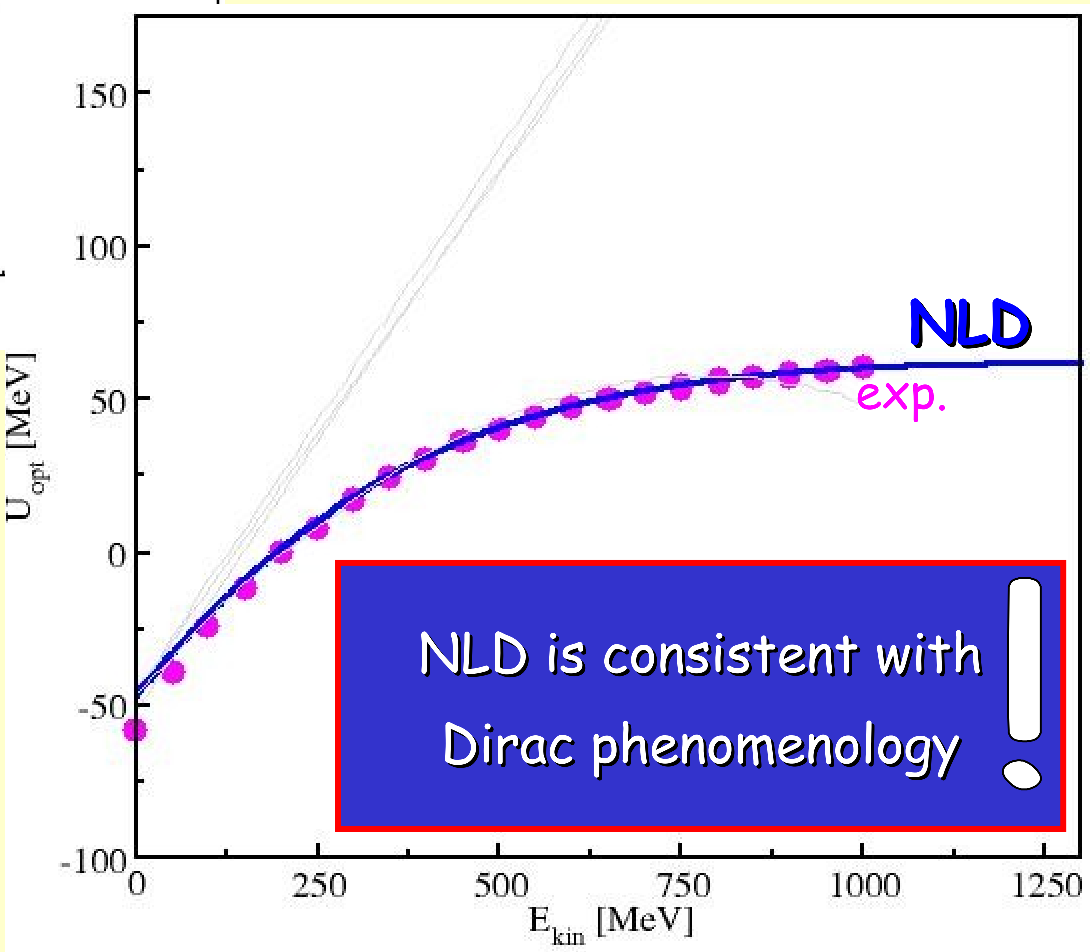


high ρ → high momenta

In-medium proton SEP (real part)



NLD is consistent with Dirac phenomenology !

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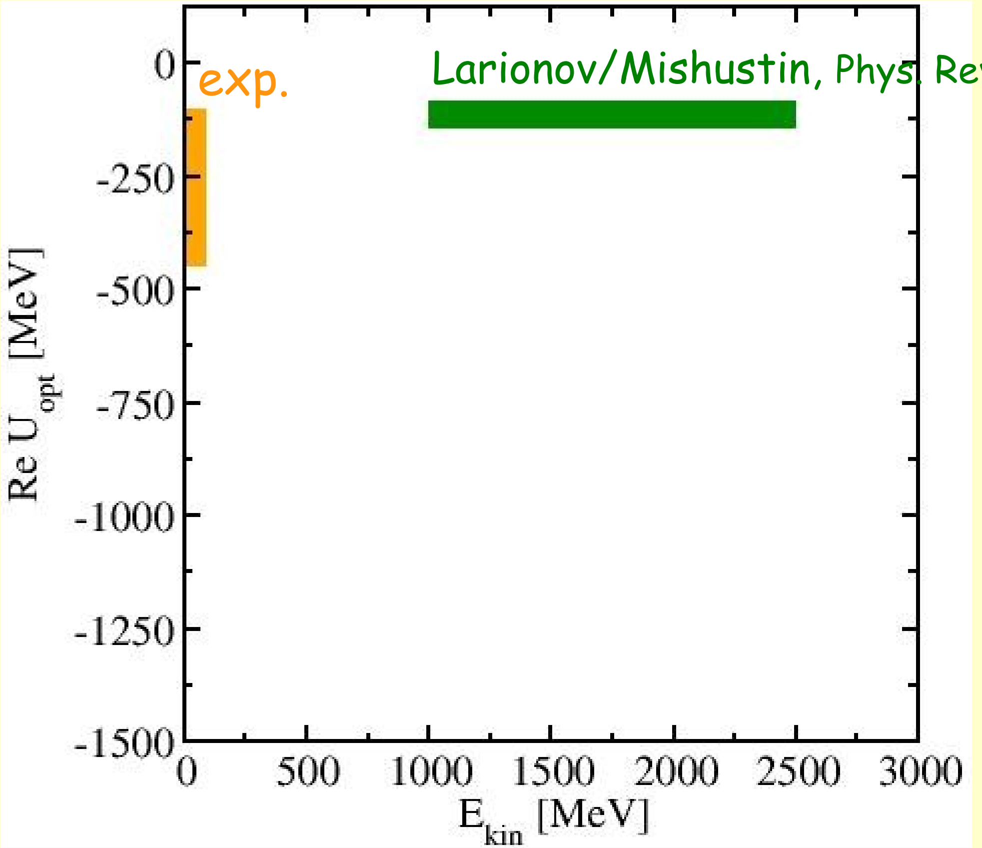
NLD results: MD & optical potentials (anti-proton)...

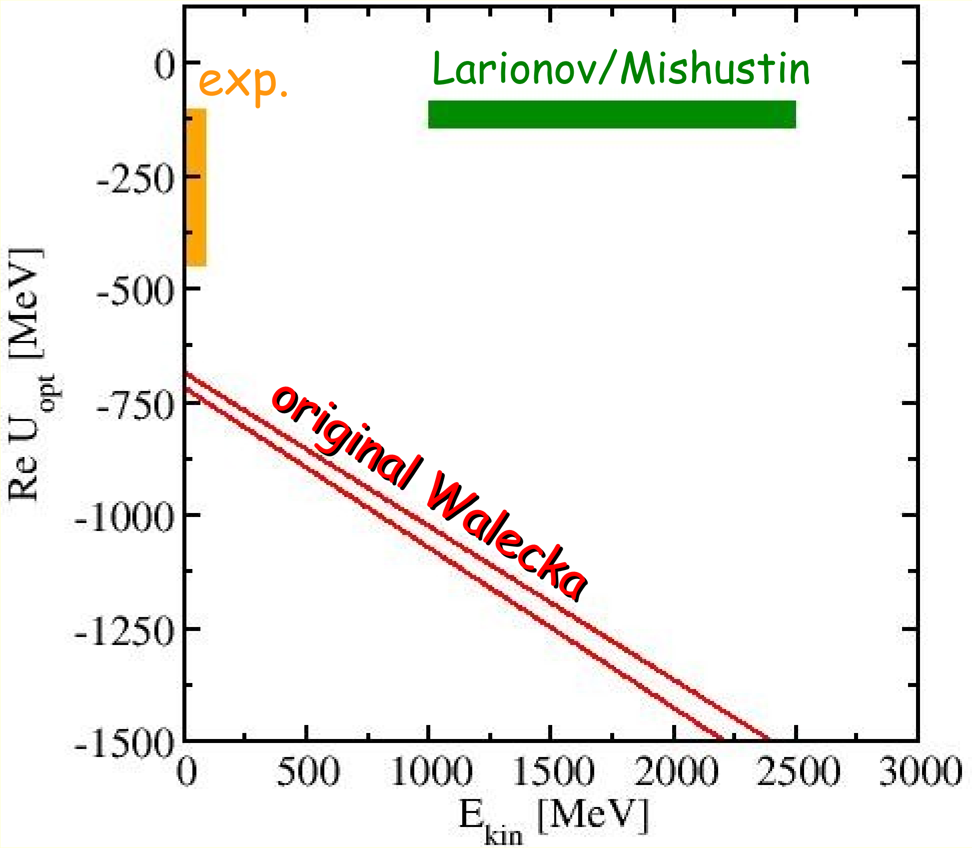
In-medium anti-proton SEP (real part)



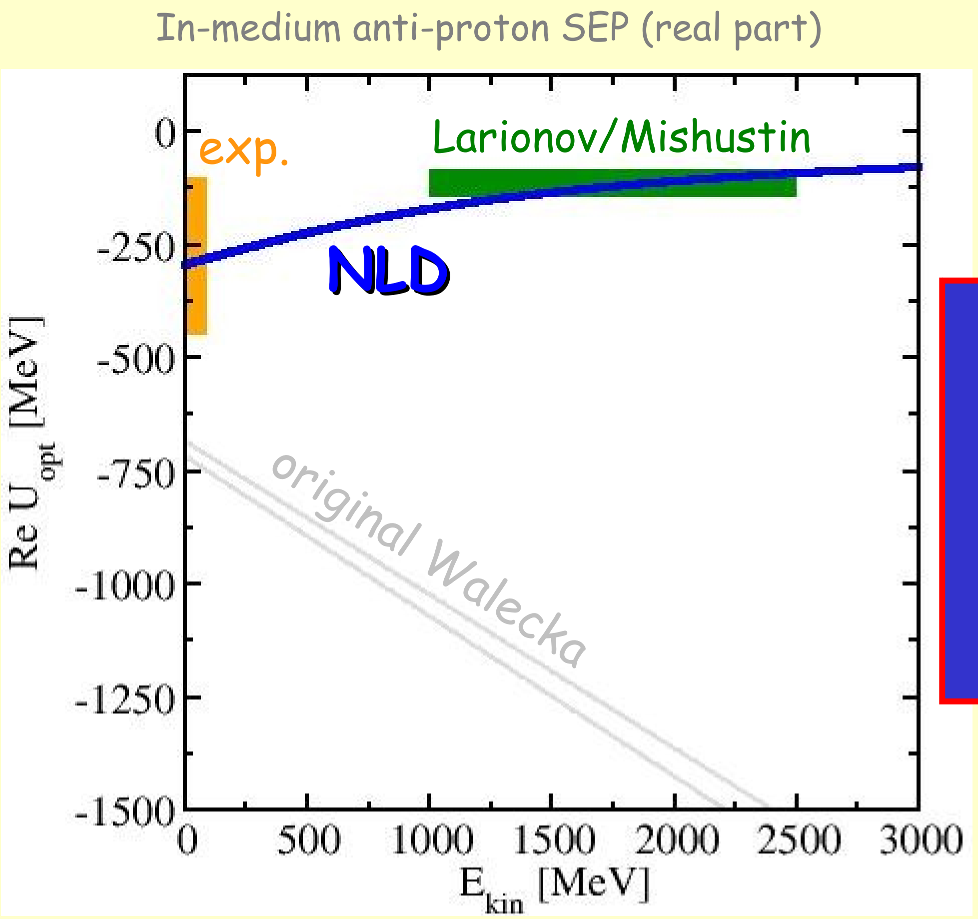
Larionov/Mishustin, Phys. Rev. C80 ('09) 021601(R).

NLD results: MD & optical potentials (anti-proton)...

In-medium anti-proton SEP (real part)



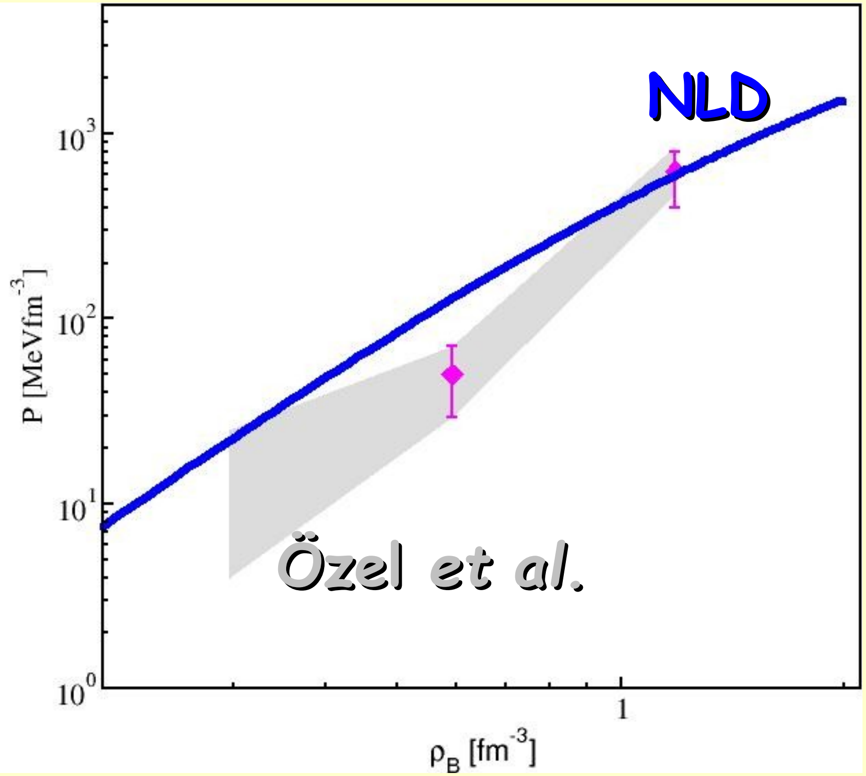
NLD results: MD & optical potentials (anti-proton)...



good description of phenomenology
also for in-medium
anti-proton interaction !

Also: NLD provides the imaginary part of SEP for anti-proton in-medium interactions using dispersion relation (without subtractions) → **Phys. Lett. B703, ('11) 193**

NLD results: high-density EoS at β-equilibrium...



Consistent with analyses of F. Özel..!
Phys. Rev. **D82**, 101301 (2010).

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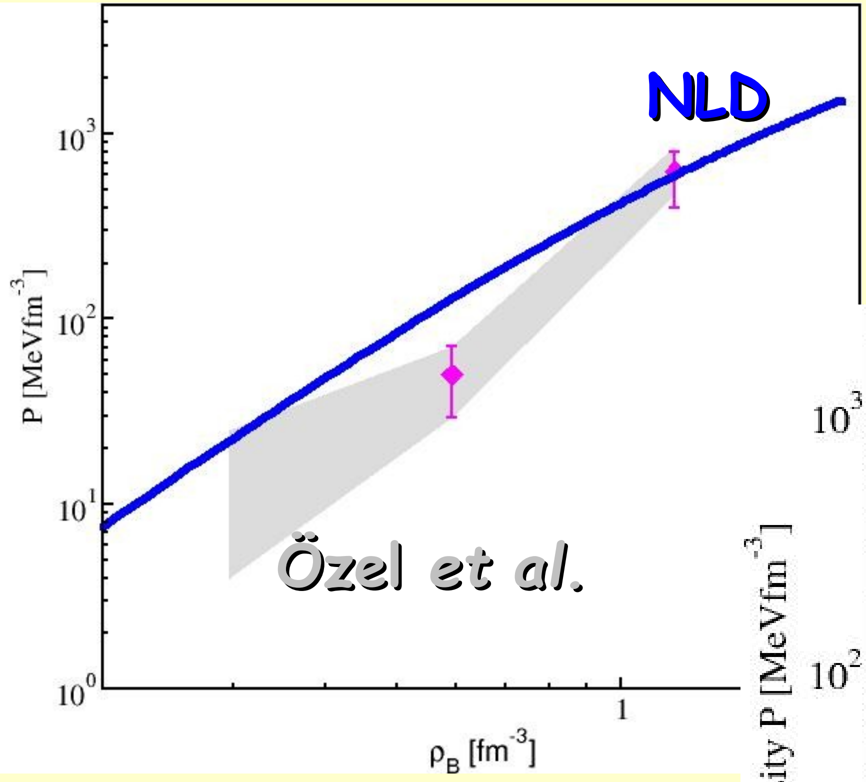

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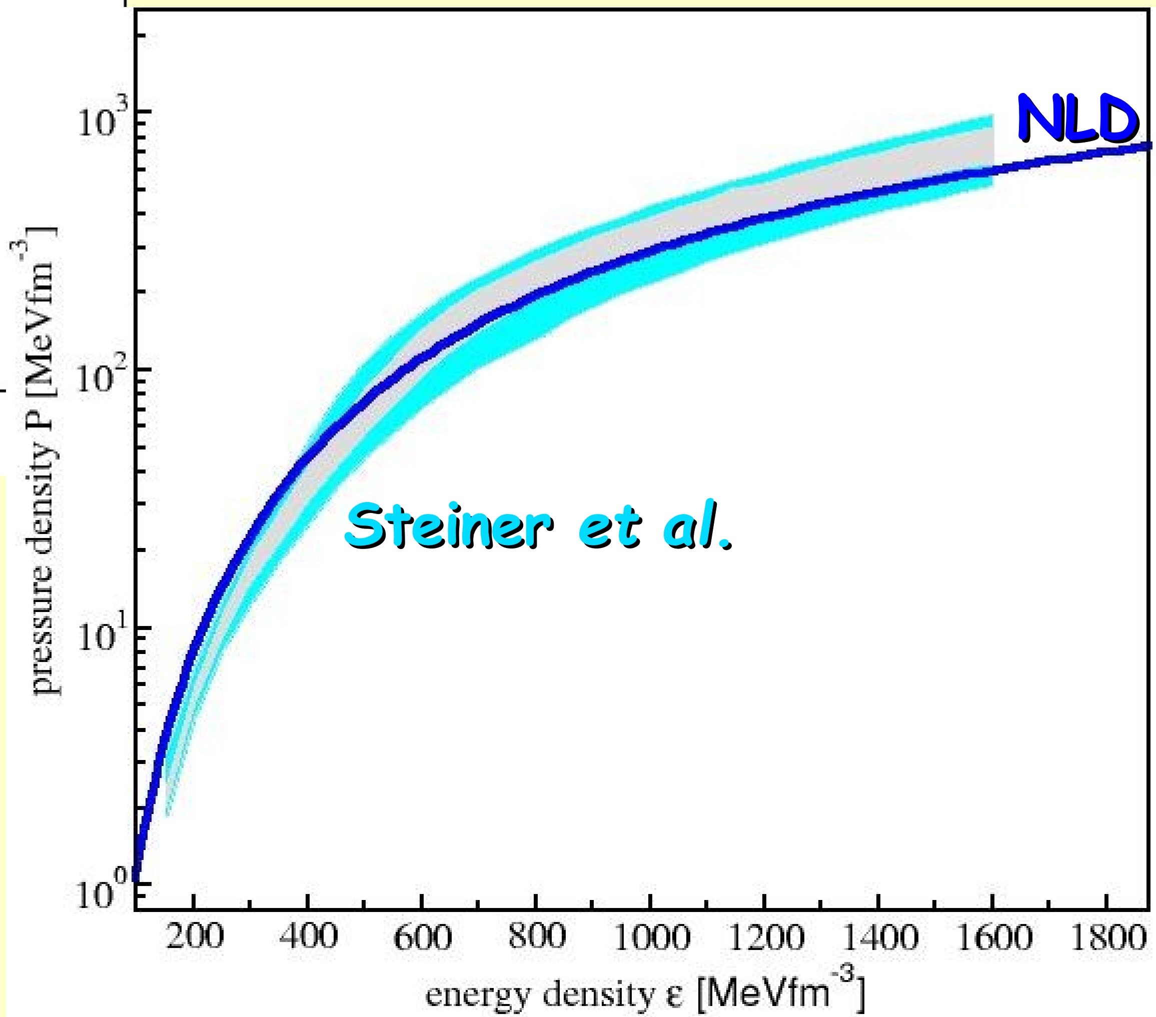

… and A.W. Steiner !
Astrophys. J. 722, 33 (2010).

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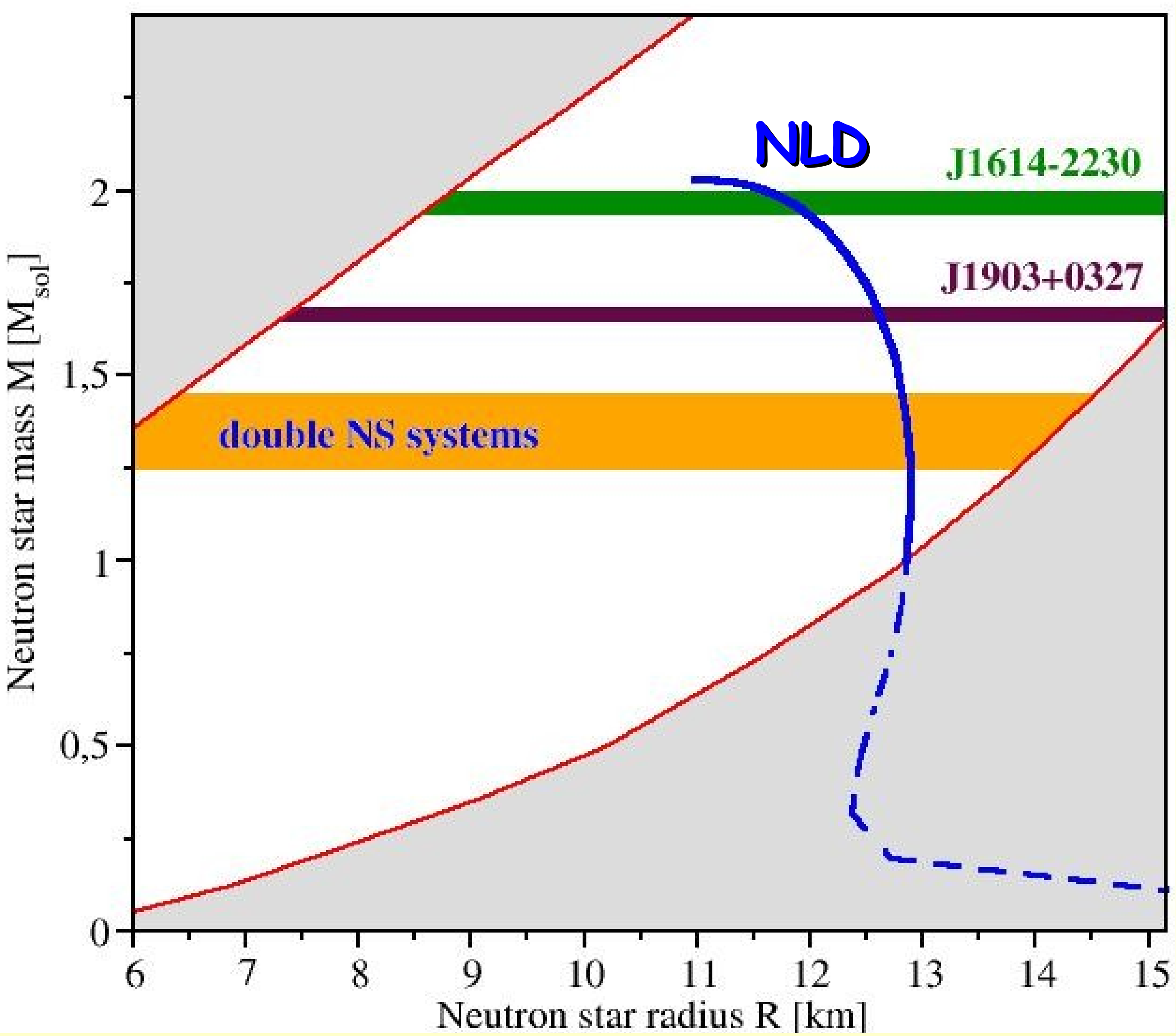
NLD results: NS mass…

Compatible with …

Lattimer/Prakash, Science 304 ('04) 536, Phys. Rep. 442 ('07) 109



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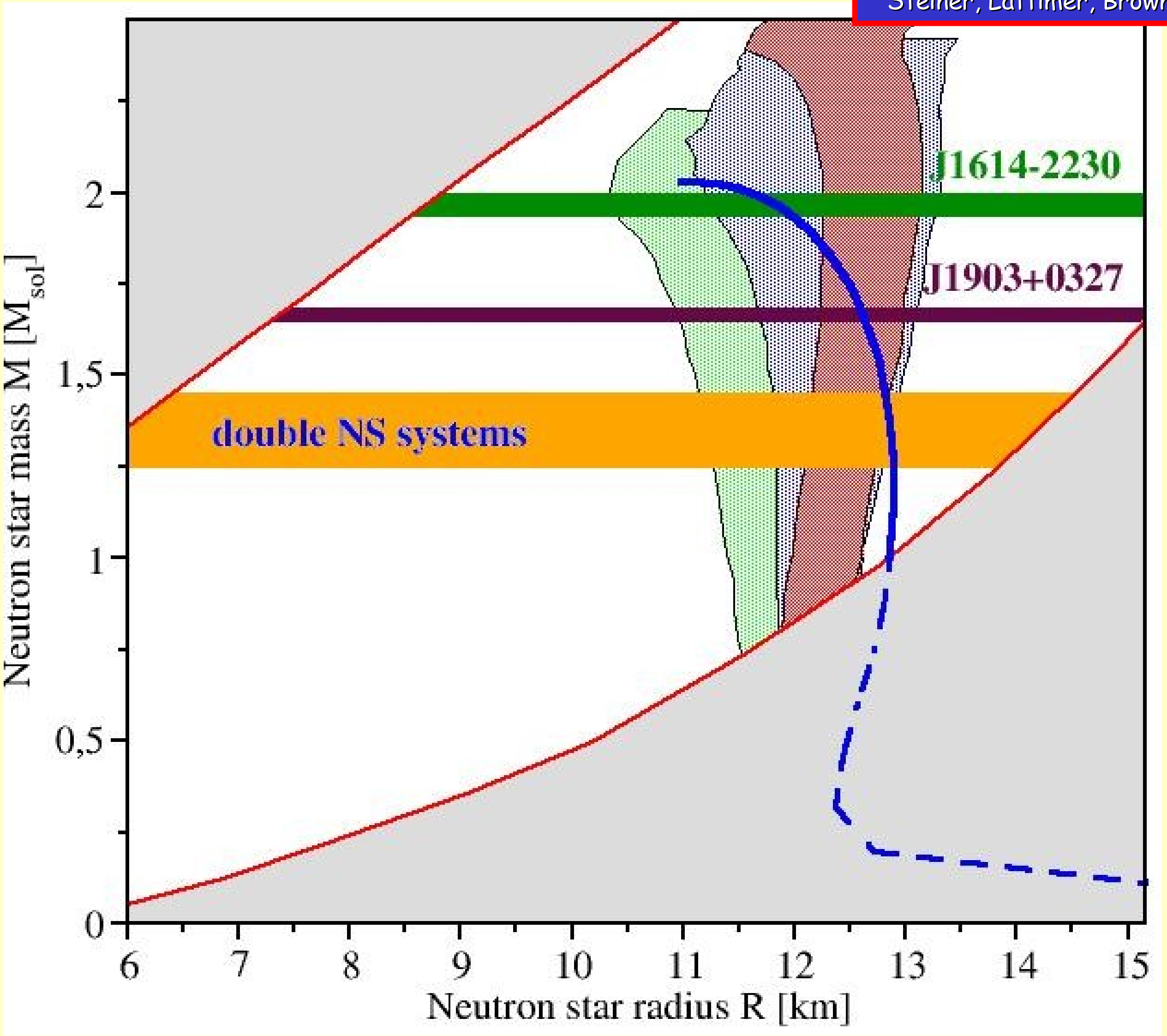
NLD results: NS mass...

Compatible with all observations !

Lattimer/Prakash, Science 304 ('04) 536, Phys. Rep. 442 ('07) 109
Steiner, Lattimer, Brown, arXiv: 1205.6871



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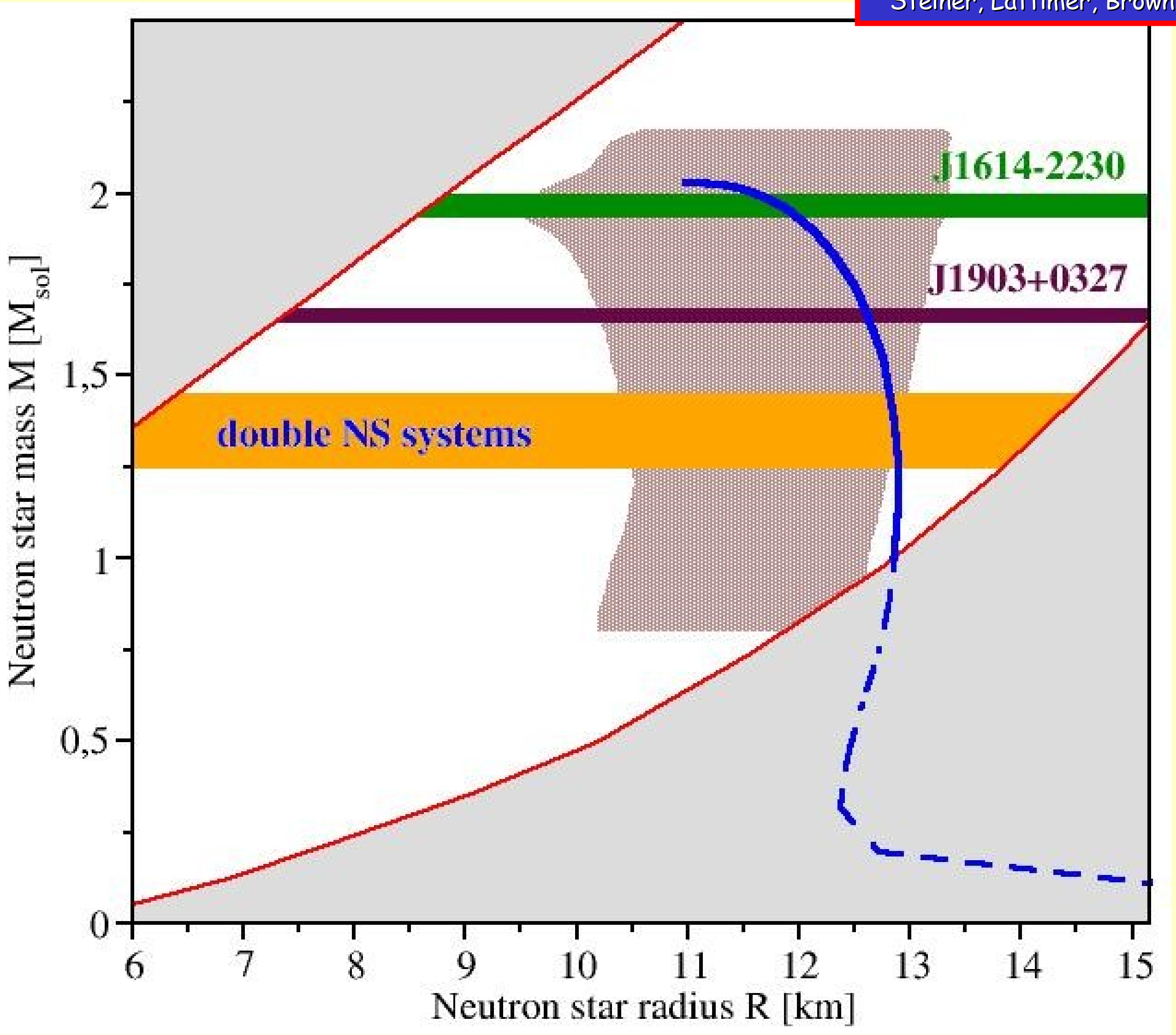

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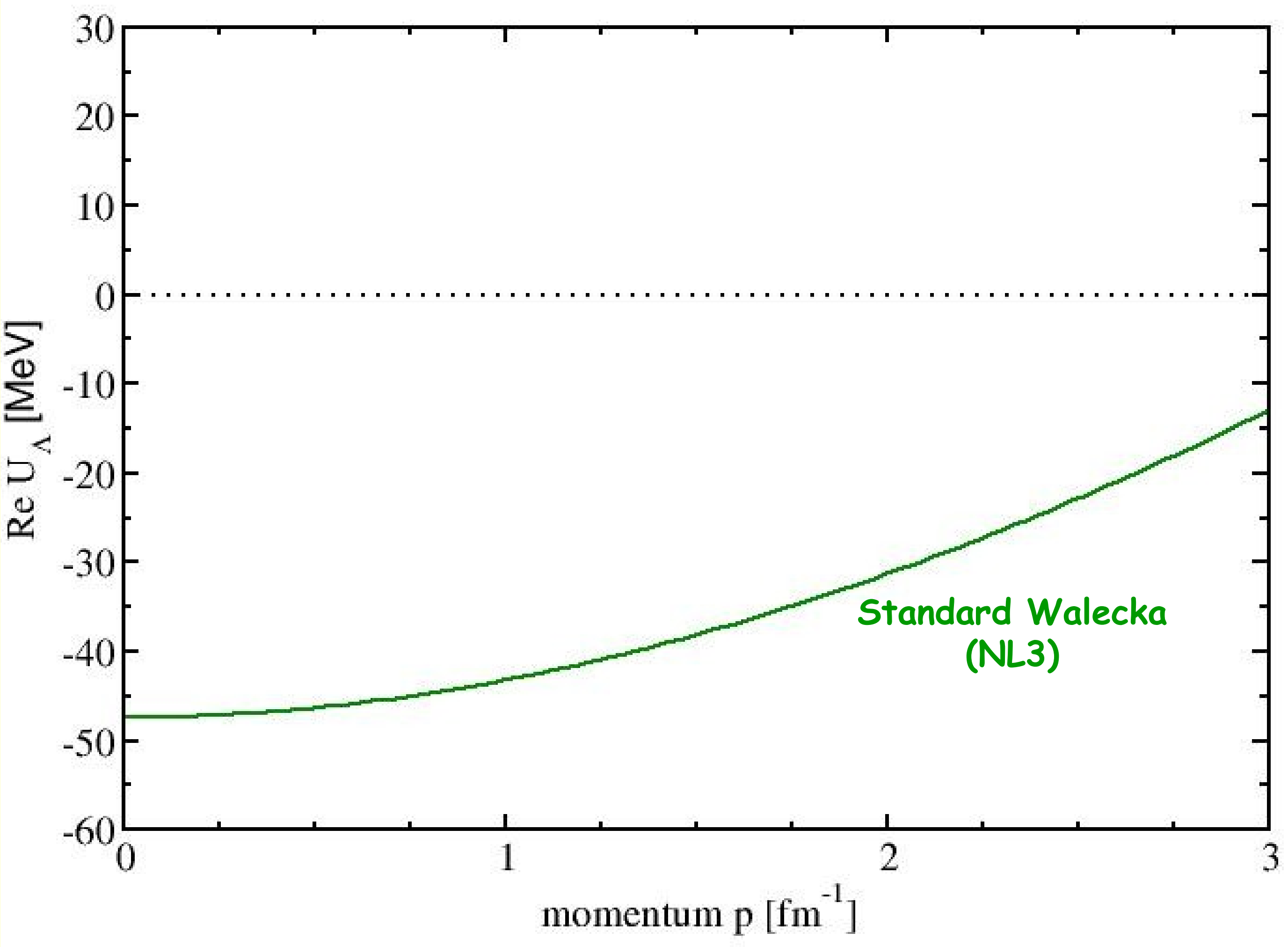
NLD results: in-medium Λ-opt. potential…

NLD + SU(3) for standard meson-nucleon couplings
Hyperon cut-off regulates MDI



Gaitanos & Violaris, in prep.

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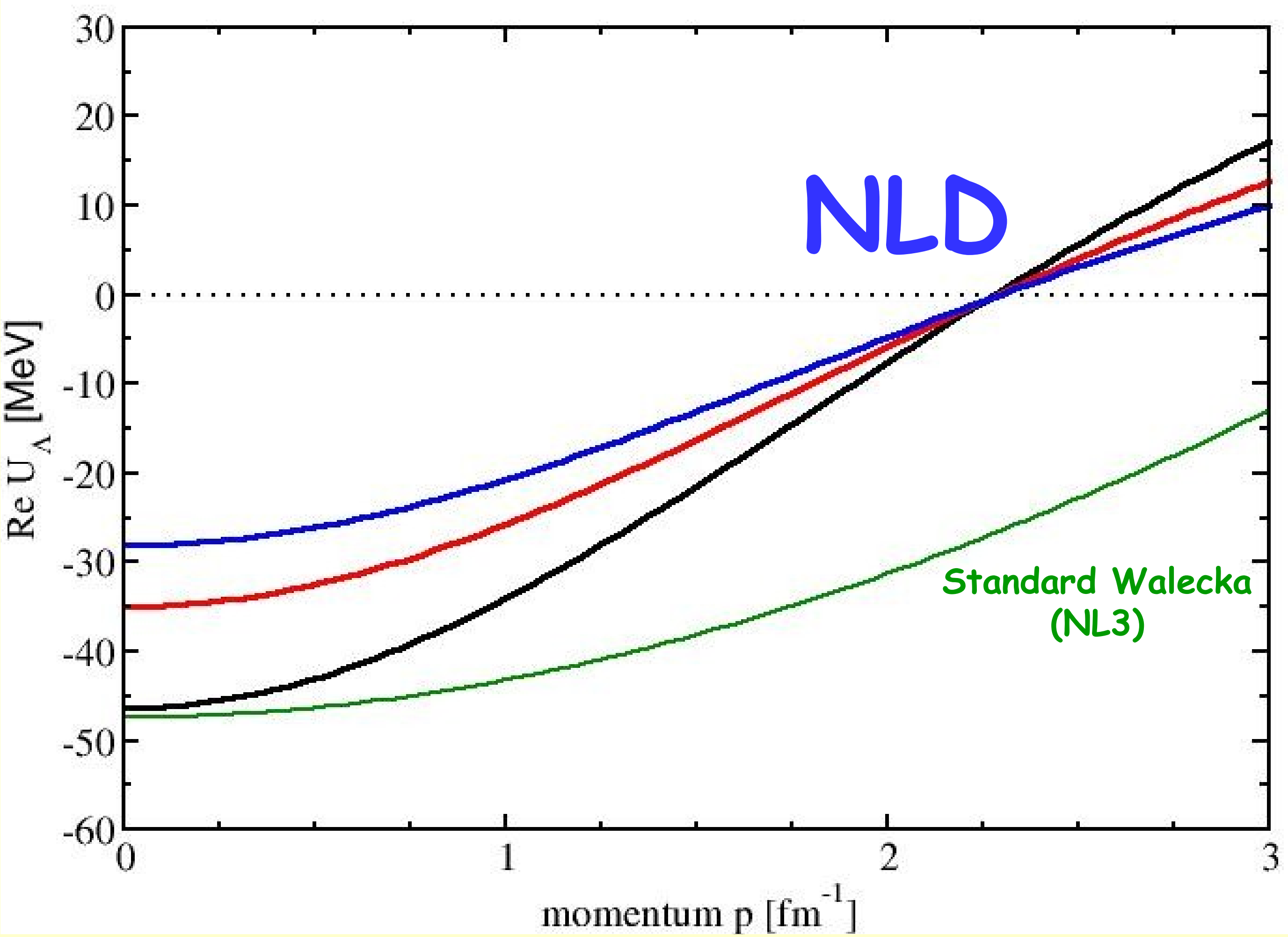

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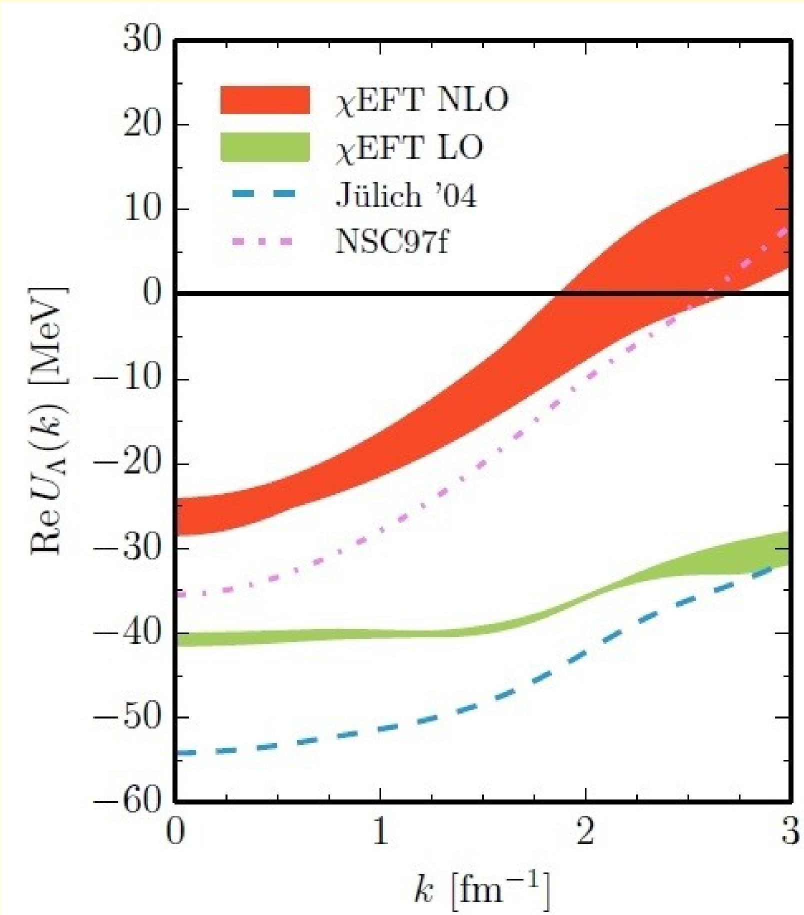
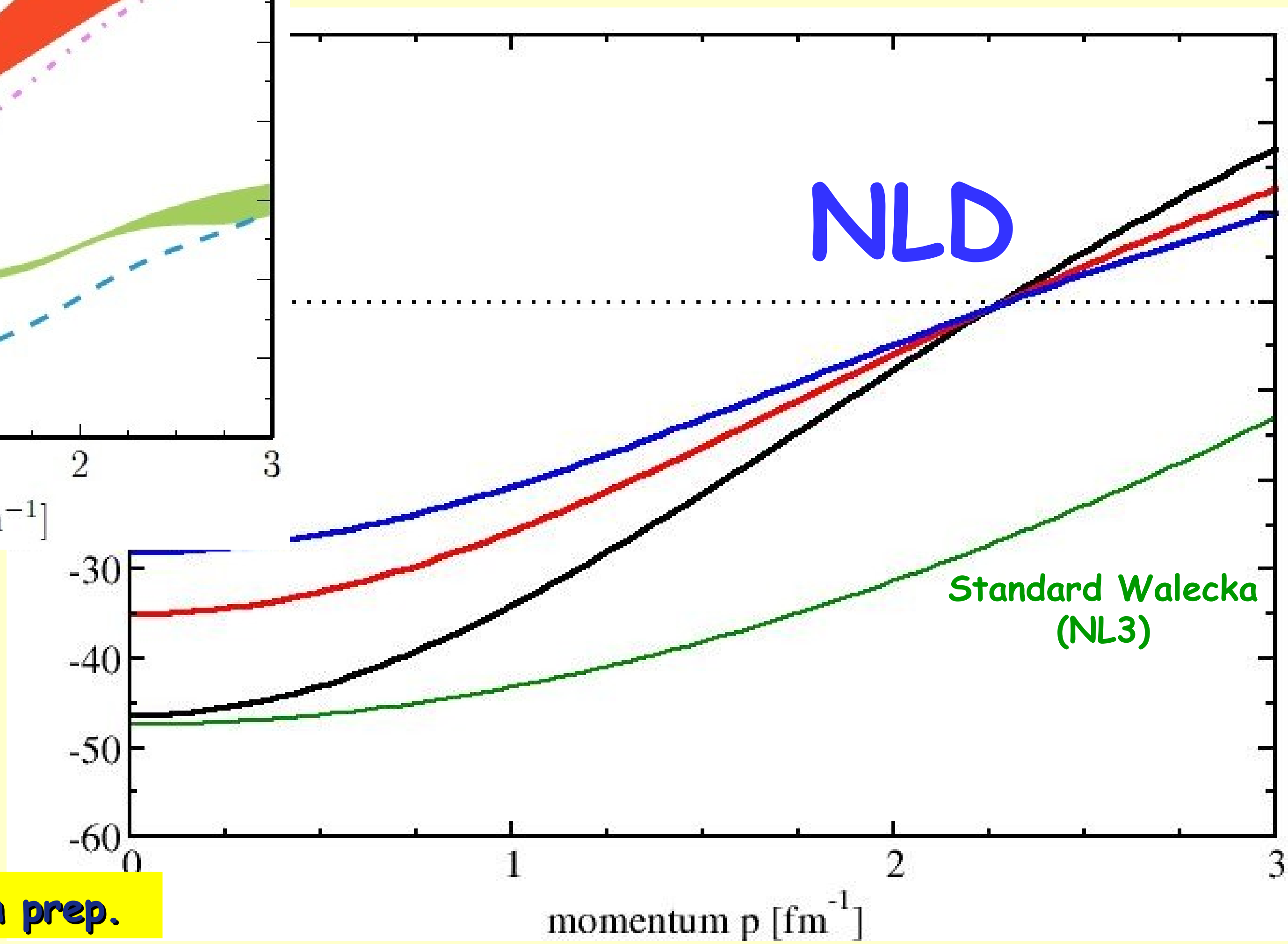


NLD versus chiral-EFT (Haidenbauer, et al., EPJA52 (16) 15)

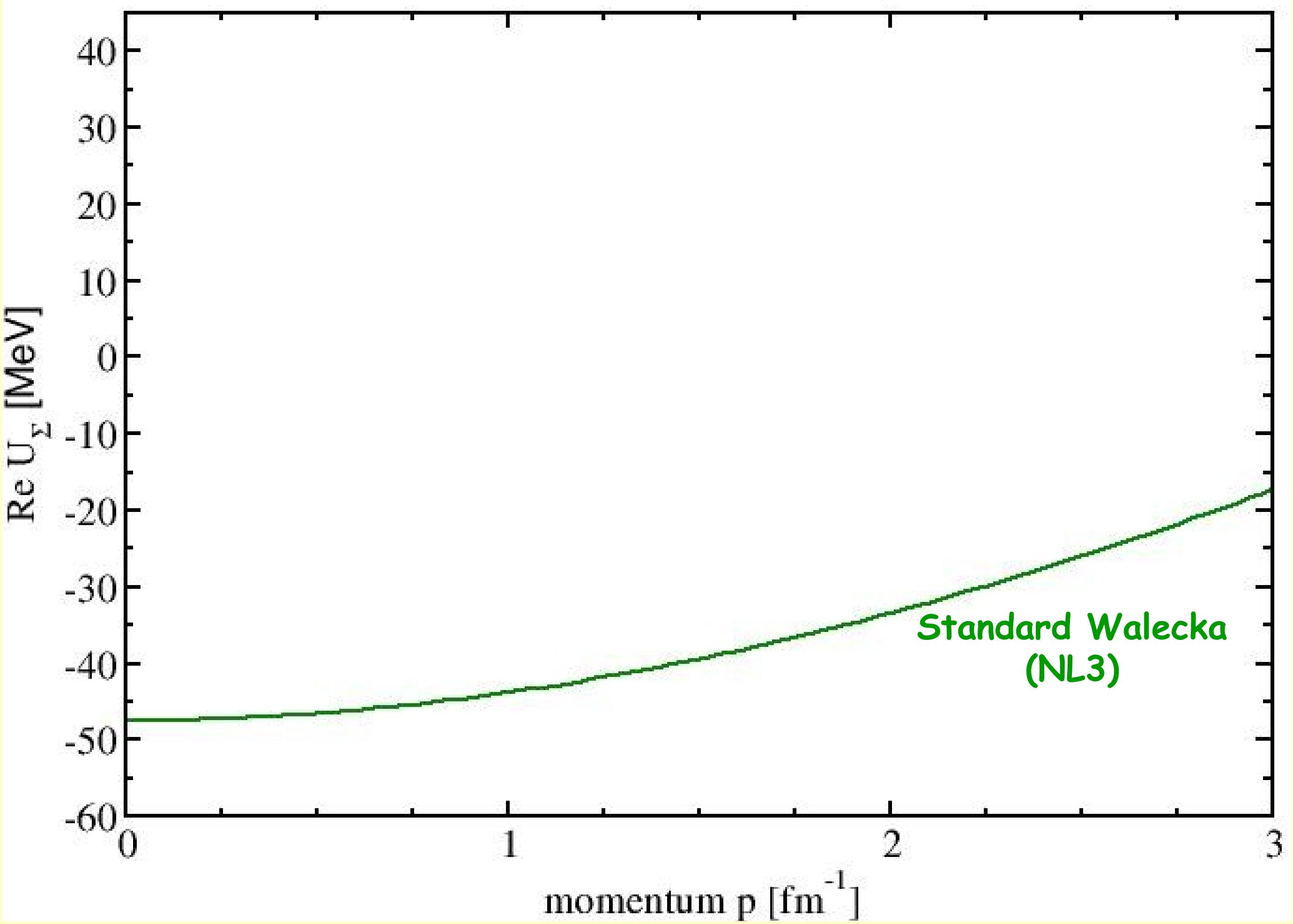
Compares well with NLO-calculations
(cut-off Λ=0.7 & 1 GeV for σ & ω)



Gaitanos & Violaris, in prep.

NLD results: in-medium Σ-opt. potential…

Σ-opt. potential attractive in conventional RMF+SU(3)



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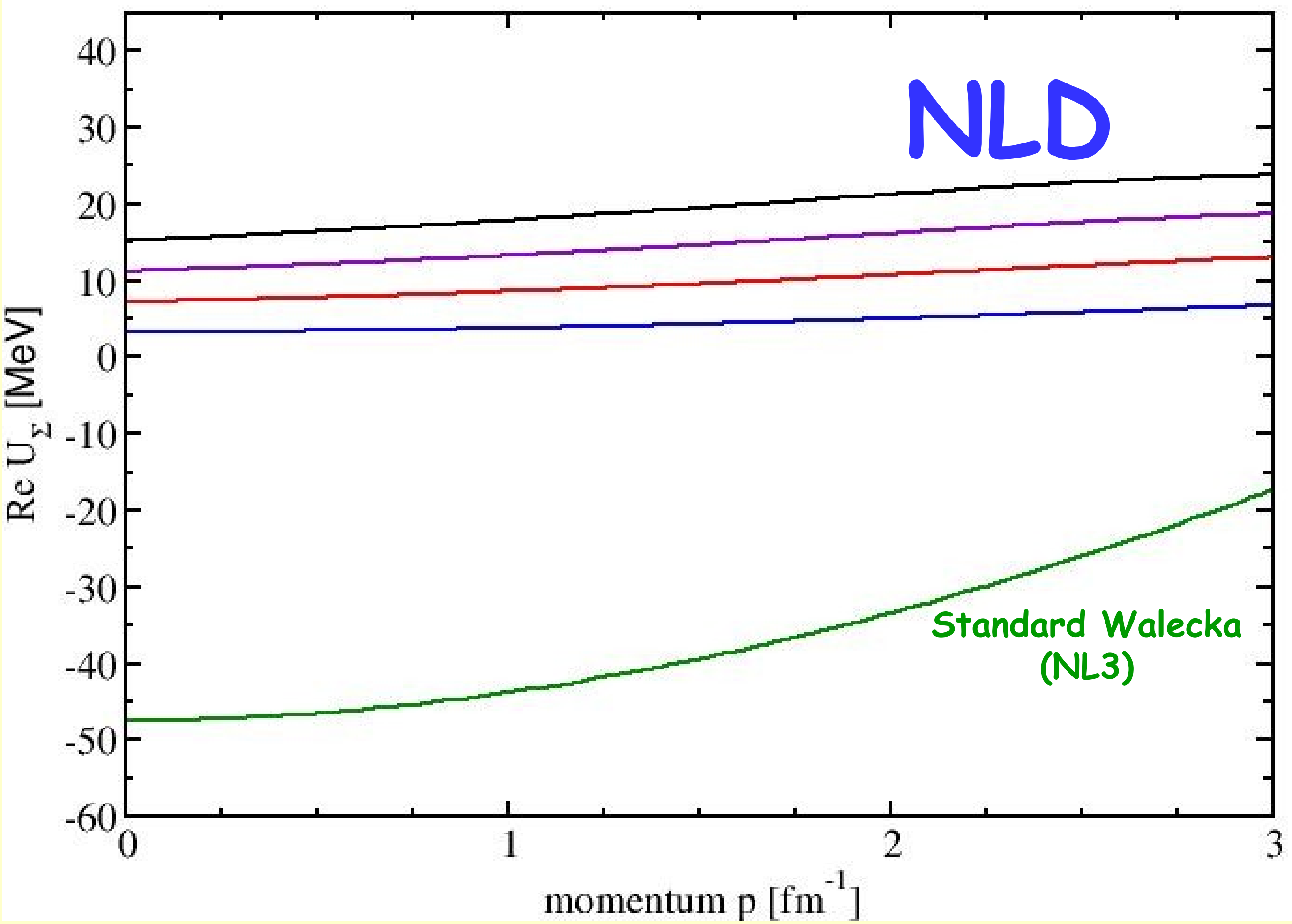
Hyperon (Σ) cut-off Λ in NLD induces repulsion!



Gaitanos & Violaris, in prep.

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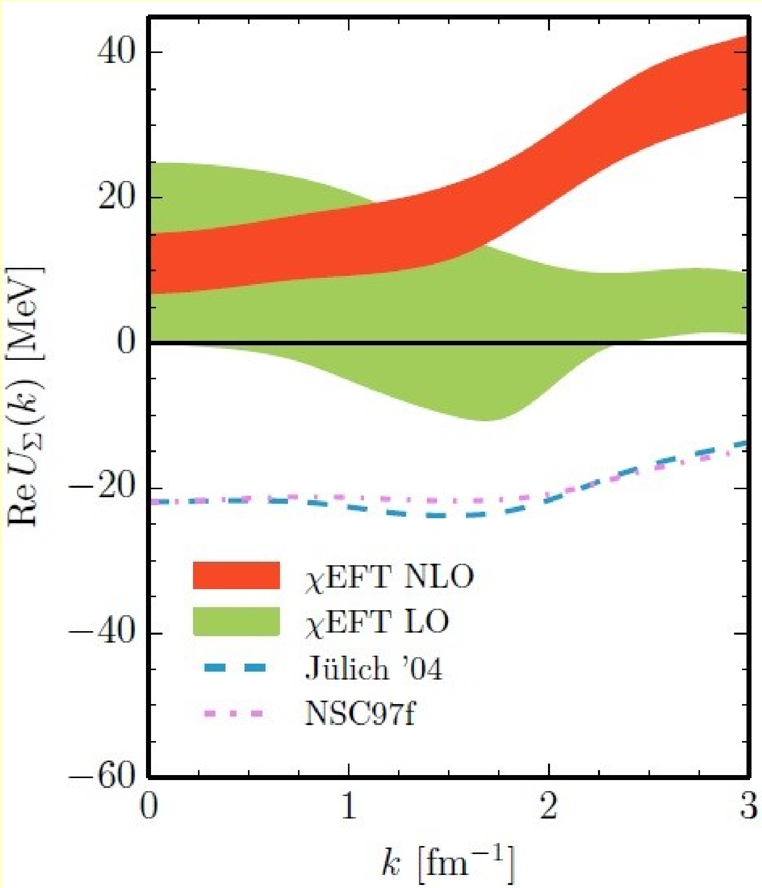
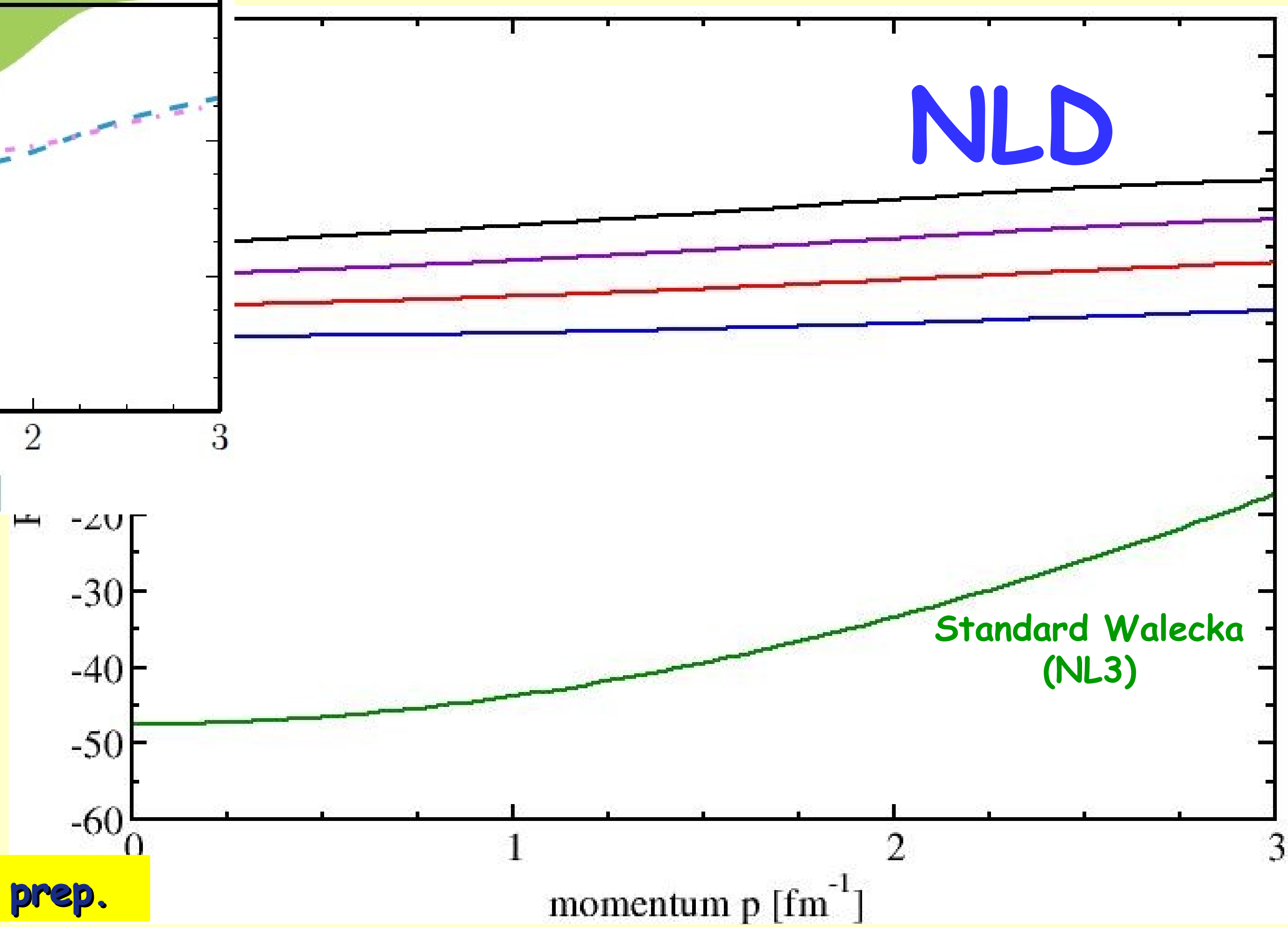
Σ-opt. potential attractive in conventional RMF+SU(3)

Hyperon (Σ) cut-off Λ in NLD induces repulsion
in good agreement with chiral-EFT





Gaitanos & Violaris, in prep.

Final remarks & outlook...

- **NLD model**

→ keeping simplicity (RMF) to describe complexity (**non-linear ρ & p dependences)**

→ realized by covariant introduction of regulators on a Lagrangian level

→ in RMF: cut-off Λ regulates high ρ- & p-components of mean-fields

→ cut-off Λ regulates also p-dependence of hyperon opt. pot.!

- **NLD Results**

→ EoS soft at low ρ (K~250 MeV), but stiff at high ρ
remarkable agreement with microscopic DBHF

→ Correct MD for in-medium proton (!) and (!) antiproton interactions

→ compatible with all recent observations of high-ρ EoS & NS

→ compatible with recent results from chiral-EFT for hyperons in matter

- **Future/under progress developments**

→ apply NLD to finite nuclei (done by others...)

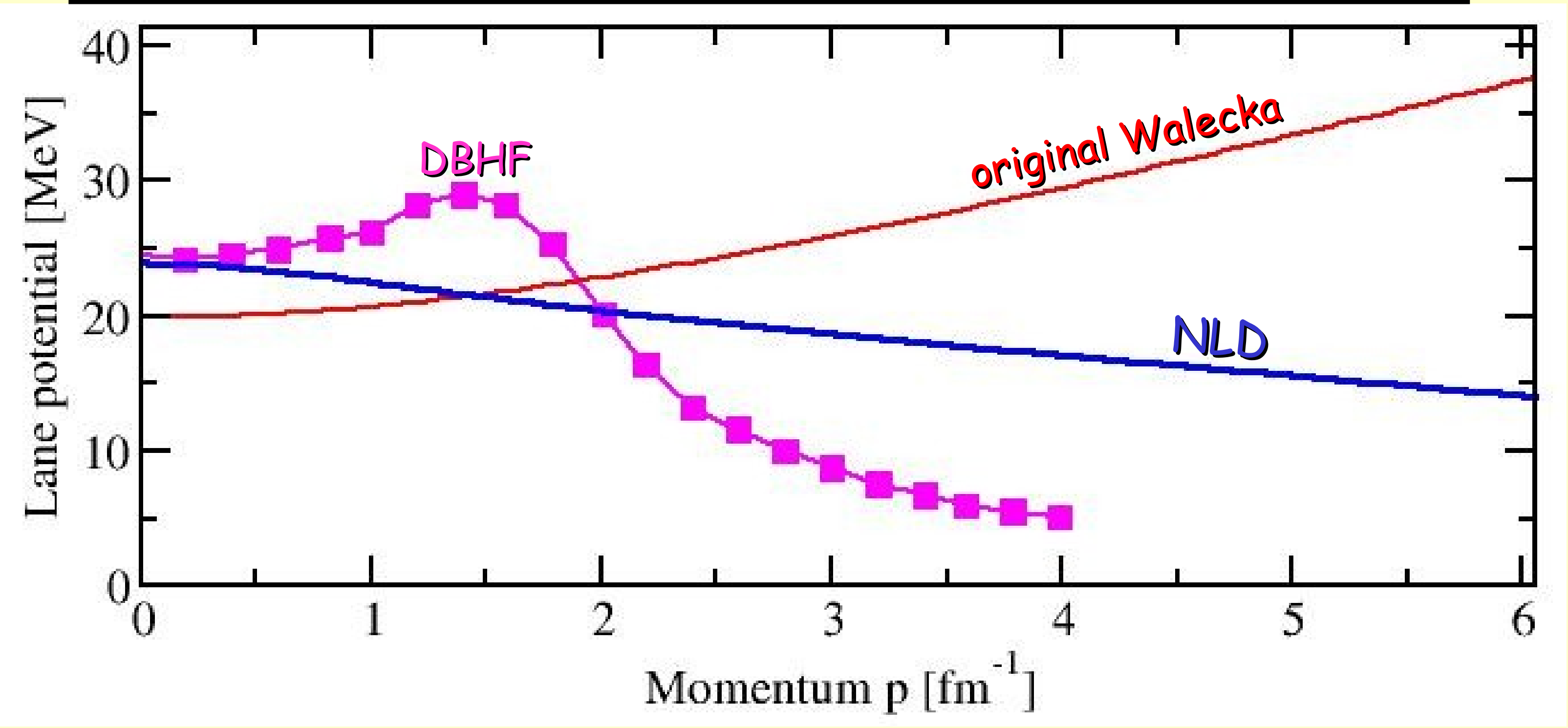
→ apply NLD to p-nucleus scattering in Eikonal approx. (done, it works)

→ apply NLD to heavy-ion collisions (under progress)

Back up slides

Asymmetric nuclear matter: (Lane) optical potential…

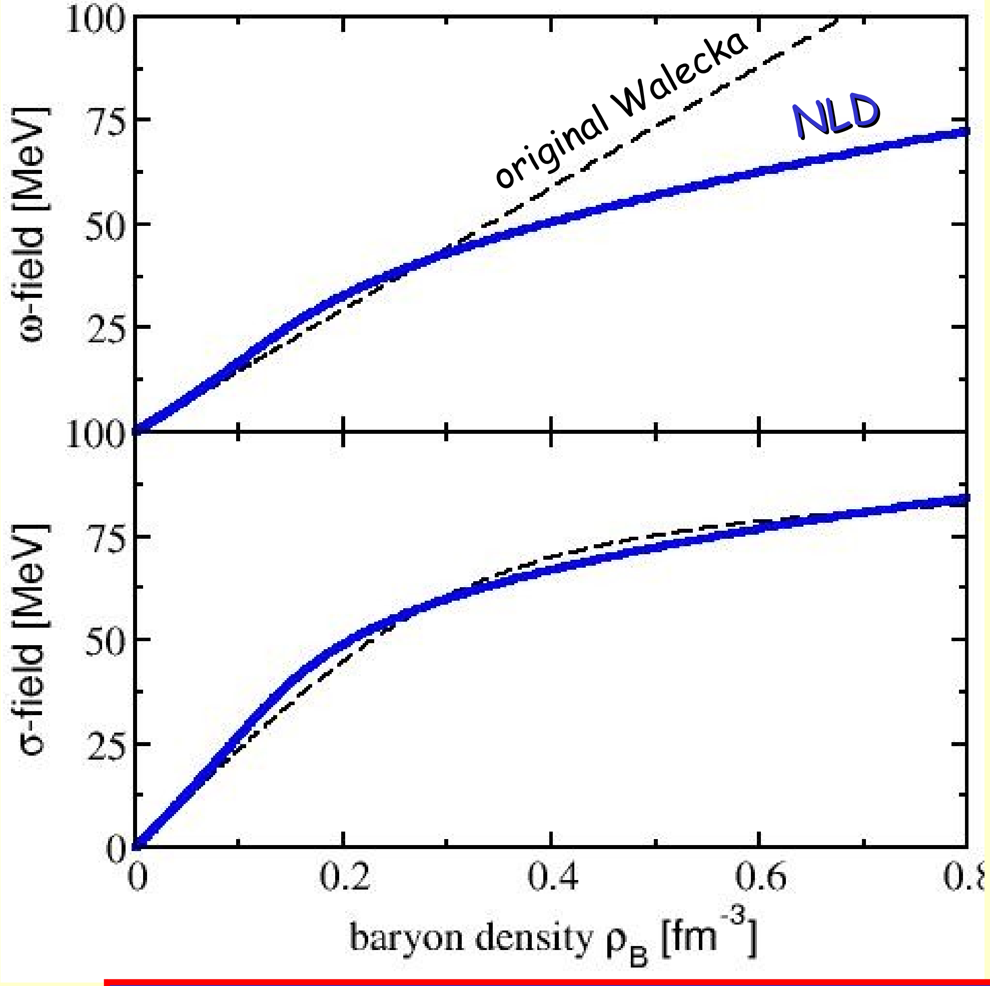
$$U_{\text{lane}} = (U_{\text{opt,n}} - U_{\text{opt,p}})/(2\alpha), \; U_{\text{opt}} = \frac{E}{m}\Sigma_v - \Sigma_s + \frac{1}{2m}\left(\Sigma_s^2 - \Sigma_v^2\right)$$



NLD (Λ=0.770 GeV)

Consistent with microscopic DBHF

Nuclear matter: NLD meson fields (density dependence)...



$$\omega \sim \rho_0 = \frac{\kappa}{(2\pi)^3} \int_{p<p_F} d^3p \, e^{-\frac{E-m}{\Lambda}}$$

NLD ω field

increasing NL damping with density !

$$\sigma \sim \rho_s = \frac{\kappa}{(2\pi)^3} \int_{p<p_F} d^3p \left(\frac{m^*}{E^*}\right) e^{-\frac{E-m}{\Lambda}}$$

NLD σ field

Scalar damping dominates...

NLD effect

Strong vector-field suppression with increasing baryon density

convergent behavior at $\rho_B \to \infty$!