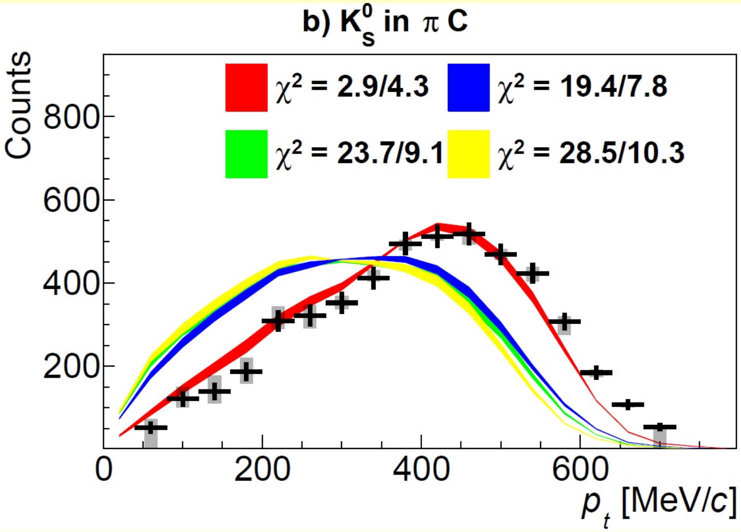
First test for hyperon potentials & implications to neutron star matter

Theodoros Gaitanos

ΤΜΗΜΑ ΦΥΣΙΚΗΣ

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ



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DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

HADES

HIC for FAIR Helmholtz International Center

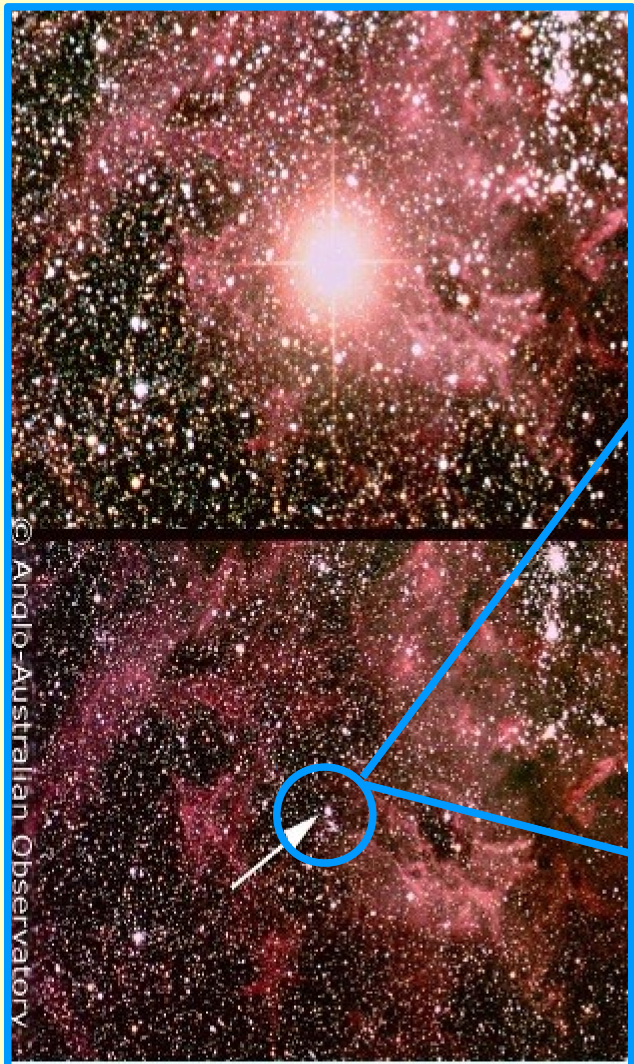
Tübingen, 15.11.19

Introduction...

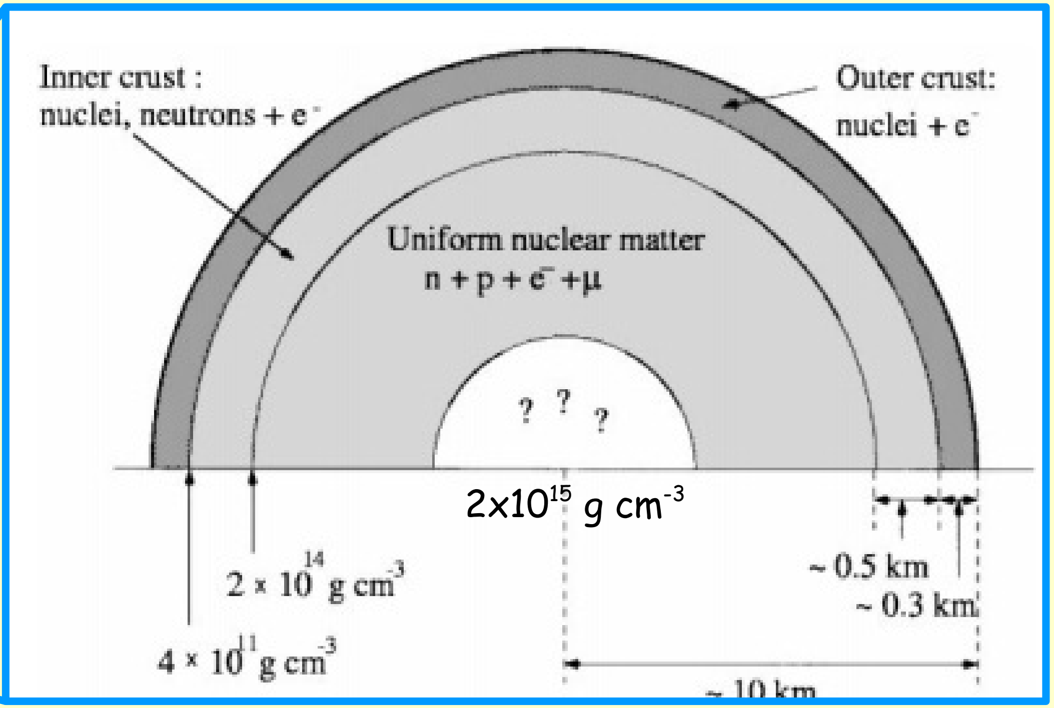
Neutron Stars (NS)

- stable "cosmic nucleus" made of p,n,e^-,...
- densest visible matter in the universe

  1.5-2 x solar mass inside **10km radius**



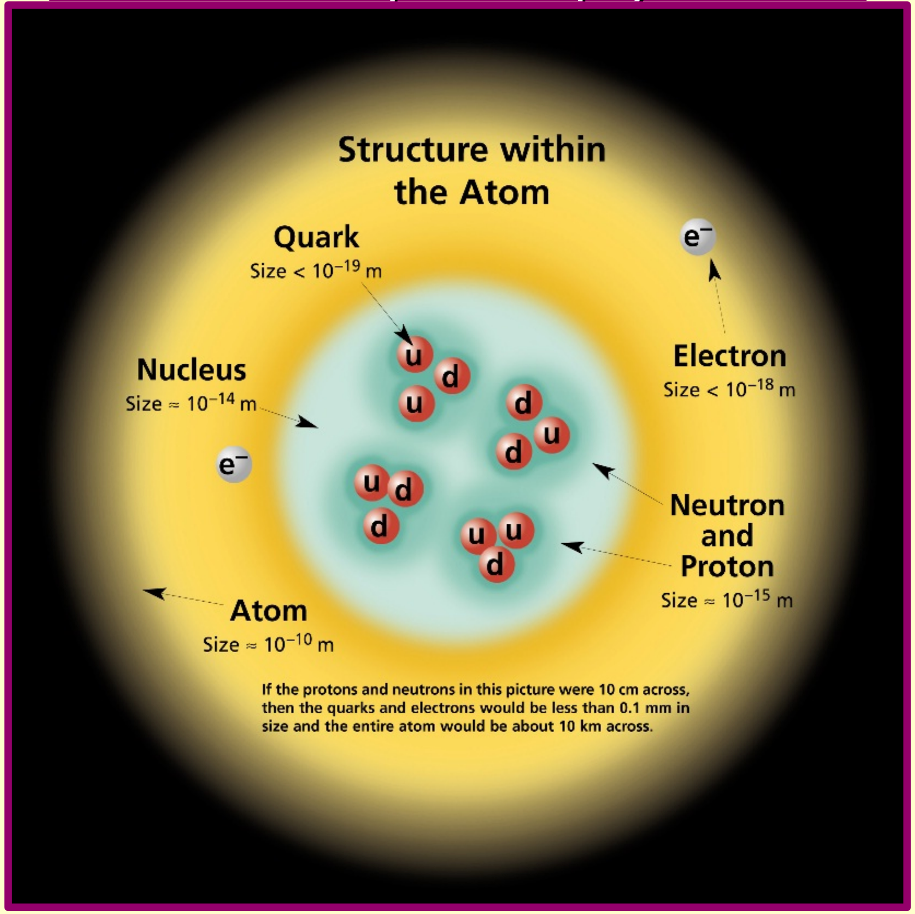
SN 1987A



earth's average density~5.5 $g\ cm^{-3}$
earth's radius ~6.371km

Introduction…

Units in particle physics



Introduction...

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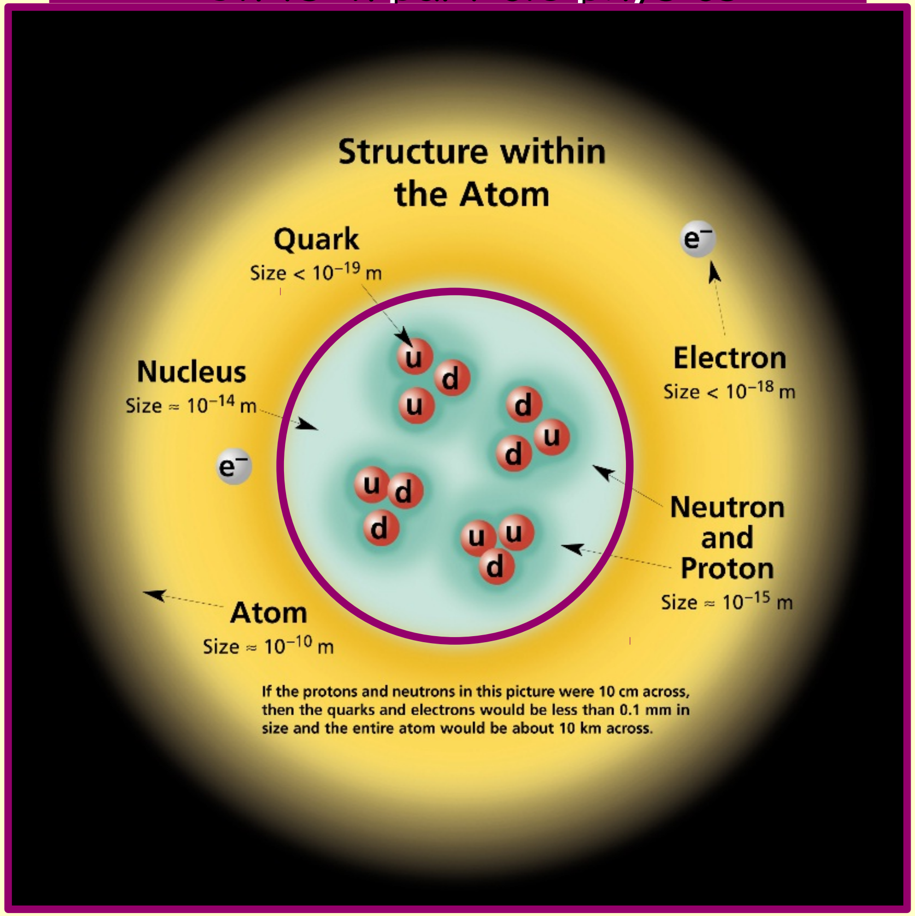


Units:

$\hbar = c = 1$

1 GeV=1.8 10^{-24} g

1 fm = 10^{-15} m

Temperature units:

[1MeV]~[10^{10}K]

nuclei:T~0MeV

(earth:T~180K-330K)

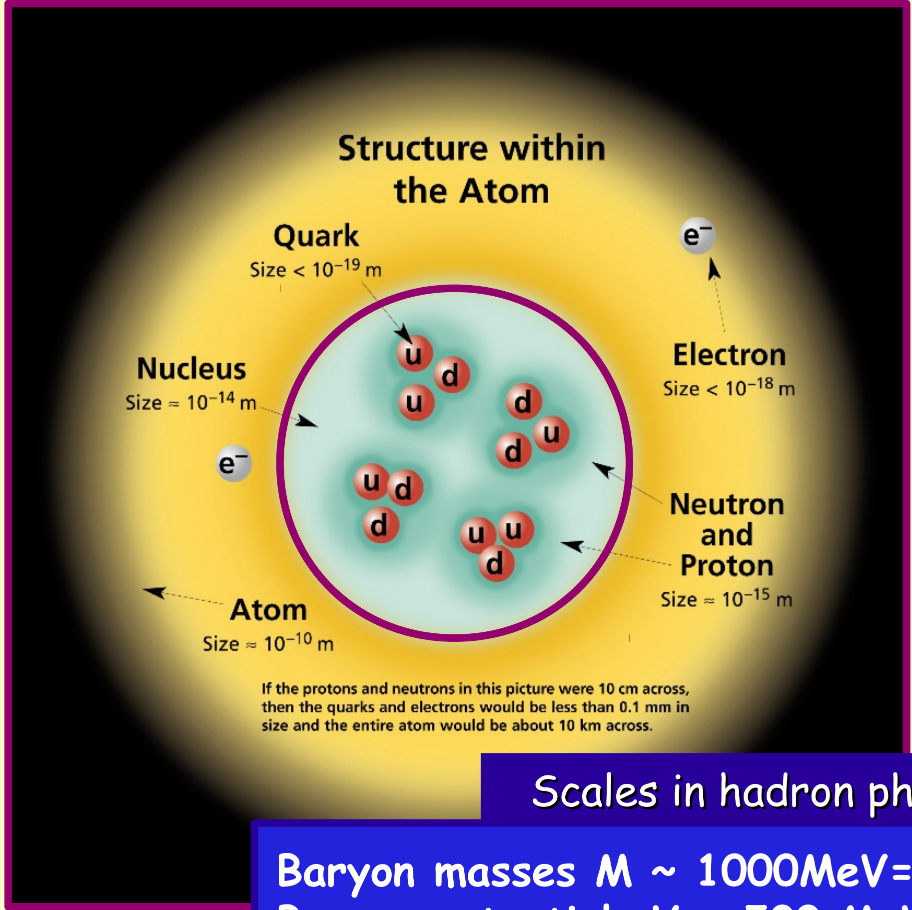
Density units:

nuclei:ρ_0 ~ 2.5 10^{14} g cm^{-3} = 0.165 fm^{-3}

(earth:ρ ~ g cm^{-3})

Introduction…

Units in particle physics



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nuclei:ρ_0 ~ 2.5 10^{14} g cm^{-3} = 0.165 fm^{-3}

(earth:ρ ~ g cm^{-3})

Scales in hadron physics:

Baryon masses M ~ 1000MeV=1GeV

Baryon potentials V ~ 500 MeV (~M!)

Nuclear ground state ~ 8 MeV (small number!)

That means for us…

T~1MeV is a cold relativistic system

T~50MeV is a rather hot relativistic system

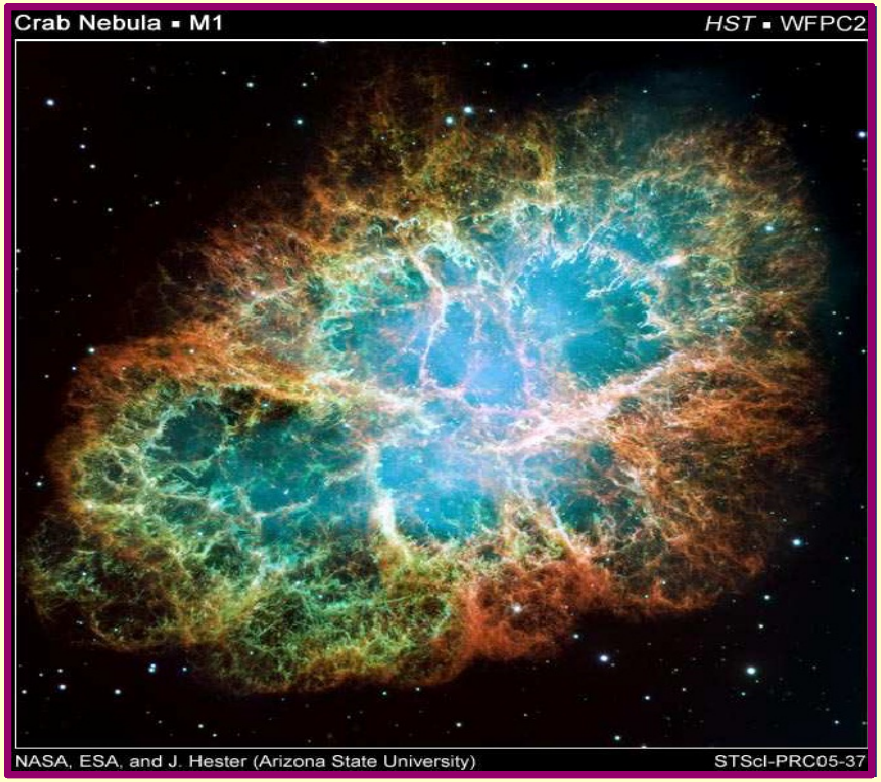
→ static neutron stars are cold objects

→ neutron star binaries can be cold/hot

Introduction…

explore astrophysics…

- Properties of low/high density warm matter (supernovae, neutron stars)



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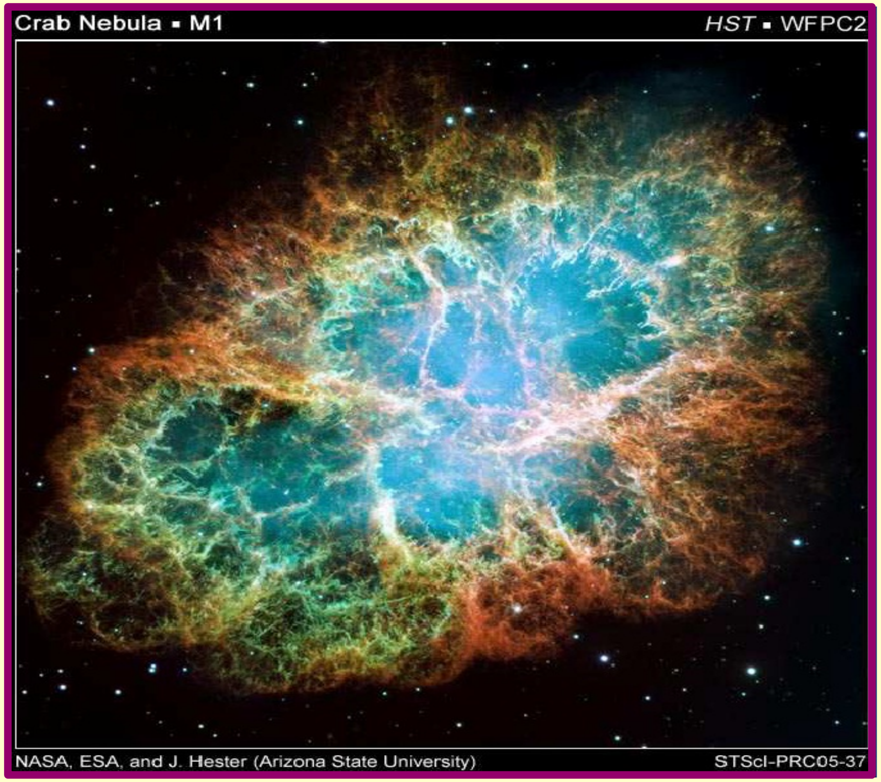
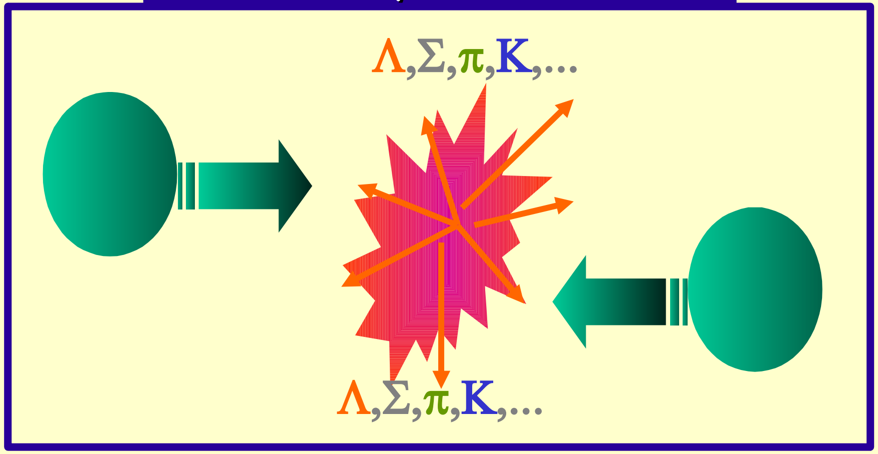
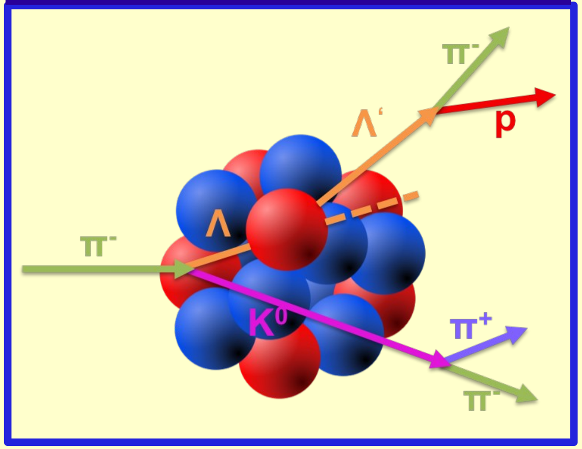


…in the laboratory

HIC: Heavy-Ion Collisions

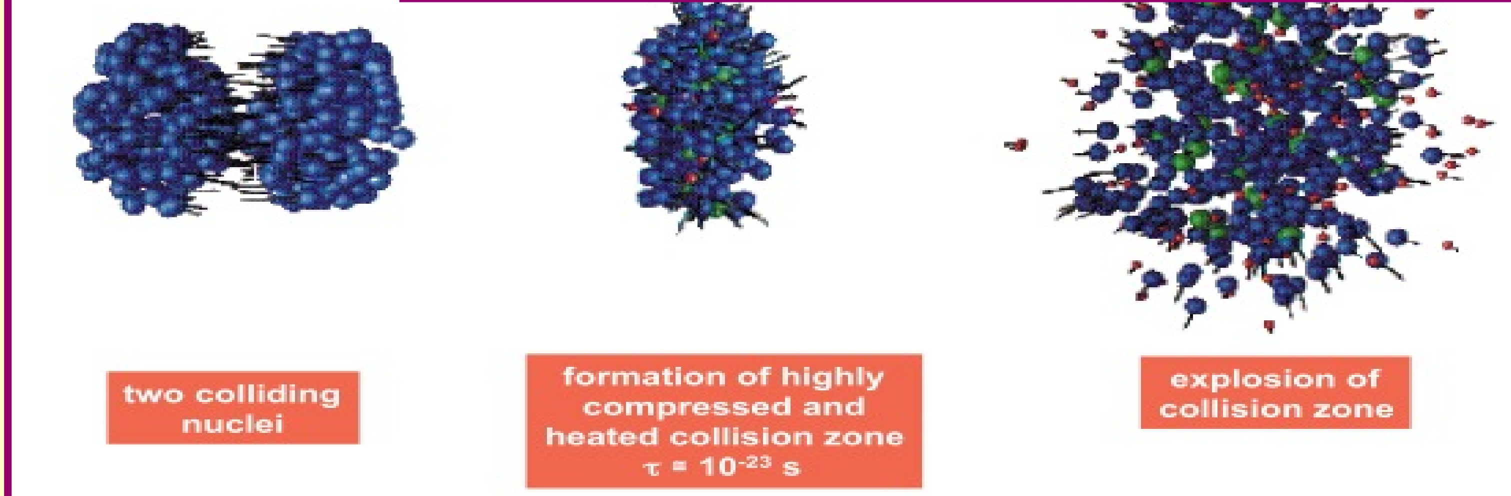


Hadron-induced reactions

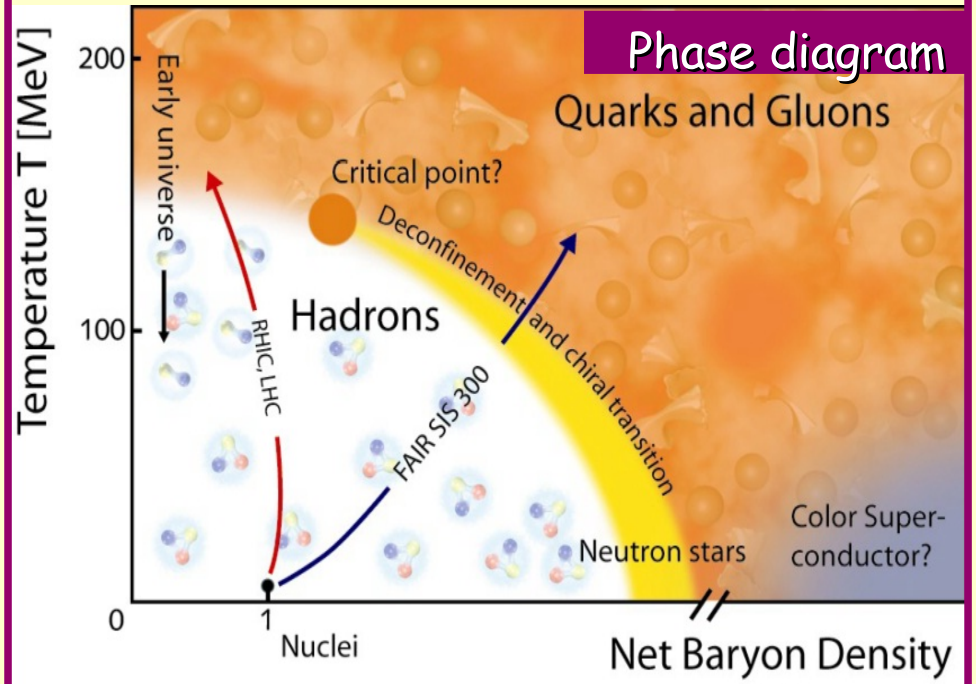


Introduction…

Cosmic matter in the Lab: Heavy-ion collisions



Phase diagram



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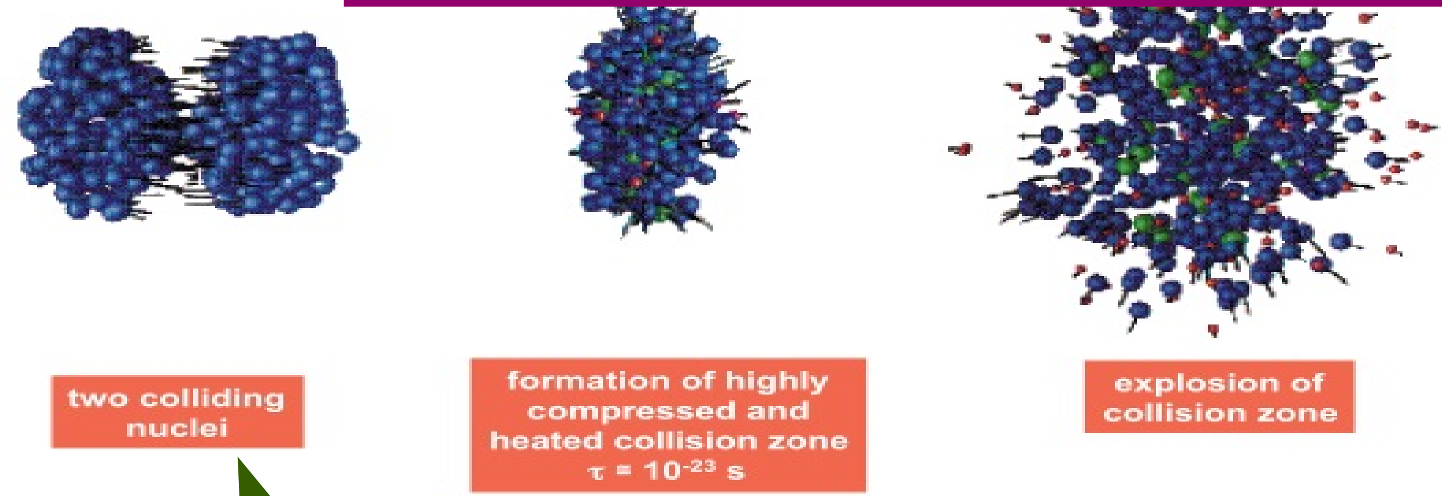

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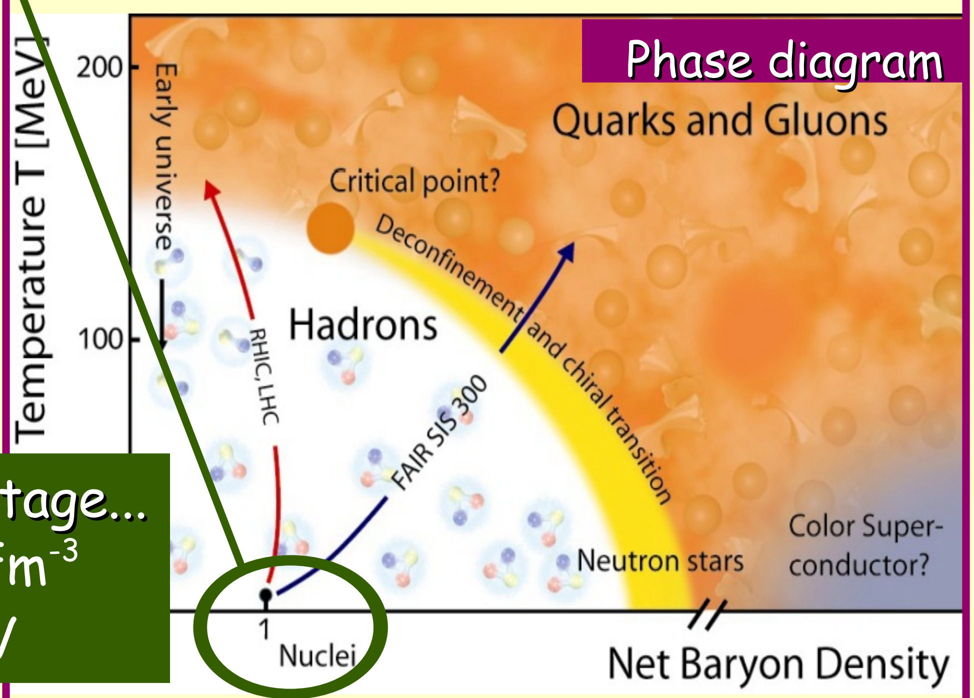
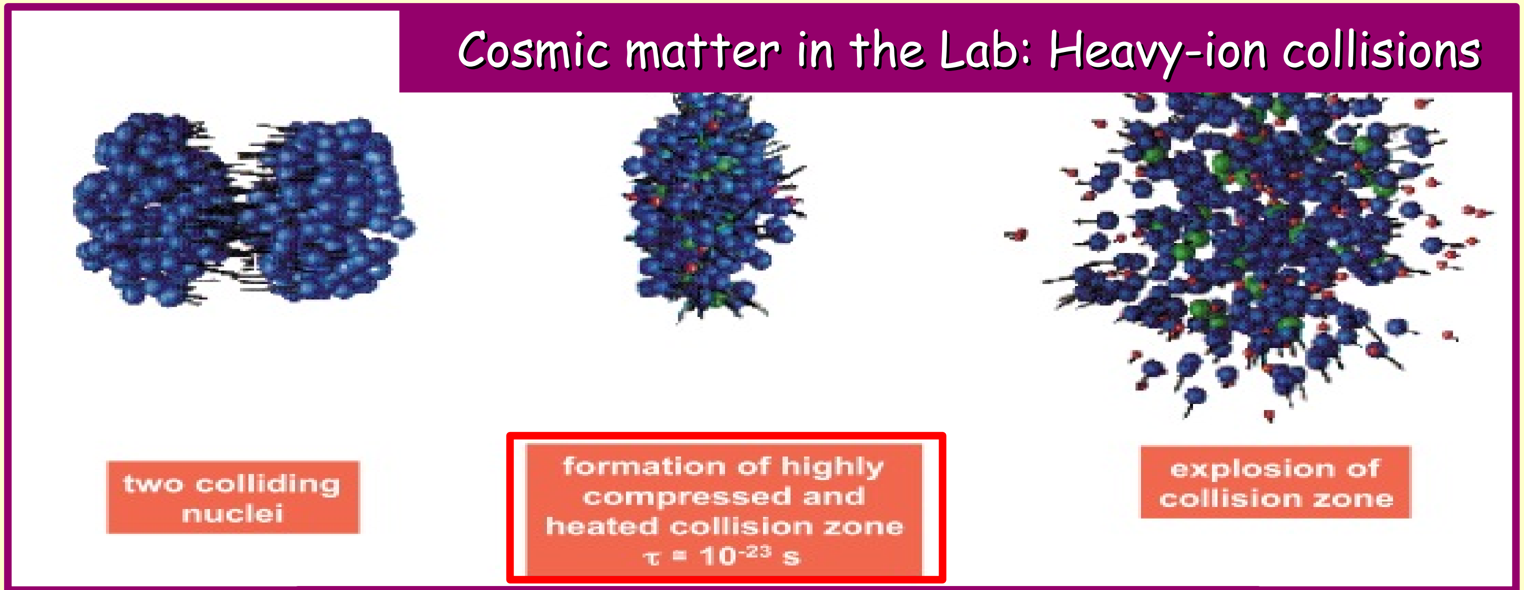
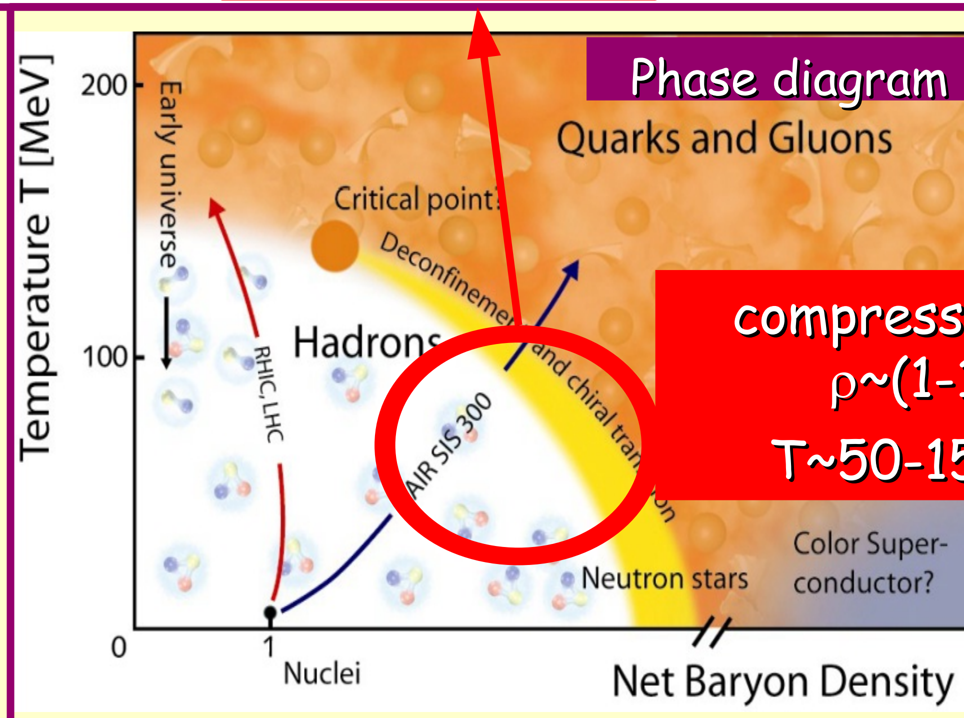


Initial stage…
$\rho_0 \sim 0.16 fm^{-3}$
$T \sim 0$ MeV

Introduction…

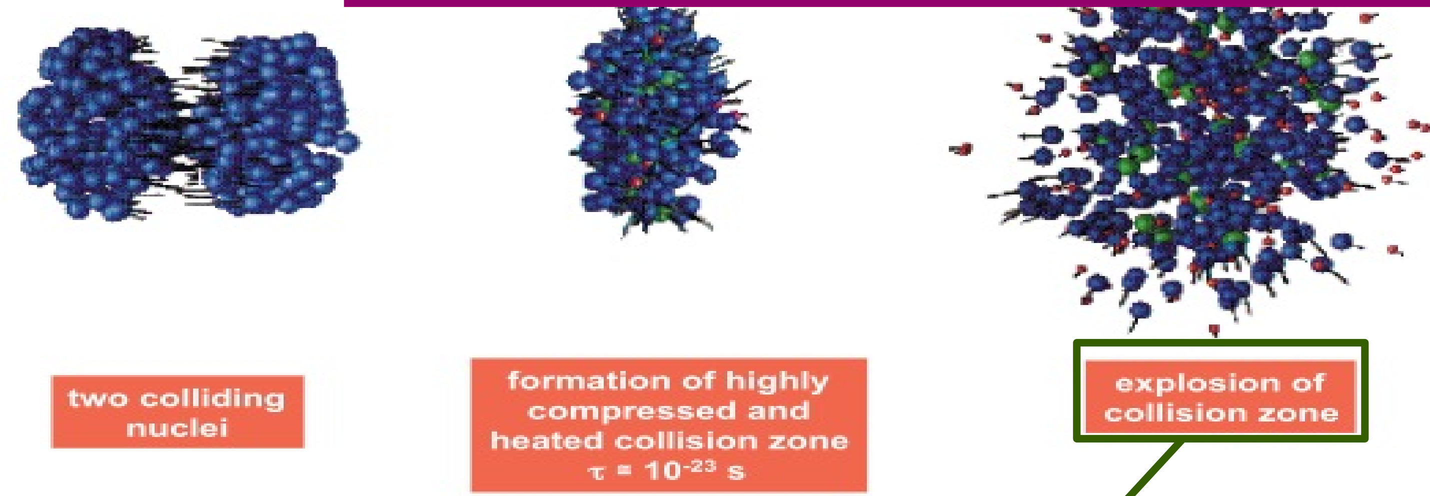




compressed stage
$\rho \sim (1\text{-}10)\rho_0$
T~50-150 MeV

Introduction…

Cosmic matter in the Lab: Heavy-ion collisions



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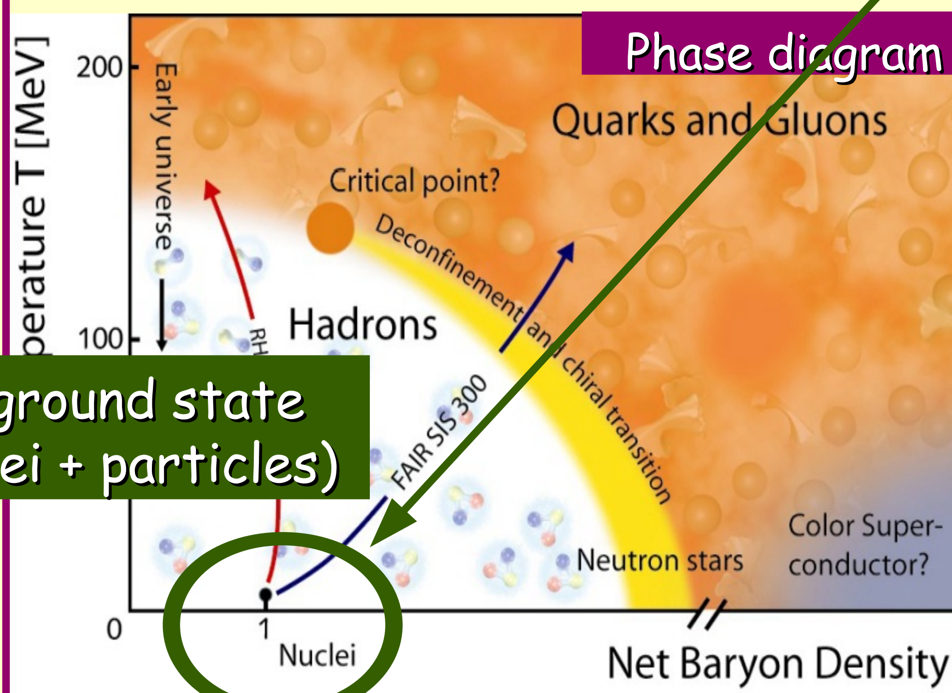
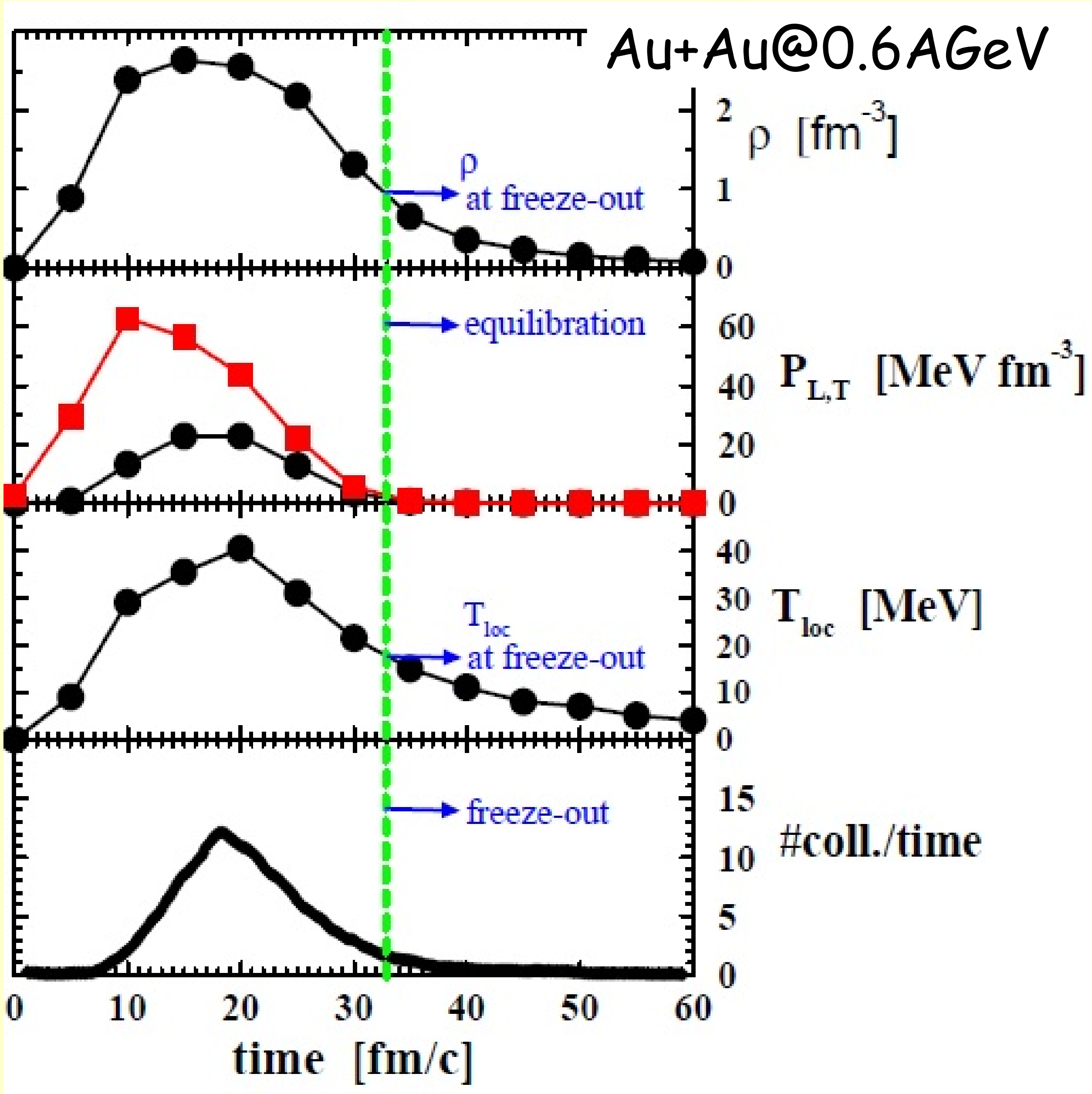
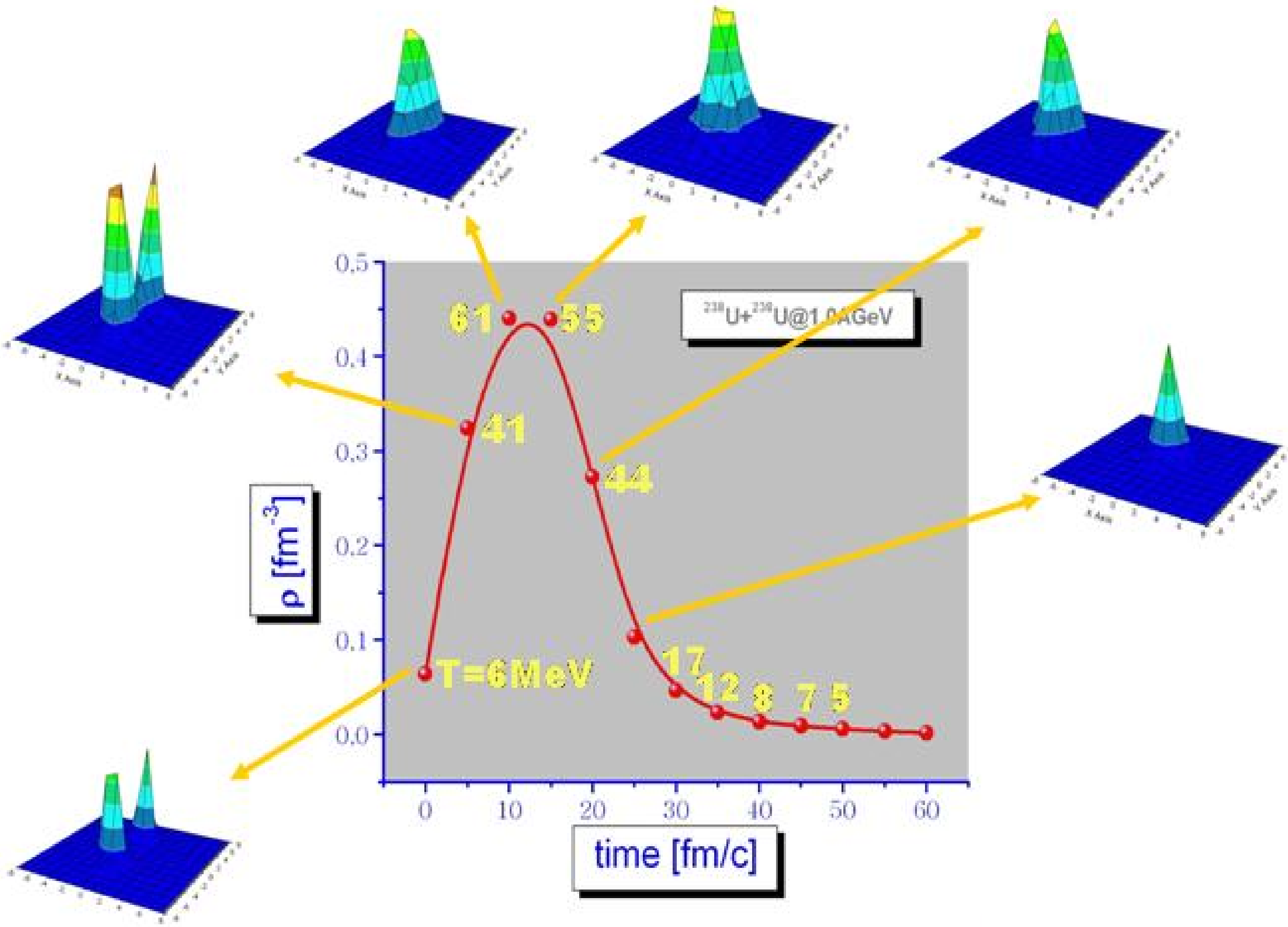


Back to ground state (light nuclei + particles)

Densities & temperatures in participant matter



Density & temperature evolution at the center



Introduction…

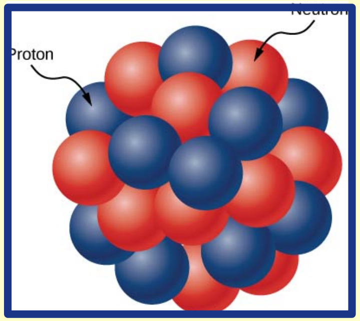
Experiments on heavy-ion collision

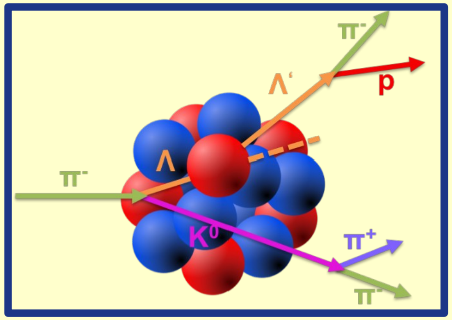
Relativistic **H**eavy **I**on **C**ollider (RHIC), Brookhaven seit 2000

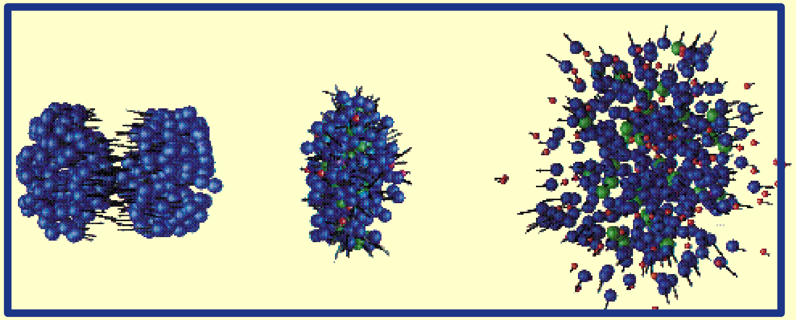
Large **H**adron **C**ollider (LHC), Cern, ab 2008

Facility for **A**ntiproton and **I**on **R**esearch (FAIR), GSI, ab 2011

Theory: Relativistic nuclear/hadron models...







Involves

Elementary particles & interactions → **quantum mechanics**

Particle velocities v~c → **relativistic kinematics & dynamics**

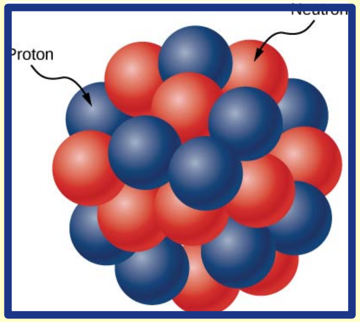
Exact treatment

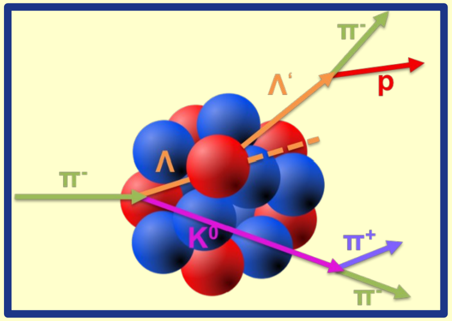
Relativistic quantum transport theory of a many-body nuclear system

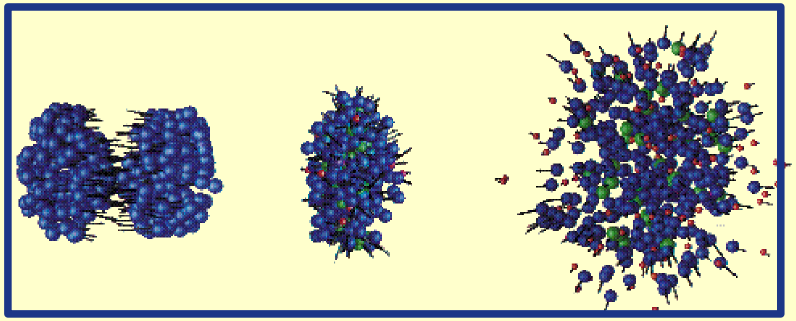
Practical applications...

Relativistic quantum transport theory of a many-body nuclear system

Theory: Relativistic nuclear/hadron models...







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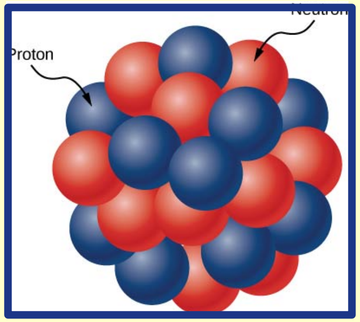

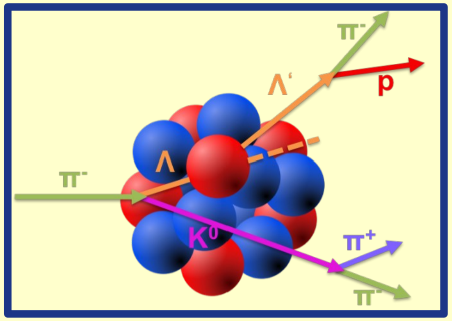

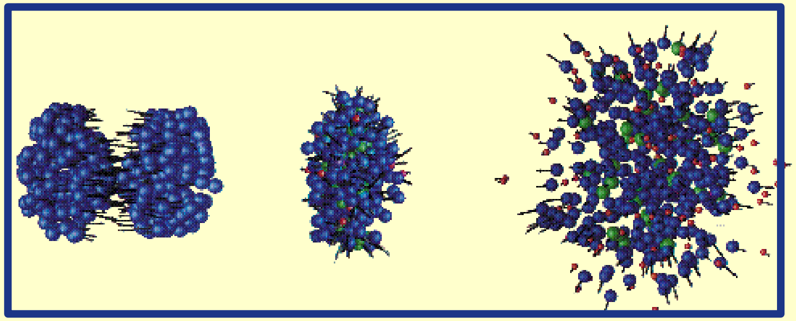

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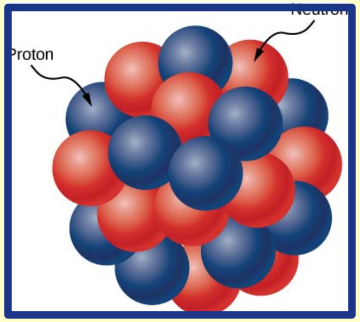

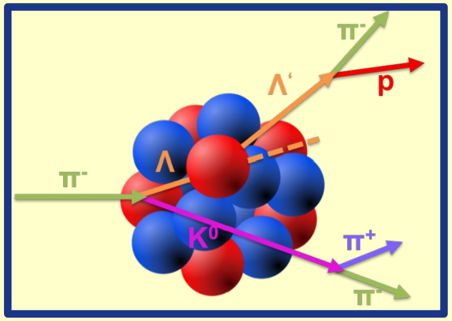

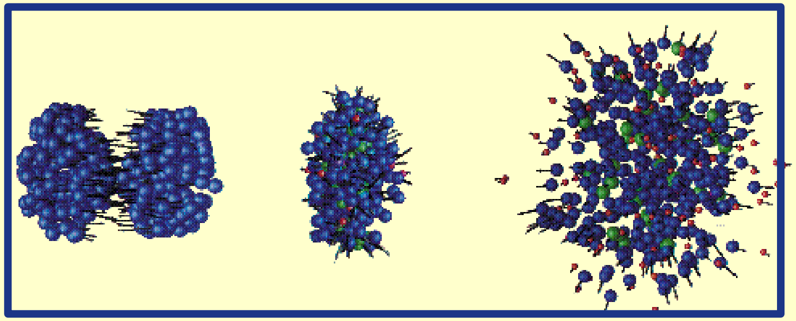

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Elementary particles & interactions → **quantum mechanics**

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Exact treatment

Relativistic quantum transport theory of a many-body nuclear system

Practical applications (on computer) **approximations !**

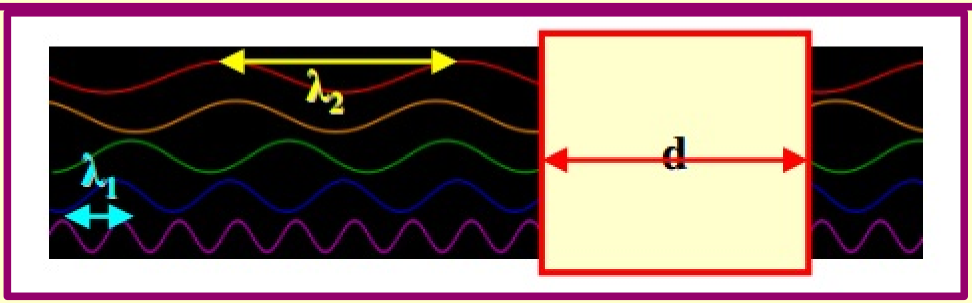
Relativistic ~~quantum~~ transport theory of a (many-body) nuclear system

Theory: Relativistic nuclear/hadron models...

classical mechanics ↔ quantum mechanics

elem. particles (t,x) ↔ wave packets $\Psi(t,x)$

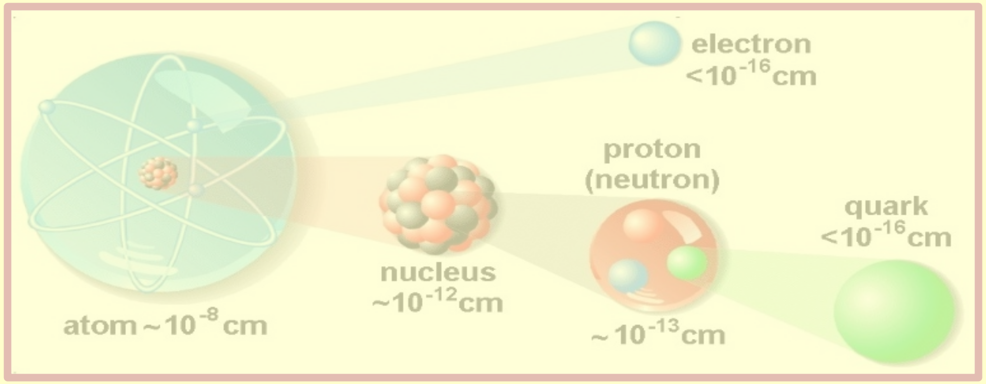
Correspondence principle (Niels Bohr, 1923):
Wave nature of particles not visible, when de Broglie wave length $\lambda=h/p$ small compared to considered scales



$\lambda_2 \sim d$

$\lambda_1 < d$

Considered scales here:
nuclear radius $d \sim 10^{-15}$m =1fm



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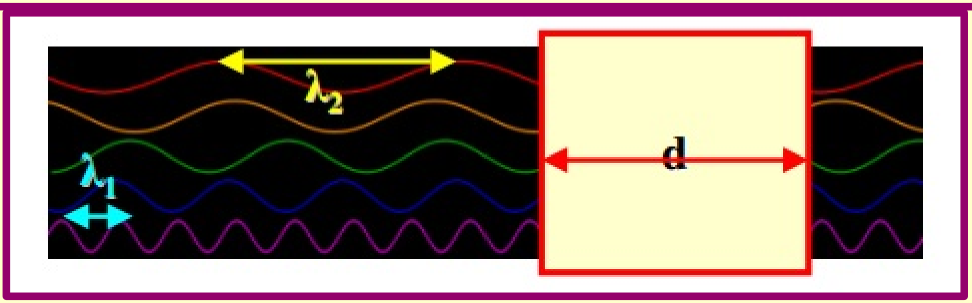

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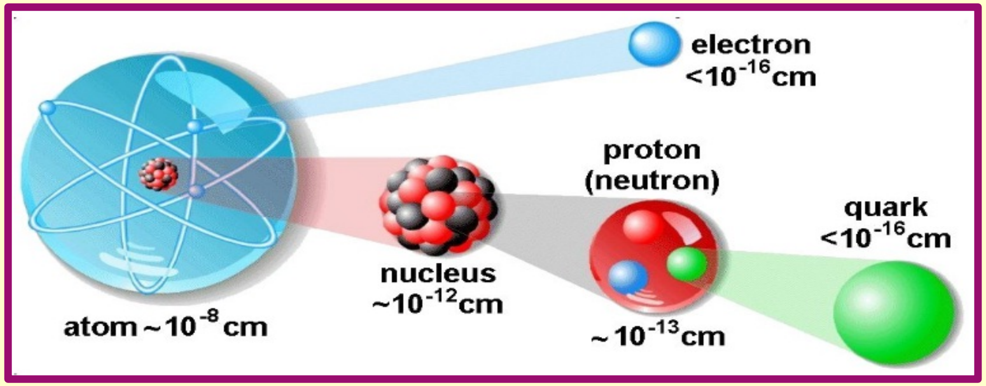
Considered scales here:
nuclear radius d ~ (5-10)x10^{-15}m ~ 10^{-14}fm



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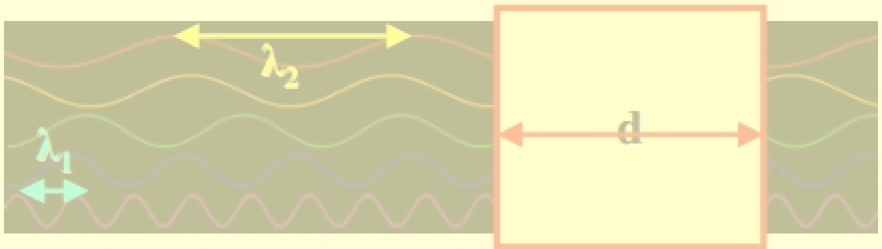

$\lambda_2 \sim d$

$\lambda_1 < d$

proton E_{kin}	$\lambda = h/p$
1 MeV	$2{,}86 \cdot 10^{-14}$ m
10 MeV	$9{,}03 \cdot 10^{-15}$ m
100 MeV	$2{,}79 \cdot 10^{-15}$ m
1 GeV	$7{,}31 \cdot 10^{-16}$ m
10 GeV	$1{,}23 \cdot 10^{-16}$ m *
100 GeV	$1{,}23 \cdot 10^{-17}$ m *

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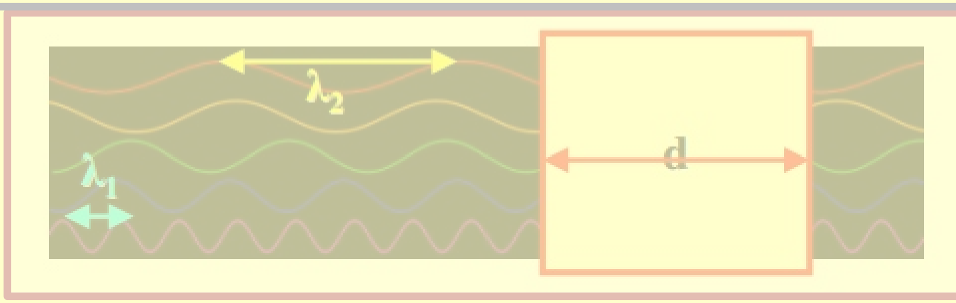

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} classical description possible

Theory: Relativistic transport & covariant EoS…

Literature on (relativistic) kinetic theory…

- 1. Primer L. Boltzmann, Wien. Ber. **66** (1872) 275
- 2. Primer…L. Nordheim, Proc. R. Soc. London **A119** (1928) 689

  E.A. Uehling, G.E. Uhlenbeck, Phys. Rev. **43** (1933) 552

- Theoretical background

  Non-Relativistic kinetic theory

  L.P. Kadanoff, G. Baym, „*Quantum Statistical Mechanics*" (Benjamin, N.Y. 1962)

  Relativistic kinetic theory

  S.R. de Groot, W.A. van Leeuwen, C.G. van Weert

  „*Relativistic kinetic theory*" (North Holland, Amsterdam, 1980)

  Modern Relativistic Quantum Transport Theory

  W. Botermans, R. Malfliet, Phys. Rep. **198** (1990) 115 (←difficult to understand…)

- First applications to HIC…

  P. Danielewicz, Ann. Phys. **152** (1984) 239 & 305

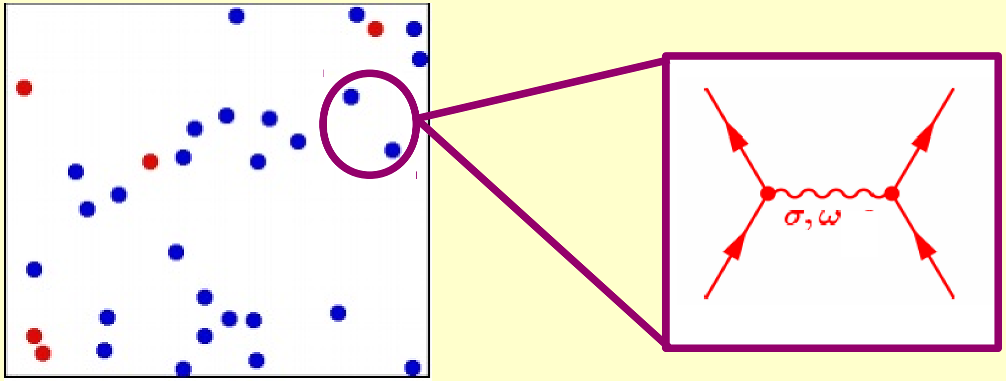
  G.F. Bertsch, S. Das Gupta, Phys. Rep. **160** (1988) 189

Relativistic applications to HIC…

B. Blättel, V. Koch, U. Mosel, Rep. Prog. Phys. **56** (1993) 1

Theory: Relativistic Hadro-Dynamics...

Principle: Lagrangian formalism for fields

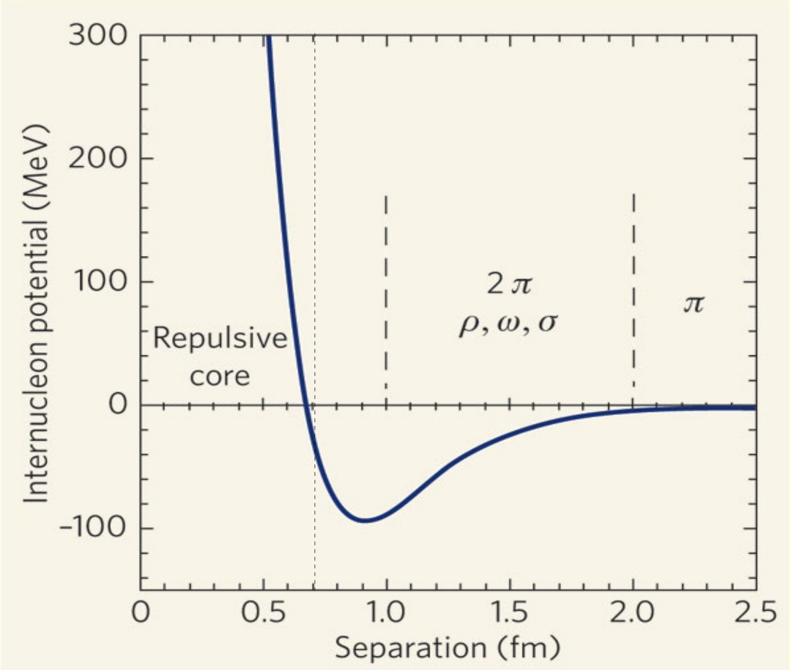


Degrees of freedom

Nucleons → Dirac Spinor Ψ

Interaction → σ, ω mesons

Interaction: short range attractive & repulsive for r<0.8 fm



Yukawa's concept

screened Coulomb potential

$$V(r) = -g^2 \frac{1}{r} e^{-mr}$$

coupling strength — particle mass

Theory: Relativistic Hadro-Dynamics…

Classical mechanics versus relativistic field theory

Point-like particles

dof: coordinates [illegible]

Velocities [illegible]

Lagrange function

[illegible]

Equations of motion

$$\frac{d\mathcal{L}}{dq_i} - \frac{d}{dt}\frac{d\mathcal{L}}{d\dot{q}_i} = 0$$

relativistic fields

$$\varphi(t, \vec{r}) = \varphi(x)$$

[illegible]

Lagrangian density

[illegible]

Equations of motion

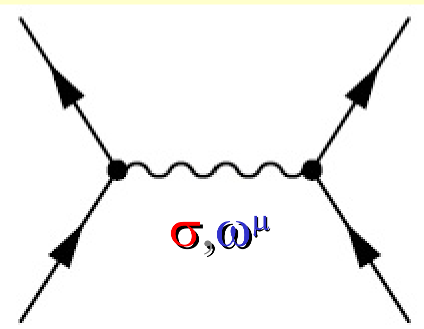
$$\frac{\partial\mathcal{L}}{\partial\varphi} - \partial_\mu \frac{\partial\mathcal{L}}{\partial(\partial_\mu\varphi)} = 0$$

Theory: Relativistic Hadro-Dynamics…

Free Lagrangian for the Dirac field (spin ½ nucleons)

[illegible]

Interaction Lagrangian: minimal coupling (analogy to electrodynamics)



σ → scalar (spin 0) field

ω^μ → vector (spin 1) field

δ → scalar (spin 0) field

ρ^μ → vector (spin 1) field

$$\mathcal{L}_{int} = g_\sigma \overline{\Psi}\Psi\sigma - g_\omega \overline{\Psi}\gamma_\mu\Psi\omega^\mu$$
$$+ g_\delta \overline{\Psi}\vec{\tau}\,\Psi\vec{\delta} - g_\rho \overline{\Psi}\gamma_\mu\vec{\tau}\,\Psi\vec{\rho}^{\,\mu}$$

Full Lagrangian:

$$\mathcal{L} = \overline{\Psi}\gamma_\mu\left(i\partial^\mu - g_\omega\omega^\mu - g_\rho\vec{\tau}\,\vec{\rho}^{\,\mu}\right)\Psi - \left(m - g_\sigma\sigma - g_\delta\vec{\tau}\,\vec{\delta}\right)\overline{\Psi}\Psi$$
$$+\mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\delta + \mathcal{L}_\rho$$

J.D. Walecka, Ann. Phys. (N.Y.) 83 (1974) 497

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

NLD Lagrangian : as in conventional RHD

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

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$$+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu - \frac{1}{4}\vec{G}_{\mu\nu}\vec{G}^{\mu\nu}$$
$$+\mathcal{L}_{int}$$

Interaction Lagrangian : as in conventional RHD

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

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NLD Lagrangian : as in conventional RHD

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

Interaction Lagrangian : as in conventional RHD + non-linear derivative operators

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

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

NLD Lagrangian : as in conventional RHD

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

Interaction Lagrangian : as in conventional RHD + non-linear derivative operators

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

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

NLD Lagrangian : as in conventional RHD

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

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$$\overrightarrow{\xi} = -\frac{v^\alpha i\overrightarrow{\partial}_\alpha}{\Lambda}$$

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

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with the following tensors

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

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NLD: The formalism…

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with the following tensors

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 with $\xi = -\frac{v_\alpha p^\alpha}{\Lambda}$

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

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

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

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

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

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meson-field equations

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

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Equation of State (EoS)

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

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Features of NLD model…

cut-off Λ regulates

1) DD & MD of selfenergies

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

meson-field equations

$$m_{\sigma}^{2}\sigma + \frac{\partial U}{\partial \sigma} = g_{\sigma}\sum_{i=p,n}\left\langle \overline{\Psi}_{i}\mathcal{D}\Psi_{i}\right\rangle = g_{\sigma}\rho_{s}$$

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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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Features of NLD model…

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

meson-field equations

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Equation of State (EoS)

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

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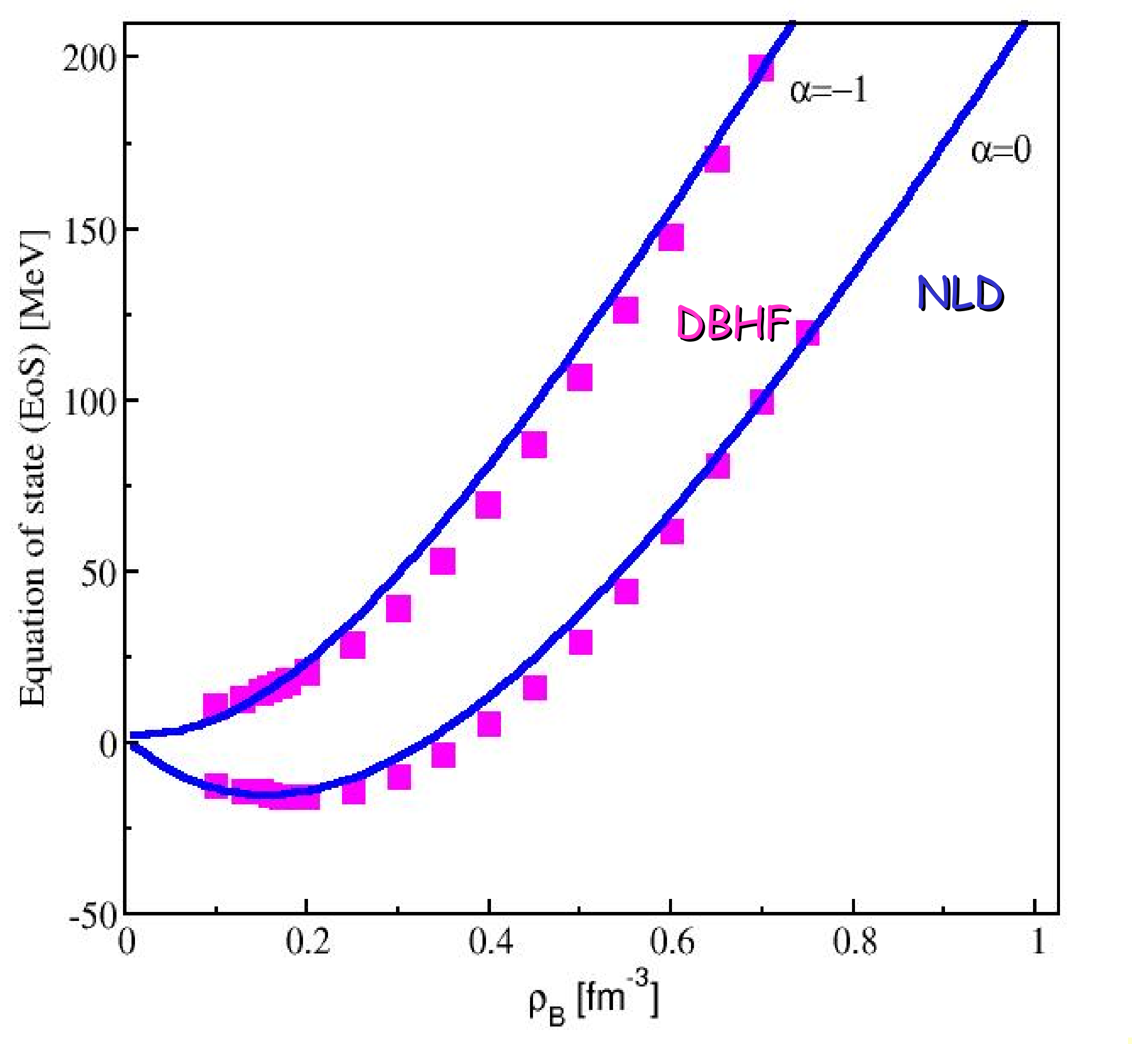
cut-off Λ regulates

1) DD & MD of selfenergies

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

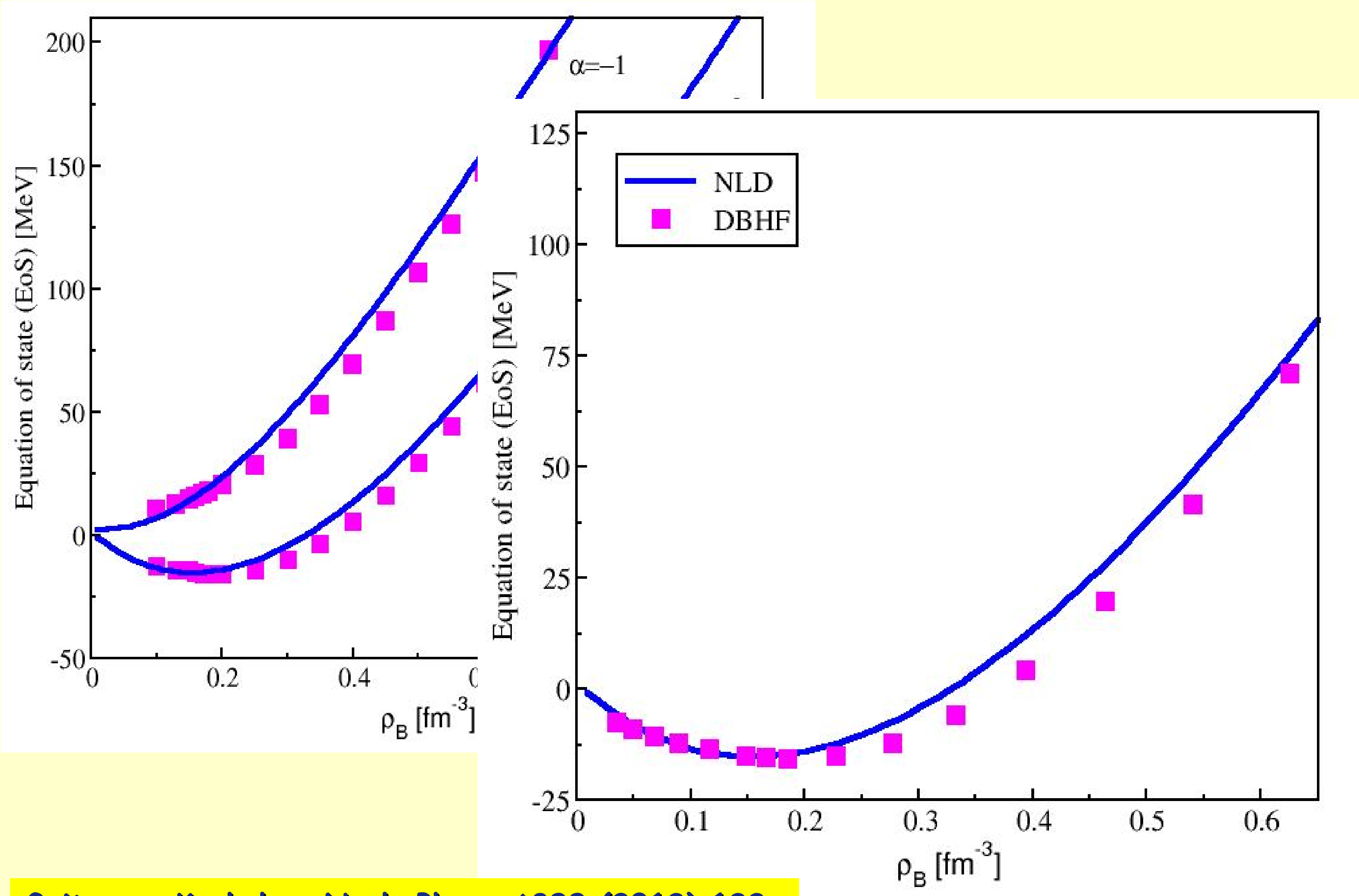
3) fully thermodynamic consistent (important for neutron stars)

Nuclear EoS...



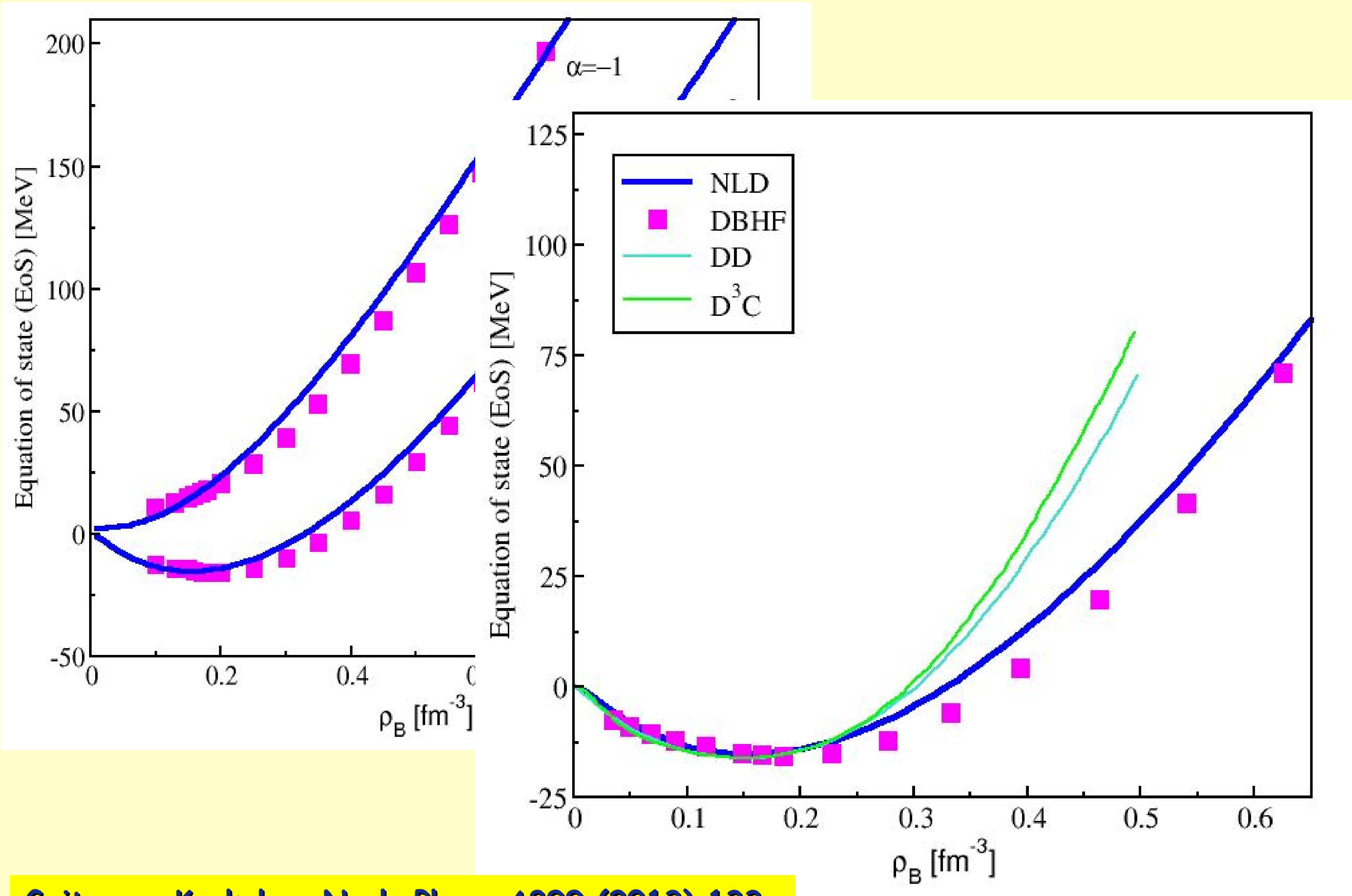
Gaitanos, Kaskulov, Nucl. Phys. A899 (2013) 133

Nuclear EoS...



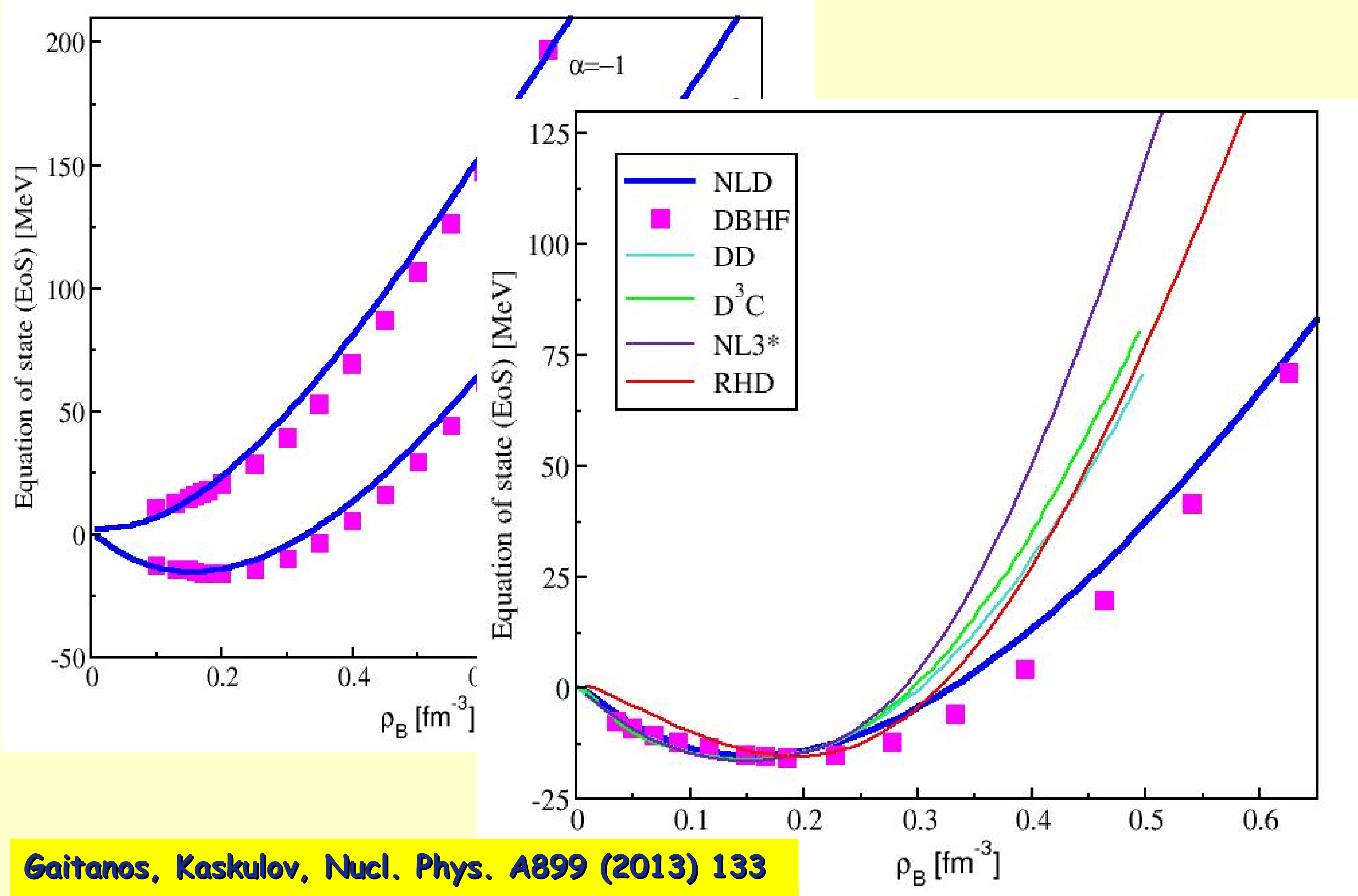
Gaitanos, Kaskulov, Nucl. Phys. A899 (2013) 133

Nuclear EoS...



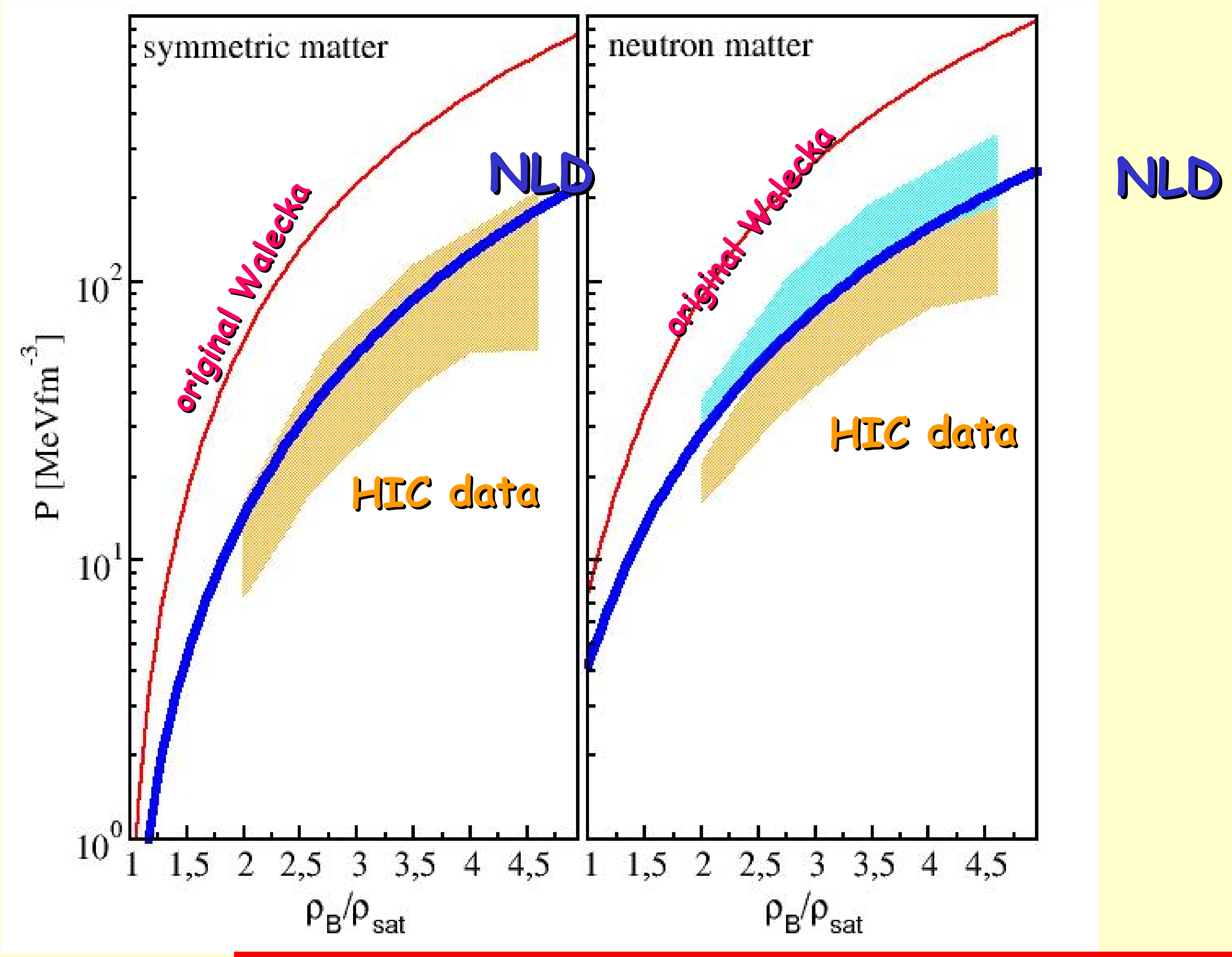
Gaitanos, Kaskulov, Nucl. Phys. A899 (2013) 133

Nuclear EoS...



Gaitanos, Kaskulov, Nucl. Phys. A899 (2013) 133
Gaitanos, Kaskulov, Nucl. Phys. A940 (2015) 181

NLD results: EoS...



NLD model is consistent with HIC phenomenology

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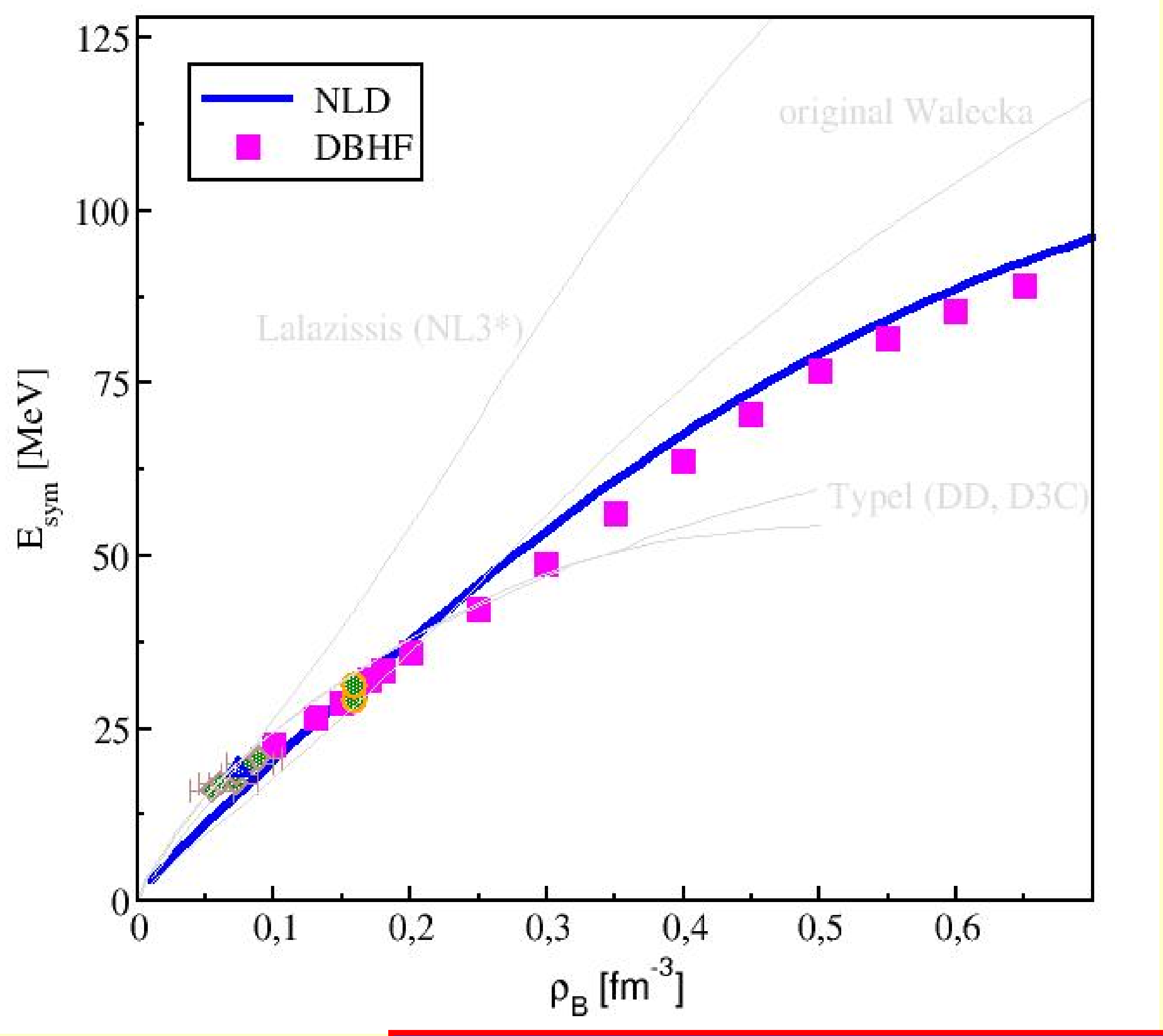
NLD results: symmetry energy...



Remarkable agreement with microscopic DBHF !

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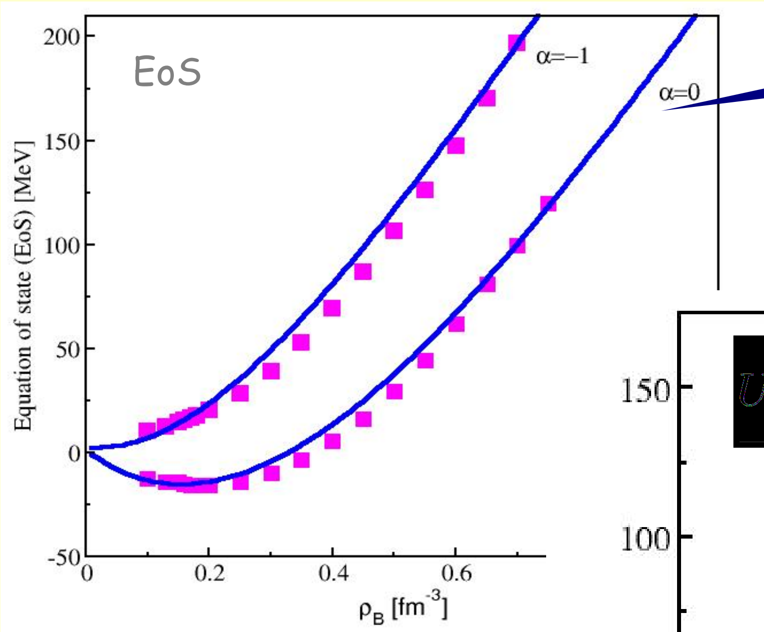
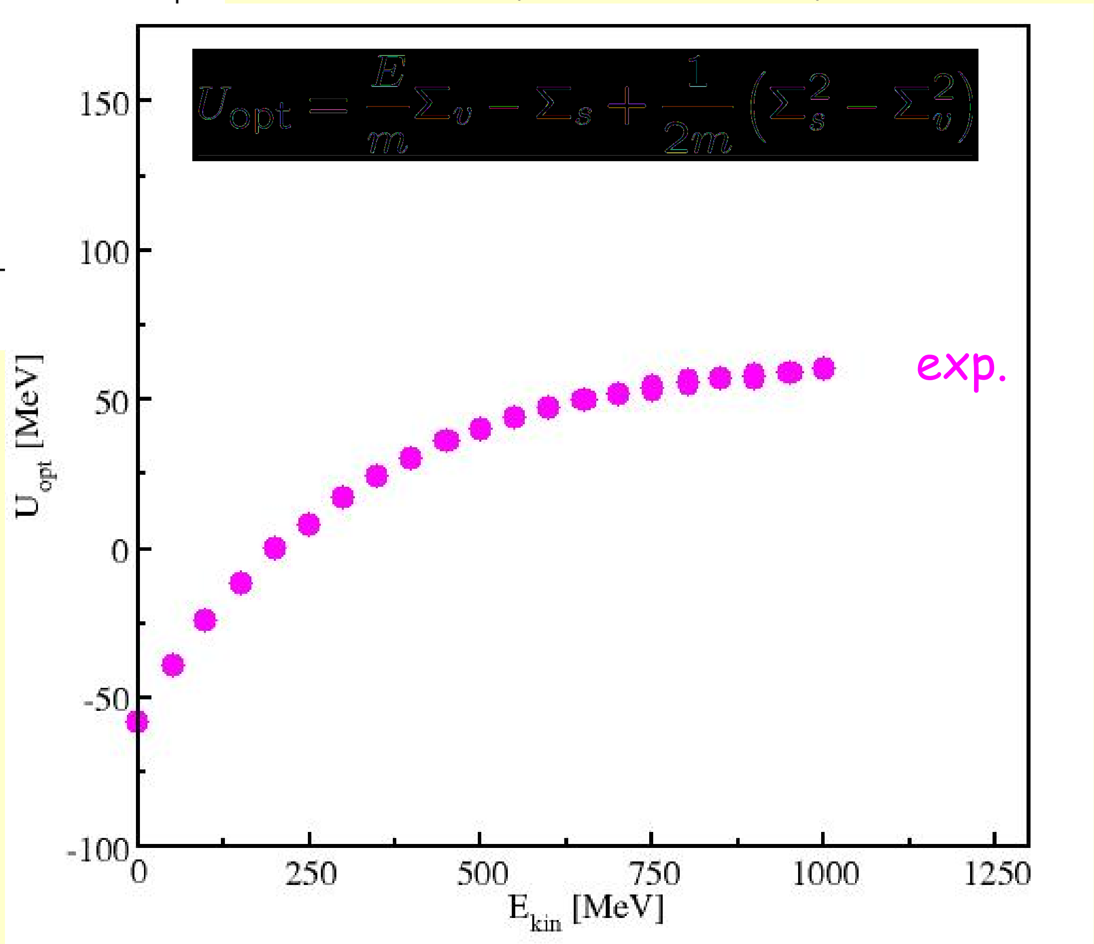
NLD results: MD & optical potentials…



high ρ → high momenta

In-medium proton SEP (real part)



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NLD results: MD & optical potentials...

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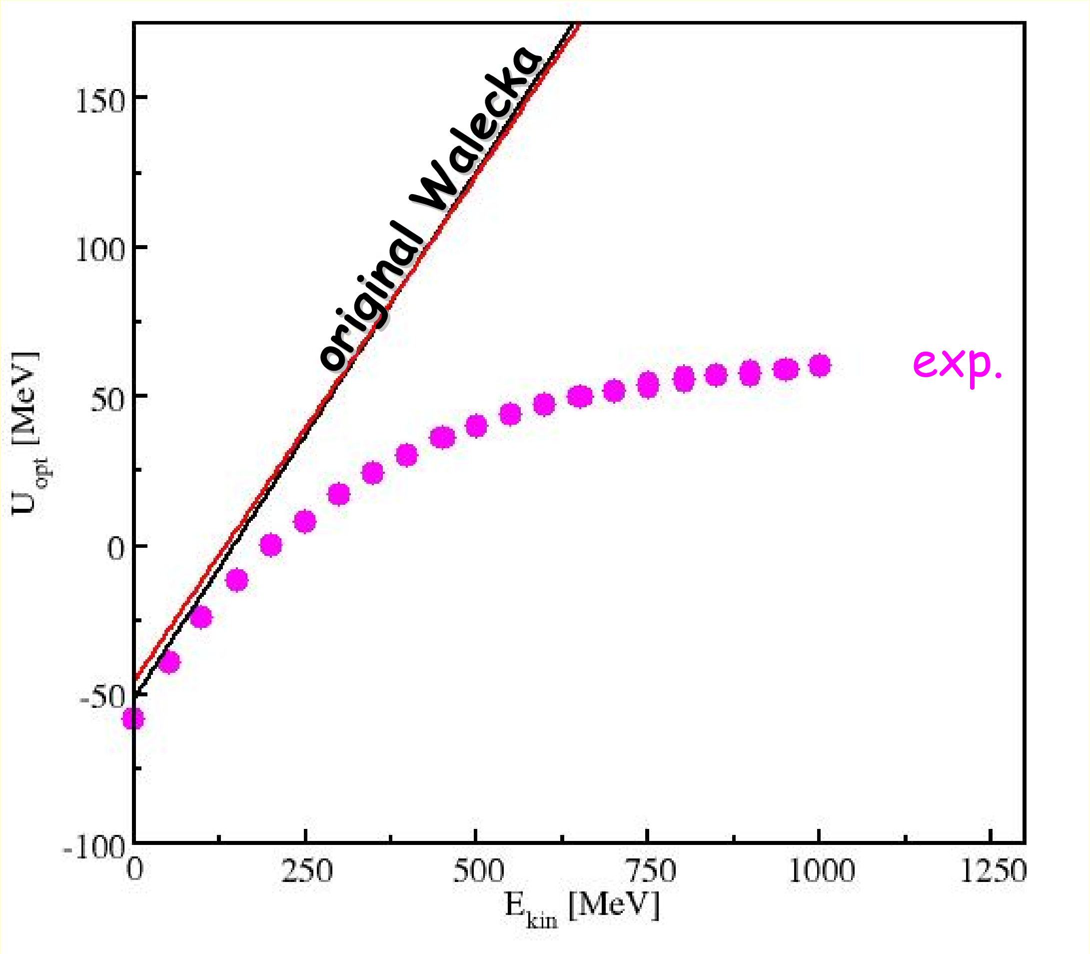

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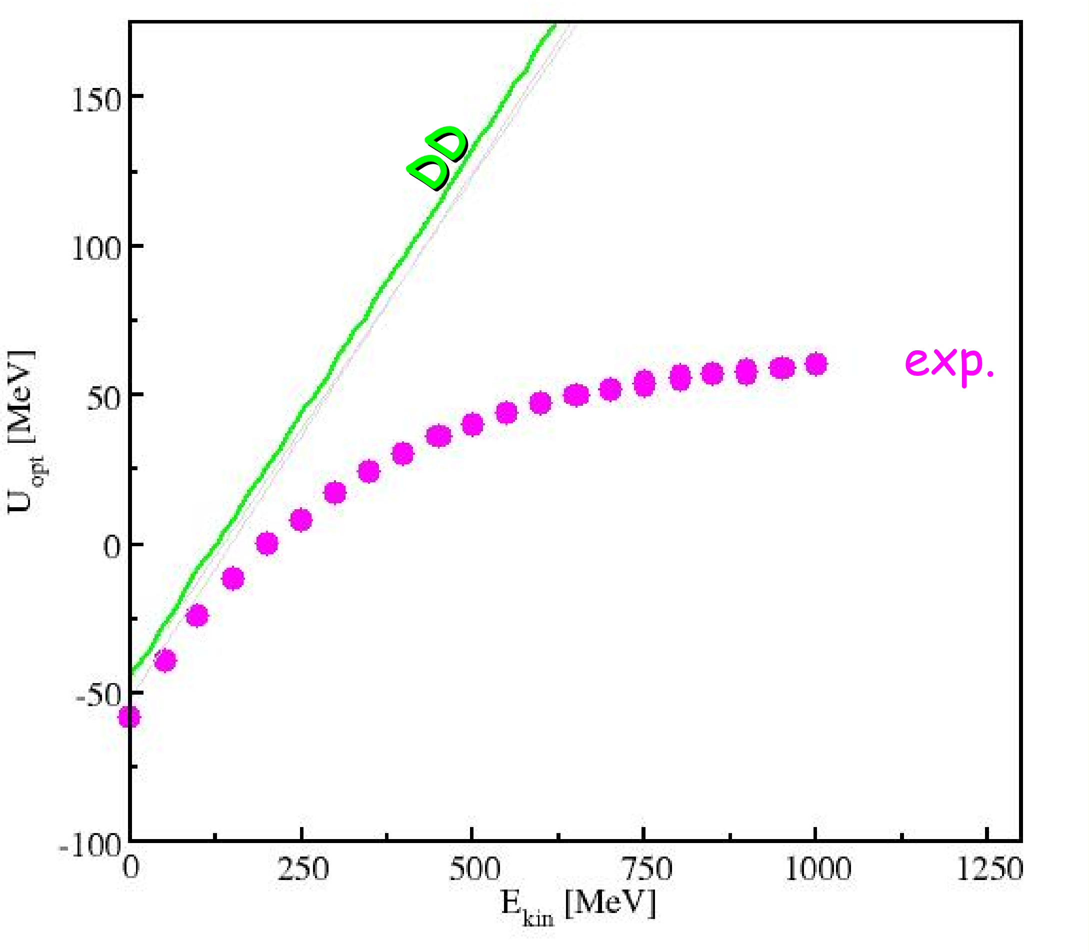

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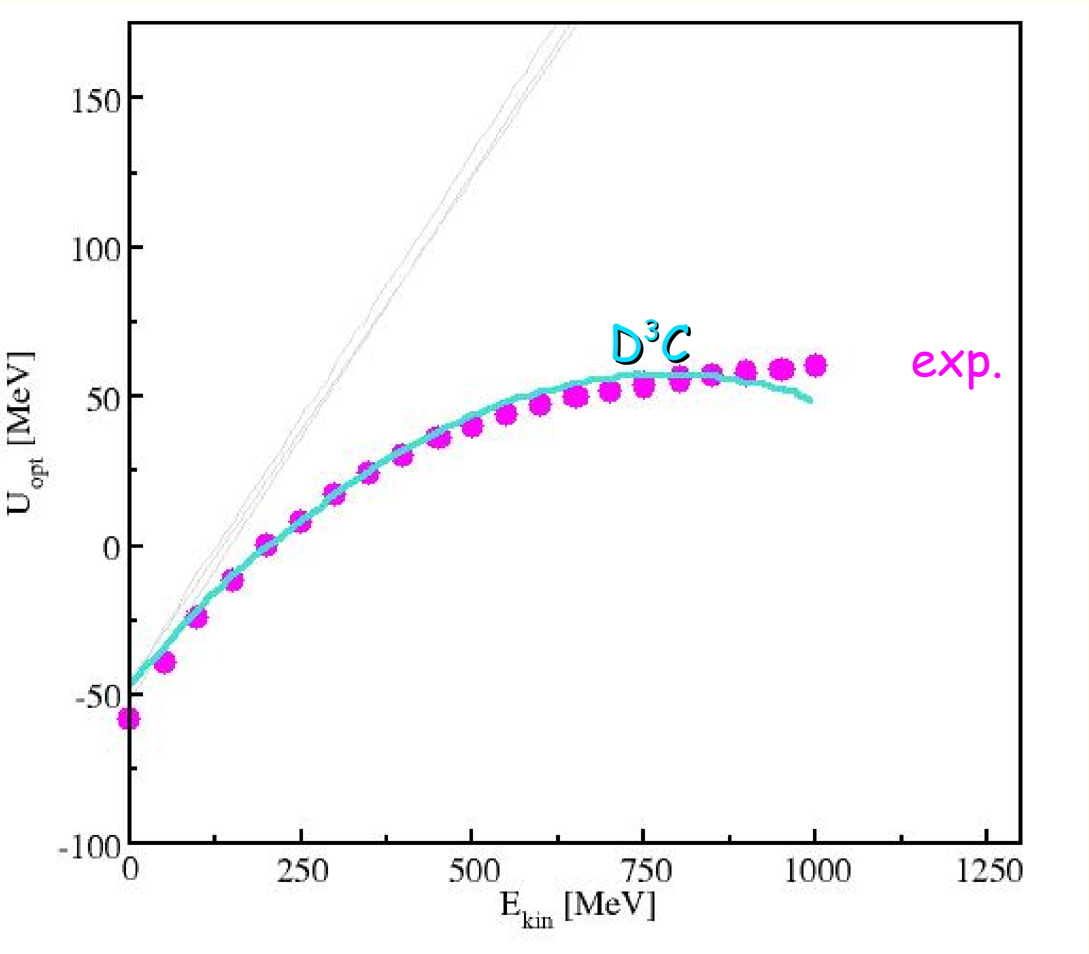
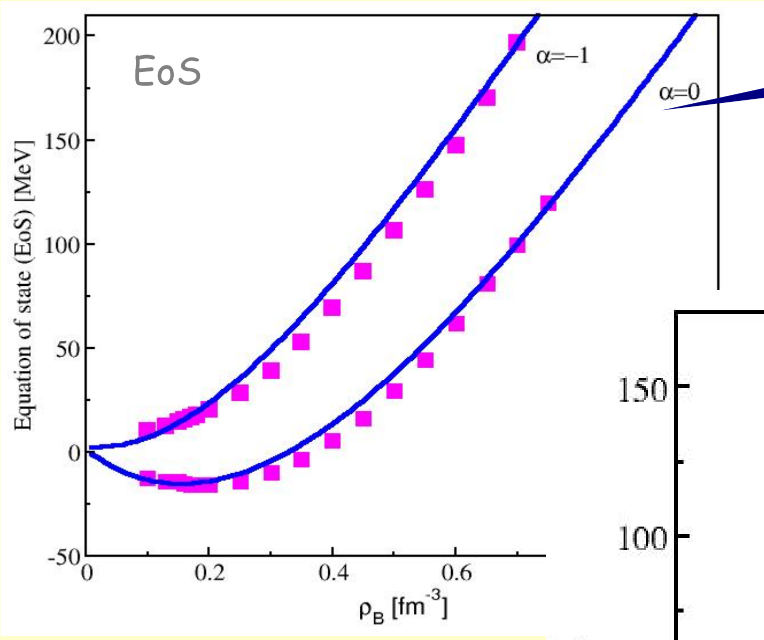
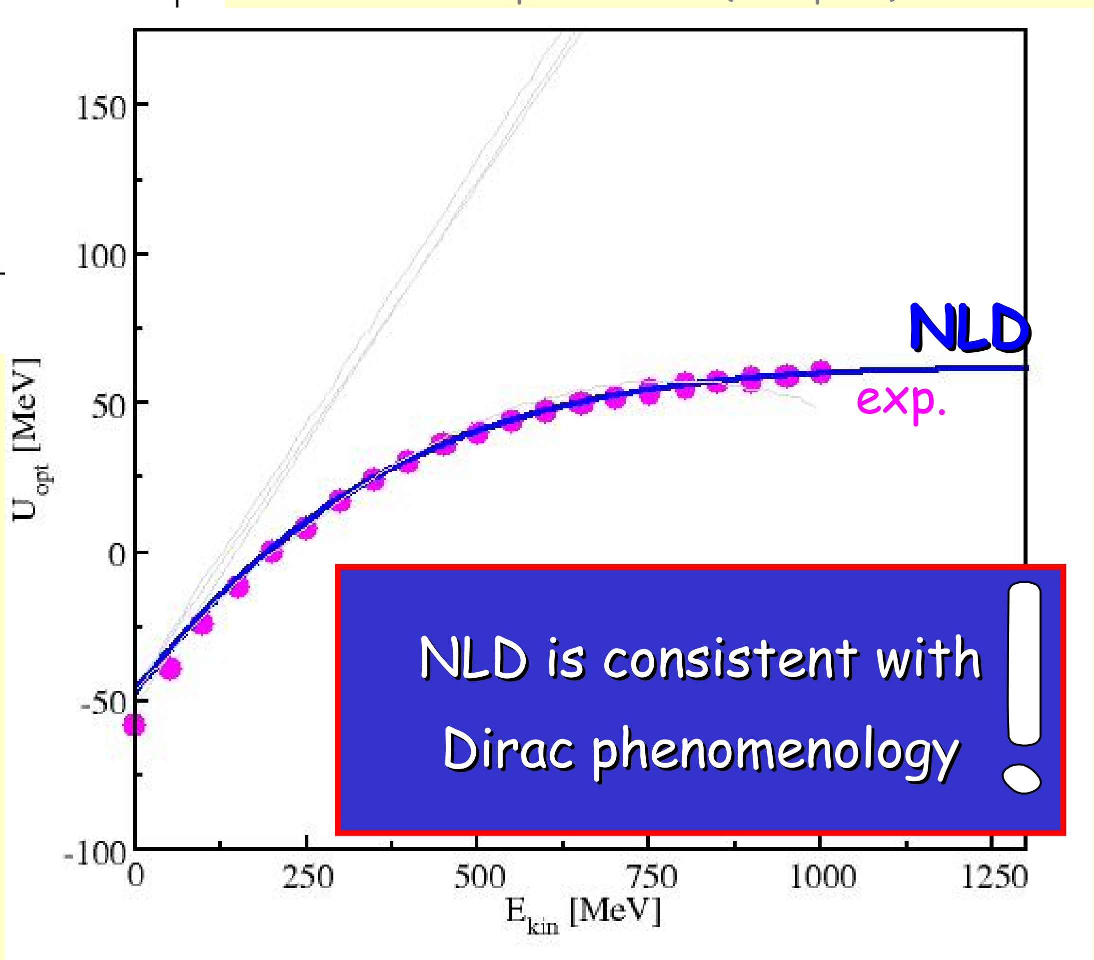


NLD results: MD & optical potentials...



high ρ → high momenta

In-medium proton SEP (real part)



NLD is consistent with Dirac phenomenology !

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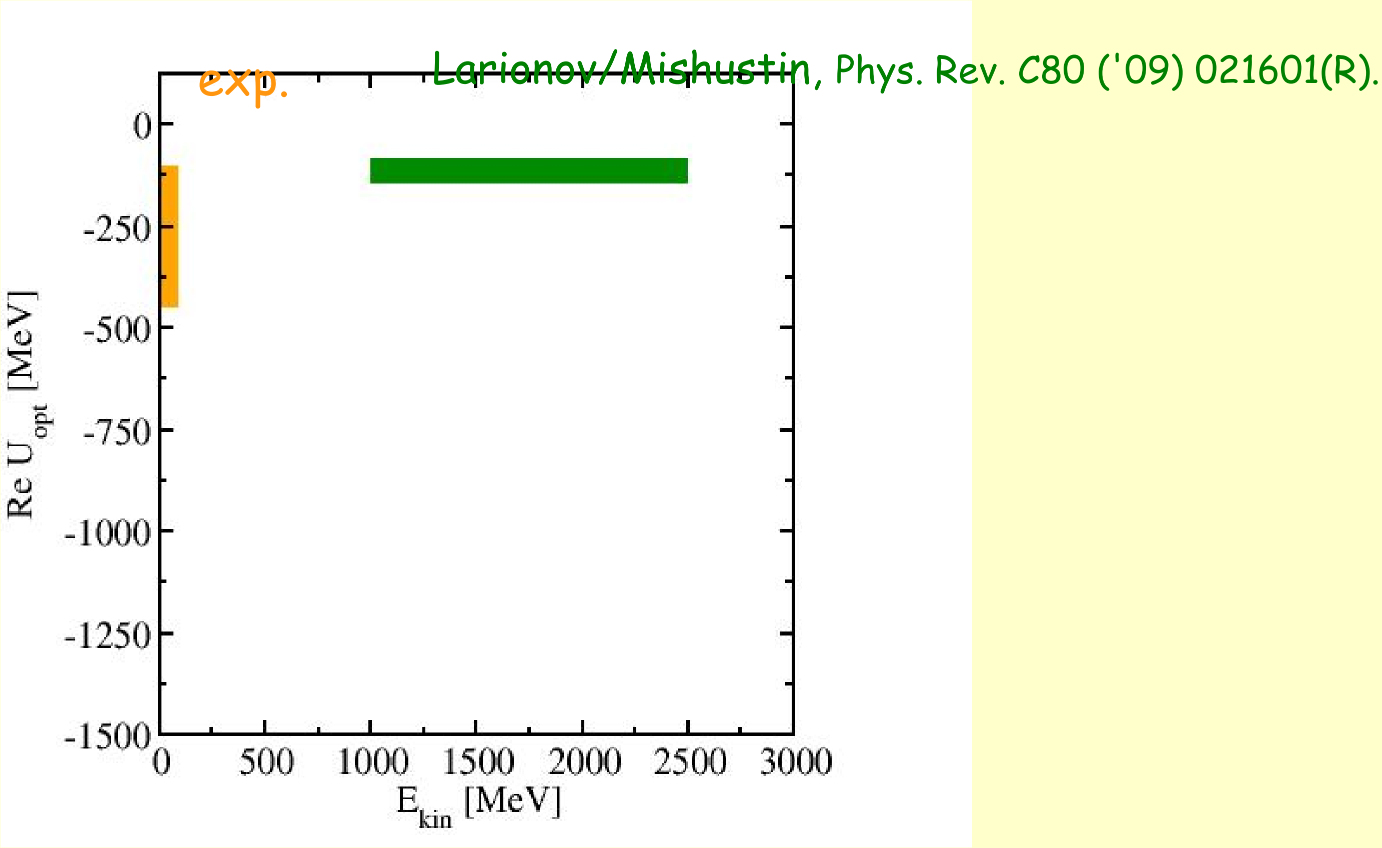
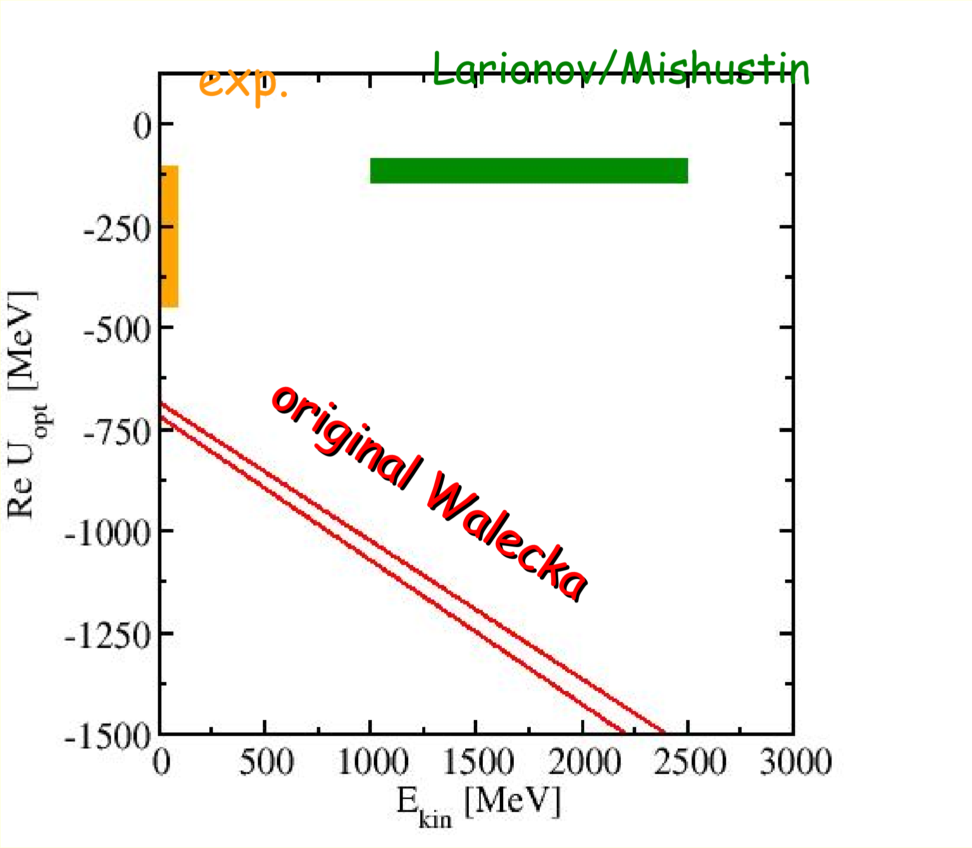
NLD results: MD & optical potentials (anti-proton)...

In-medium anti-proton SEP (real part)



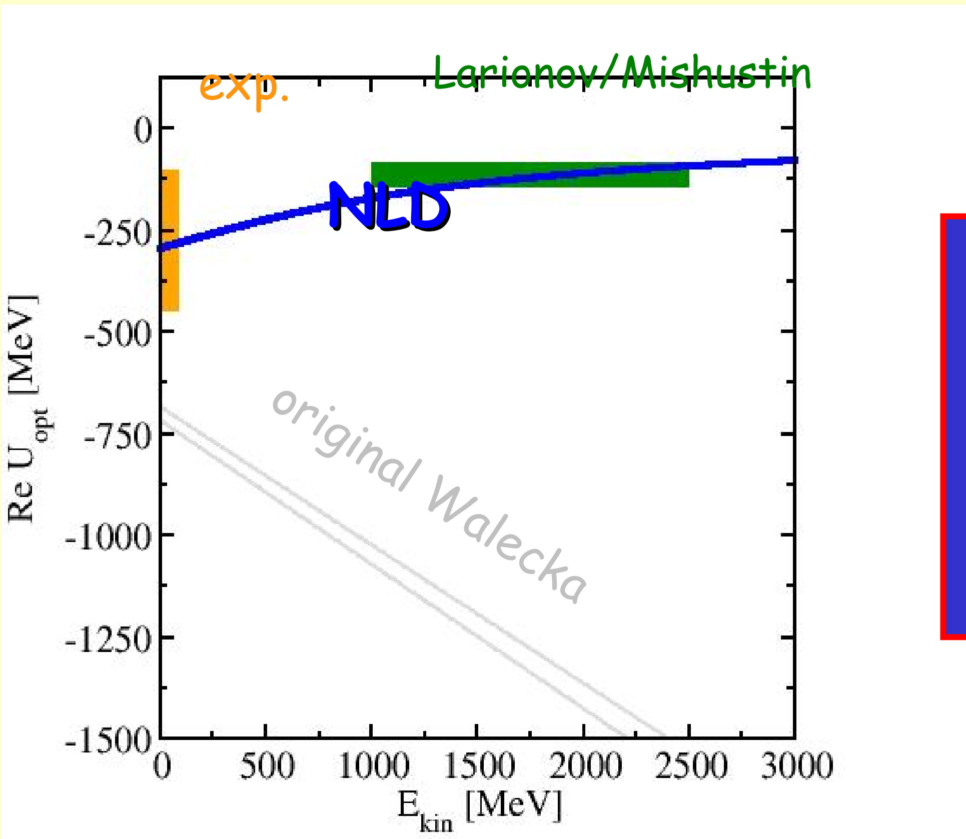
NLD results: MD & optical potentials (anti-proton)...

In-medium anti-proton SEP (real part)



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

In-medium anti-proton SEP (real part)



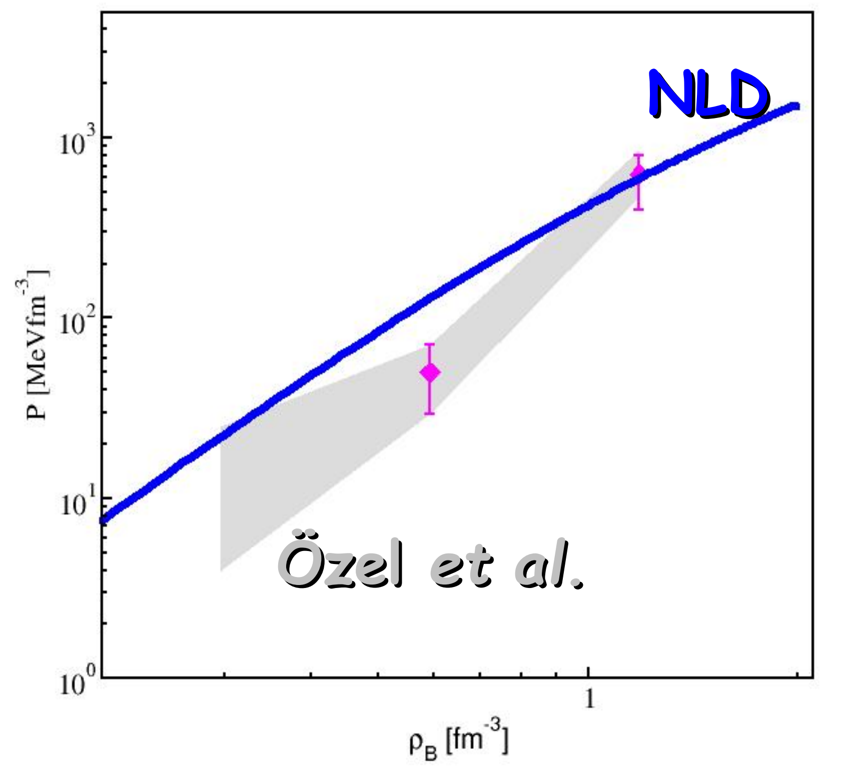
good description of phenomenology

also for in-medium

anti-proton interaction !

Also: NLD provides the <u>imaginary part</u> 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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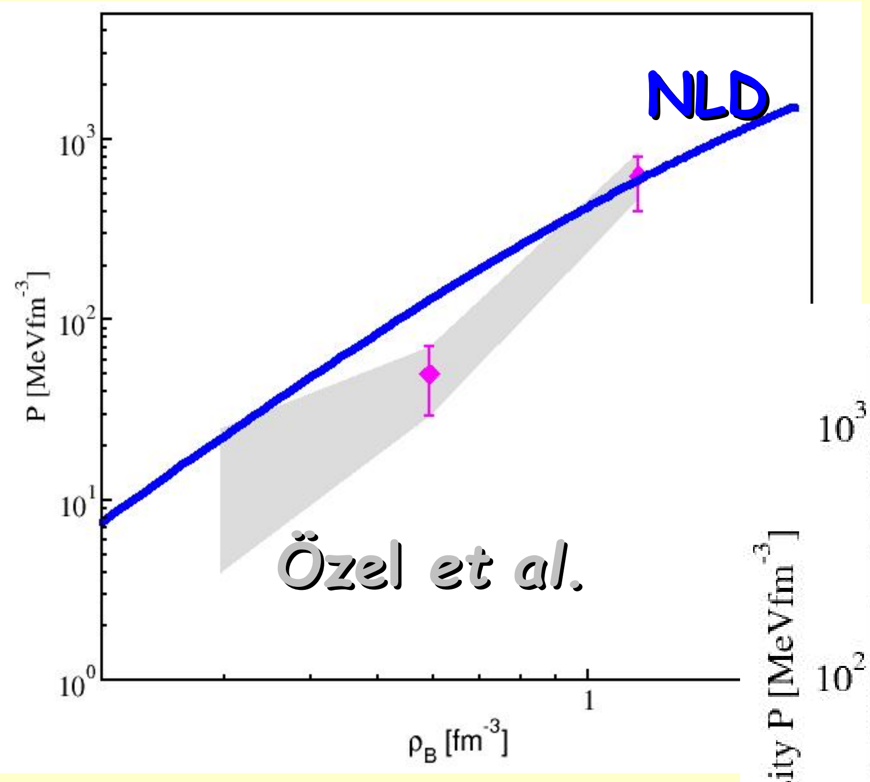
NLD results: high-density EoS at β-equilibrium...



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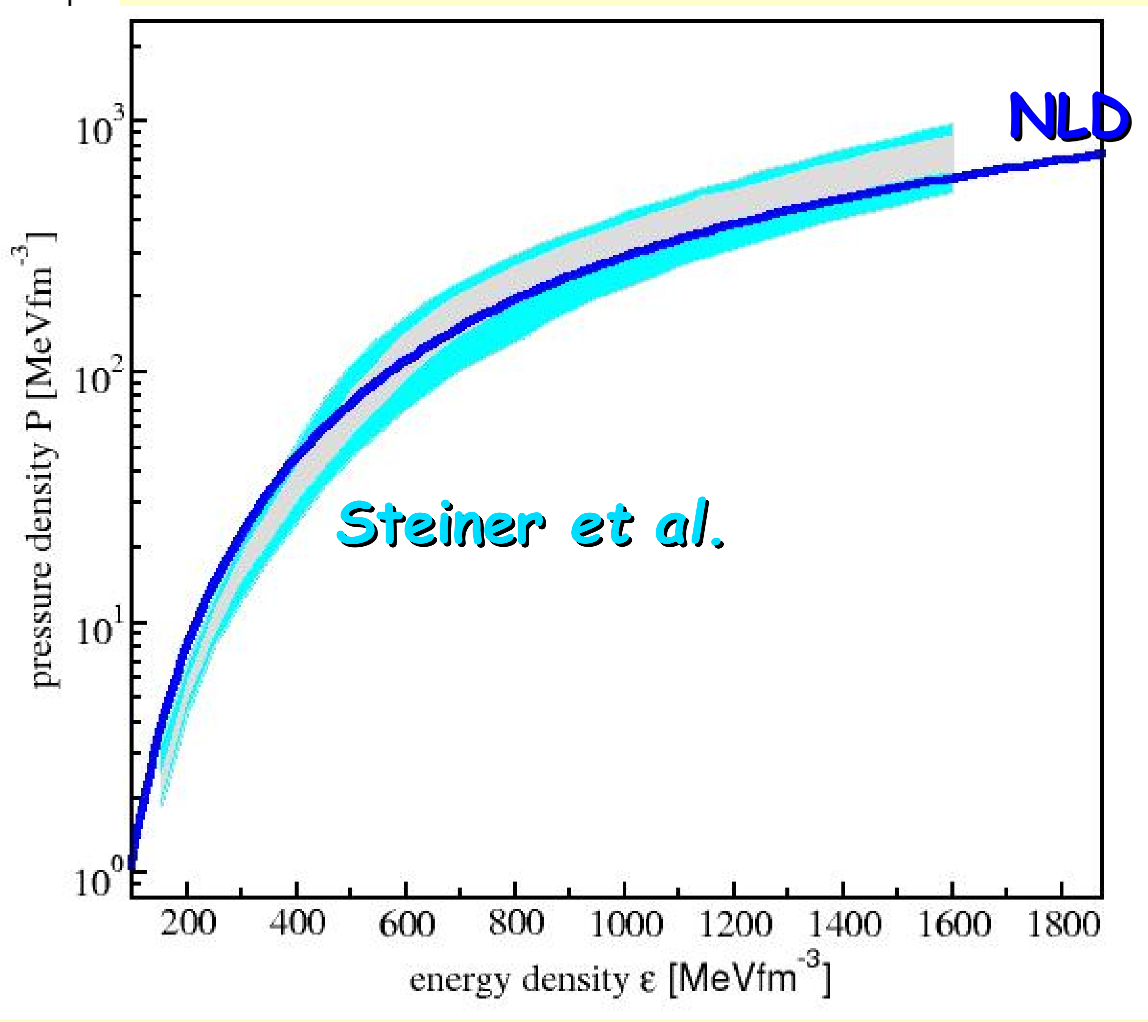

... and A.W. Steiner !
Astrophys. J. 722, 33 (2010).

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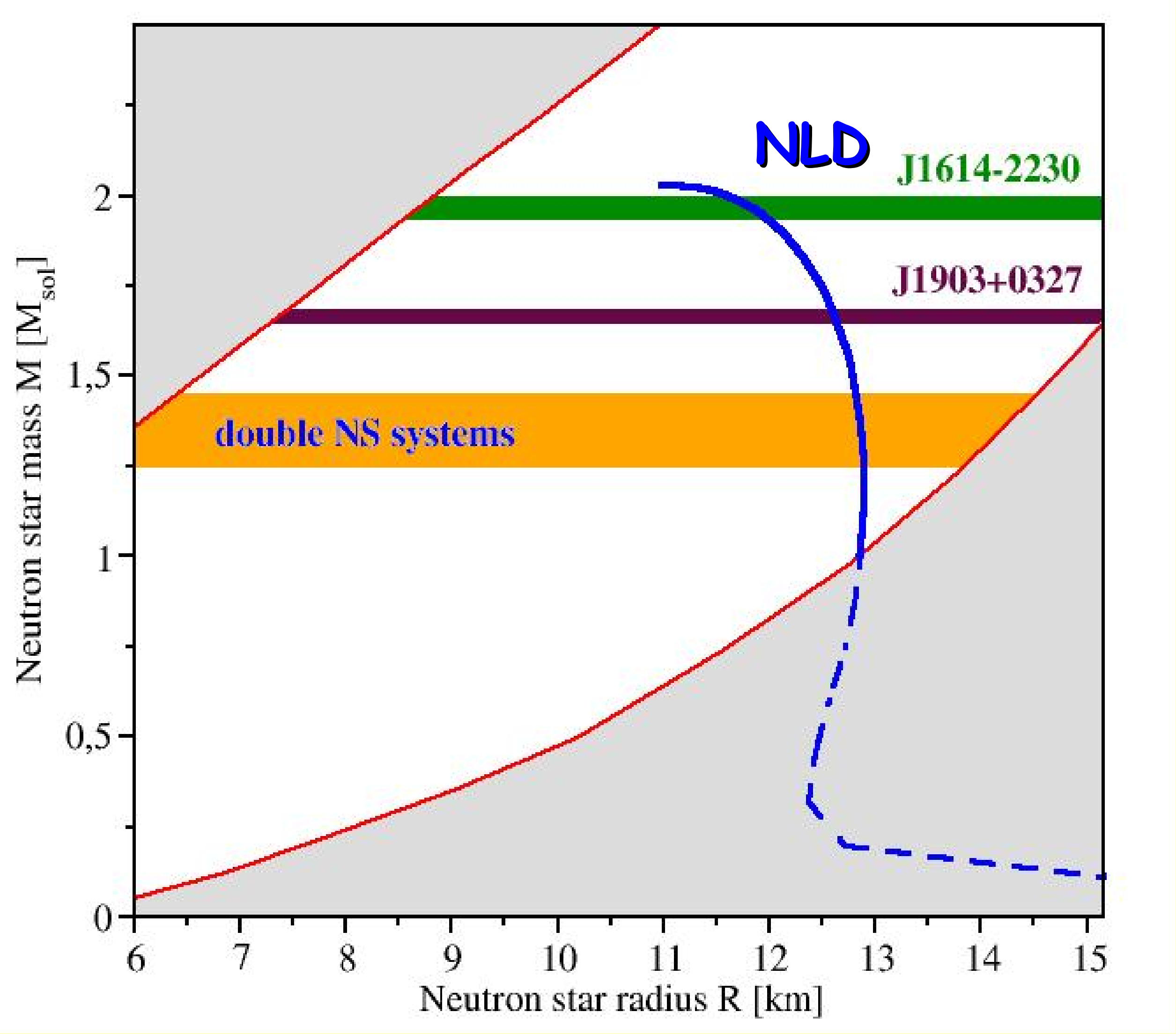
NLD results: NS mass...

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



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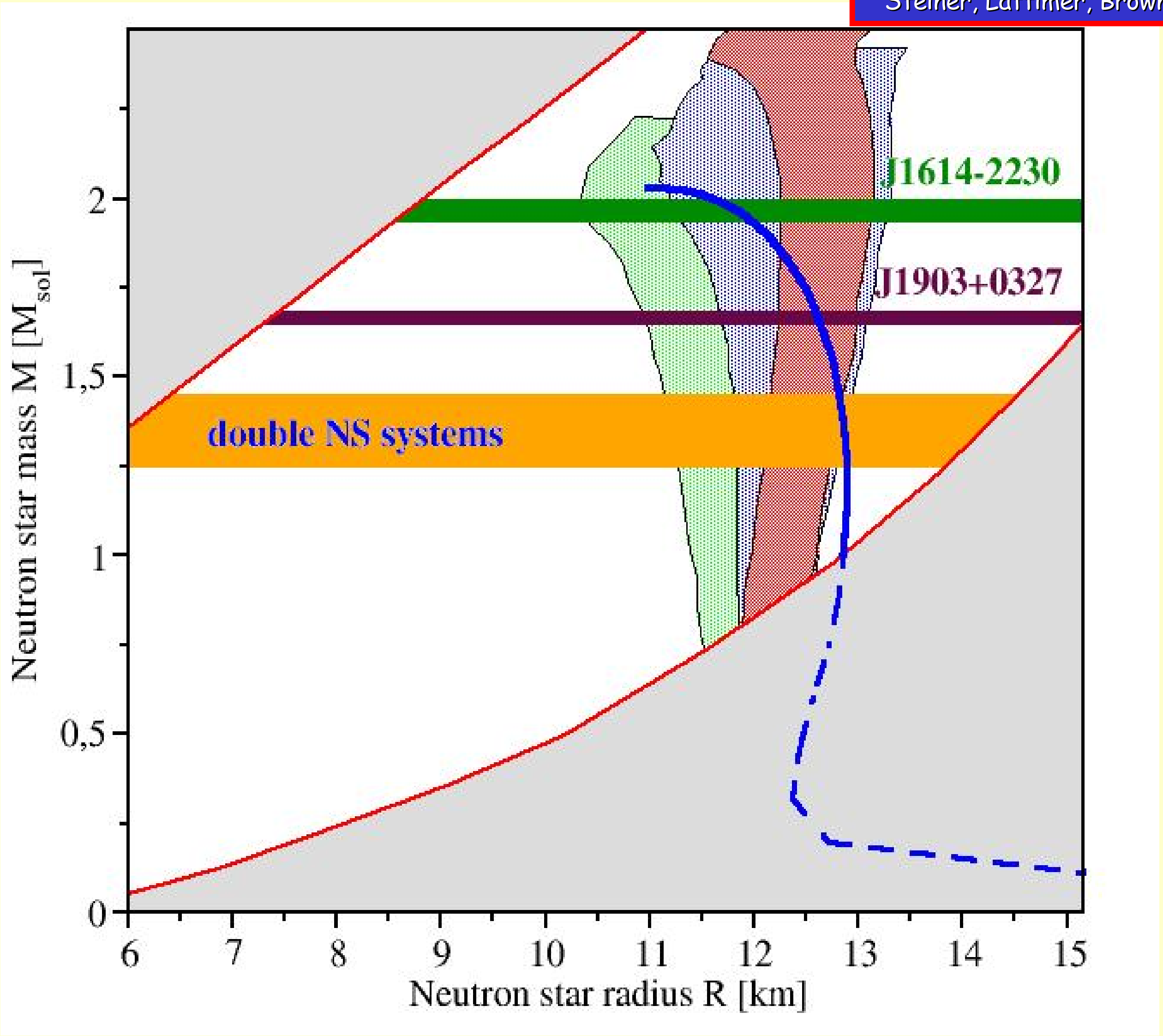
NLD results: NS mass…

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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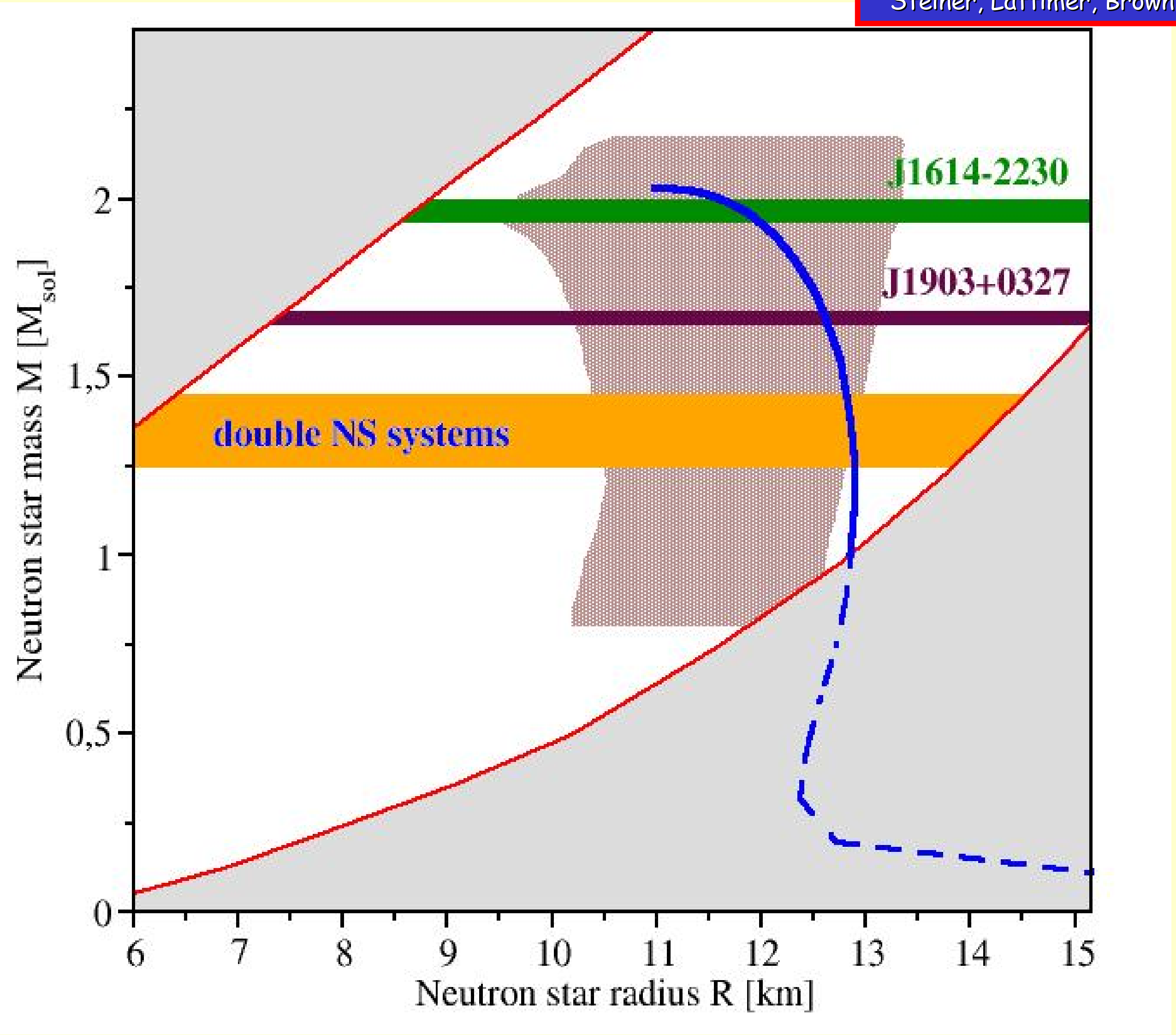
NLD results: NS mass...

Compatible with all observations !

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

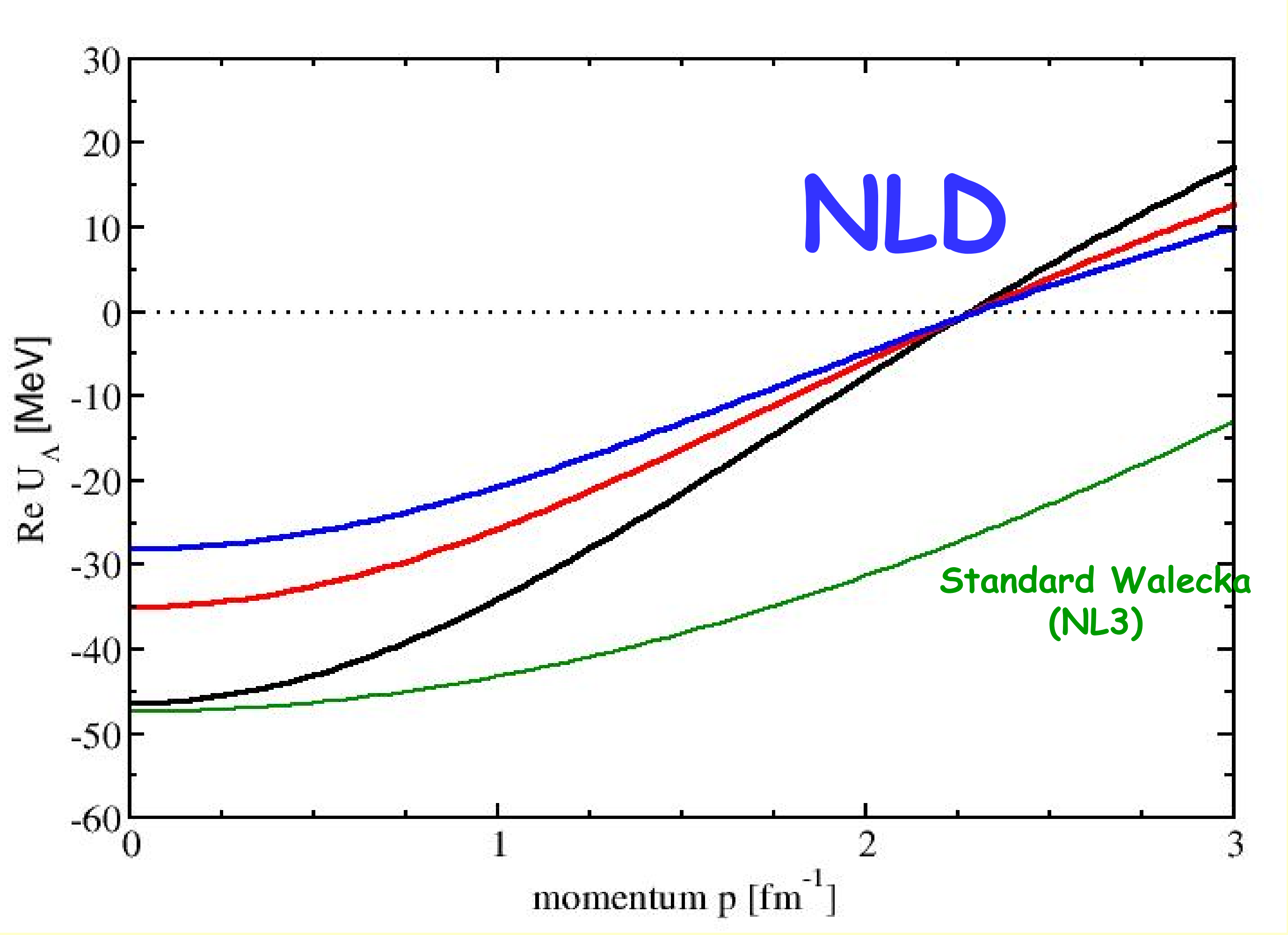


Nucl. Phys. A899 (2013) 133

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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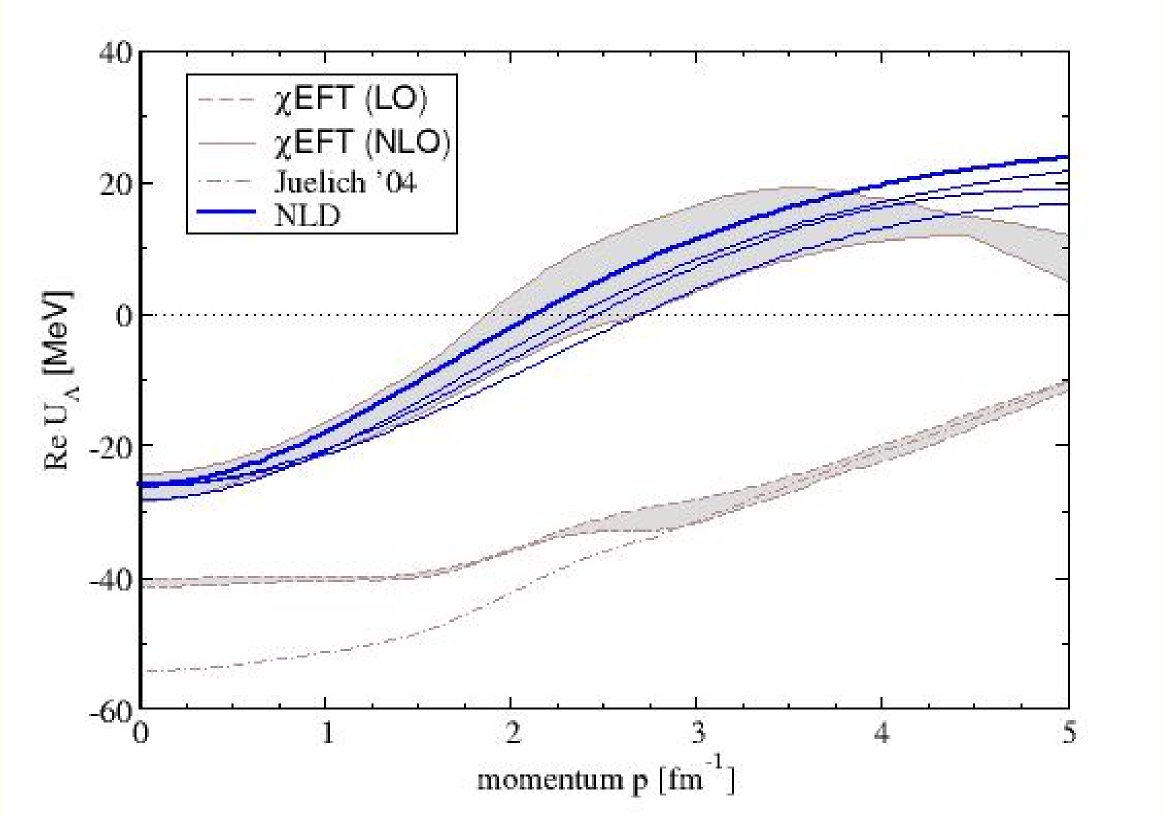

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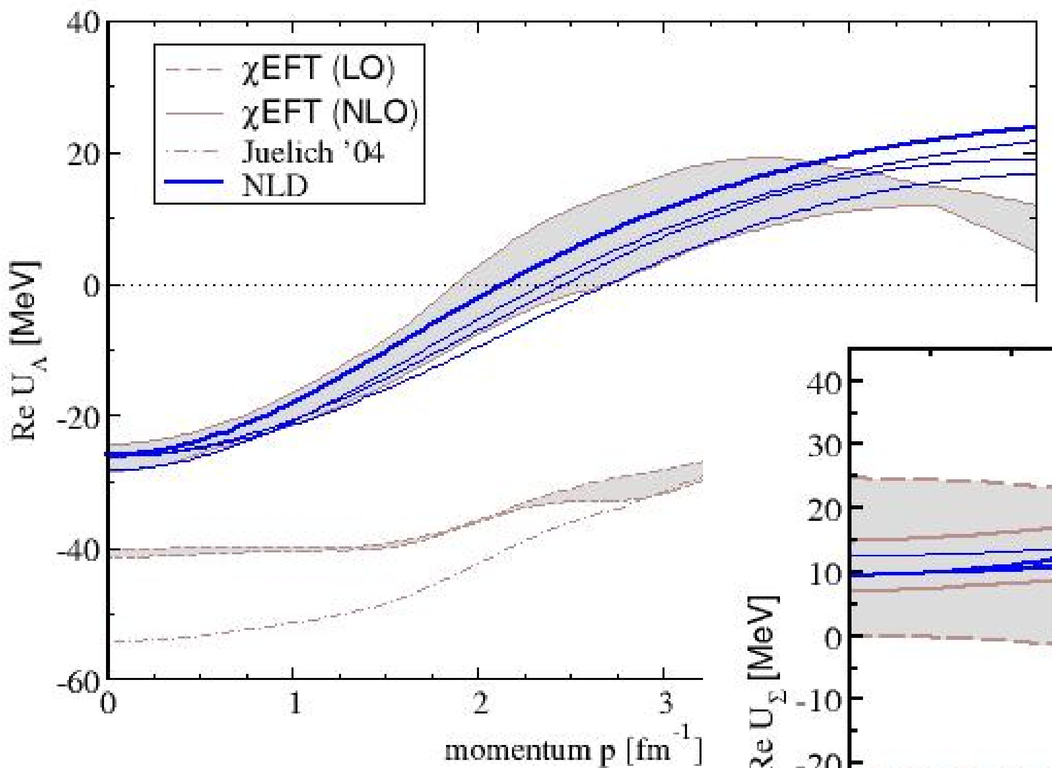

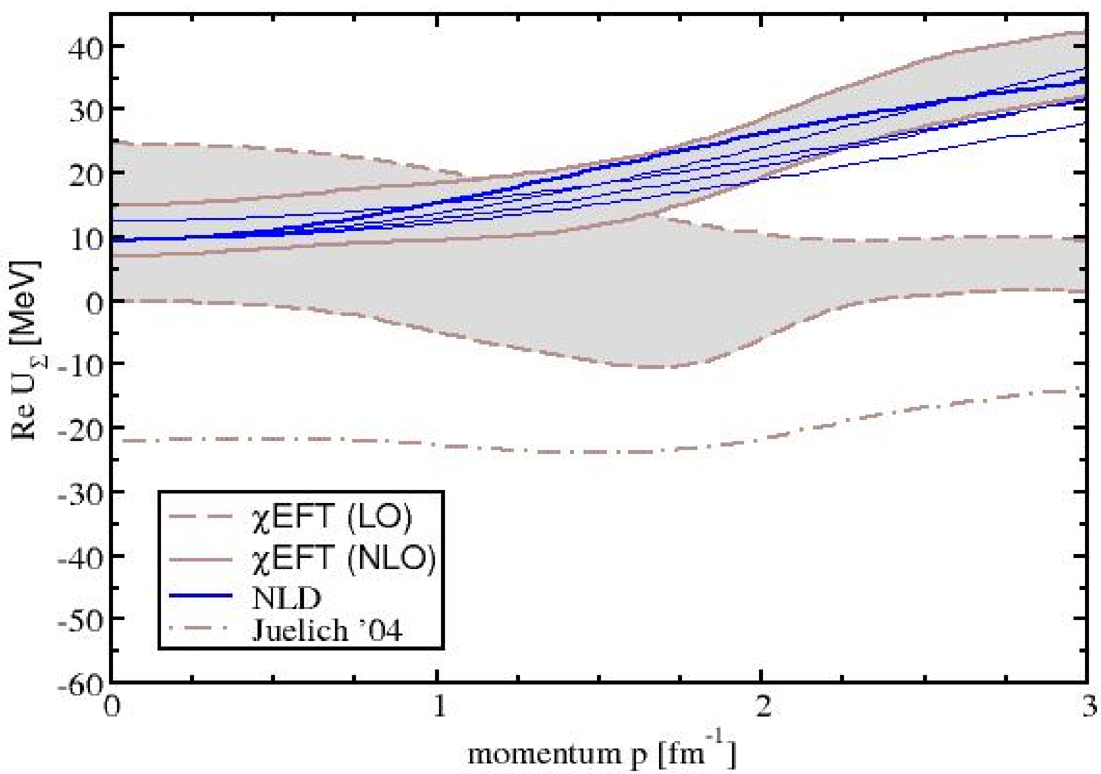

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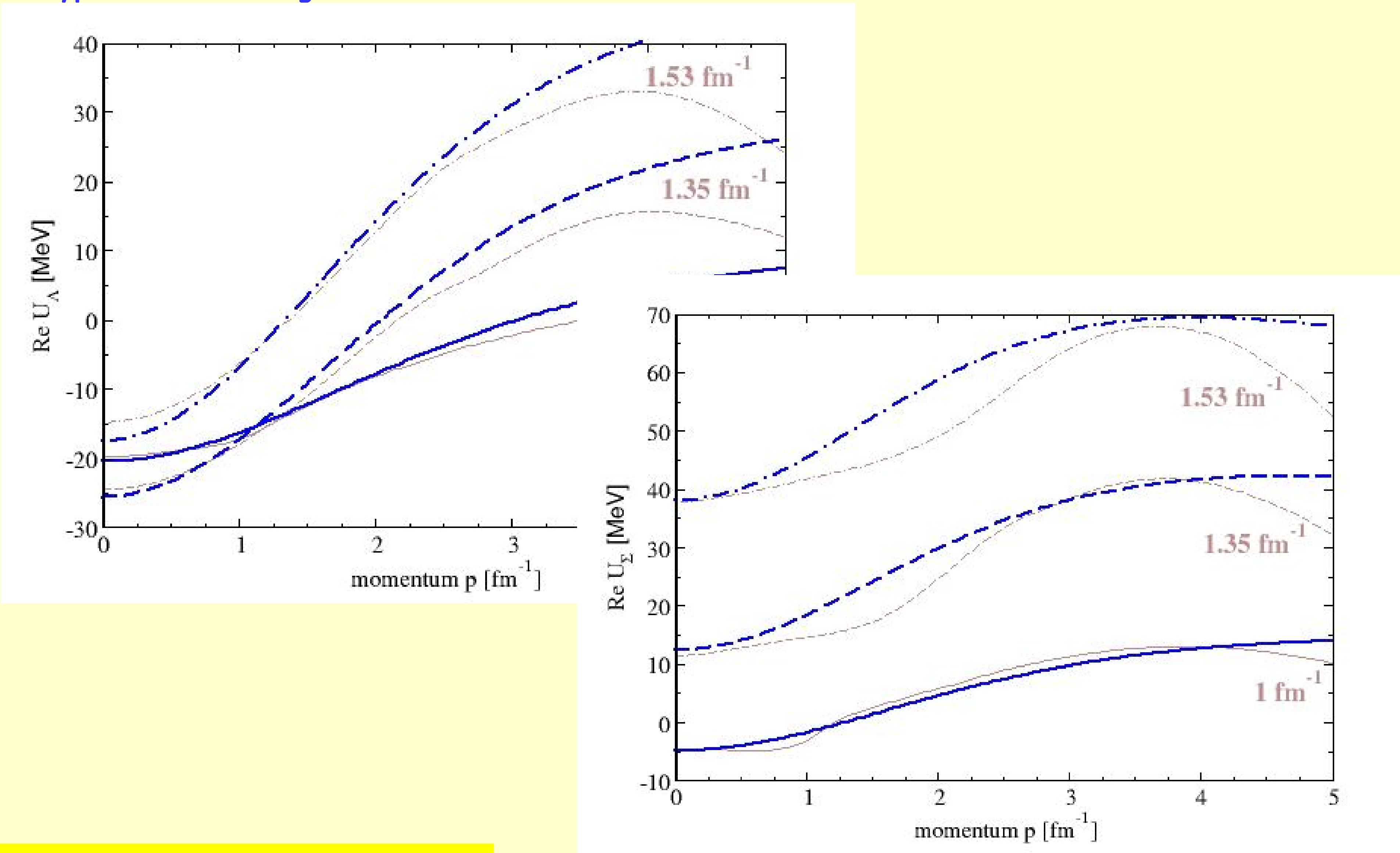


Gaitanos & Violaris, in prep.

Explore in-medium Λ-pot: HADES experiment...

Key Information

- HADES Spectrometer at GSI
- Secondary π^--beam 1.7 GeV/c

	Target	W	C
	Segment Length [mm]	2.4	7.2
	ρ [g/cm^3]	19.3	1.85
	A	183.84	12.011
	Statistics [$x10^8$]	1.69	2.00

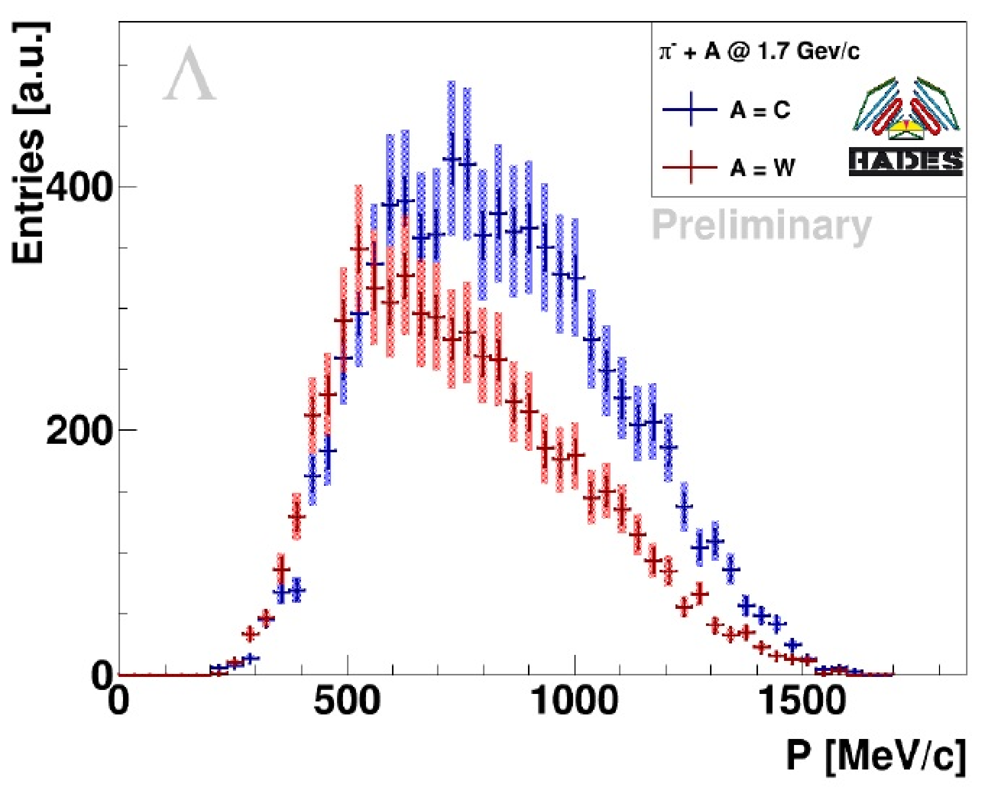
Idea:

- Search for Charge Pattern 2+ 2- ($\Lambda \rightarrow p + \pi^-, K^0 \rightarrow \pi^+ + \pi^-$)
- Make best assignment of bouble π^- occurence by minimizing:
  $\Delta M_\Lambda = M_{INV}(p + \pi^-) - M(\Lambda)_{PDG}$
  $\Delta M_{K0} = M_{INV}(\pi^+ + \pi^-) - M(K0)_{PDG}$
  For all π^- Combination
- Cut on 2D ΔM_Λ vs. ΔM_{K0}

Icons from: https://www.flaticon.com/

Gaitanos & Violaris & HADES, in progress...

Explore in-medium Λ-pot: HADES new data...



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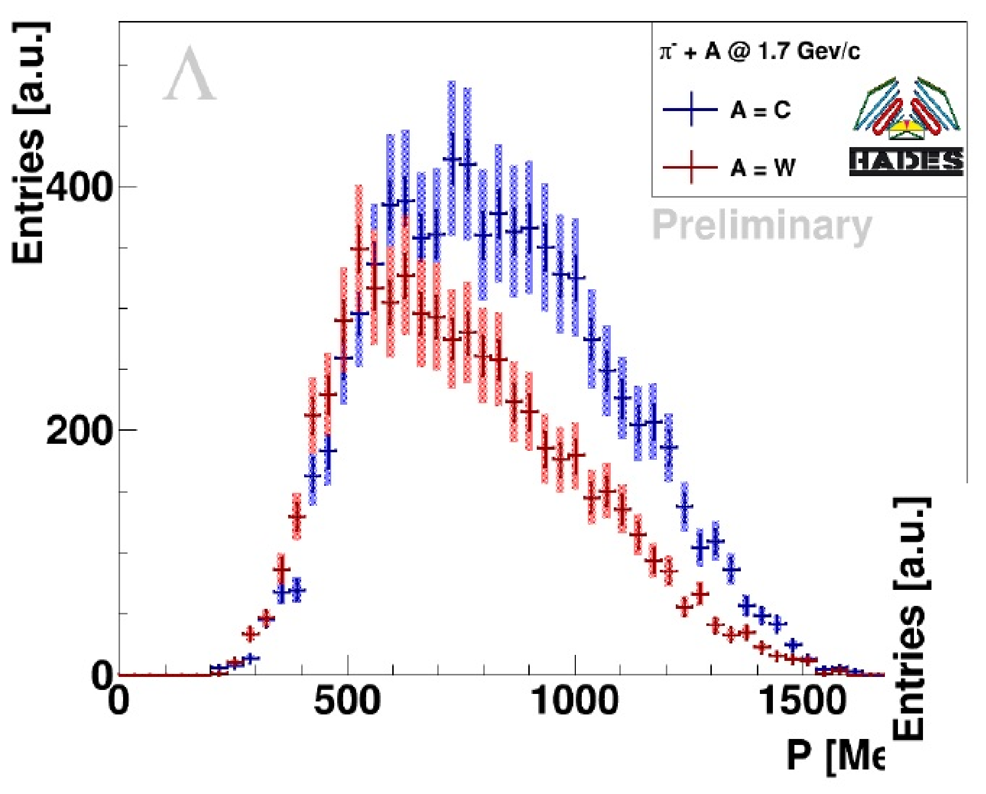

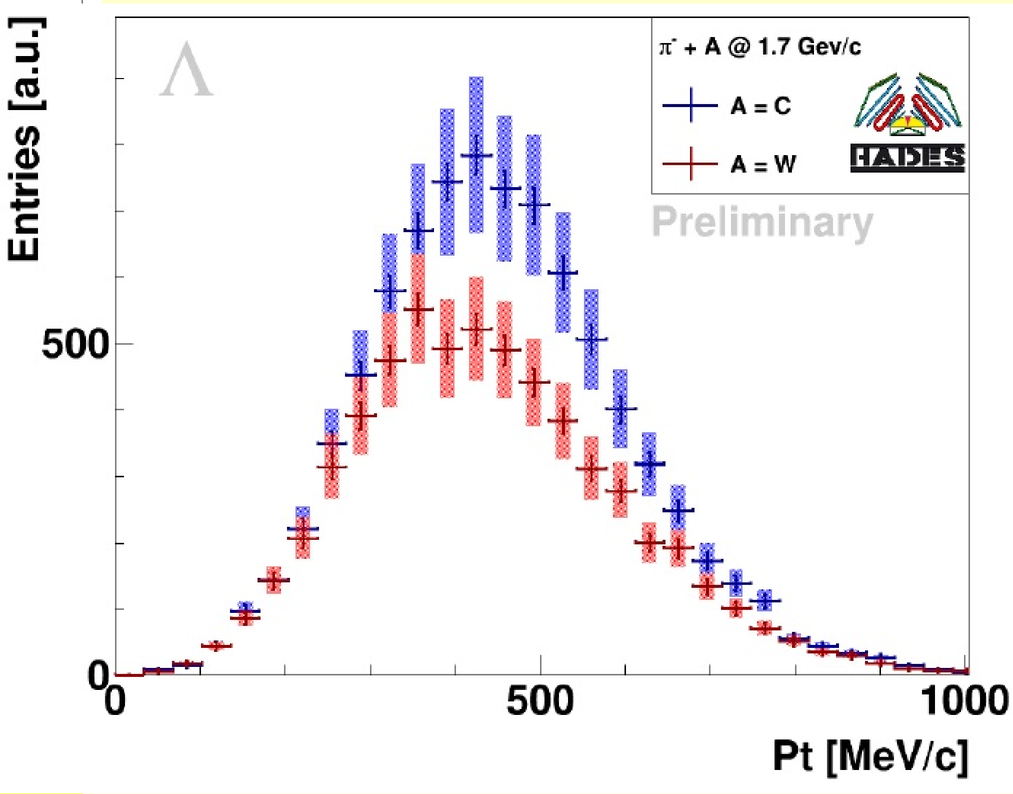

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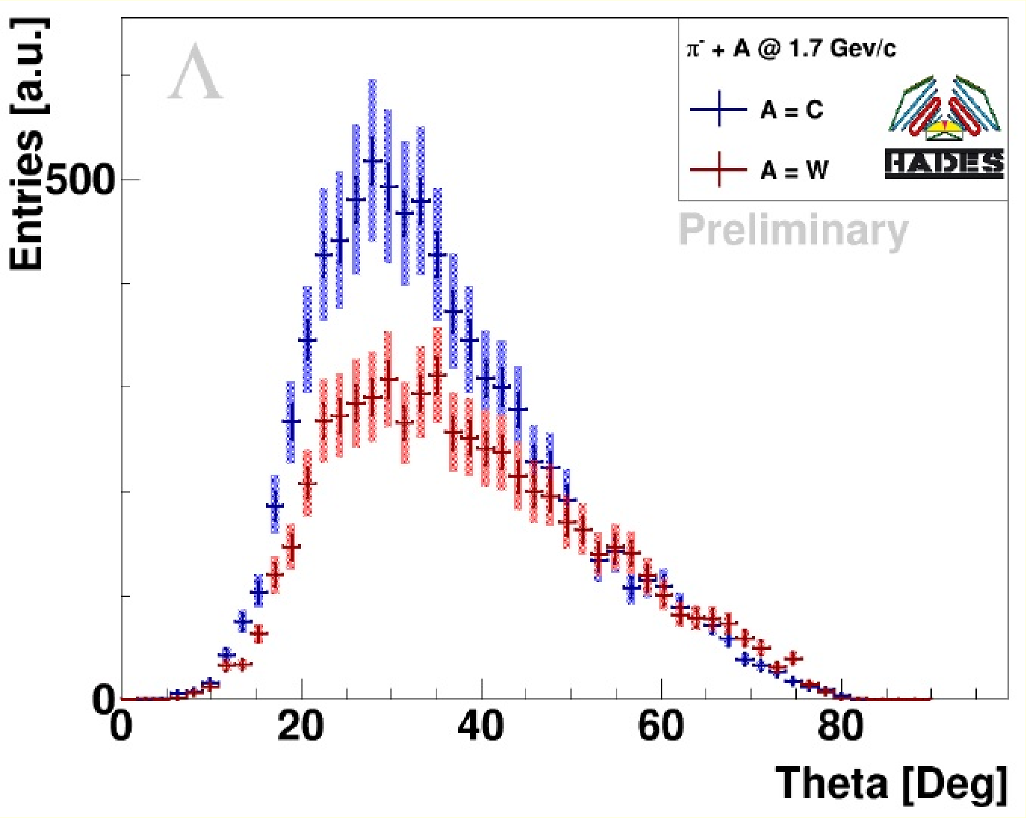

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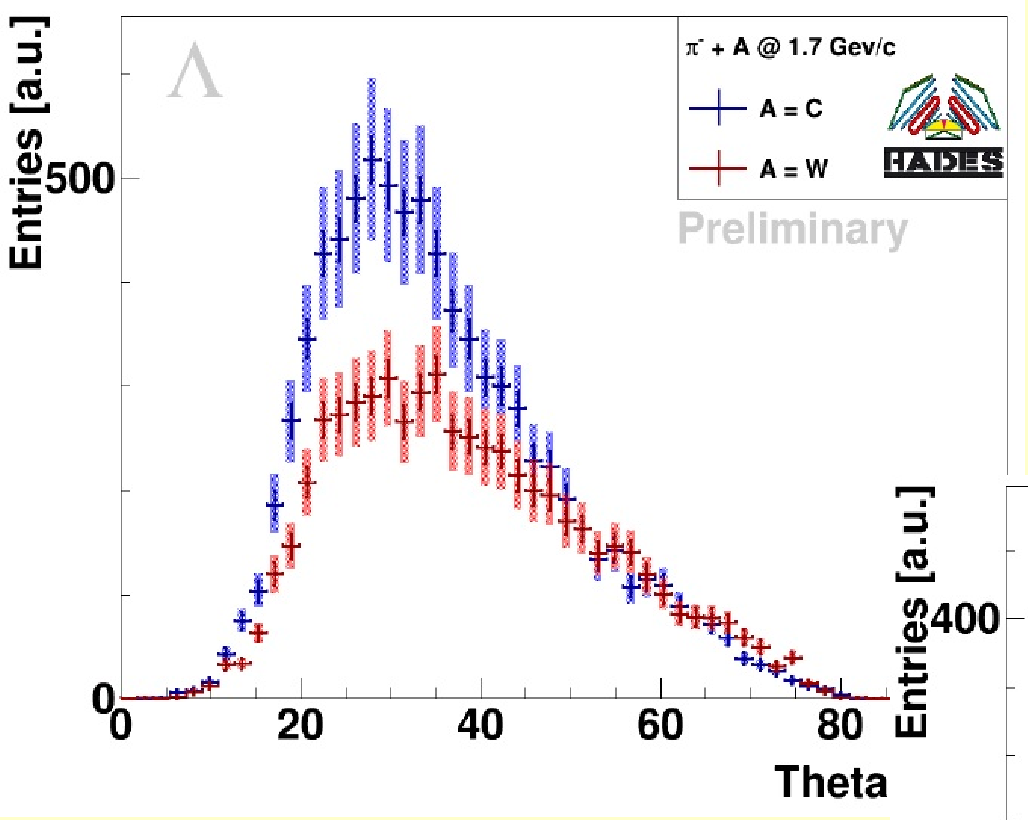
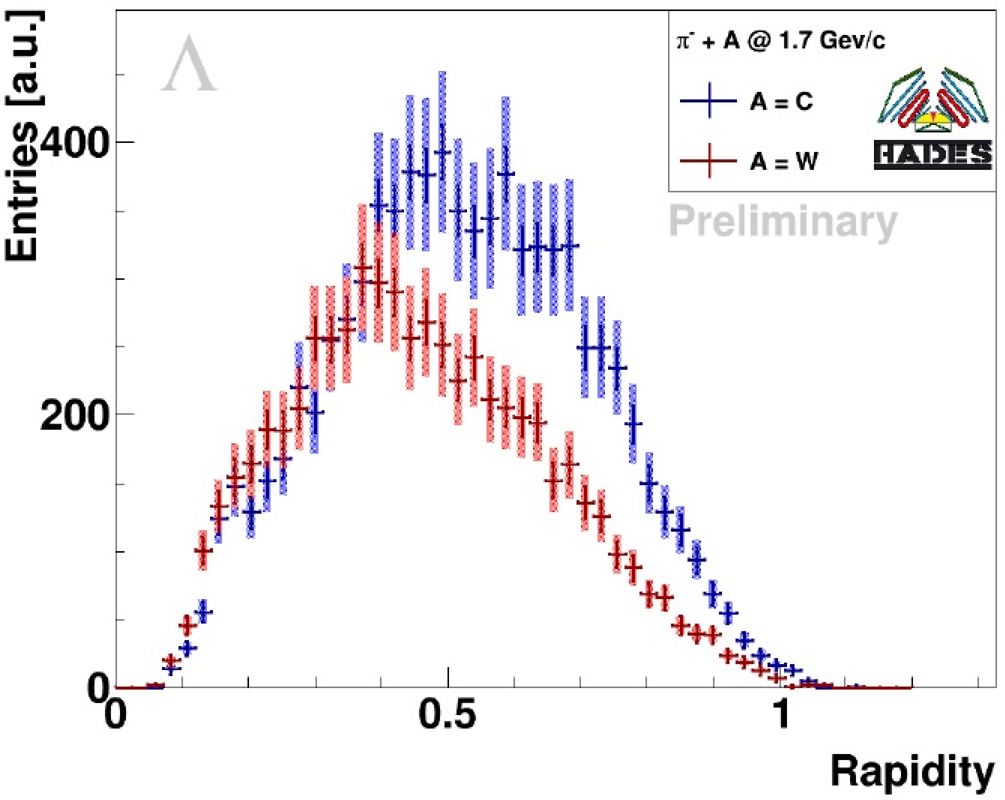
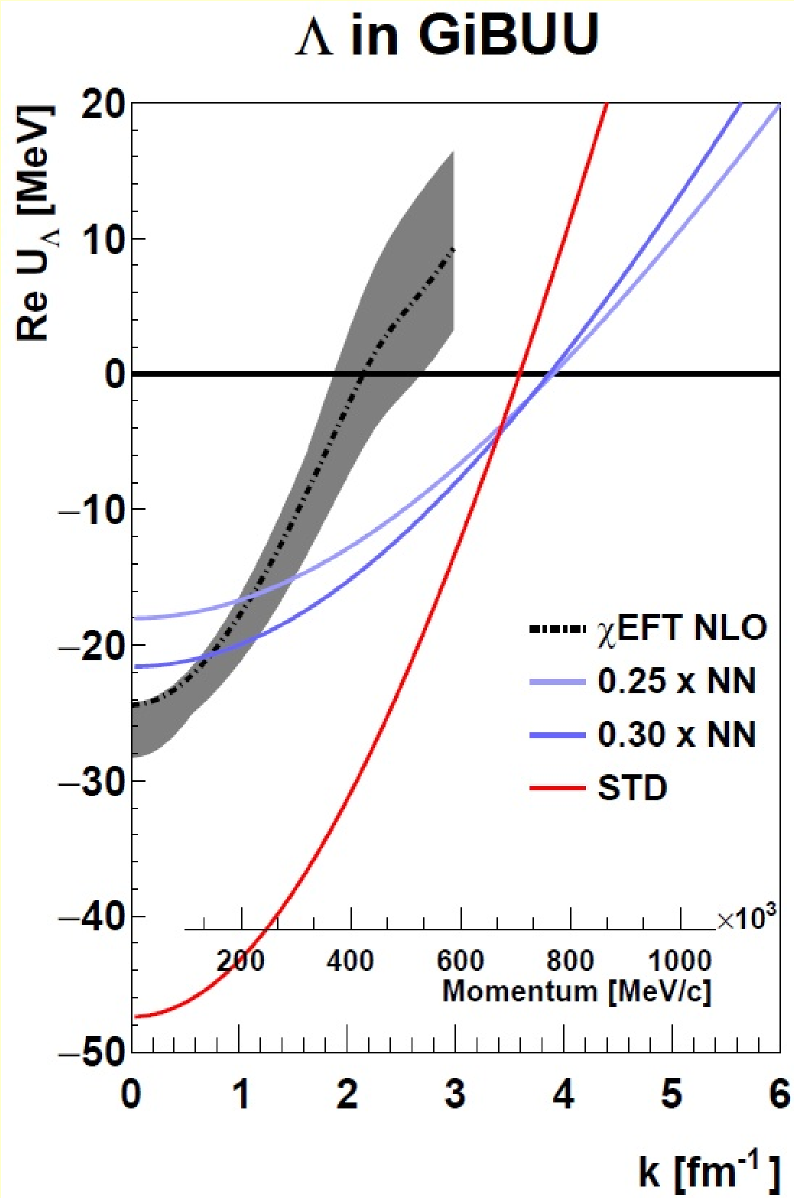
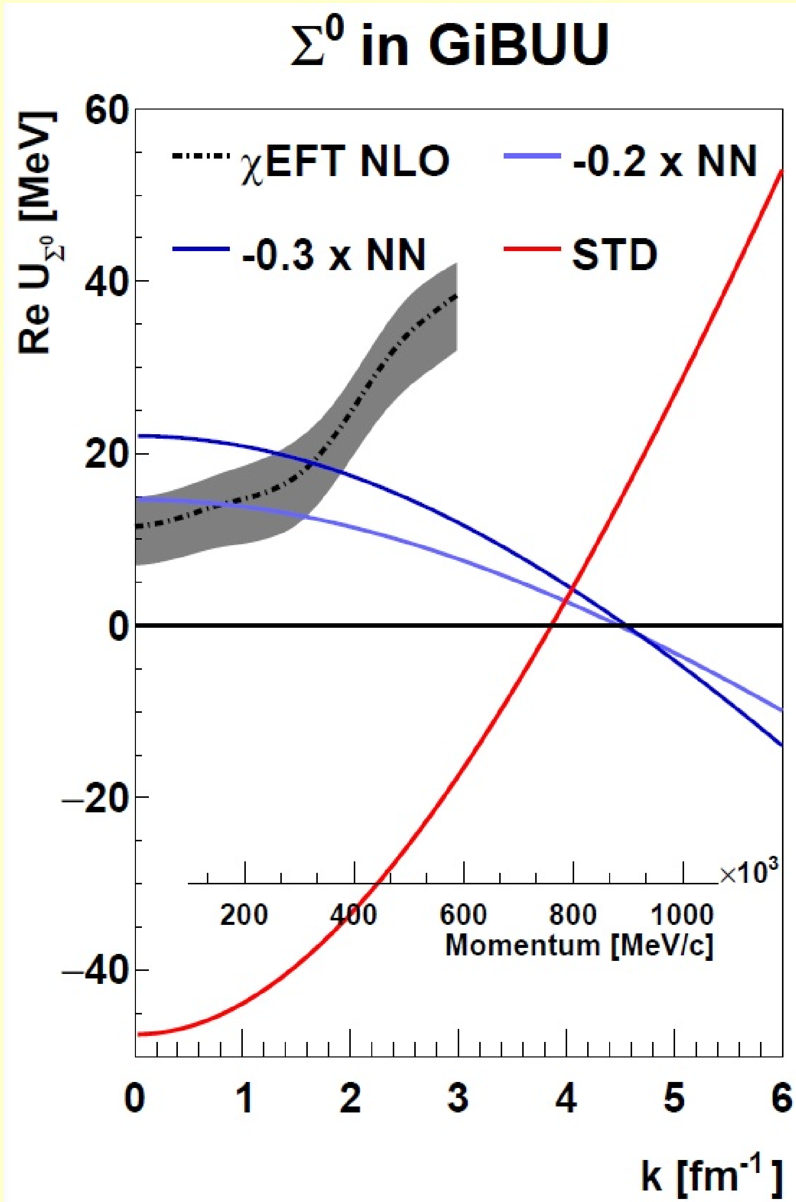




Gaitanos & Violaris & HADES, in progress...

Hyperon potentials & new HADES data: the input...





Gaitanos & HADES, submitted to Phys. Rev. Letters...

Hyperon potentials & new HADES data: the comparison...

PRELIMINARY

Gaitanos & HADES, submitted to Phys. Rev. Letters...

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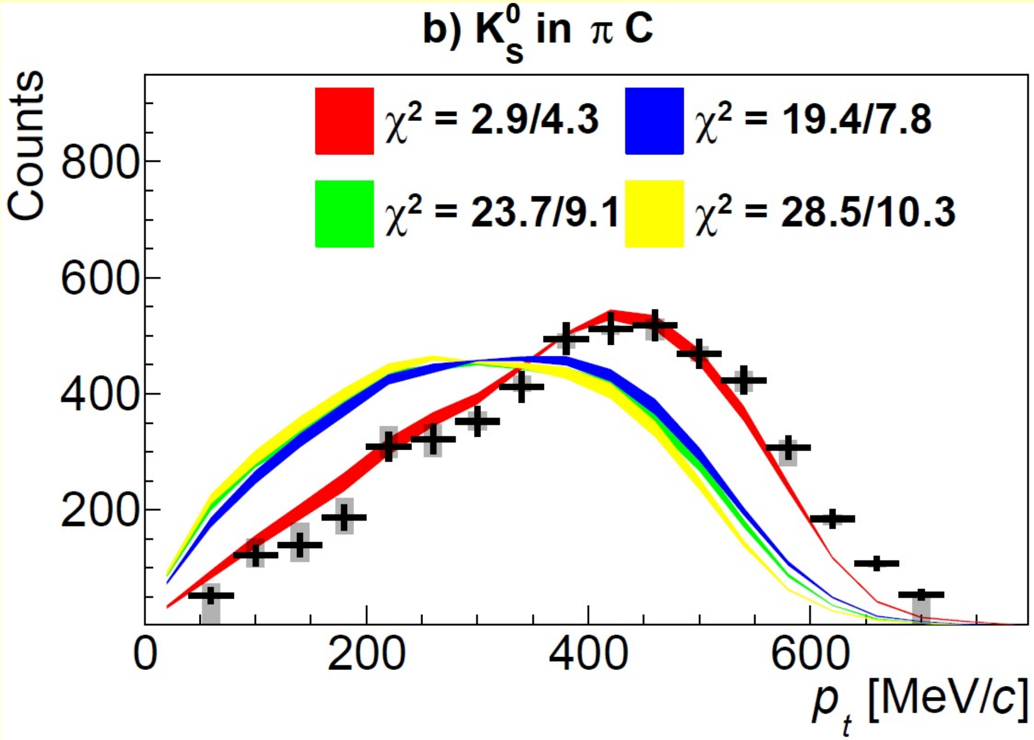


PRELIMINARY

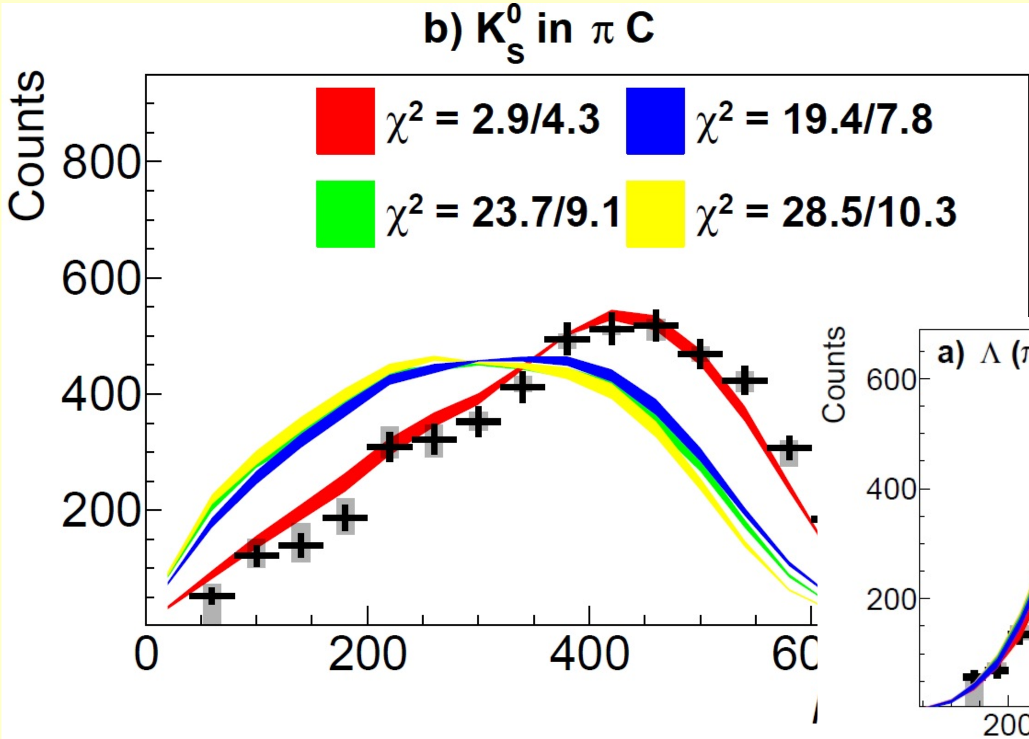
$U_{\Lambda,\Sigma}$ assumptions vs data

Red (STD) → Λ,Σ attractive

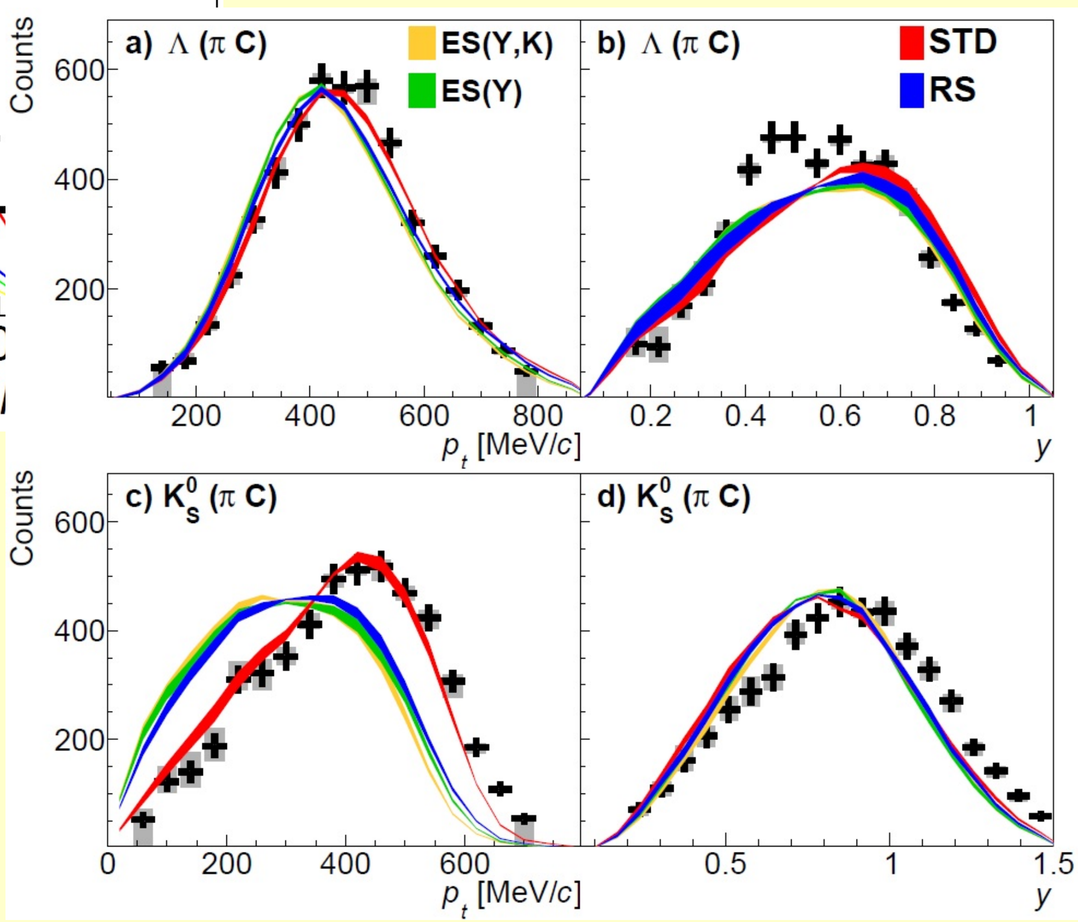
Blue (RS) → Σ repulsive!

Gaitanos & HADES, submitted to Phys. Rev. Letters...

Hyperon potentials & new HADES data: the comparison...



PRELIMINARY



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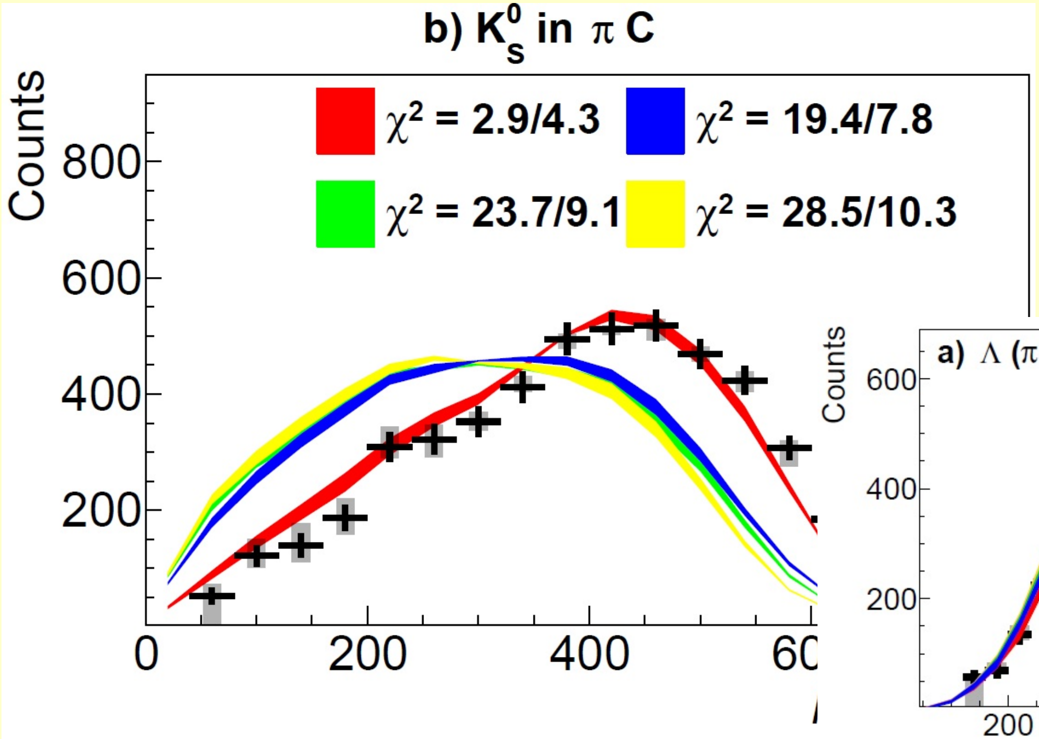

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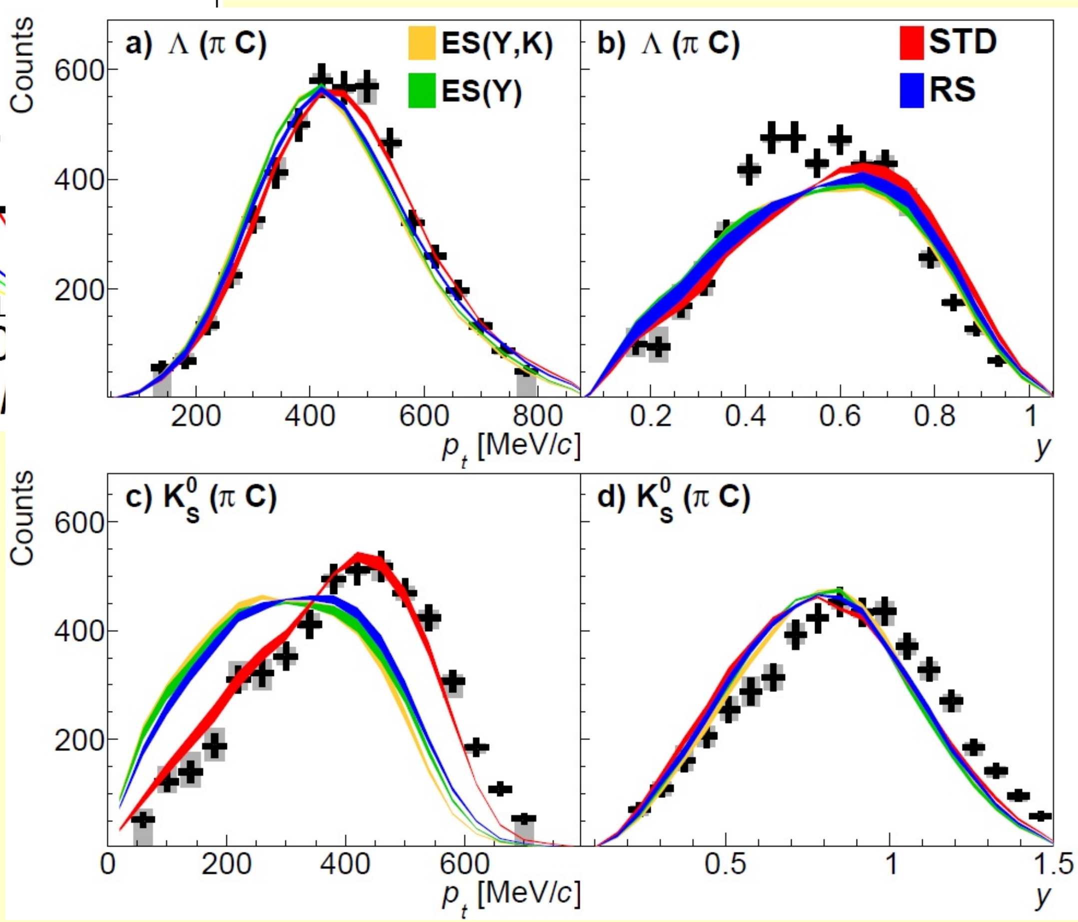
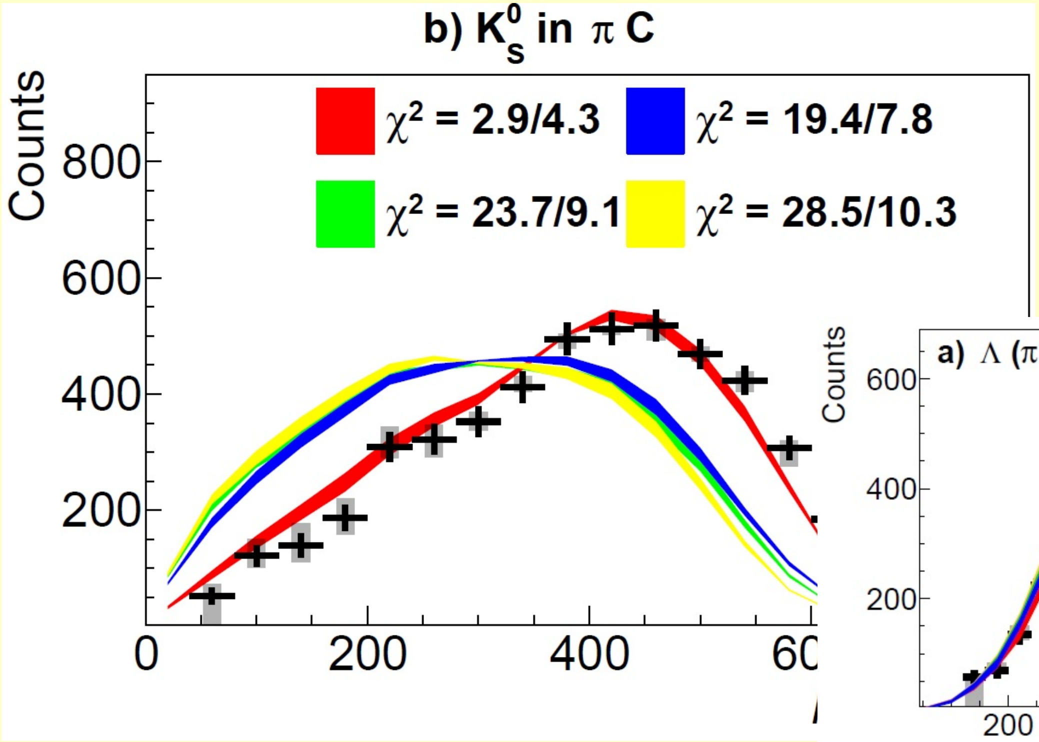


Conclusion

Σ-repulsive potential not supported by new precise HADES measurements

Gaitanos & HADES, submitted to Phys. Rev. Letters...

Hyperon potentials & new HADES data: the comparison...



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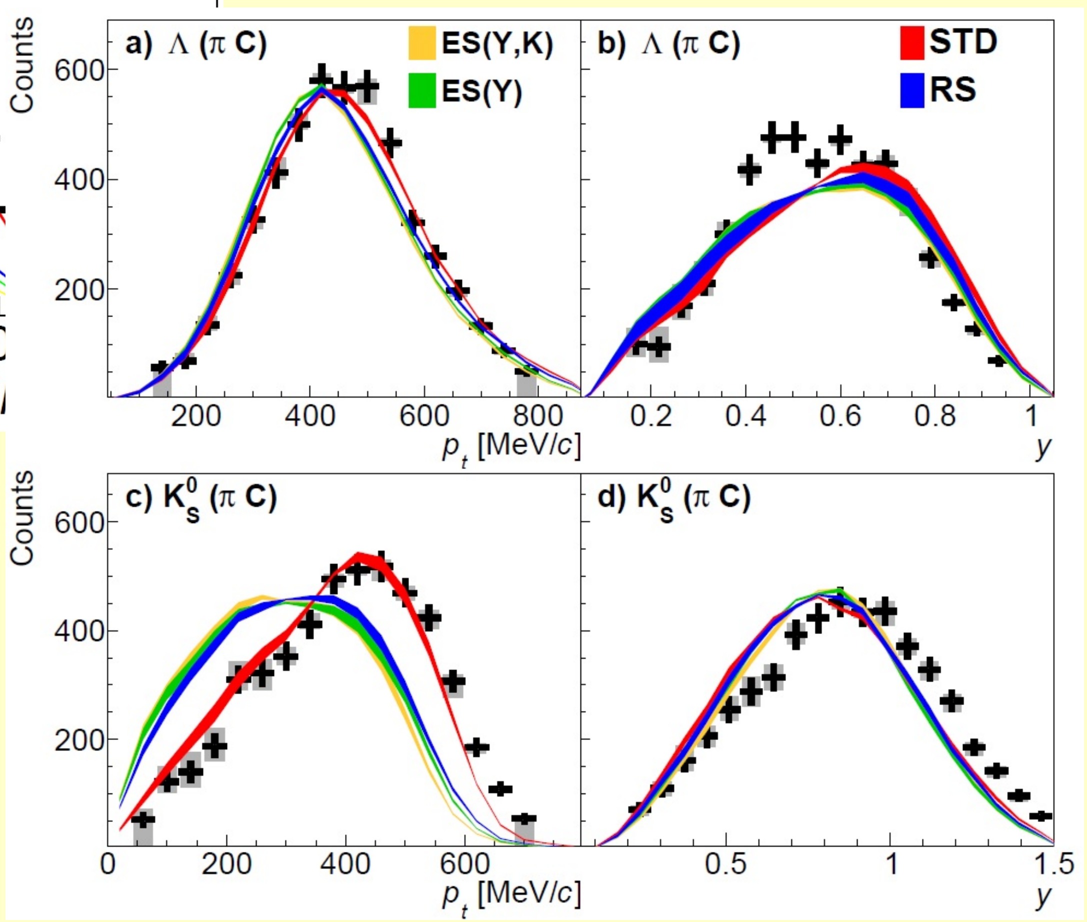


Consequences

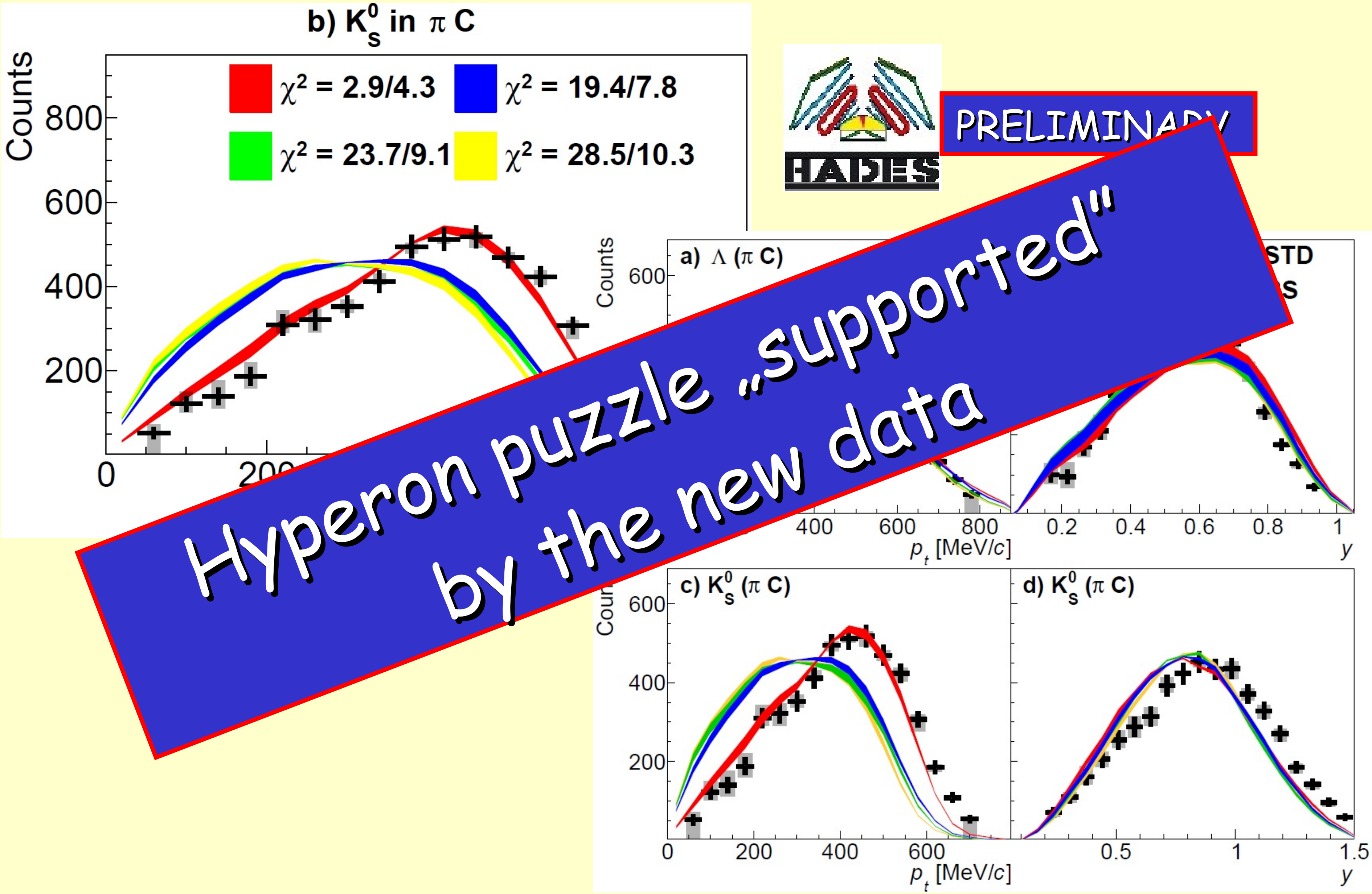
→ EoS with hyperons seems soft

→ Soft EoS for neutron stars,

if hyperons included

Gaitanos & HADES, submitted to Phys. Rev. Letters...

Hyperon potentials & new HADES data: the comparison…

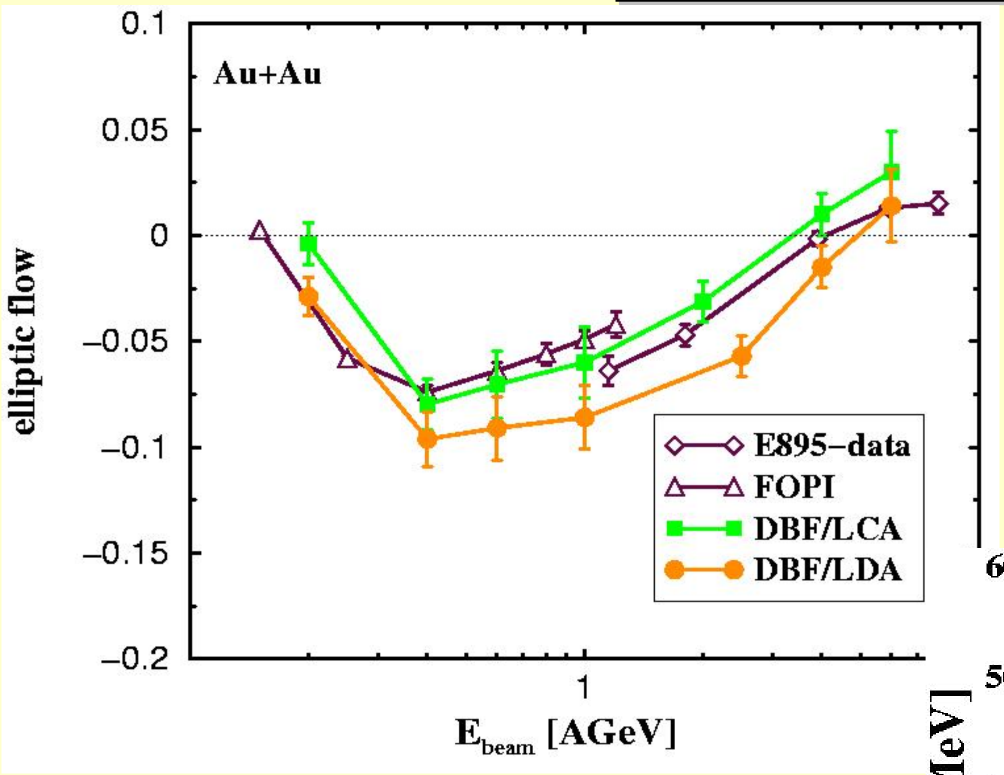


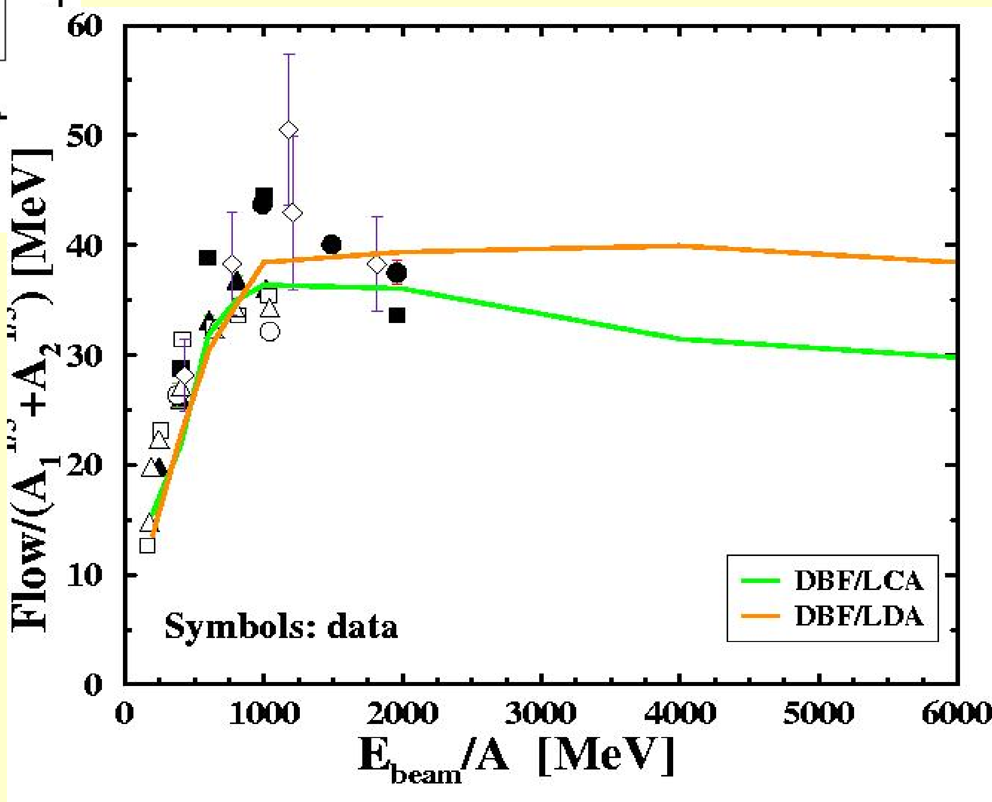
Hyperon puzzle „supported" by the new data

Gaitanos & HADES, submitted to Phys. Rev. Letters...

Backup slides

Nuclear EoS from HIC





Gaitanos, Fuchs, Wolter, Faessler,
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