

Title: Equation of State and Neutrino Opacity in Core Collapse Supernova

Date: Jun 20, 2011 11:00 AM

URL: <http://pirsa.org/11060014>

Abstract: We present new equations of state (EOS) of nuclear matter for a wide range of temperatures densities and proton fractions for use in supernova and neutron star merger simulations. We employ a full relativistic mean field (RMF) calculation for matter at intermediate density and high density and the Virial expansion of a nonideal gas for matter at low density. We tabulate the resulting EOS in the temperature range $T = 0 - 80$ MeV the density range $n_B = 10^{-10} - 10^2$ cm⁻³;

Nuclear Equation of State and consistent neutrino opacity

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Los Alamos National Lab, USA

“Microphysics in Computational Relativistic Astrophysics”

Perimeter Institute, Waterloo, Canada

June 20-24, 2011

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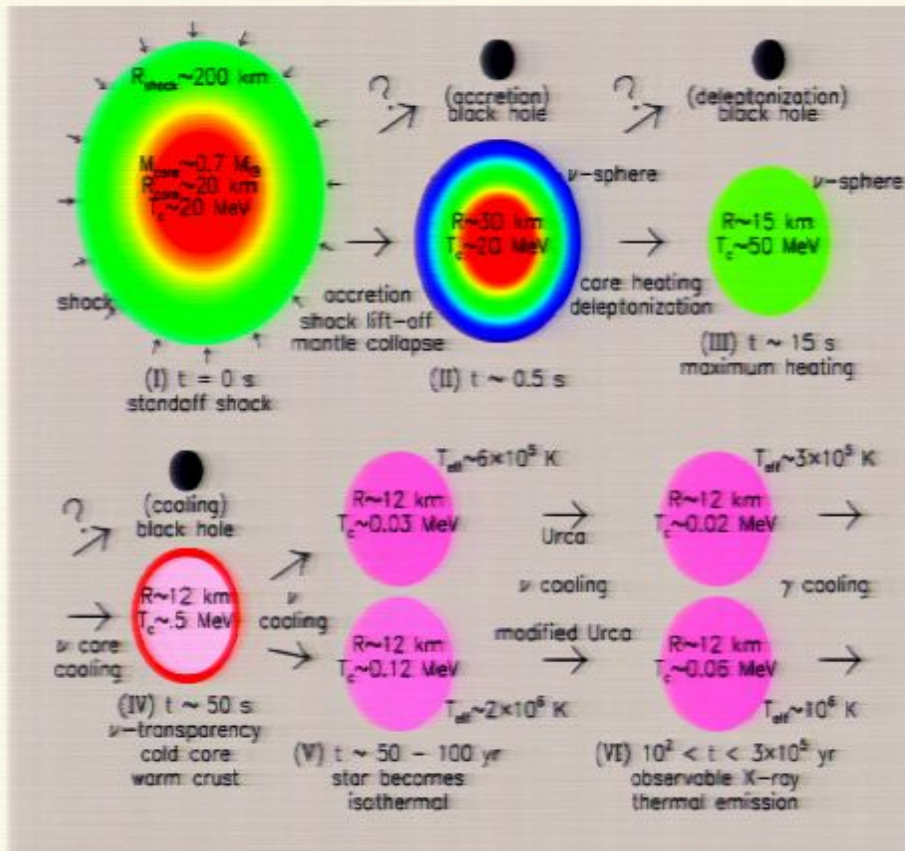
Outline

- Introduction
- Composition of matter
- Methods to construct EOS
- Constraints: nuclear exp., observation, micro. cal.
- Consistent neutrino opacity
- Conclusions

Actual Size



Introduction: supernova



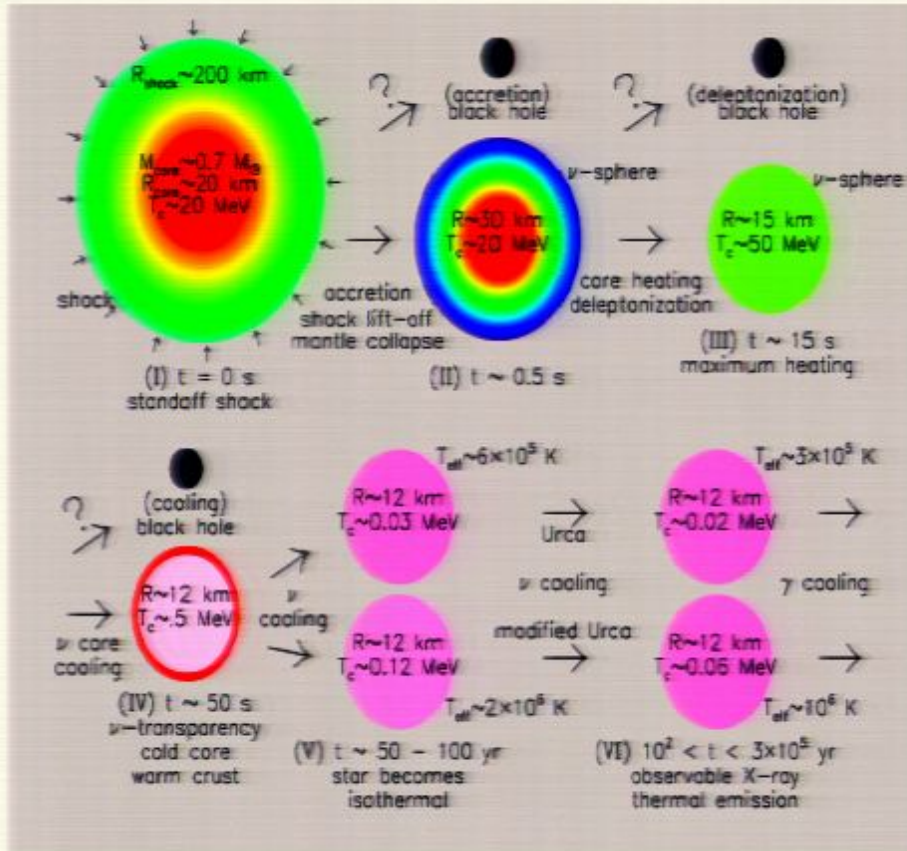
- GR Energy: $3 \cdot 10^{53}$ ergs
 $\sim 10^{58}$ ν (~ 15 MeV)
 ~ 20 events detected from SN1987A
- Explosion of mantle: $\sim 10^{51}$ ergs
- How ν -matter reactions transfers energy and leads to explosion of mantle is crucial.
- We need to know the EOS
- ν -matter reactions

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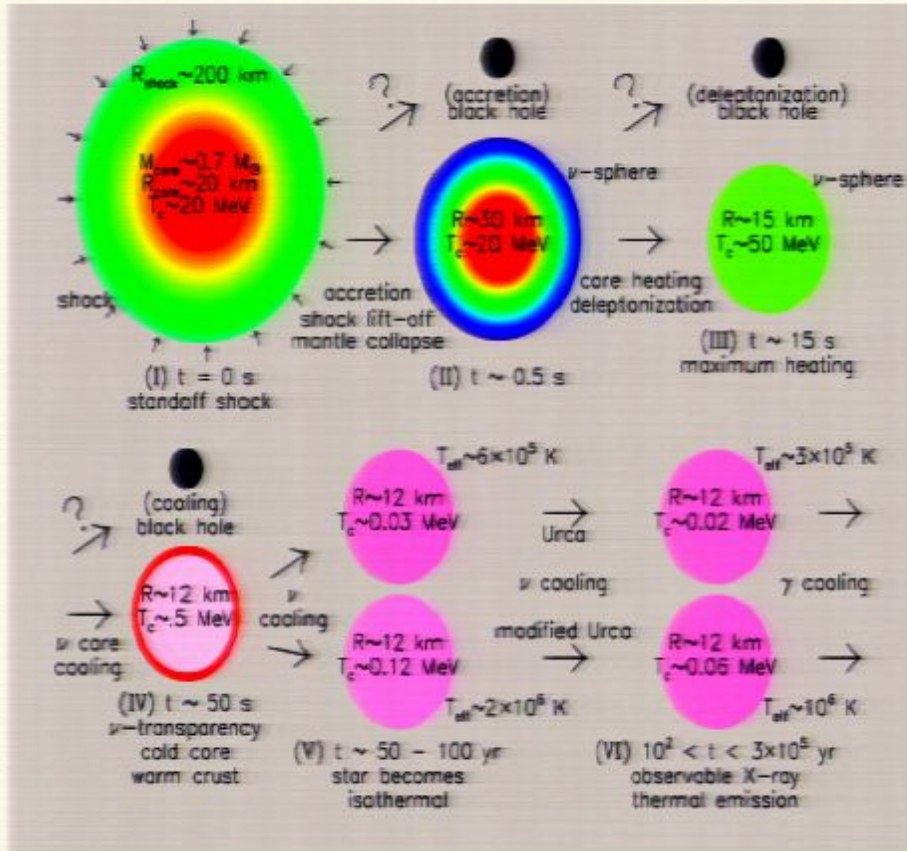
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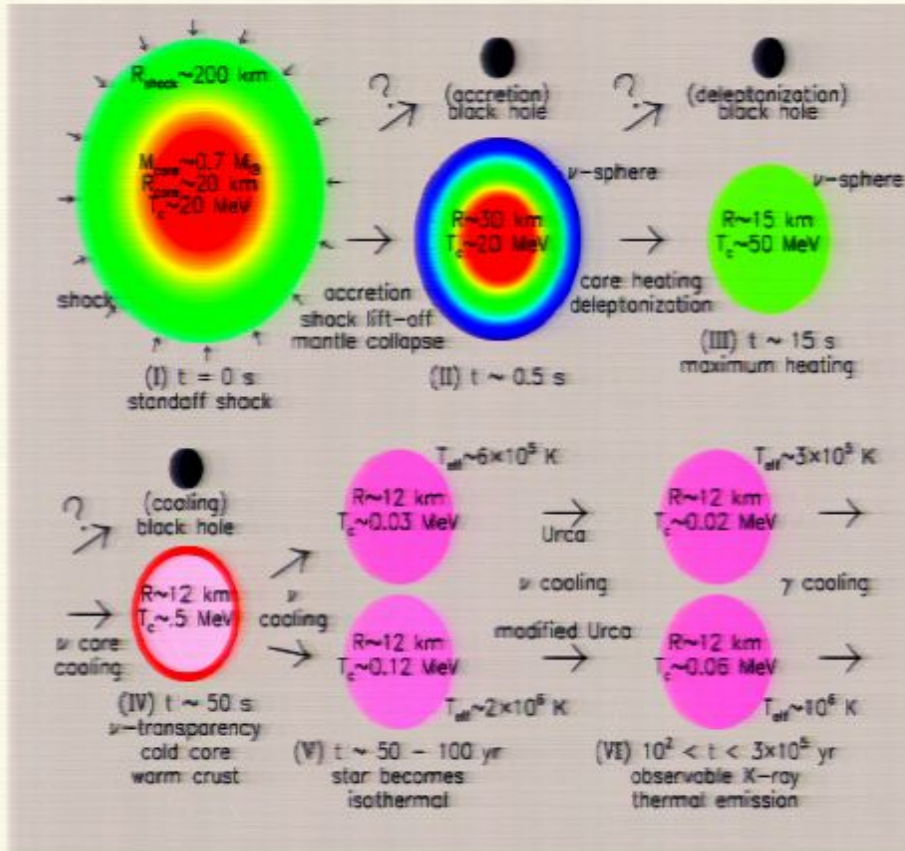
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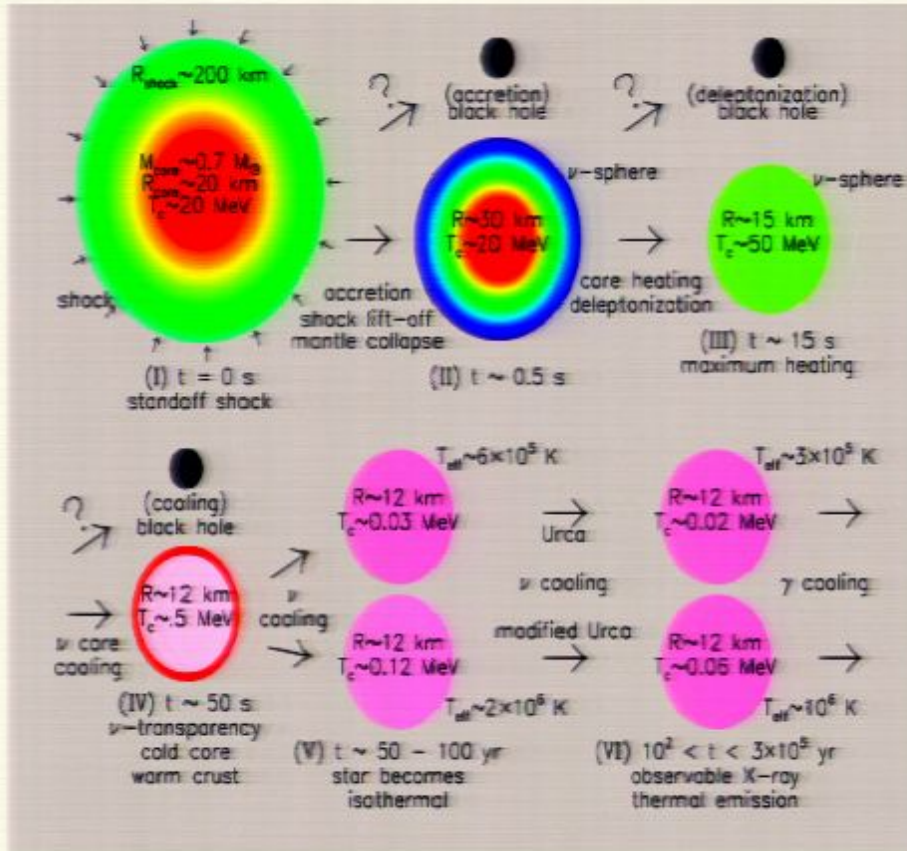
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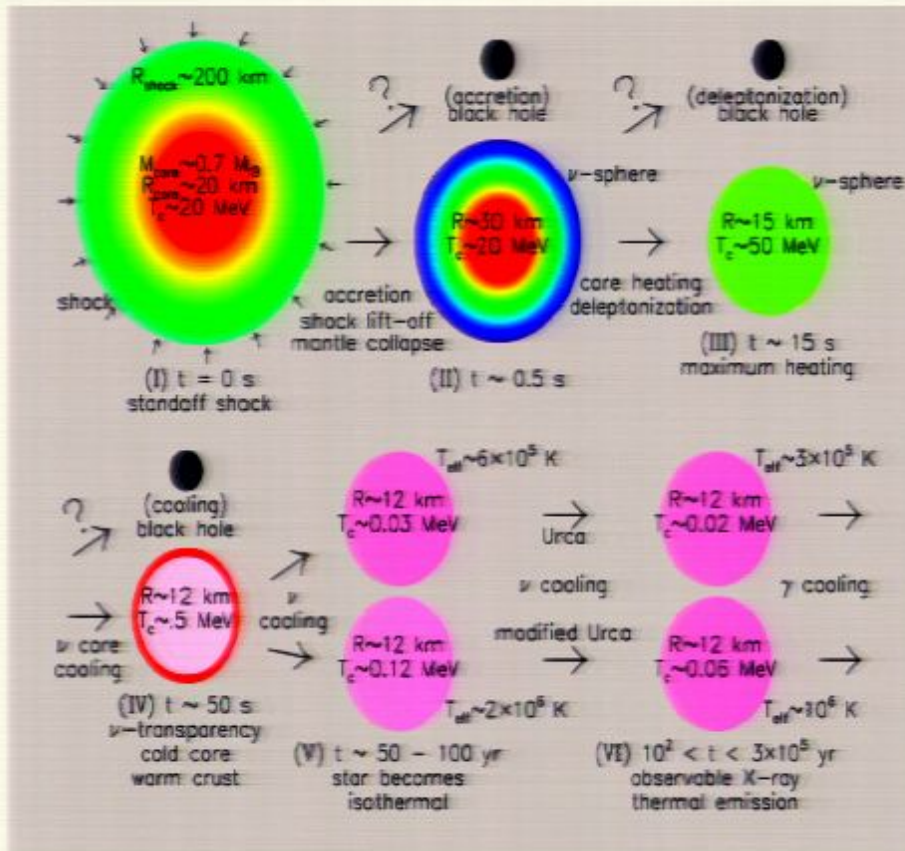
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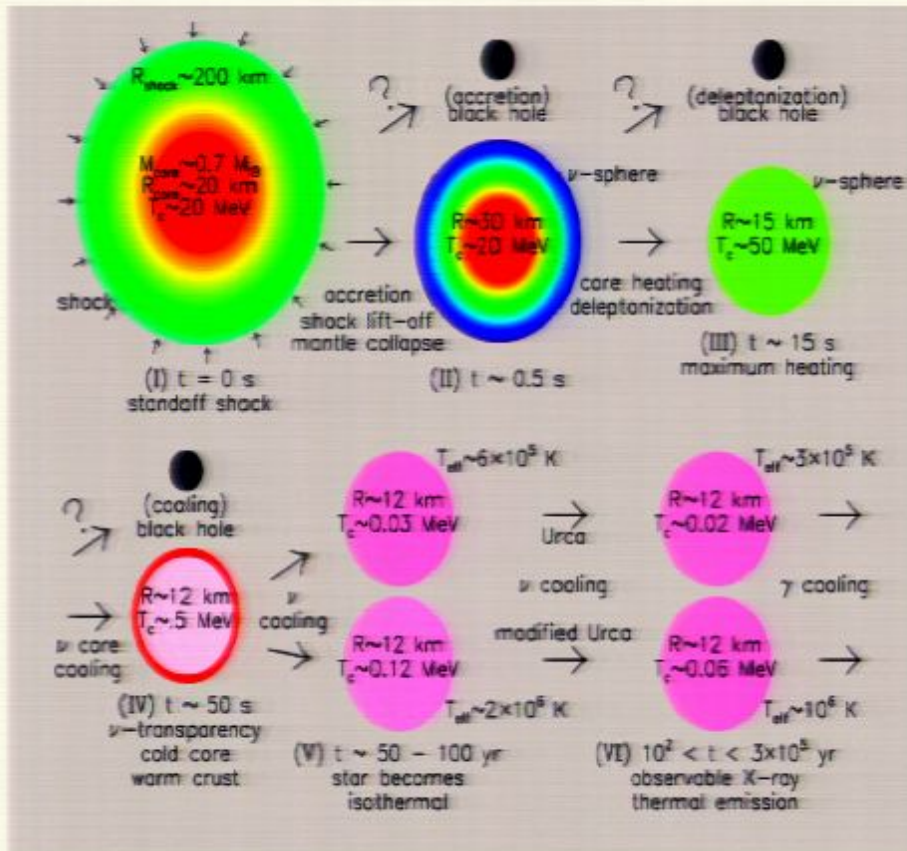
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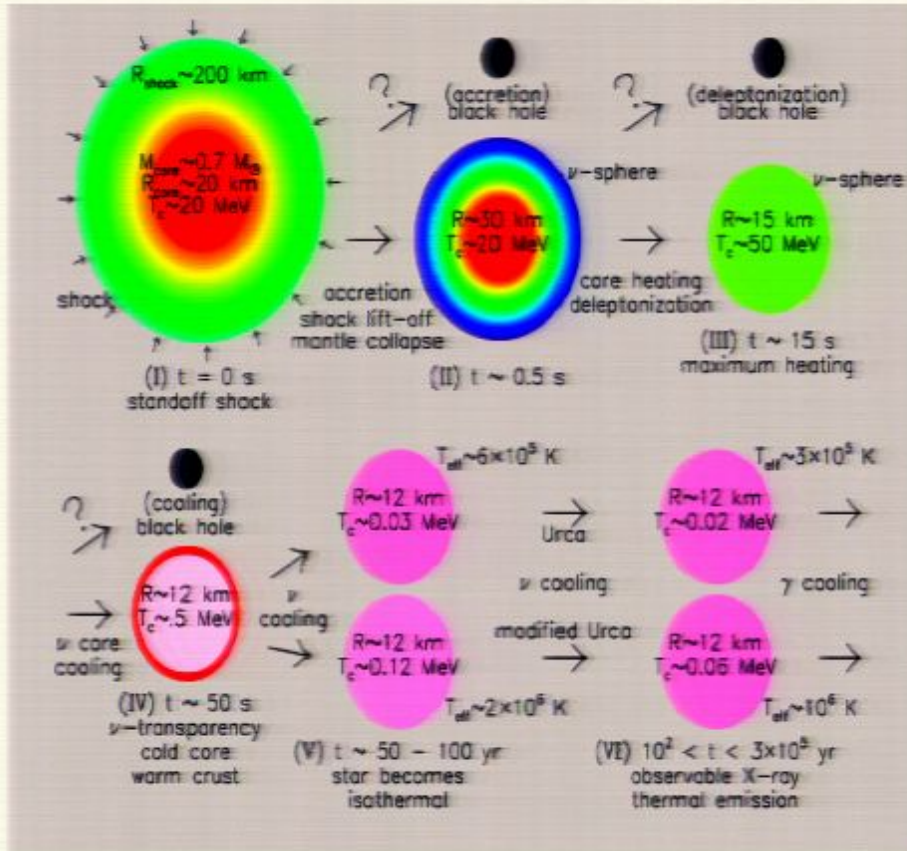
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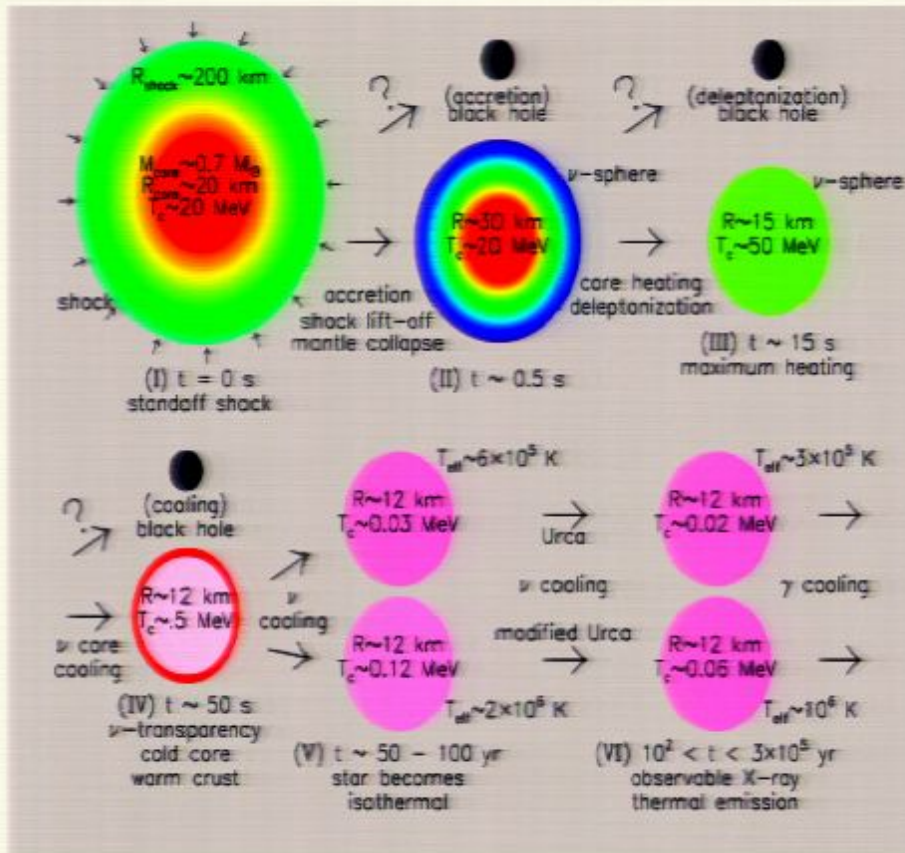
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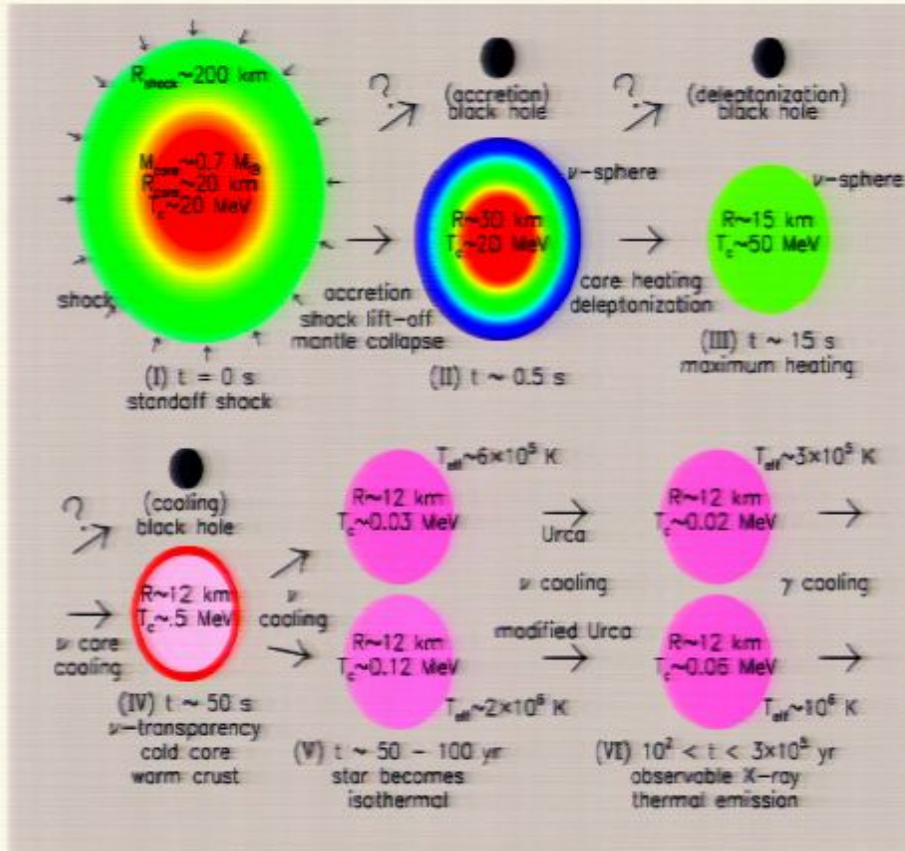
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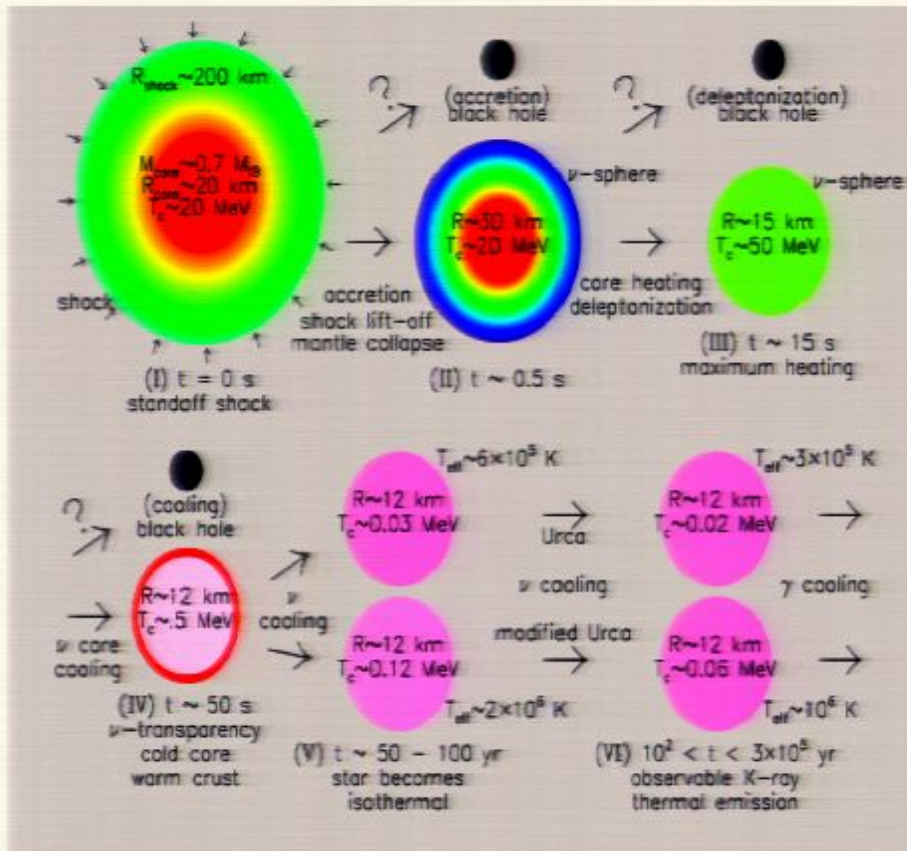
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Baryon Density [fm^{-3}]	1E-13	1E-3	1E0
Particle spacing [fm]	~1E5	~10	~1
Phases	Gas	Solid (low T)	Liquid

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VGA-1

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- depends strongly on density, temperature and neutron-proton asymmetry
- affects thermodynamic properties, and dynamic properties (leptons)
- different points of view
 - **chemical picture:**

mixture of different nuclear species and nucleons in chemical equilibrium

problems:
 - properties of particles in the medium
 - interaction between particles
 - model dependences in mass table of nuclei, and partition function
 - **physical picture:**

correlations of nucleons \Rightarrow formation of bound states/resonances

long range Coulomb force \Rightarrow lattice structure (Proto-Neutron Star crust)

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- standard hadronic EoS (LS, STOS):
neutron, proton, α particle, representative heavy nucleus
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 - extensions in recent EoS tables:
 - light clusters (2H, 3H, 3He, 4He)
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 - ⇒ in astrophysical simulations:
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This talk: **nucleons + nuclei** only

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- Expand grand partition function - pressure in powers of $z=e^{\mu/T}$:

$$\begin{aligned} \frac{\log Q}{V} &= \frac{P}{T} = \frac{2}{\lambda_n^3} [z_n + z_p] + (z_p^2 + z_n^2) [b_n] + 2z_p z_n [b_{pn}] \\ &\quad + \frac{1}{\lambda_\alpha^3} [z_\alpha + z_\alpha^2 b_\alpha] + 2z_\alpha (z_n + z_p) [b_{\alpha n}] \\ &\quad + \sum_i \frac{1}{\lambda_i^3} z_i \Omega_i \end{aligned}$$

- 2nd virial coef. b_2 determined from elastic scattering phase shifts: model-independent
- Four virial coefficients: Horowitz & Schwenk, '06
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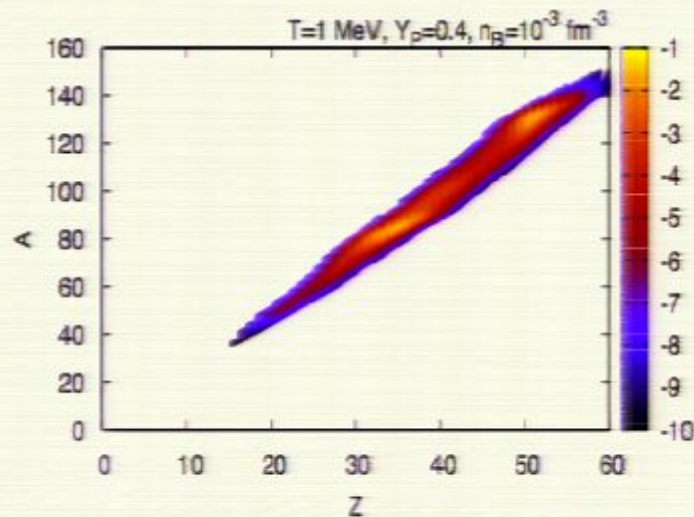
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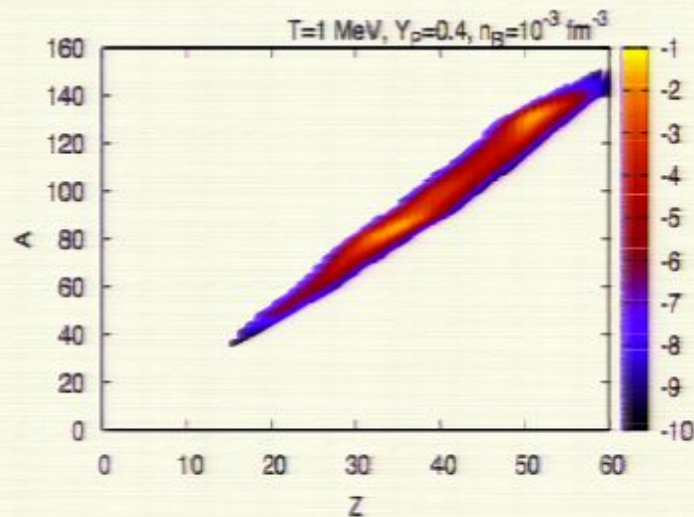
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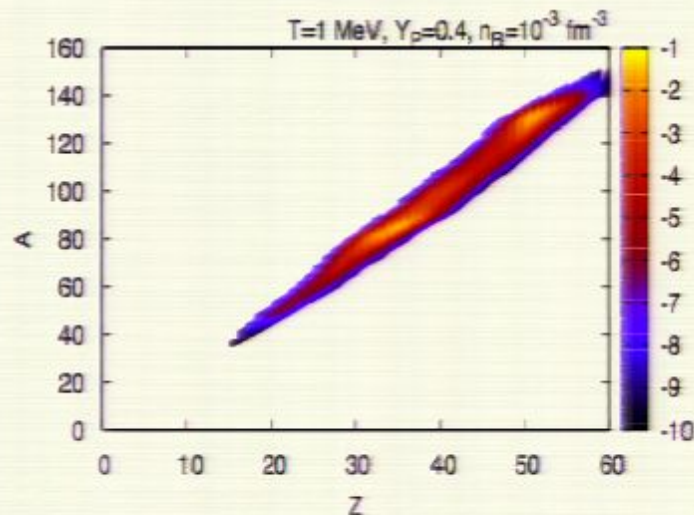
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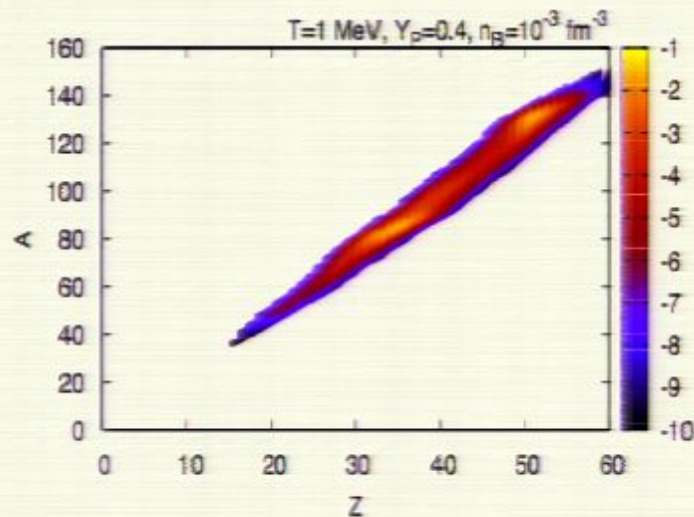
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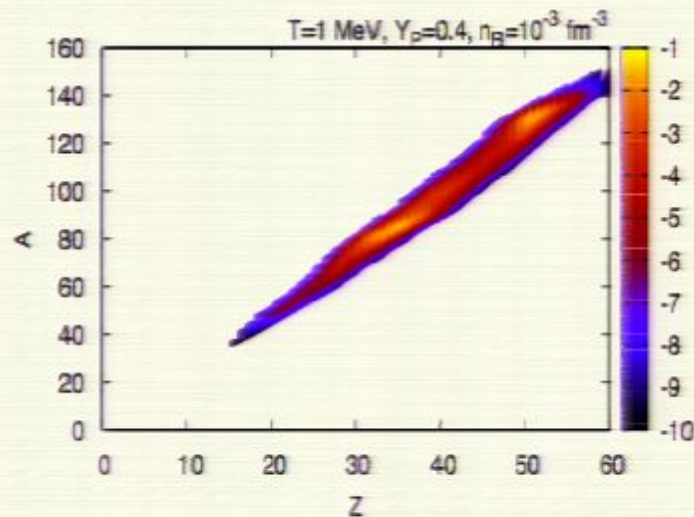
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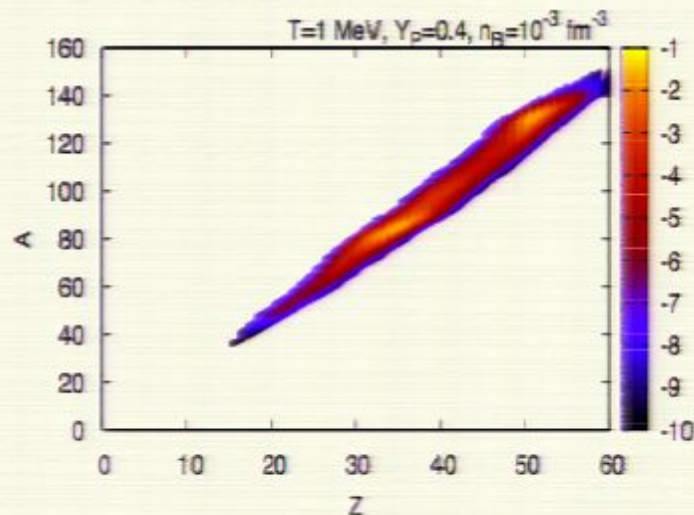
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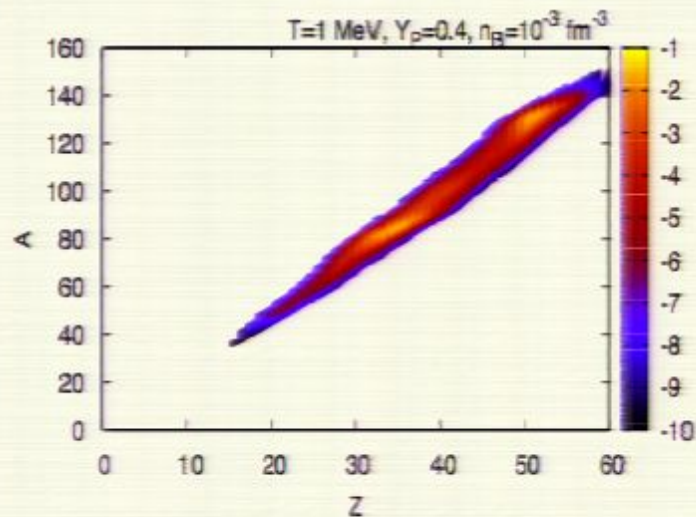
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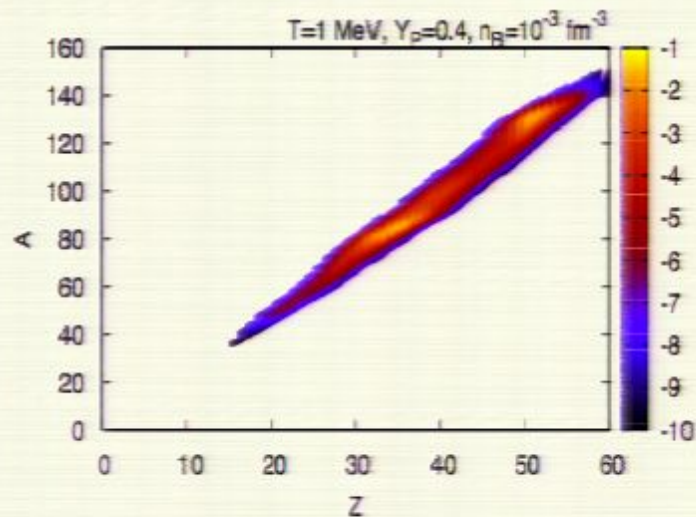
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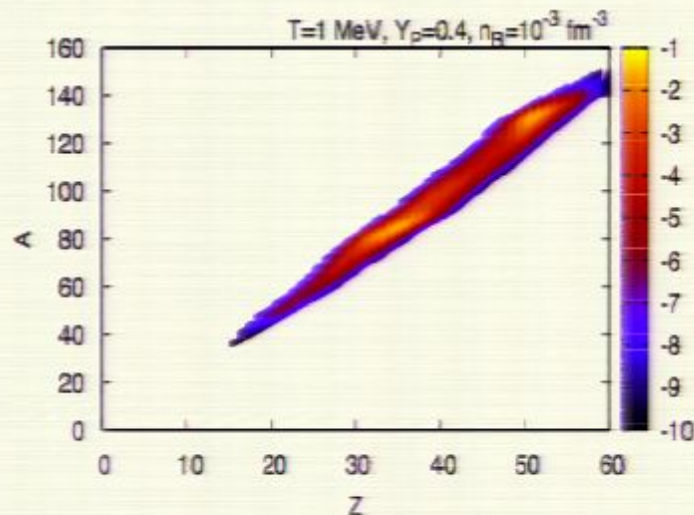
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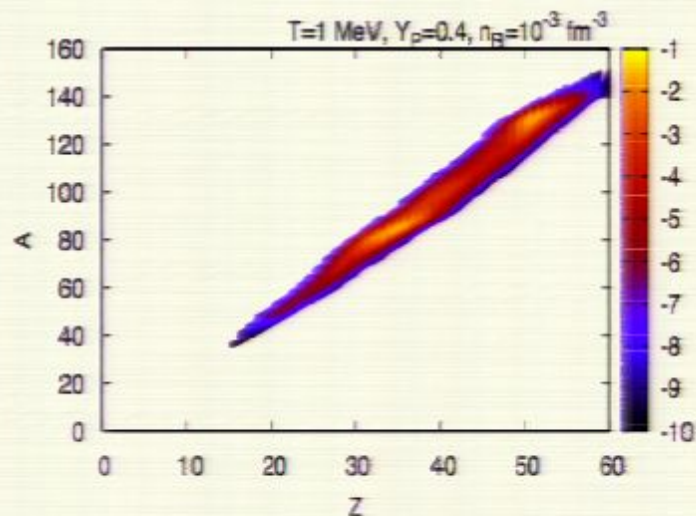
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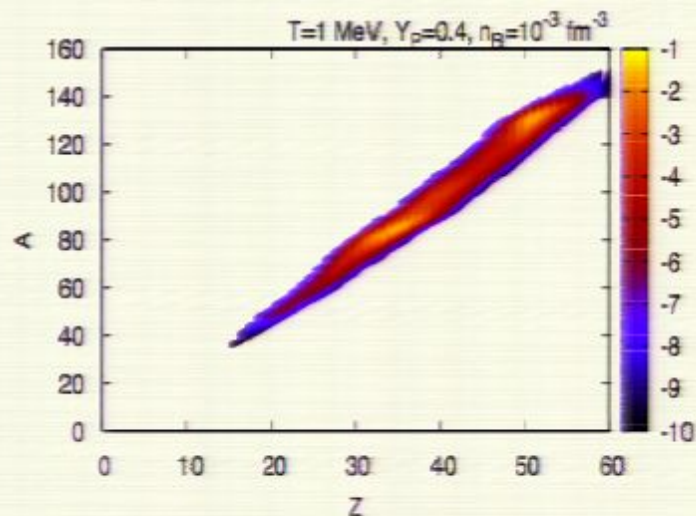
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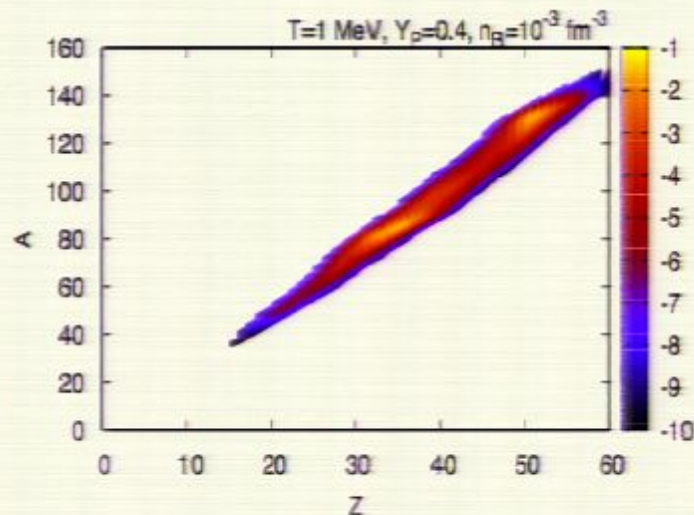
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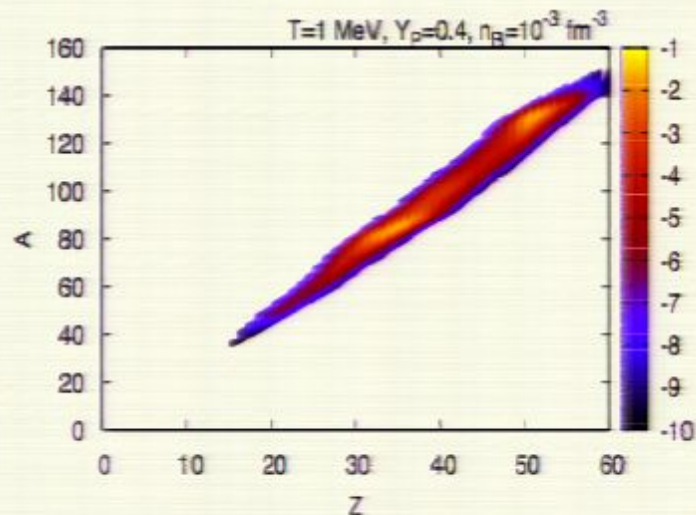
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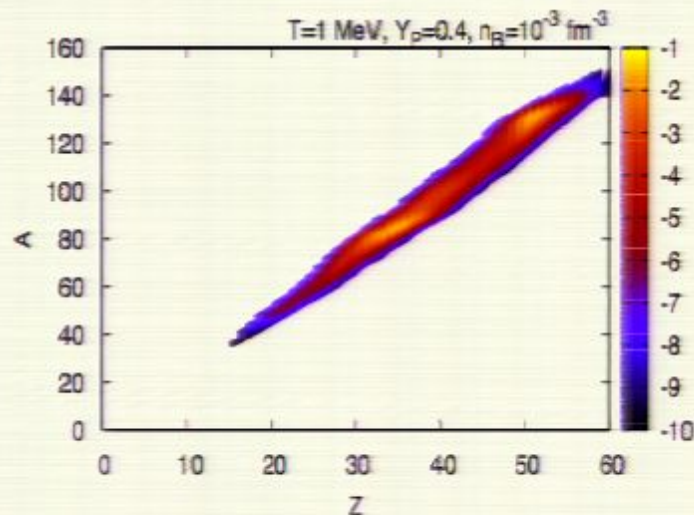
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- include Coulomb correction in Wigner-Seitz approximation – each species of nuclei has a neutralizing electron cloud
- no dissolution of nuclei at high densities (\Rightarrow “transition” to “solid” below)

problems:

- model dependence in mass table and level density



- The mass distribution of heavy nuclei is often a multi peaked Gaussian distribution.
- This may greatly influence the lepton capture rate, and neutrino reheating.
 \Rightarrow need neutrino opacity table (this talk)
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Methods: virial expansion II

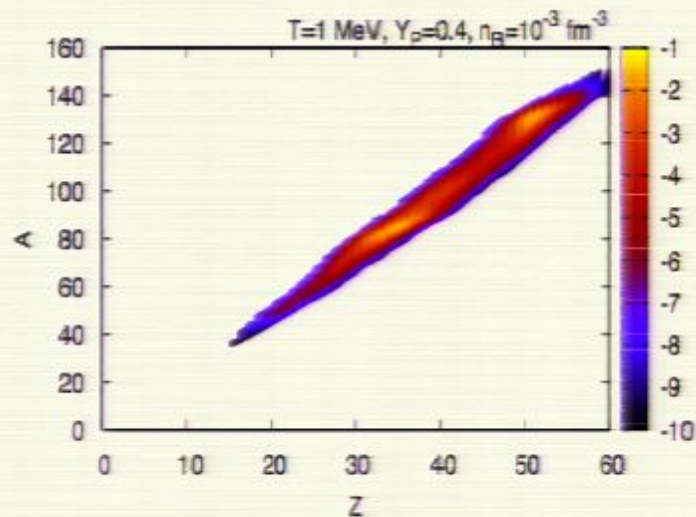
Densities (much) below saturation: matter in (non-ideal) gas phase

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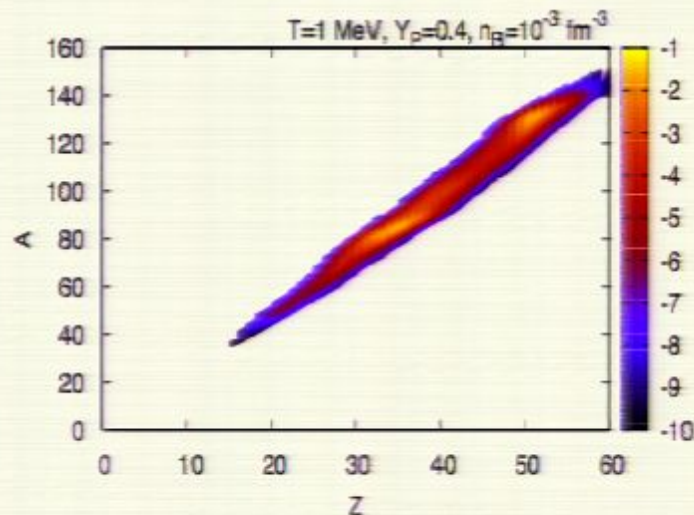
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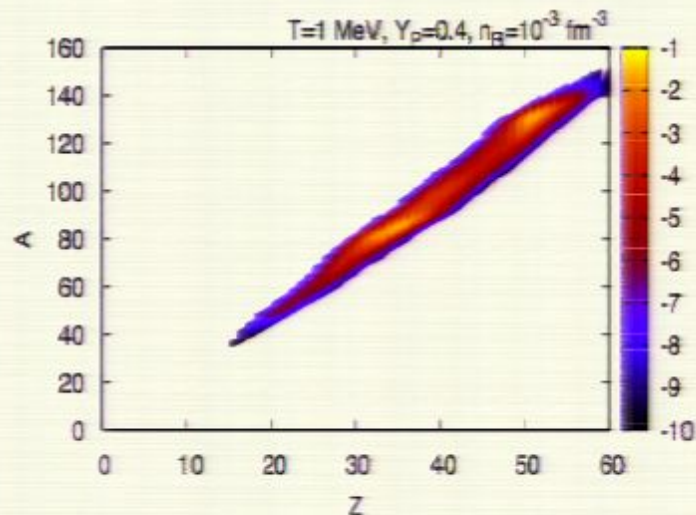
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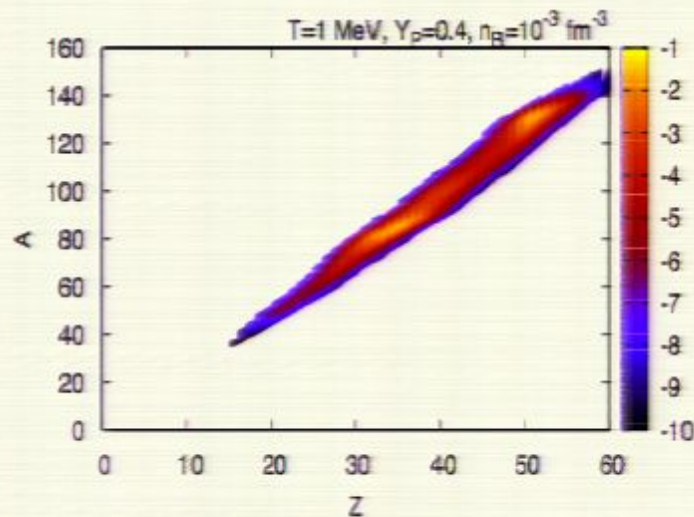
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Methods: rela. mean field model

Densities $\sim 10^4 \text{ fm}^{-3}$, and up to beryon saturation

- at higher densities, dense matter may form crystal structures (BCC) due to long range Coulomb interaction: example – Neutron Star crust
- describe nuclear interactions via relativistic mean field model:

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 \mathcal{L}_{\text{int}} = & \bar{\psi} \left[\overset{\text{attractive}}{g_s \phi} - \left(\overset{\text{repulsive}}{g_v V_\mu} + \frac{g_\rho}{2} \tau \cdot \mathbf{b}_\mu + \overset{\text{Iso-vector}}{\frac{e}{2}(1 + \tau_3) A_\mu} \right) \gamma^\mu \right] \psi \\
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κ, λ : incompressibility
 ζ : stiffness
 Λ_v : symmetry energy

- Ψ : Nucleon fields
- Meson/photon fields: classical expectation value \rightarrow mean field
- density dependent coupling g_s to reproduce low density neutron matter in micro. cal.
- approximated BCC lattice with spherical cell, solve mean field Hartree equation inside the cell exactly at finite temperature
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κ, λ : incompressibility
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Methods: rela. mean field model

Densities $\sim 10^4 \text{ fm}^{-3}$, and up to beryon saturation

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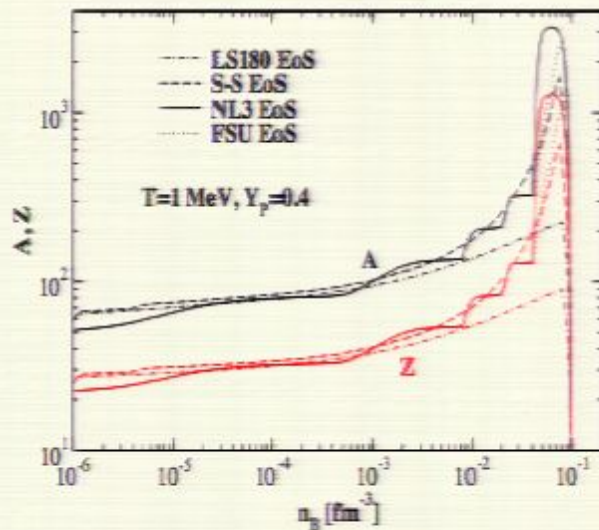
- at higher densities, dense matter may form crystal structures (BCC) due to long range Coulomb interaction: example – Neutron Star crust
- describe nuclear interactions via relativistic mean field model:

$$\begin{aligned}
 \mathcal{L}_{\text{int}} = & \bar{\psi} \left[\overset{\text{attractive}}{g_s \phi} - \left(\overset{\text{repulsive}}{g_v V_\mu} + \frac{g_\rho}{2} \tau \cdot \mathbf{b}_\mu + \frac{e}{2} (1 + \tau_3) A_\mu \right) \gamma^\mu \right] \psi \\
 & - \frac{\kappa}{3!} (g_s \phi)^3 - \frac{\lambda}{4!} (g_s \phi)^4 + \frac{\zeta}{4!} g_v^4 (V_\mu V^\mu)^2 \\
 & + \Lambda_v g_\rho^2 \mathbf{b}_\mu \cdot \mathbf{b}^\mu g_v^2 V_\nu V^\nu.
 \end{aligned} \tag{1}$$

κ, λ : incompressibility
 ζ : stiffness
 Λ_v : symmetry energy

- Ψ : Nucleon fields
- Meson/photon fields: classical expectation value \rightarrow mean field
- density dependent coupling g_s to reproduce low density neutron matter in micro. cal.
- approximated BCC lattice with spherical cell, solve mean field Hartree equation inside the cell exactly at finite temperature
- above \sim half nuclear density, uniform nuclear matter forms.

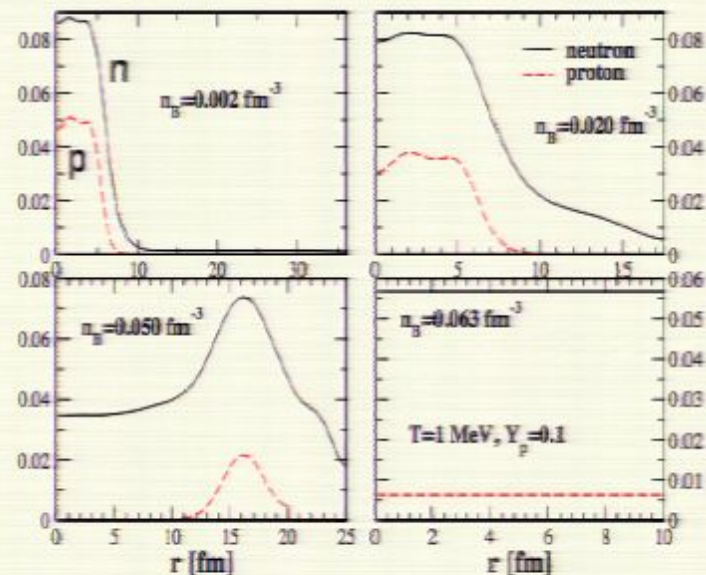
Methods: shell effects, PNS crust



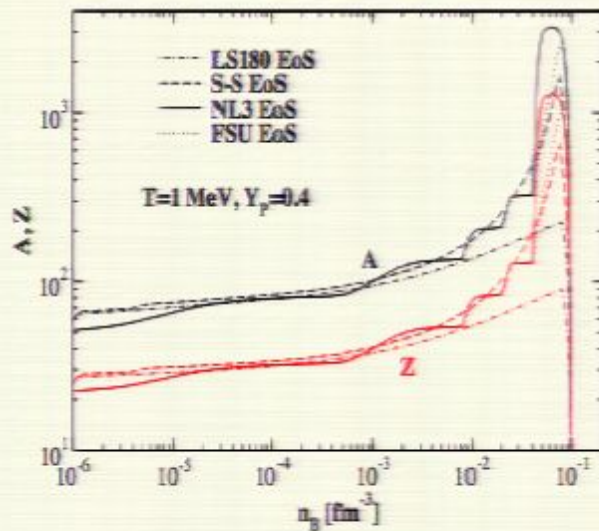
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Density profile of nuclei in crust of PNS



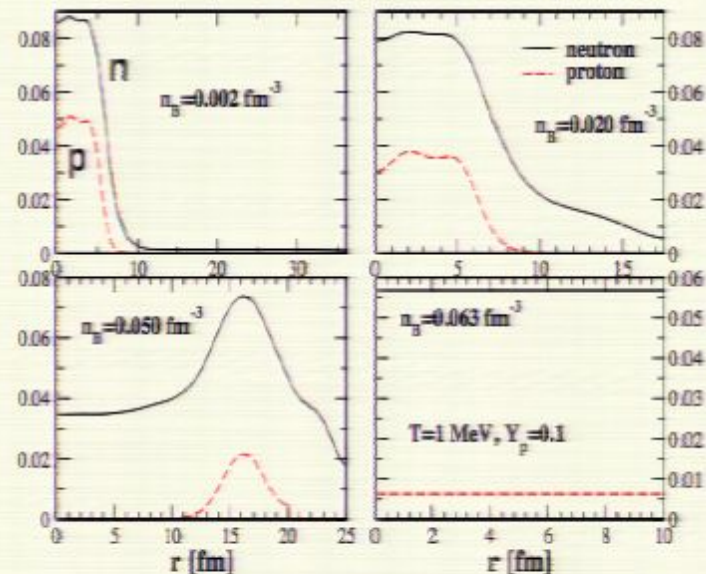
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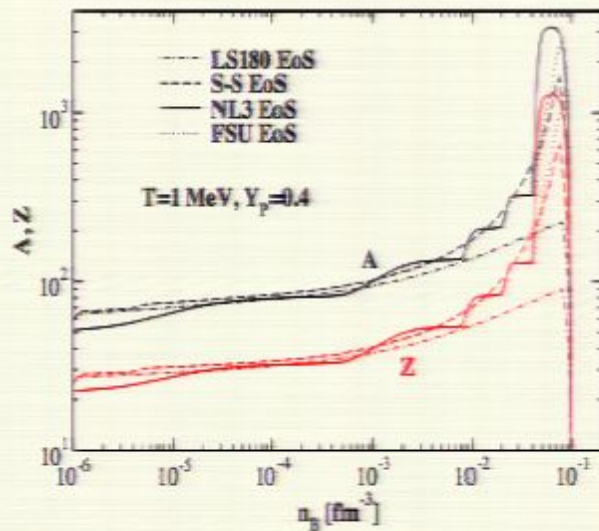
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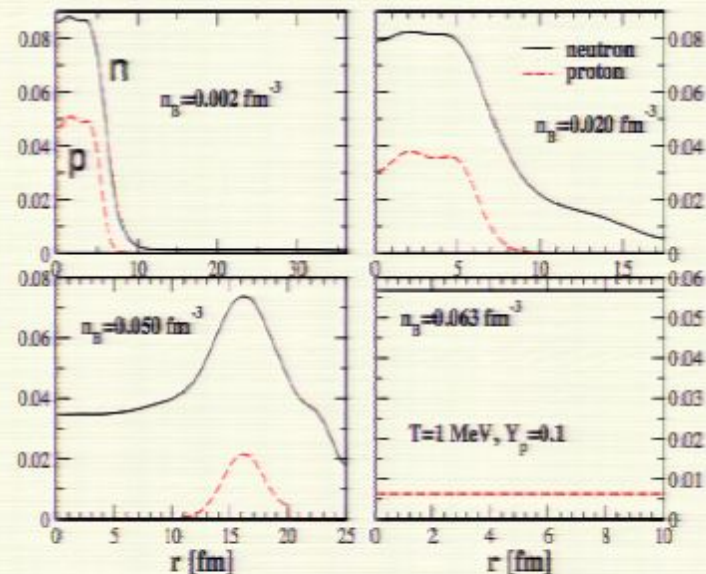
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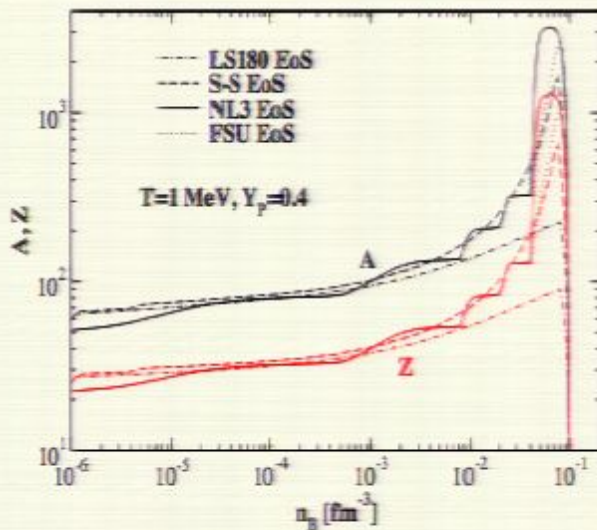
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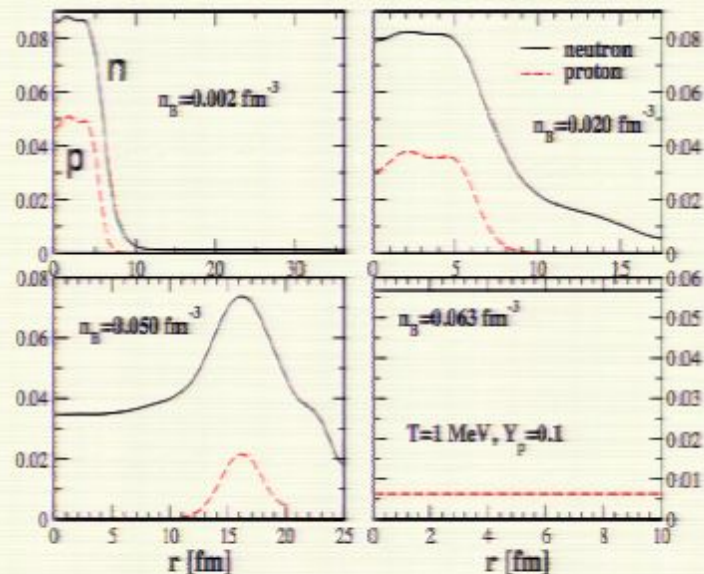
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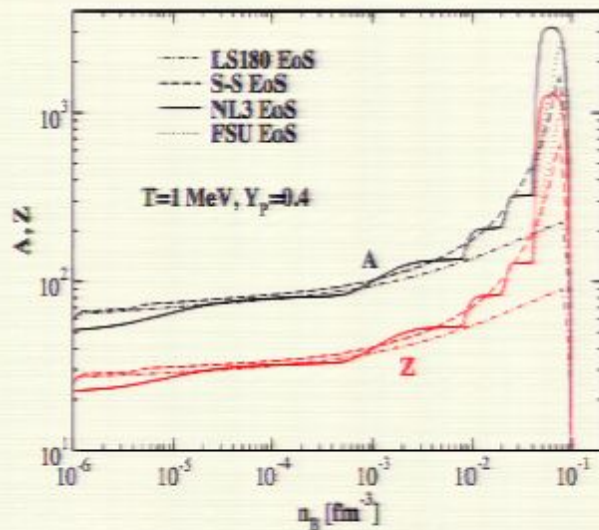
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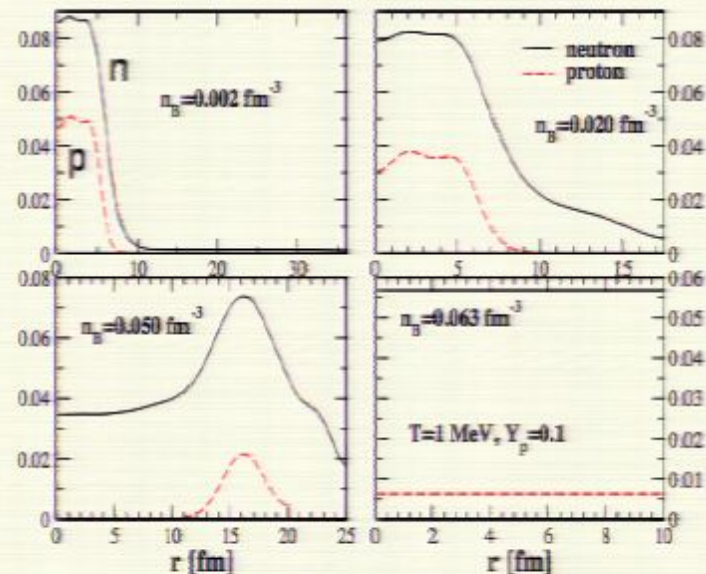
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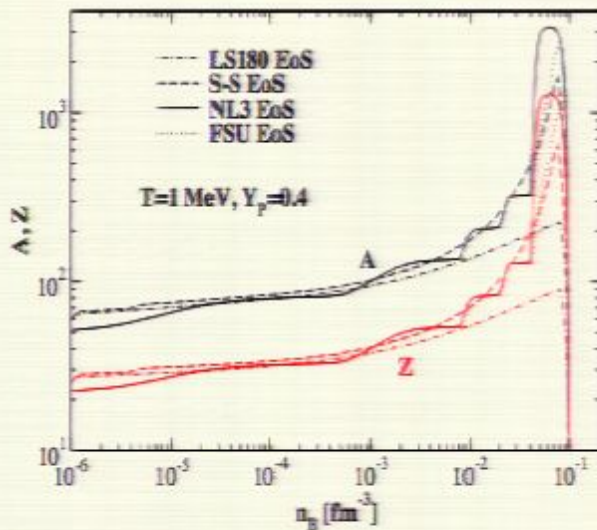
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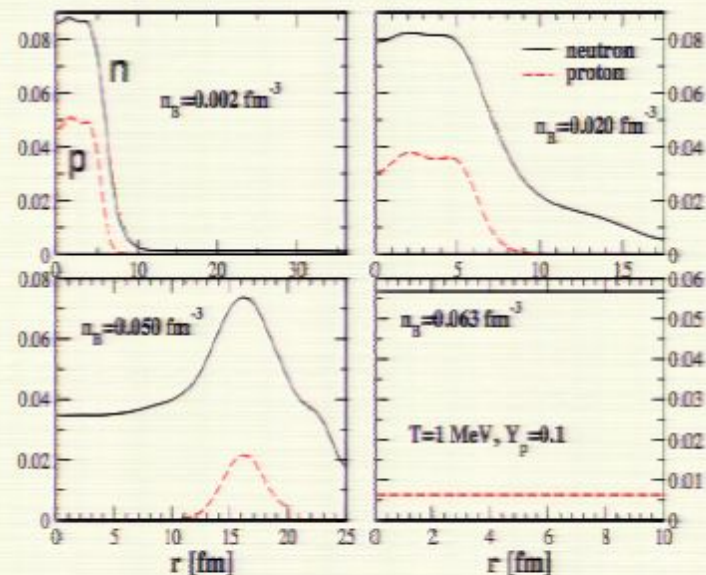
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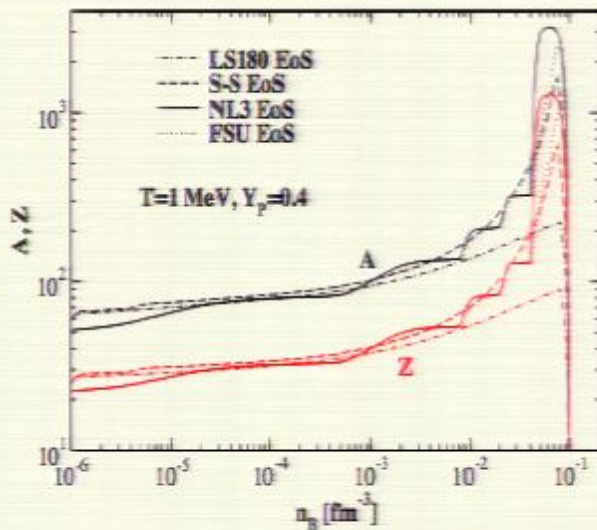
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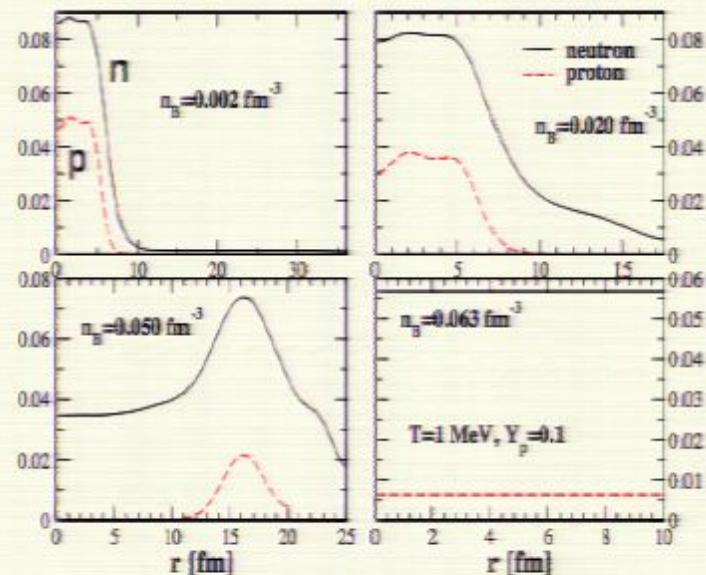
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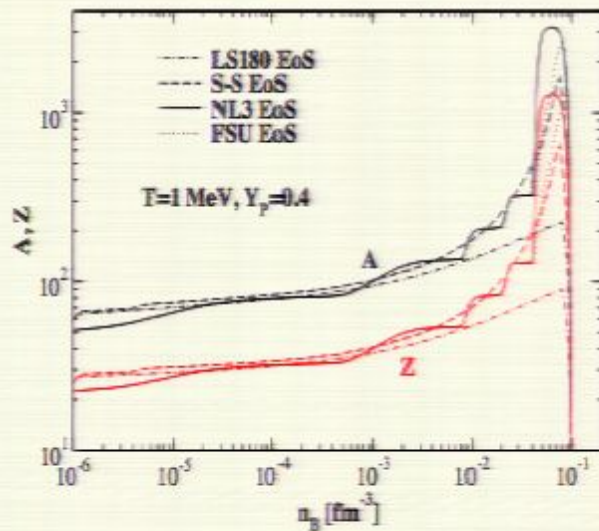
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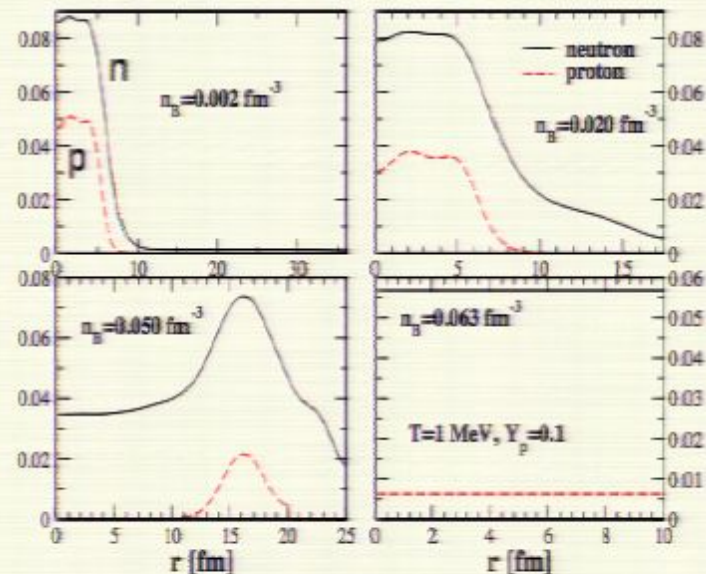
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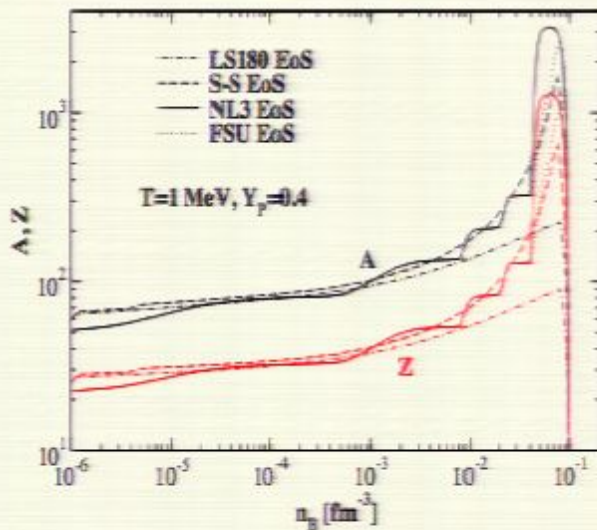
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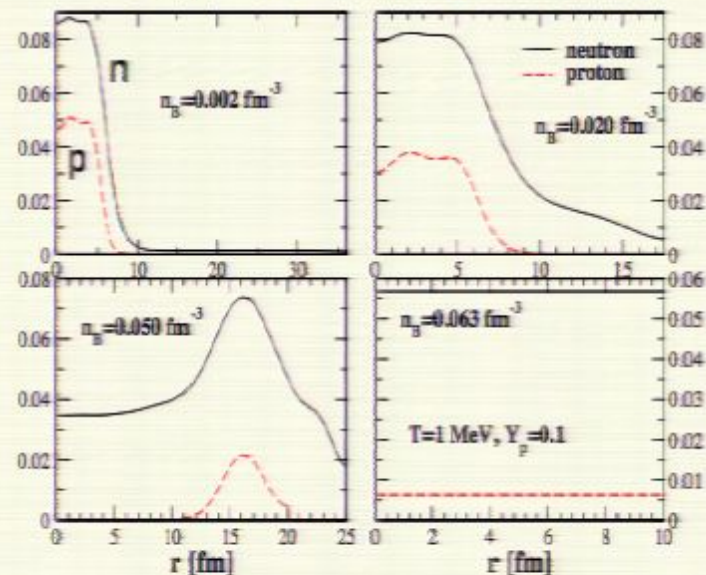
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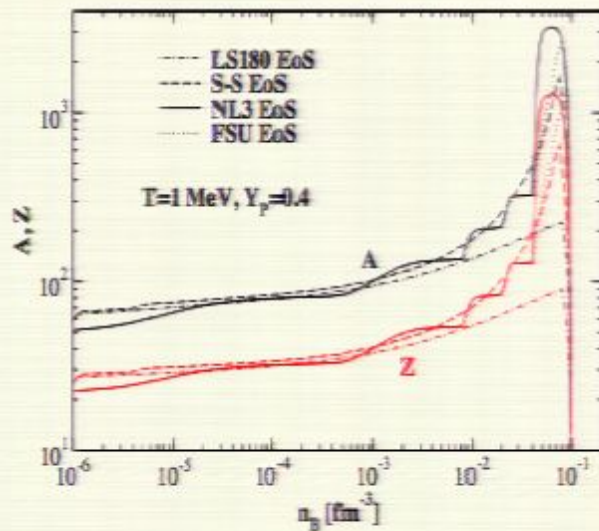
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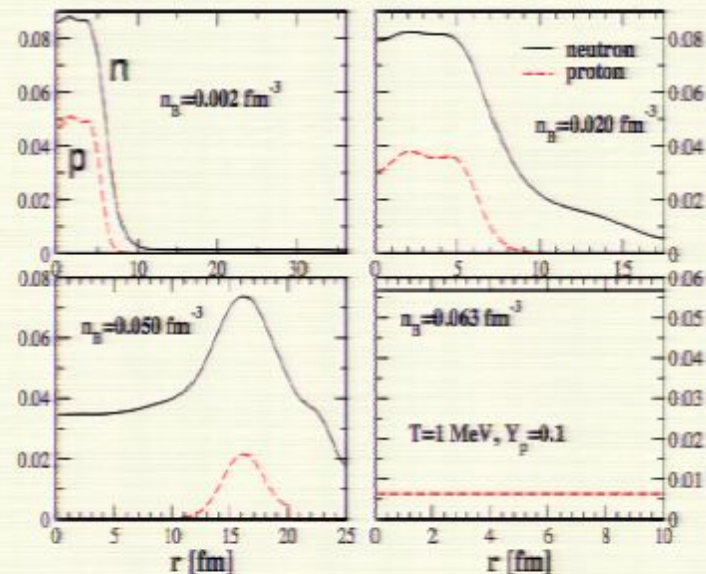
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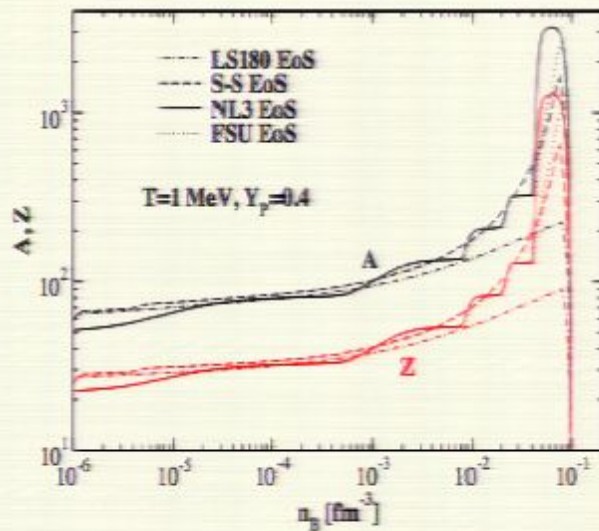
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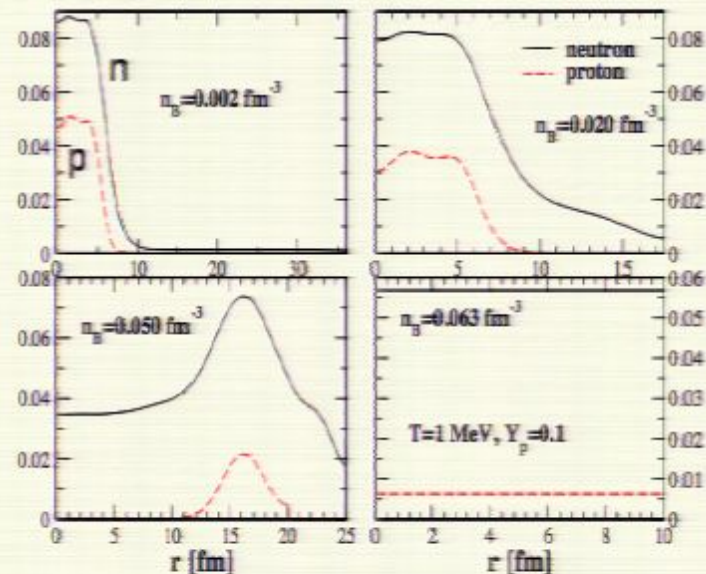
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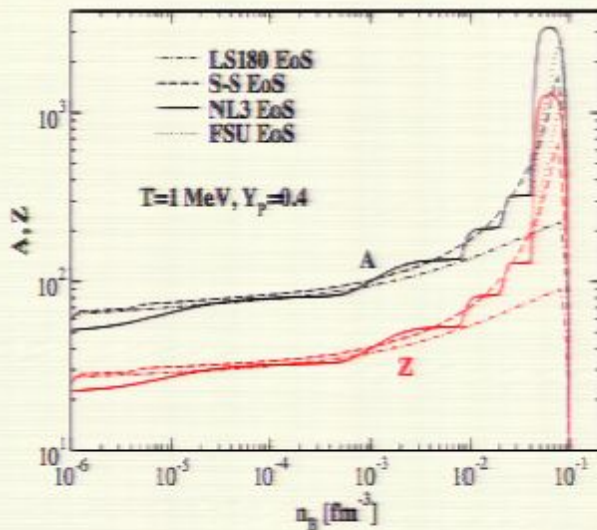
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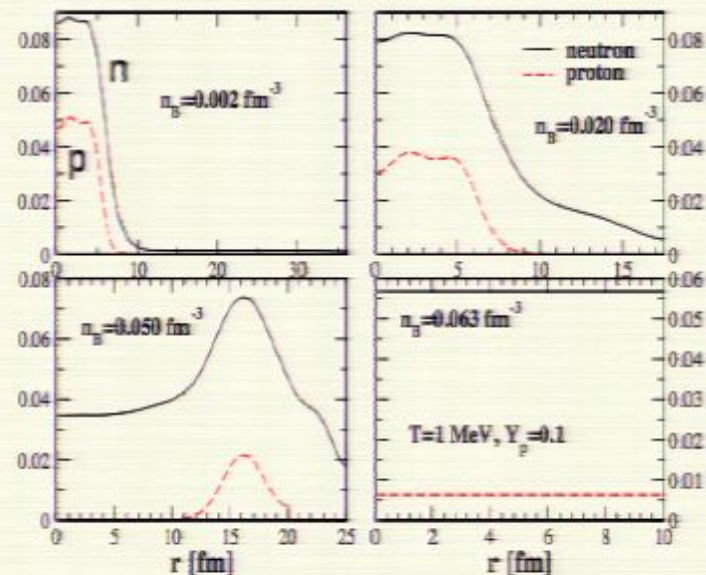
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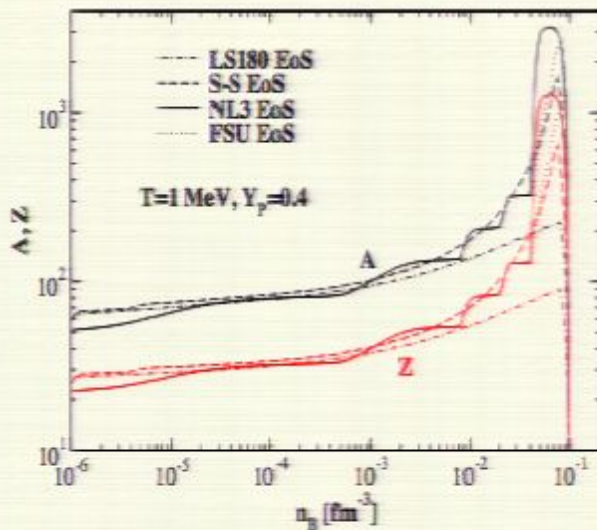
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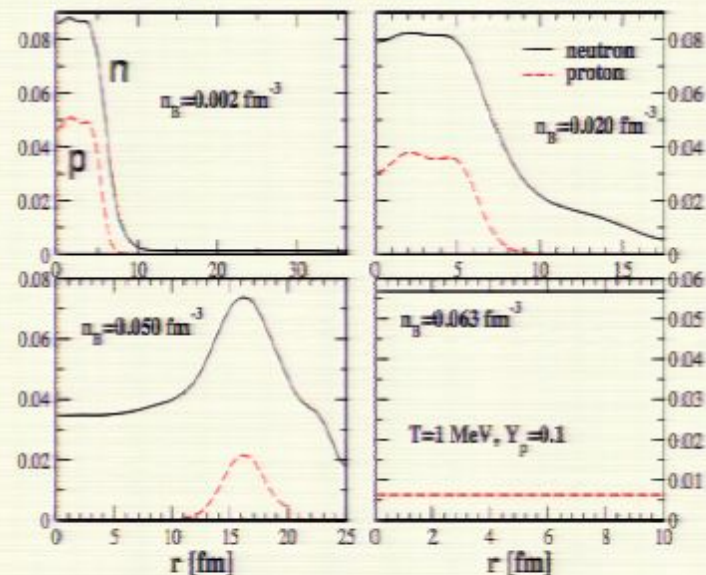
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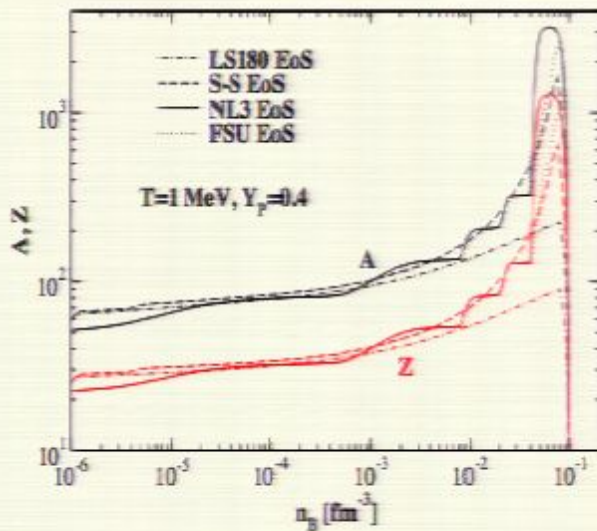
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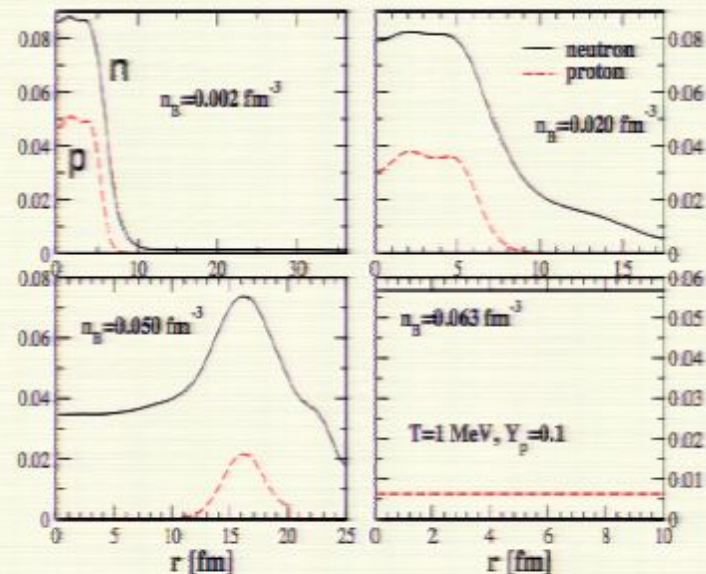
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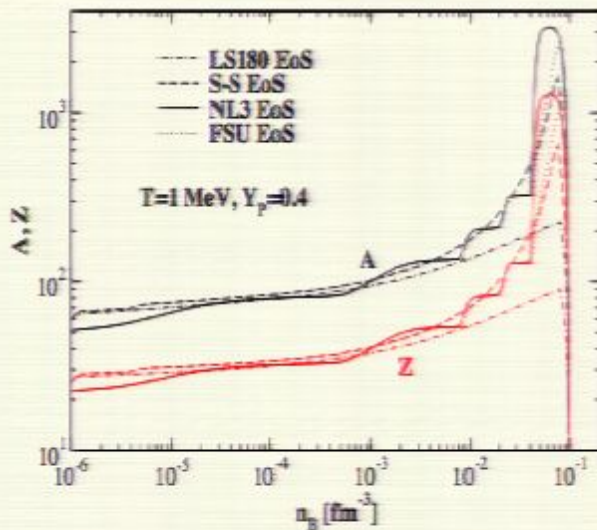
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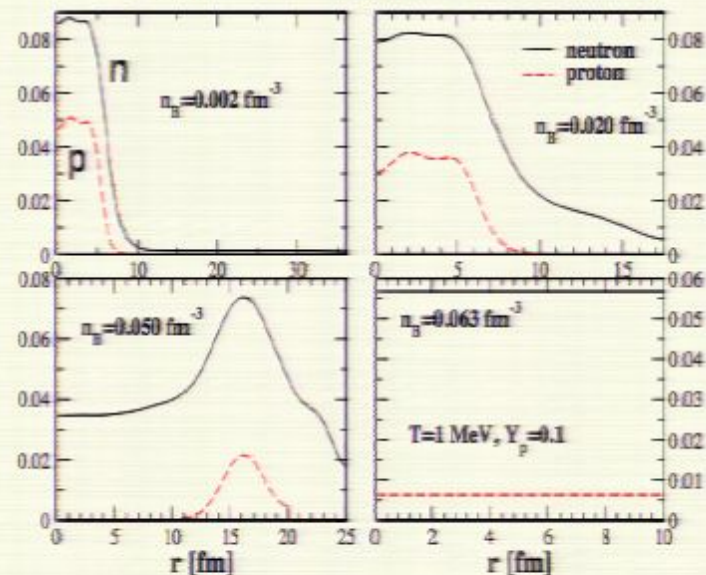
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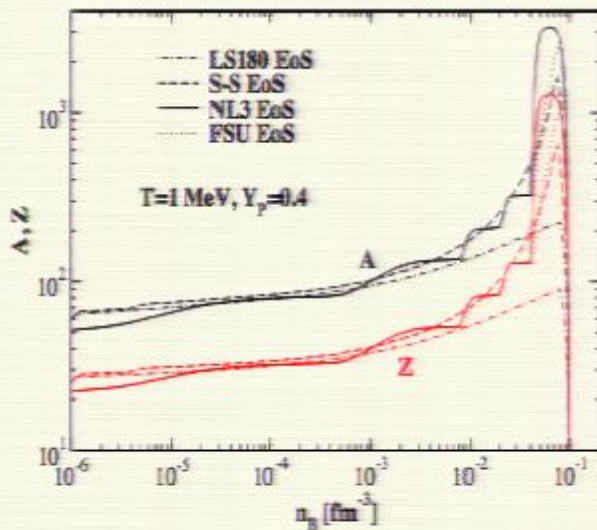
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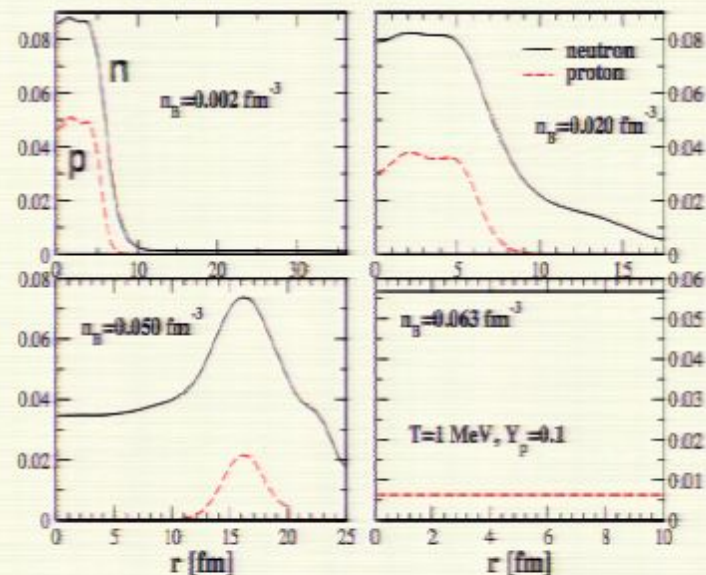
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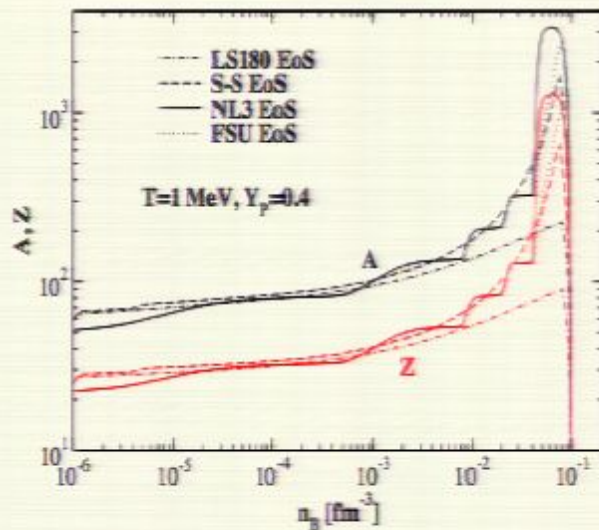
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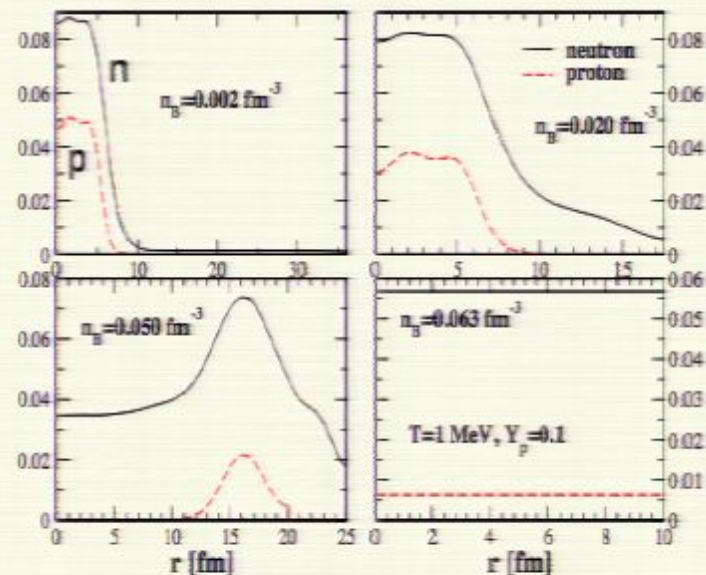
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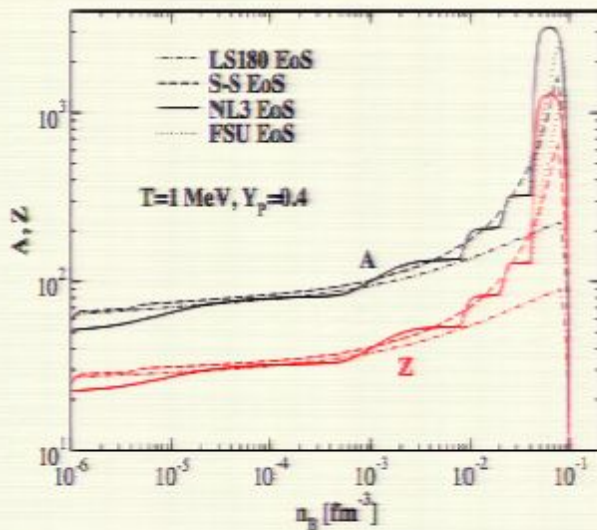
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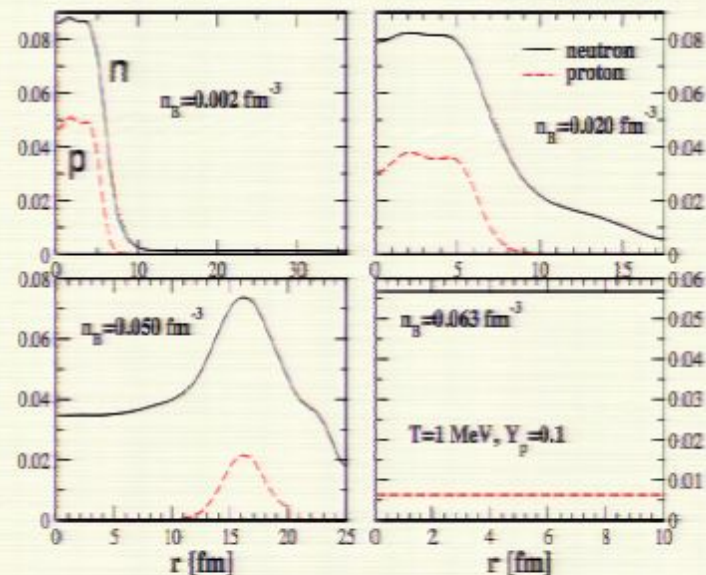
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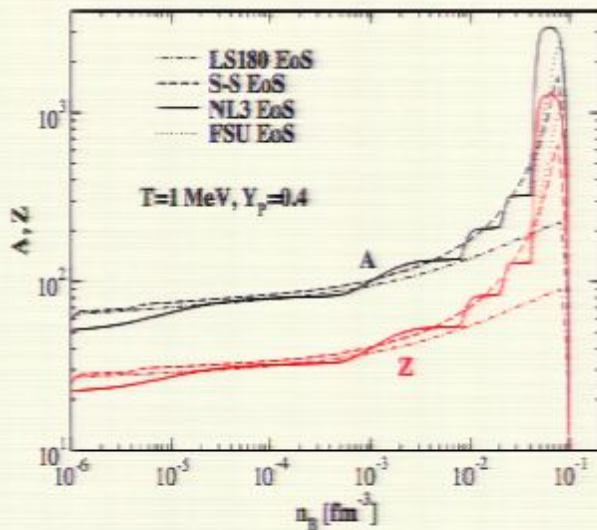
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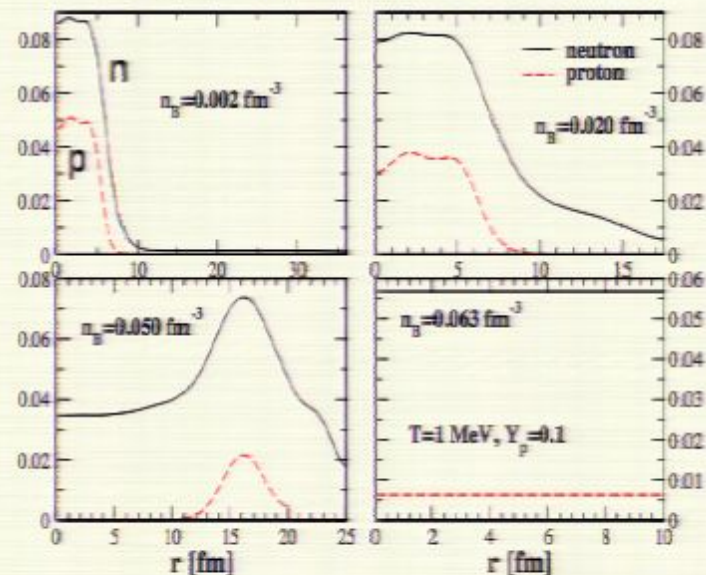
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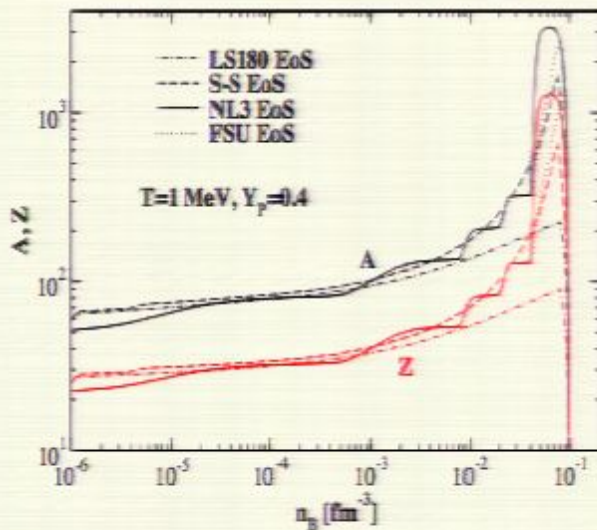
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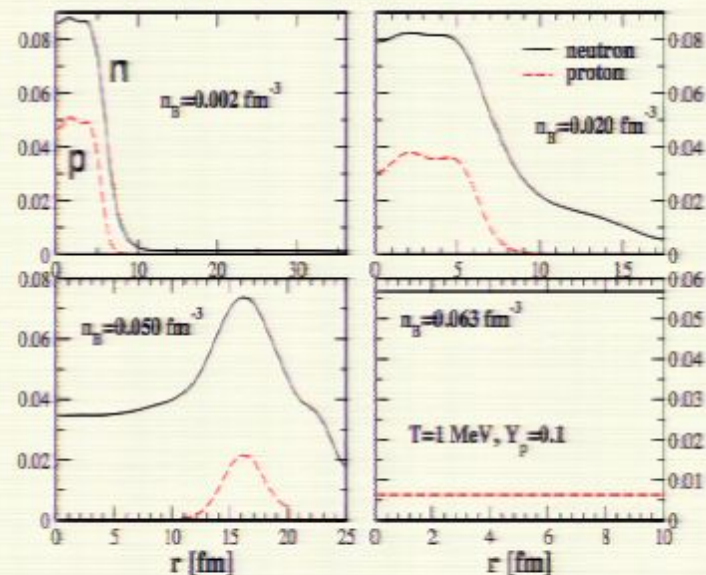
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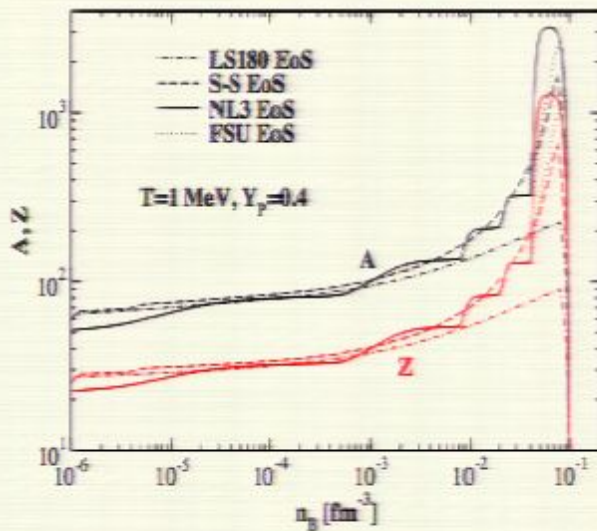
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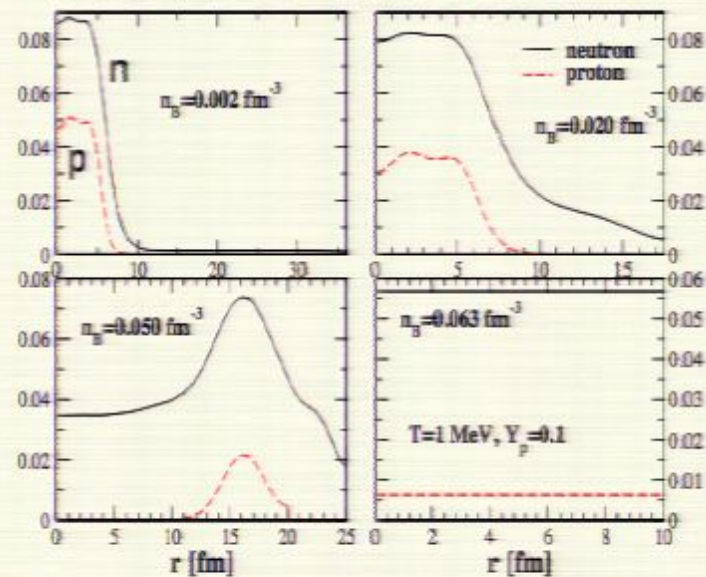
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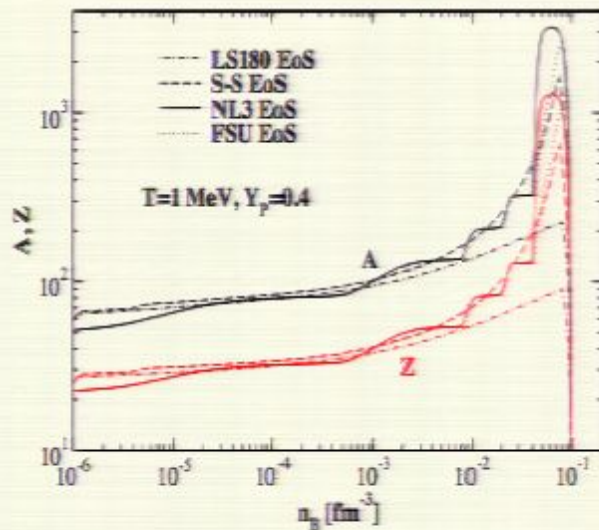
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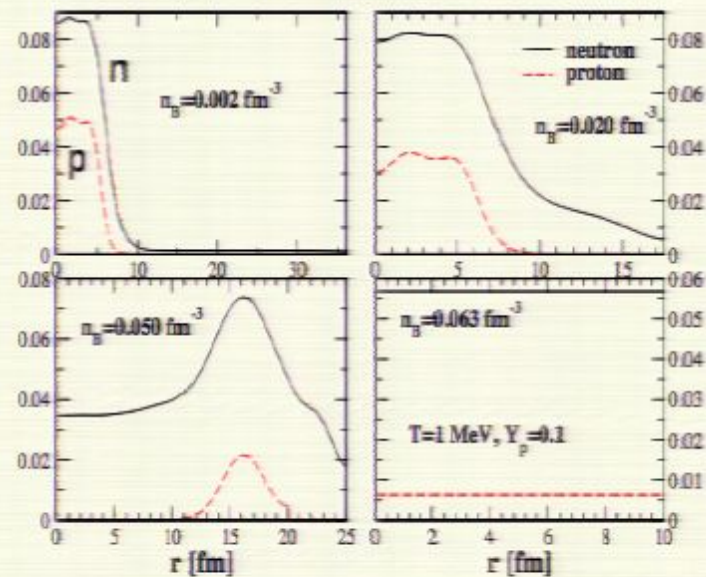
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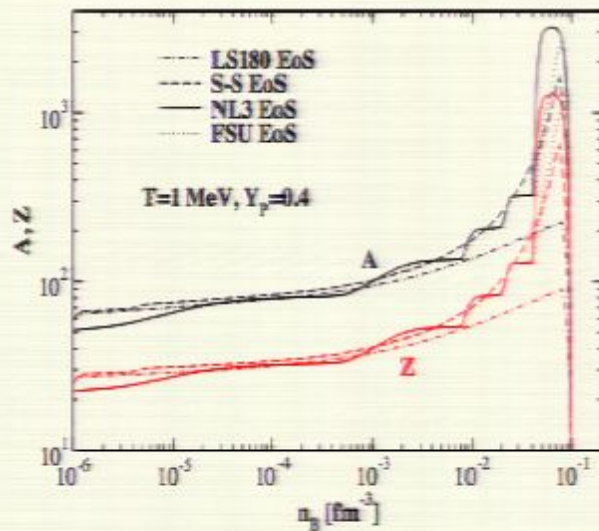
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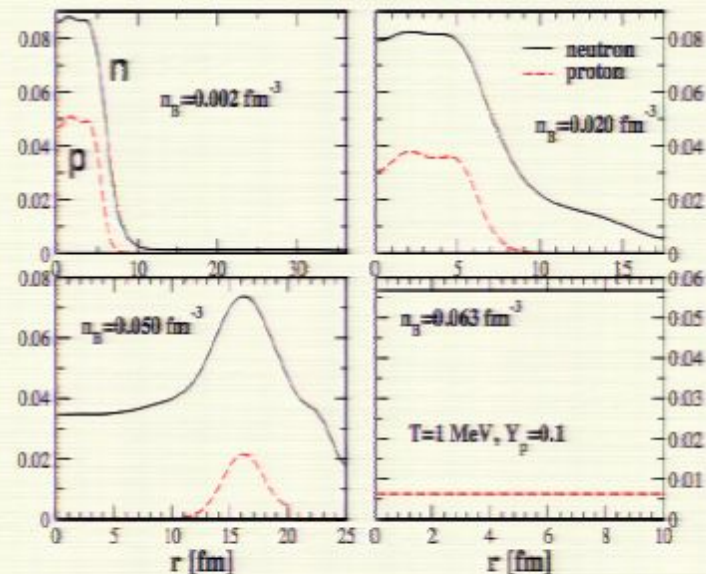
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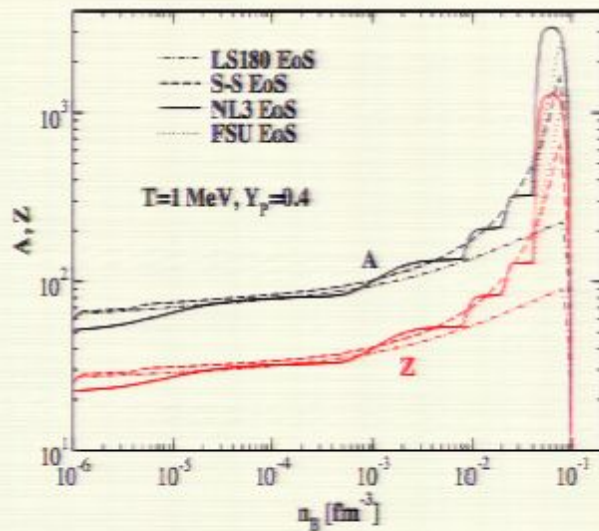
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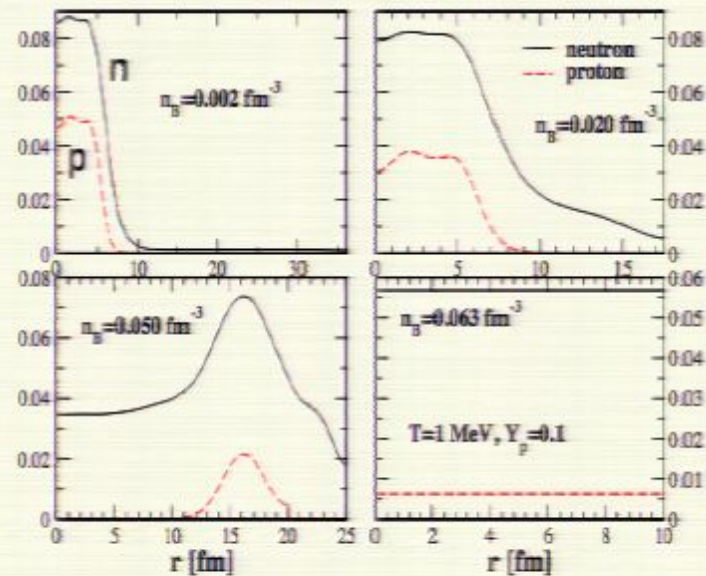
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Methods: complete EoS tables

Parameters	Minimum	Maximum	Number of grid
T [MeV]	0, $10^{-0.8}$	$10^{1.9}$	109
$\text{Log}_{10}(n_B)$ [fm^{-3}]	-8	0.2	328
Y_p	0, 0.05	0.56	53

- We match the EOS at high density from RMF model, and EOS at low density from Virial expansion in thermodynamically consistent way, and generate finer tables.
- We perform adiabatic compression tests: thermodynamic consistency is well preserved.
- Comparisons with the standard hadronic EoS - LS, STOS
 - thermodynamics – similar, but high density EoS differ in stiffness
 - composition – very different
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 - properties of nuclei – neutron rich matter: **uncertain R_n in ^{208}Pb**
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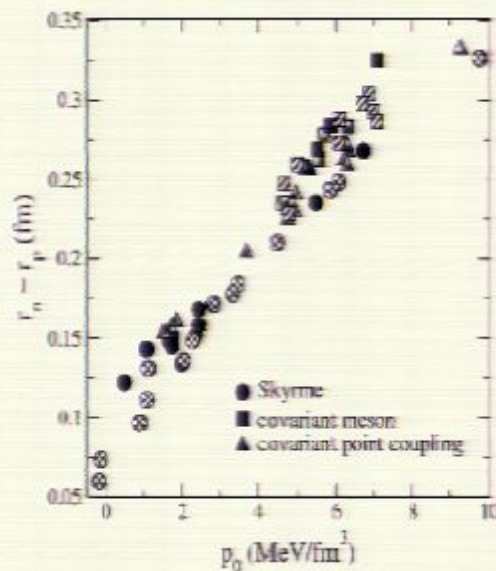
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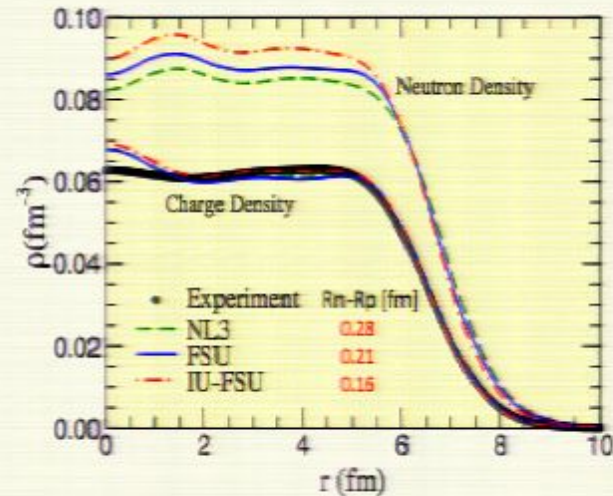
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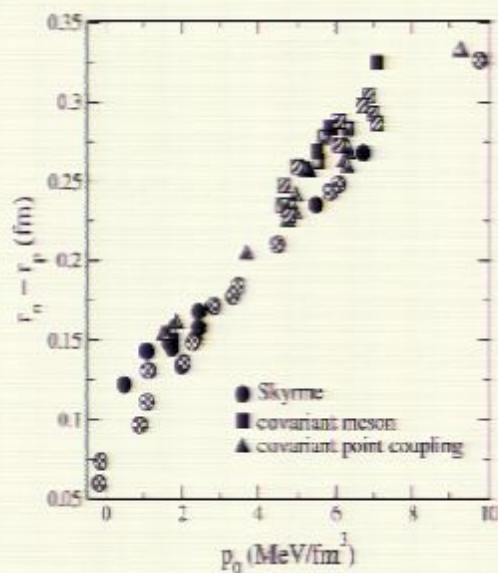
Furnstahl, '02



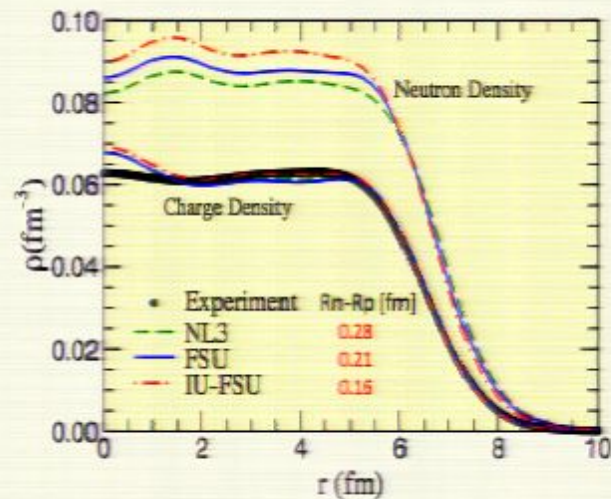
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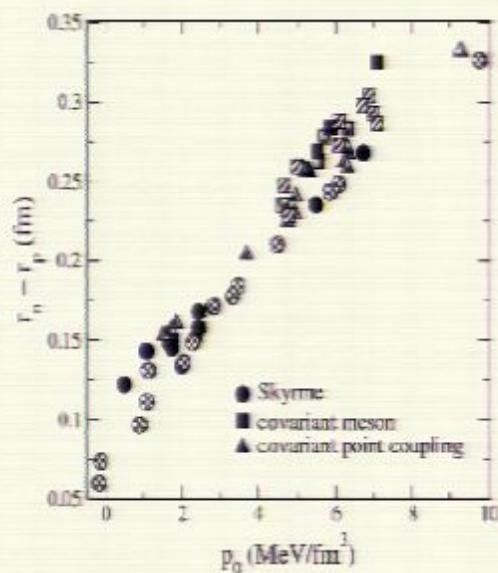
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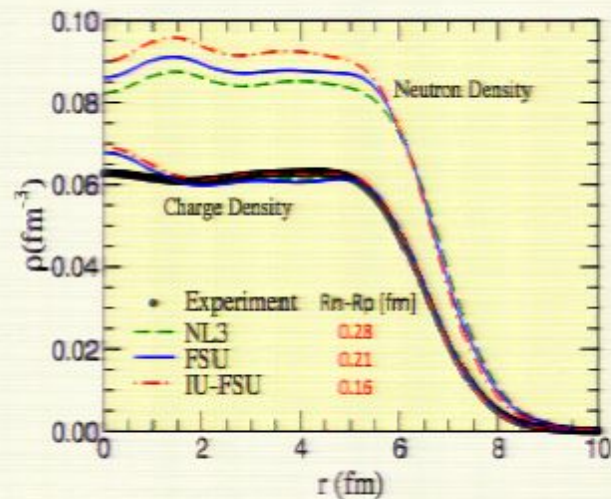
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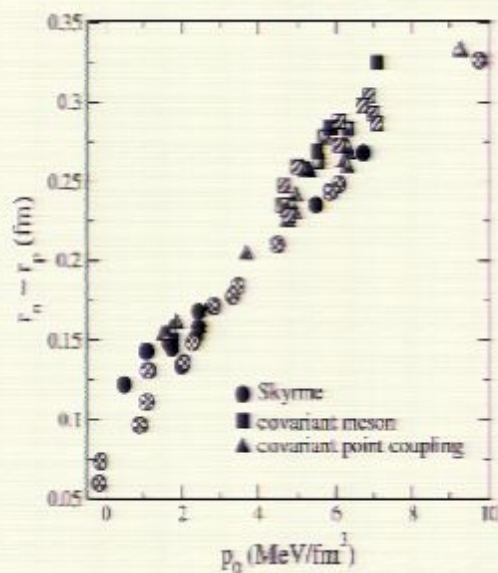
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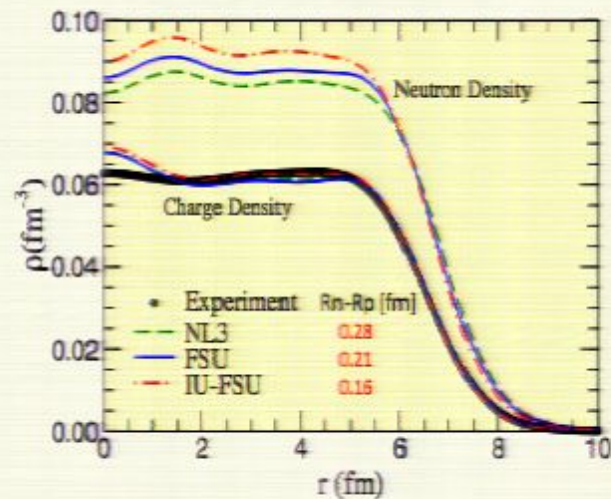
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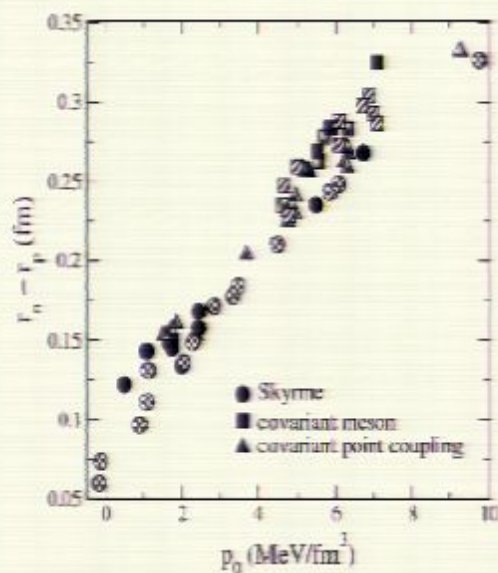
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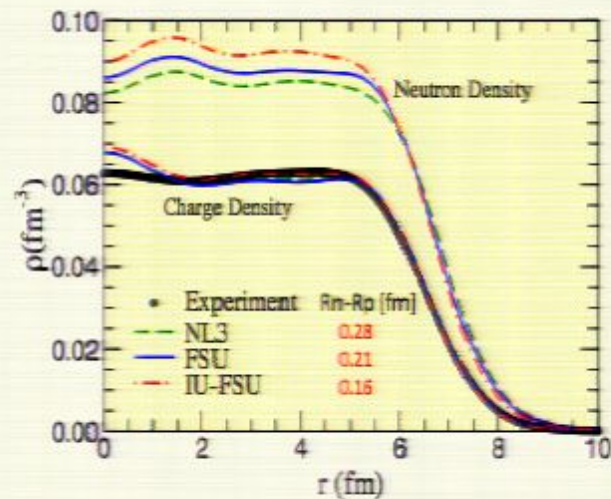
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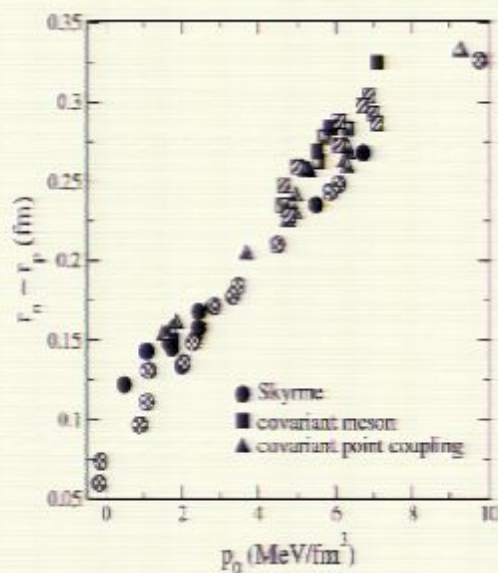
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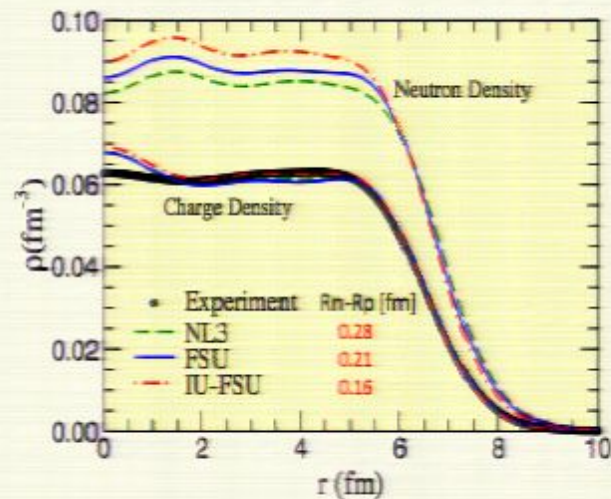
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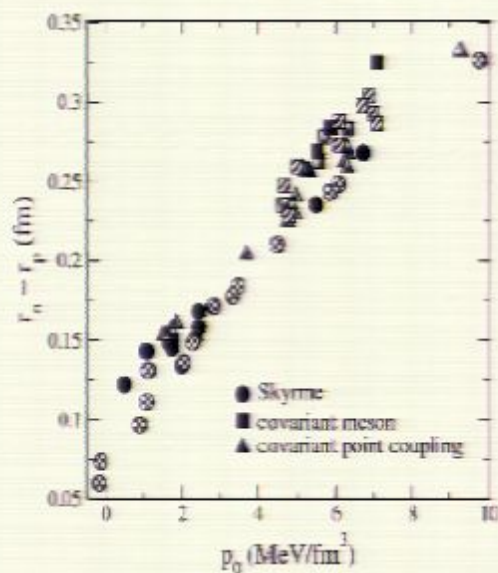
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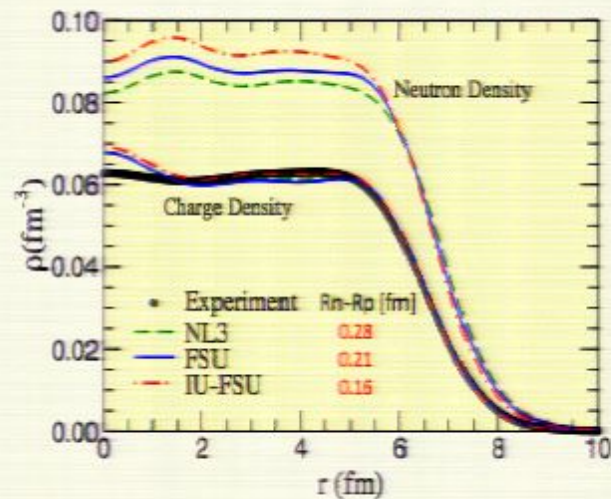
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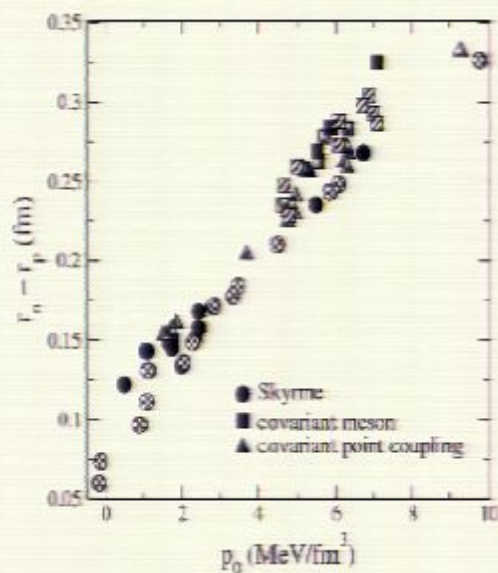
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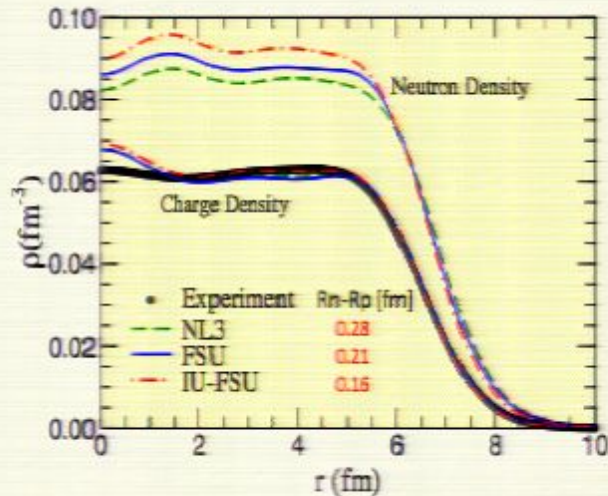
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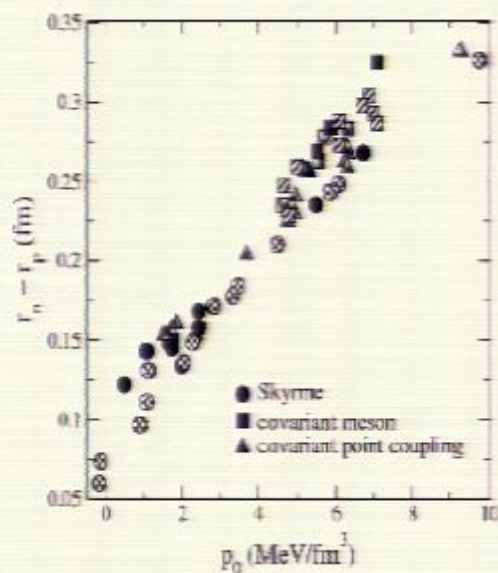
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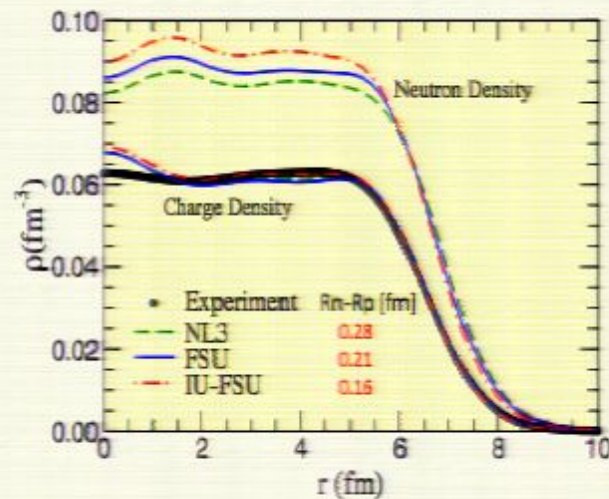
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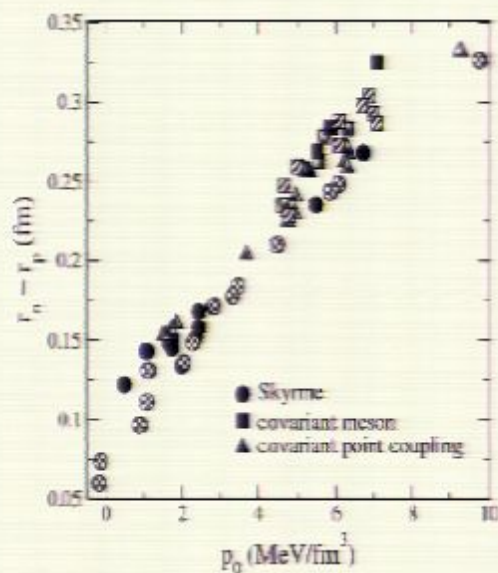
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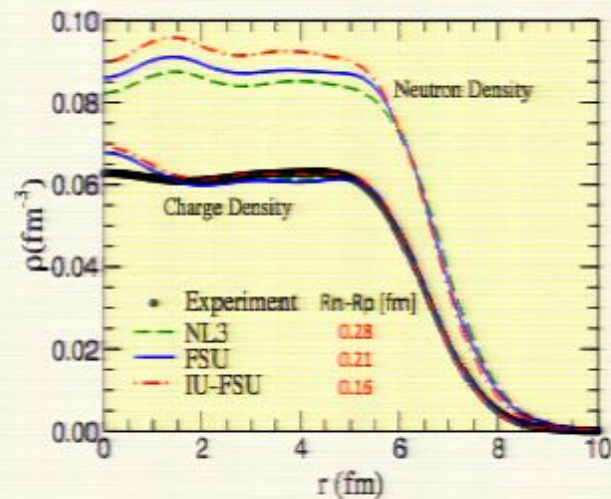
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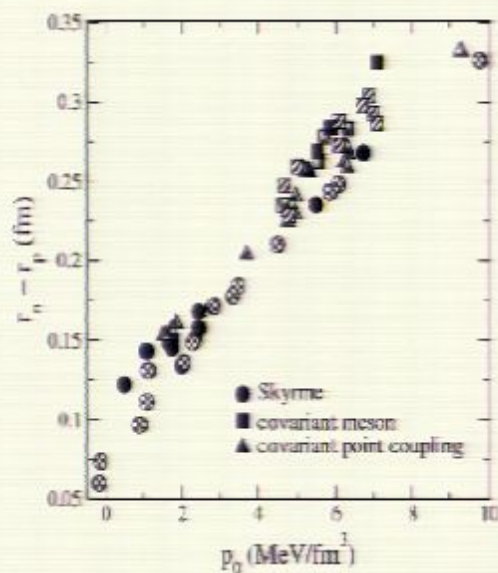
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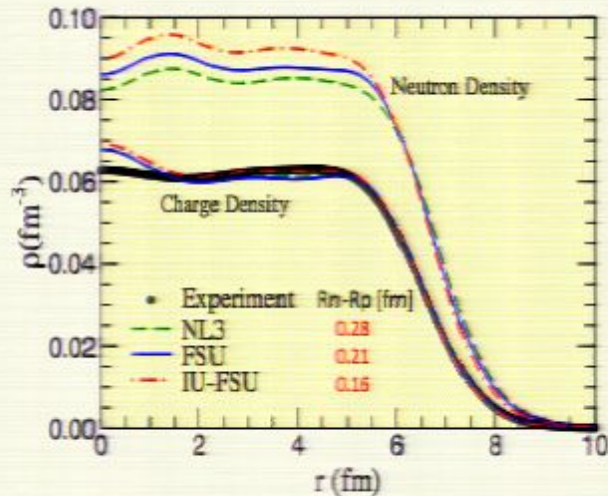
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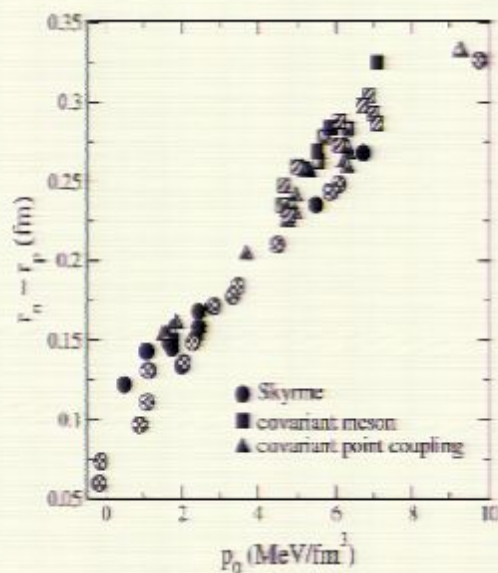
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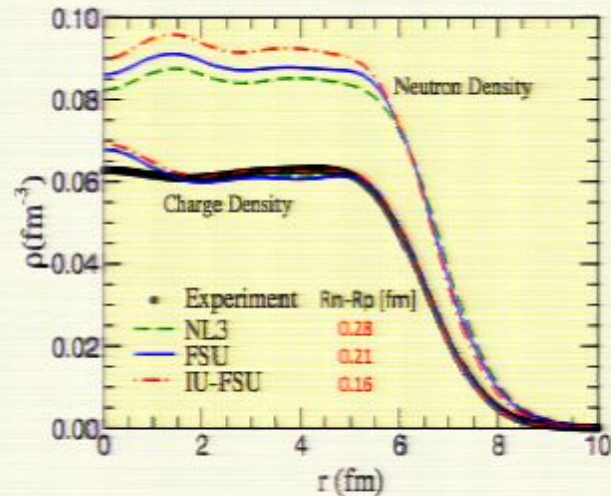
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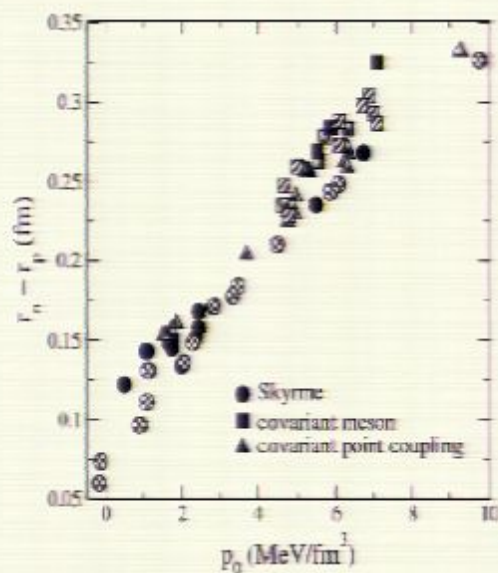
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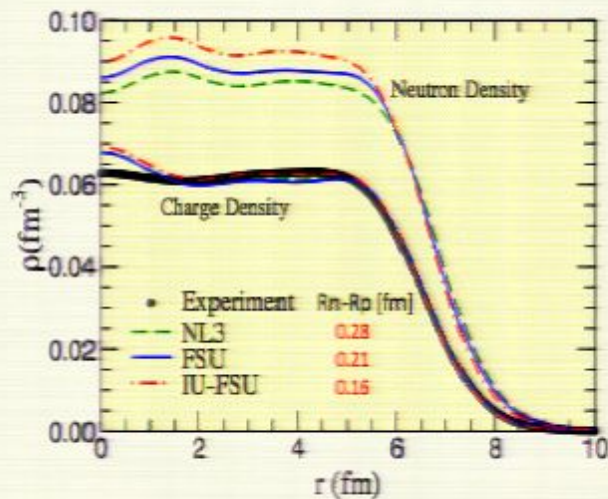
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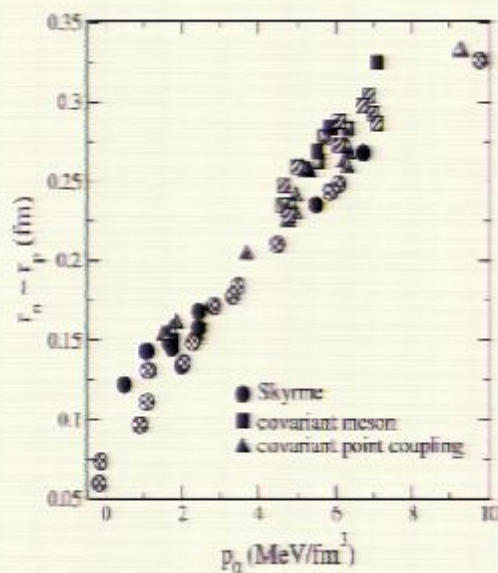


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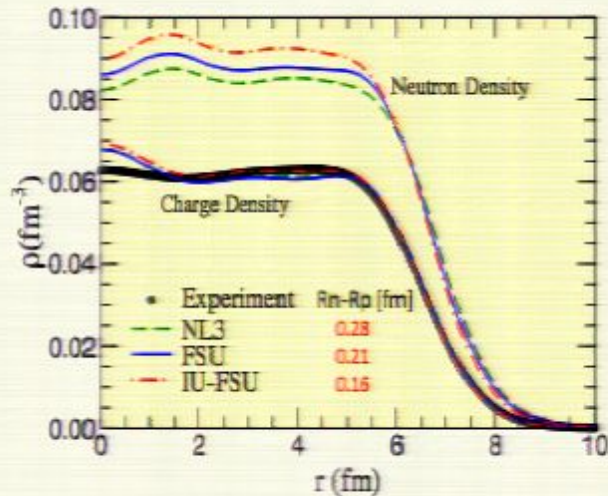
F. Fattoyev, C. Horowitz, J. Piekarewicz, GS, '10

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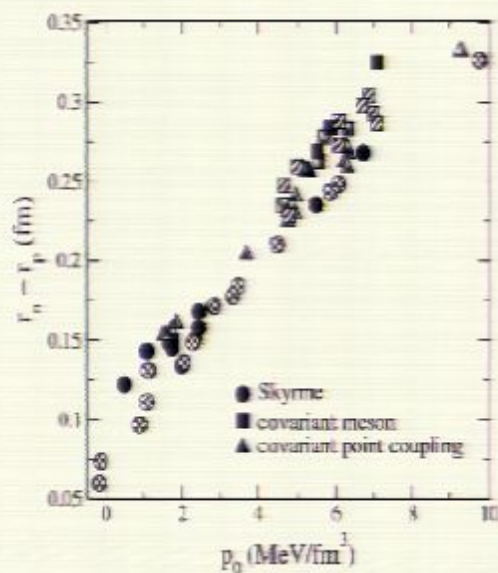
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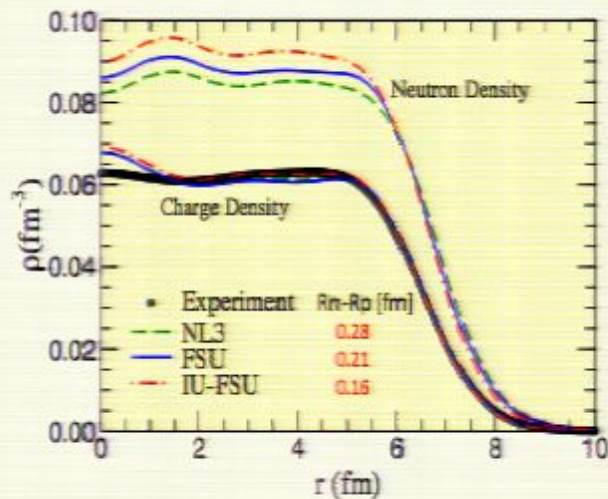
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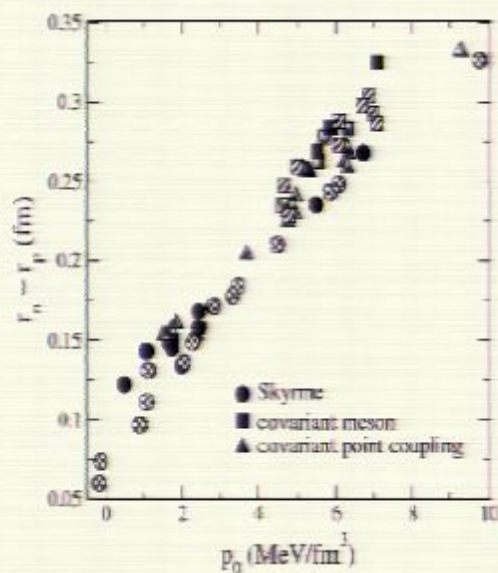
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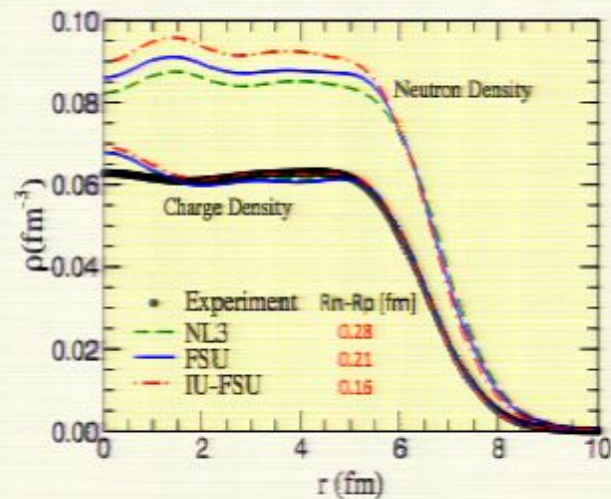
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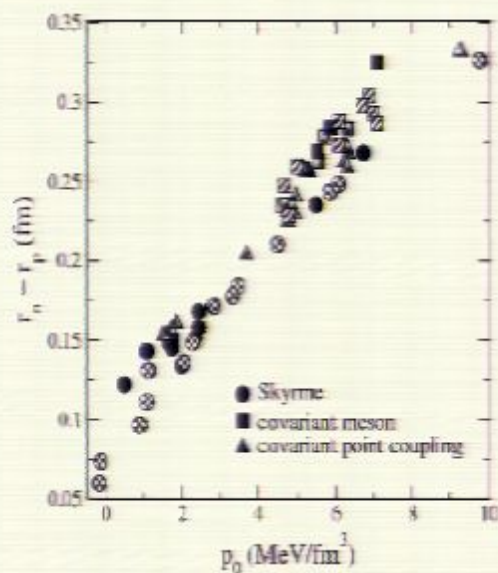
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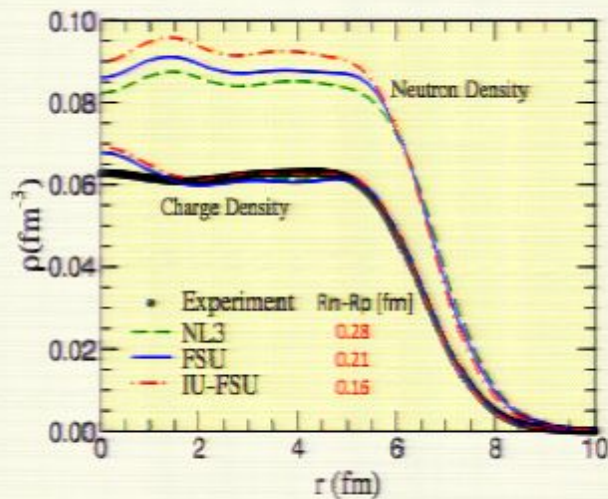
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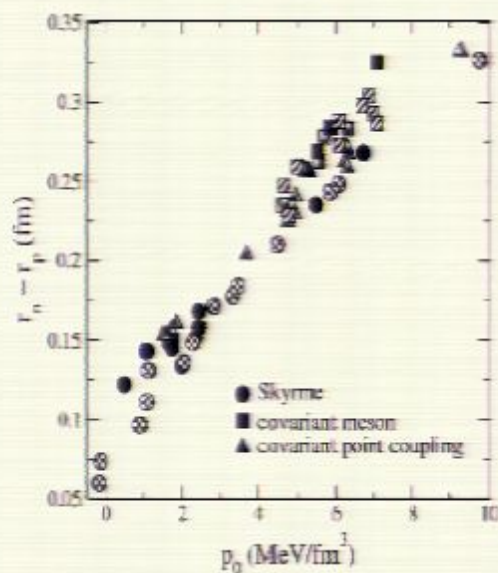
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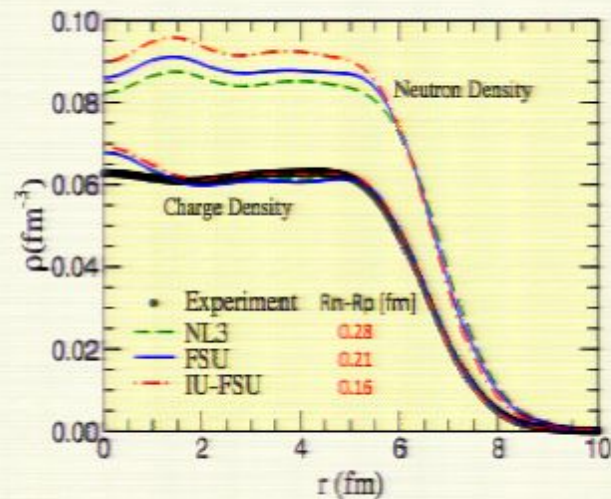
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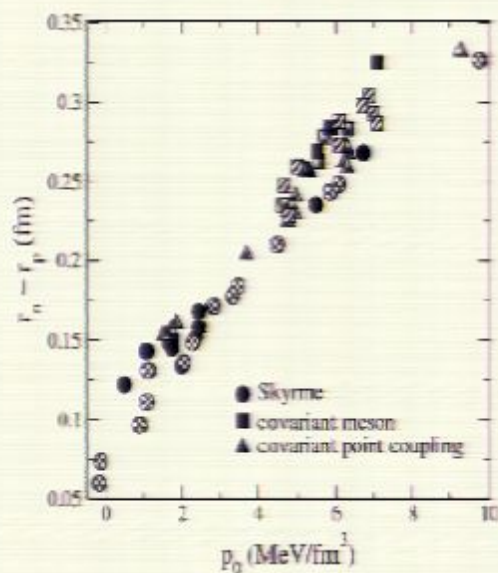
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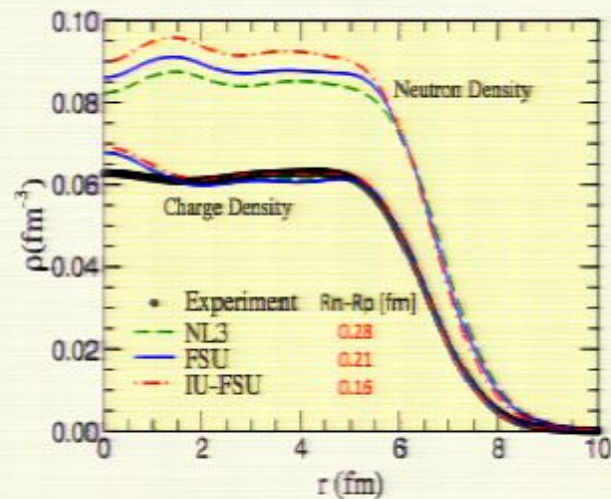
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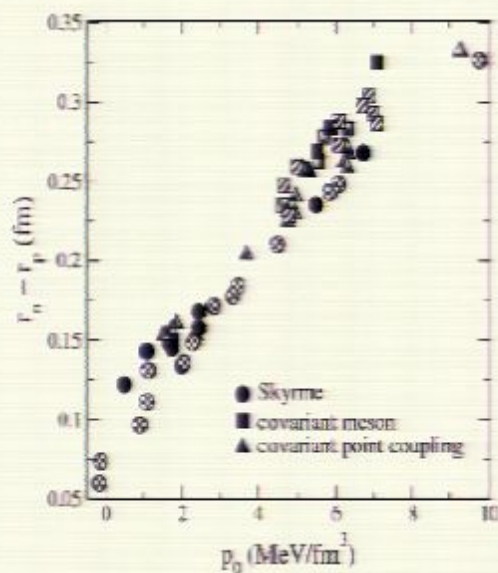
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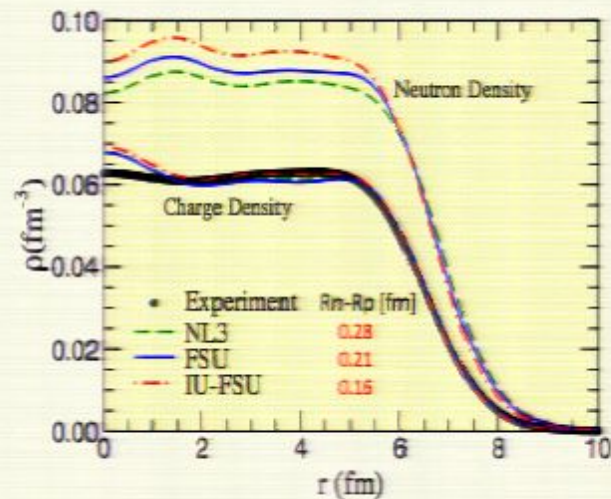
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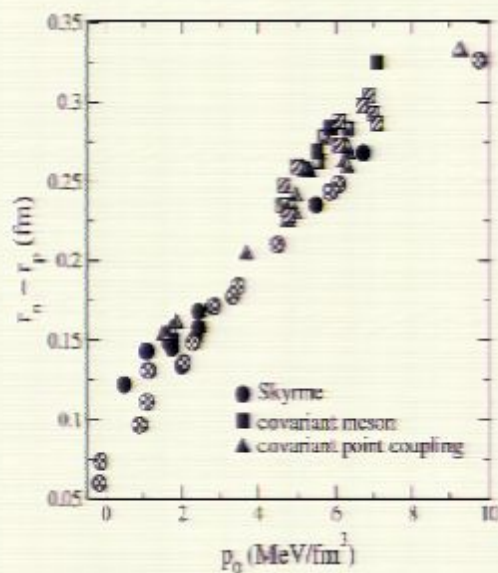
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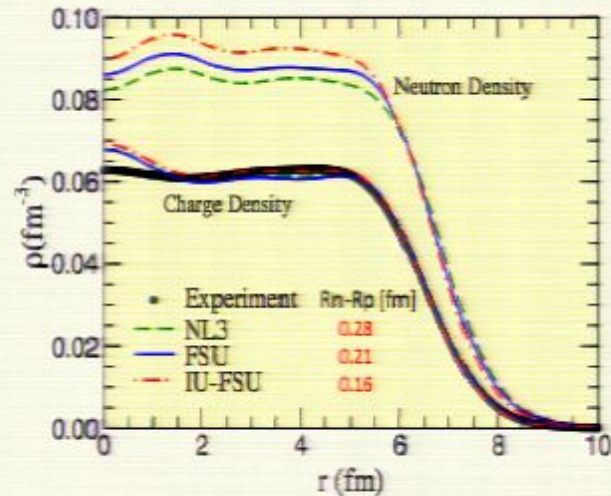
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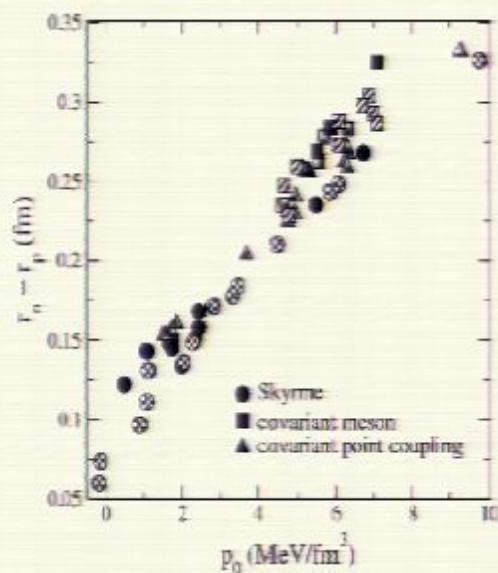
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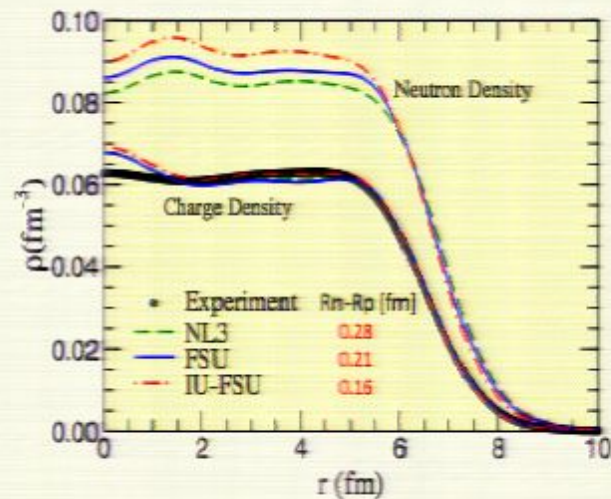
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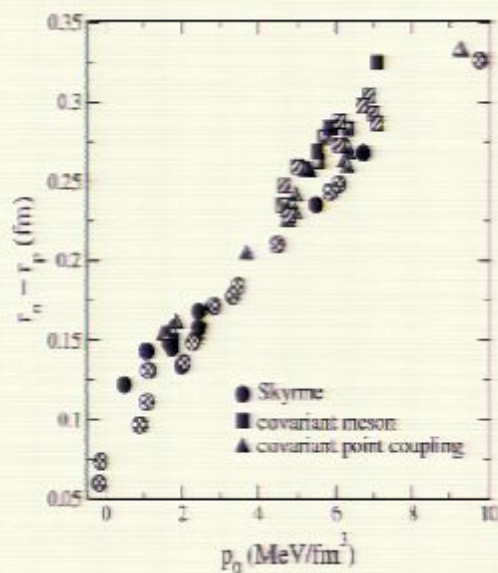
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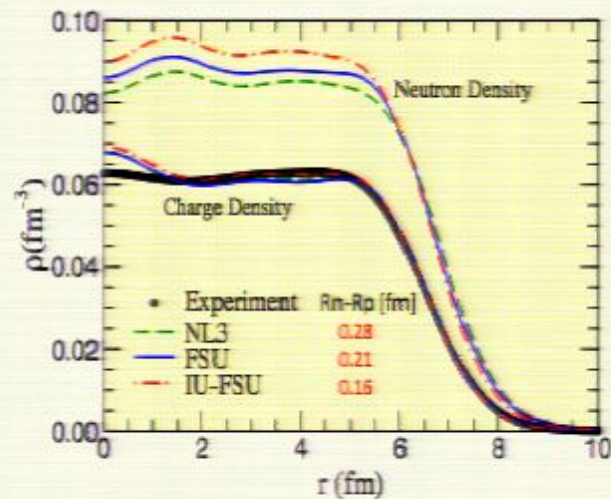
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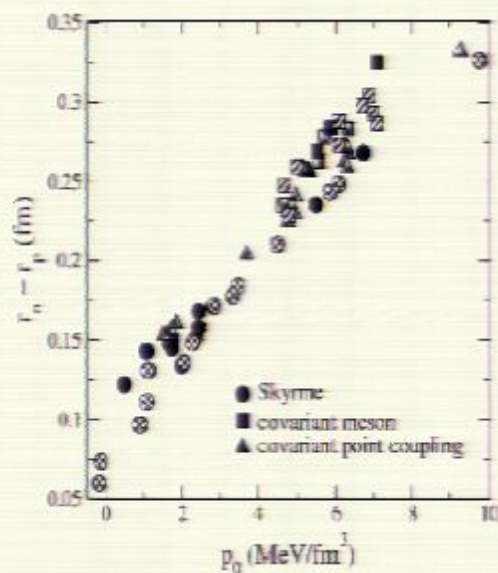
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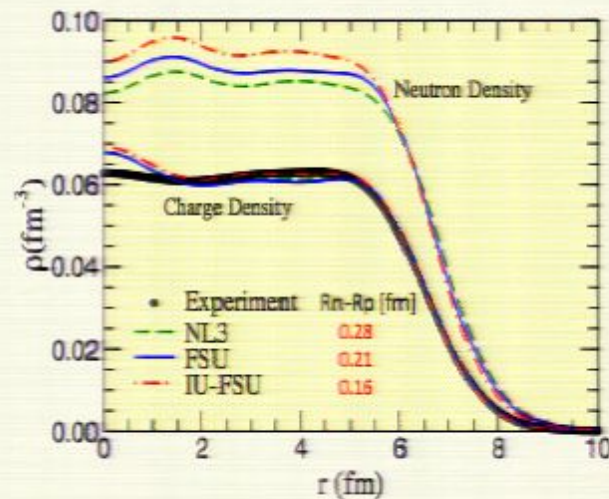
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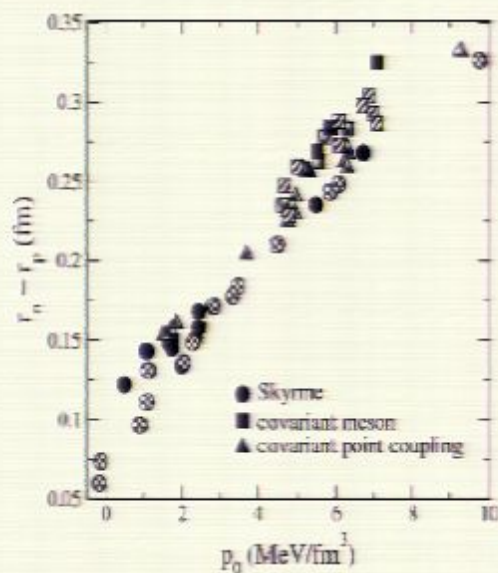
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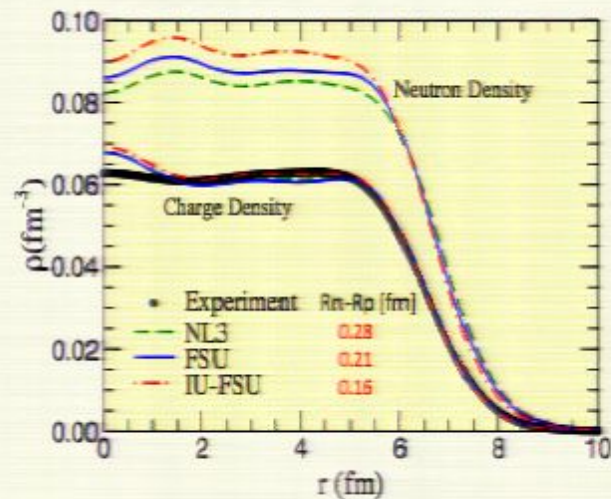
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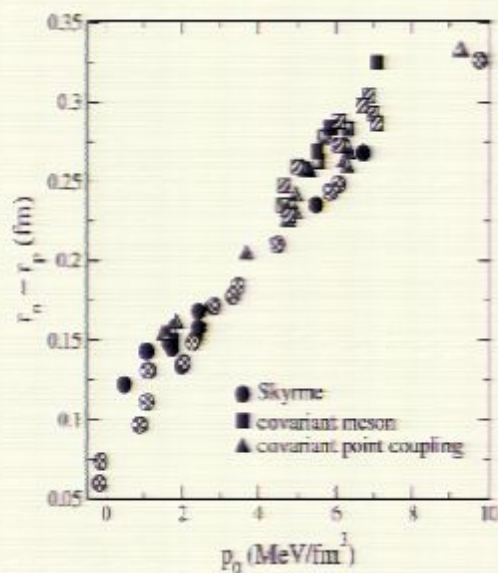
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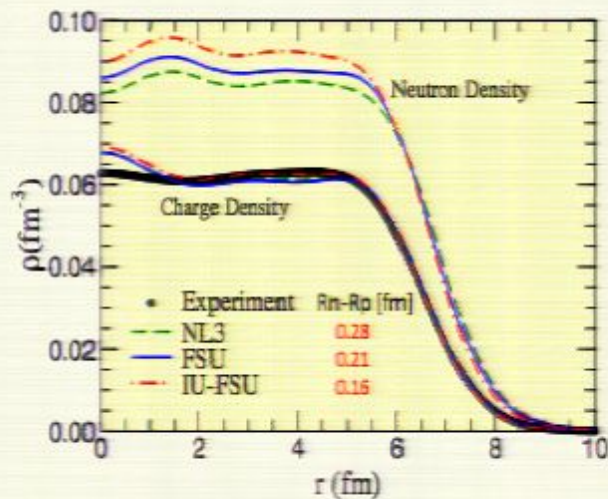
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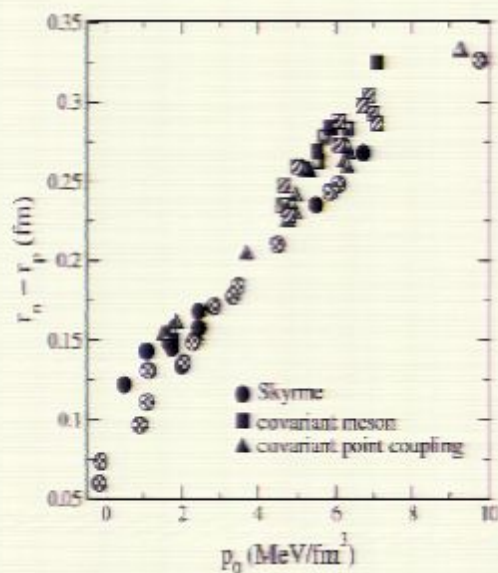
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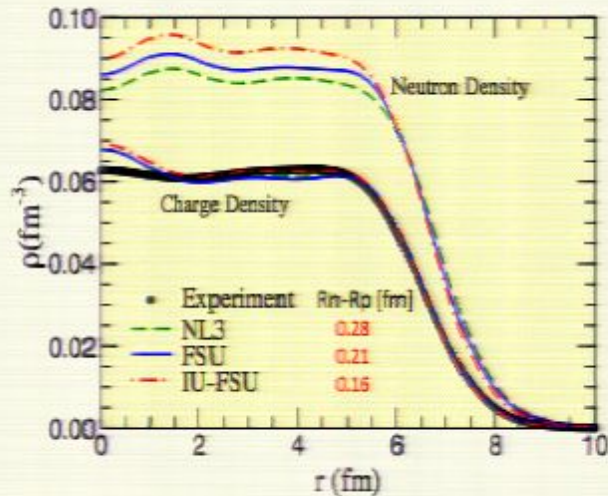
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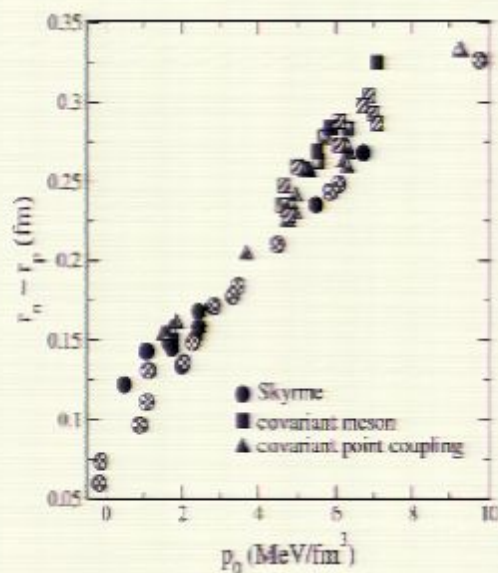
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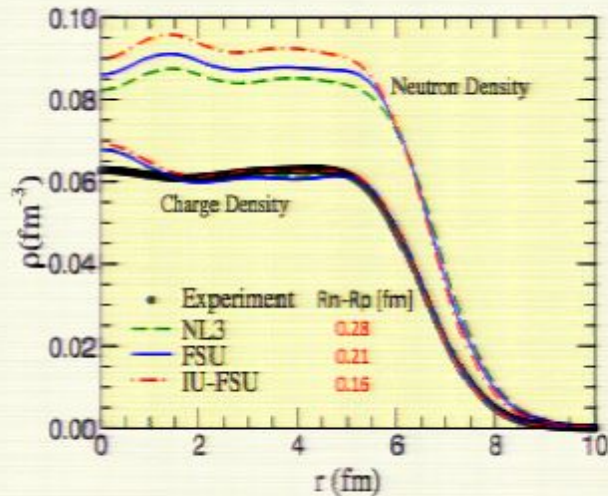
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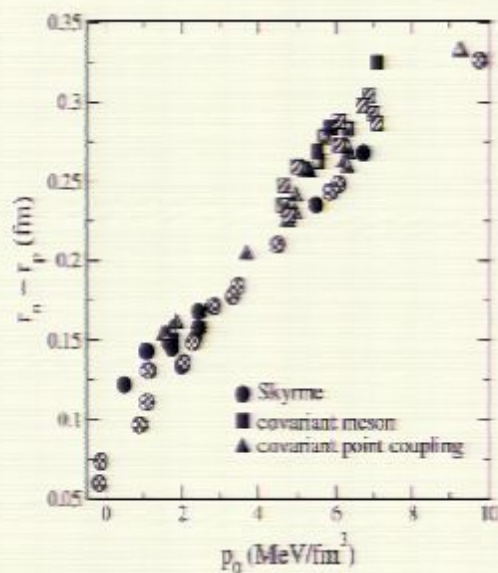
Furnstahl, '02



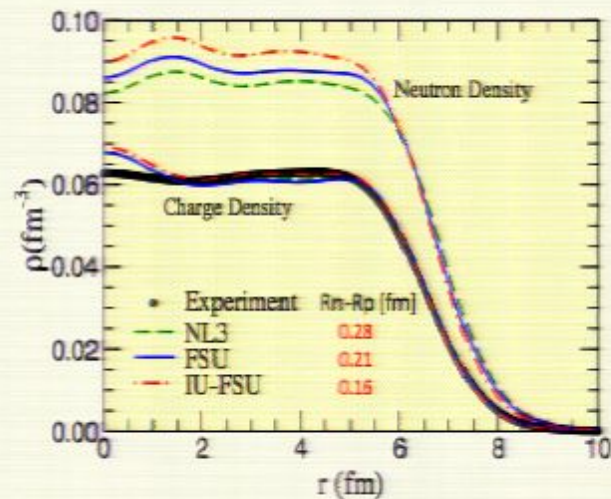
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

Constraints: nuclear experiments

- Charge radius in 208Pb well determined: 1%
- Neutron radius in 208Pb: 5% deviation among model predictions
- Neutron skin sensitive to EoS: A stiffer EOS (around saturation) indicates a larger neutron radius and neutron skin in 208Pb.



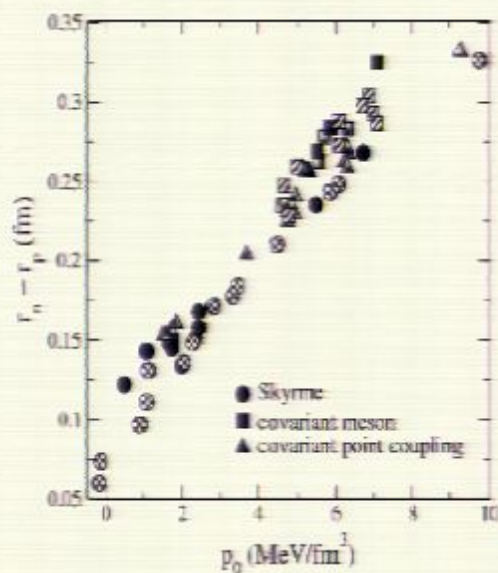
Furnstahl, '02



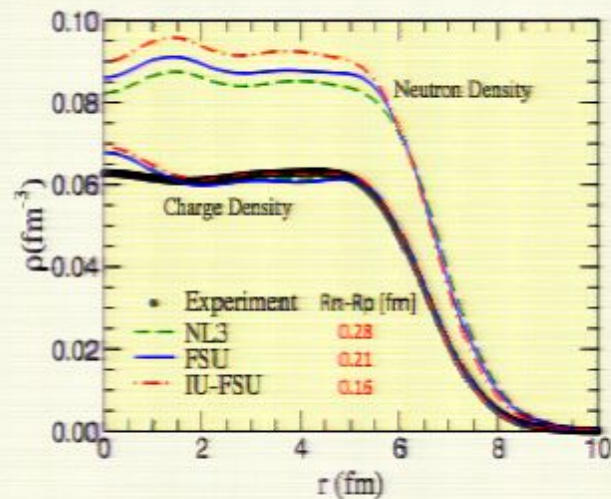
PREX I: 0.34±0.15-0.17 fm (2011)

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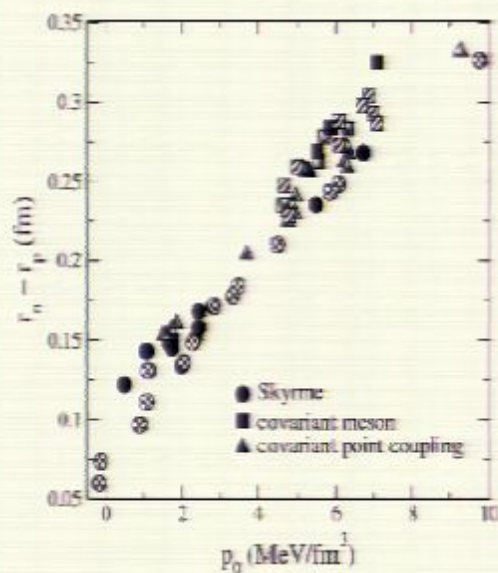
Furnstahl, '02



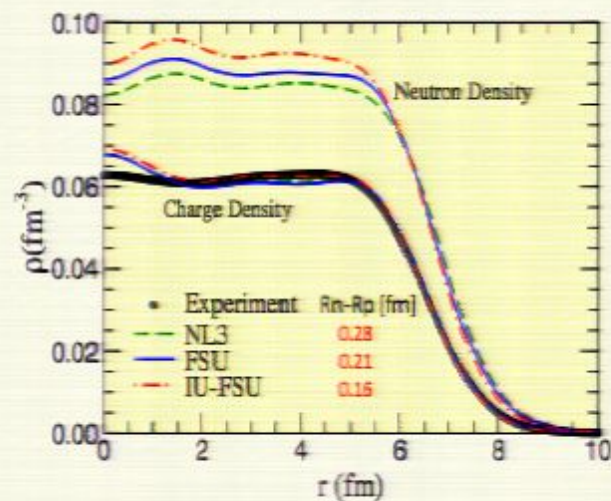
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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Furnstahl, '02

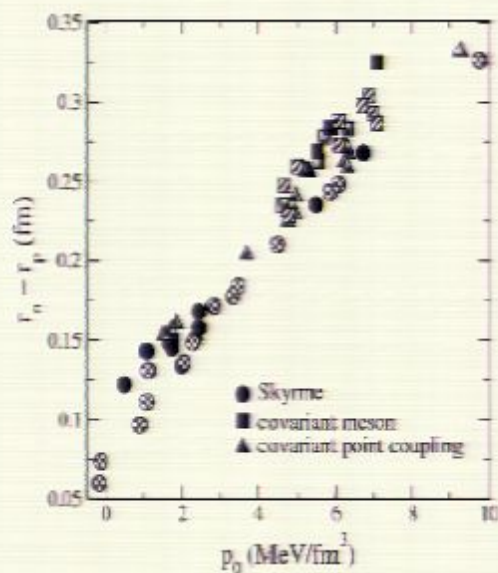


PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

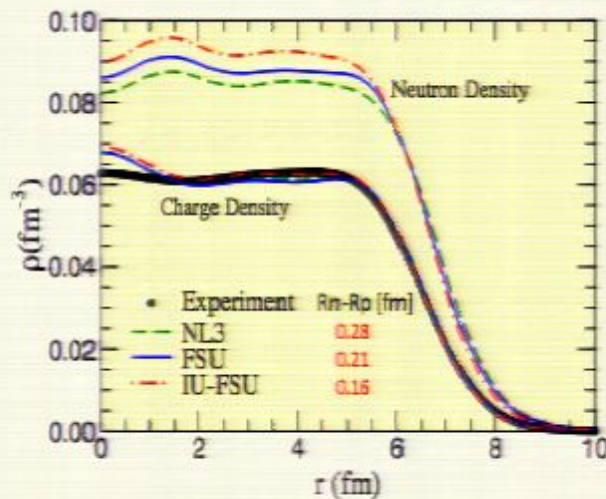
F. Fattoyev, C. Horowitz, J. Piekarewicz, GS, '10

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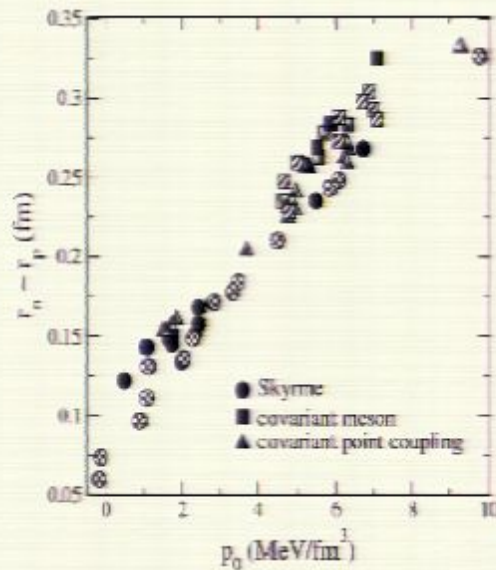
Furnstahl, '02



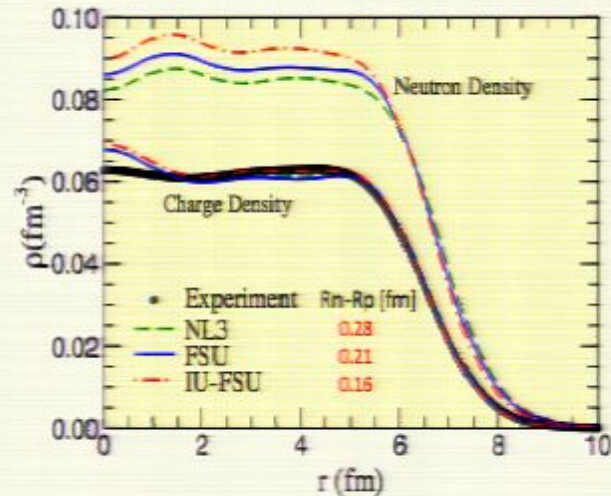
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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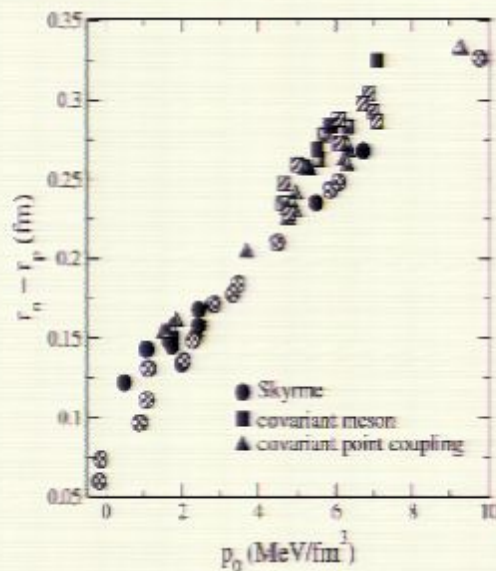
Furnstahl, '02



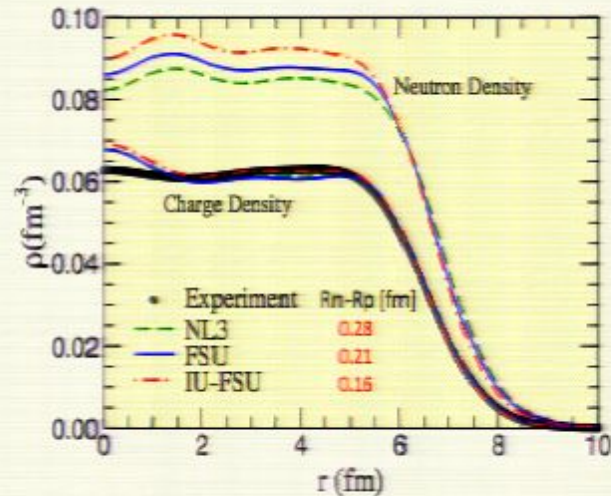
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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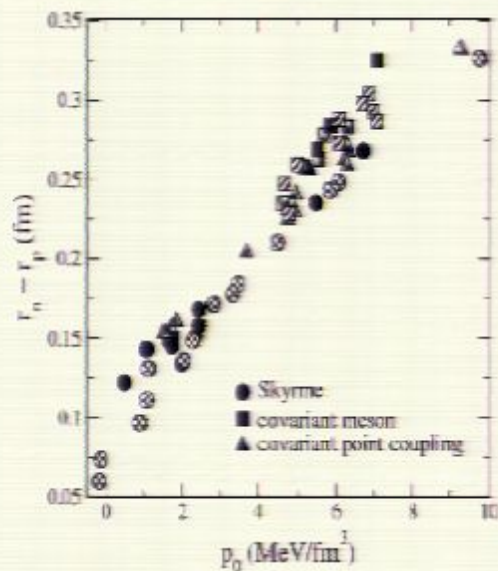
Furnstahl, '02



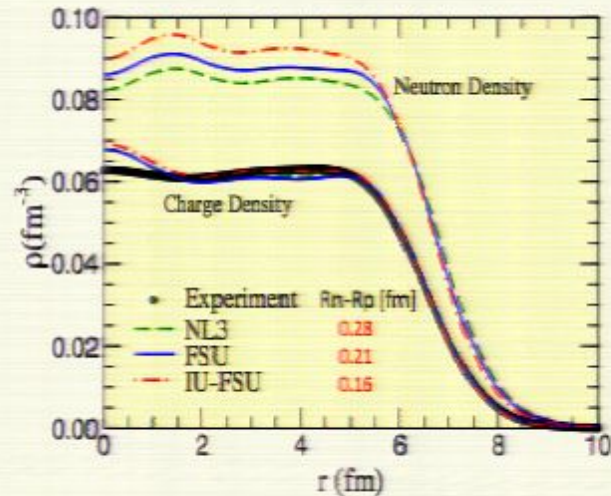
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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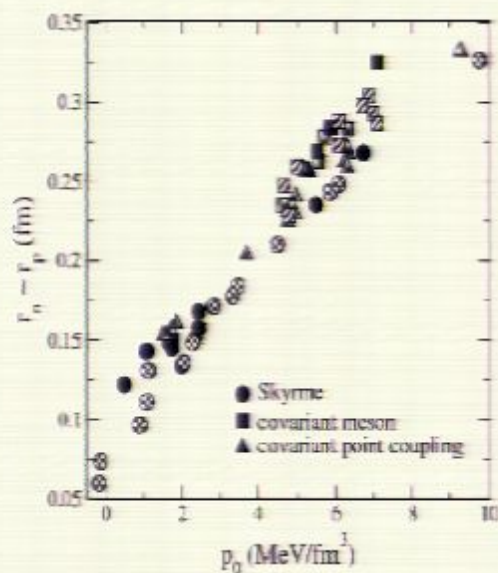
Furnstahl, '02



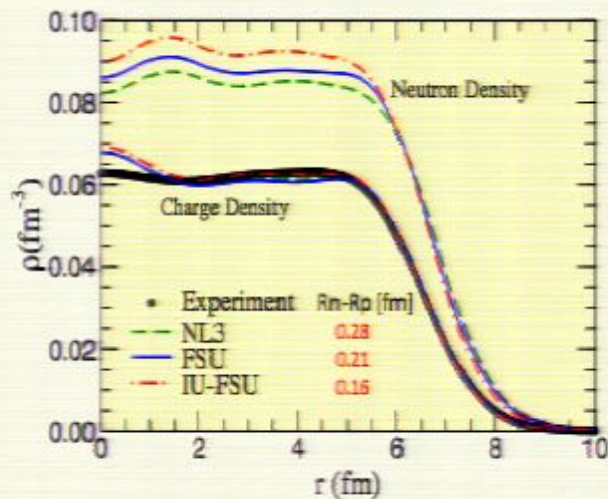
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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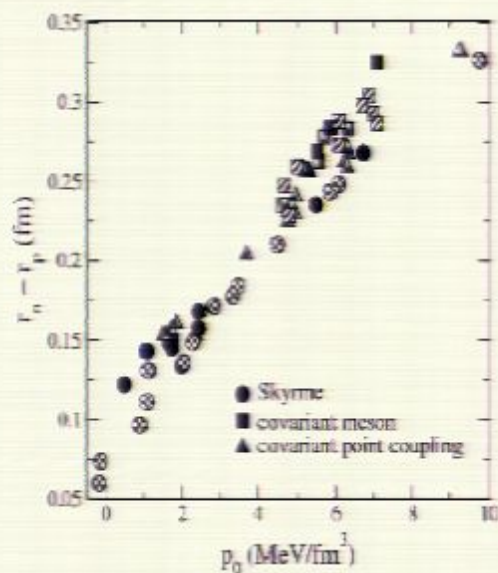
Furnstahl, '02



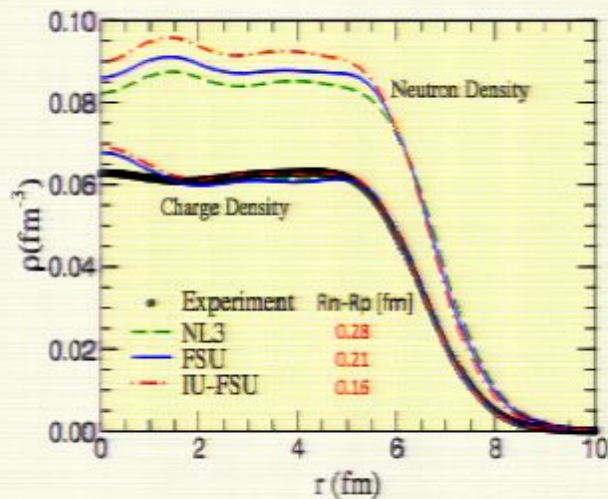
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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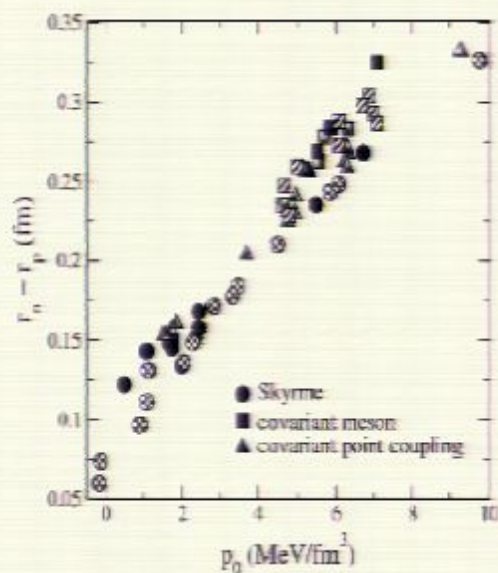
Furnstahl, '02



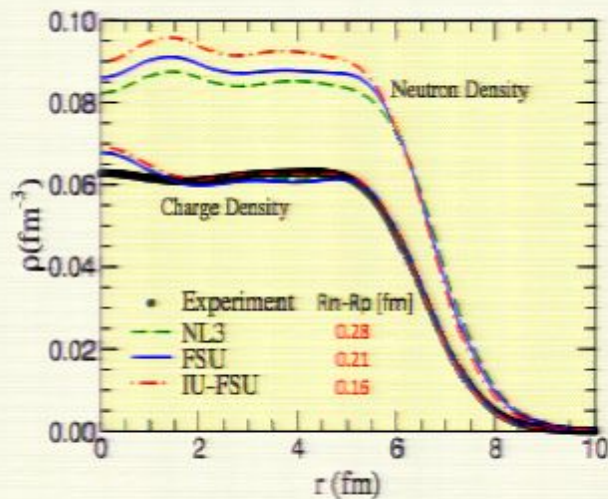
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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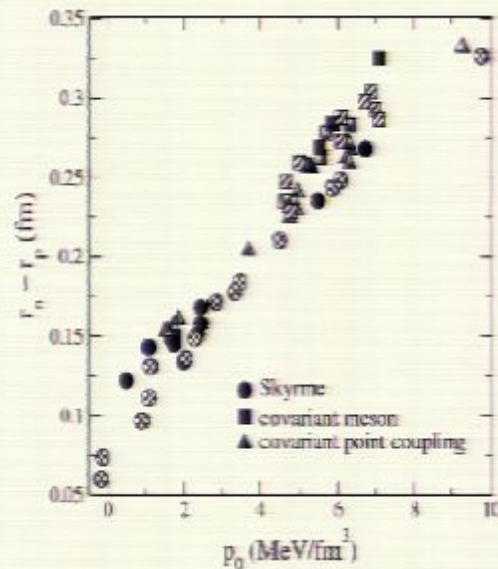
Furnstahl, '02



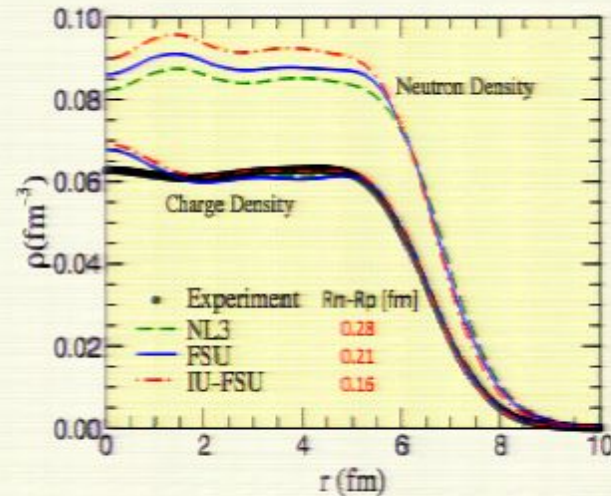
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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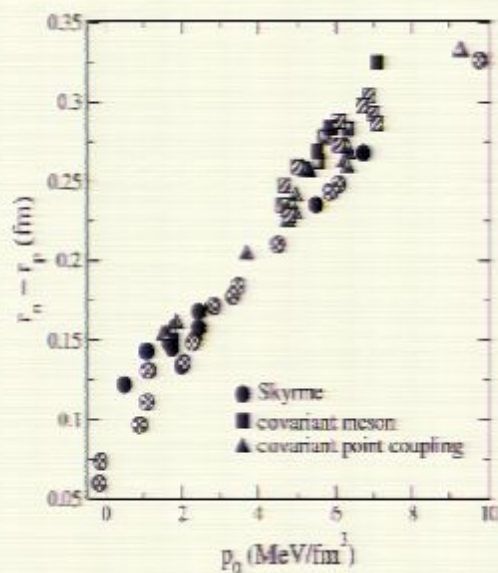
Furnstahl, '02



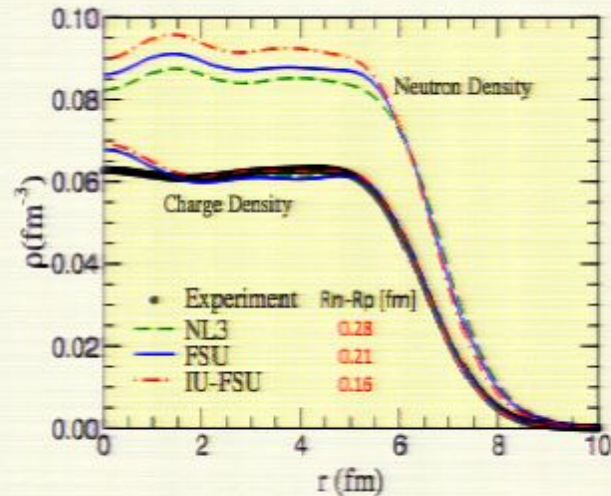
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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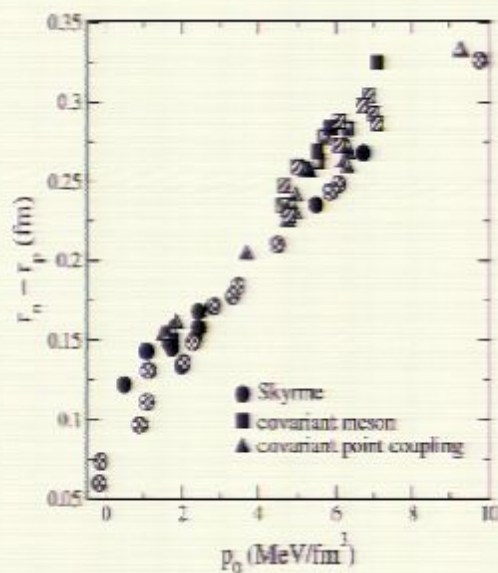
Furnstahl, '02



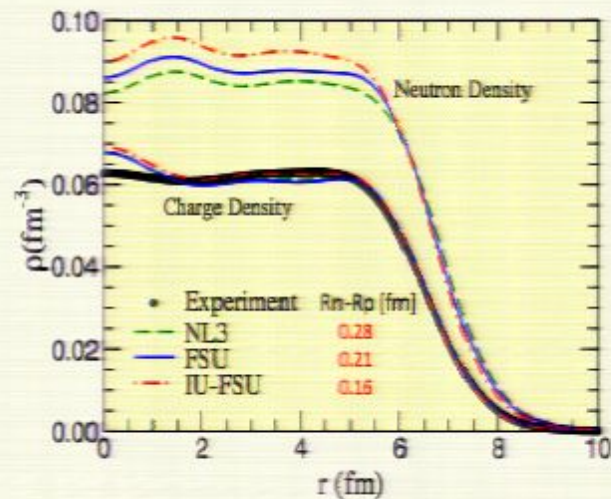
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

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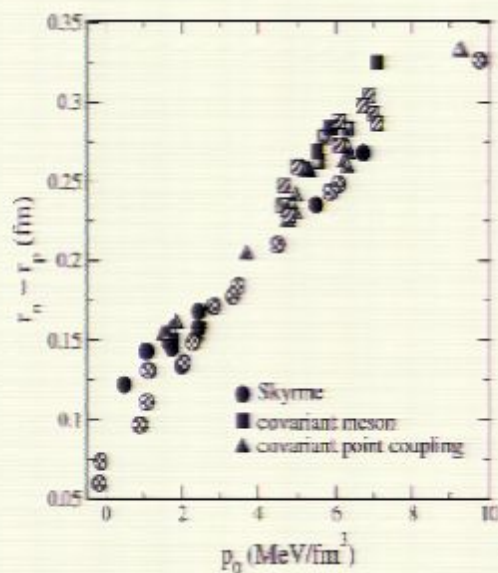
Furnstahl, '02



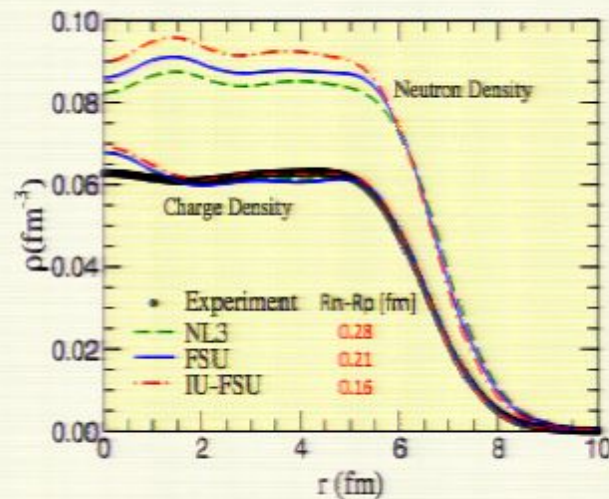
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Furnstahl, '02



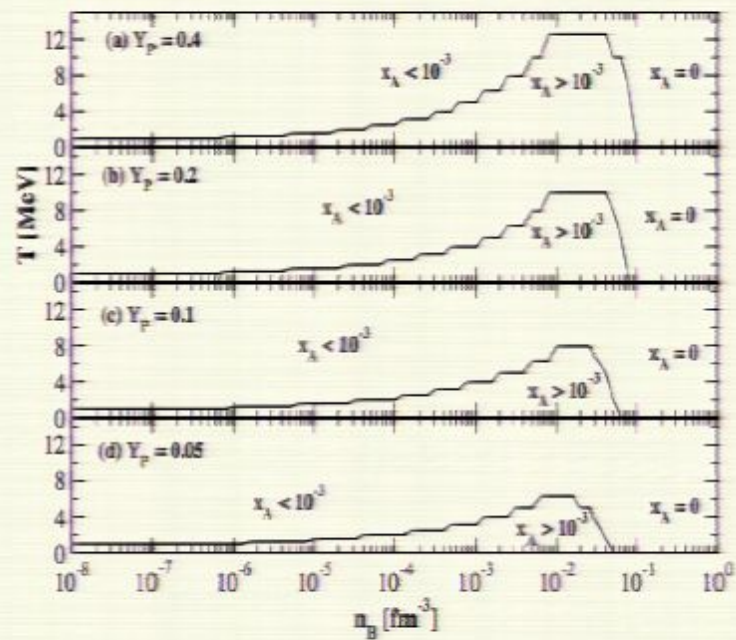
PREX I: $0.34 \pm 0.15 - 0.17$ fm (2011)

Compositions in T-n plots

Neutrino-matter interaction

- Inside contour – heavy nuclei ($A > 4$) $> 10^{-3}$
- 1st order: nucleons
- 2nd order: light nuclei, $A \leq 4$
- 3rd order: heavy nuclei

Problem: neutrino reheating in the mantle, where nuclei are abundant ?

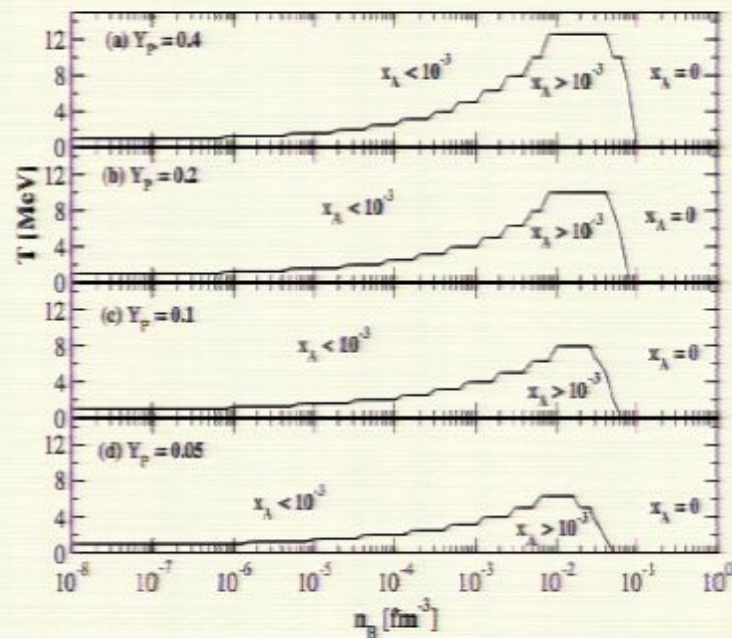


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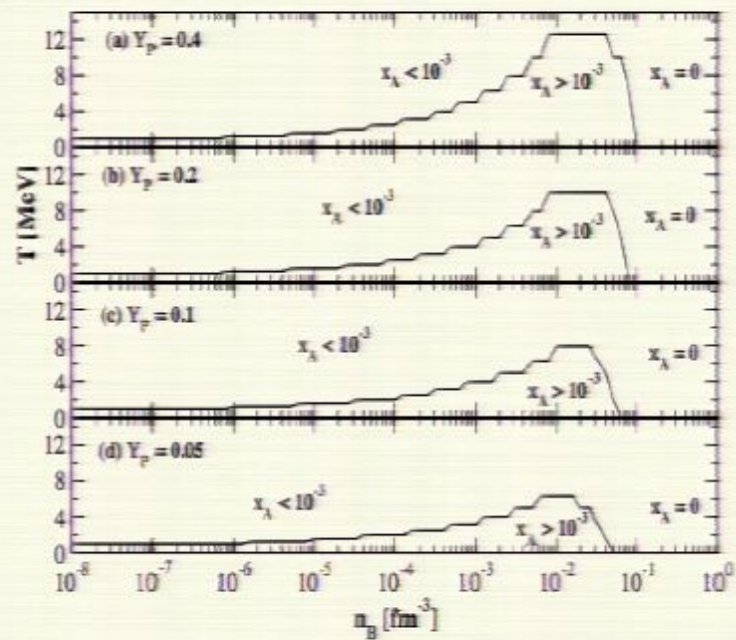


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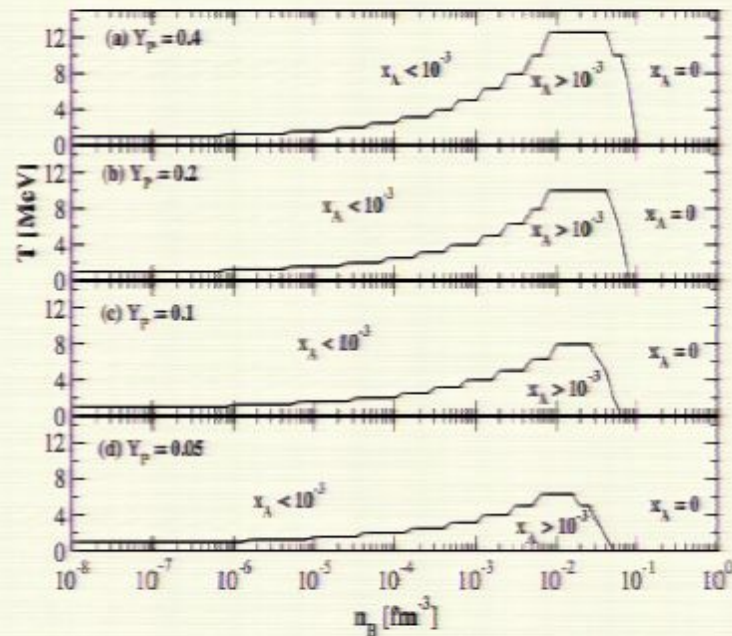


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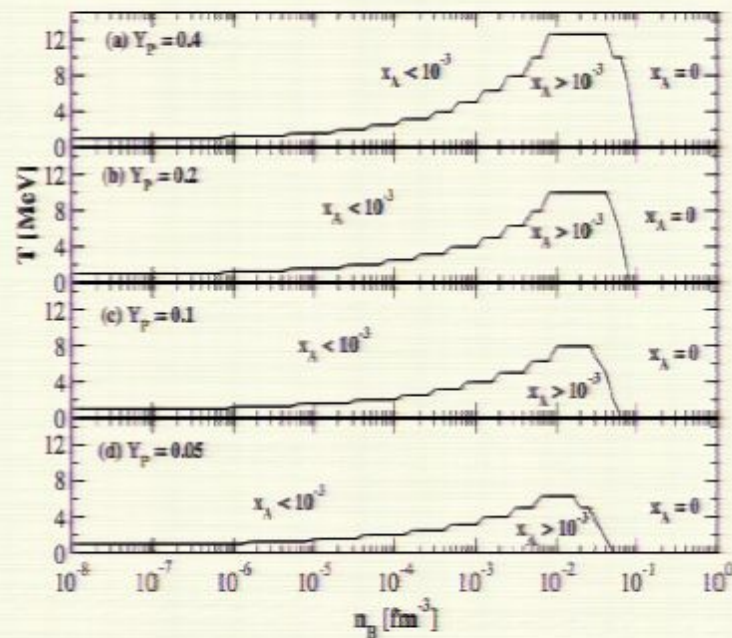


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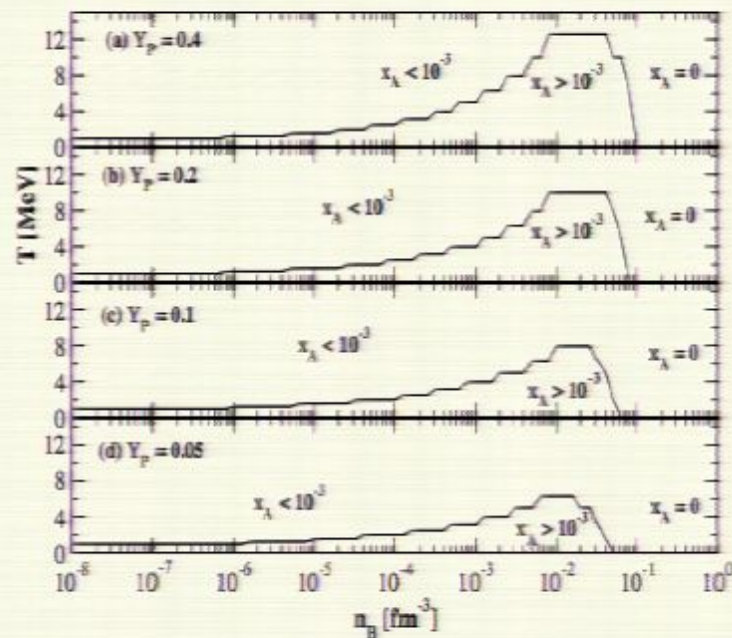


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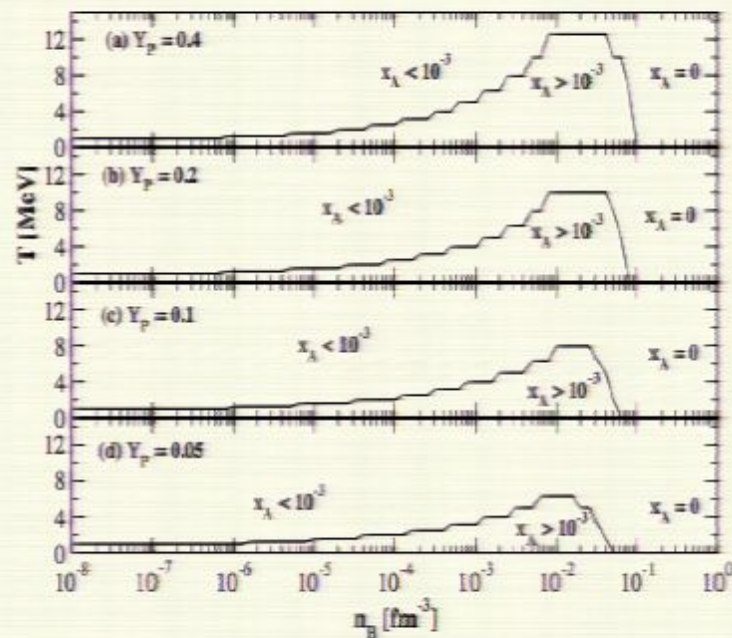


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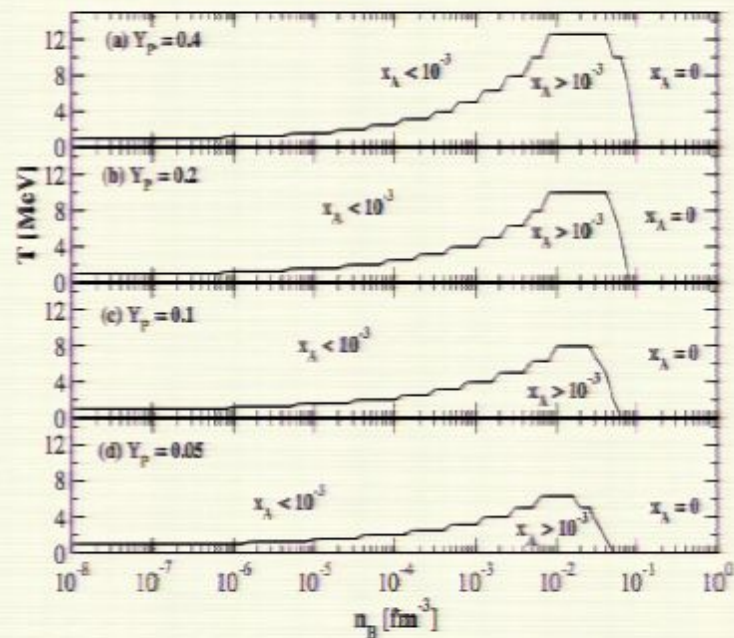


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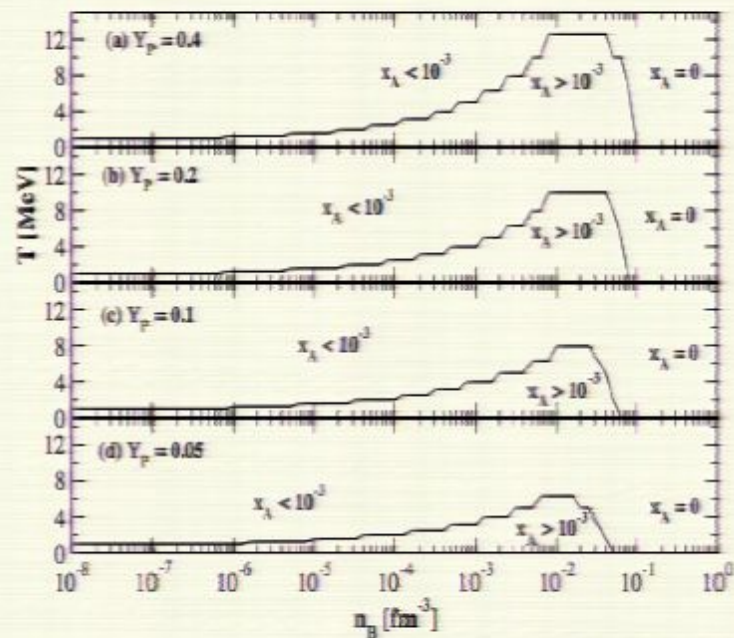


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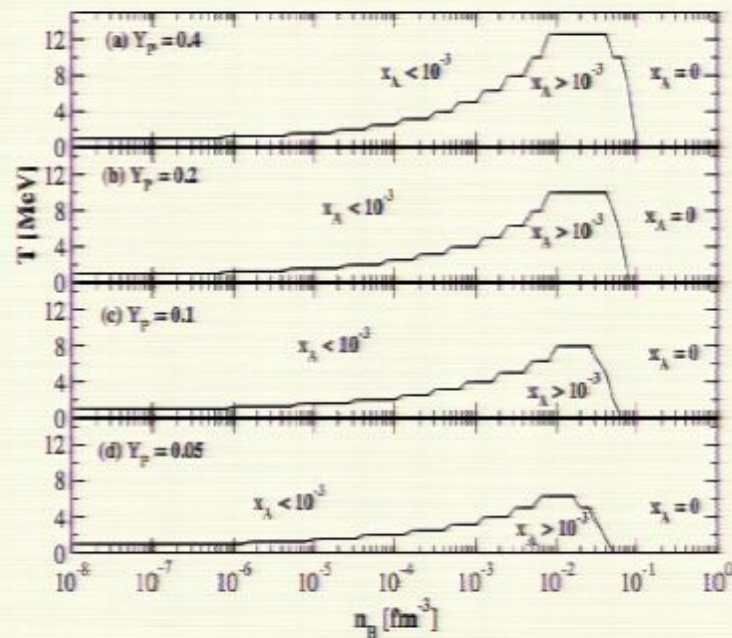


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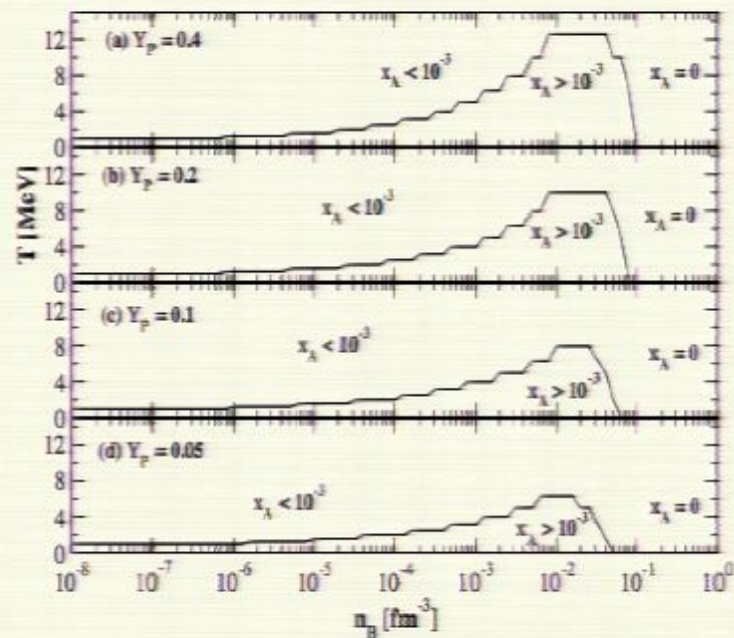


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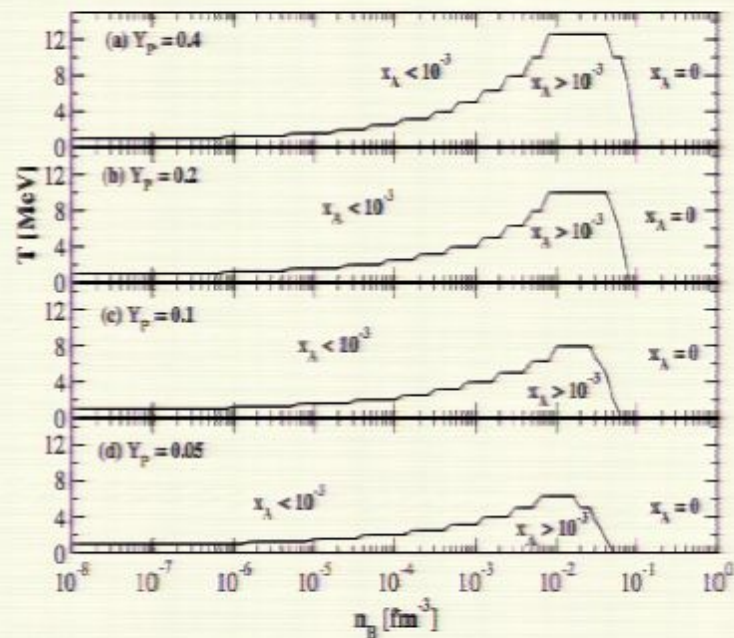


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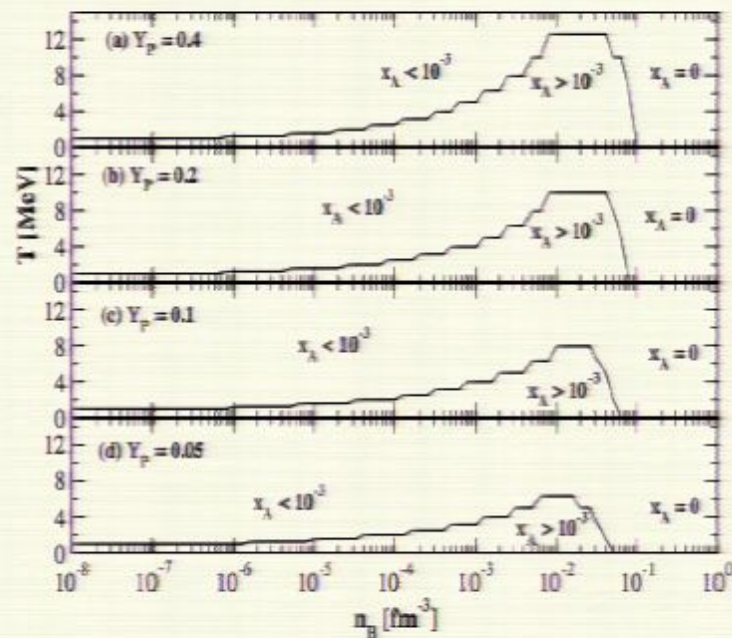


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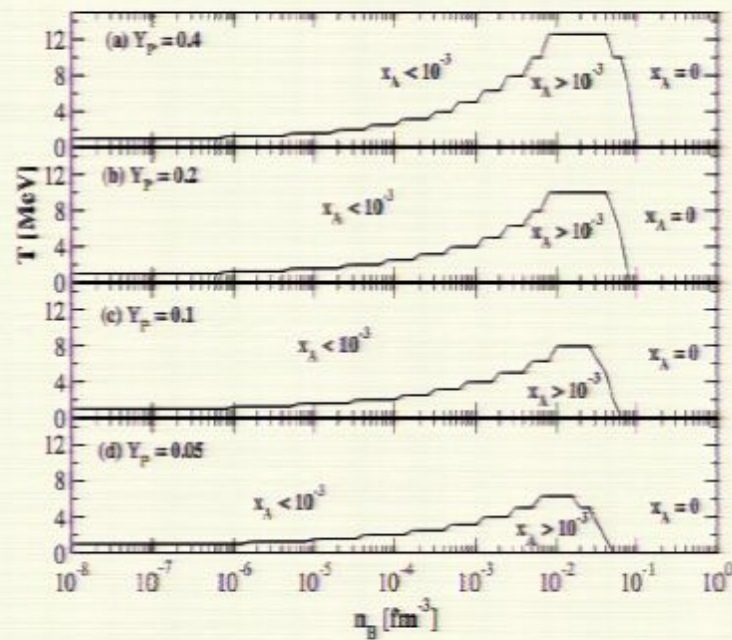


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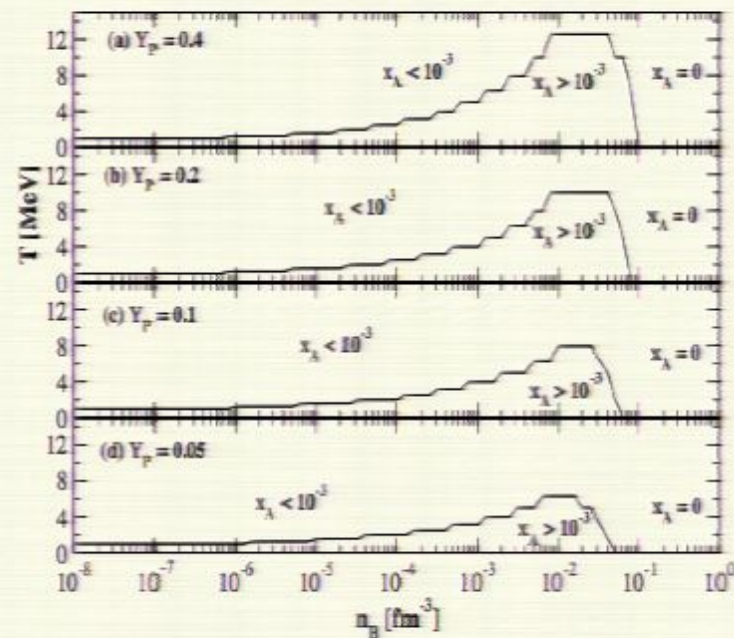


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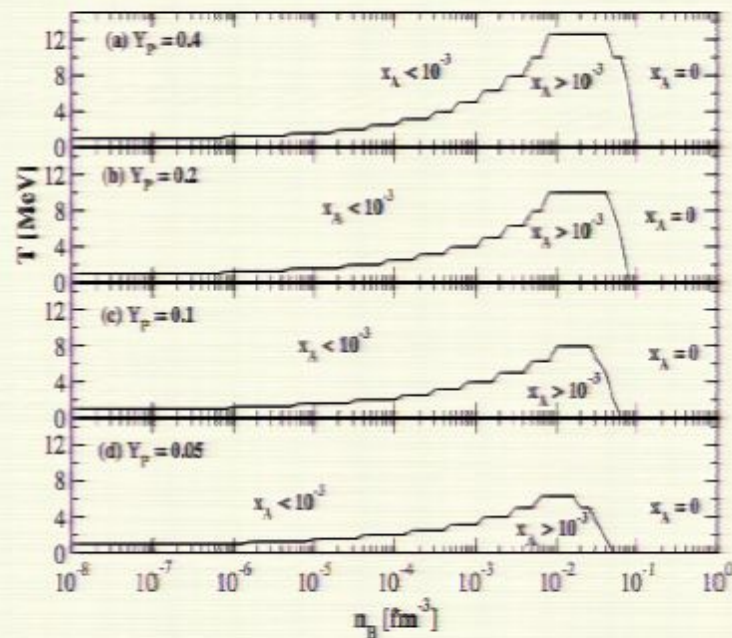


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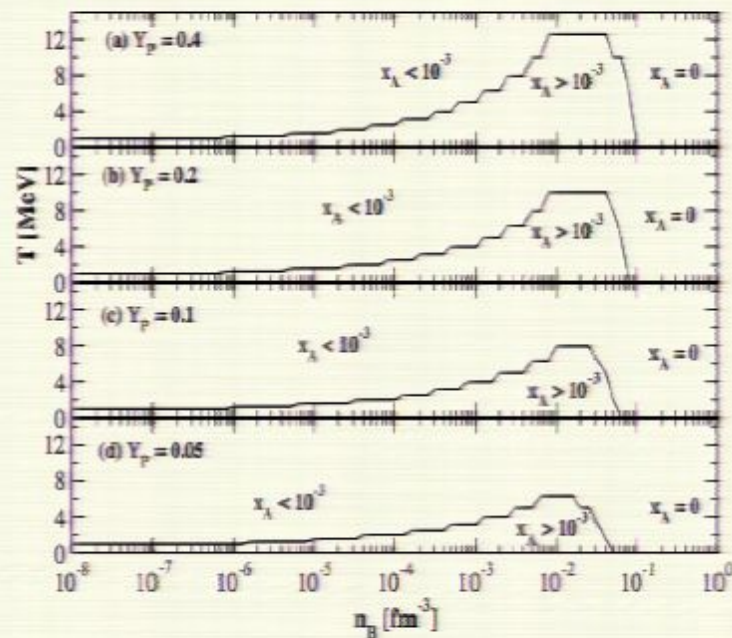


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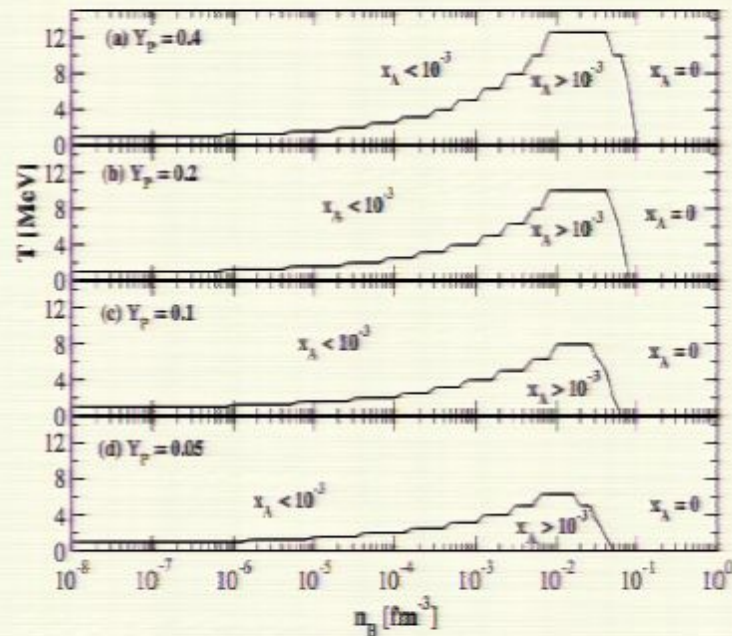


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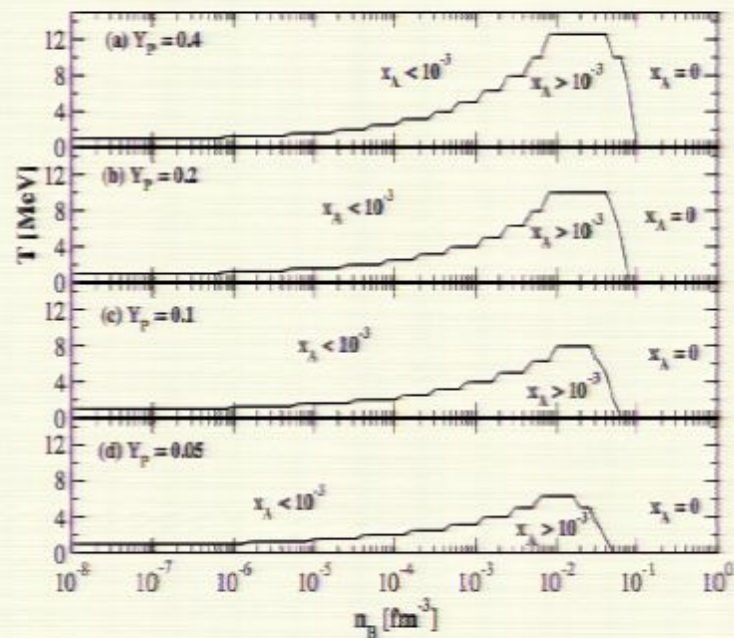


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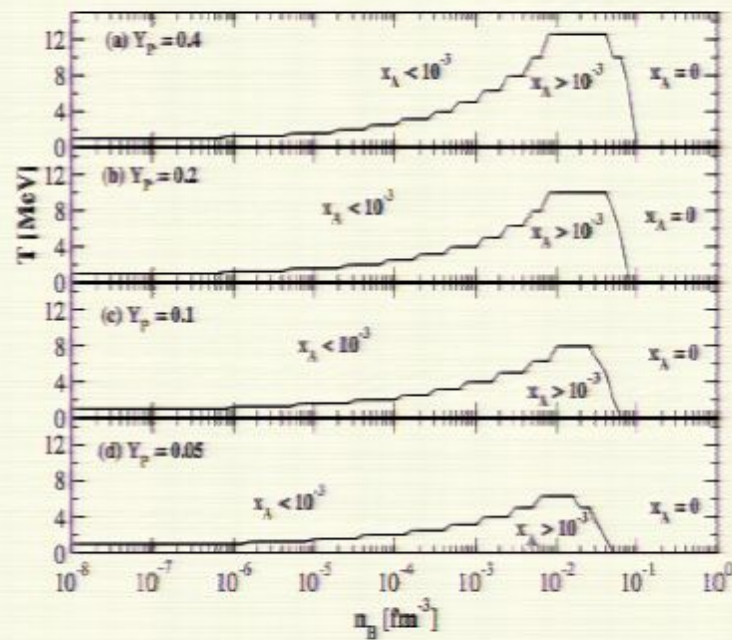


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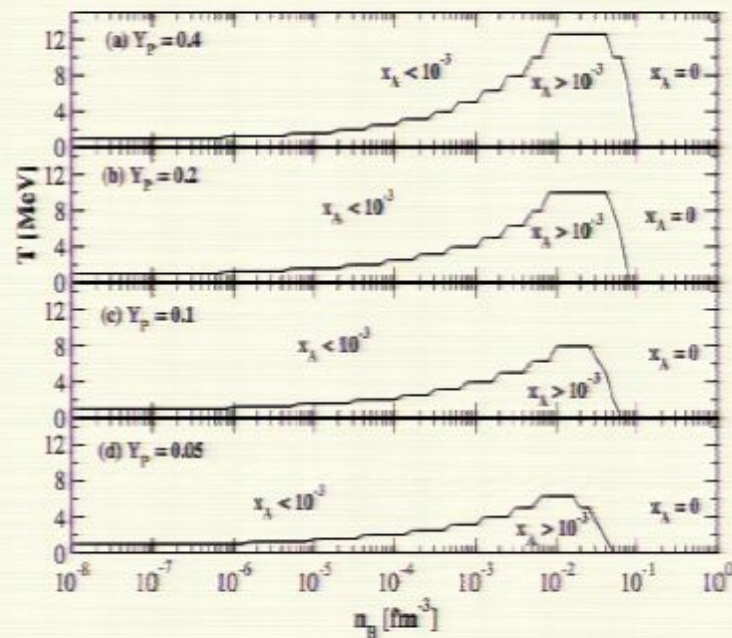


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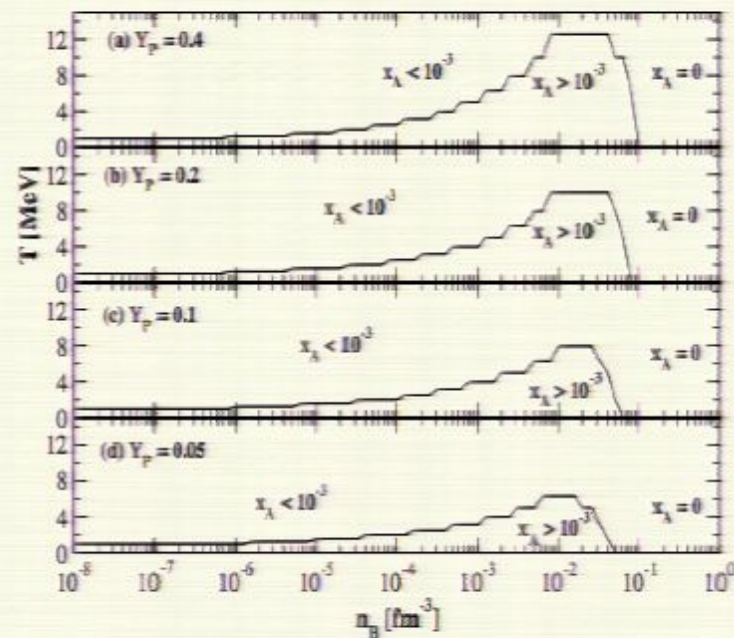


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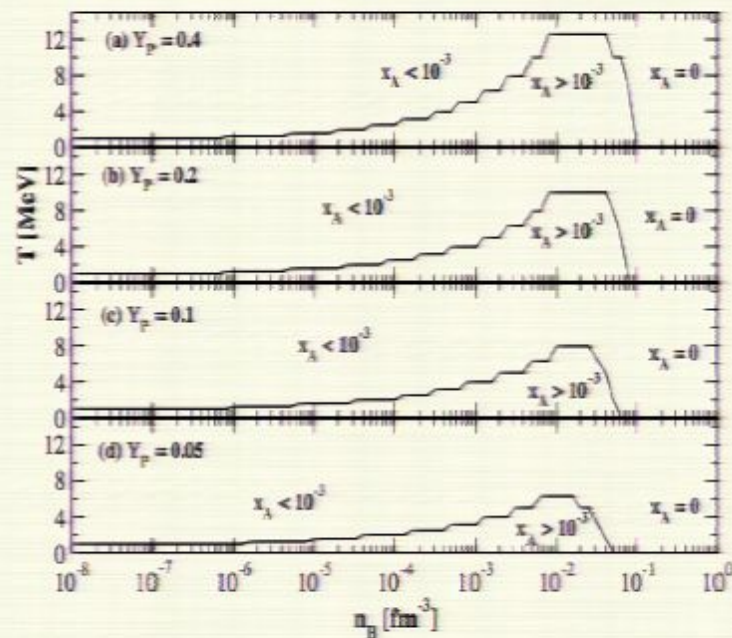


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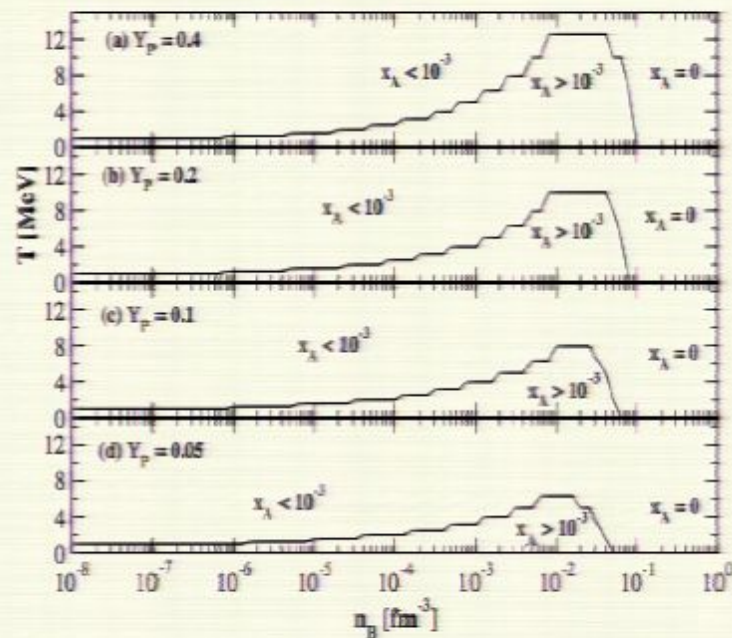


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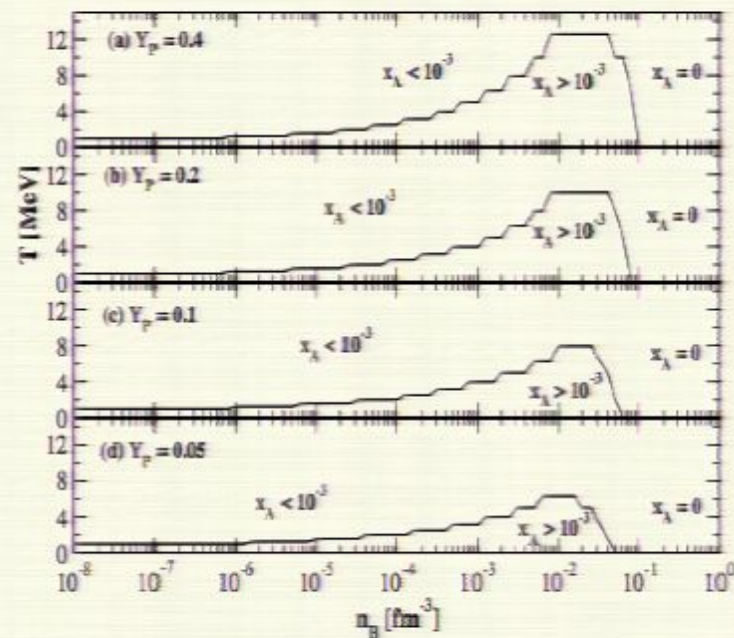


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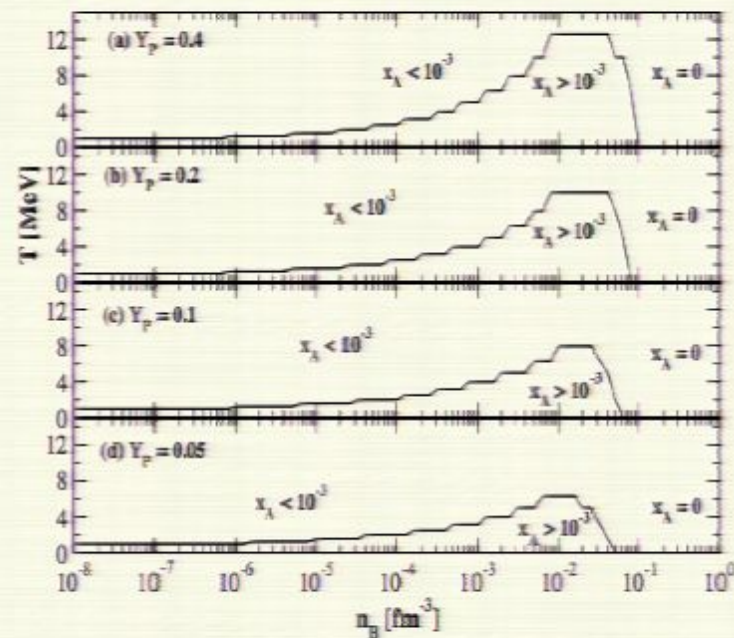


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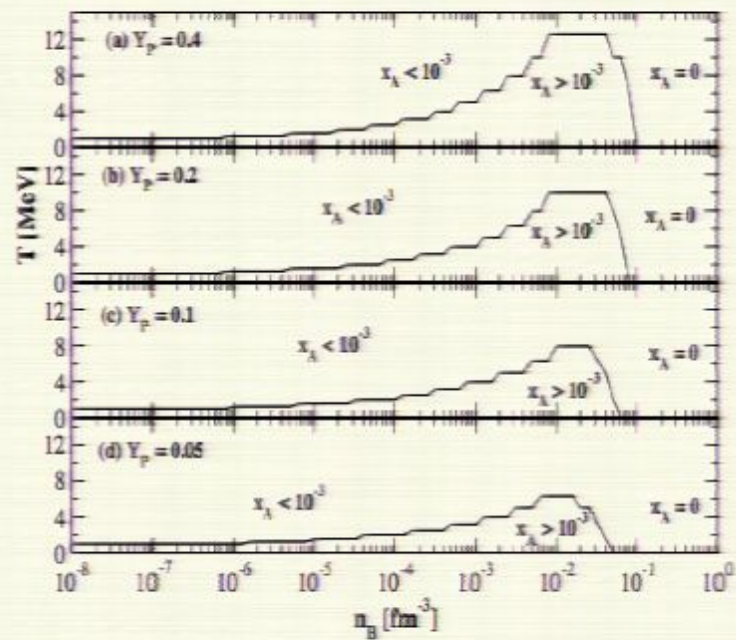


Compositions in T-n plots

Neutrino-matter interaction

- Inside contour – heavy nuclei ($A > 4$) $> 10^{-3}$
- 1st order: nucleons
- 2nd order: light nuclei, $A \leq 4$
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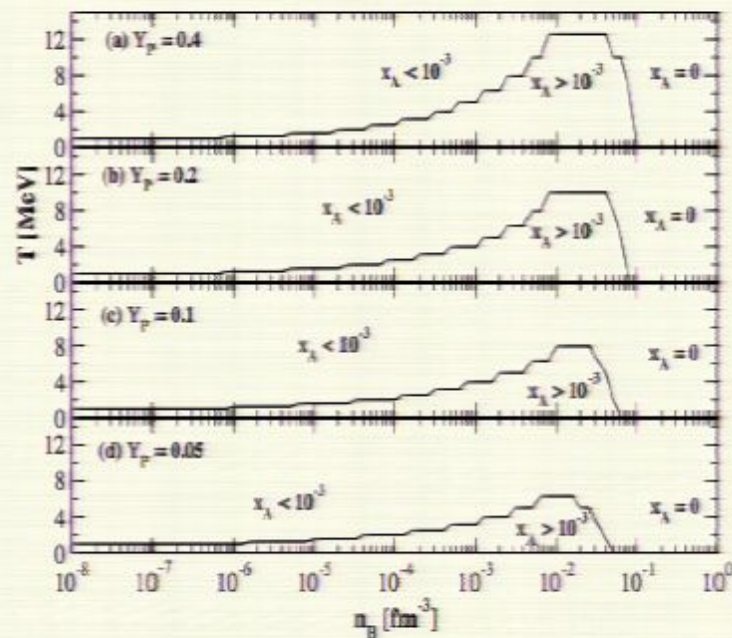


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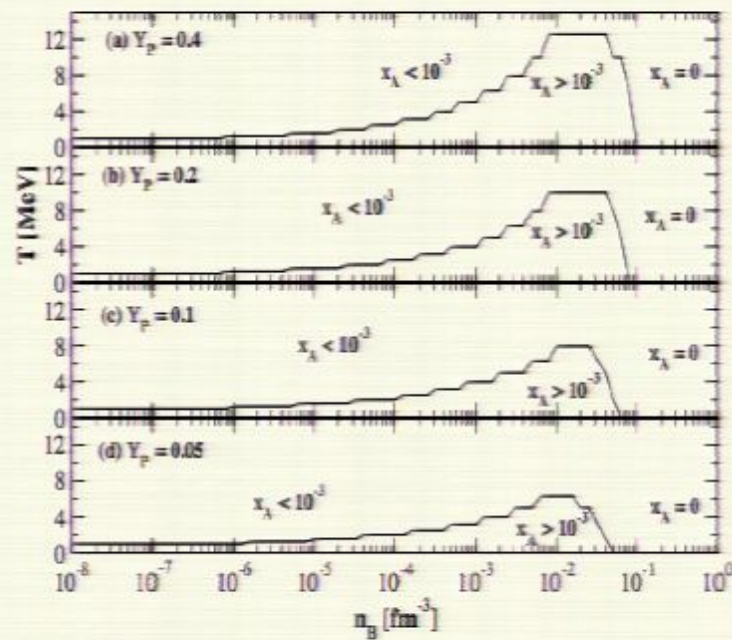


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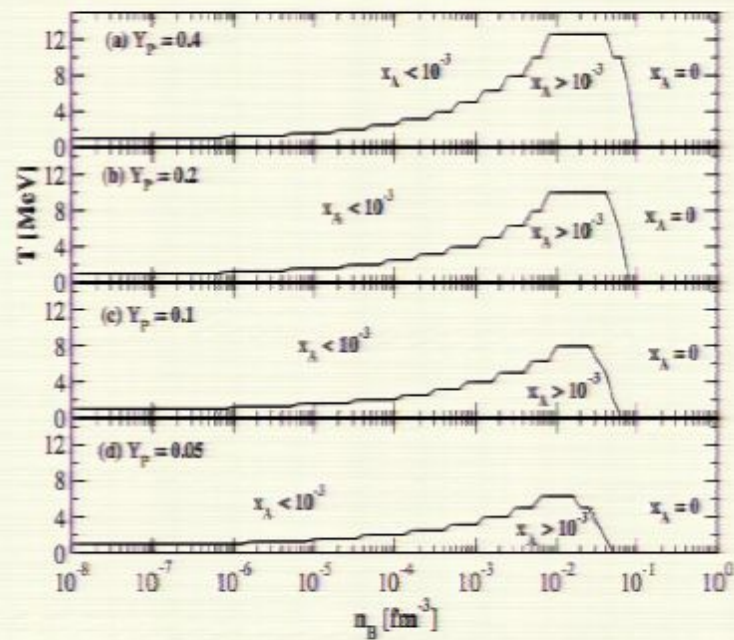


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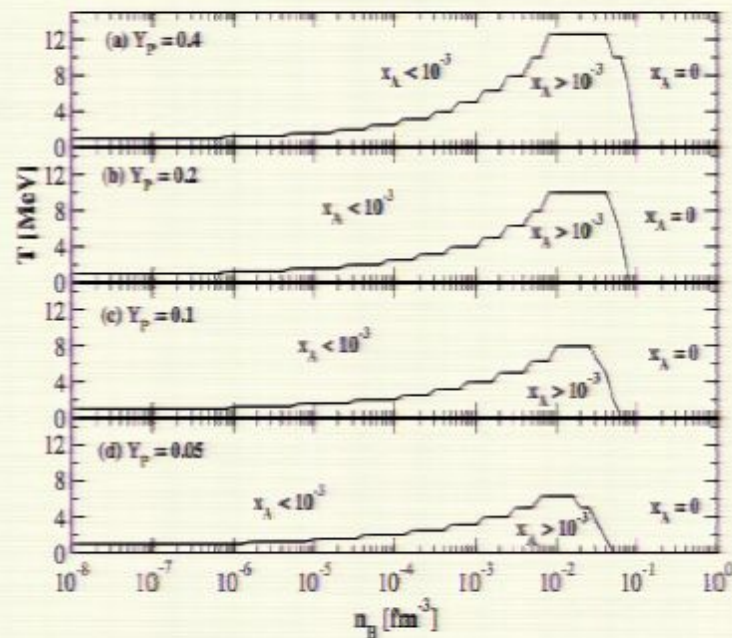


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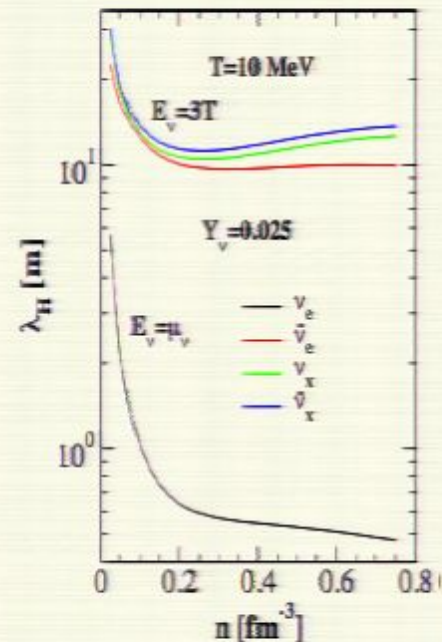
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Nucleon in free space



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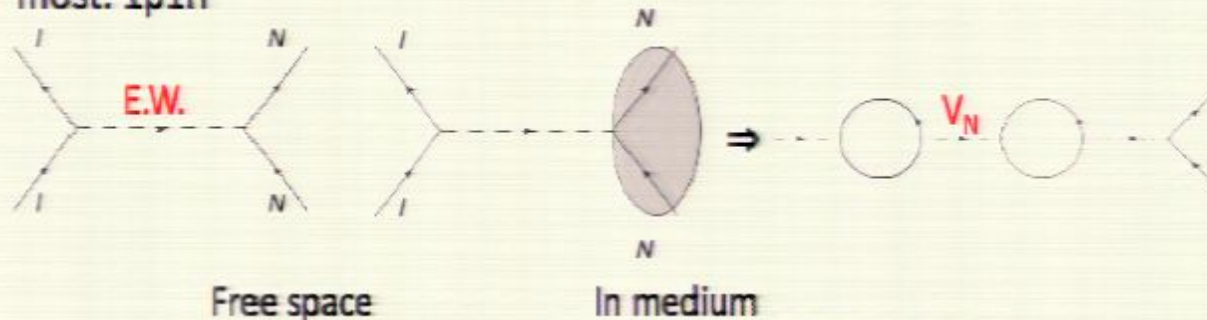
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- Interference in ν -nucleon (in medium) scatterings:

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- most: 1p1h



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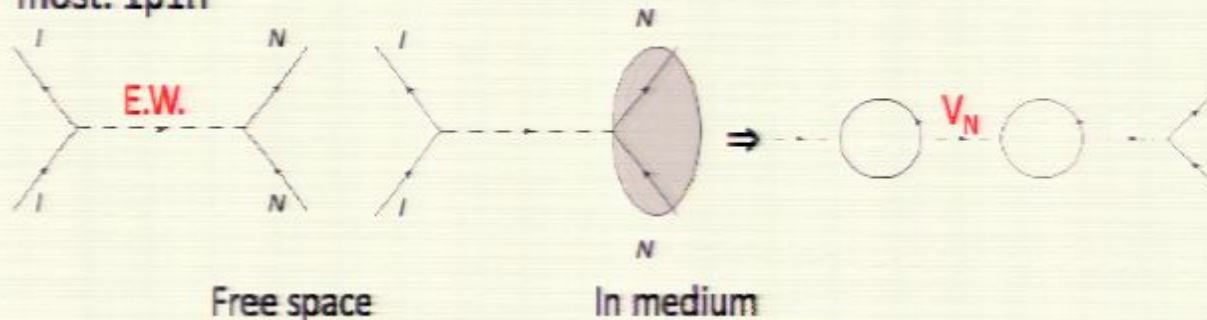
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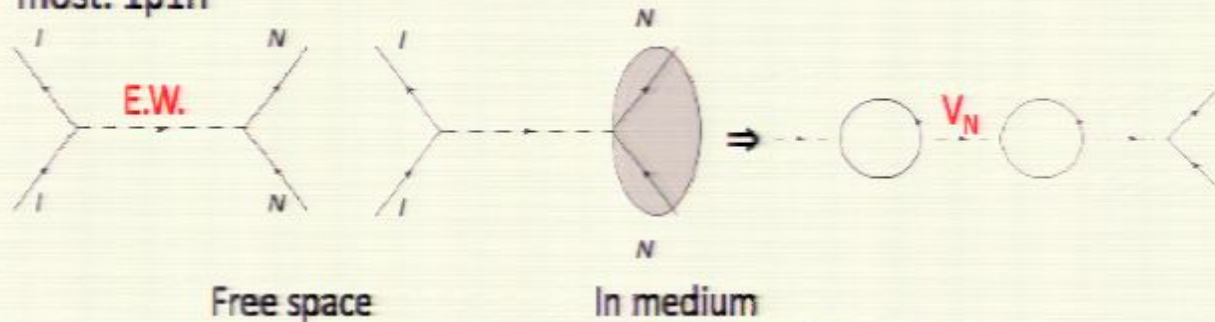
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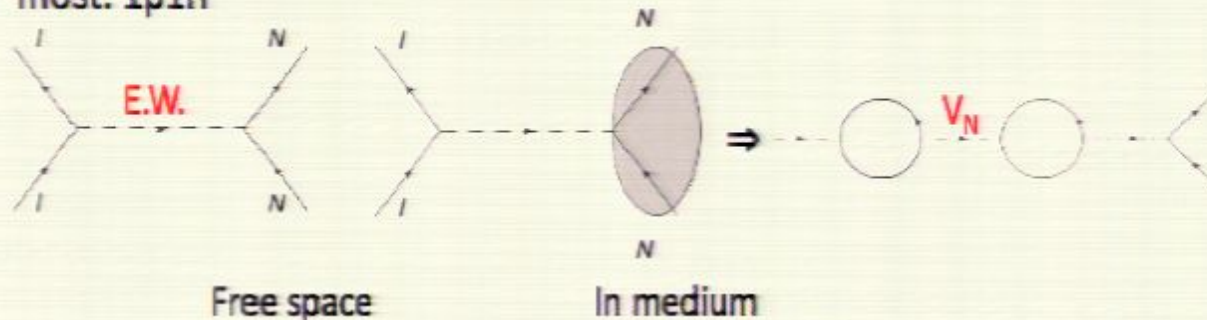
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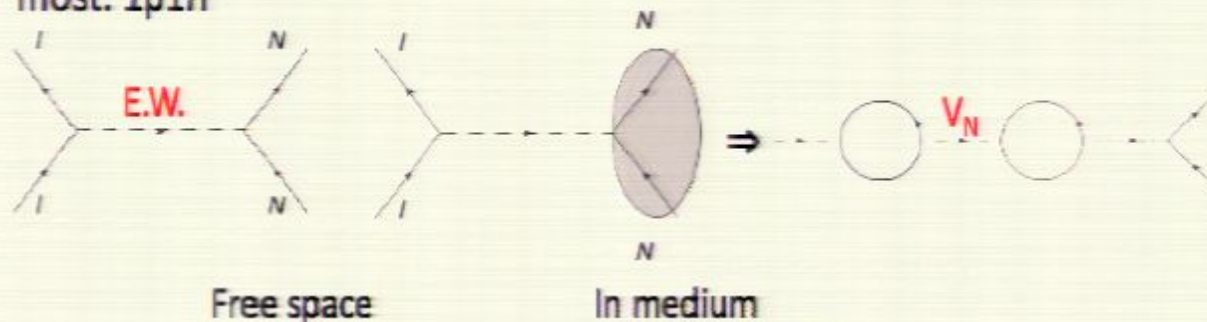
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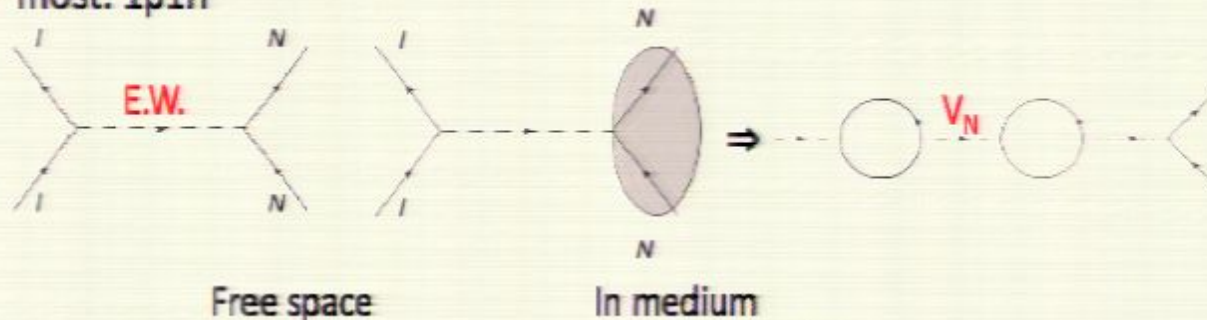
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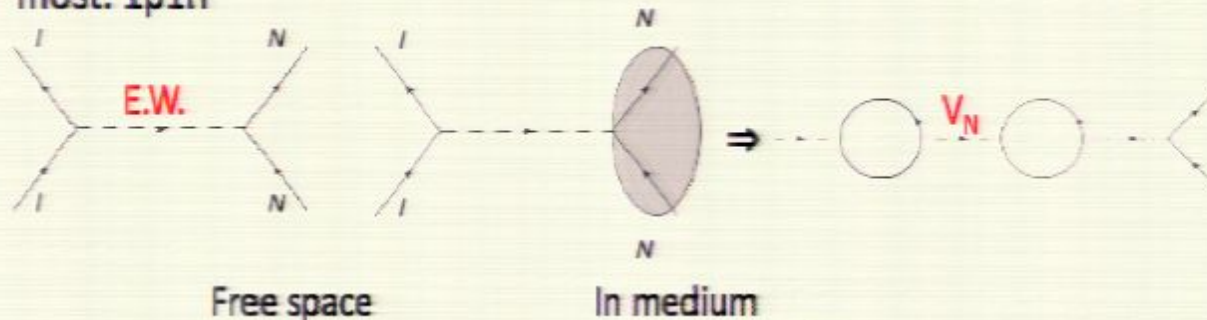
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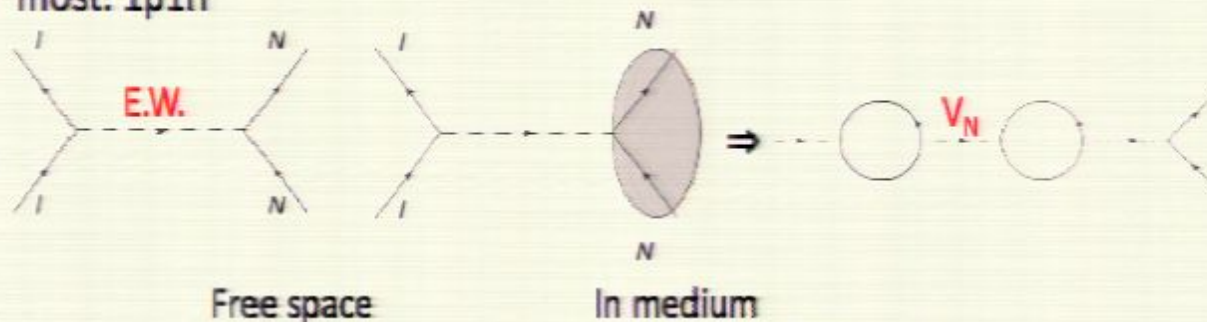
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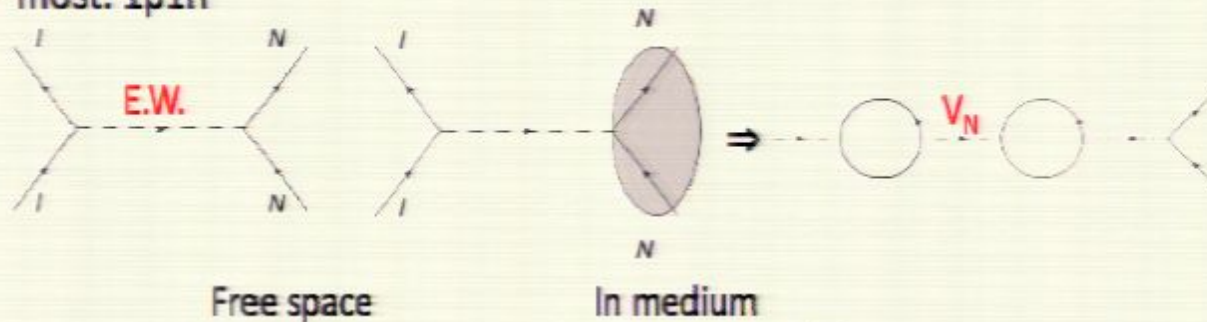
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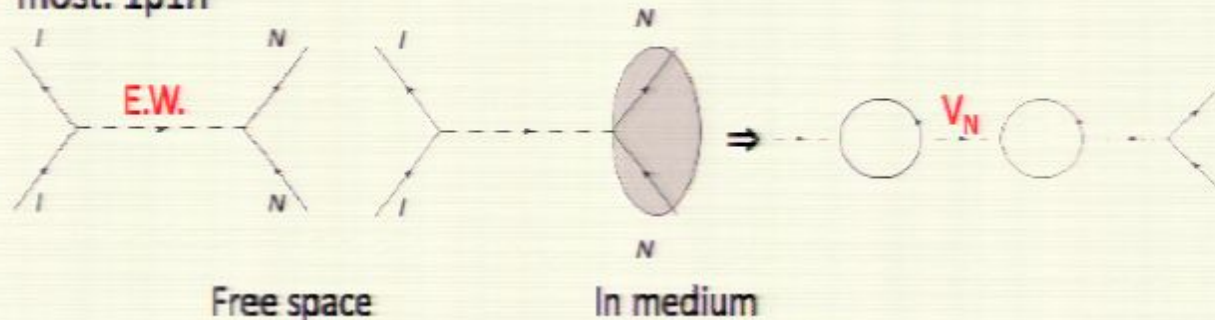
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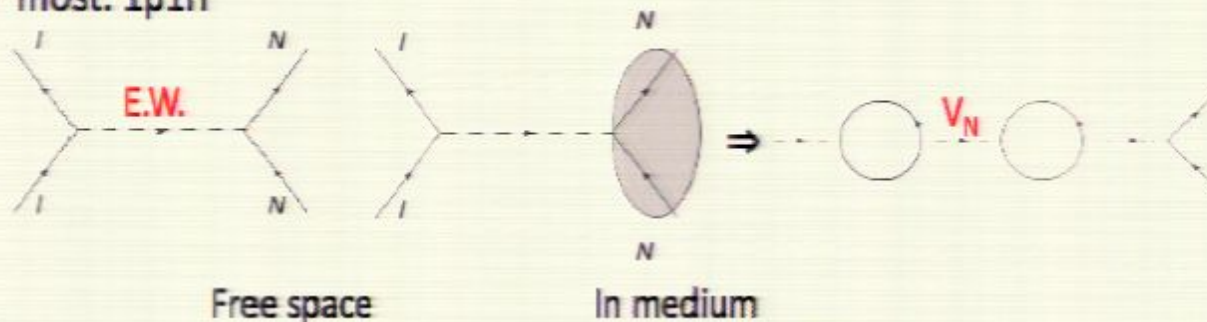
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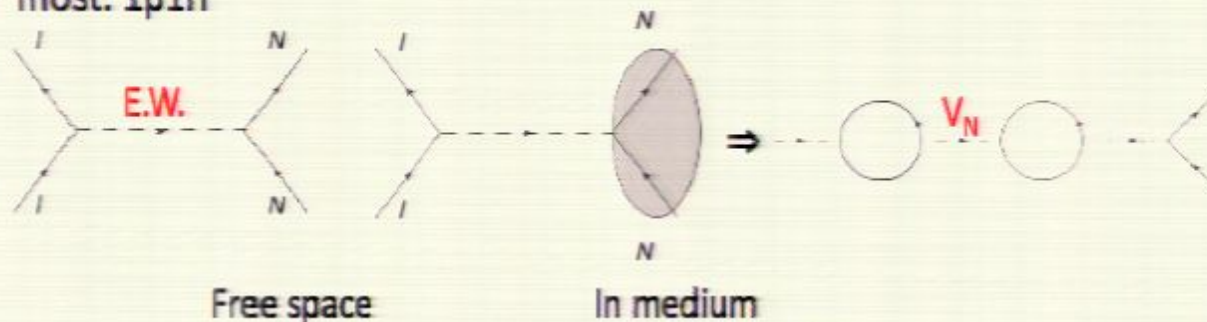
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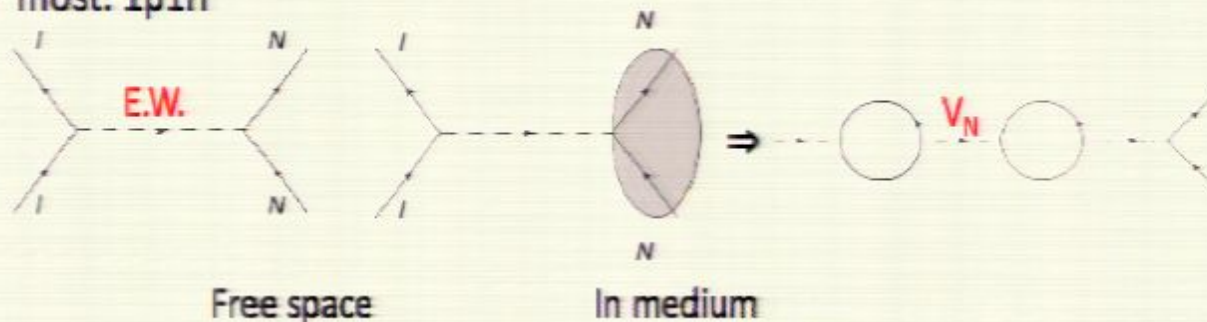
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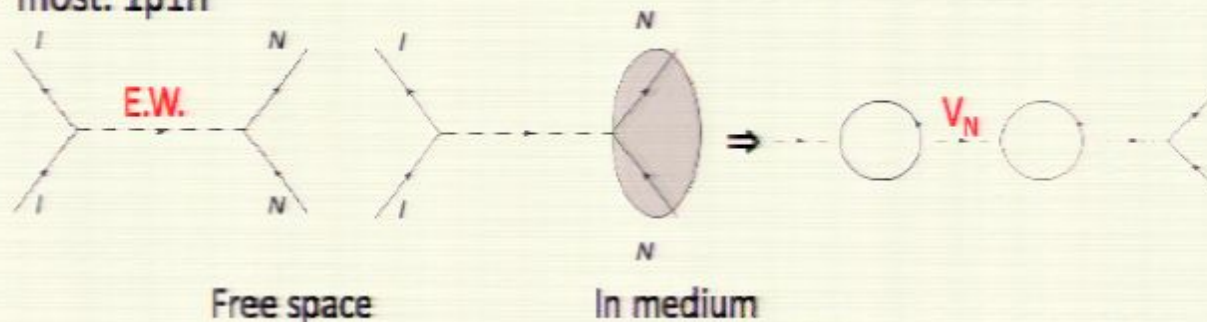
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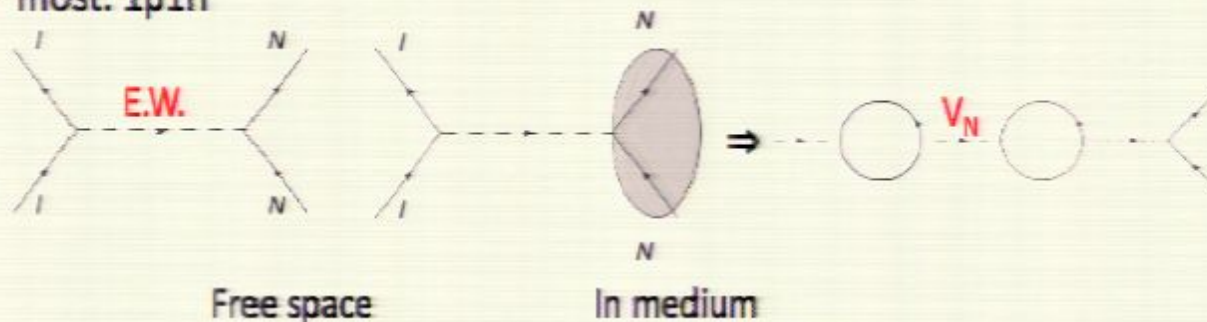
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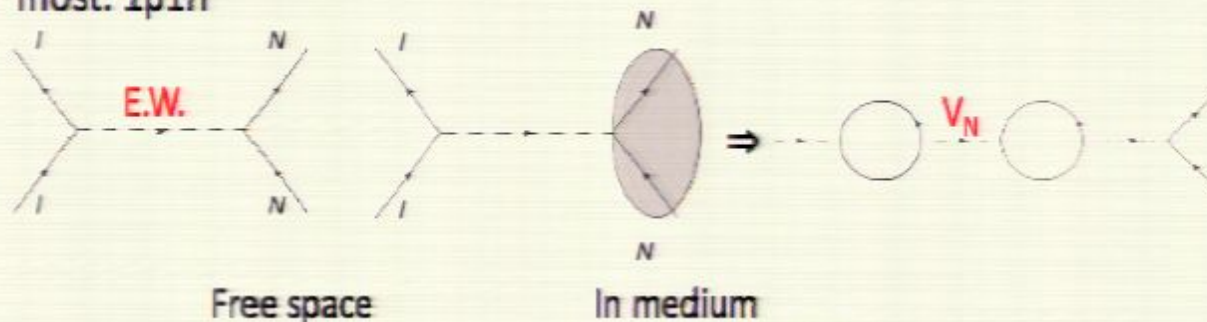
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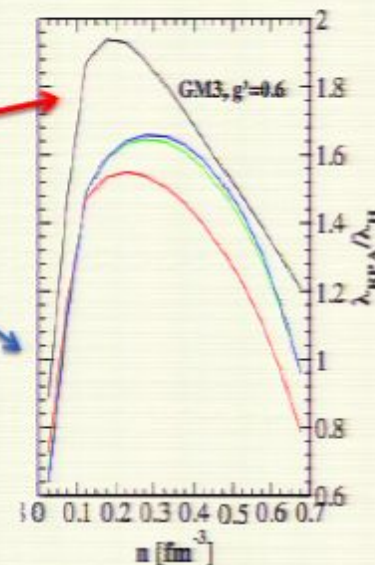
Neutrino opacity II: RPA response - npe

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 - Repulsive force – suppress response
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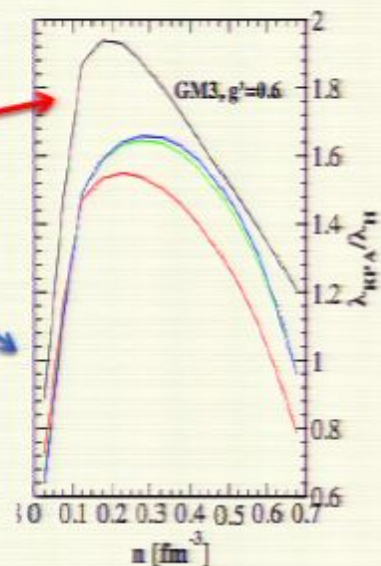


Reddy, Prakash, Lattimer, Pons, '99; Cirigliano, Reddy, GS, in preparation

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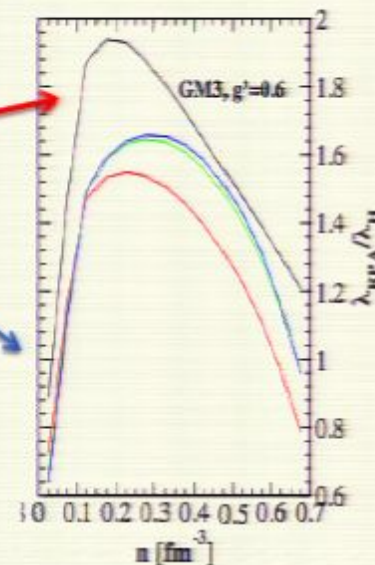


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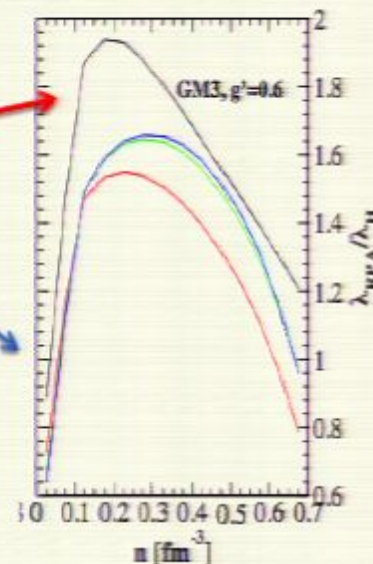


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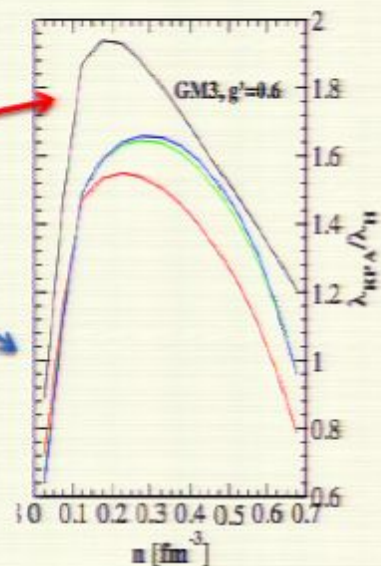


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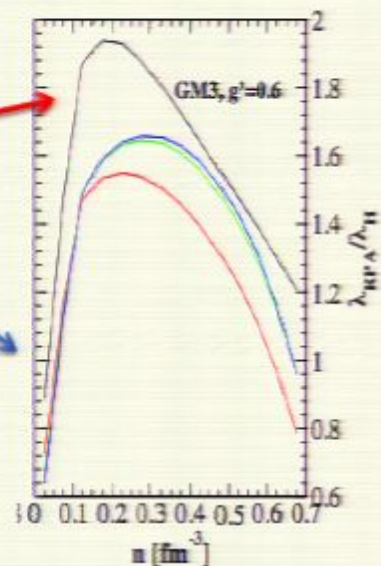


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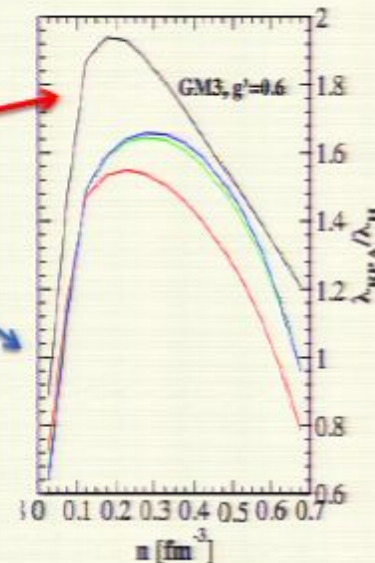


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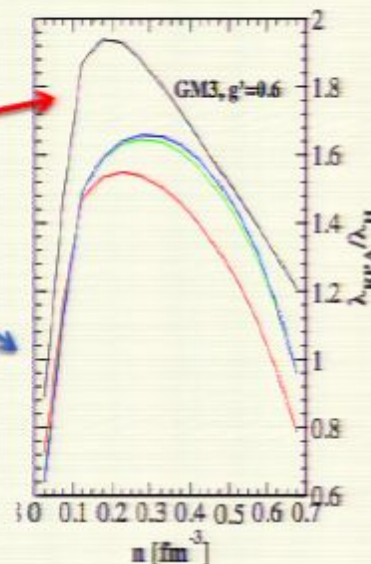


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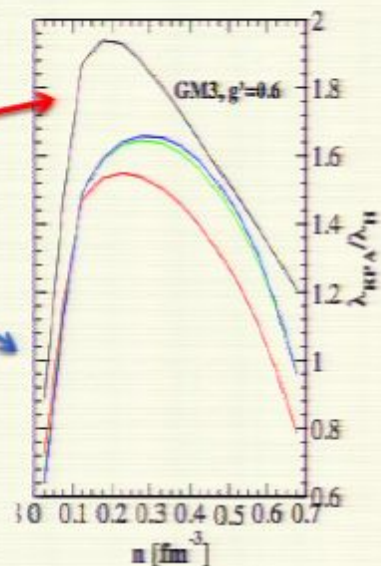


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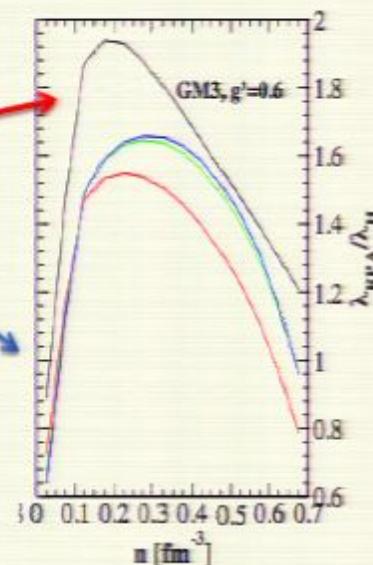


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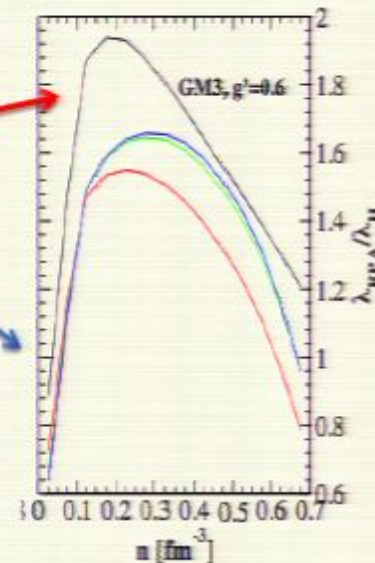


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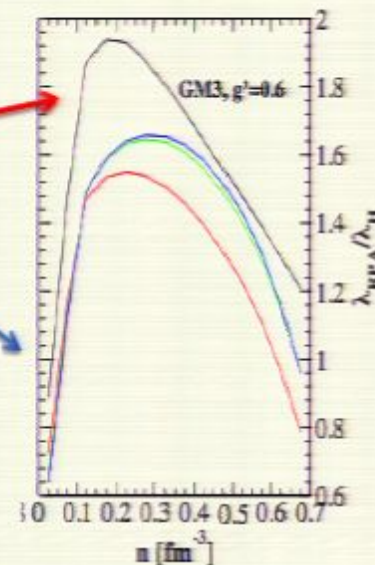


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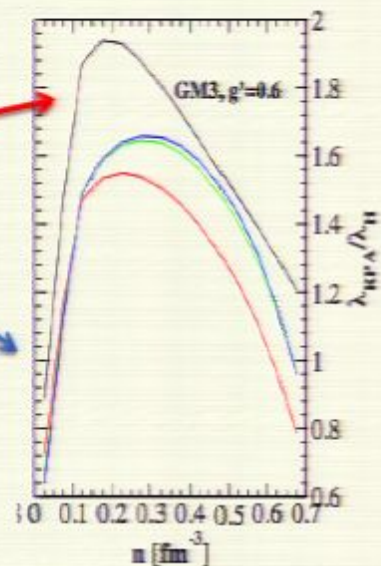


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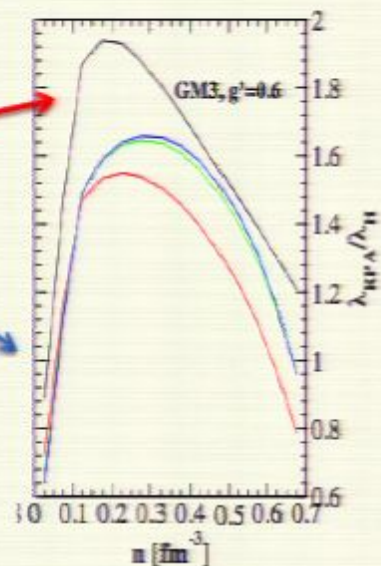


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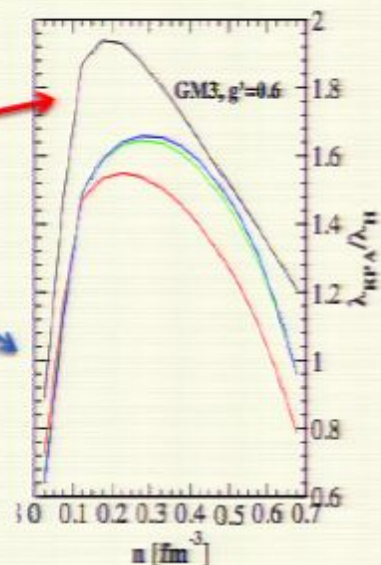


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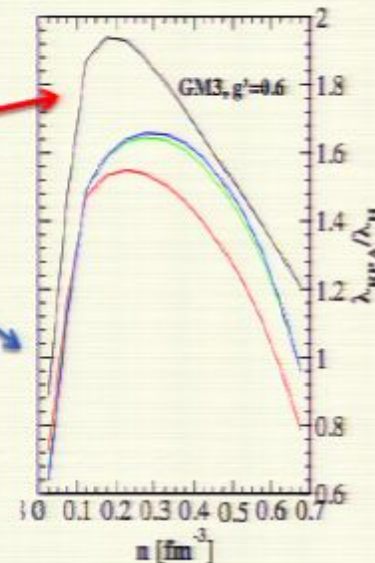


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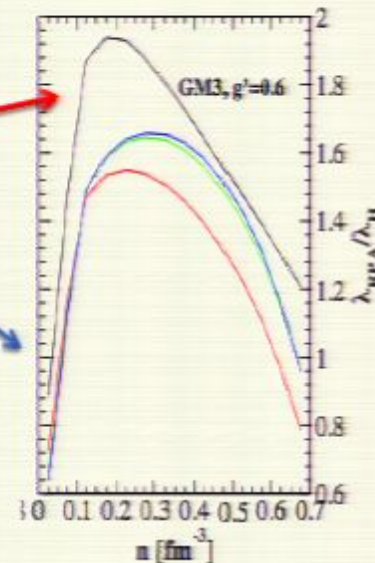


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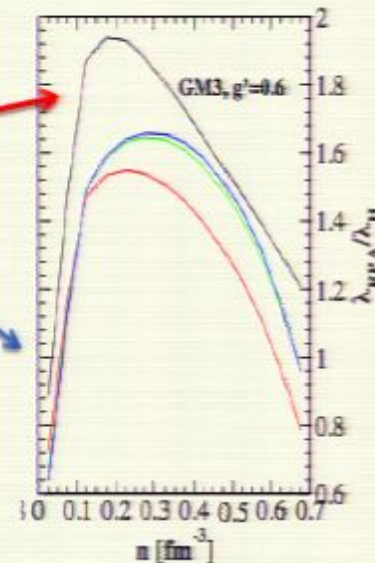


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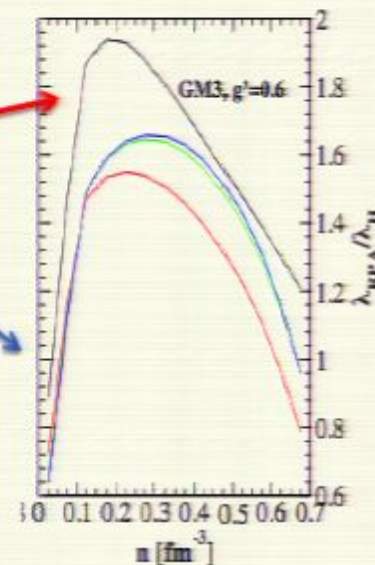


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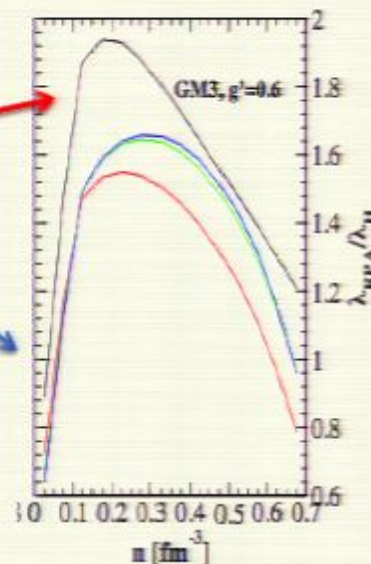


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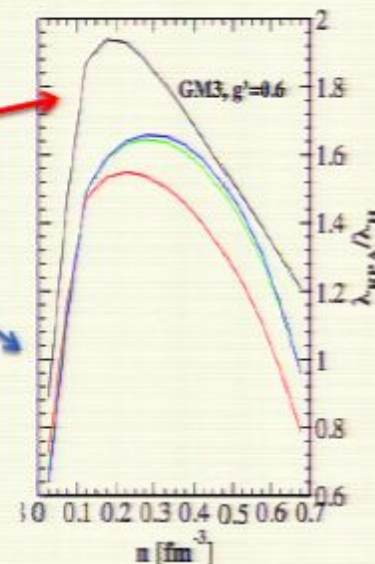


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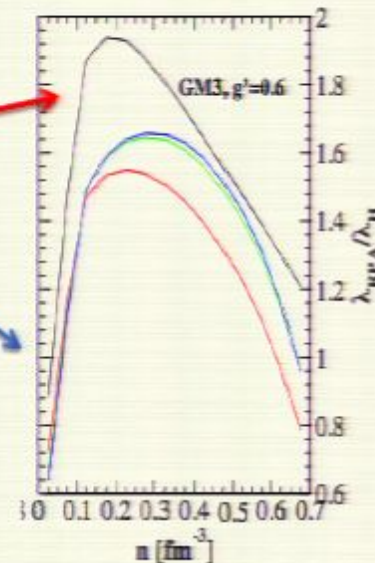


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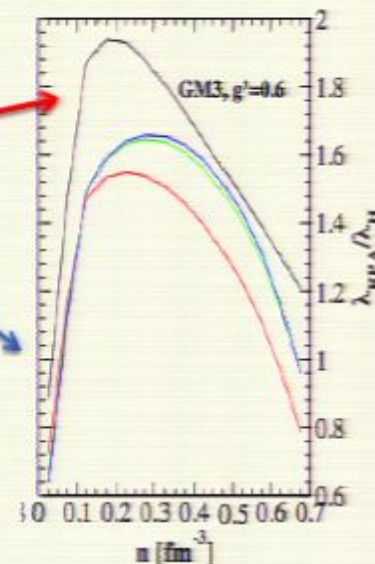


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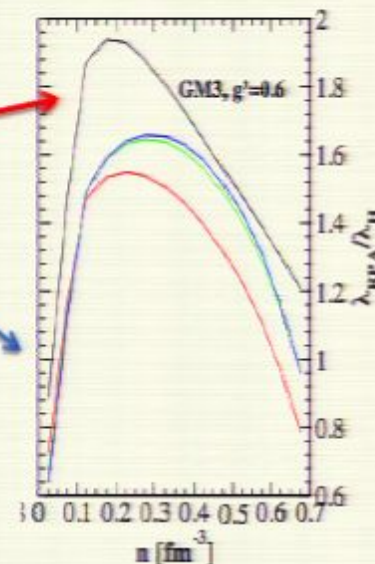


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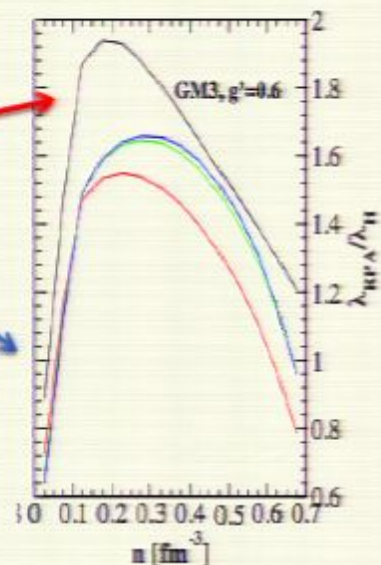


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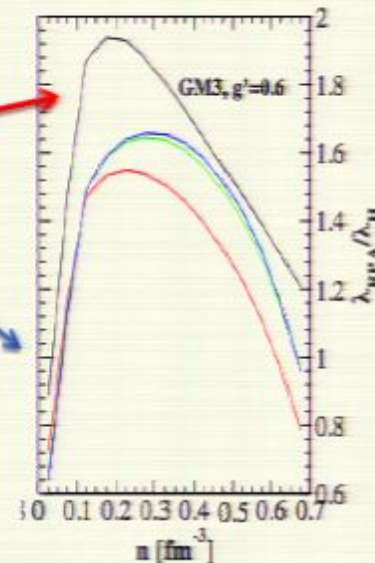


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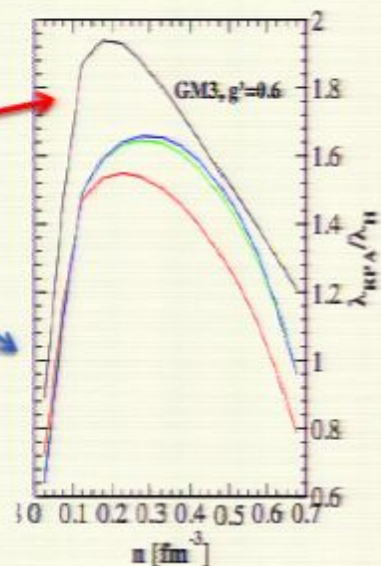


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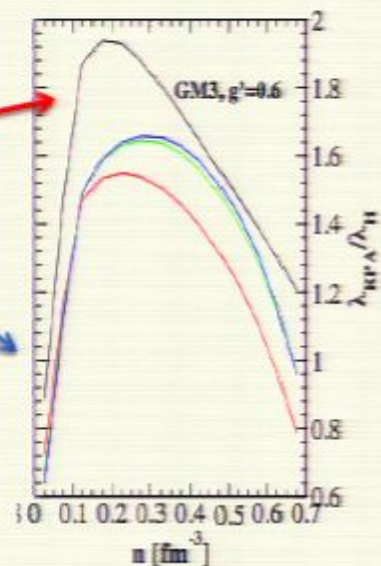


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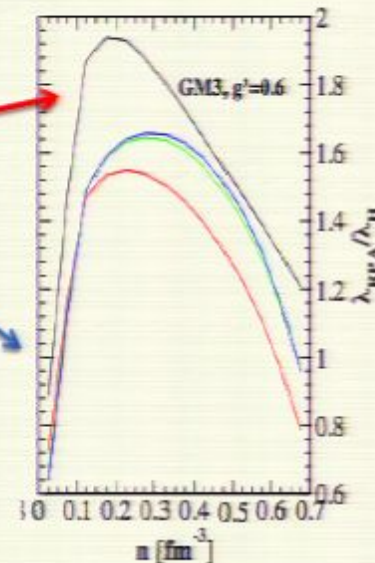


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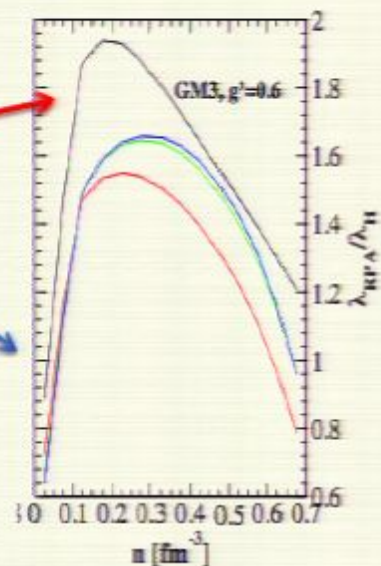


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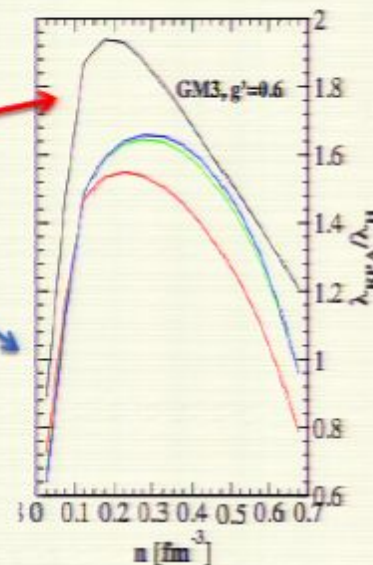


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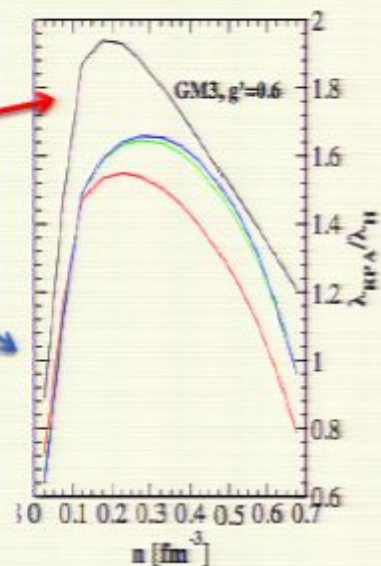


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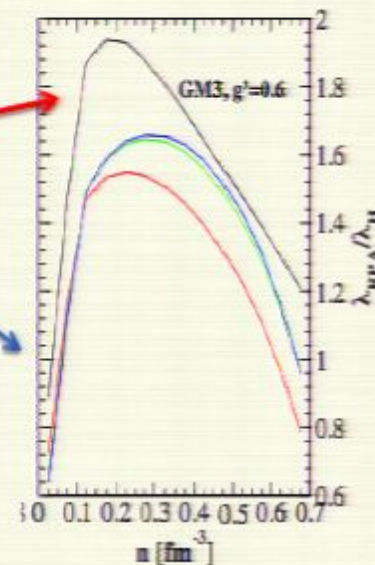


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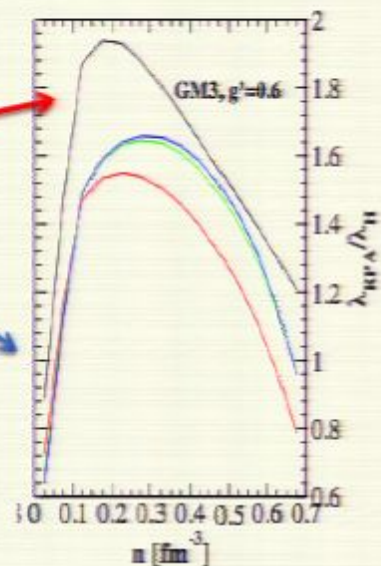


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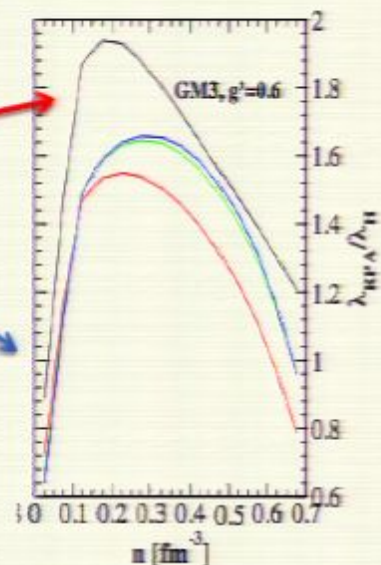


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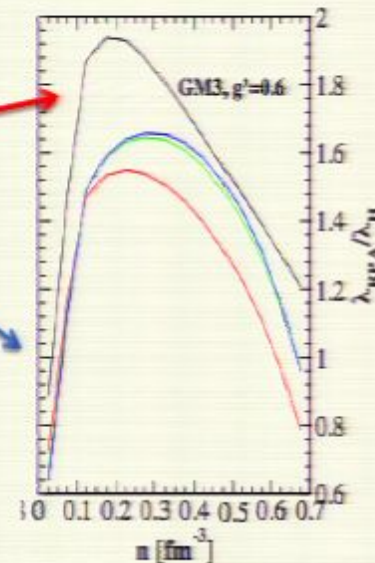


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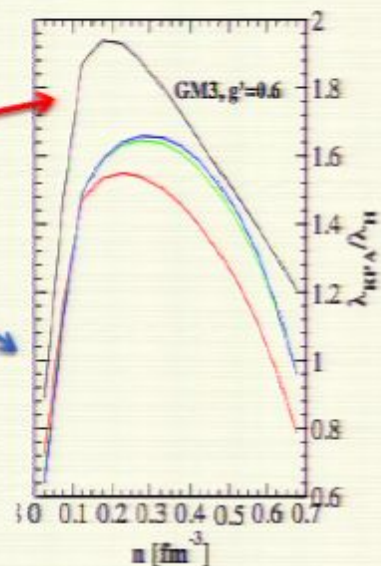


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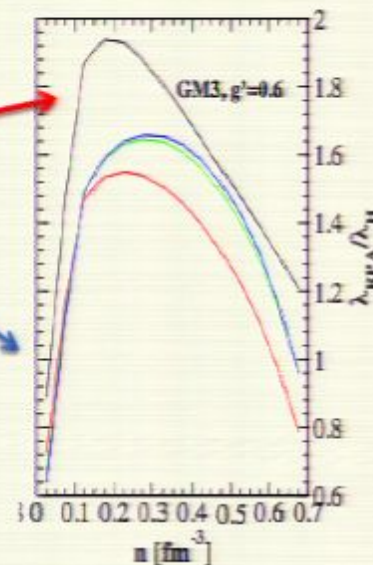


Reddy, Prakash, Lattimer, Pons, '99; Cirigliano, Reddy, GS, in preparation

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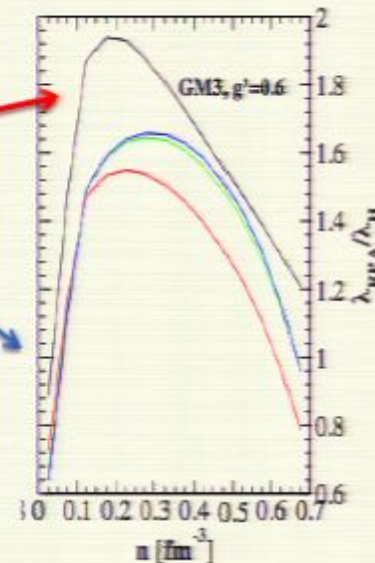


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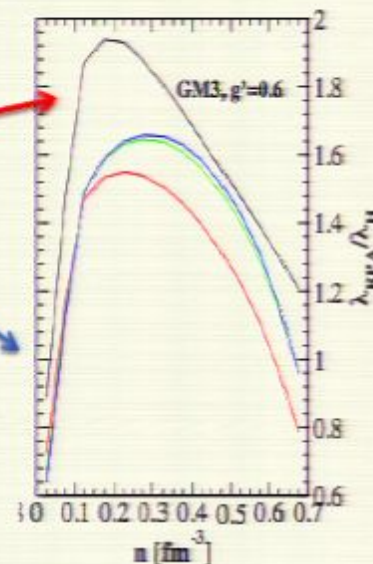


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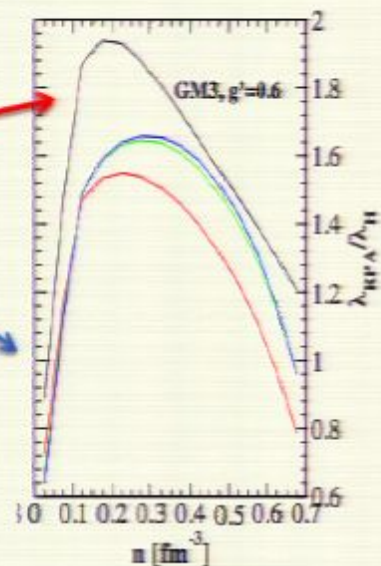


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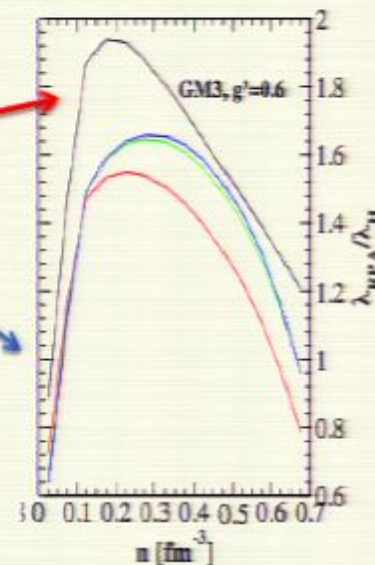
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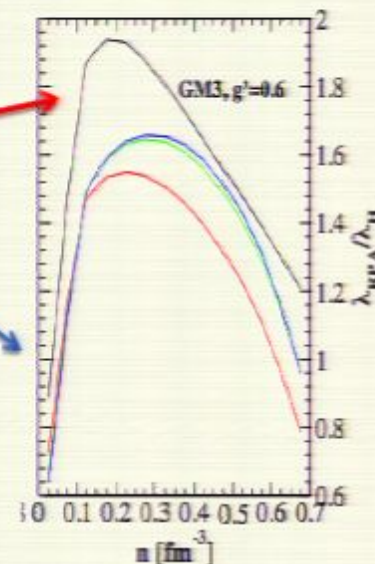


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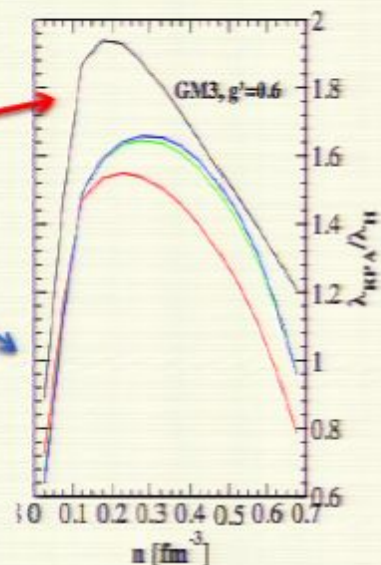


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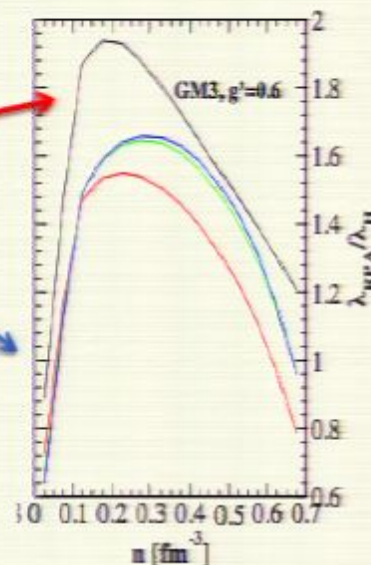


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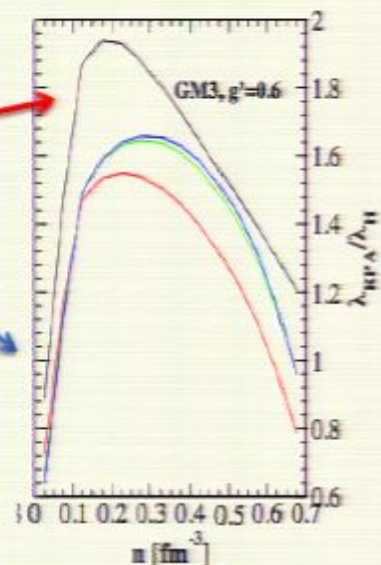


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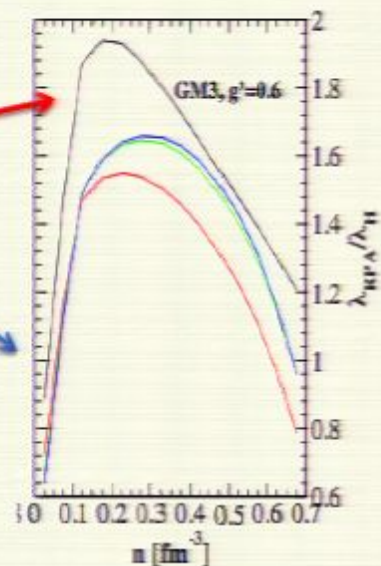


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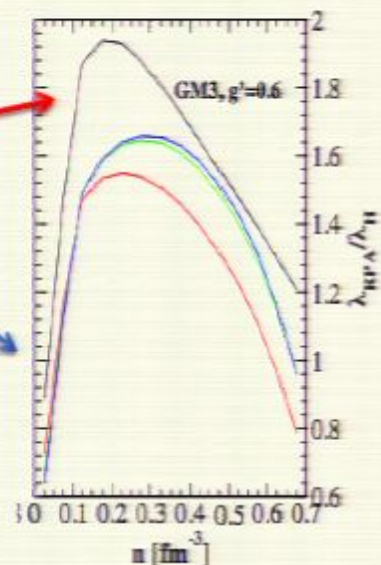


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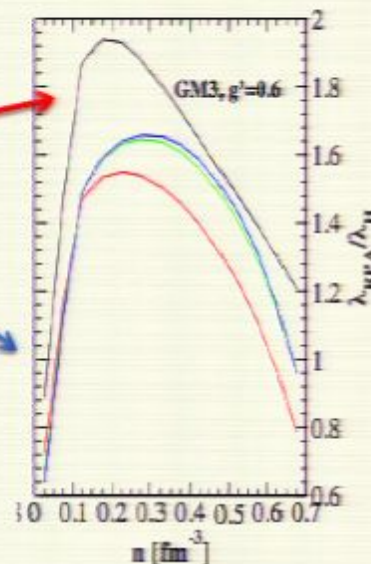


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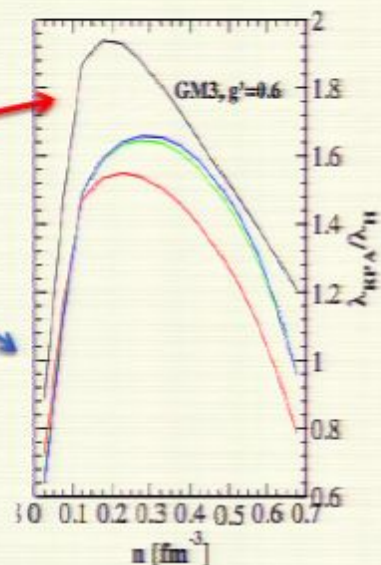


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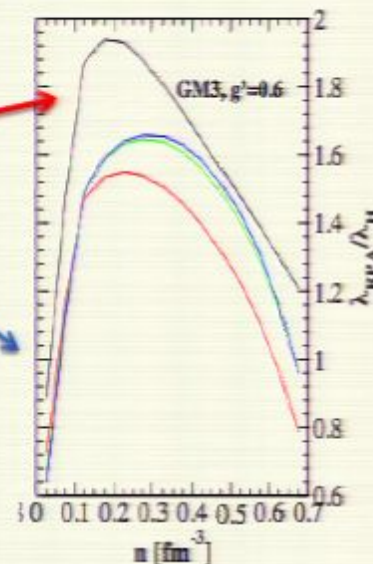


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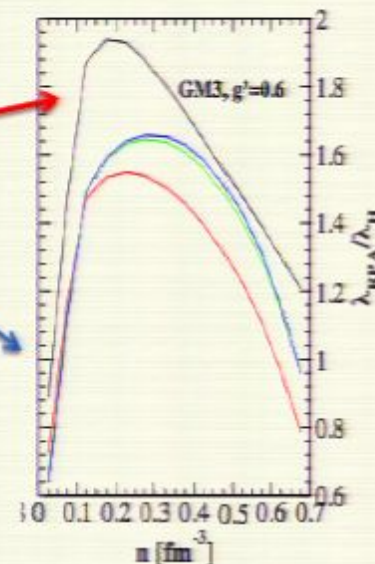


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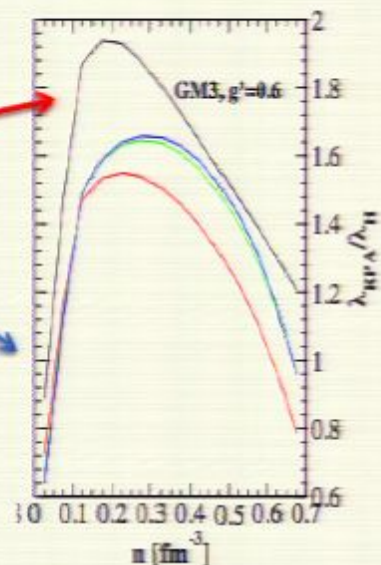


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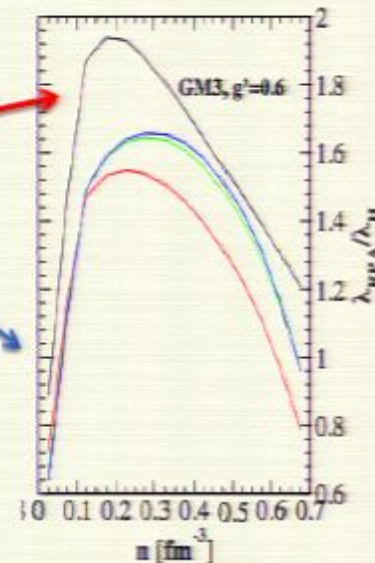


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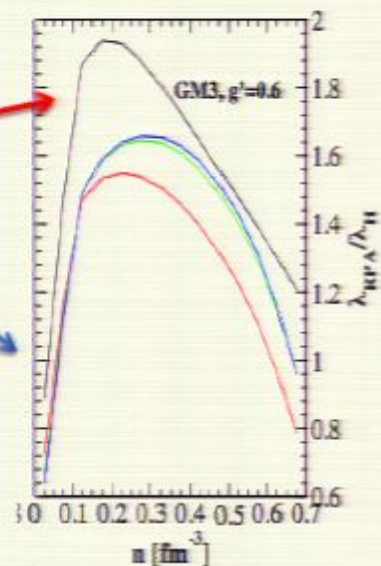


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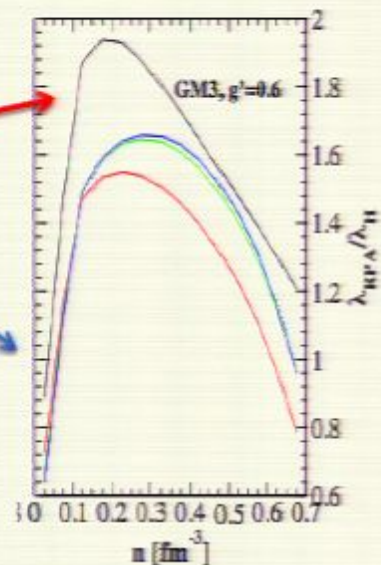


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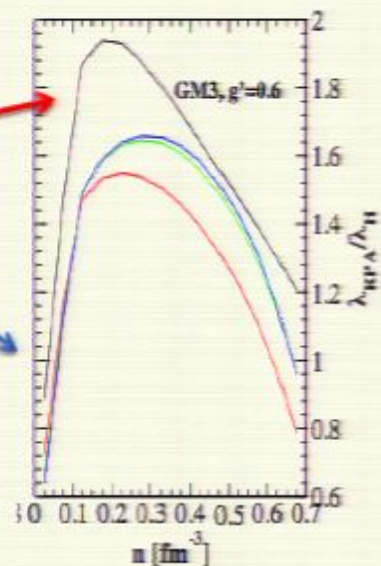


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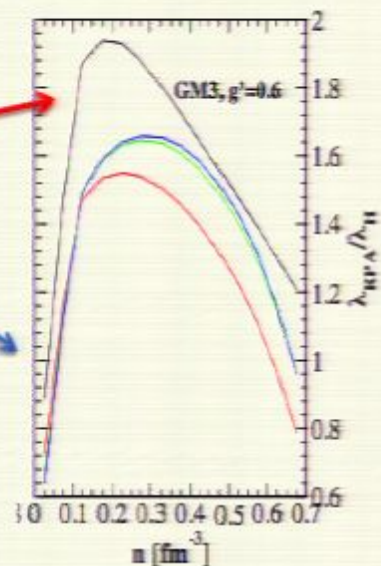


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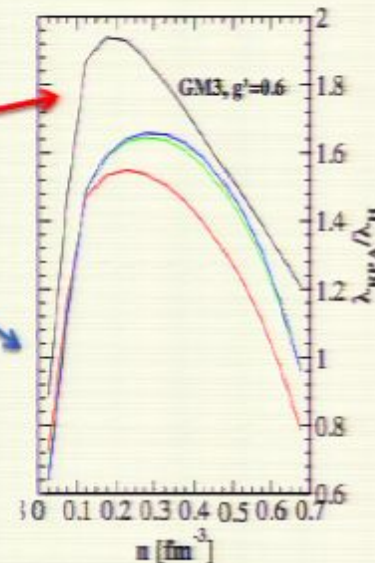


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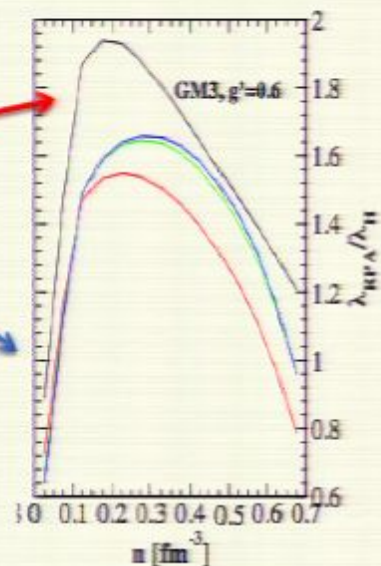


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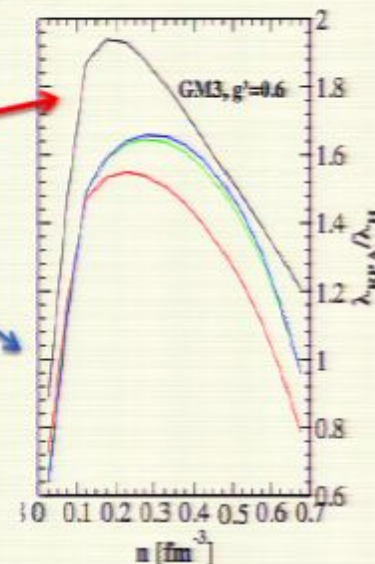


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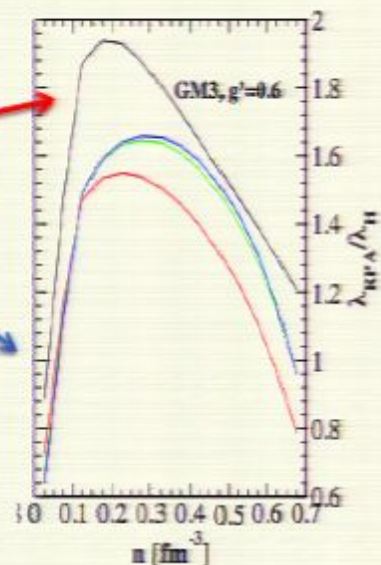


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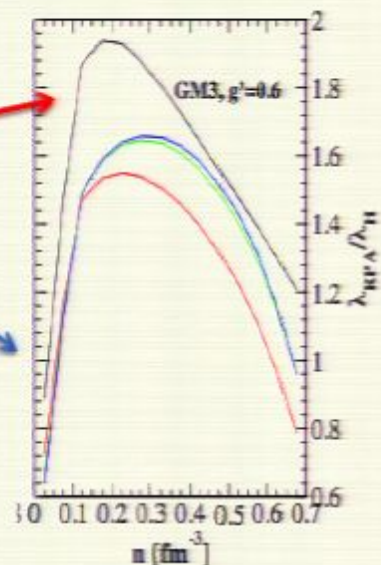


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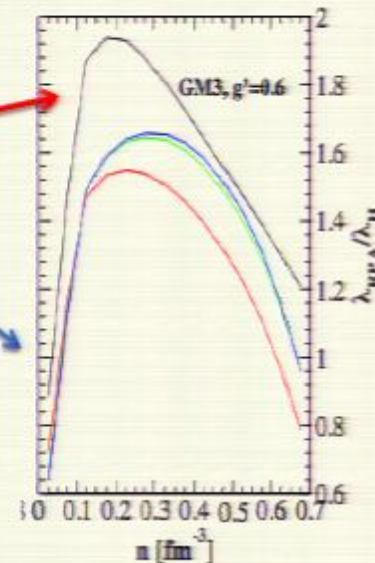


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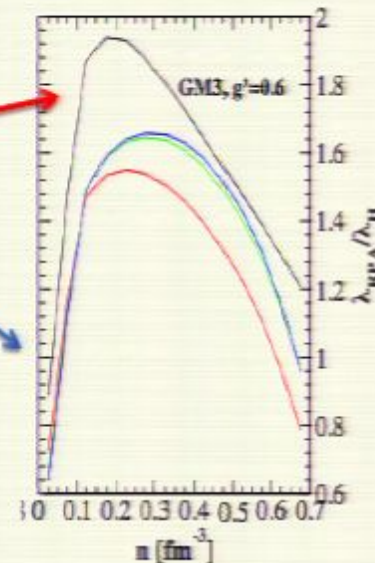


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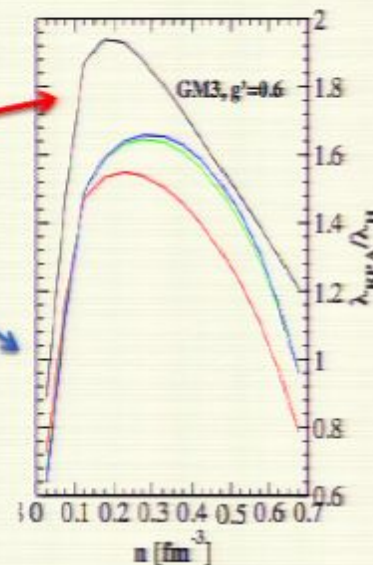


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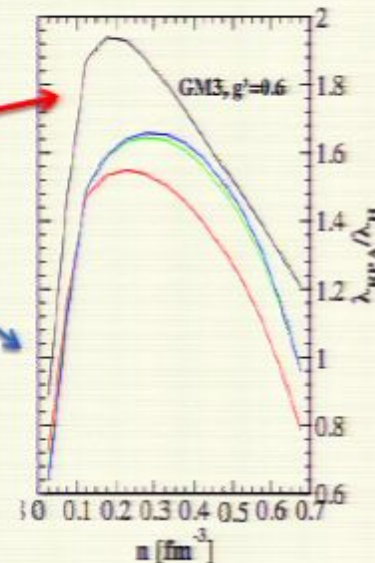


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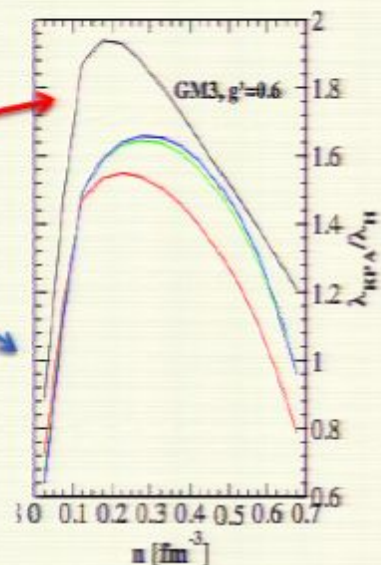


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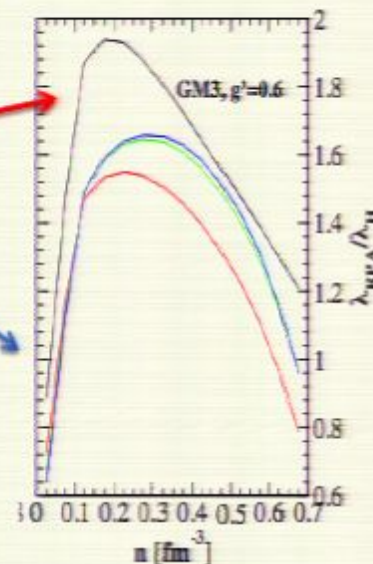


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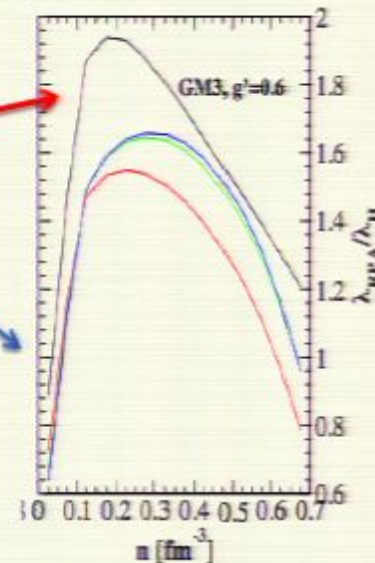


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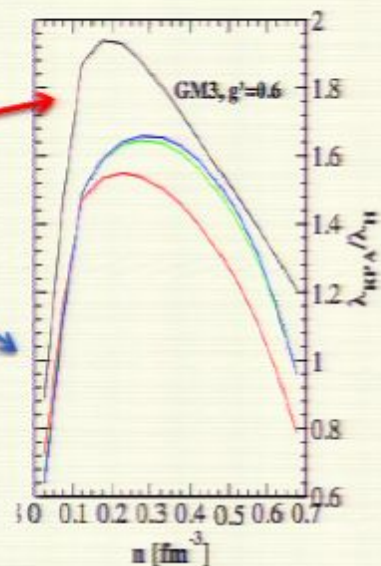


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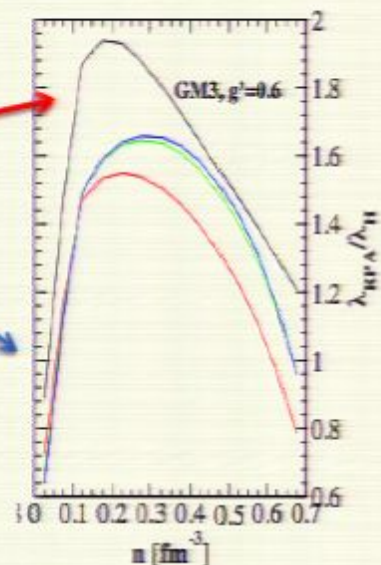


Reddy, Prakash, Lattimer, Pons, '99; Cirigliano, Reddy, GS, in preparation

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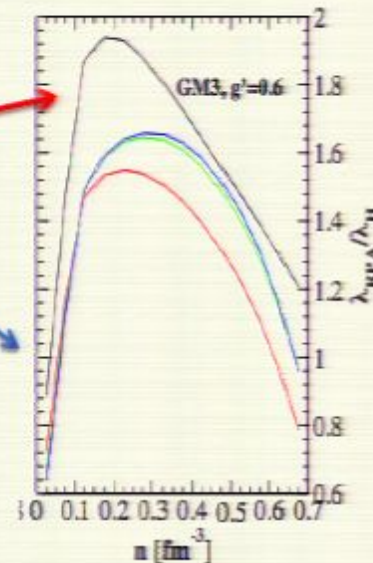


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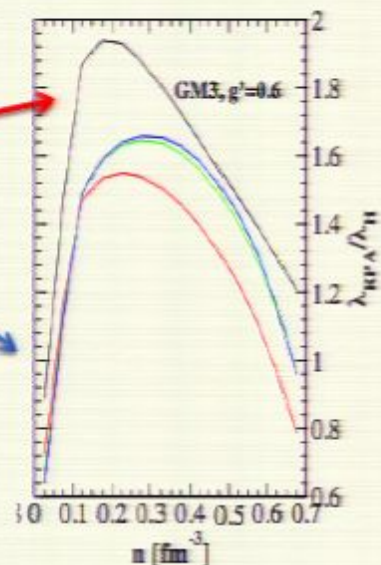


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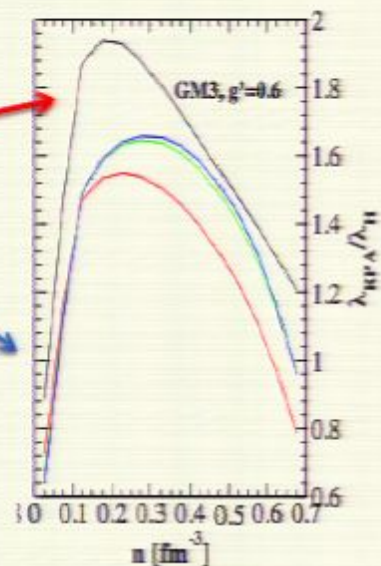


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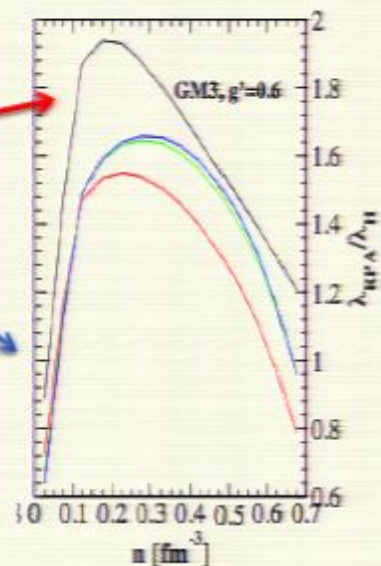


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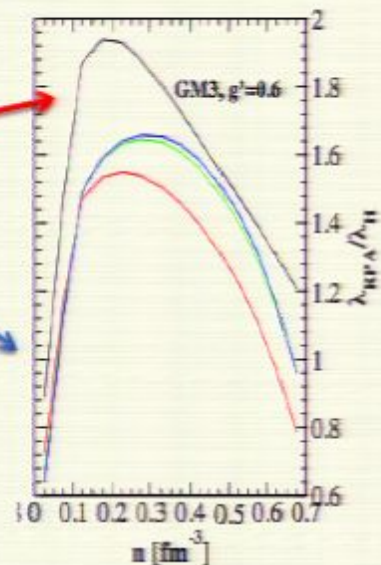


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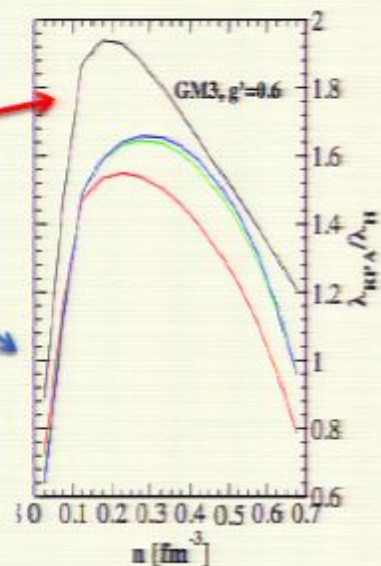


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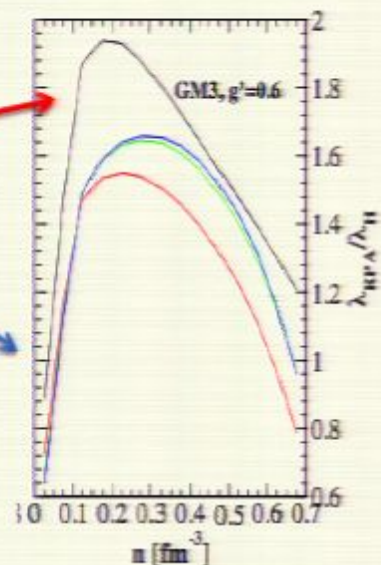


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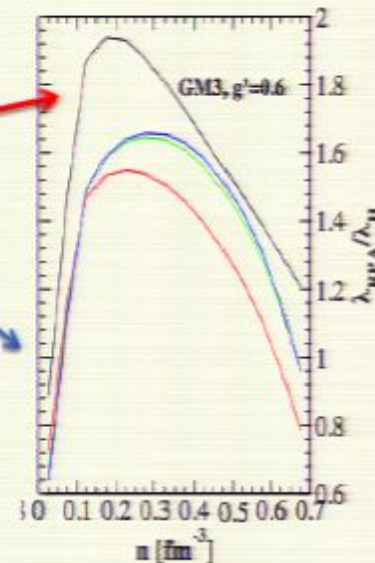


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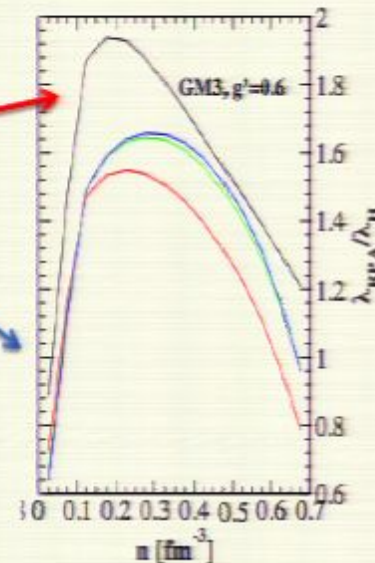


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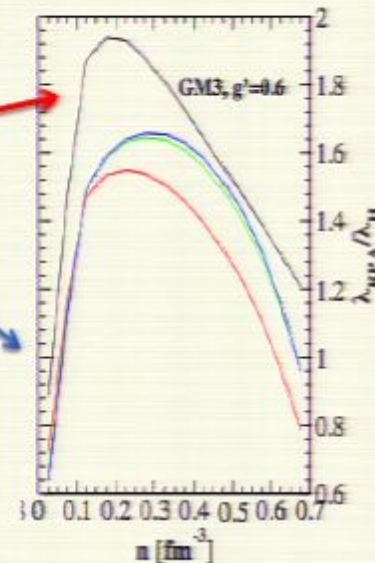


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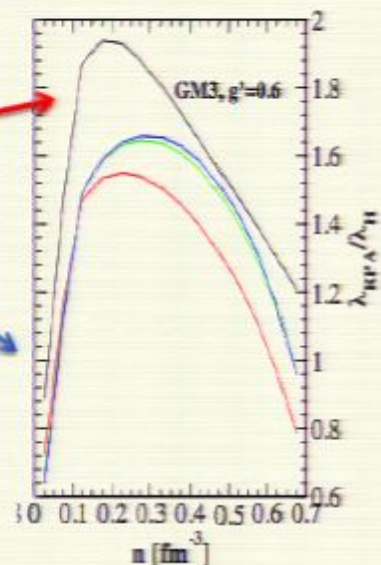


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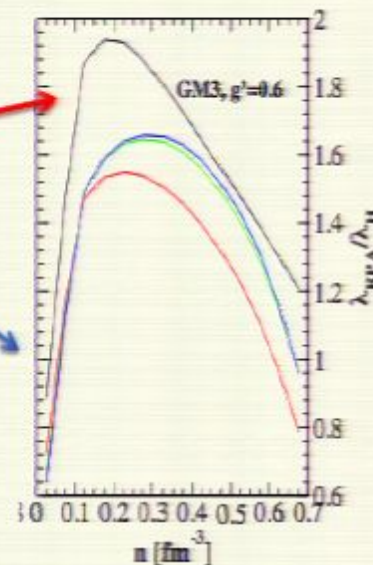


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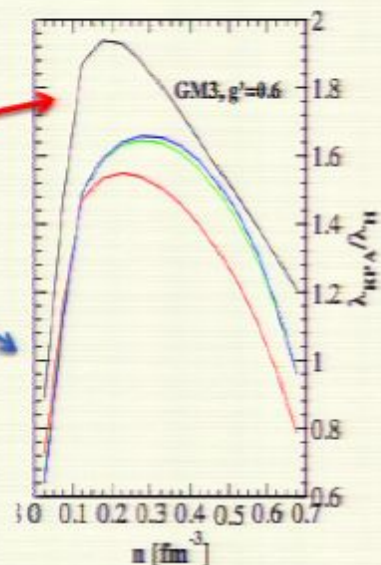


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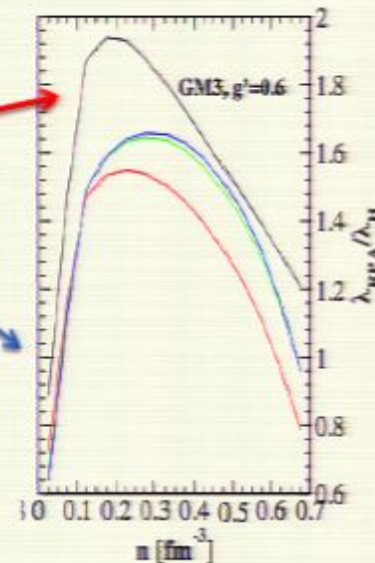


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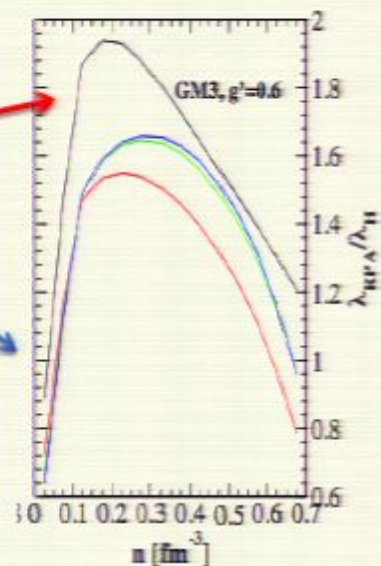


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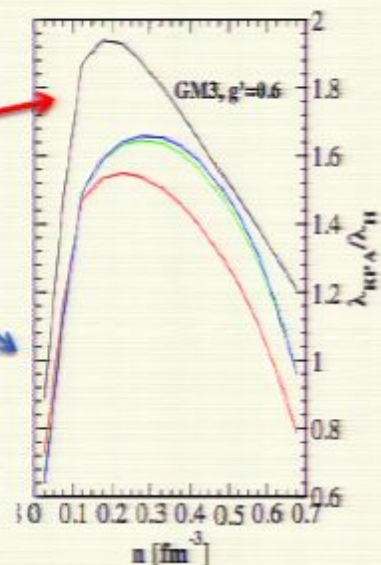


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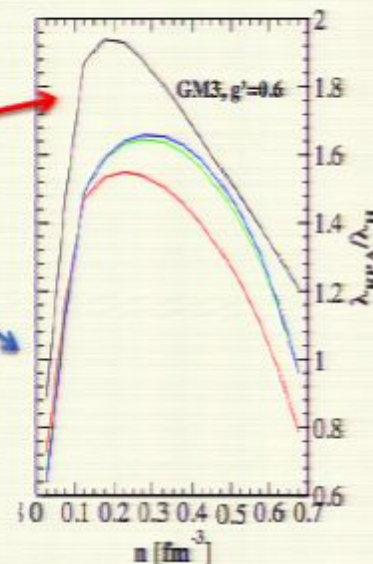


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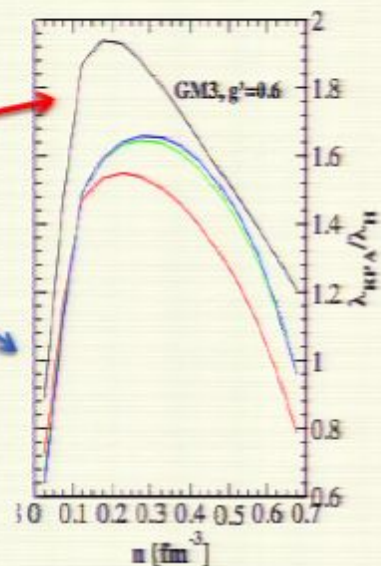


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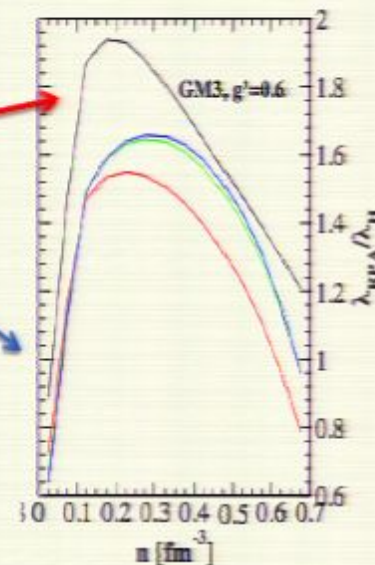


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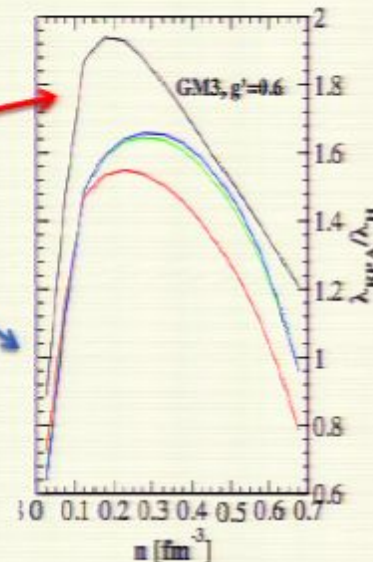


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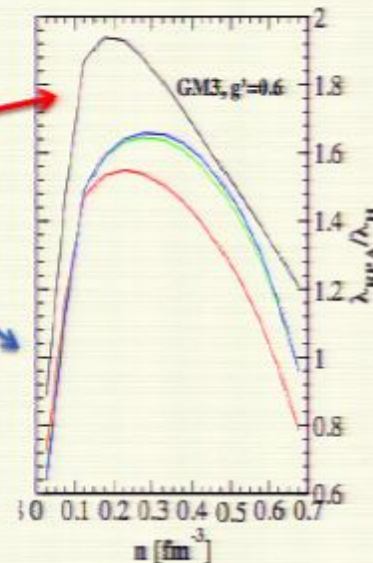


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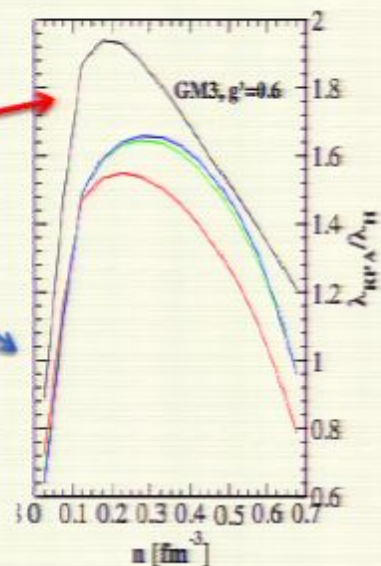


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No Signal

VGA-1

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