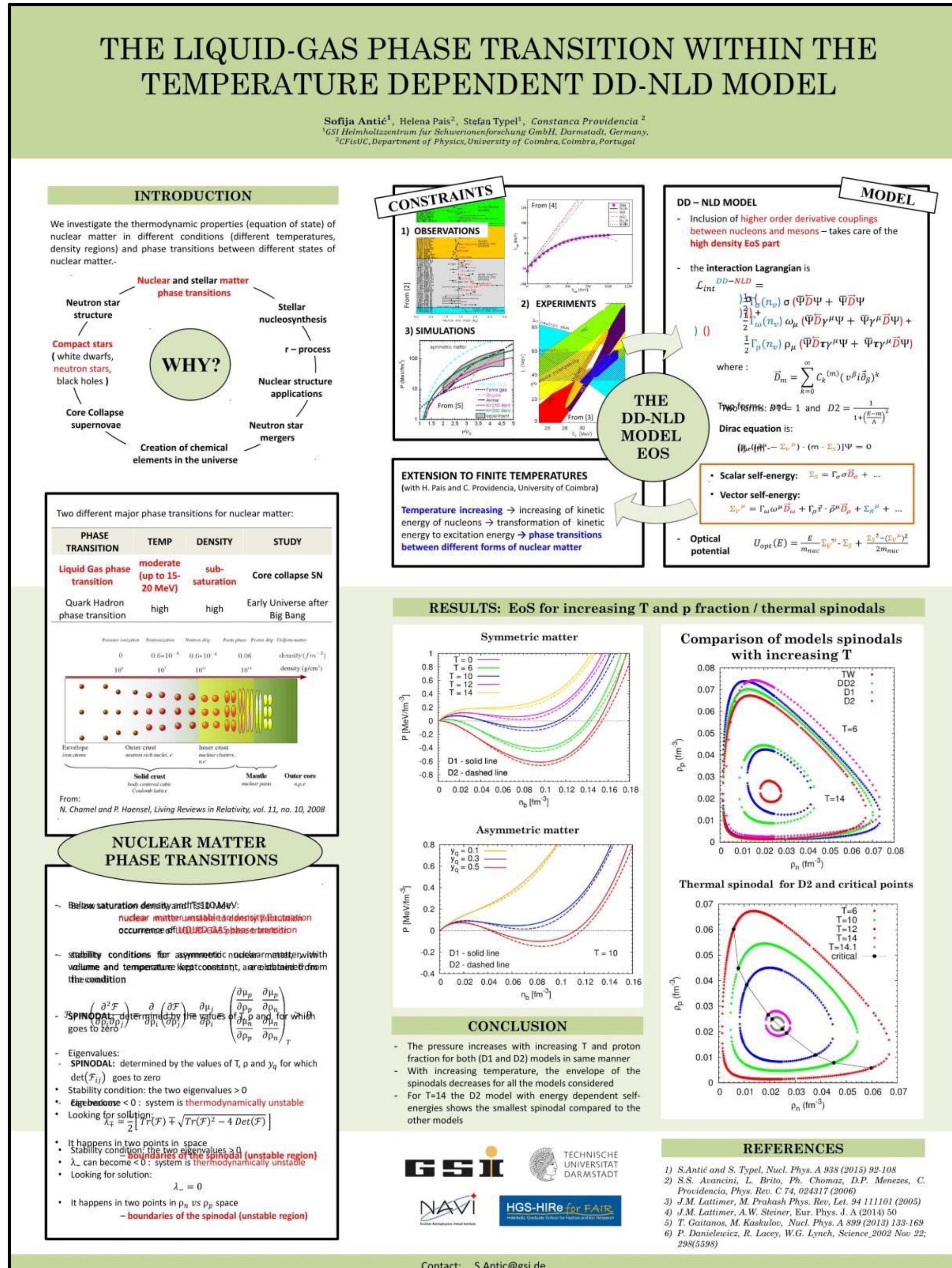
NewCompStar School 2016, Coimbra, Portugal - 5th – 9th Sept. 2016

THE LIQUID-GAS PHASE TRANSITION WITHIN THE TEMPERATURE DEPENDENT DD-NLD MODEL

Sofija Antić[1], Helena Pais[2], Stefan Typel[1], Constanca Providencia [2]
[1]*GSI Helmholtzzentrum fur Schwerionenforschung GmbH, Darmstadt, Germany,*
[2]*CFisUC, Department of Physics, University of Coimbra, Coimbra, Portugal*

MY POSTER

☺



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INTRODUCTION
We investigate the thermodynamic properties (equation of state) of nuclear matter in different conditions (different temperatures, density regions) and phase transitions between different states of nuclear matter.-
Nuclear and stellar matter phase transitions
WHY?
Neutron star structure
Stellar nucleosynthesis
Compact stars (white dwarfs, neutron stars, black holes)
r – process
Nuclear structure applications
Core Collapse supernovae
Neutron star mergers
Creation of chemical elements in the universe
Two different major phase transitions for nuclear matter:
PHASE TRANSITION | TEMP | DENSITY | STUDY
Liquid Gas phase transition | moderate (up to 15-20 MeV) | sub-saturation | Core collapse SN
Quark Hadron phase transition | high | high | Early Universe after Big Bang
From: N. Chamel and P. Haensel, Living Reviews in Relativity, vol. 11, no. 10, 2008
NUCLEAR MATTER PHASE TRANSITIONS
Eigenvalues:
SPINODAL: determined by the values of T, ρ and yq for which det(Fij) goes to zero
Stability condition: the two eigenvalues > 0
λ– can become < 0 : system is thermodynamically unstable
Looking for solution:
λ– = 0
It happens in two points in ρn vs ρp space – boundaries of the spinodal (unstable region)
CONSTRAINTS
1) OBSERVATIONS
2) EXPERIMENTS
3) SIMULATIONS
THE DD-NLD MODEL EOS
EXTENSION TO FINITE TEMPERATURES
(with H. Pais and C. Providencia, University of Coimbra)
Temperature increasing → increasing of kinetic energy of nucleons → transformation of kinetic energy to excitation energy → phase transitions between different forms of nuclear matter
MODEL
DD – NLD MODEL
Inclusion of higher order derivative couplings between nucleons and mesons – takes care of the high density EoS part
the interaction Lagrangian is
Dirac equation is:
Scalar self-energy:
Vector self-energy:
Optical potential
RESULTS: EoS for increasing T and p fraction / thermal spinodals
Symmetric matter
D1 - solid line
D2 - dashed line
Asymmetric matter
Comparison of models spinodals with increasing T
Thermal spinodal for D2 and critical points
CONCLUSION
The pressure increases with increasing T and proton fraction for both (D1 and D2) models in same manner
With increasing temperature, the envelope of the spinodals decreases for all the models considered
For T=14 the D2 model with energy dependent self-energies shows the smallest spinodal compared to the other models
REFERENCES
1) S.Antić and S. Typel, Nucl. Phys. A 938 (2015) 92-108
2) S.S. Avancini, L. Brito, Ph. Chomaz, D.P. Menezes, C. Providencia, Phys. Rev. C 74, 024317 (2006)
3) J.M. Lattimer, M. Prakash Phys. Rev, Let. 94 111101 (2005)
4) J.M. Lattimer, A.W. Steiner, Eur. Phys. J. A (2014) 50
5) T. Gaitanos, M. Kaskulov, Nucl. Phys. A 899 (2013) 133-169
6) P. Danielewicz, R. Lacey, W.G. Lynch, Science 2002 Nov 22; 298(5598)
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EoS model

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Liquid-gas PT

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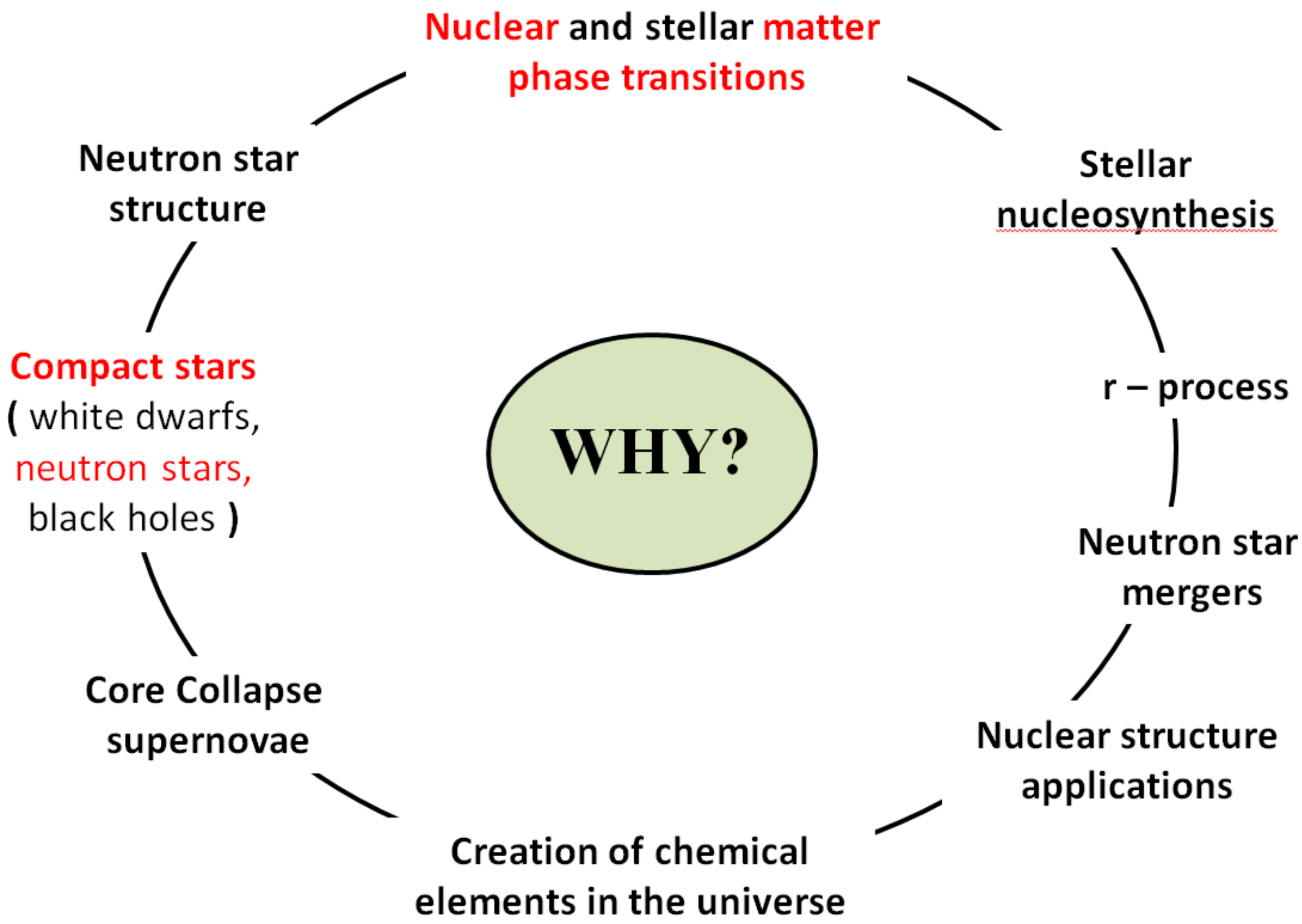
EoS model


Nuclear and stellar matter
phase transitions
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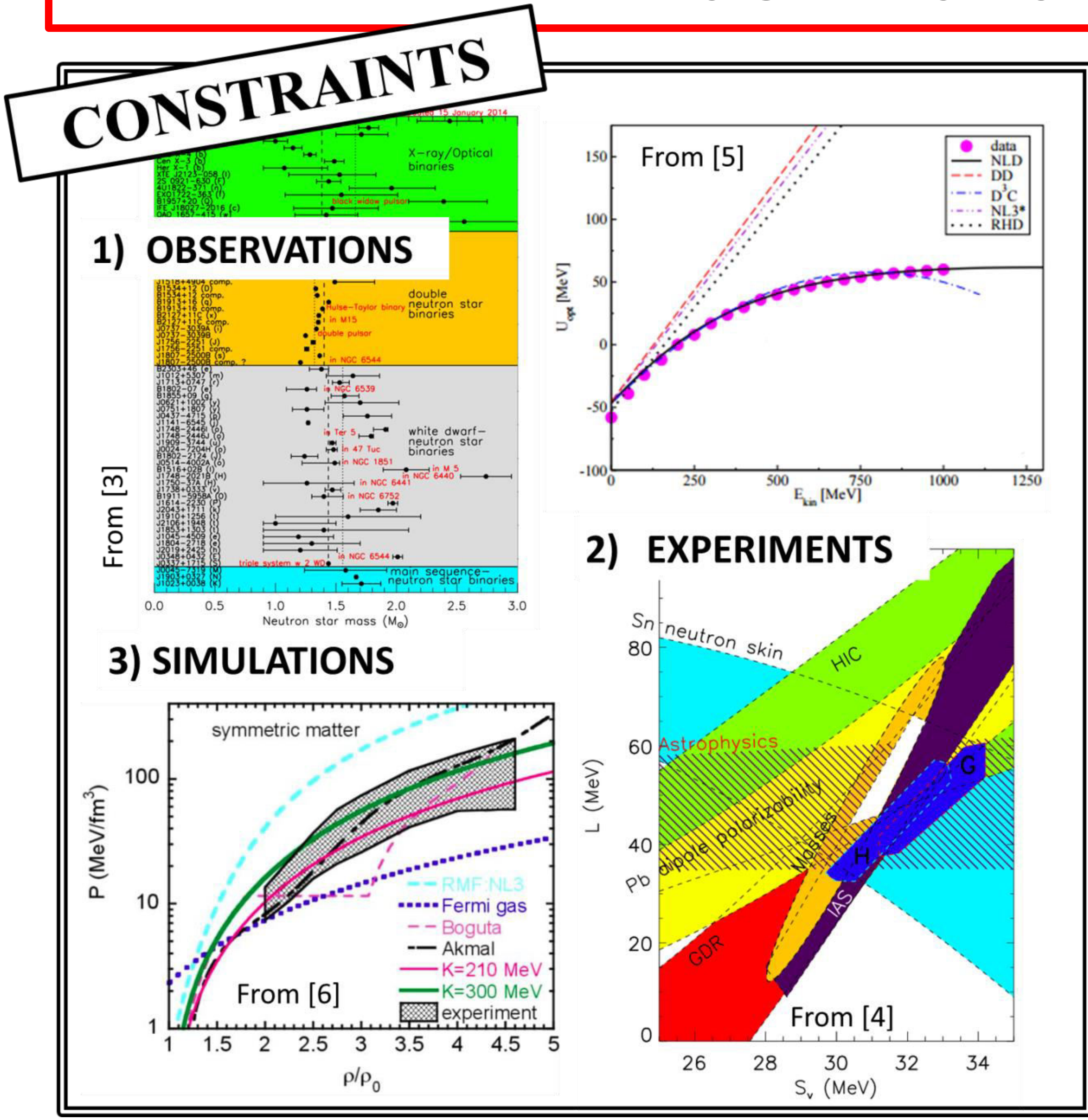
structure
WHY?

EoS model



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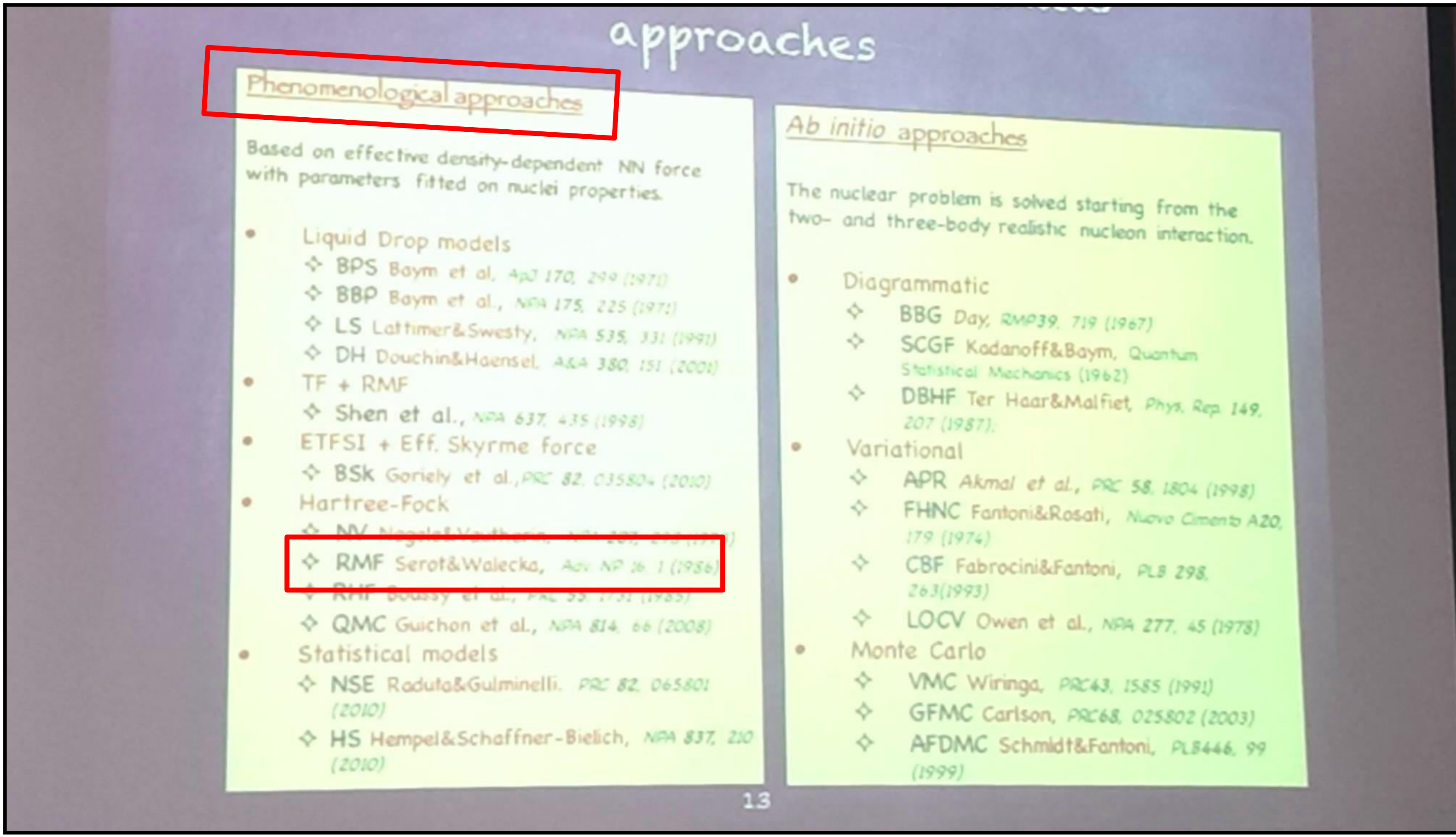
DD – NLD model



Slide of yesterday's lecture of Fiorella Burgio

DD – NLD model

DD – NLD model

- the **interaction Lagrangian** is

$$\mathcal{L}_{int}^{\sim\text{ walecka}} =$$

$$\frac{1}{2}\Gamma_\sigma \quad \sigma\,(\bar{\Psi} \quad \Psi + \bar{\Psi} \quad \Psi)$$

$$\frac{1}{2}\Gamma_\omega \quad \omega_\mu\,(\bar{\Psi} \quad \gamma^\mu\Psi + \bar{\Psi}\gamma^\mu \quad \Psi) +$$

$$\frac{1}{2}\Gamma_\rho \quad \rho_\mu\,(\bar{\Psi} \quad \boldsymbol{\tau}\gamma^\mu\Psi + \bar{\Psi}\boldsymbol{\tau}\gamma^\mu \quad \Psi)$$

DD – NLD model

Density–Dependent

- the **interaction Lagrangian** is

$$\mathcal{L}_{int}{}^{DD} = \frac{1}{2}\Gamma_\sigma(n_v)\,\sigma\,(\bar{\Psi}\ \ \Psi + \bar{\Psi}\ \ \Psi)$$

$$\frac{1}{2}\Gamma_\omega(n_v)\,\omega_\mu\,(\bar{\Psi}\ \ \gamma^\mu\Psi + \bar{\Psi}\gamma^\mu\ \ \Psi) +$$

$$\frac{1}{2}\Gamma_\rho(n_v)\,\rho_\mu\,(\bar{\Psi}\ \ \boldsymbol{\tau}\gamma^\mu\Psi + \bar{\Psi}\boldsymbol{\tau}\gamma^\mu\ \ \Psi)$$

DD – NLD model

Density–Dependent

Non-Linear Derivative

- the **interaction Lagrangian** is

$$\mathcal{L}_{int}{}^{DD-NLD} =$$

$$\frac{1}{2}\Gamma_\sigma(n_v)\,\sigma\,(\bar{\Psi}\overleftarrow{\mathcal{D}}\Psi + \bar{\Psi}\overrightarrow{\mathcal{D}}\Psi)$$

$$\frac{1}{2}\Gamma_\omega(n_v)\,\omega_\mu\,(\bar{\Psi}\overleftarrow{\mathcal{D}}\gamma^\mu\Psi + \bar{\Psi}\gamma^\mu\overrightarrow{\mathcal{D}}\Psi) +$$

$$\frac{1}{2}\Gamma_\rho(n_v)\,\rho_\mu\,(\bar{\Psi}\overleftarrow{\mathcal{D}}\boldsymbol{\tau}\gamma^\mu\Psi + \bar{\Psi}\boldsymbol{\tau}\gamma^\mu\overrightarrow{\mathcal{D}}\Psi)$$

DD – NLD model

Density–Dependent

Non-Linear Derivative

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$$\frac{1}{2}\Gamma_\sigma(n_v)\,\sigma\,(\bar{\Psi}\overleftarrow{D}\Psi + \bar{\Psi}\overrightarrow{D}\Psi)$$

$$\frac{1}{2}\Gamma_\omega(n_v)\,\omega_\mu\,(\bar{\Psi}\overleftarrow{D}\gamma^\mu\Psi + \bar{\Psi}\gamma^\mu\overrightarrow{D}\Psi) +$$

$$\frac{1}{2}\Gamma_\rho(n_v)\,\rho_\mu\,(\bar{\Psi}\overleftarrow{D}\boldsymbol{\tau}\gamma^\mu\Psi + \bar{\Psi}\boldsymbol{\tau}\gamma^\mu\overrightarrow{D}\Psi)$$

where : $\overrightarrow{D}_m = \sum_{k=0}^{\infty} C_k{}^{(m)}(v^\beta i\overrightarrow{\partial}_\beta)^k$

- Two forms: $D1 = 1$ and $D2 = \frac{1}{1+\left(\frac{E-m}{\Lambda}\right)^2}$

DD – NLD model

Density–Dependent

Non-Linear Derivative

- the **interaction Lagrangian** is

$$\mathcal{L}_{int}{}^{DD-NLD} =$$

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- Two forms: $D1 = 1$ and $D2 = \frac{1}{1+\left(\frac{E-m}{\Lambda}\right)^2}$

WHY?

DD – NLD model

- **Dirac equation** is:

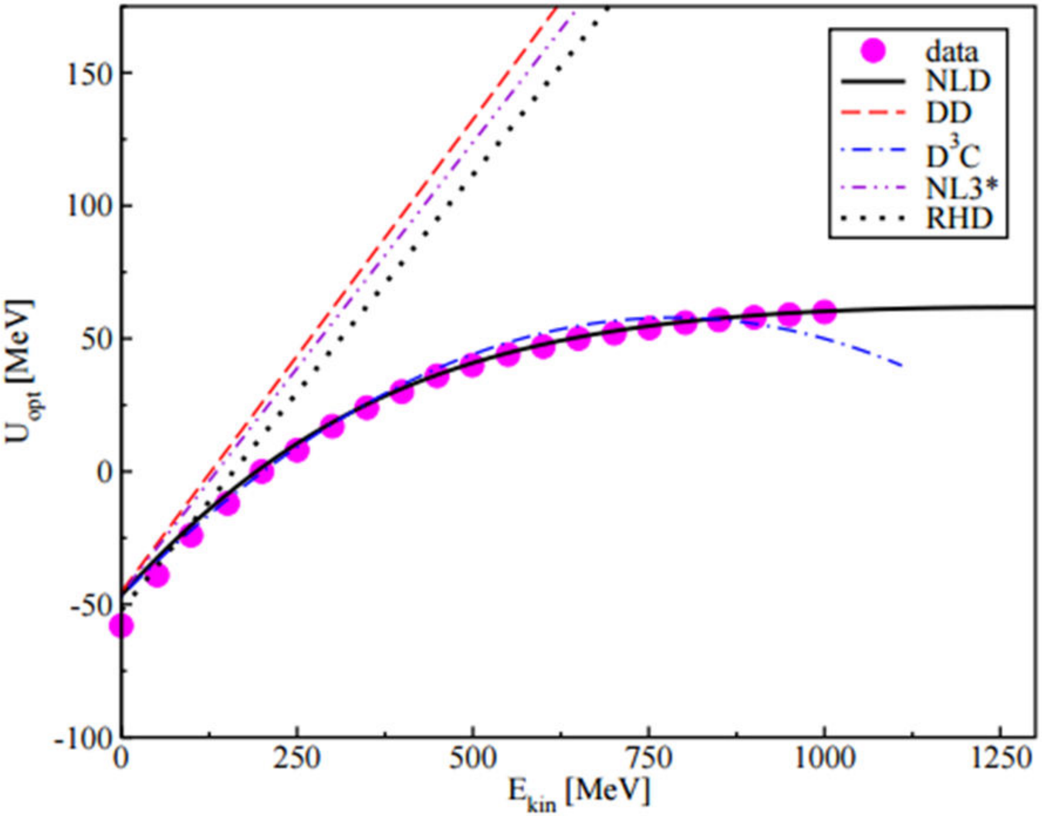
$$[\gamma_\mu(i\partial^\mu - \Sigma_V{}^\mu) - (m - \Sigma_S)]\Psi = 0$$

- **Scalar self-energy:** $\Sigma_S = \Gamma_\sigma \sigma \vec{D}_\sigma + \ldots$
- **Vector self-energy:**

$$\Sigma_V{}^\mu = \Gamma_\omega \omega^\mu \vec{D}_\omega + \Gamma_\rho \vec{\tau} \cdot \vec{\rho}^\mu \vec{D}_\rho + \Sigma_R{}^\mu + \ldots$$

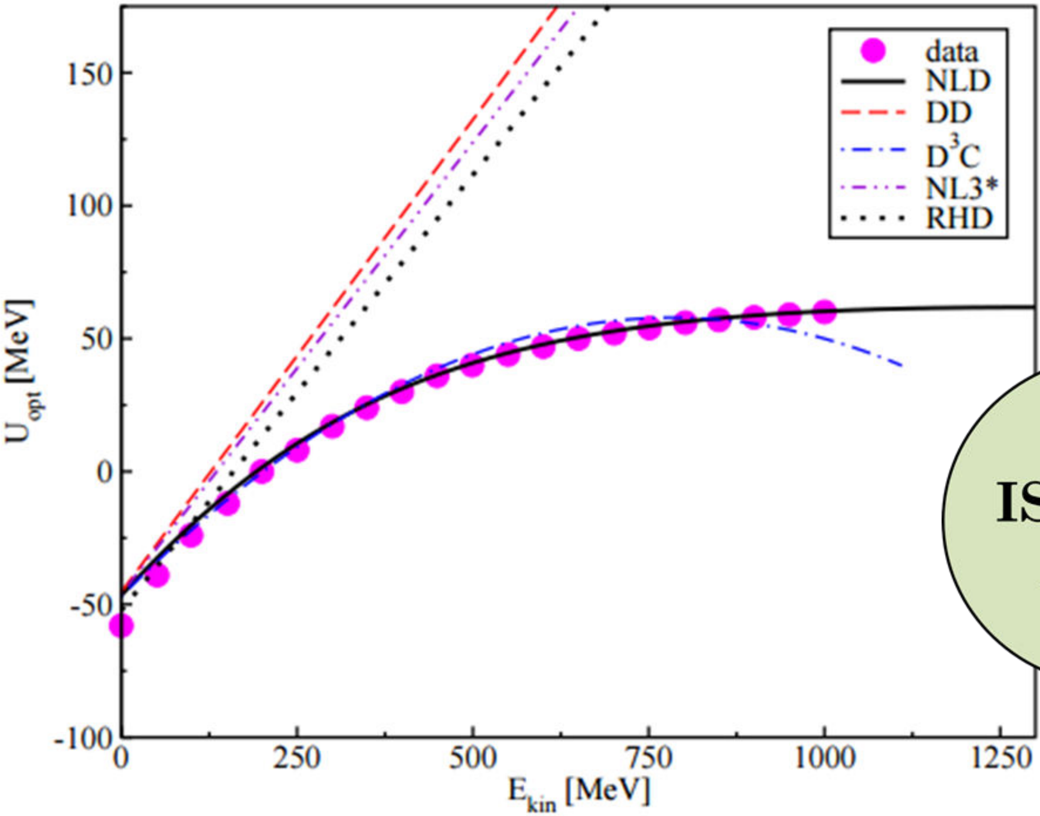
- **Optical potential** $U_{opt}(E) = \frac{E}{m_{nuc}} \Sigma_V{}^\mu - \Sigma_S + \frac{\Sigma_S{}^2 - (\Sigma_V{}^\mu)^2}{2m_{nuc}}$

DD – NLD model



- **Optical potential** $U_{opt}(E) = \frac{E}{m_{nuc}} \Sigma_V{}^{0} - \Sigma_S + \frac{\Sigma_S{}^2 - (\Sigma_V{}^{0})^2}{2m_{nuc}}$

DD – NLD model



IS THAT ALL?

- **Optical potential** $U_{opt}(E) = \frac{E}{m_{nuc}} \Sigma_V^0 - \Sigma_S + \frac{\Sigma_S{}^2 - (\Sigma_V{}^0)^2}{2m_{nuc}}$

DD – NLD model

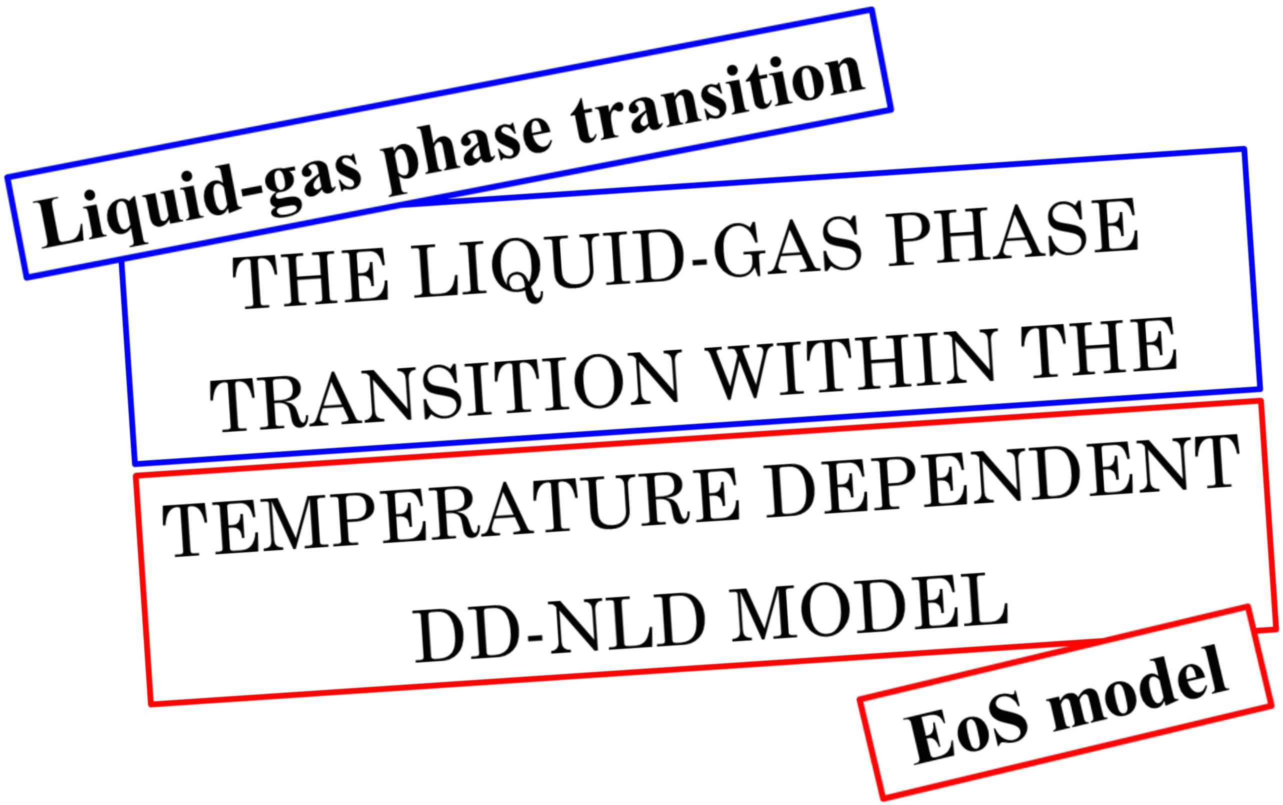
- Parameterization:
  - Fit to nuclear saturation properties
  - Fit to nuclei properties (binding en, radii…)

- Application:
  - infinite nuclear matter (SM, NM, PM)
  - NS at T = 0 (to get M-R relation)

S.Antić and S. Typel, Nucl. Phys. A 938 (2015) 92-108

DD – NLD model

- Parameterization:
  - Fit to nuclear saturation properties
  - Fit to nuclei properties (binding en, radii…)



Liquid – Gas Phase Transition

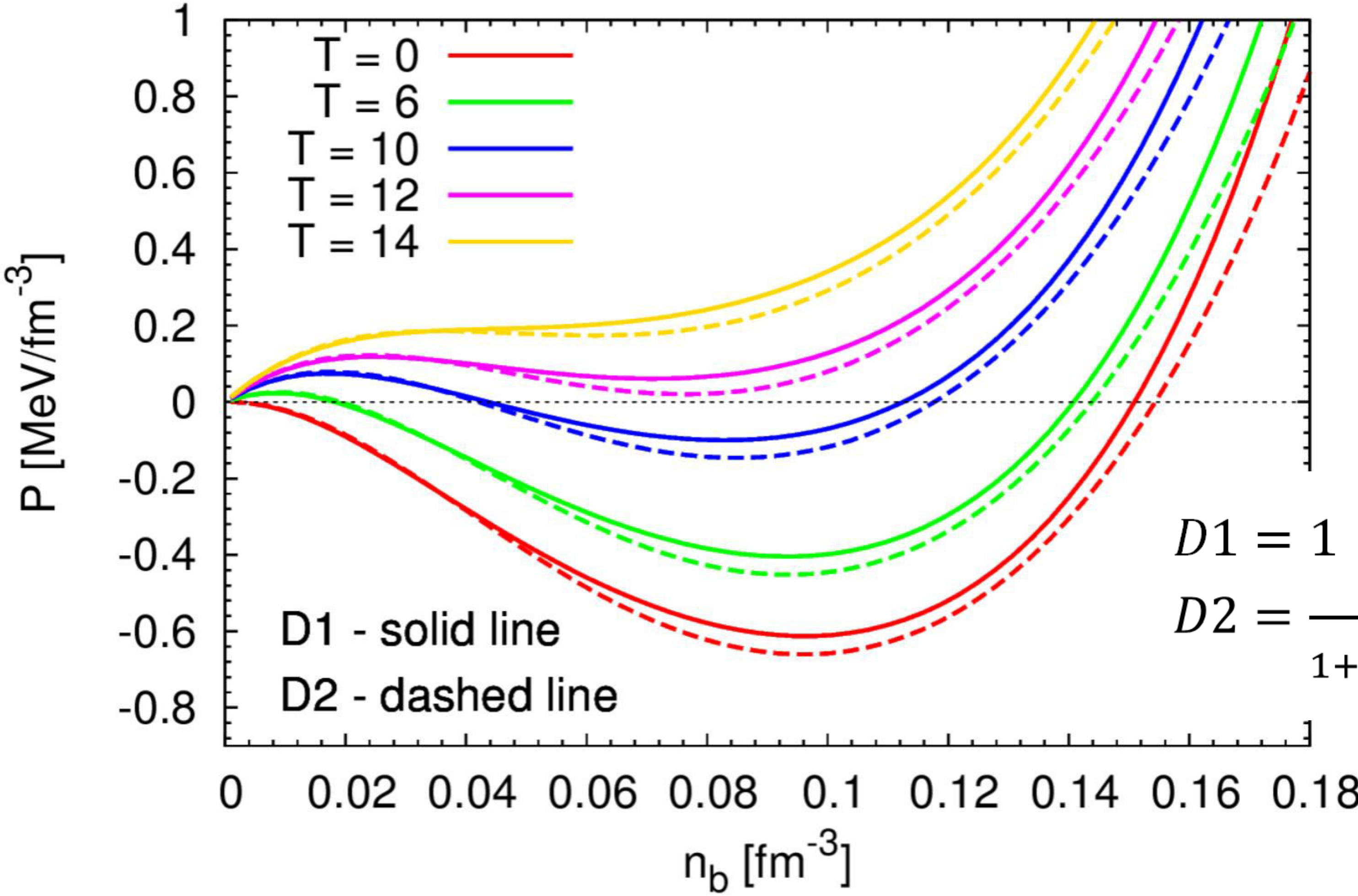
- To study LGPT :

    model exstension, implement T dependence

$$n_B \sim \int d^3p \qquad \longrightarrow \qquad n_B \sim \int \frac{1}{1+e^{\frac{(E-\mu)}{T}}}\, d^3p$$

- The finite temperature description necessary for general astrophysical applications (i.e. in order to provide the EoS tables for CCSN simulations)

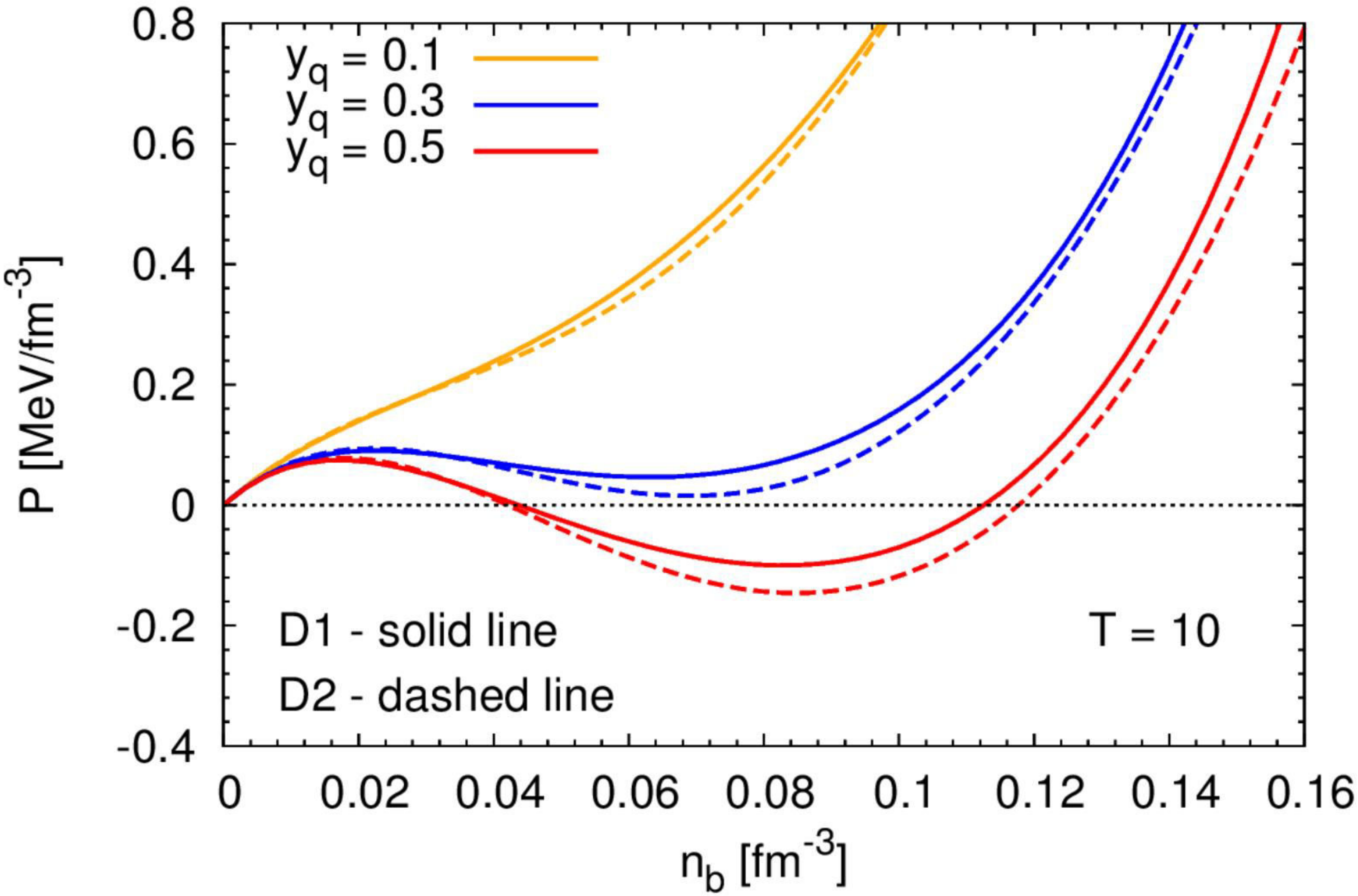
Symmetric matter with change of T



$$D1 = 1$$

$$D2 = \frac{1}{1+\left(\frac{E-m}{\Lambda}\right)^2}$$

SM to NM matter with change of y_q



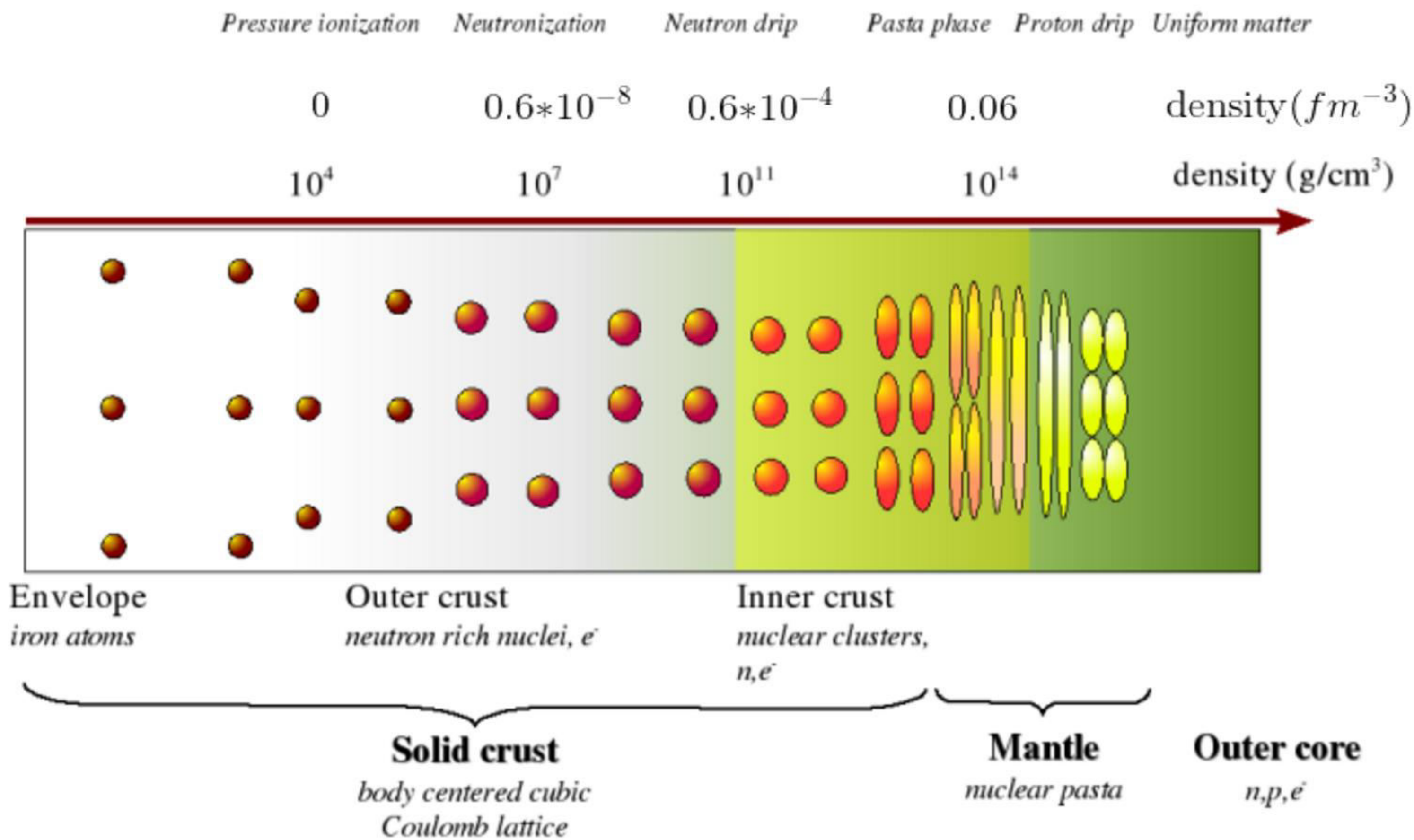
Liquid – Gas Phase Transition

- Two different major phase transitions for nuclear matter:

PHASE TRANSITION	TEMP	DENSITY	STUDY
Liquid Gas phase transition	**moderate (up to 15-20 MeV)**	**sub-saturation**	**Core collapse SN**
Quark Hadron phase transition	high	high	Early Universe after Big Bang

- Below saturation density and T$\lesssim$10 MeV:
  - nuclear matter unstable to density fluctuation
  - occurrence of LIQUID-GAS phase transition

Liquid – Gas Phase Transition



Liquid – Gas Phase Transition

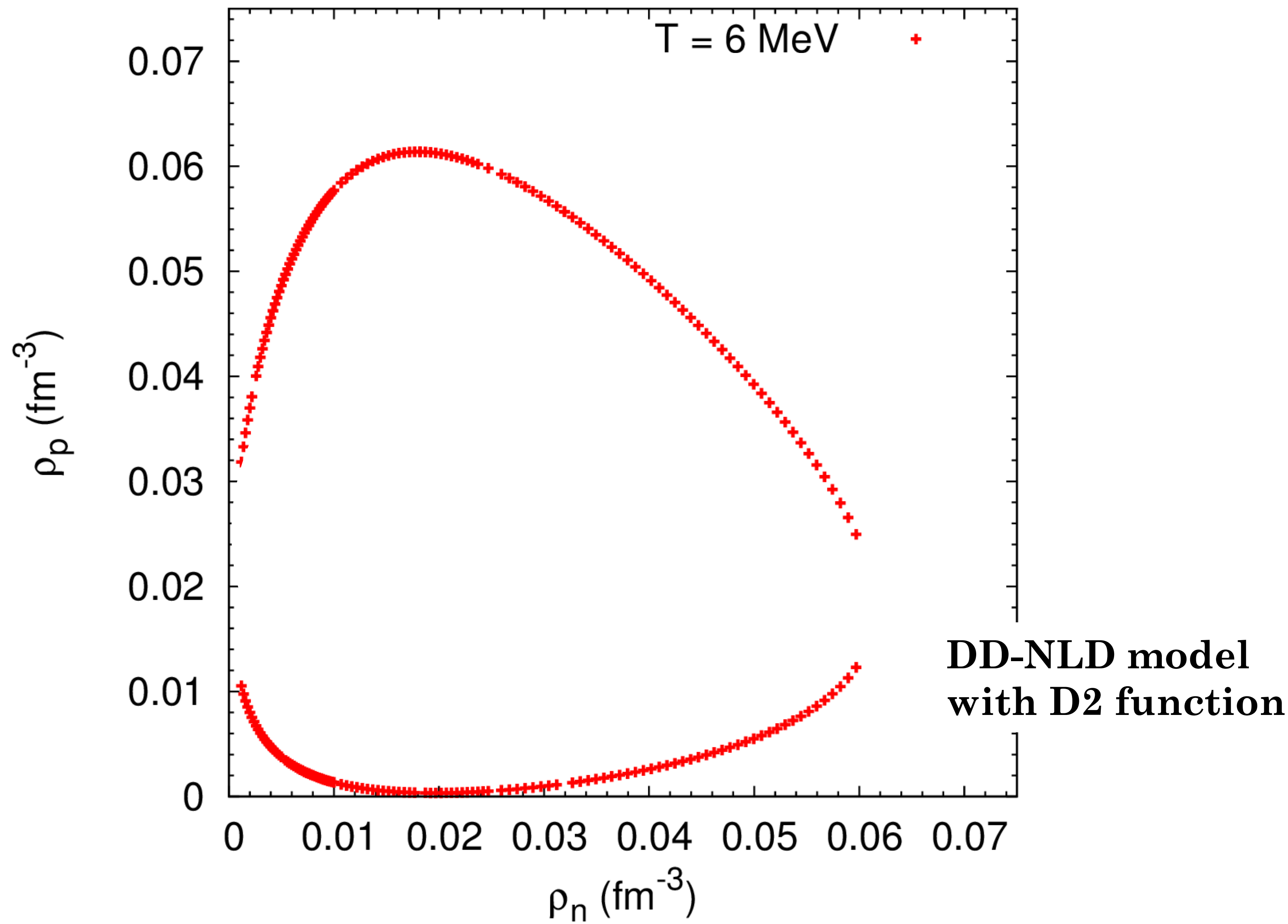
- Stability condition (T=const, V=const):

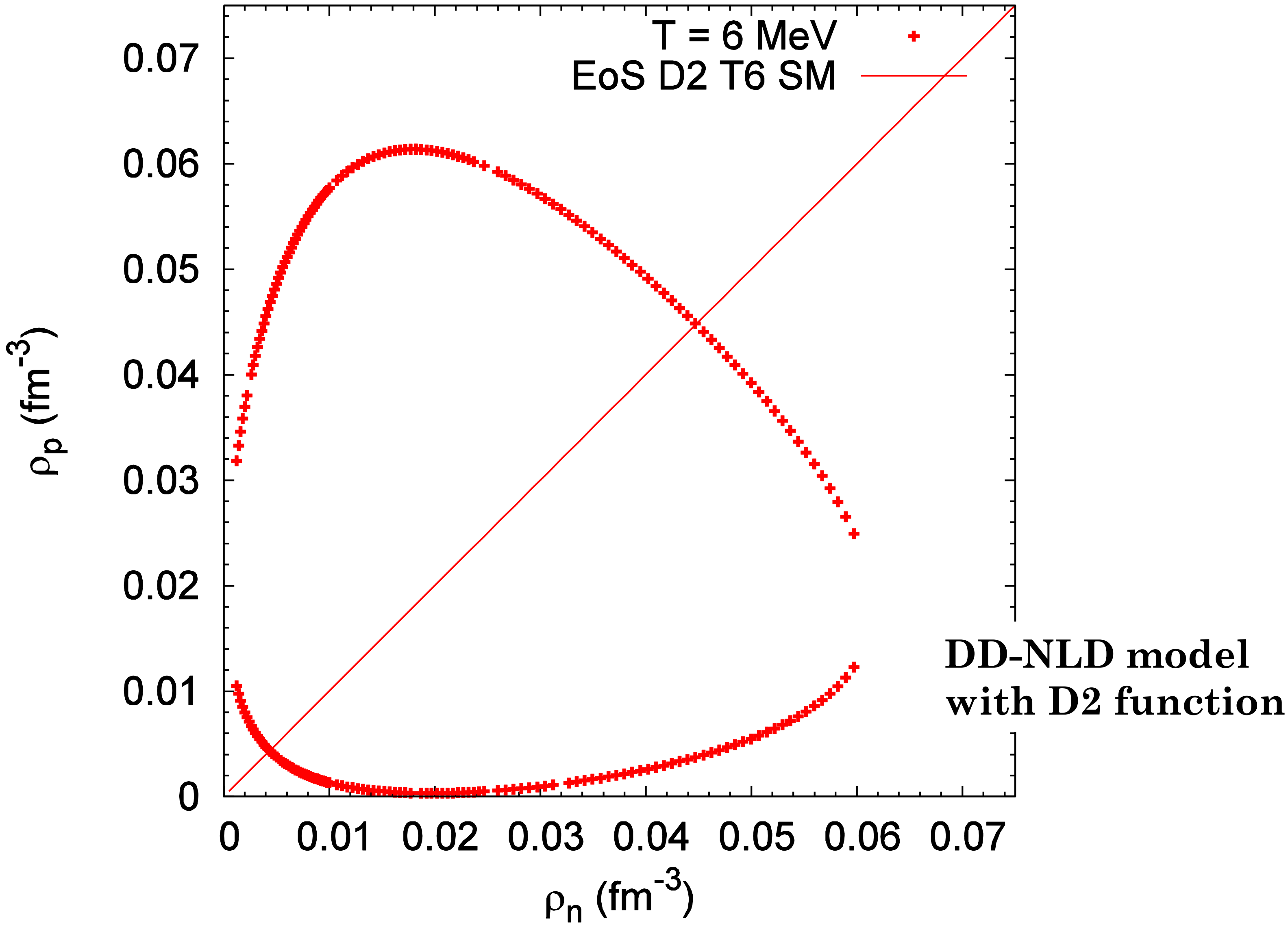
$$\mathcal{F}_{ij} = \left(\frac{\partial^2 \mathcal{F}}{\partial \rho_i \partial \rho_j}\right) = \frac{\partial}{\partial \rho_i}\left(\frac{\partial \mathcal{F}}{\partial \rho_j}\right) = \frac{\partial \mu_j}{\partial \rho_i} = \begin{pmatrix} \frac{\partial \mu_p}{\partial \rho_p} & \frac{\partial \mu_p}{\partial \rho_n} \\ \frac{\partial \mu_n}{\partial \rho_p} & \frac{\partial \mu_n}{\partial \rho_n} \end{pmatrix}_T > 0$$

- **SPINODAL:** determined by the value of T, ρ and y_p for which $det(\mathcal{F}_{ij})$ goes to zero
- Stability condition: the two eigenvalues > 0
- λ_- can become < 0 : system is thermodynamically unstable
- Looking for solution:

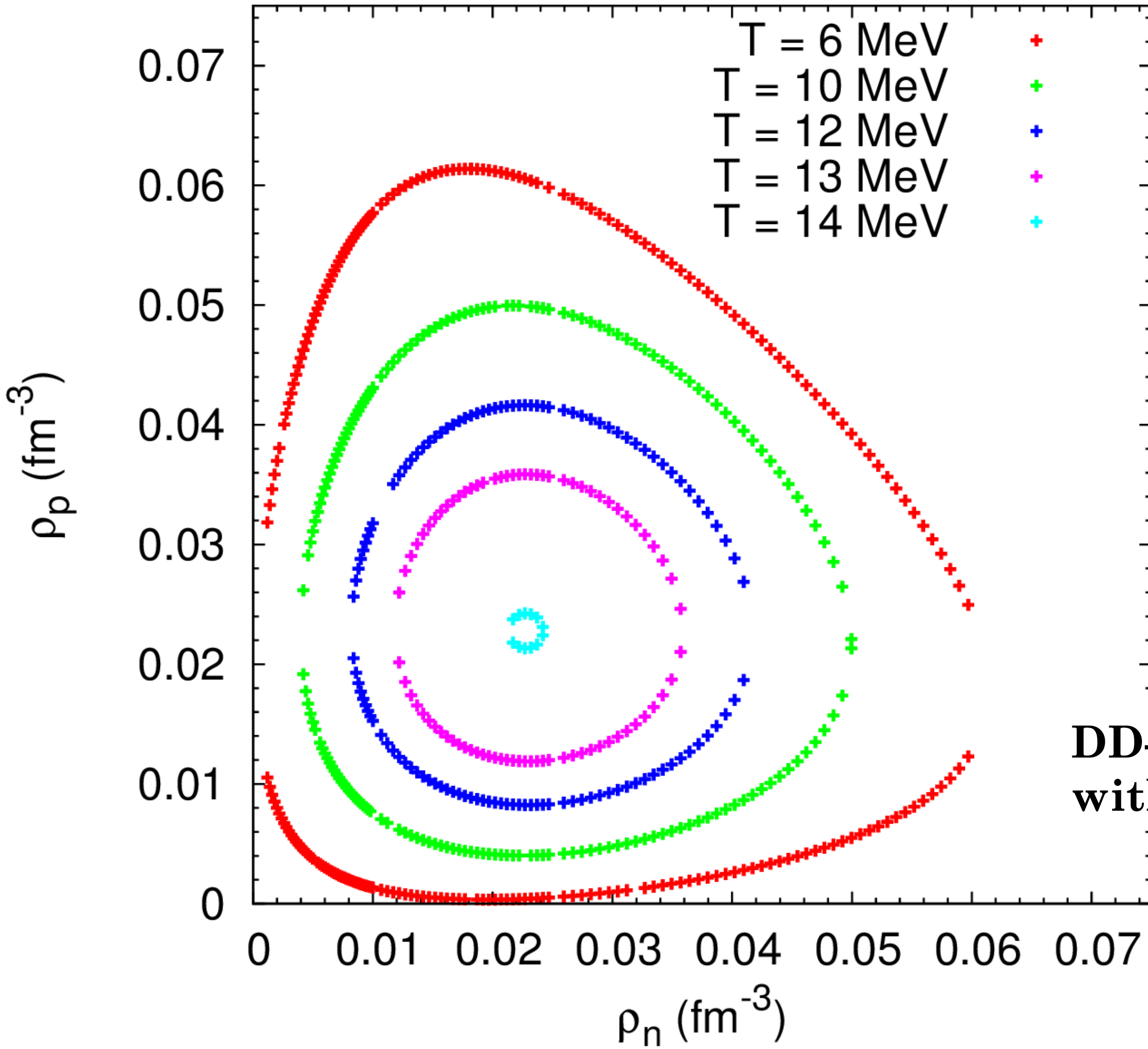
$$\lambda_- = 0$$

- It happens in two points in ρ_n vs ρ_p space – **boundaries of the spinodal (unstable region)**


T = 6 MeV
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
ρp (fm-3)
ρn (fm-3)
DD-NLD model
with D2 function

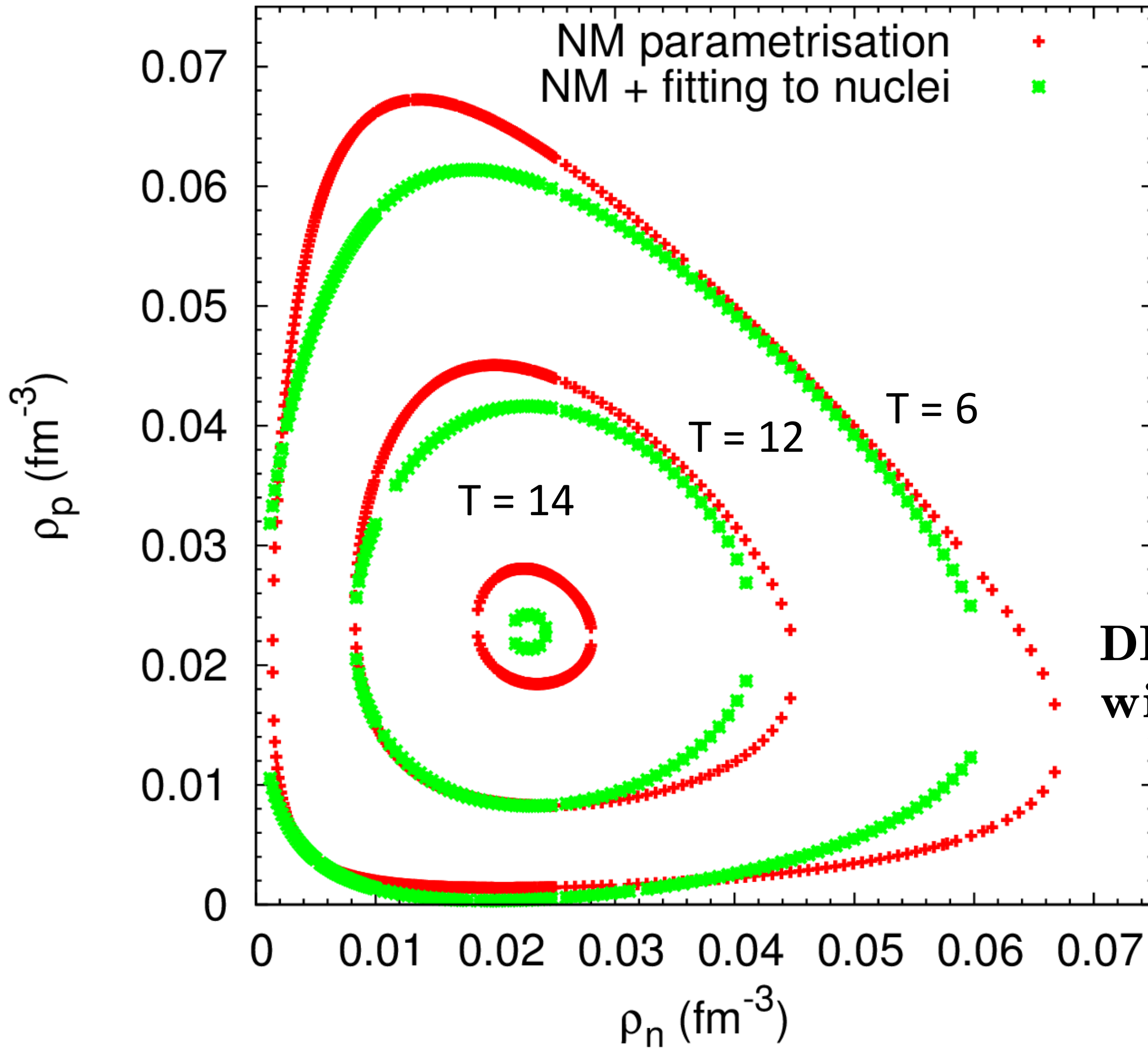


T = 6 MeV
EoS D2 T6 SM
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
ρ_p (fm^{-3})
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
ρ_n (fm^{-3})
DD-NLD model
with D2 function



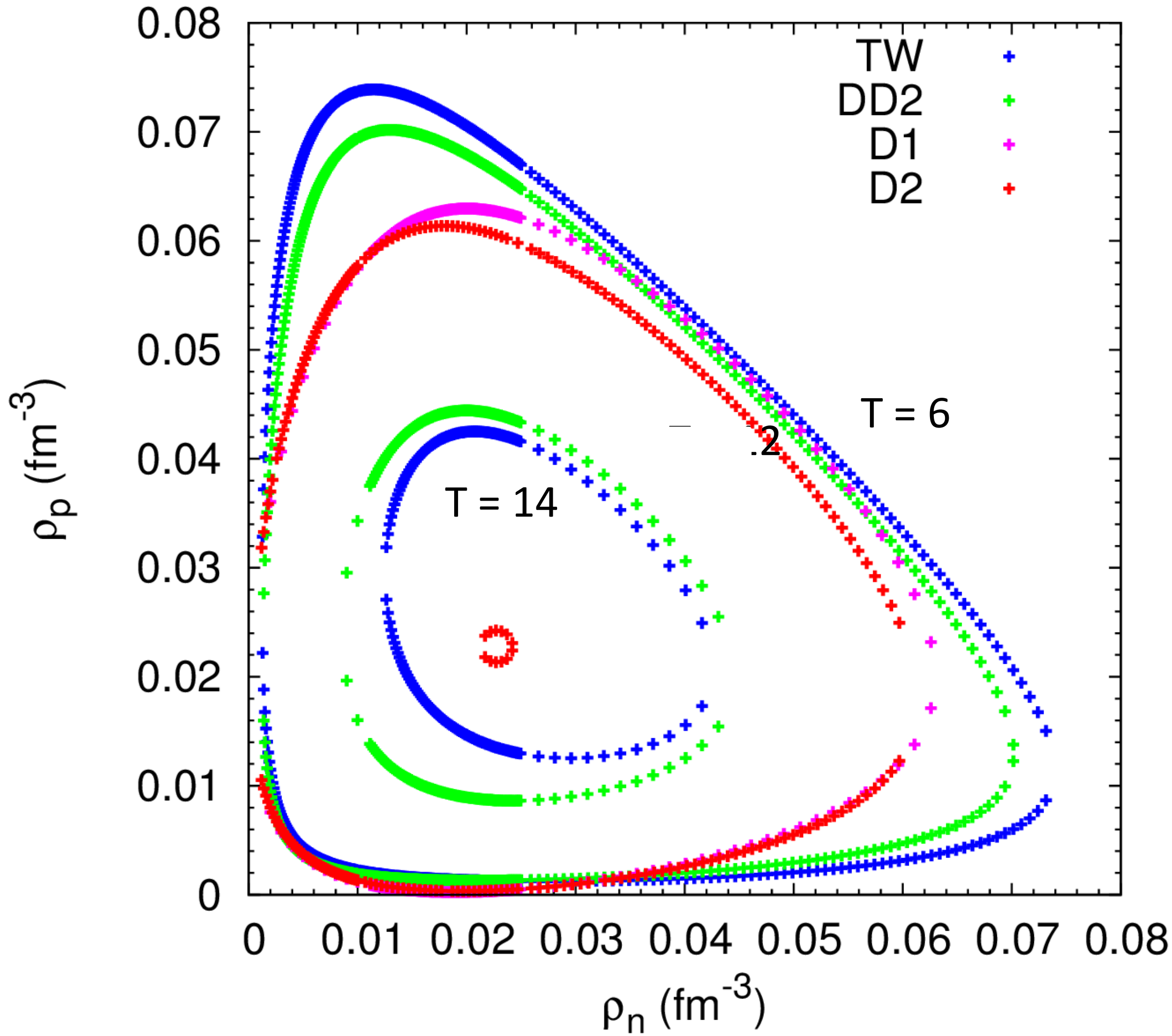
DD-NLD model with D2 function

Different parameterizations



DD-NLD model with D2 function

Comparison to previous models



CONCLUSIONS

- The pressure increases with increasing T and proton fraction for both (D1 and D2) models in same manner
- With increasing temperature, the envelope of the spinodals decreases for all the models considered
- For T=14 the D2 model with energy dependent self-energies shows the smallest spinodal compared to the other models

FUTURE WORK

- …work in progress…
- Further studies of sub-saturational region and the change of spinodal
- Binodal calculation (coexistence region)
- Explore the parameter space?
- …

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Thank you ☺

Questions?

GSI NAVI Nuclear Astrophysics Virtual Institute TECHNISCHE UNIVERSITÄT DARMSTADT HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research