

Molecular dynamics studies from heavy-ion collisions to neutron stars

T. Furuta, F. Gulminelli, C. Leclercq and O. Juilliet

LPC Caen (CNRS-IN2P3/ENSICAEN et Universite), Caen, France

K. H. O. Hasnaoui and A. Ono

Department of Physics, Tohoku University, Sendai, Japan

Introduction

Antisymmetrized Molecular Dynamics

Applications

- Thermodynamics of finite low-density system
- Heavy-ion collisions
- Star matter calculation

Summary

Introduction

The properties of nuclear matter at different environments (T, ρ, \dots)

= Nuclear equation of state (EOS)

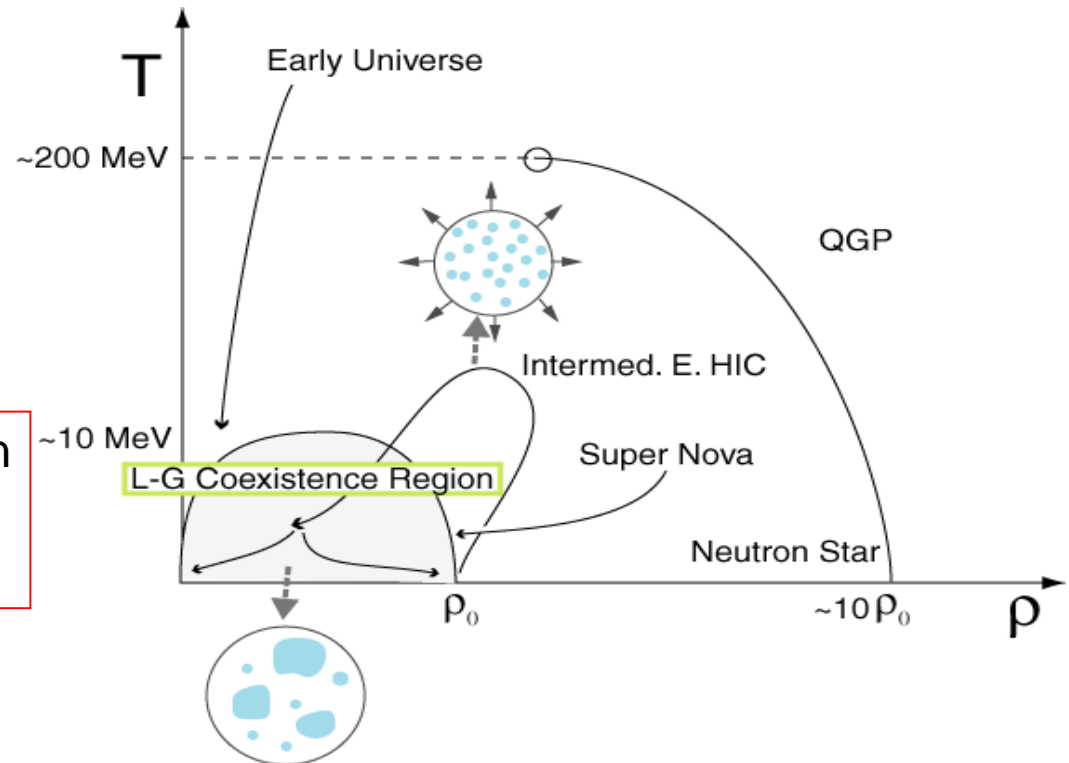
Liquid-gas phase coexistence region
 $\rho < \rho_0$ $T \leq 10 \text{ MeV}$
(Nuclear liquid-gas phase transition)

Homogeneous phase is unstable
Existence of clusters
Density inhomogeneity

Relevant to

- Multifragmentation in heavy-ion collisions
- Inner crust of neutron star

Molecular Dynamics is good



Good points

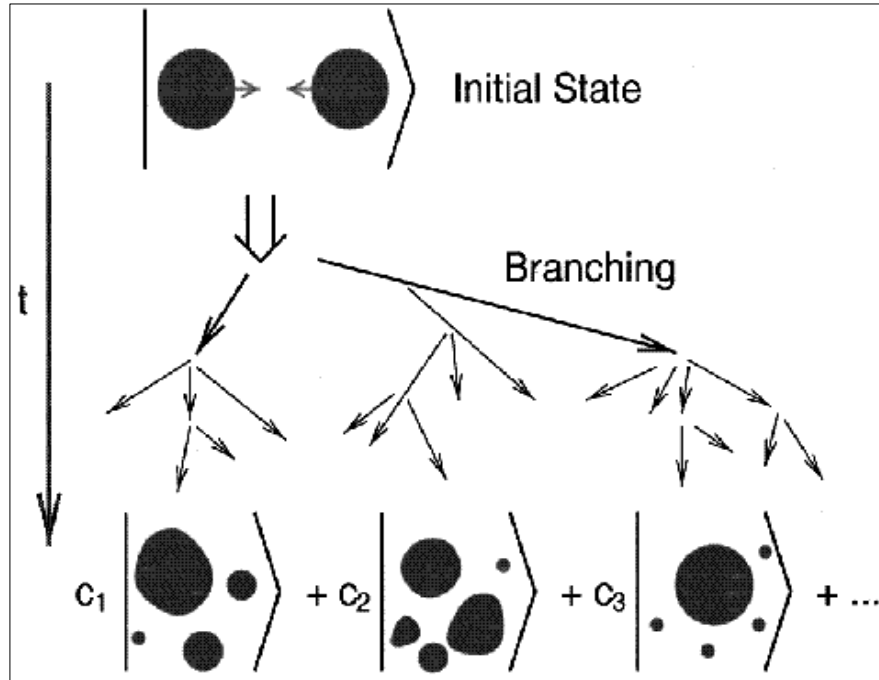
- Appearance of clusters
 - Interaction between clusters
 - Wide range applicability
- Dynamical process of heavy-ion collision
Thermodynamics of neutron star

Antisymmetrized Molecular Dynamics (AMD)

Antisymmetrized Molecular Dynamics (AMD)

A. Ono et al. PTP 87(1992)1185

A. Ono et al. Prog. Part. Nucl. Phys. 53(2004)501



Time evolution

$$\frac{d}{dt} \mathbf{Z} = \text{EOM for wave packet centroids} + \text{Stochastic process}$$

Effective interaction (f.g. Gogny, Skyrme)
+ Coulomb force

Stochastic process

1. Two-nucleon collision
2. Wave packet branching

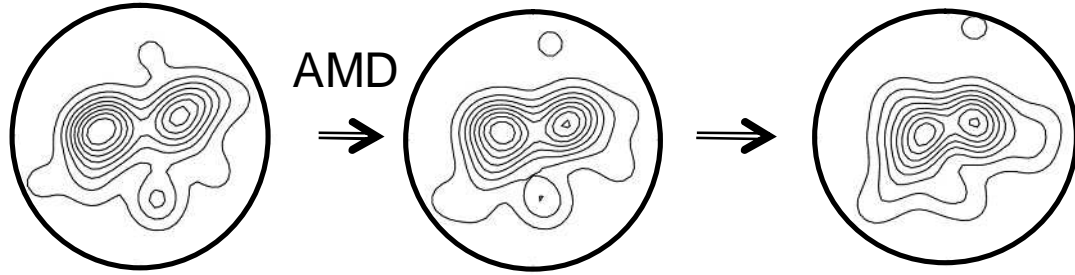
Approximately reproduce the prediction of MF propagation (short time)

$$|\Phi(\mathbf{Z})\rangle \propto \det_{ij} \left[e^{-\nu(\vec{r}_j - \vec{Z}_i)^2} \chi_i \right]$$

$$\mathbf{Z} = \{\vec{Z}_1, \dots, \vec{Z}_A\}$$

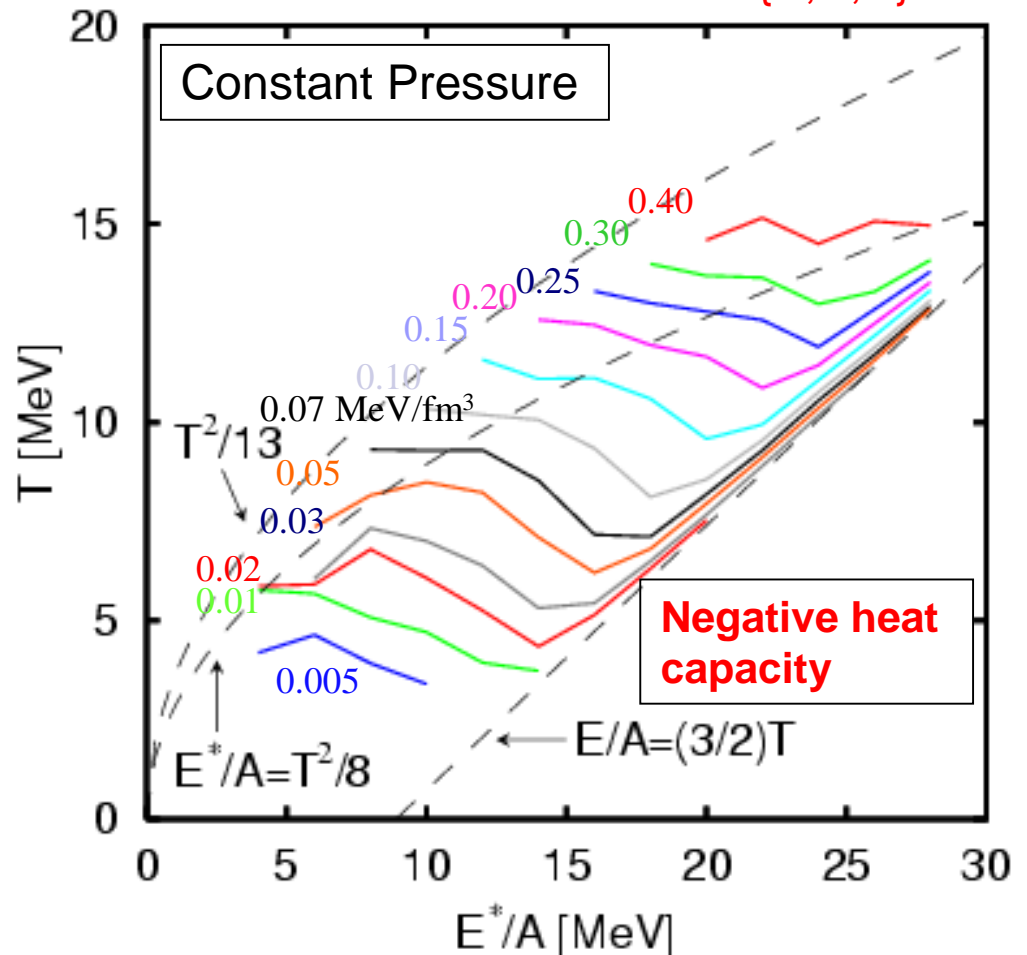
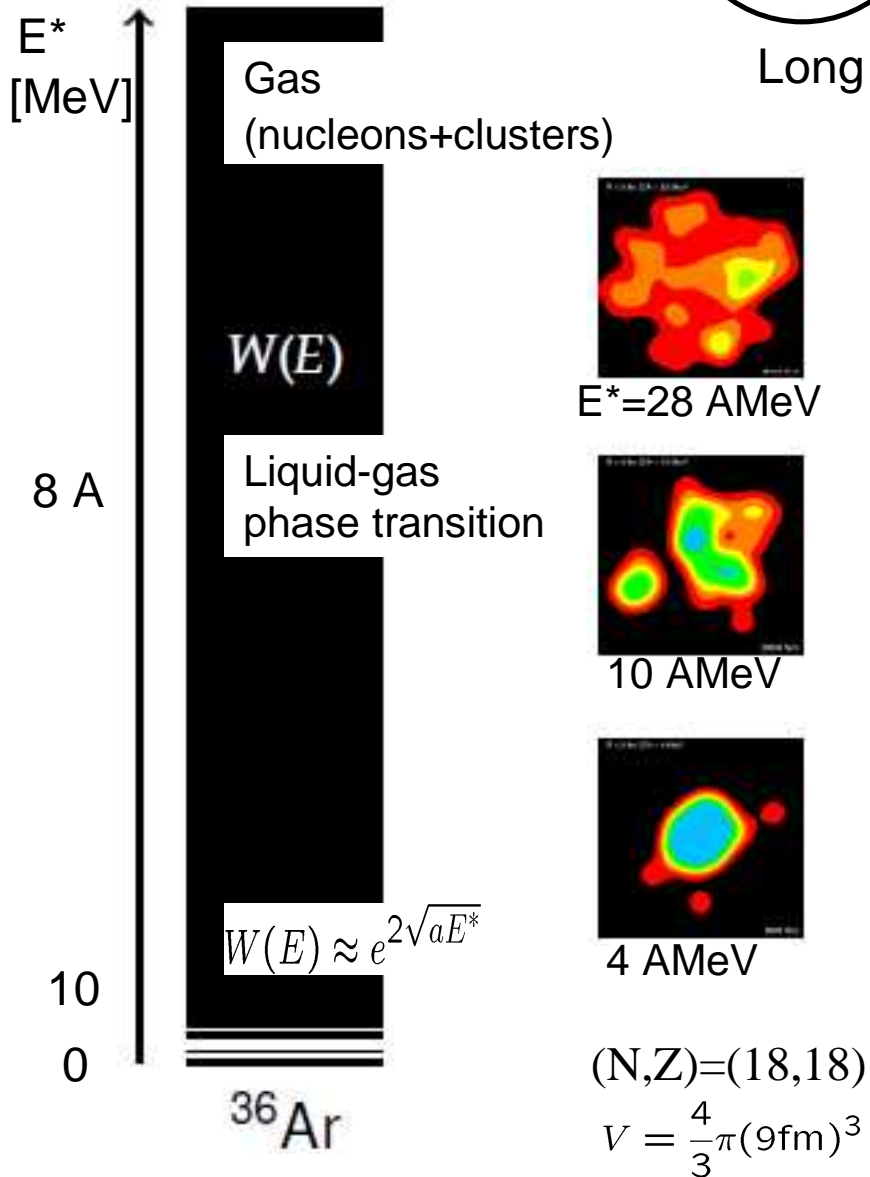
$$\vec{Z} = \sqrt{\nu} \vec{R} + i \frac{\vec{P}}{2\hbar\sqrt{\nu}}$$

Thermodynamics of finite low-density system



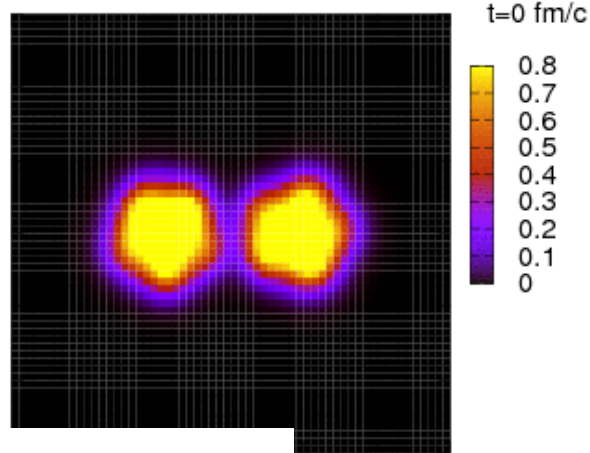
Long time evolution

= microcanonical ensemble $\{E, V, A\}$



Heavy-ion collisions

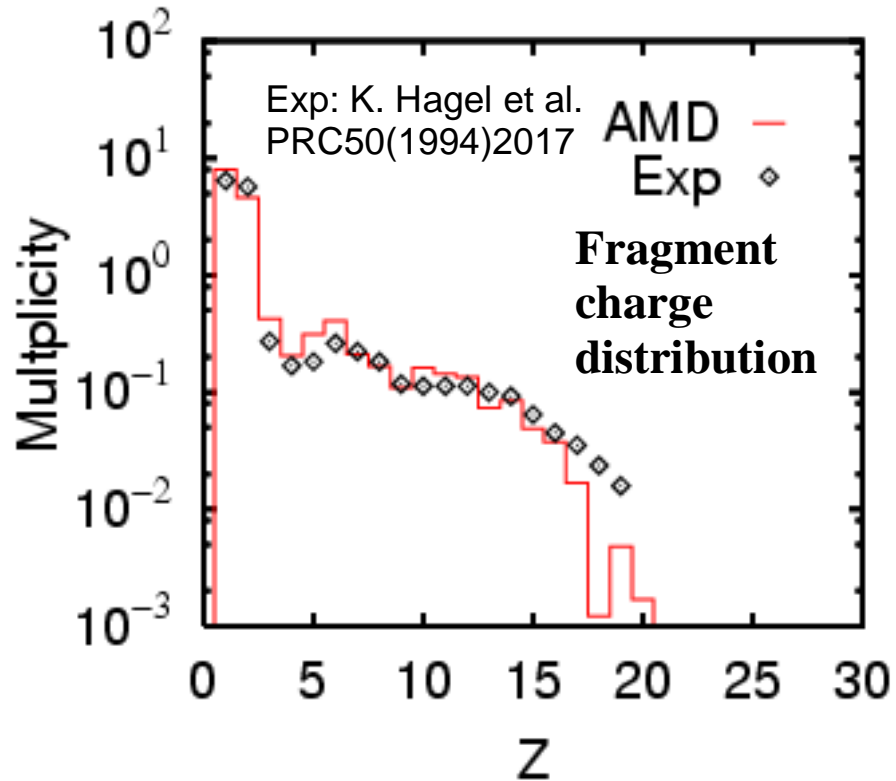
$^{40}\text{Ca} + ^{40}\text{Ca} @ 35 \text{ A MeV}$



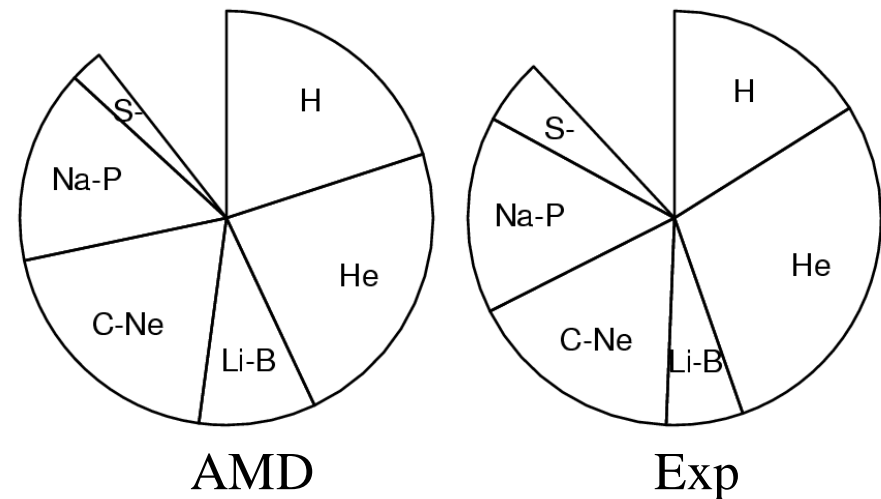
Simulation of many events independently

t=300fm/c

Secondary decay
Exp. filter
& event selection



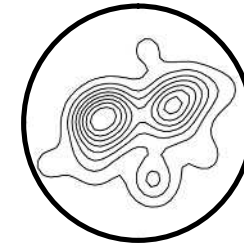
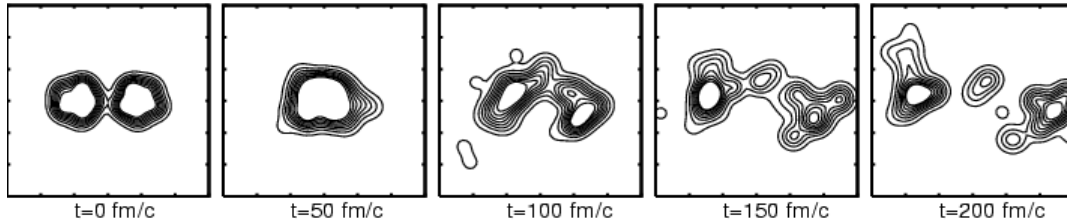
Charge partition



Comparison of reaction and equilibrium

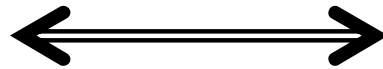
T.F. and A.O. PRC79 (2009) 014608

$^{40}\text{Ca} + ^{40}\text{Ca} @ 35\text{A MeV}$ $b_{\text{imp}} = 0$



{States at a reaction time t }

Half of Ca + Ca system



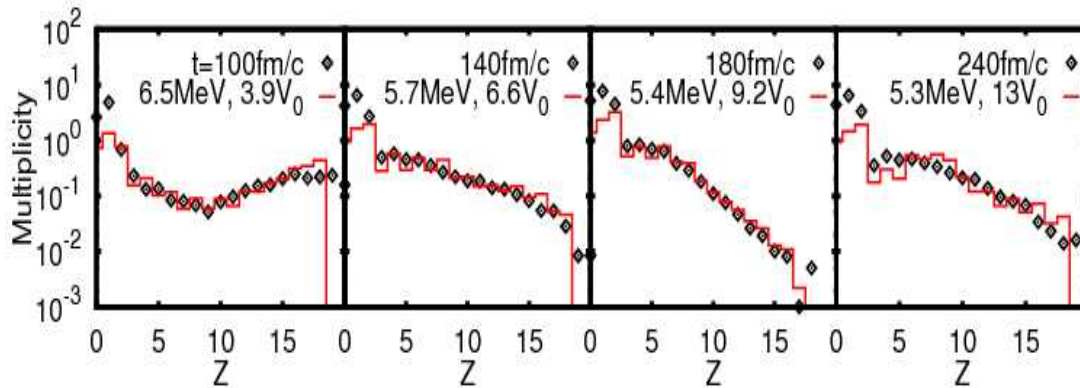
Equilibrium ensemble

{ $E, V, A=36$ }

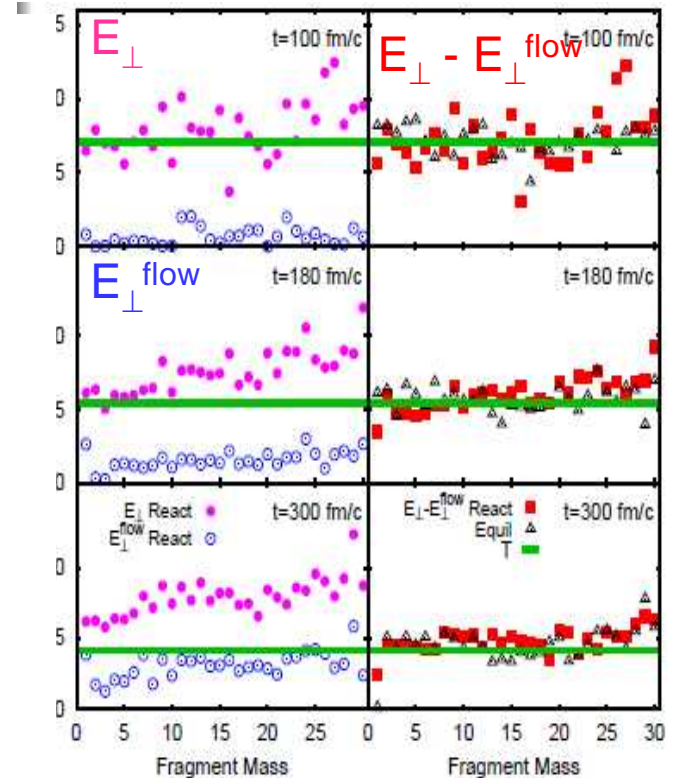
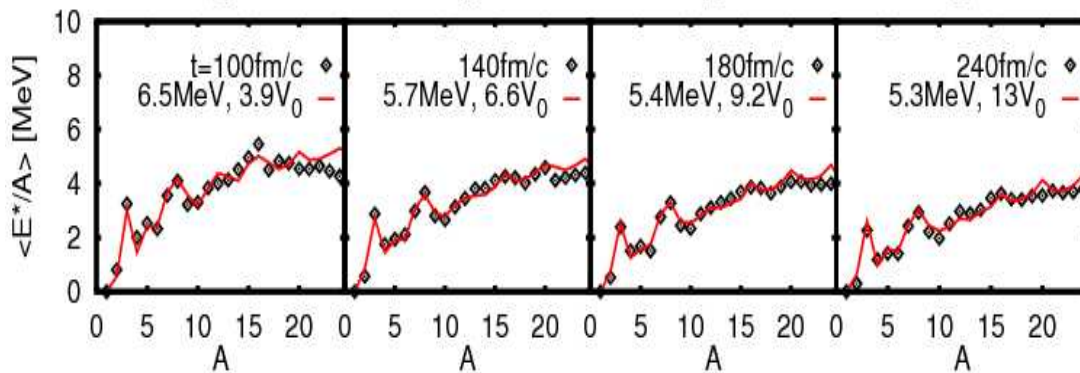
Reaction

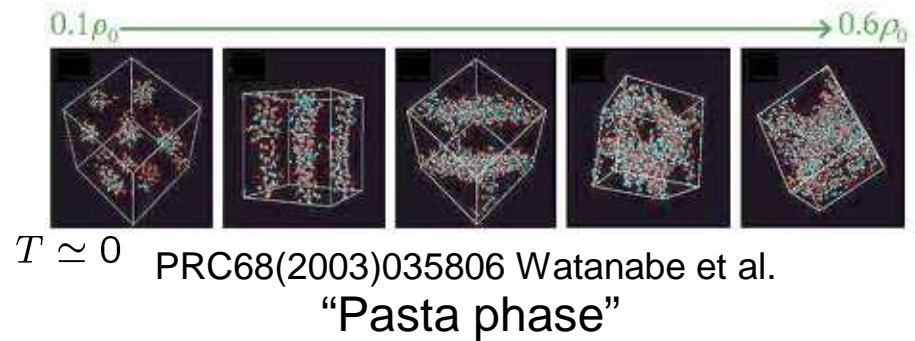
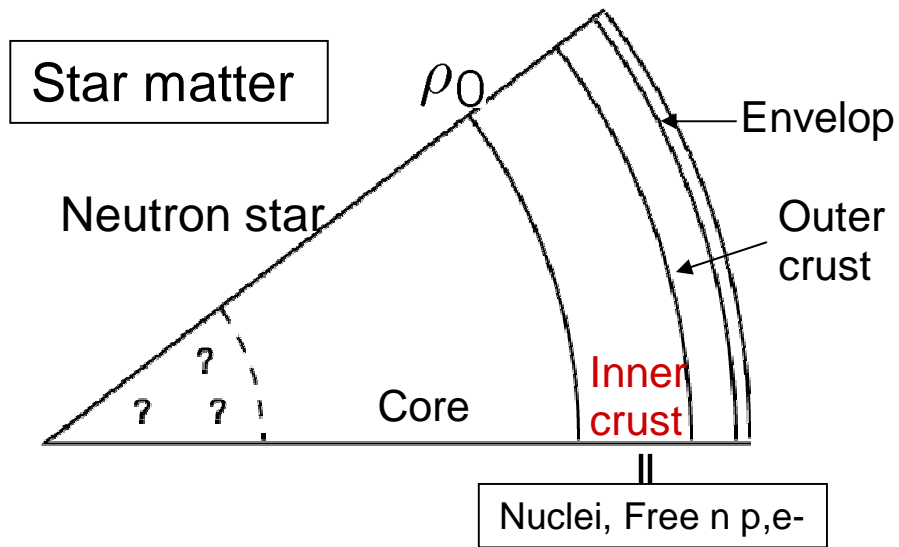
Equilibrium

$Y(Z)$



$\langle E^*/A \rangle$





Density inhomogeneities in the inner crust and consequences on structural properties and cooling dynamics

There are studies including density inhomogeneities

D.G.Ravenhall et al. PRL50 (1983) 2066

M. Hashimoto et al. PTP71 (1984) 320

T. Maruyama et al. PRC72 (2005) 015802

S. S. Avancini et al. PRC78 (2008)015802

J. M. Lattimer and F. D. Swesty NPA535 (1991) 331

H. Shen et al. NPA637 (1998) 435

Talk of S. Typel

W. G. Newton and J. R. Stone PRC79 (2009) 055801

C. Ishizuka et al. NPA723 (2003) 517

Talk of F. Gulminelli

- Molecular dynamics approach

C. J. Horowitz et al. PRC70 (2004) 065806

G. Watanabe et al. PRC68 (2003) 035806

Finite T many different configurations beyond MF
 Appearance of many configuration with different partition
 of fragments and fermionic aspects are essential

—————> New framework with AMD

Framework for star matter

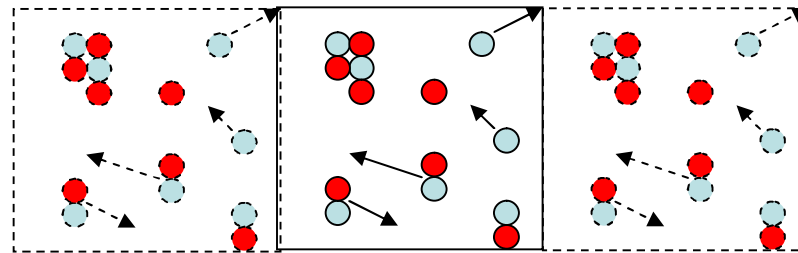
New ingredients

- Inclusion of electron effects

ρ_{electron} : background minus charge

$$\Delta V_c(\vec{x}) = \rho_{\text{proton}}(\vec{x}) + \rho_{\text{electron}}$$

- Extension to infinite system



Periodic boundary condition

Numerical improvements

Computational time A^4

Too heavy for very large **A~1000** system

- Introduction of Skyrme functional

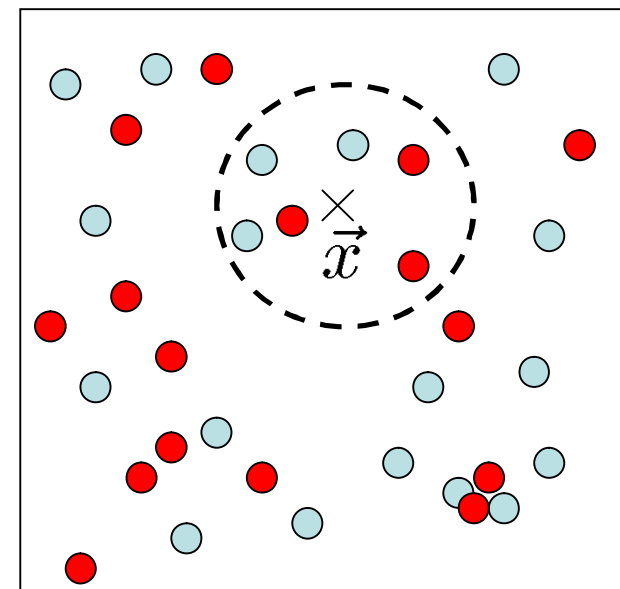
$$\langle V \rangle = \int d\vec{x} V(\rho(\vec{x}), \tau(\vec{x}), \Delta(\vec{x}), \vec{J}(\vec{x}))$$

$$\rho(\vec{x}), \tau(\vec{x}), \Delta\rho(\vec{x}), \vec{J}(\vec{x})$$

$$\rho(\vec{x}) = \left(\frac{2\nu}{\pi}\right)^{3/2} \sum_{i=1}^{\mathbf{a}} \sum_{j=1}^{\mathbf{a}} e^{-\nu(\vec{x}-R_{ij})^2} B_{ij} B_{ji}^{-1}$$

→ Reduction of computational time $a^2 V$

A → a



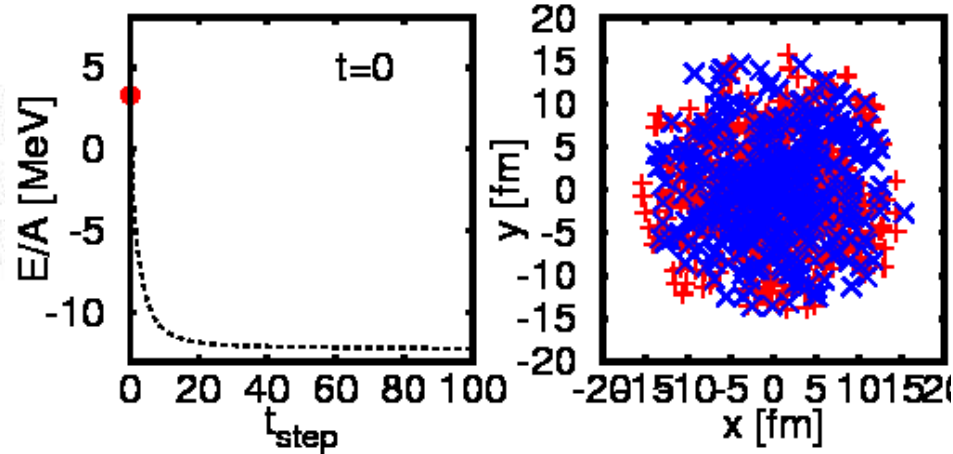
Numerical test

$A = 1000$ SLy4 Cooling w/o Coulomb w/o stochastic process

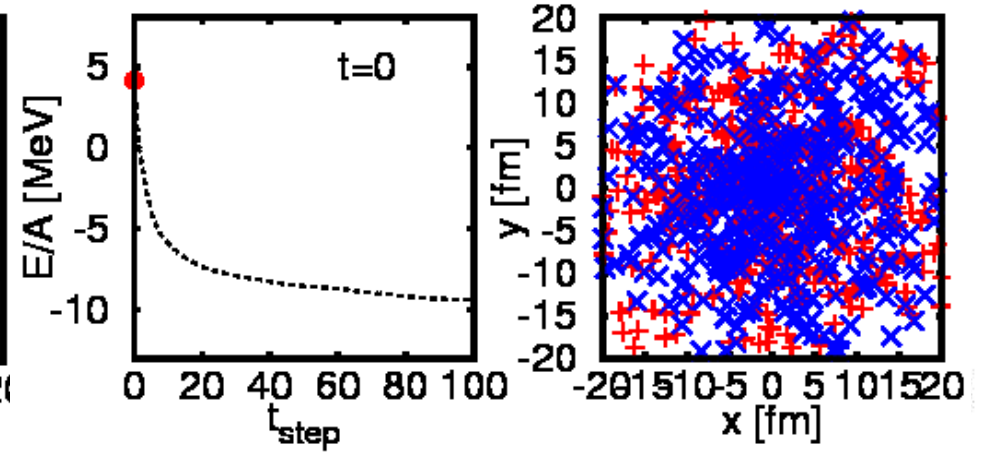
+ Proton centroids

x Neutron centroids

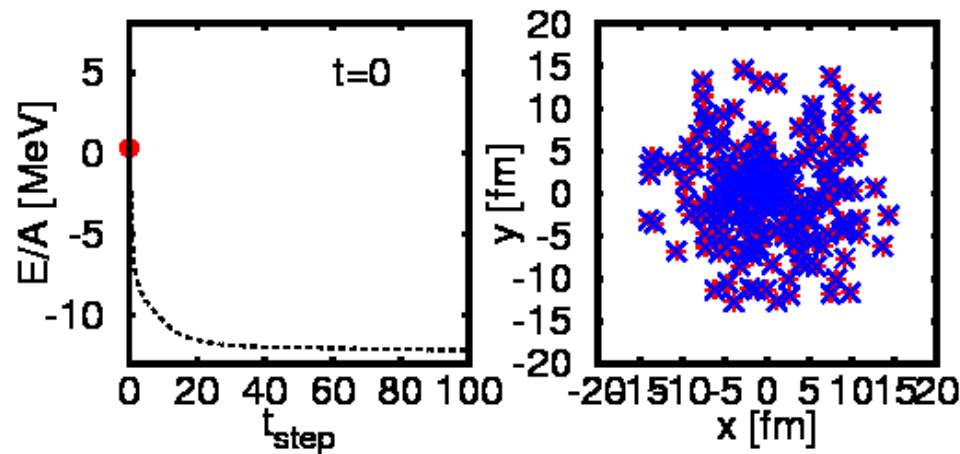
• Random spherical distribution (small)



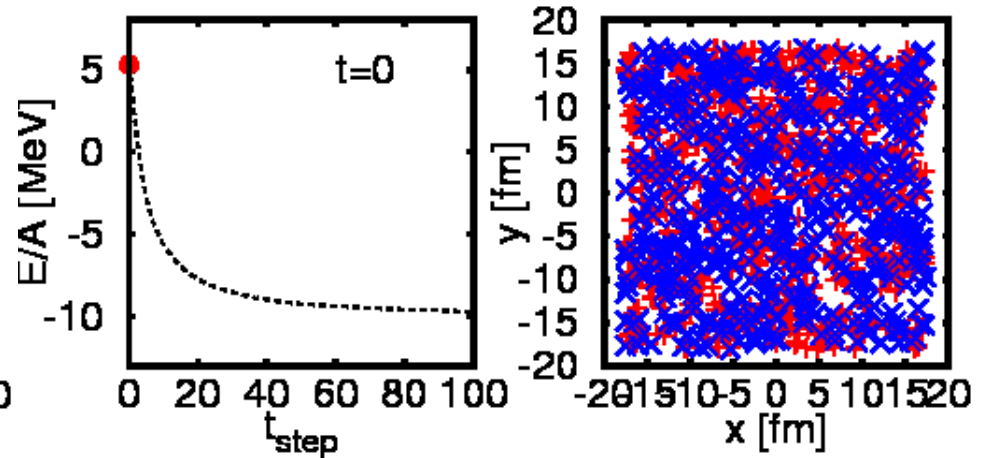
• Random spherical distribution (large)



• Random alpha distribution



• Random cubic distribution



$t_{\text{comp}} \sim 10\text{hrs}$ (Normal computer with 1 CPU)

There are many local minimums $\xrightarrow{\text{Finite } T}$ Mixed configuration of excited states of many different fragment partitions

Summary

Molecular dynamics approach

Good for the studies of Inhomogeneous nuclear matter

From heavy-ion collisions to neutron star matter within a single framework

Applications

- Thermodynamics of finite low-density system
Description of liquid-gas phase transition
- Simulation of heavy-ion collisions
Reproduction of experimental data
Equilibrium seems achieved during the reaction time
- Star matter calculation
Possibility of consistent framework