Transiciones de fase en la corteza de las estrellas de neutrones ?

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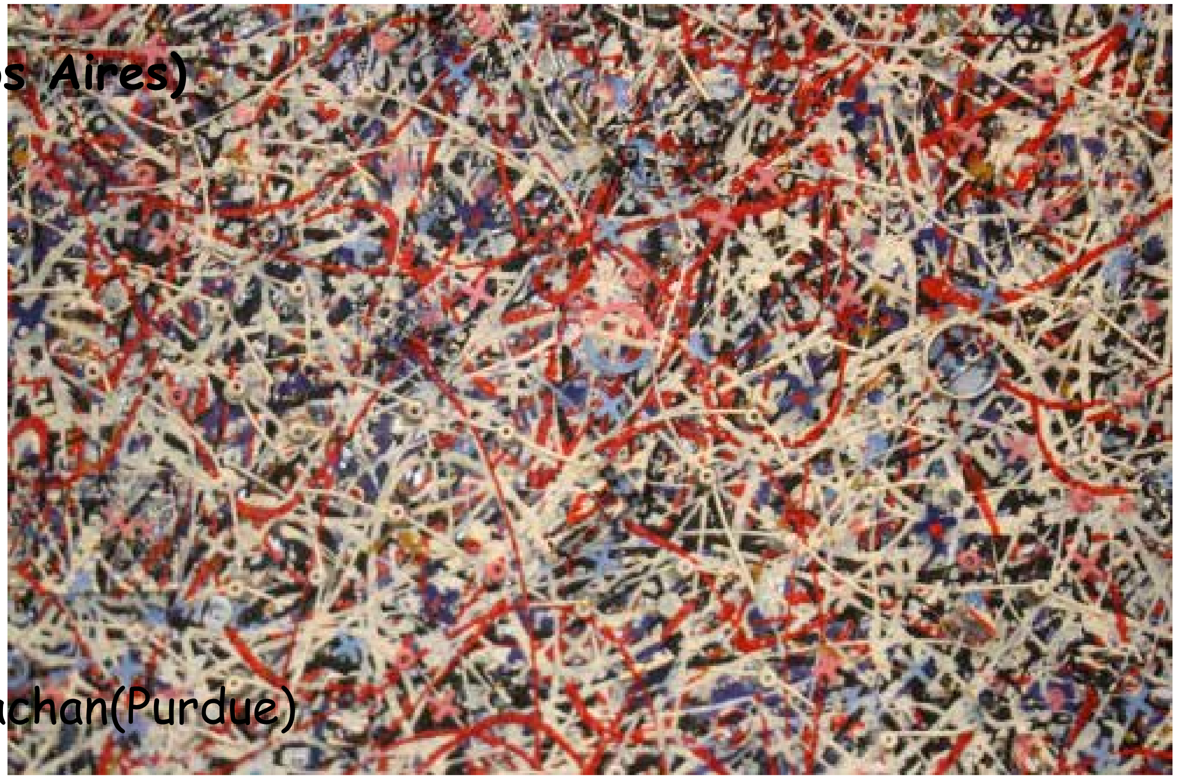

LAFEC

Astrofísica Nuclear

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- A.Chernomoretz
- P.Alcain
- J.Nichols

SocioFisica

- Dinámica Peatonal (pánico)
  - C.O.Dorso
  - G.Frank
- Complex Networks Formación de Opiniones
  - C.O.Dorso
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  - S.Pinto
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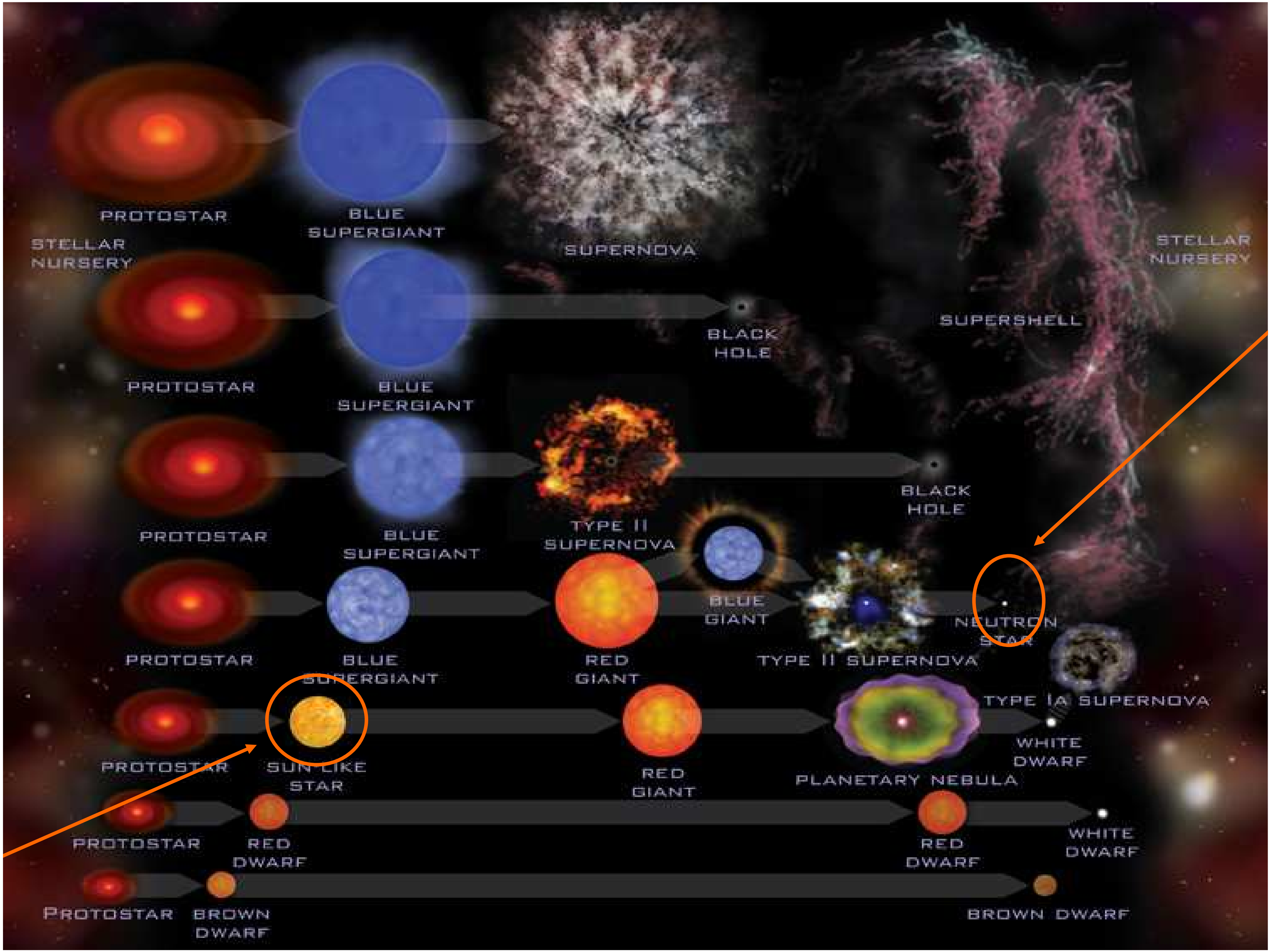
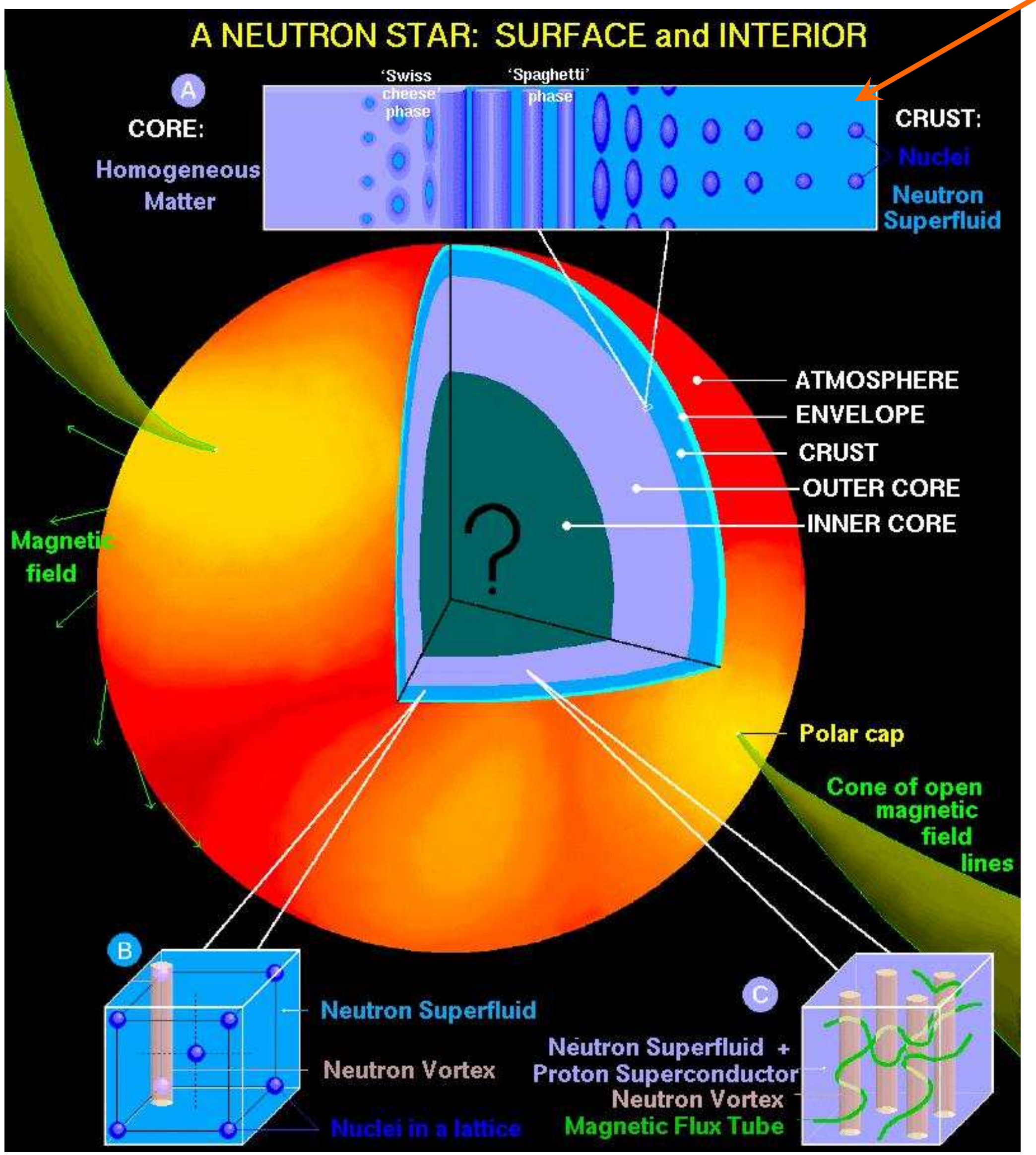

PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

Astrofísica Nuclear: Estrellas de Neutrones

(circa 2010)



- $M \sim 1.4\ M_\odot \rightarrow 2\ M_\odot$
- $R \sim 10$ km
- $\rho \sim 10^6\ g/cm^3 \rightarrow 8 \times 10^{14}\ g/cm^3$
- $x \sim 0{,}5 \rightarrow 0{,}2$ (?)
- $T \sim 1$ MeV (10^{10} K)

Laboratorio para NEOS:

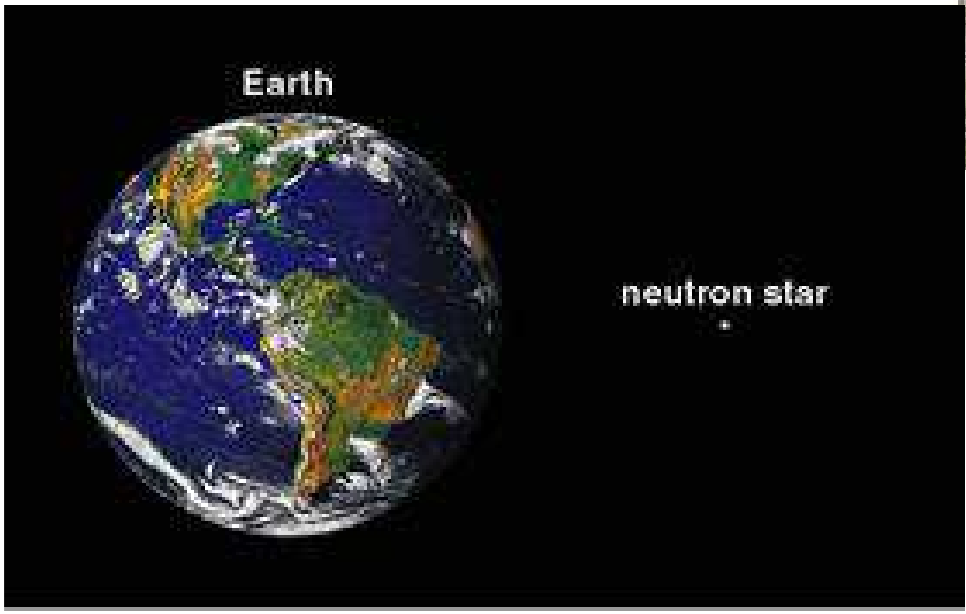
$$E(\rho, T, \delta) \sim E(T, \rho, \delta = 0) +$$

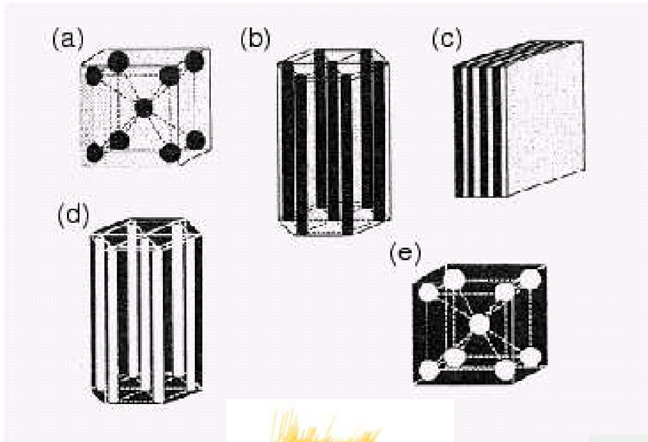
$$+ E_{Sym}(T, \rho)\delta^2,$$

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$


Comparación de una enana
blanca con la Tierra
M ≈ 1.0 M sol
R ≈ 5800 km
V esc ≈ 0.02c


Buenos
Aires


Earth
neutron star


(a)
(b)
(c)
(d)
(e)

Algunas preguntas a responder

Que es nuclear Pasta?

Cual es el efecto de las condiciones periódicas de contorno en la formación de pastas?

Rol de coulomb?

Rol del apantallamiento de Debye?

Transiciones de fase En las pastas?

Opacidad de Neutrinos y la topología de la corteza.

Nucleosintesis (Elementos mas pesados que Hierro)?

Esta Presentación:

Neutron Star

El modelo CMD
(Illinois potential)

Sistemas Finitos
Reconocimineto de fragmentos
Comportamiento critico
Energia se simetria
Isoscaling

Sistemas infinitos (NS¨)

Topologia
Coulomb

Intermezzo

Sistemas 2D y 3D
Lennard Jones + Coulomb

Illinois potential

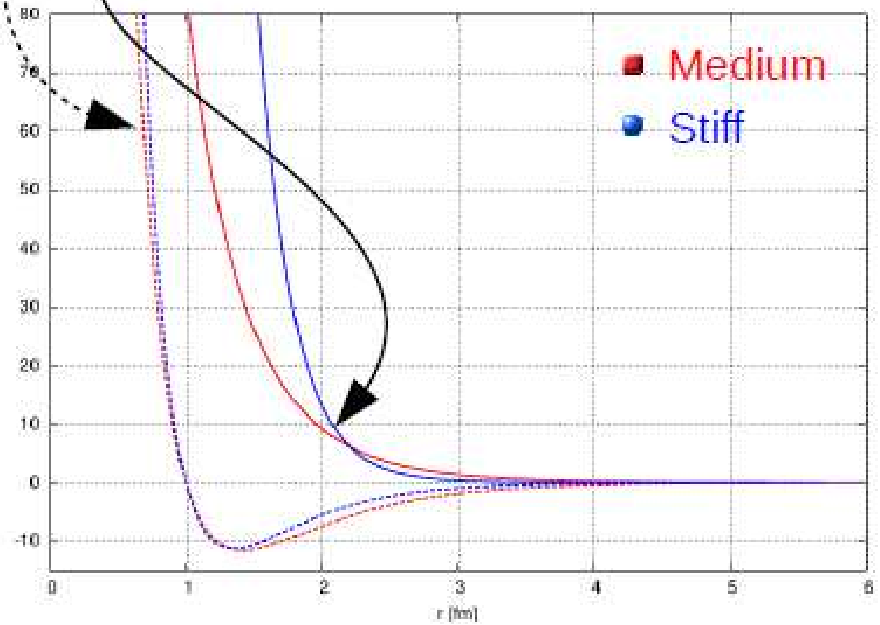
Materia Nuclear
Materia NS

El modelo nuclear CMD
y
los núcleos finitos

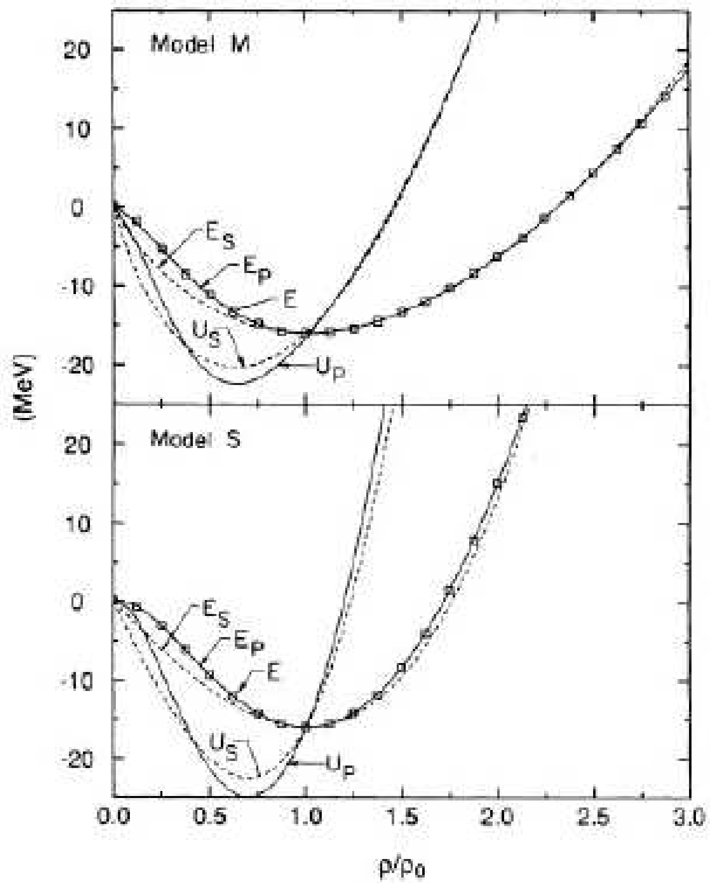
Modelo CMD

$$V_{np}(r)=V_r\left(\frac{e^{-\mu_r r}}{r}\right)-V_a\left(\frac{e^{-\mu_a r}}{r}\right)-C_{np}$$

$$V_{nn}(r)=V_{pp}(r)=V_0\left(\frac{e^{-\mu_0 r}}{r}\right)-C_{nn}$$

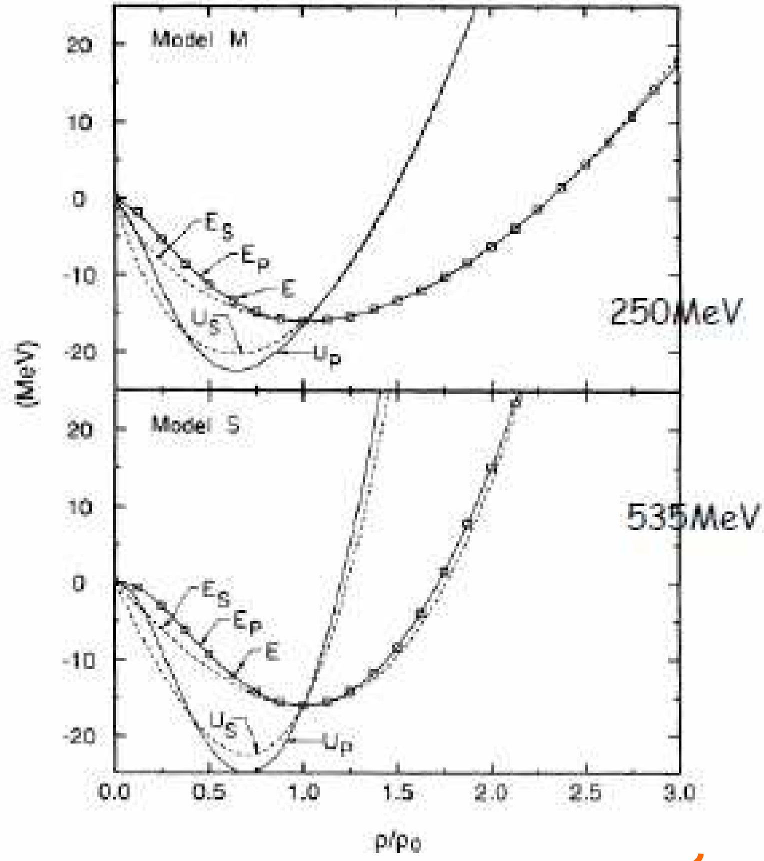


$$E(T,\rho,\delta=0)$$



- *Simulaciones de Dinámica Molecular Clásica*
- *Mecánica Estadística de sistemas 'raros'*
- *Término de Simetría de la EOS Nuclear*

Modelo CMD



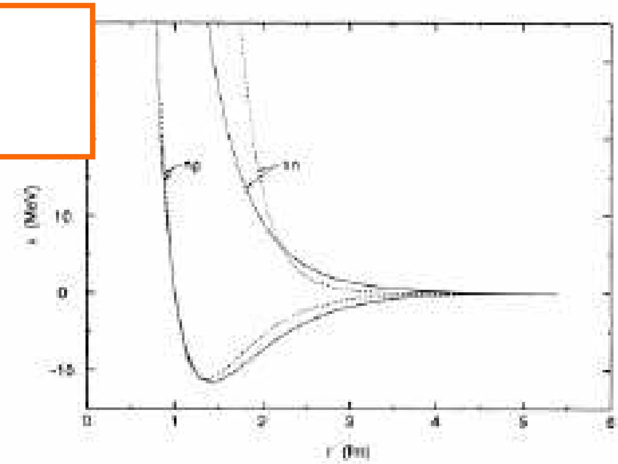


FIG. 1. The interparticle potentials v_{nn} and v_{np} for the *M* (solid) and *S* (dashed) models.

TABLE II. Energies of nuclei (MeV/nucleon) for the *M* and *S* models compared to experimental binding energies.

A	*Z*	E_M	E_S	E_{exp}
2	1	−5.76	−5.67	−1.11
3	1	−7.14	−7.26	−2.83
4	2	−7.91	−7.05	−7.07
5	2	−7.47	−6.22	−5.47
16	8	−10.39	−10.49	−7.98
40	20	−10.44	−10.60	−8.55
90	40	−9.93	−10.25	−8.71
139	57	−9.12	−9.58	−8.38
197	79	−8.38	−8.84	−7.92

Publicacion original

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Accuracy of the Vlasov-Nordheim approximation in the classical limit

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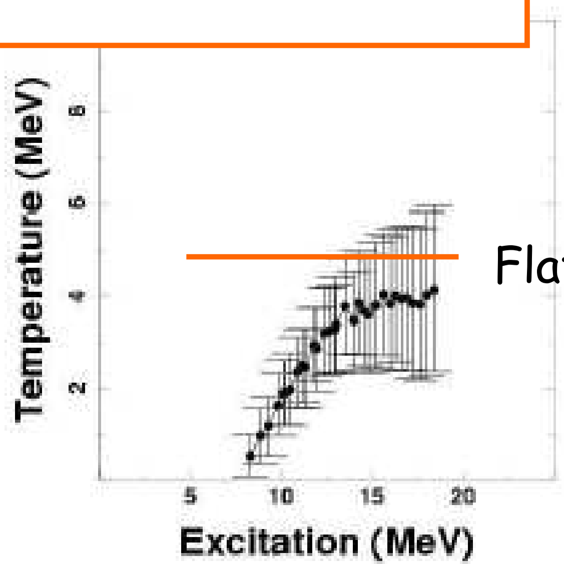
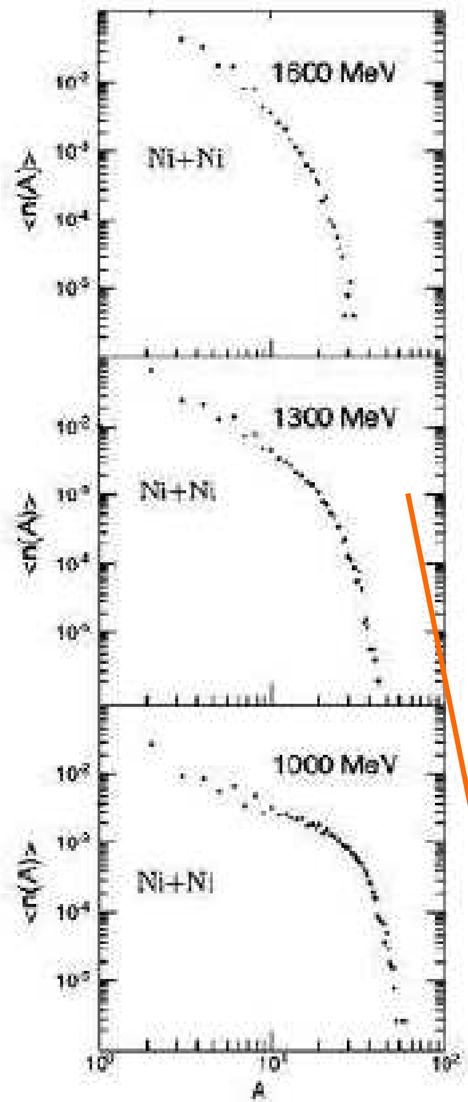
(Received 1 March 1990)

Modelo CMD

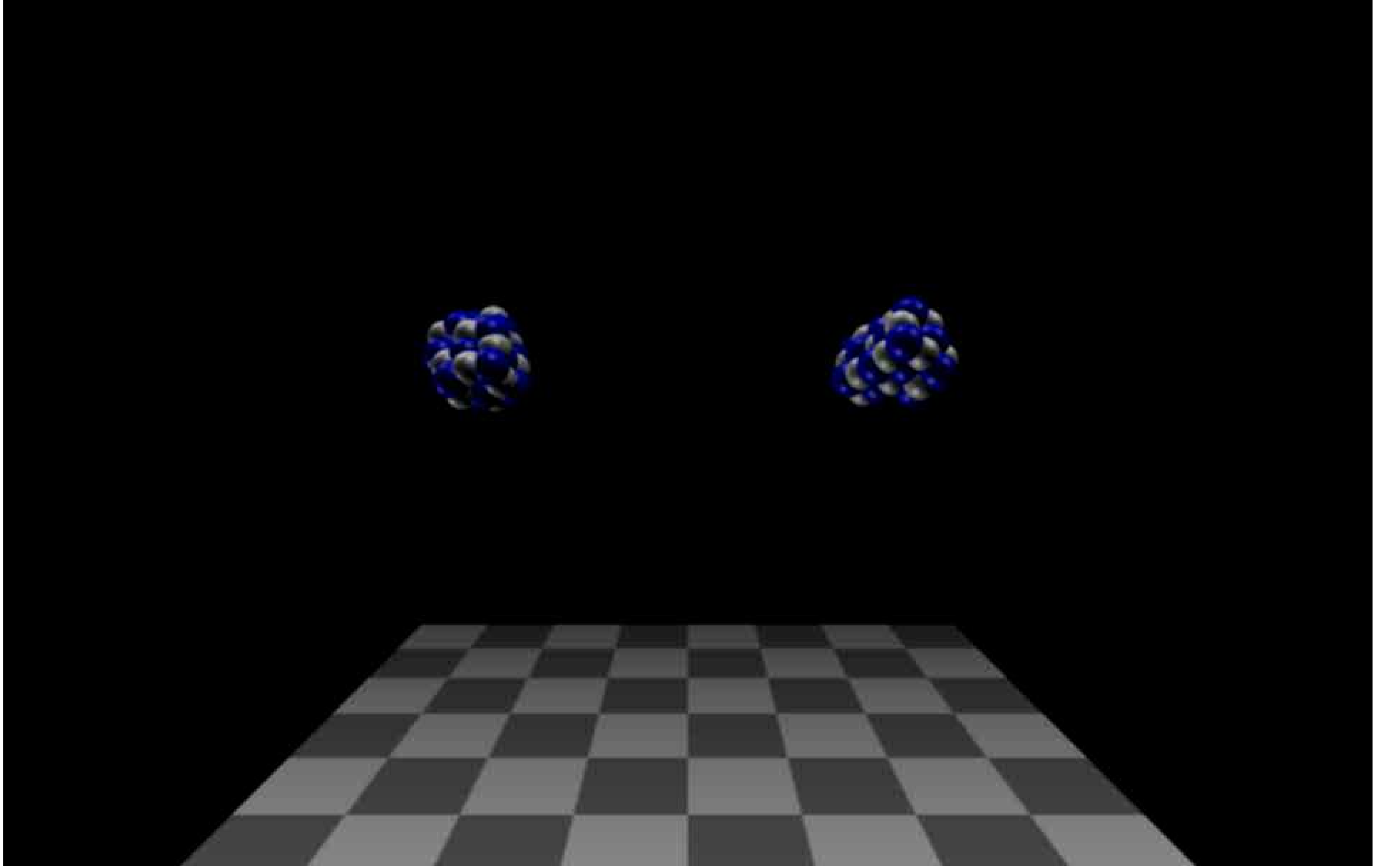
Resolver las ecuaciones de movimiento (symplectic)
Reconocer Clusters
(MST, MSTE, ECRA)
Comportamiento Critico
Curvas Calóricas
Calor especifico negativo
Isoscaling
, etc



Flat CC



Modelo CMD



Reconocimiento de Fragmentos

MST_algorithm

Given a set of particles i,j,k,..., clusters are defined such that :

$$i \in C \Leftrightarrow \exists j \in C / (r_i - r_j) < r_{clust}$$

With r_{clust} the clusterization radius

With periodic boundary conditions

MSTE algorithm

In this case clusters are defined in the following way:

$$i \in C \Leftrightarrow \exists j \in C / (\frac{p_{ij}^2}{4\mu} - v_{ij}) < 0$$

With μ the reduced mass and p_{ij} the relative momentum

Reconocimiento de Fragmentos

Early Cluster Formation Model

Given a set of particles (i,j,k..) clusters are defined as those partitions C_i that minimize the following expression:

$$E = \sum_{C_i} \left[\left(\sum_{i \in C_i} \frac{p_{ij}^2}{2m} \right)_{c.m.C_i} + \sum_{i<j \in C_i} v(r_{ij}) \right]$$

This is a highly self consistent problem that has been solved by devising a method in the spirit of simulated annealing (ECRA).
For such a problem a Markov chain in the space of partitions is constructed

C.O.Dorso & J.Randrup Phys.Lett. B 301 (1993) 328

Modelo CMD

Table 1. Comparison of coefficients obtained for different models.

Coefficient	Stiff	Medium	Experimental
C_v	16.1	17.37	15.75
C_s	−11.73	−14.38	−17.8
C_c	−0.197	−0.226	−0.177
C_{sym}	−34.07	−25.08	−23.7

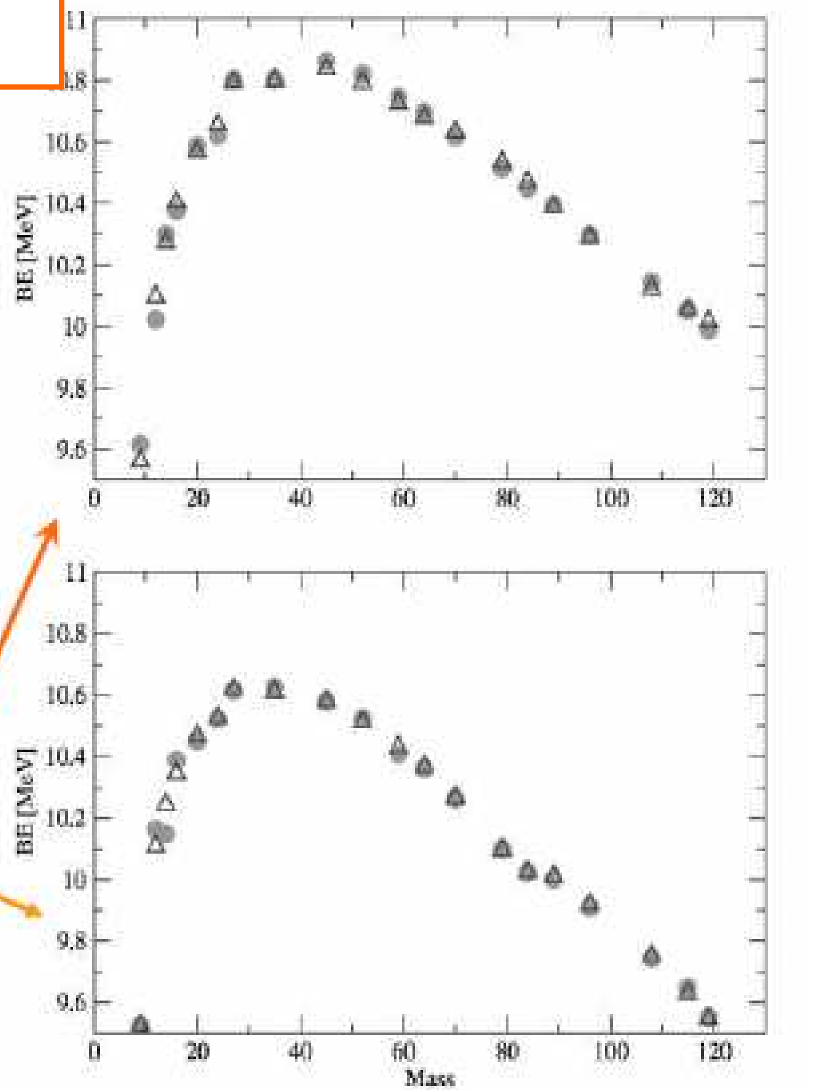
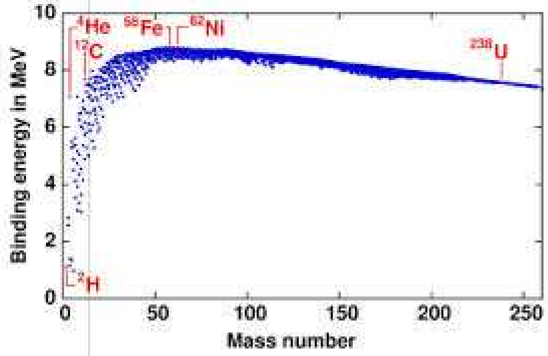


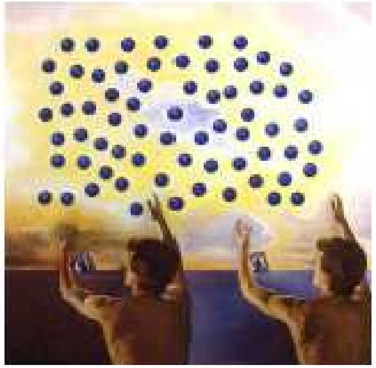
Figure 1. Energies obtained with the mass formula fit (triangles) for the stiff and m
(top and bottom panels, respectively) together with the corresponding ground st
using frictional molecular dynamics (circles).



$$E_B = C_v A - C_s A^{2/3} - C_{sym}\frac{(A-2Z)^2}{A^{1/3}} - C_C\frac{Z(Z-1)}{A^{1/3}} + \delta(A,Z)$$

CMD and isoscaling

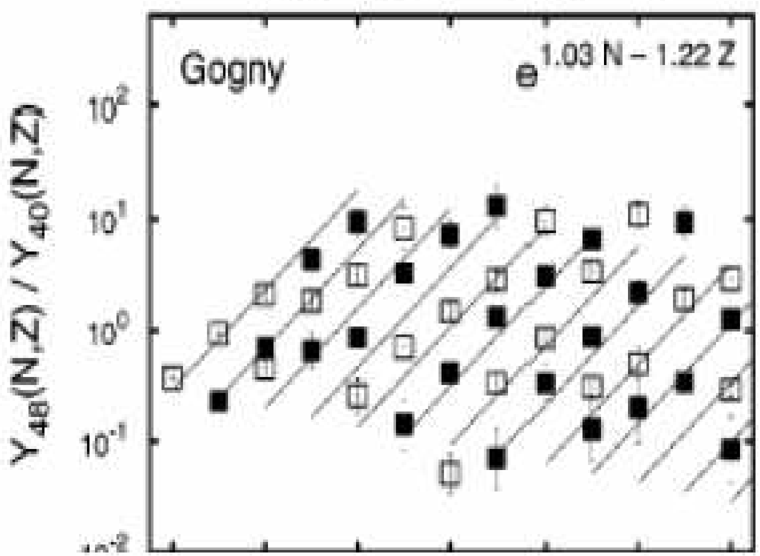
Comparison to other models



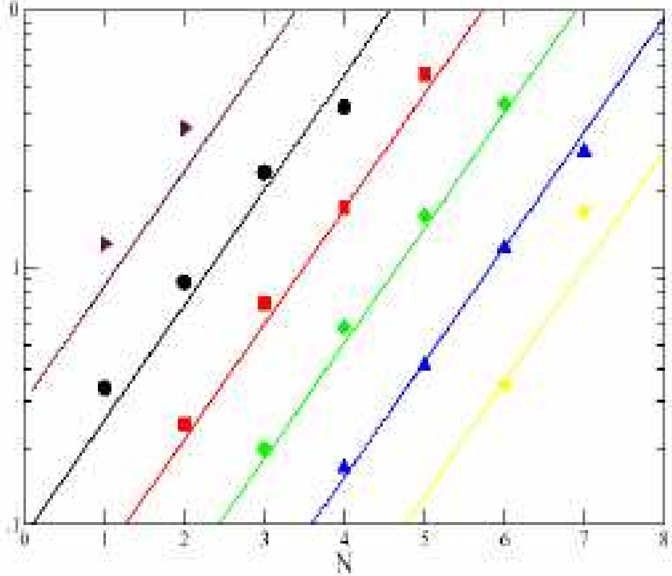
Compare ^{40}Ca - ^{48}Ca at 35 MeV/A

AMD-V: α=1.03, β=1.22 CMD: α=**1.07**, β=1.22

AMD



Classical molecular dynamics



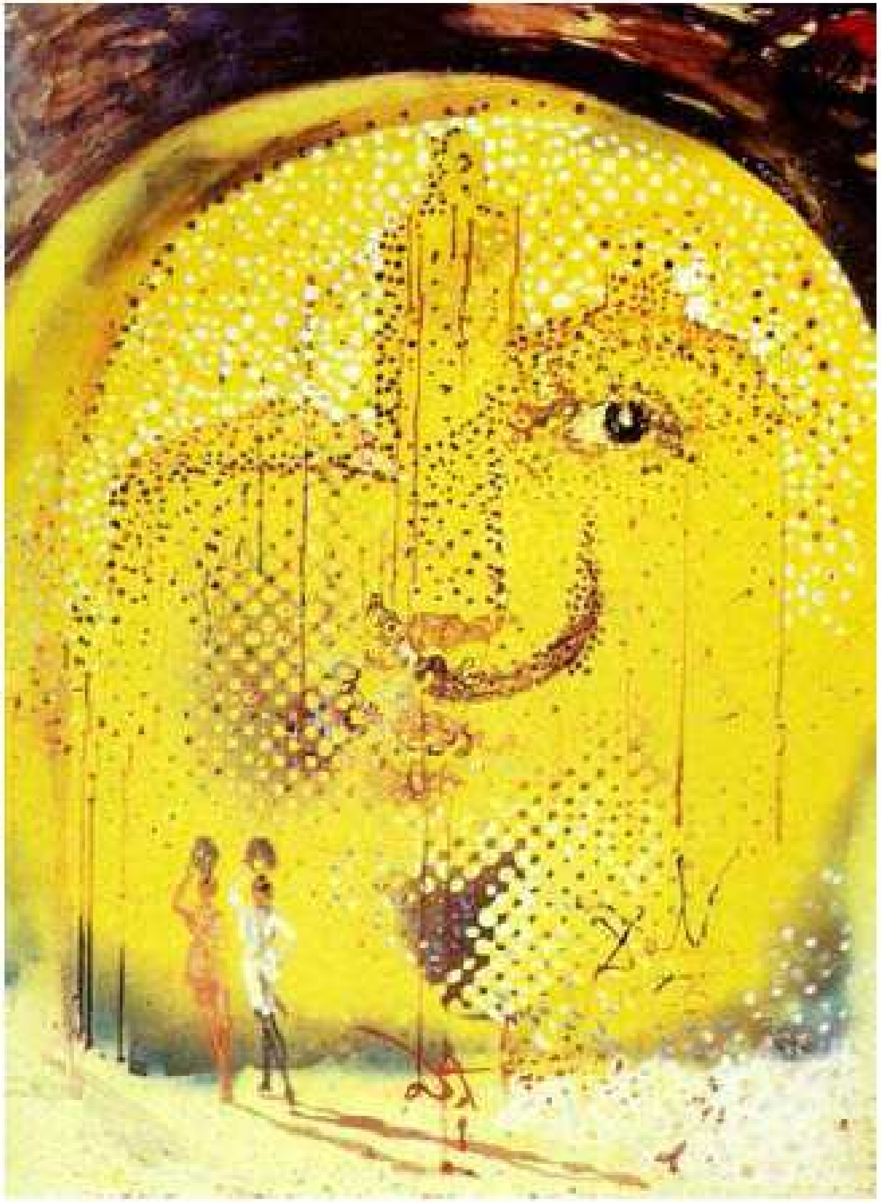
Molecular dynamics produces isoscaling

- Isoscaling is not quantal

De los nucleos

a las

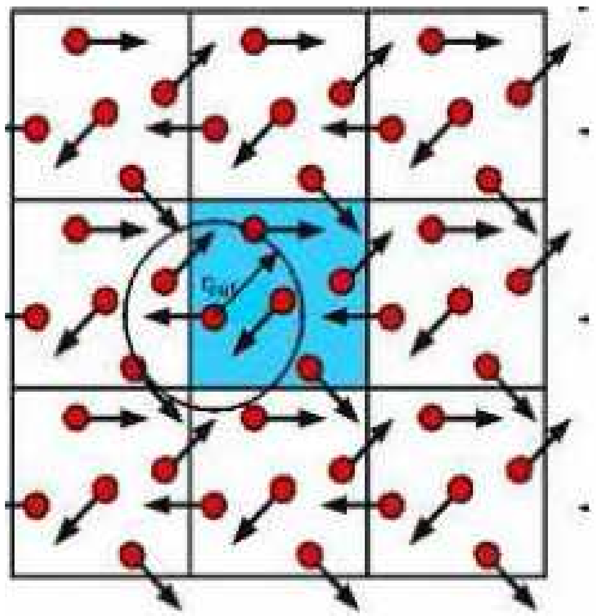
Neutron Stars

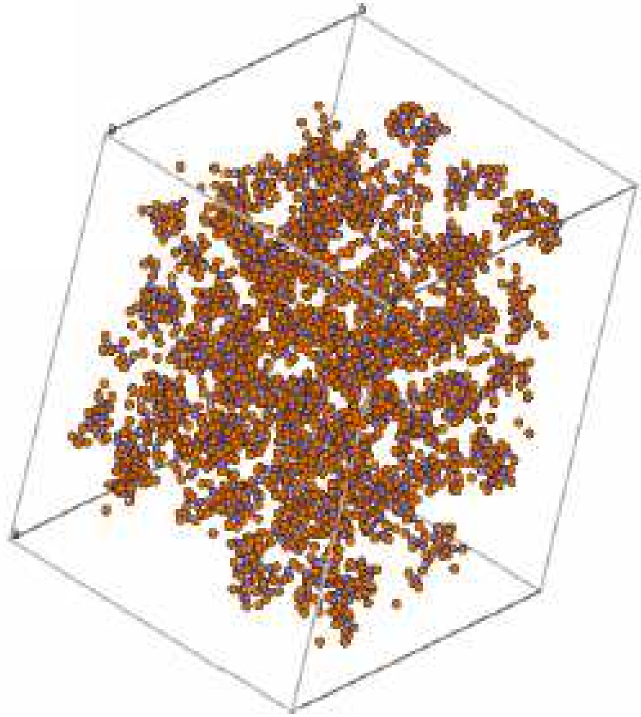


Nuestro trabajo : usar dinámica molecular con CMD para estudiar Estrellas de Neutrones

Resolver las ecuaciones dinámicas como antes
Pero ……

Usar condiciones periódicas de contorno





Para Coulomb usamos Aprox. Thomas Fermi
o
Debye

$$V_C(r) \approx \frac{e^2}{r}$$

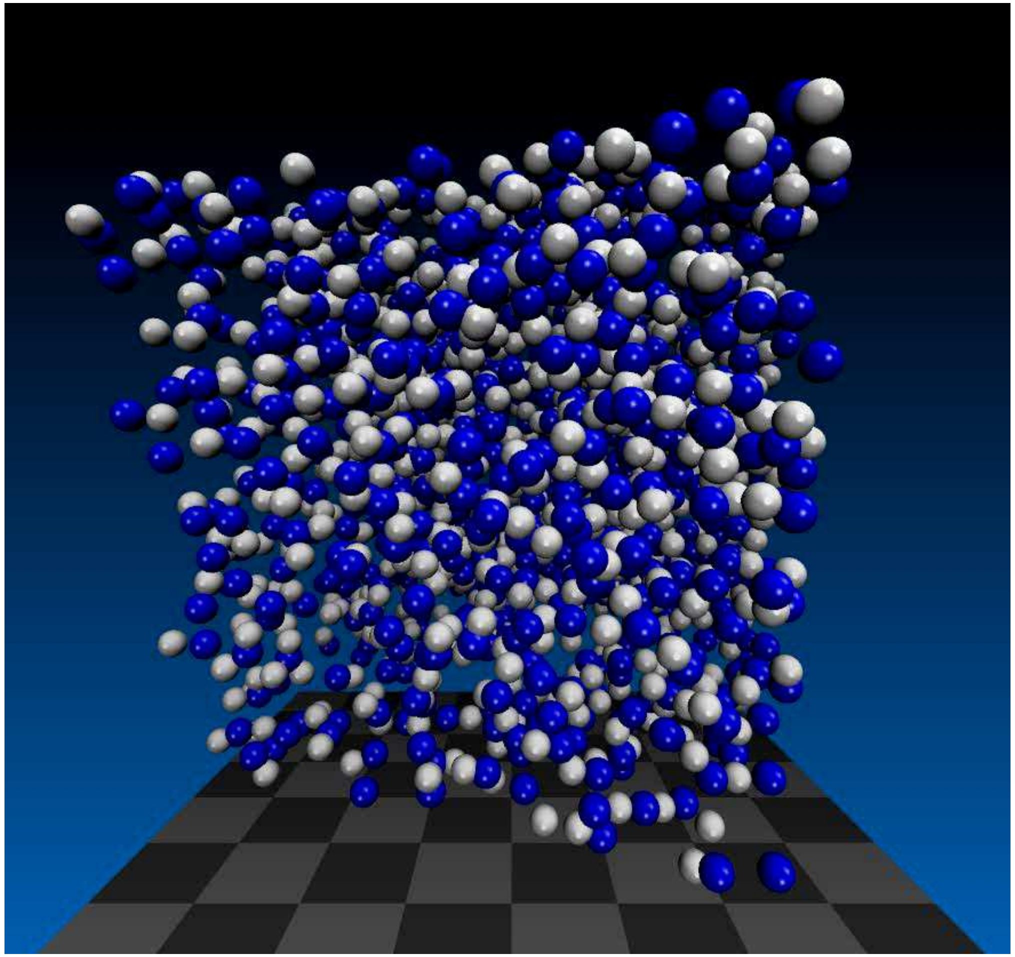
$$V_C^{TF}(r) \approx \frac{e^2}{r} \exp(-r/\lambda)$$

(sistema neutro)

$$\lambda_e = \pi^{1/2}/[2e(3\pi^2 n_e)^{1/3}]$$

5000 Partículas en celda elemental, T si going down.....

0.1MeV<T<3MeV



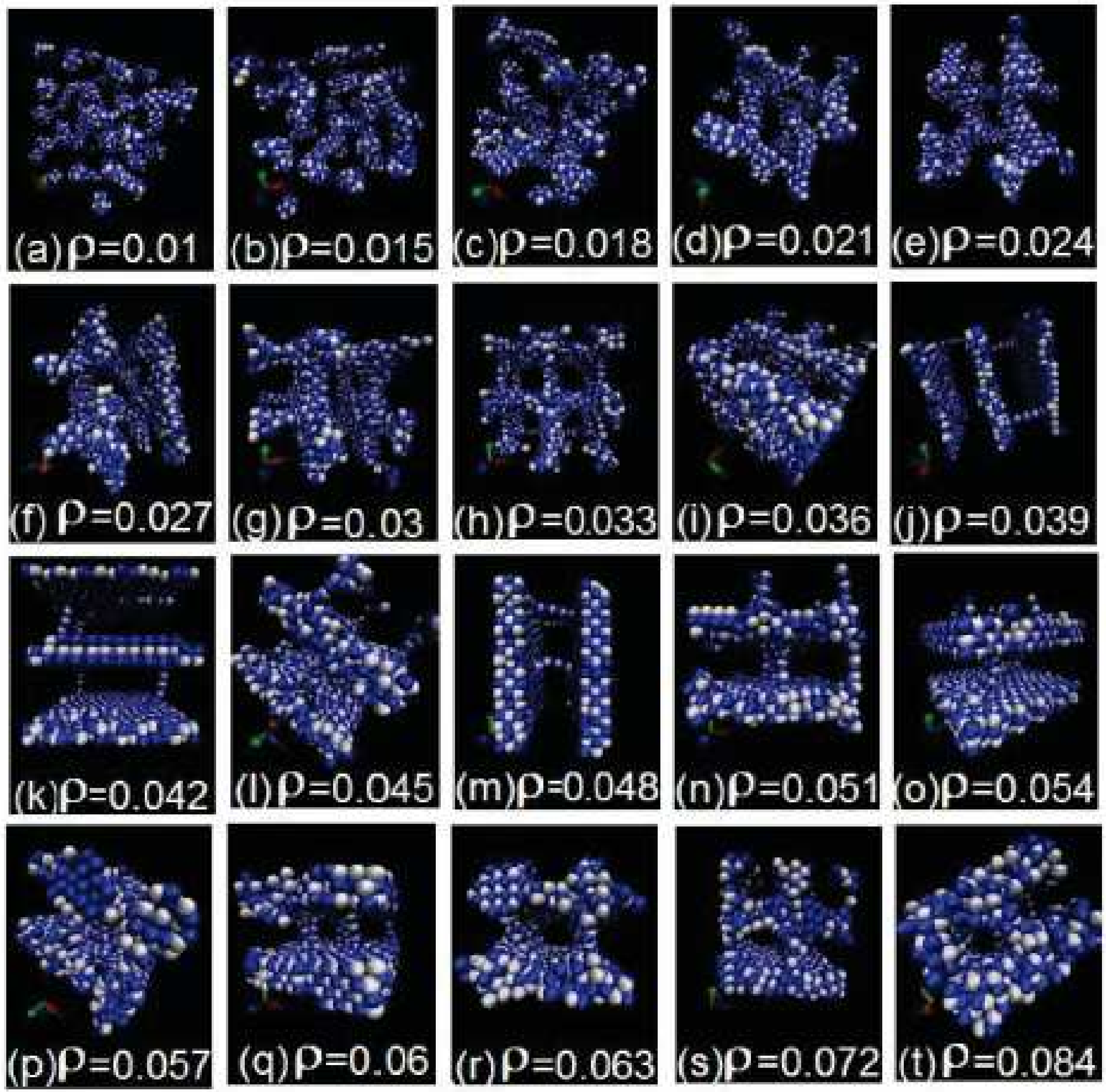
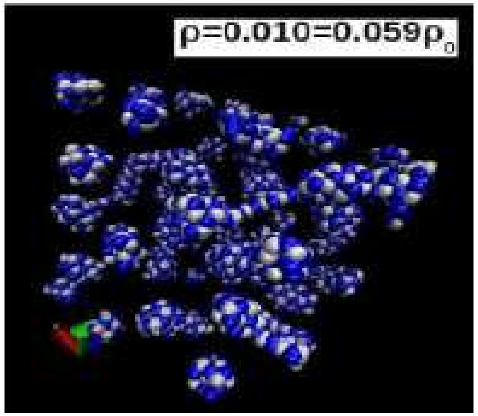


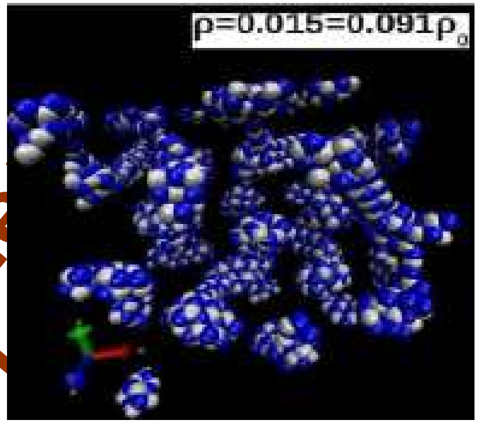
FIG. 1. (Color online) Smörgåsboard of pasta shapes corresponding to the densities shown and to $x = 0.5$ and $T = 0.1$ MeV.

Pasta !

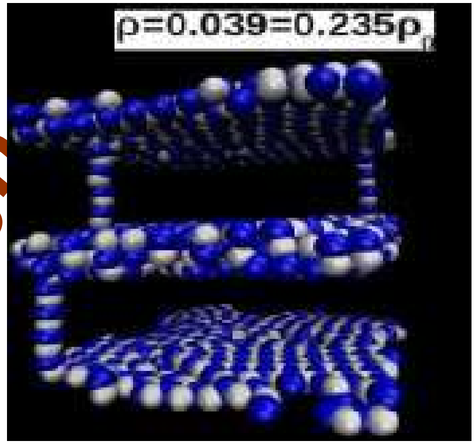
Gnocchi



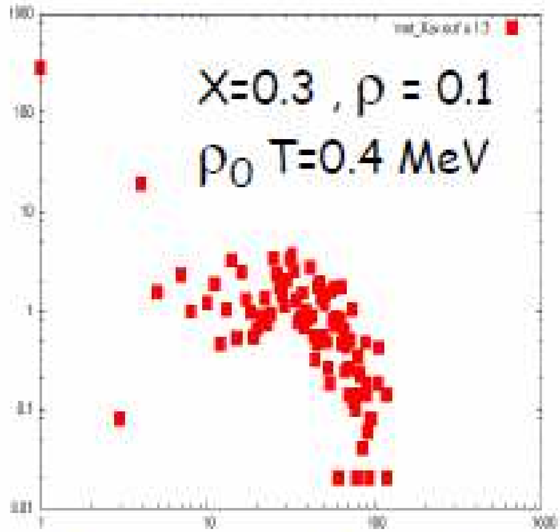
Spaghe



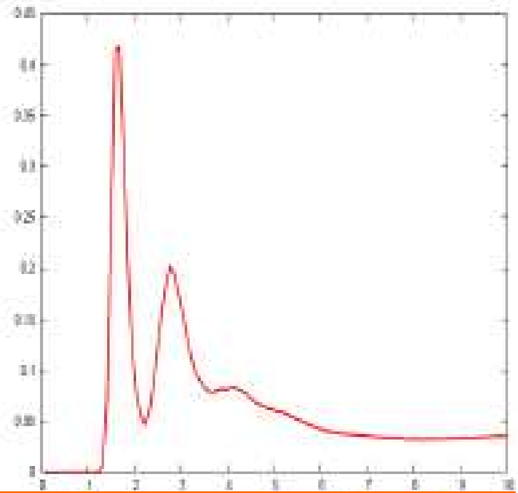
Lasagn



Study:

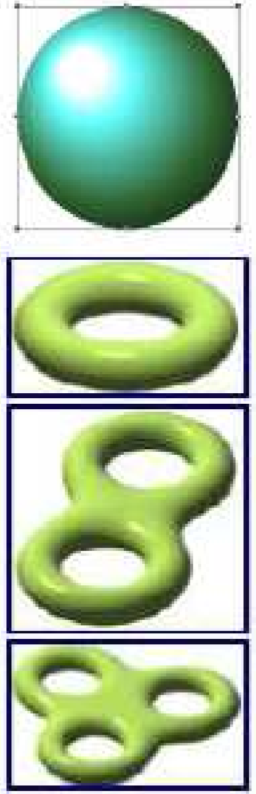


fragmentos y distribución de masas



función de correlación de pares

Topology (why?)



Euler

1

0

-1

-2

Funcionales de Minkowski

. . .

Results: Nuclear Pasta!

Fragment Size Distribution (MST)

X=0.3

$\rho=0.1\rho_0$

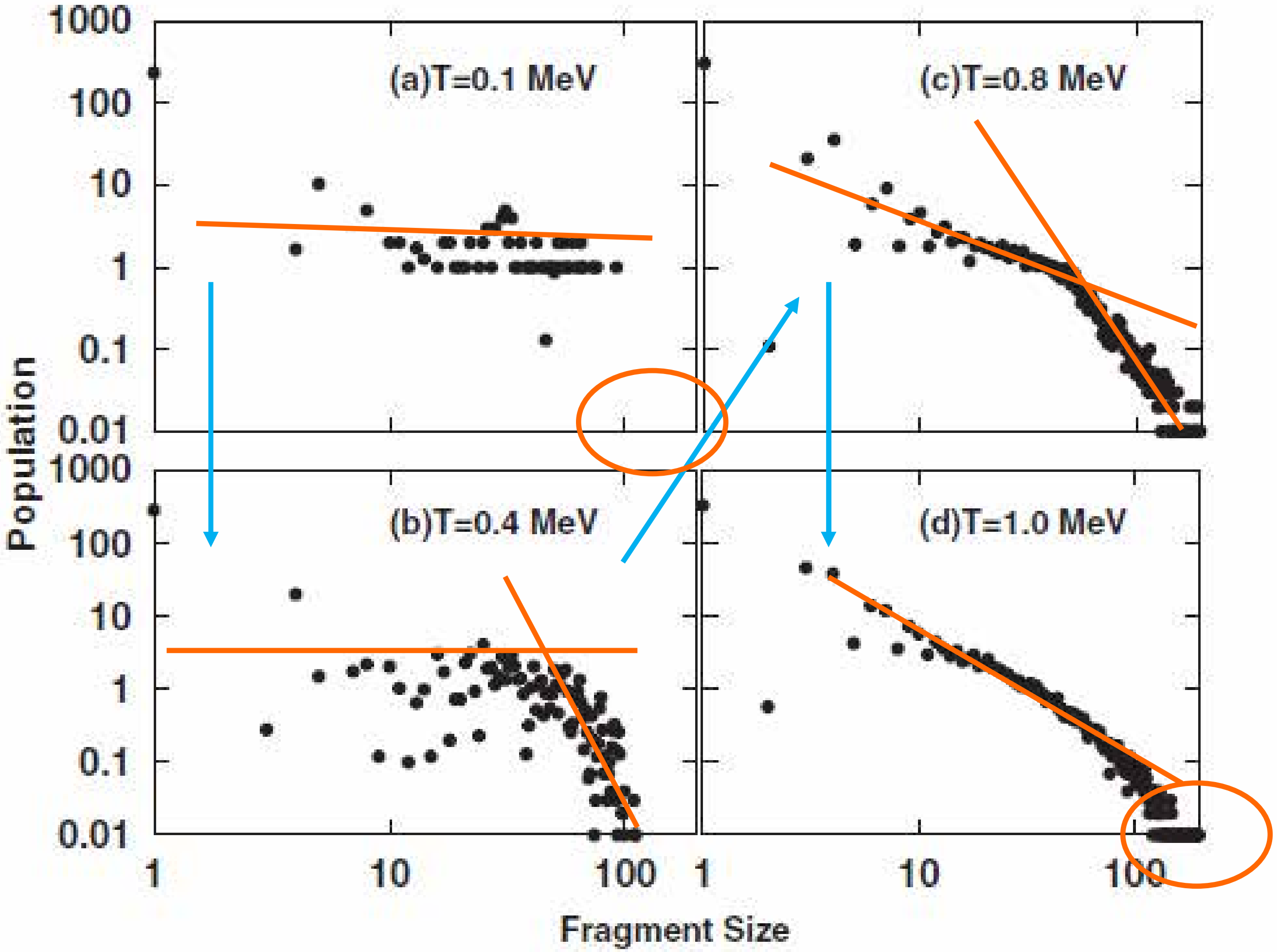


FIG. 2. Temperature evolution of the fragment size distribution obtained from 200 configurations with $x = 0.3$ and $\rho \approx \rho_0/10$.

Caracteristica de Euler

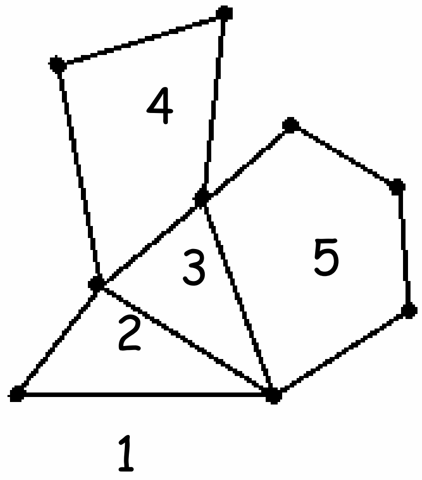
Tomar una hoja de papel

Dibujar puntos. Conectar punto con líneas de modo que : las líneas
no pueden cortarse, todo punto queda conectado a todo otro punto

Cuente el numero d puntos (D), cuente las regiones determinadas por las Líneas (R) cuente las líneas (L);

D=9, L=12, R=5

χ=D-L+R=2.... siempre



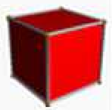
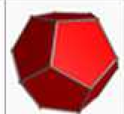
In 3D Convex Polyhedra

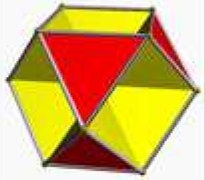
The **Euler characteristic** $\chi = V - E + F = 2$

V numbers of vertices (corners)

E numbers of edges

F numbers of faces

Name	Image	Vertices V	Edges E	Faces F	Euler characteristic: $V - E + F$
Tetrahedron		4	6	4	2
Hexahedron or cube		8	12	6	2
Octahedron		6	12	8	2
Dodecahedron		20	30	12	2
Icosahedron		12	30	20	2

Name	Image	Vertices V	Edges E	Faces F	Euler characteristic: $V - E + F$
Tetrahemihexahedron		6	12	7	1
Octahemioctahedron		12	24	12	0
Cubohemioctahedron		12	24	10	−2
Great icosahedron		12	30	20	2

In 3D non-convex polyhedra χ can have any value, and thus can be used to characterize the shape

Lo aplicamos a "Pastas"

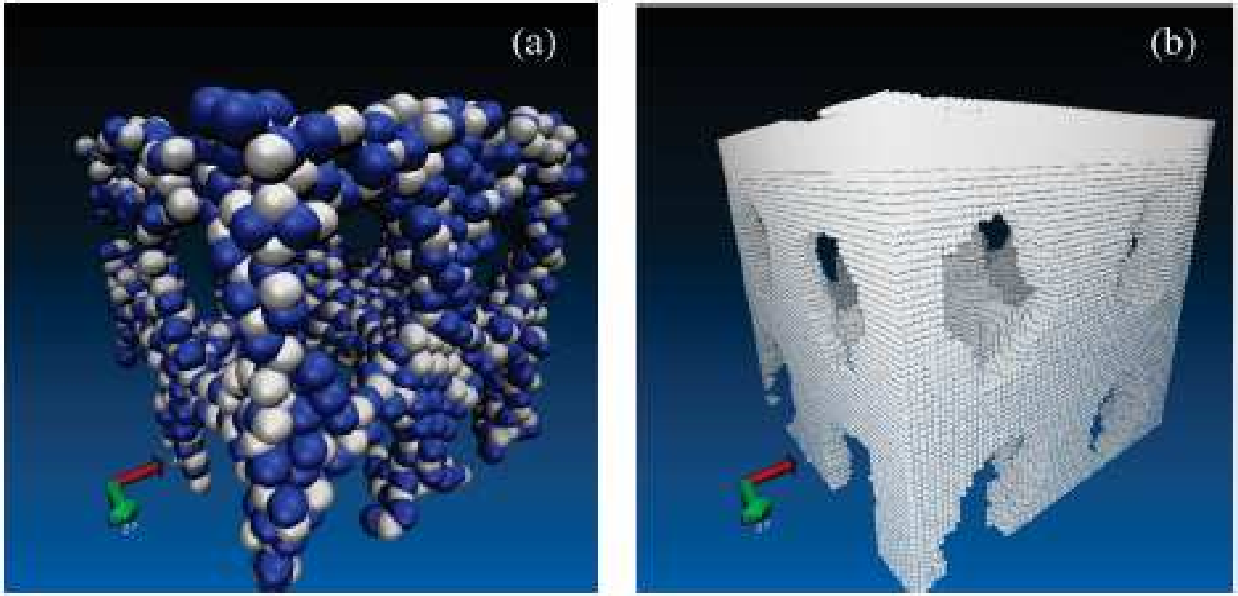
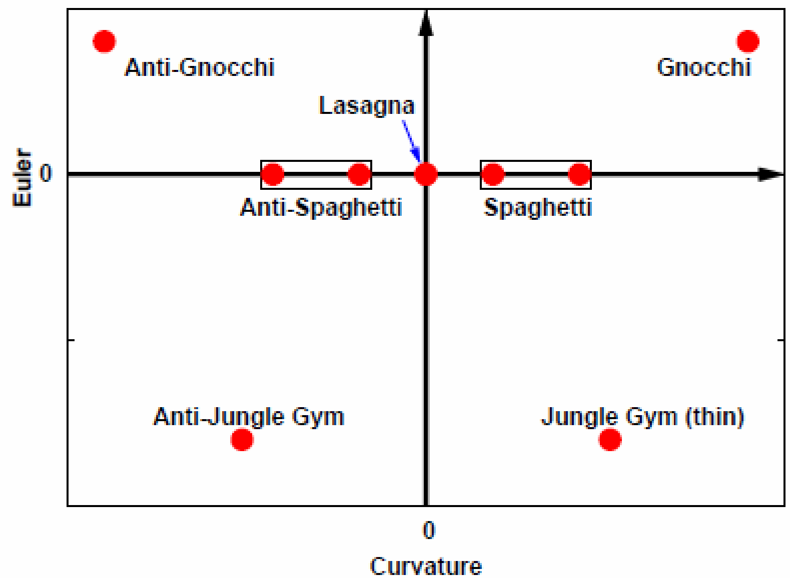


FIG. 8. (Color online) Sample transformation of a nuclear structure to a corresponding polyhedron. The structure corresponds to a case with $x = 0.5$, $\rho = 0.33$ fm^{-3}, and $T = 0.1$ MeV.

TABLE I: Classification Curvature - Euler

	Curvature < 0	Curvature ∼ 0	Curvature > 0
Euler > 0	Anti-Gnocchi		Gnocchi
Euler ∼ 0	Anti-Spaghetti	Lasagna	Spaghetti
Euler < 0	Anti-Jungle Gym		Jungle Gym



$$V = n_c, \quad A = -6n_c + 2n_f,$$
$$2B = 3n_c - 2n_f + n_c, \quad \chi = -n_c + n_f - n_e + n_v,$$

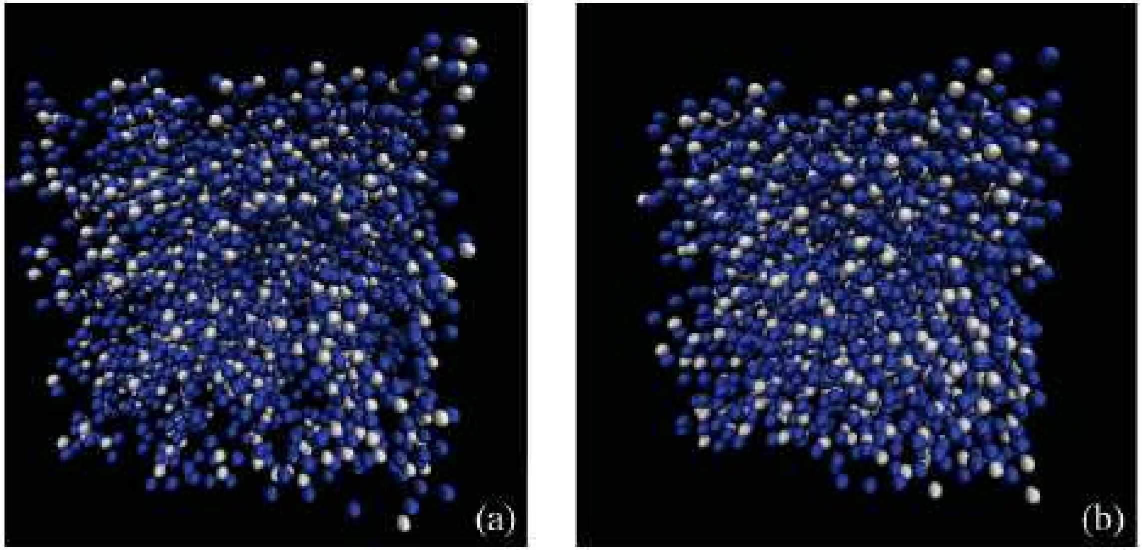
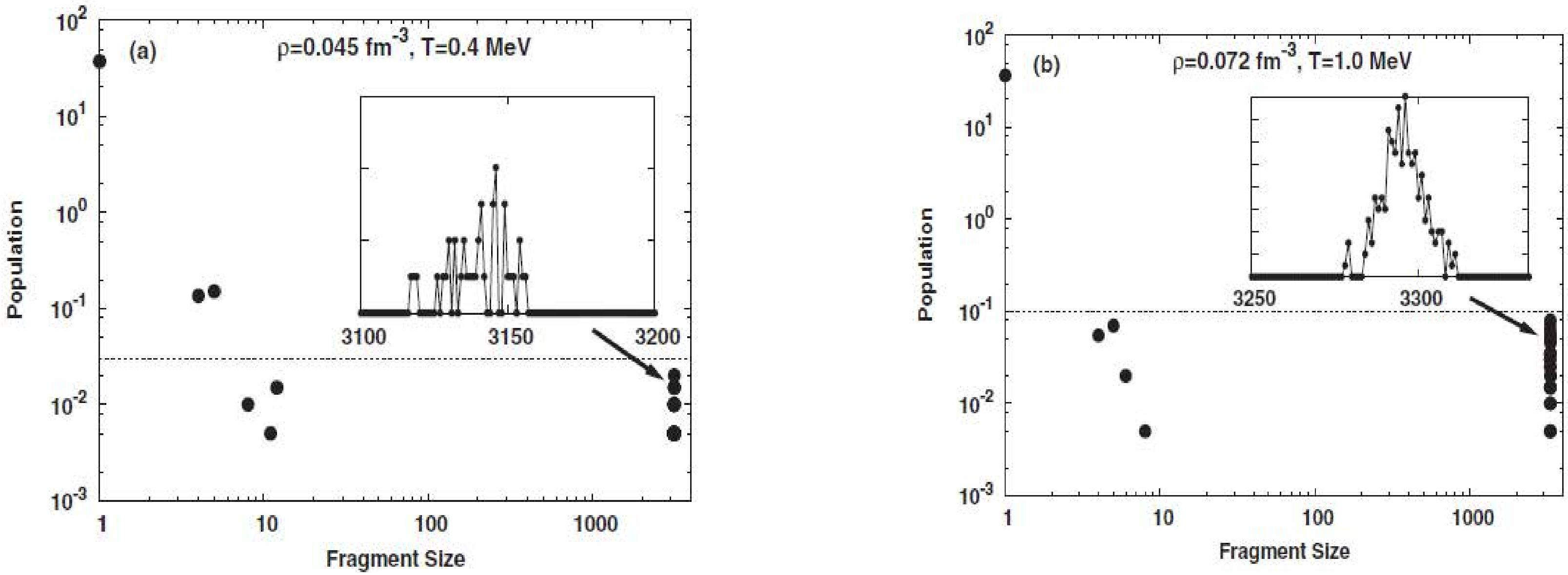
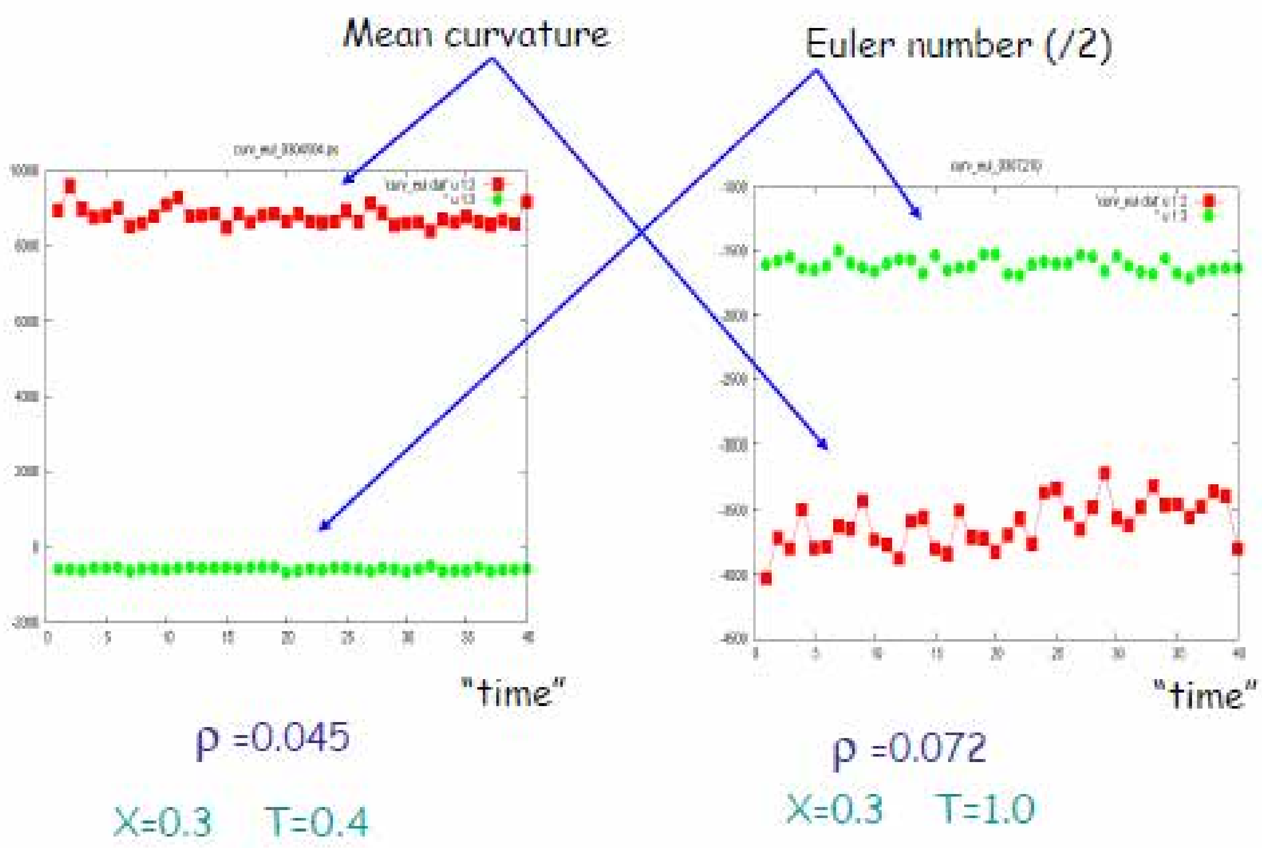


FIG. 9. (Color online) Spatial configurations formed under $T = 0.4$ MeV and $\rho = 0.045$ fm^{-3} (left) and $T = 1.0$ MeV and $\rho = 0.072$ fm^{-3} (right), both for $x = 0.3$.




Mean curvature
Euler number (/2)
"time"
"time"
ρ =0.045
X=0.3 T=0.4
ρ =0.072
X=0.3 T=1.0

The role of coulomb

We analyze the behavior of a system driven by:

$$V(r_{ij},\kappa_i,\kappa_j) = V_{Pandha}(r_{ij},\kappa_i,\kappa_j) + \alpha \cdot V_{Coul}(r_{ij},\kappa_i,\kappa_j)$$

with

$0 \le \alpha \le 1$

The role of coulomb

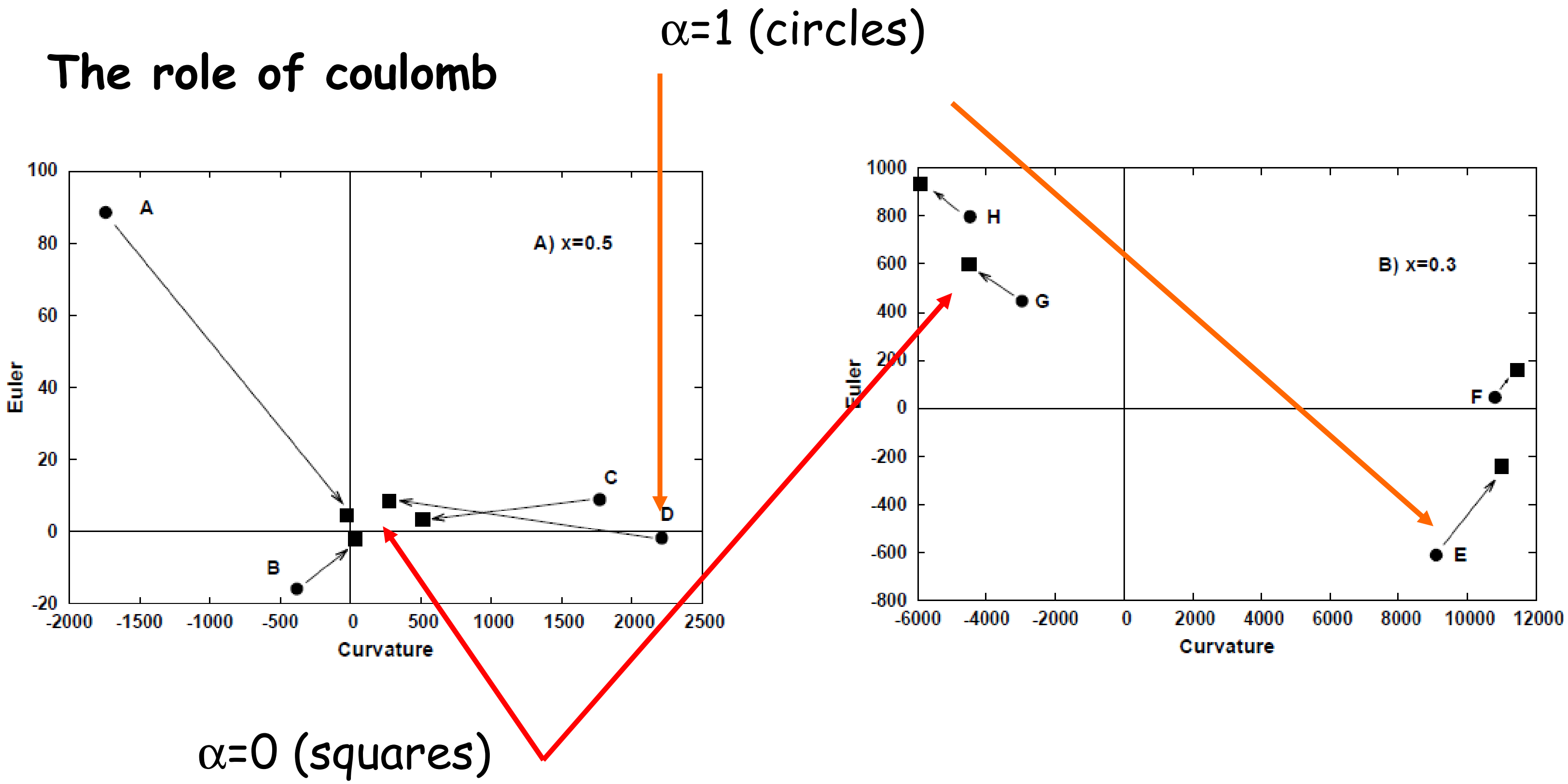


FIG. 7: Average values of the Curvature and Euler numbers of the structures listed in Table II; circles correspond to structures with Coulomb and squares to structures without Coulomb, arrows indicate the average displacement of the structures as α goes from 1 to 0.

TABLE II: Classification Curvature - Euler

	ρ	T	$\alpha = 1$		$\alpha = 0$	
	(fm^{-3})	(MeV)	Curvature	Euler	Curvature	Euler
A	0.072	1.0	-1740	89	-24	4.7
B	0.072	0.1	-382	-15.8	29.4	-1.9
C	0.015	0.1	1771	8.9	514	3.5
D	0.015	1.0	2212	-1.7	273	8.6
E	0.015	1.0	9090	-612	11011	-243
F	0.015	0.1	10804	454	11436	159
G	0.072	1.0	-2969	447	-4512	602
H	0.072	0.1	-4485	798	-5914	933

This suggests that there is pasta even without Coulomb!

Intermezzo : what is the role of Coulomb?

Illinois potential is rather complicated because :

$$V_{np}(r) = V_r\left[\exp(-\mu_r r)/r - \exp(-\mu_r r_c)/r_c\right] - V_a\left[\exp(-\mu_a r)/r - \exp(-\mu_a r_c)/r_c\right]$$

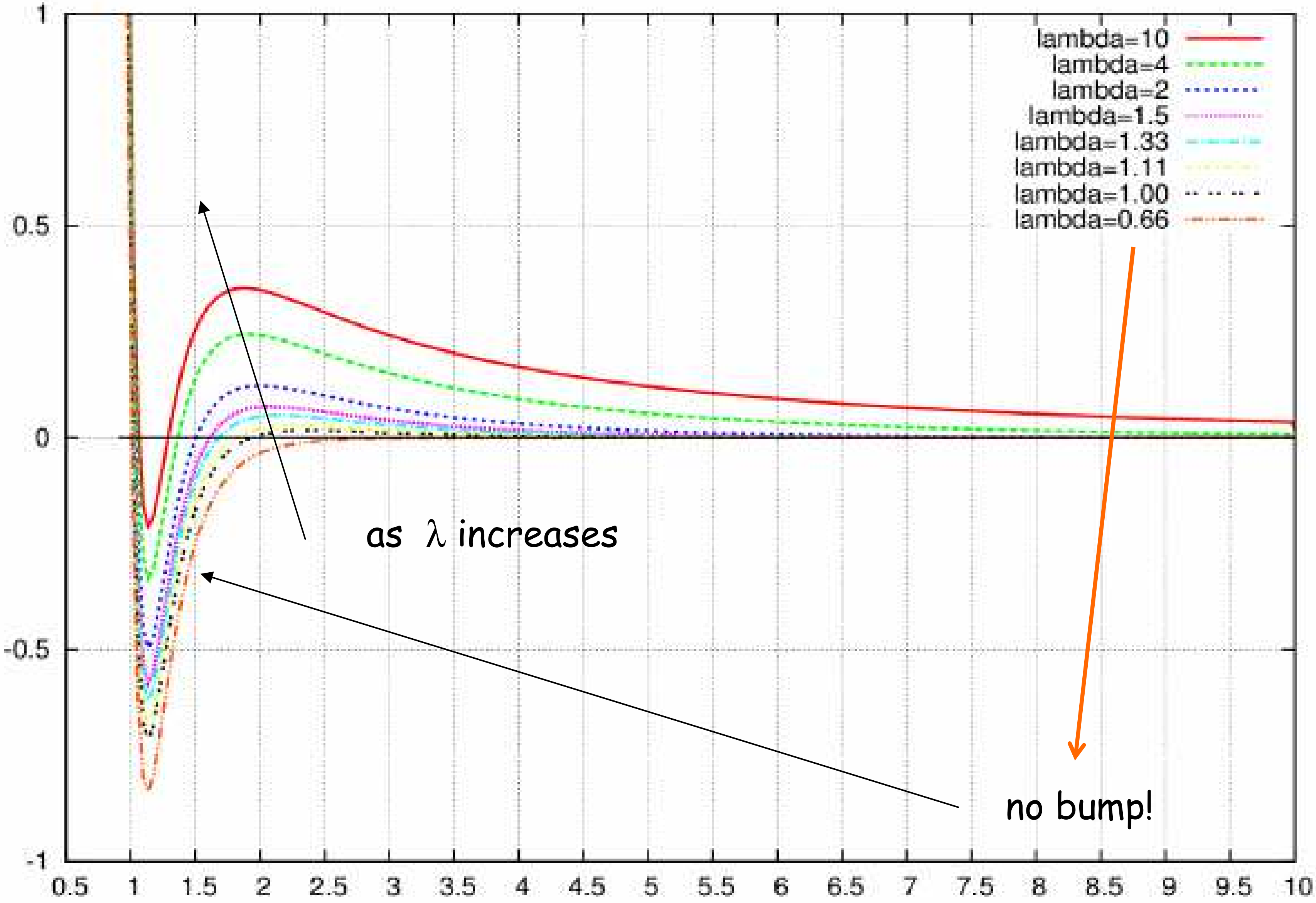
$$V_{nn}(r) = V_0\left[\exp(-\mu_0 r)/r - \exp(-\mu_0 r_c)/r_c\right]$$

$$V_{pp}(r) = V_0\left[\exp(-\mu_0 r)/r - \exp(-\mu_0 r_c)/r_c\right] + \exp\left(-\frac{r}{\lambda}\right)\cdot\left(\frac{v_c}{r}\right)$$

Lennard Jones + Coulomb

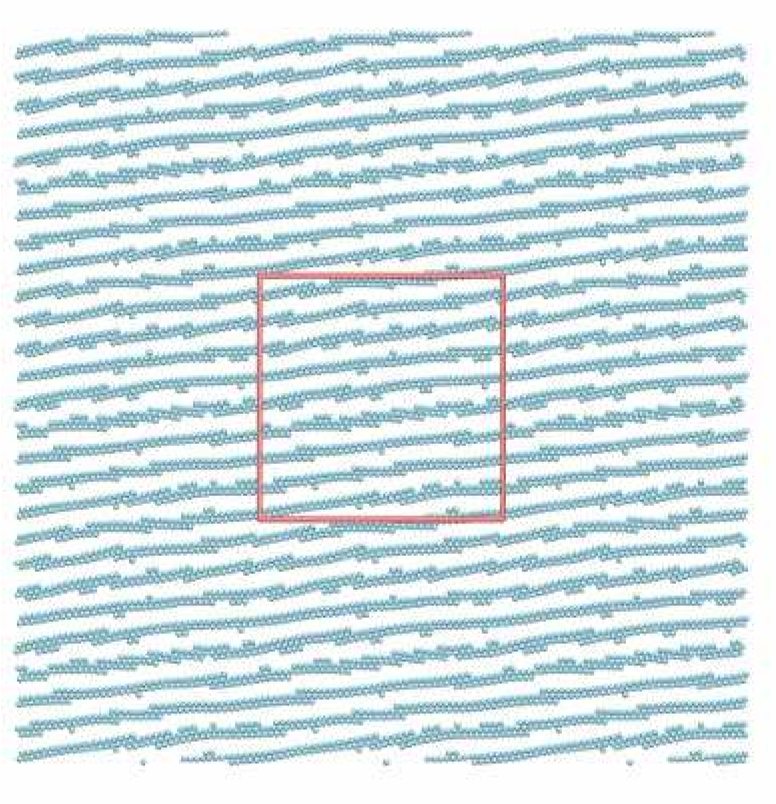
Lennard Jones +coulomb

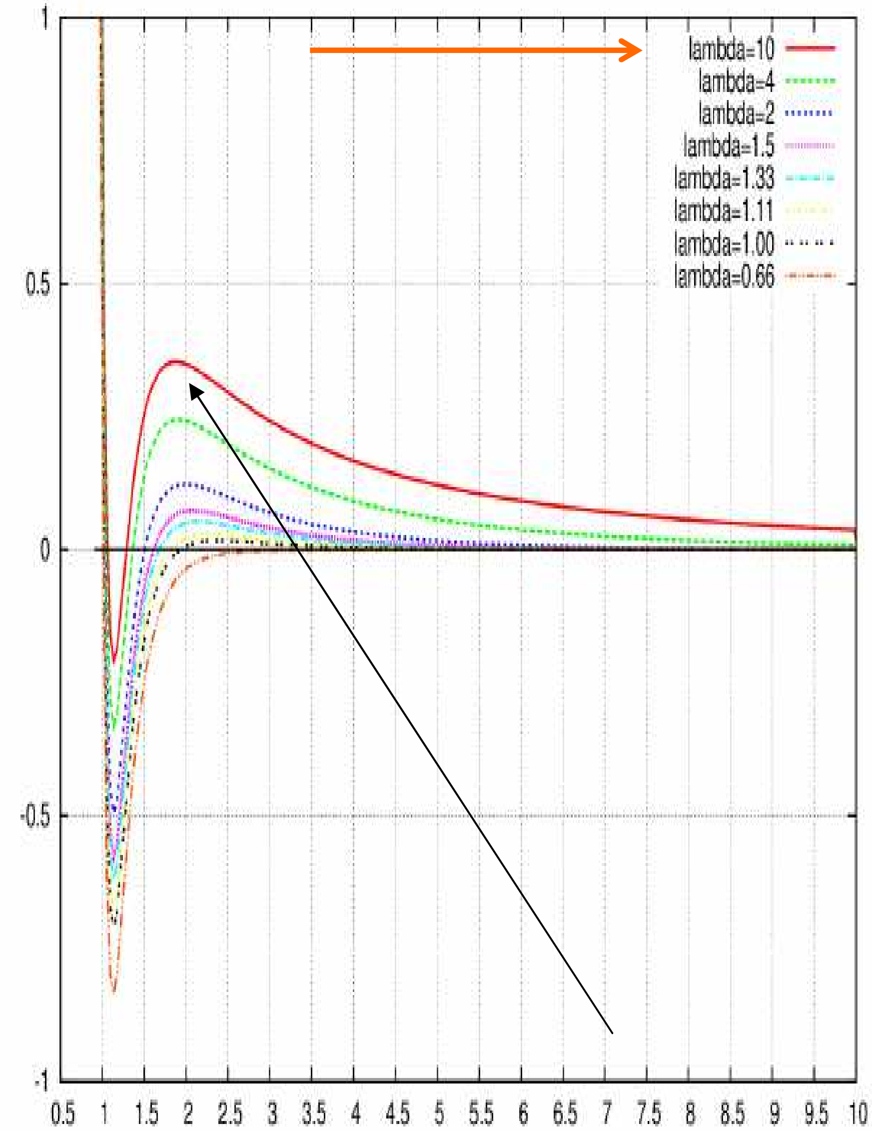
$$V(r) = V_0\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] + \exp\left(-\frac{r}{\lambda}\right)\cdot\left(\frac{v_c}{r}\right)$$

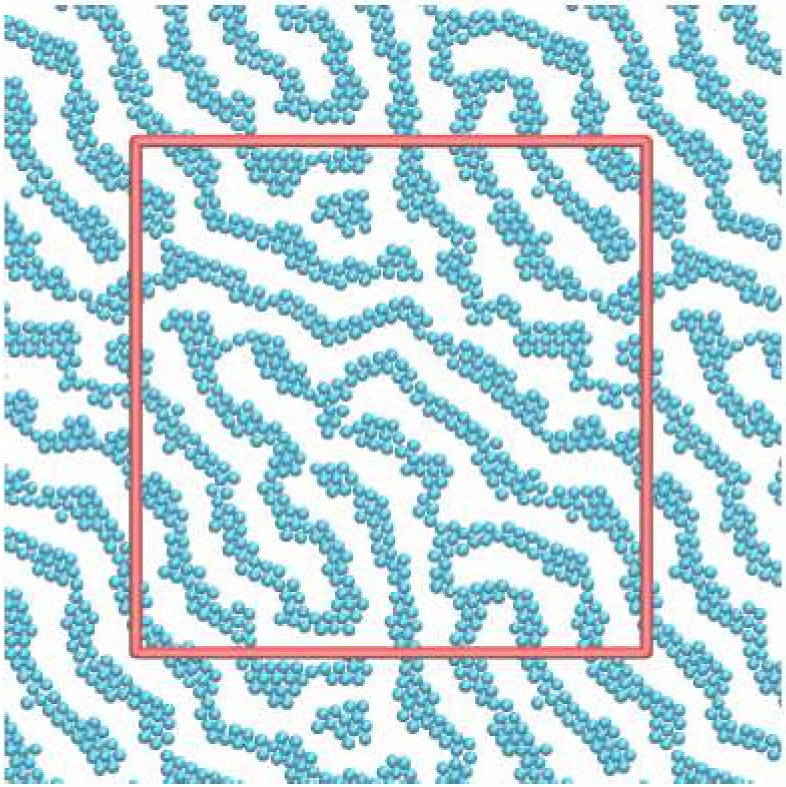


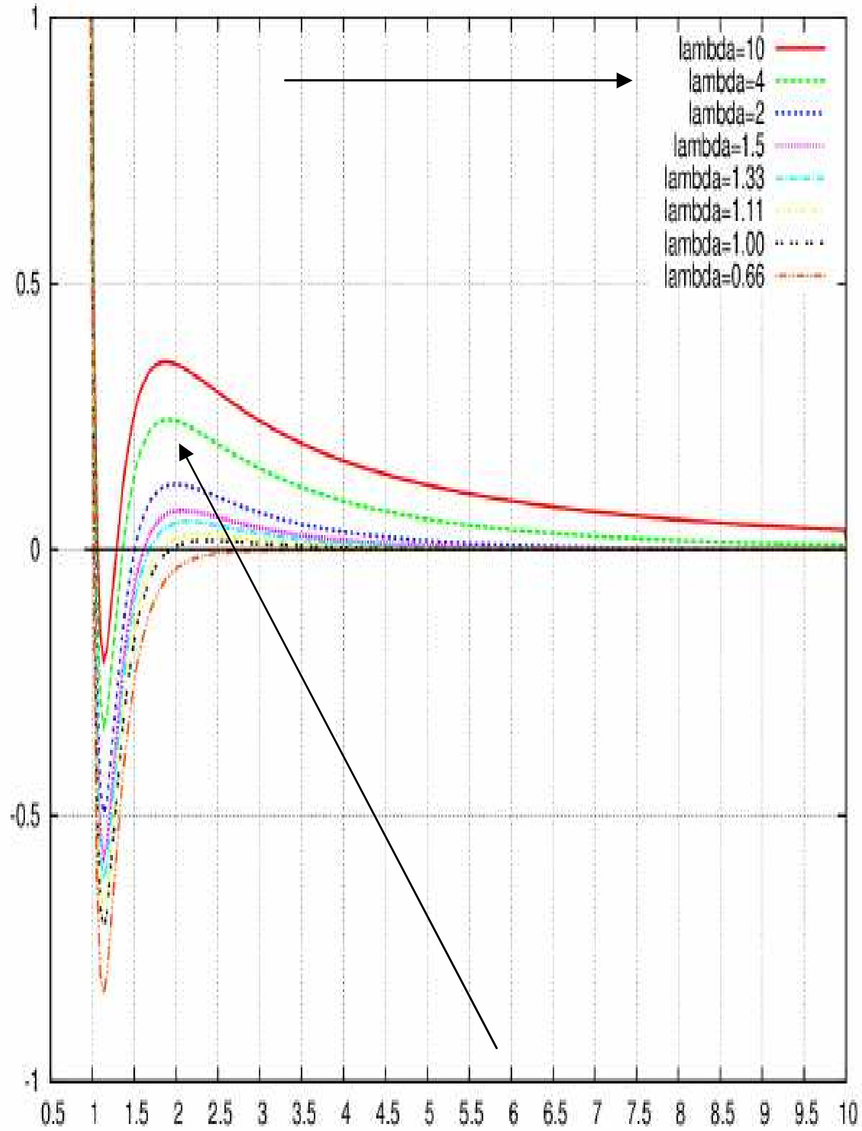
The role of coulomb

N=800





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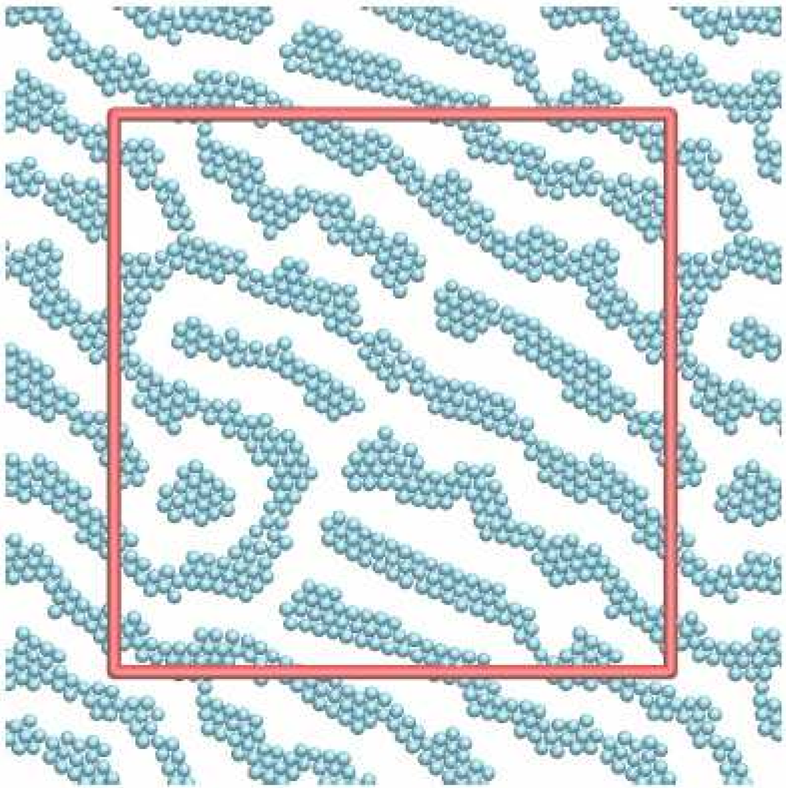

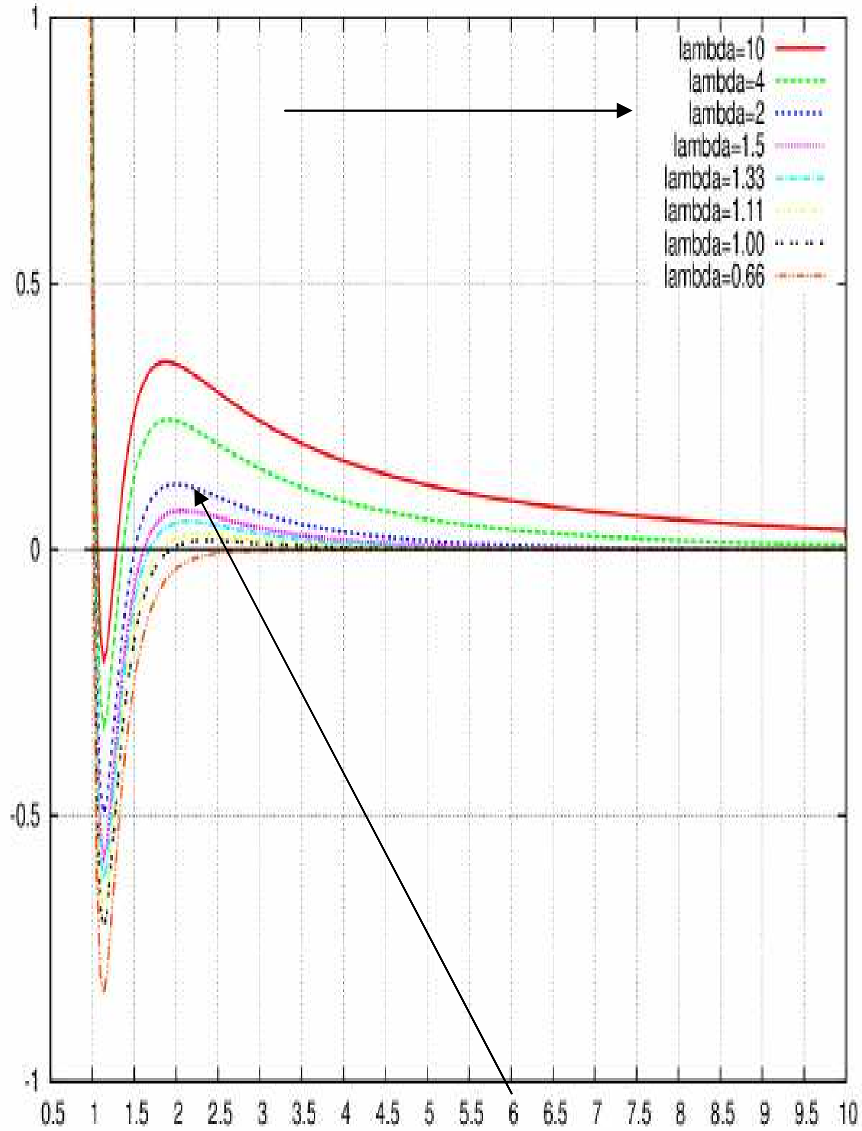

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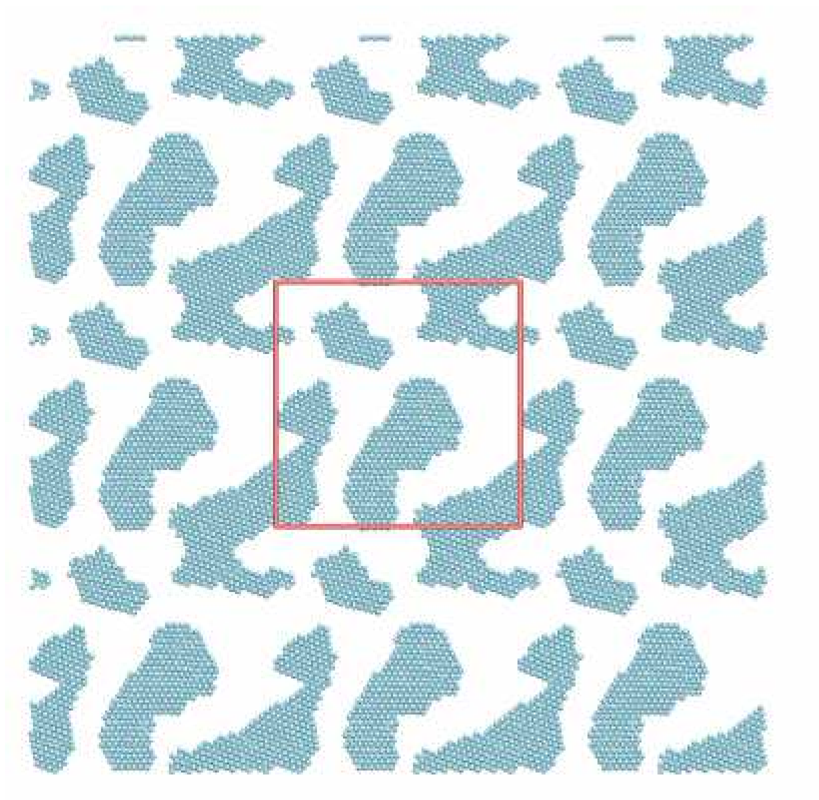

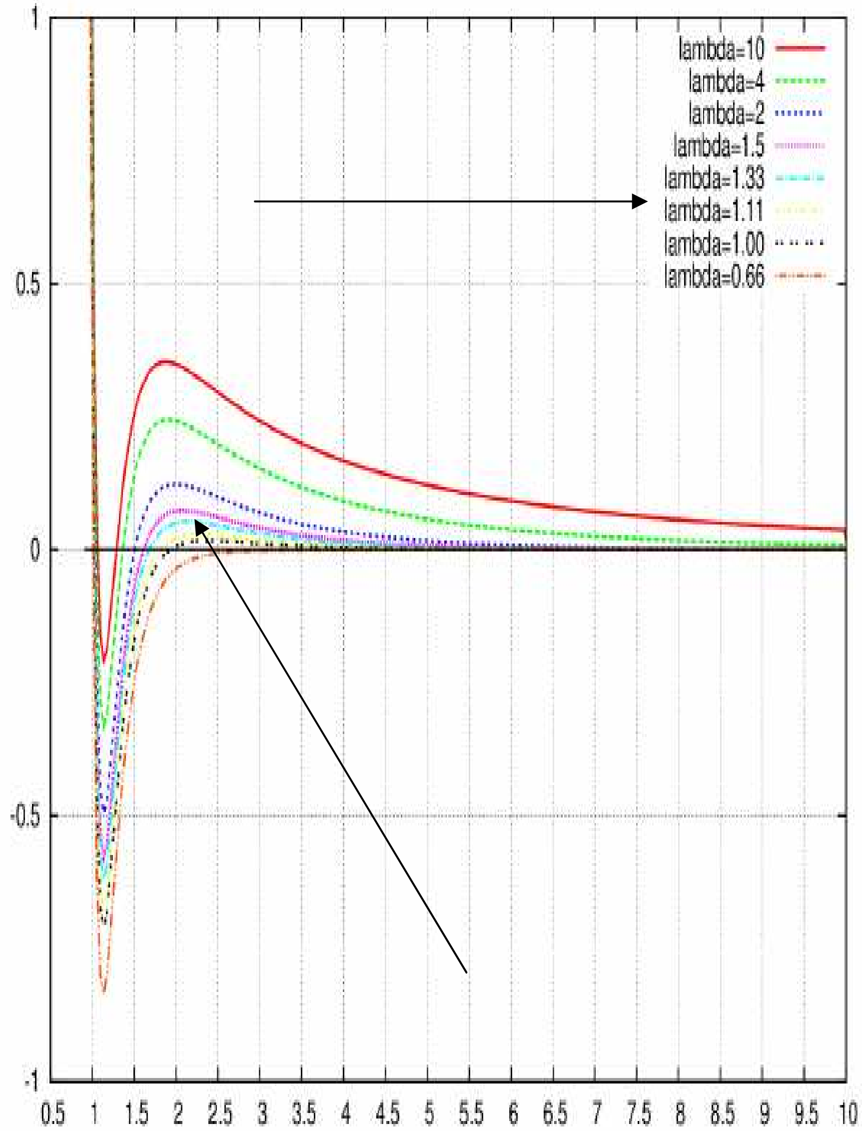
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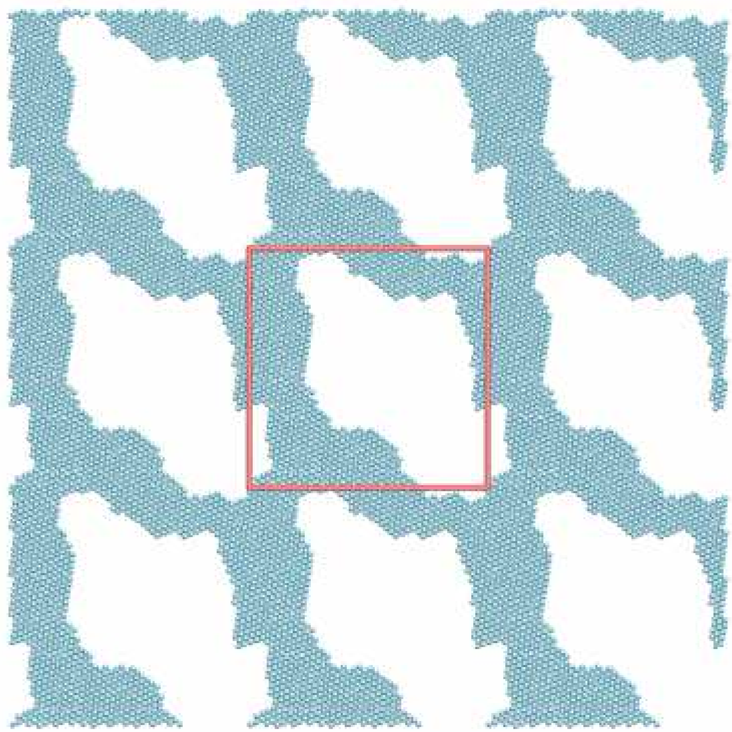

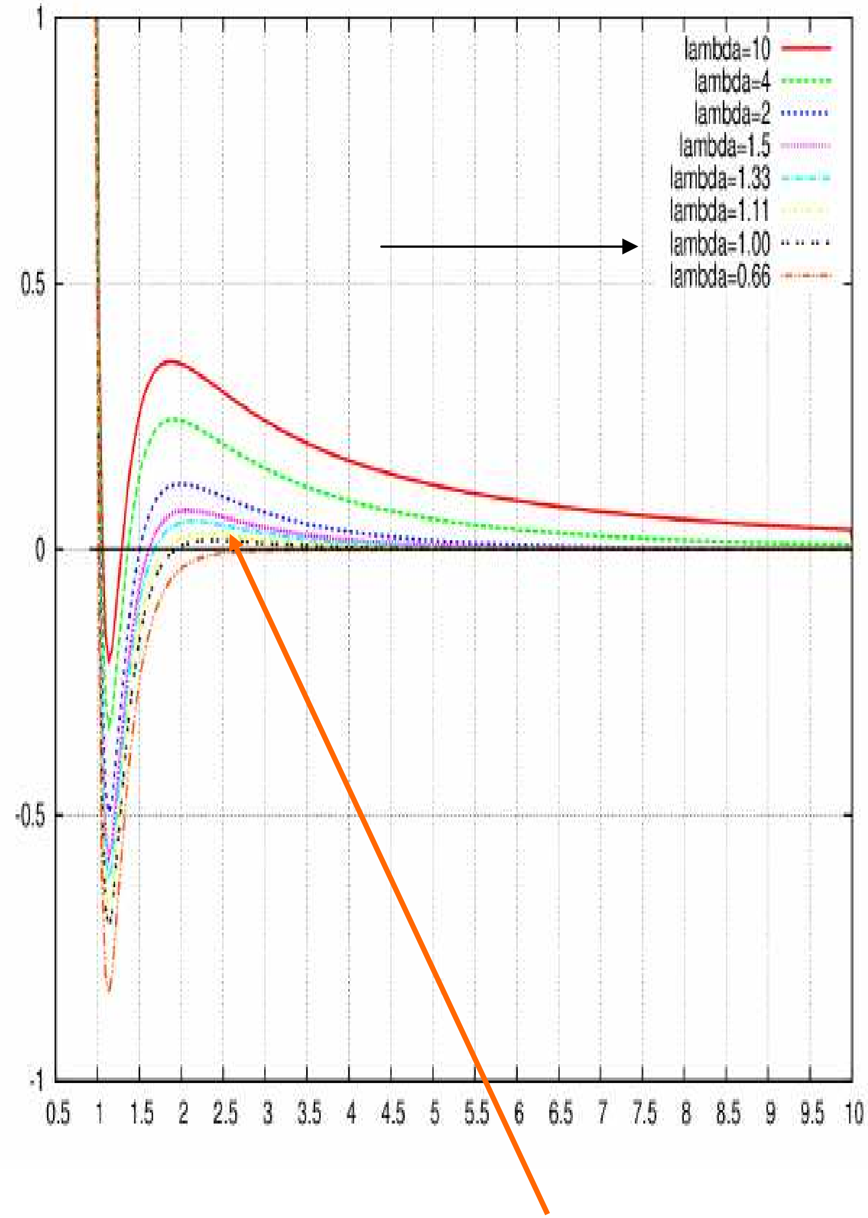

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lambda=0.66
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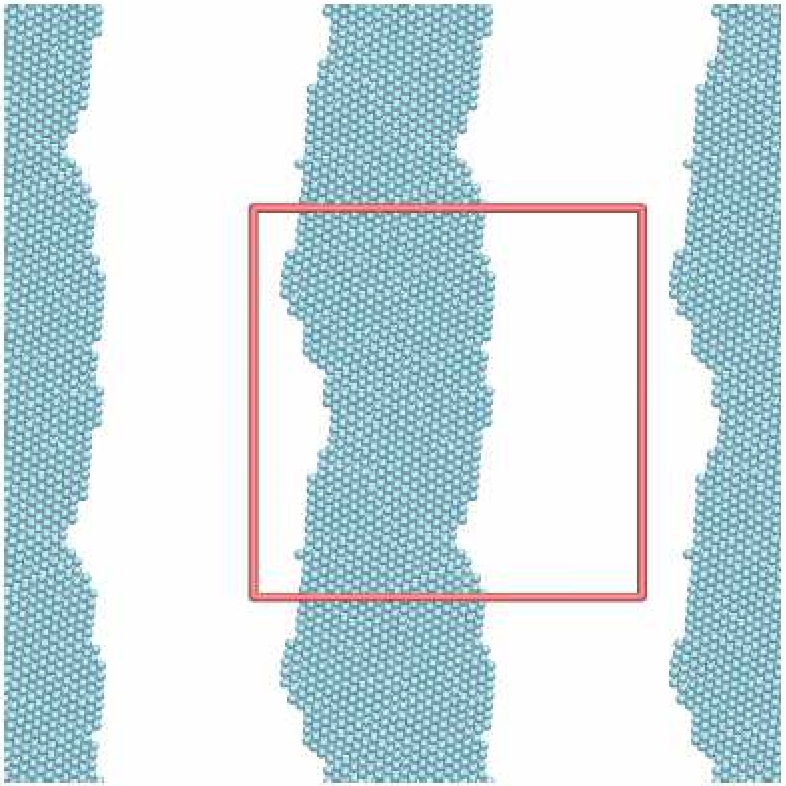
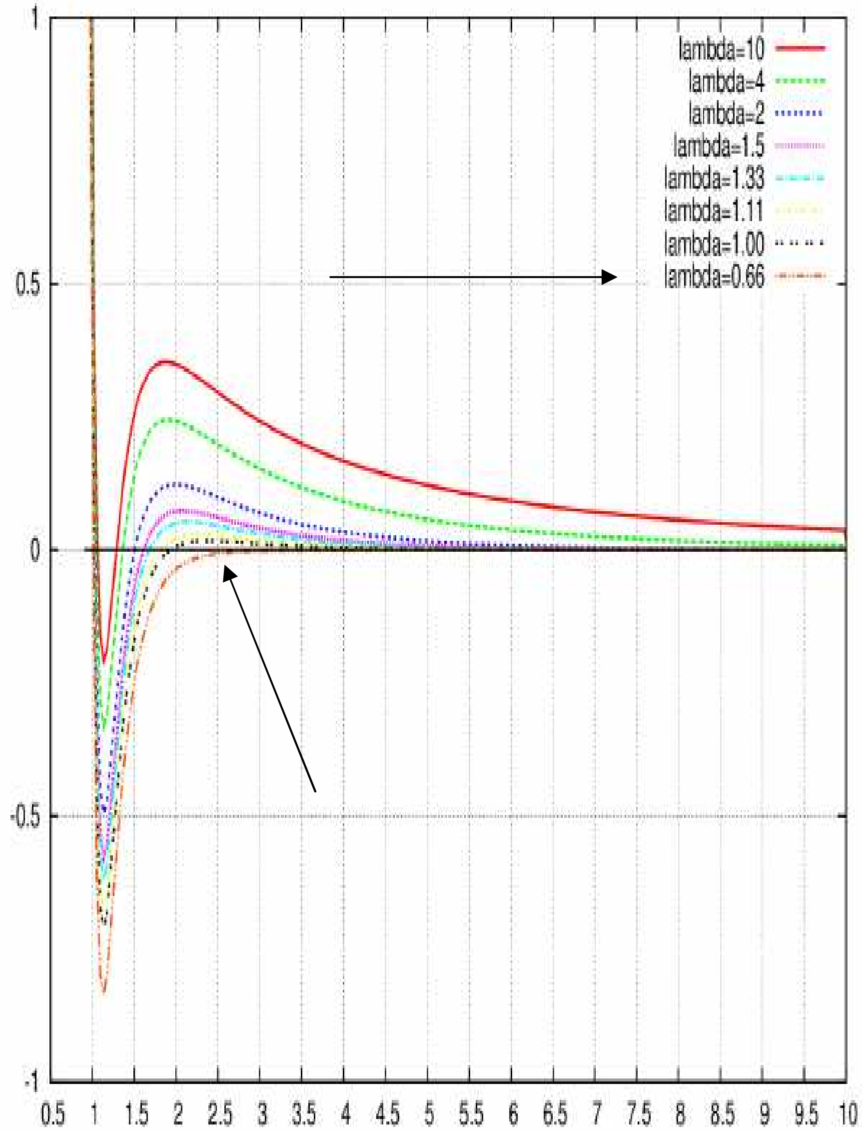
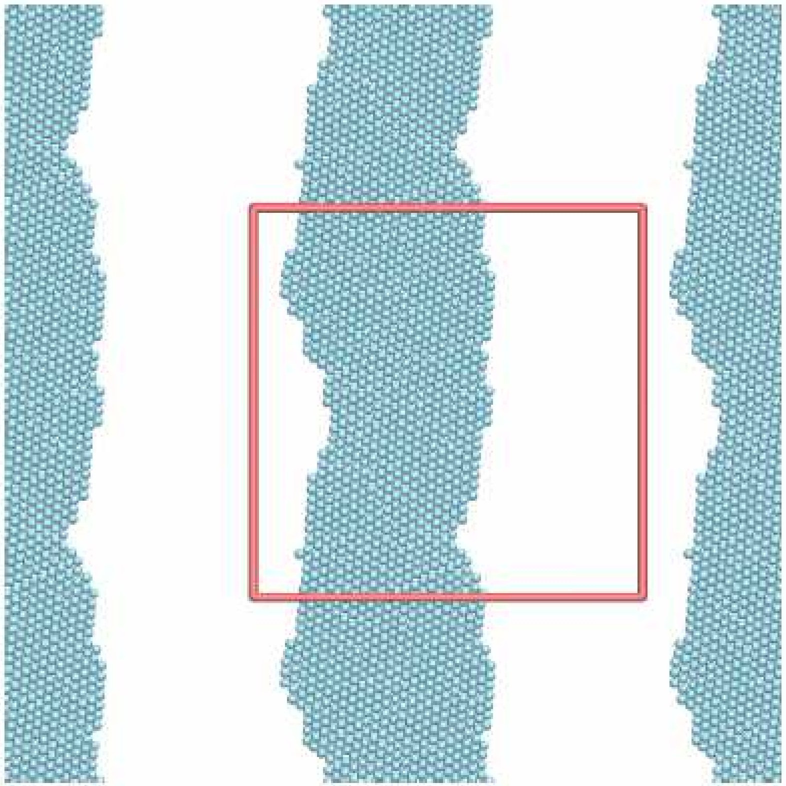
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

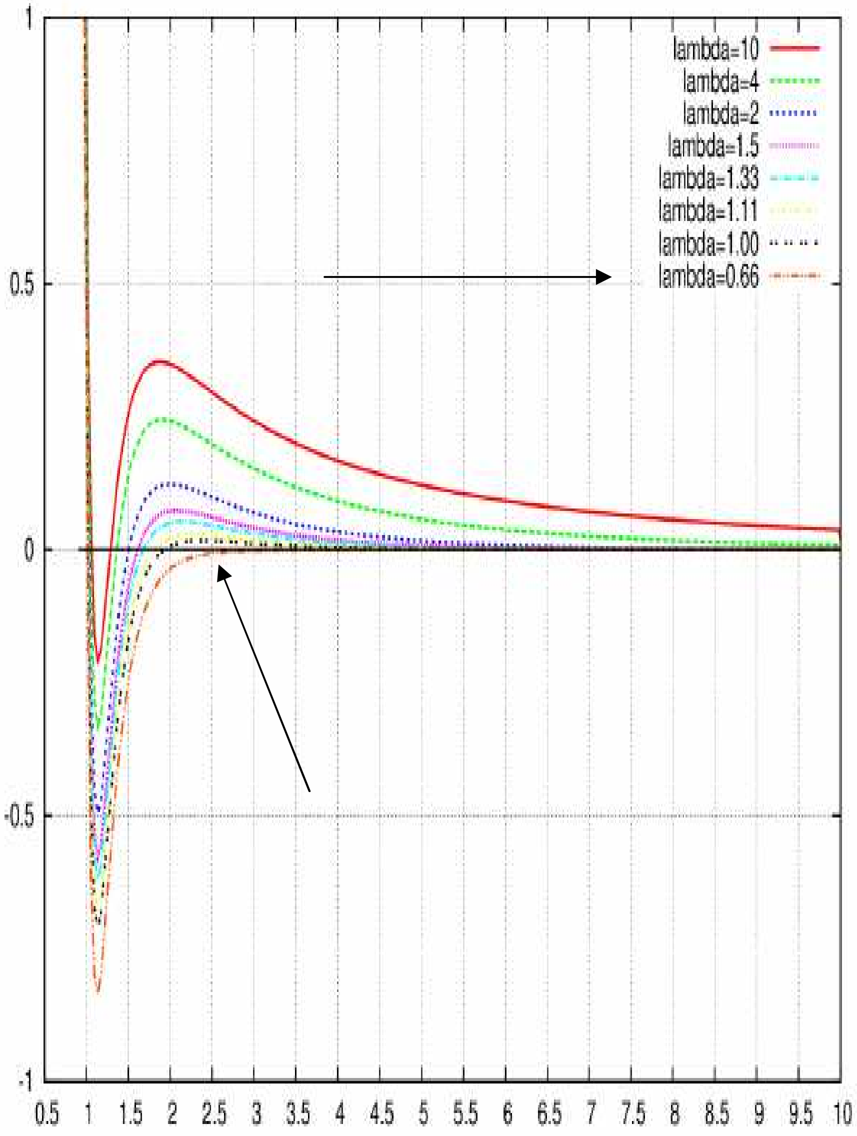




no bump, still get 'pasta'

Trivial infinite cluster
2 dimensions "no coulomb"





no bump, still get 'pasta'

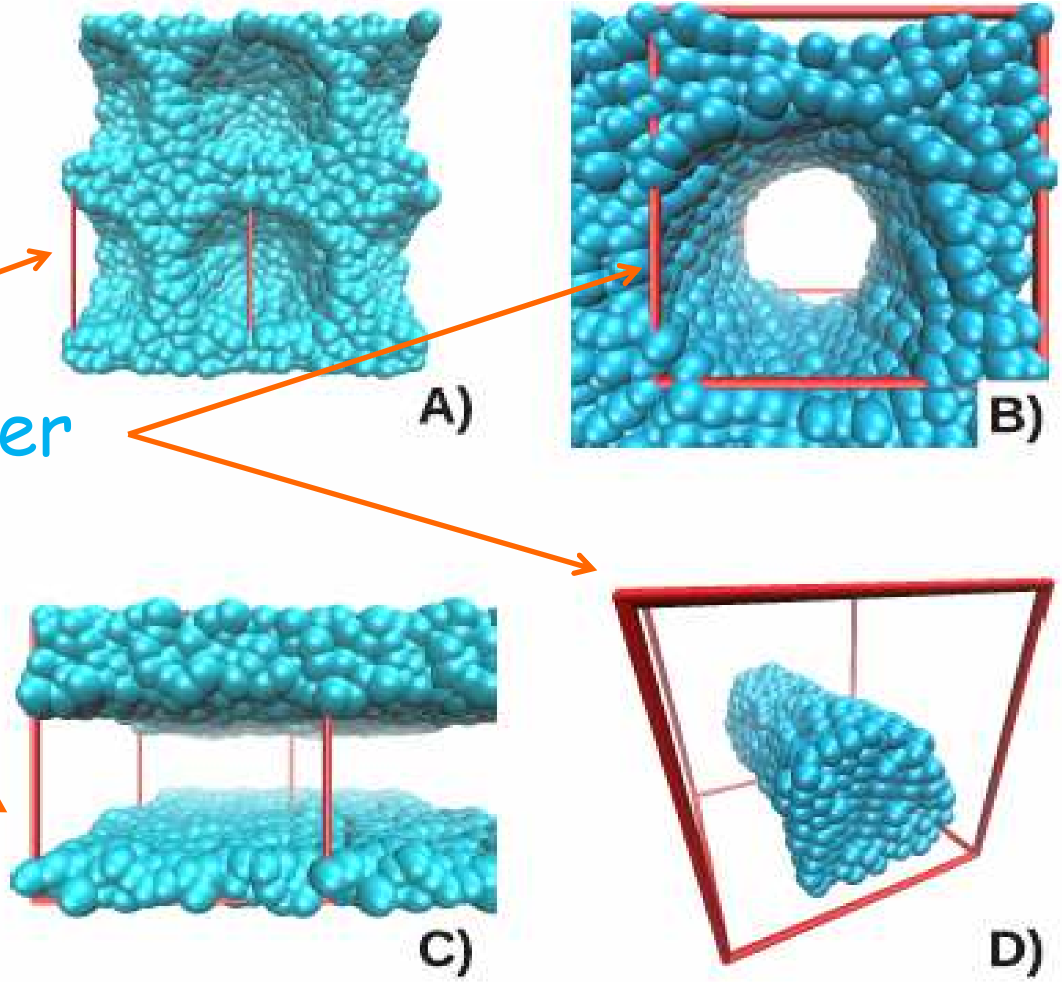
In 3 dimensions, no coulomb

$$V_{LJ}(r) = 4\epsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$$

N=5000

Temperatura muy baja

1 structure per cell



Finite size, periodic boundary conditions and the appearance of "Pasta" without Coulomb

Finite size, periodic boundary conditions and the appearance of "Pasta" without Coulomb

The system is finite but not too small, particles interact by a short range potential

Given a configuration we can write:

$$E = E_{bulk} + E_{surf}$$

$$A = E - TS$$

$$S_{sphere} = 4\pi \left(\frac{3}{4\pi} \right)^{\frac{2}{3}} \times u^{\frac{2}{3}} \times L^2$$

$$S_{rod} = 2\,(\pi)^{\frac{1}{3}} \times u^{\frac{1}{3}} \times L^2$$

$$S_{slab} = 2 \times L^2$$

Surfaces

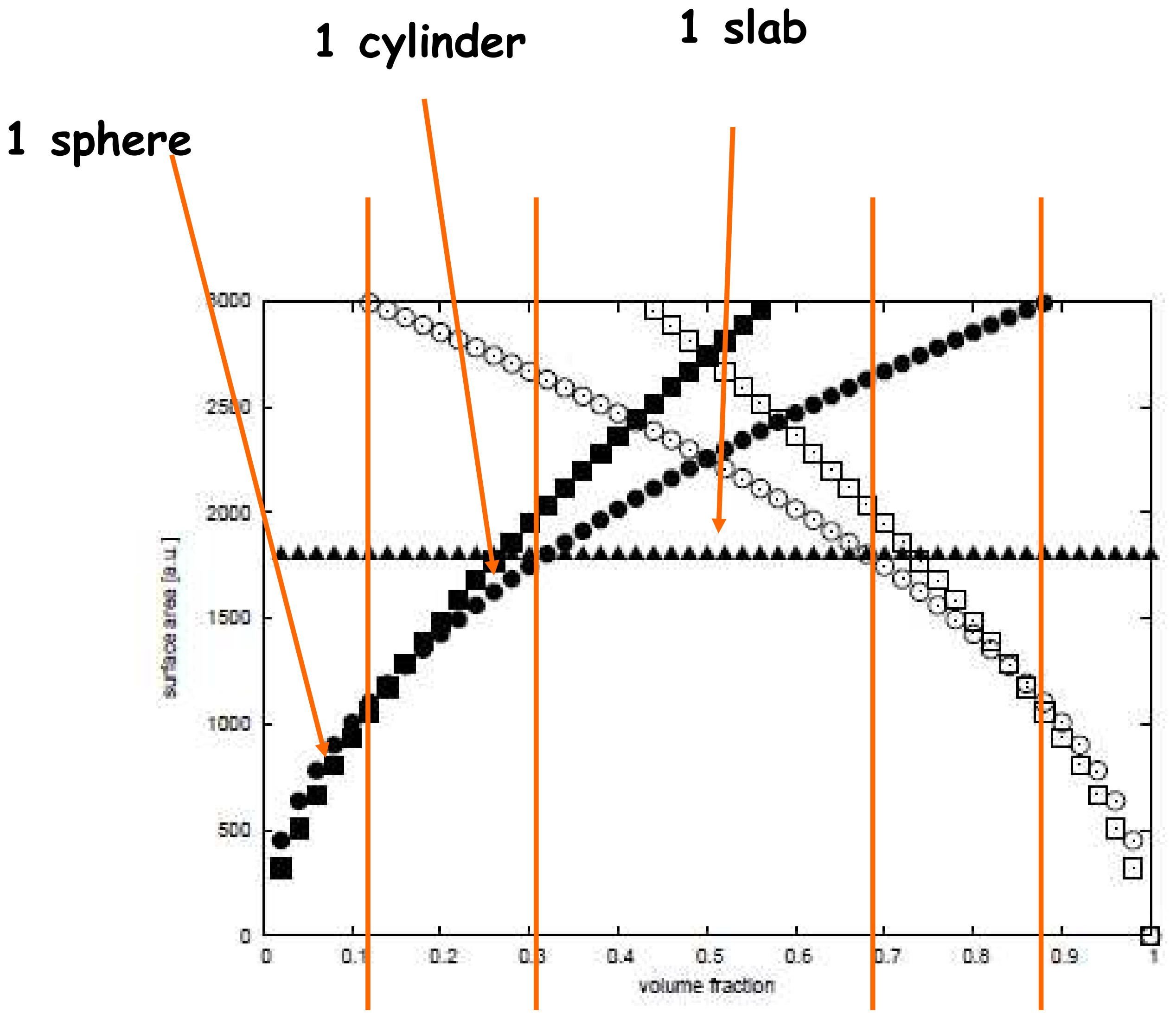


FIG. 12. Surface area of various simple shapes as a function of volume fraction for a cell of $L = 30$. The shapes are: Sphere (full squares), Cilindrical rod (full circles), slab (full triangles), cilindrical bubble (empty circles) and spherical bubble (empty squares)

En ausencia de Coulomb y debajo de una cierta T_c aparecen pseudo pastas , Una por celda, La Celda fija la escala

Las CPC siempre presentes!!!!

Nuclear Matter CMD

Back to CMD

Illinois Potential Medium

$$V_{np}(r) = V_r\left[exp(-\mu_r r)/r - exp(-\mu_r r_c)/r_c\right] - V_a\left[exp(-\mu_a r)/r - exp(-\mu_a r_c)/r_c\right]$$
$$V_{NN}(r) = V_0\left[exp(-\mu_0 r)/r - exp(-\mu_0 r_c)/r_c\right] \; ,$$

Nuclear Matter

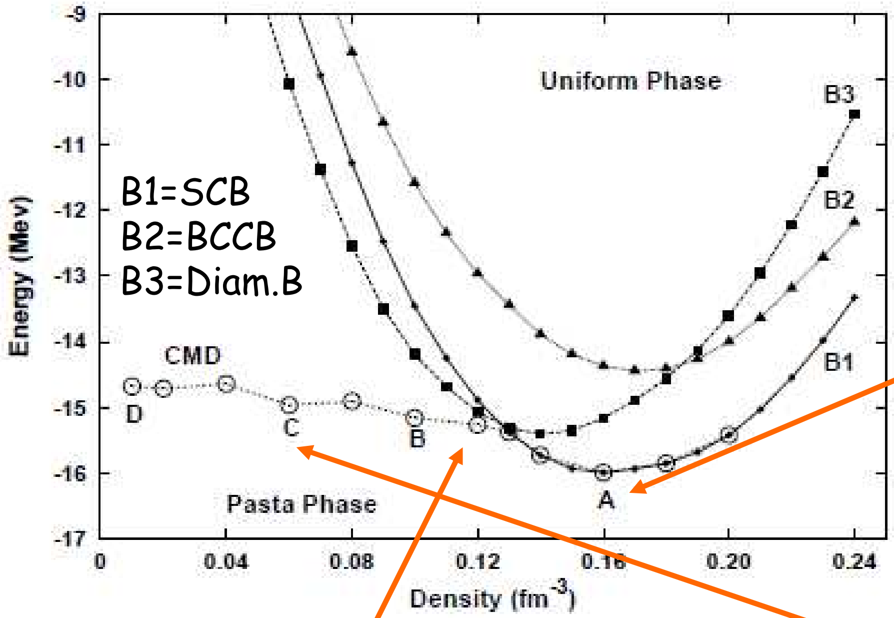


FIG. 1. Binding energies per nucleon for systems obtained with the Pandharipande medium potential for crystalline lattices with $B1$, $B2$ and $B3$ crystal geometries, and using molecular dynamics at $T = 0.001\ MeV$ (CMD). The structures corresponding to the four labeled points ("A" through "D") are shown in Figure 2.

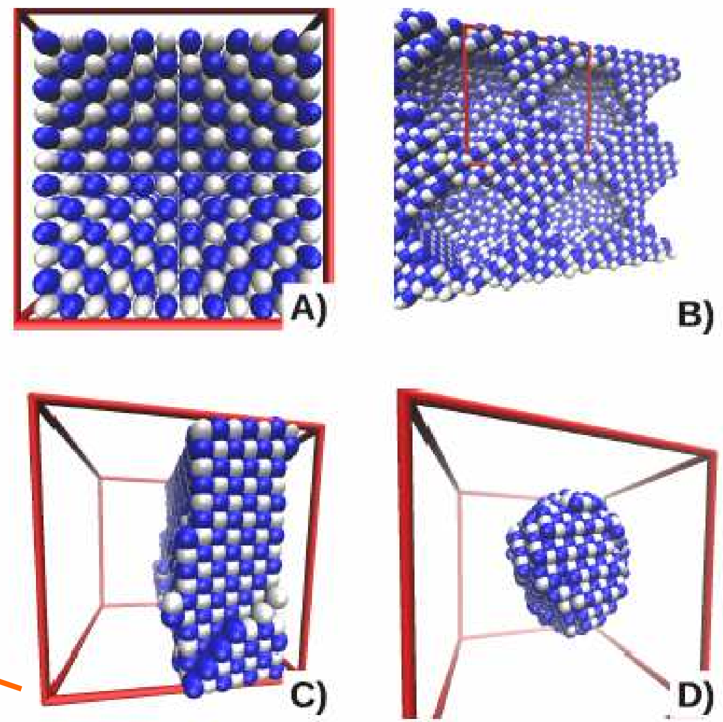
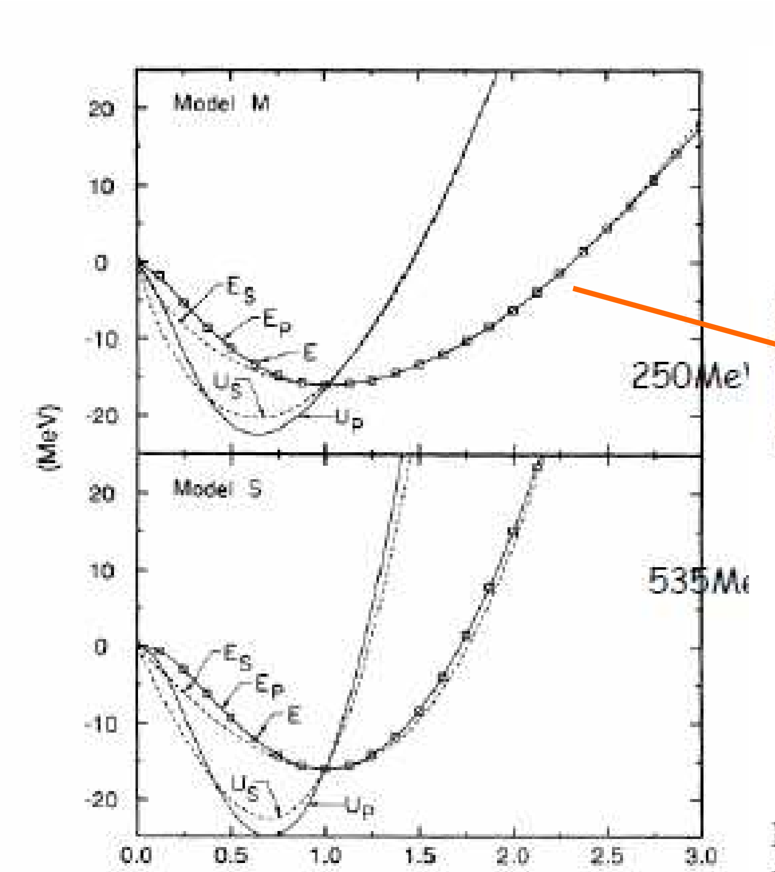


FIG. 2. (Color online) Structures corresponding to the labeled points of Figure 1. Point A corresponds to a formation in the regular ($B1$) lattice, while the rest of the points are non-homogeneous structures.

This work



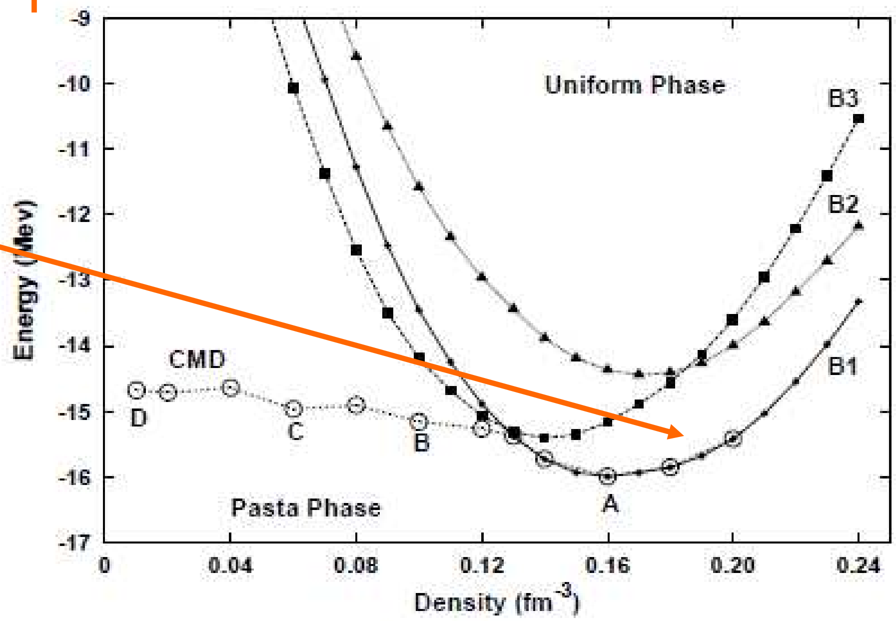


FIG. 1. Binding energies per nucleon for systems obtained with the Pandharipande medium potential for crystalline lattices with $B1$, $B2$ and $B3$ crystal geometries, and using molecular dynamics at $T = 0.001\ MeV\ (CMD)$. The structures corresponding to the four labeled points ("A" through "D") are shown in Figure 2.

original

Illinois Potential Medium

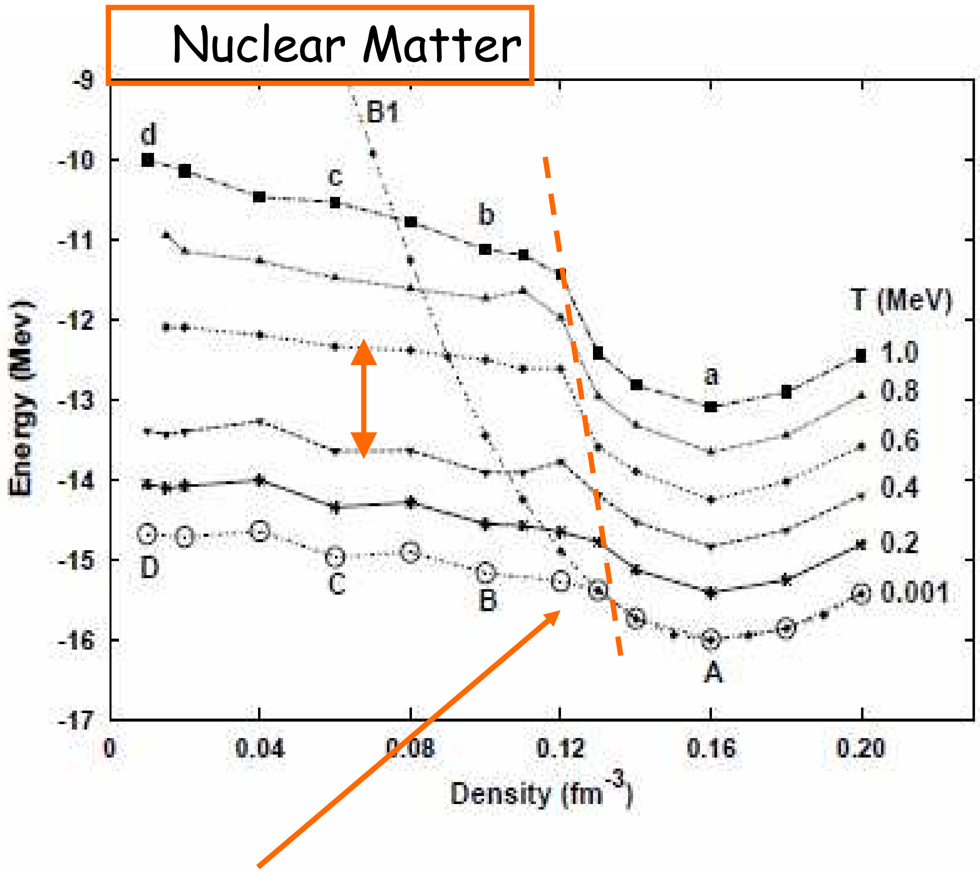


FIG. 3. Binding energies per nucleon for systems obtained with the Pandharipande medium potential at the listed temperatures.

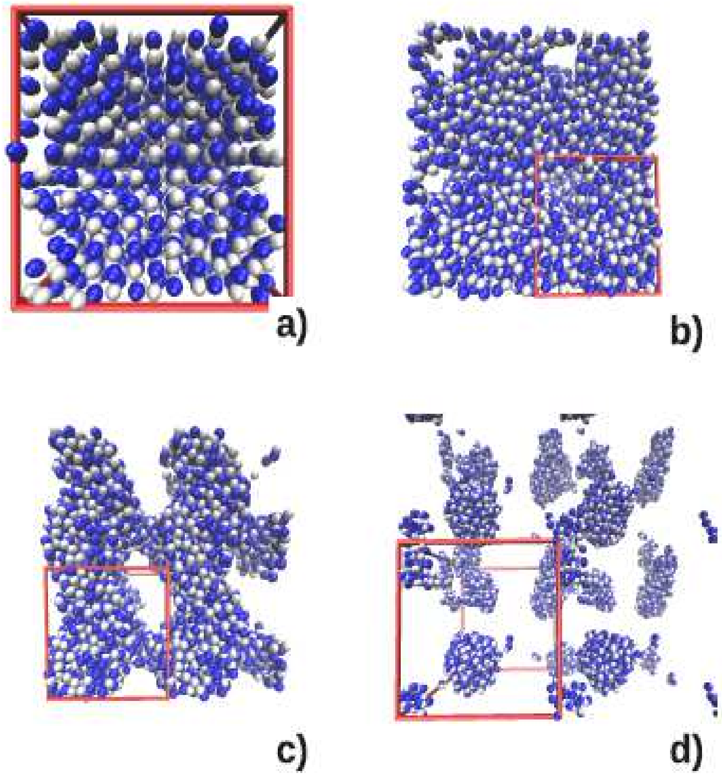
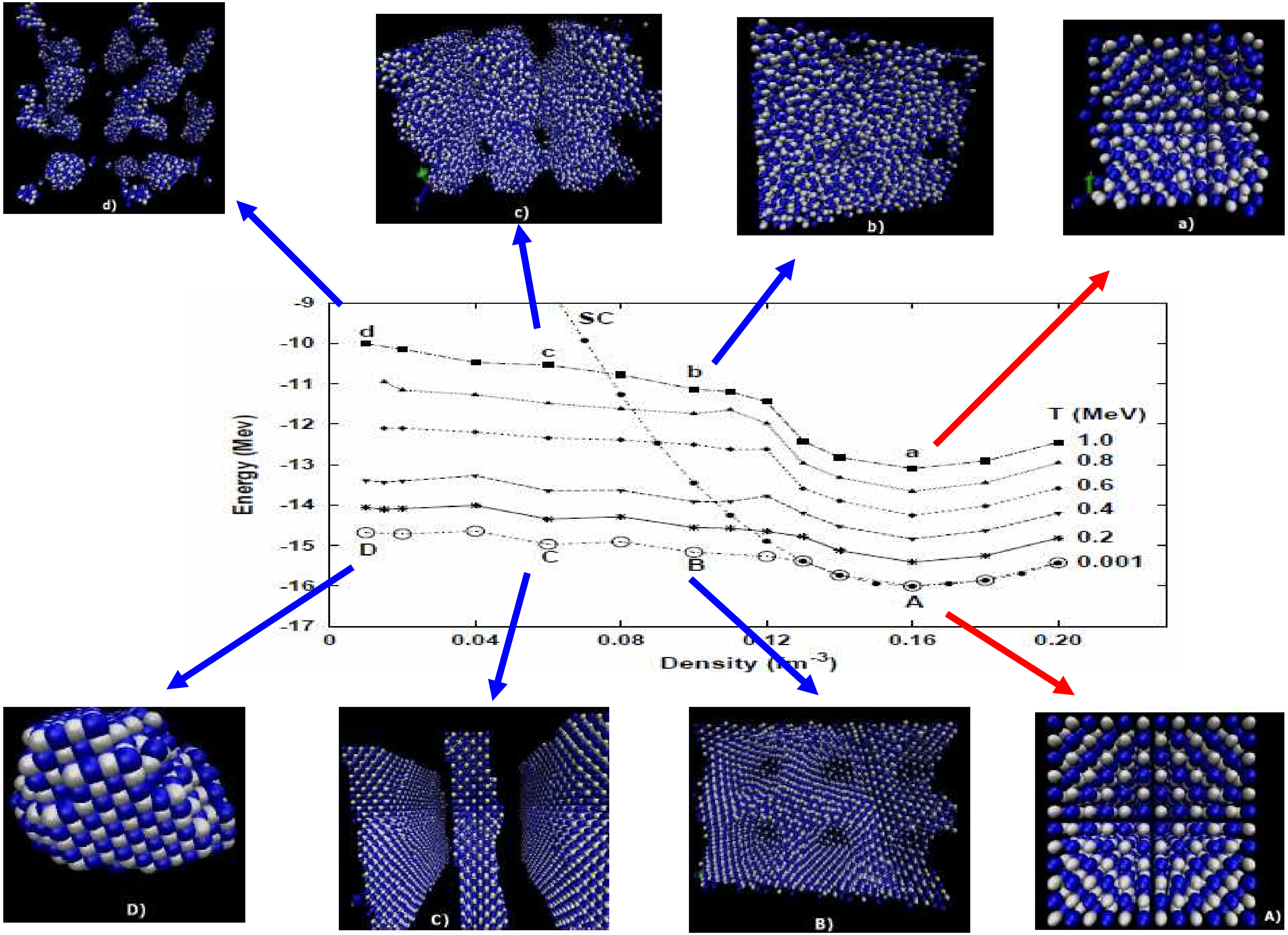


FIG. 4. (Color online) Structures corresponding to the labeled points of Figure 3 obtained with the Pandharipande medium potential at $T = 1.0\ MeV$.

Low T structures



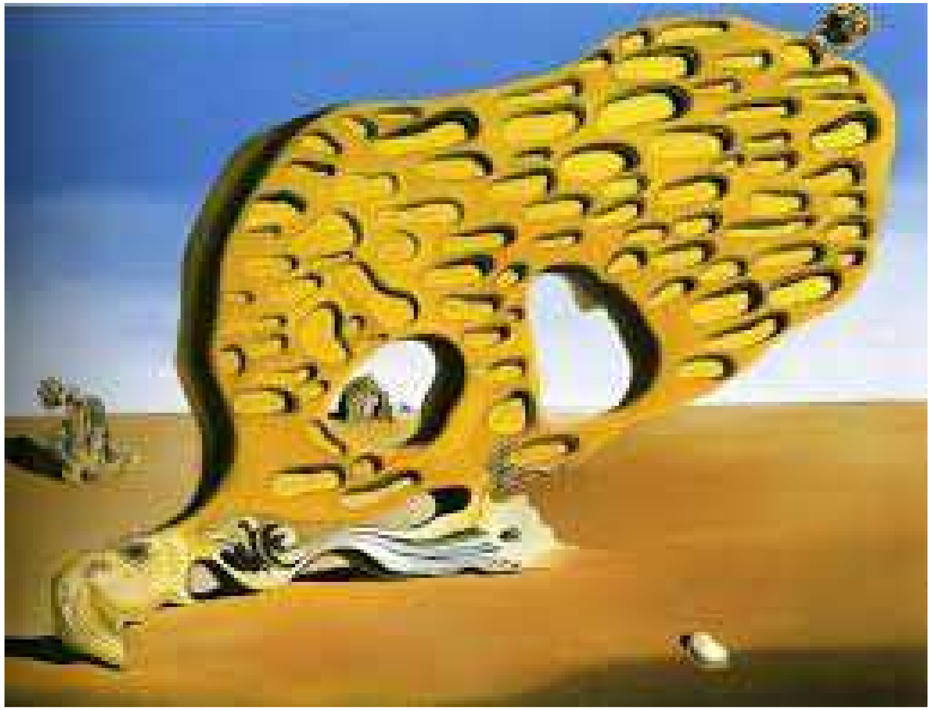
Illinois potential + screened Coulomb NS Matter?

Ahora exploramos:

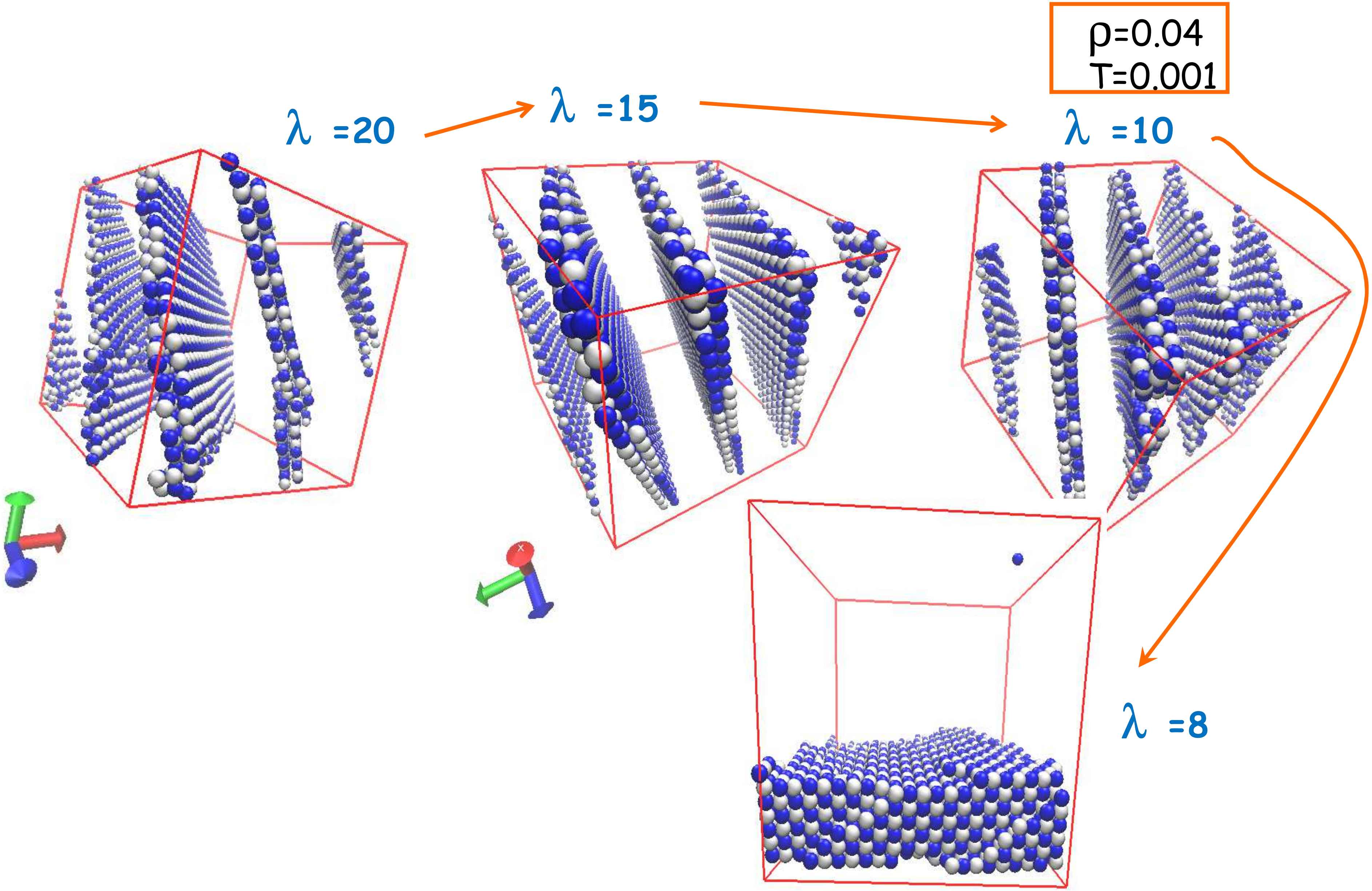
El efecto de variar λ

El efecto de variar T

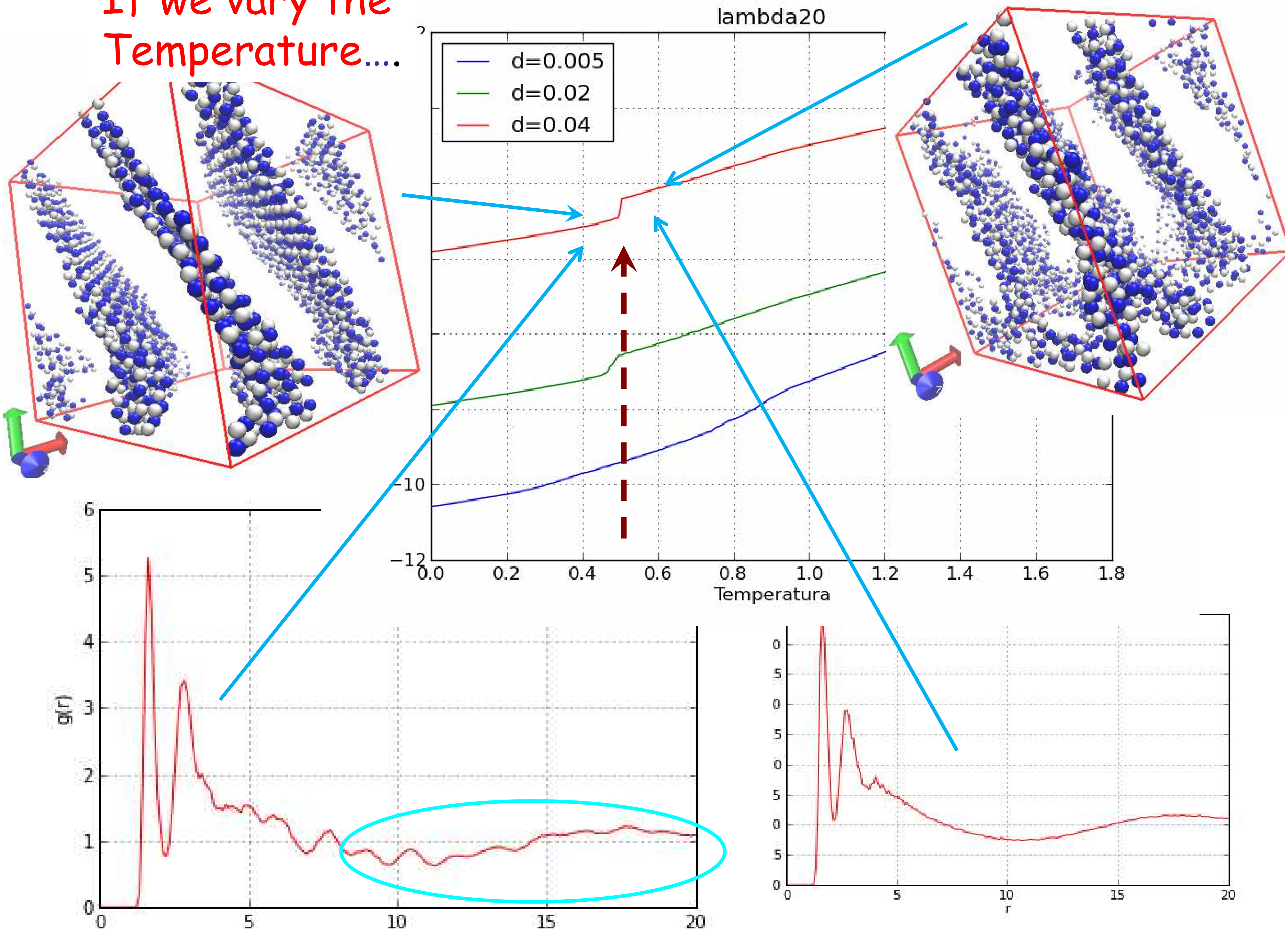
Clusters como funcion de T



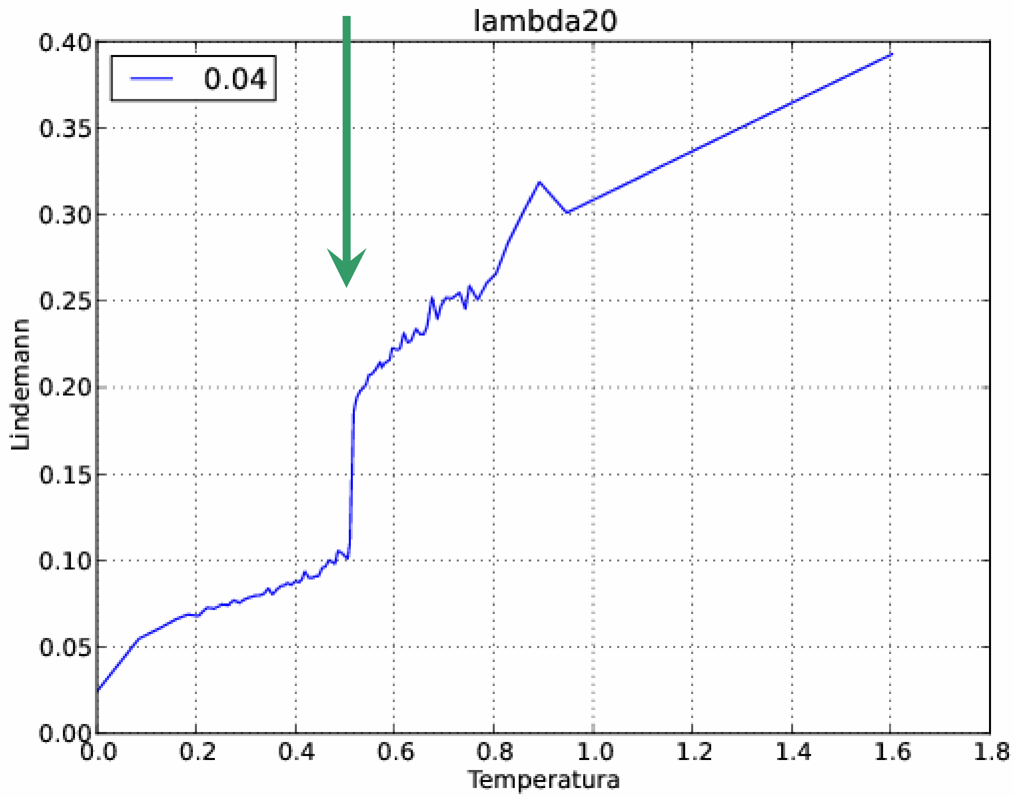
As before we fix the density and then we vary λ in order to see at which point the solution goes to a single structure per cell



If we vary the Temperature....



We now calculate de Lindemann coefficient



$$\Delta_L = \frac{1}{a'}\sqrt{\sum_i \left\langle \frac{\Delta r_i^2}{N} \right\rangle}$$

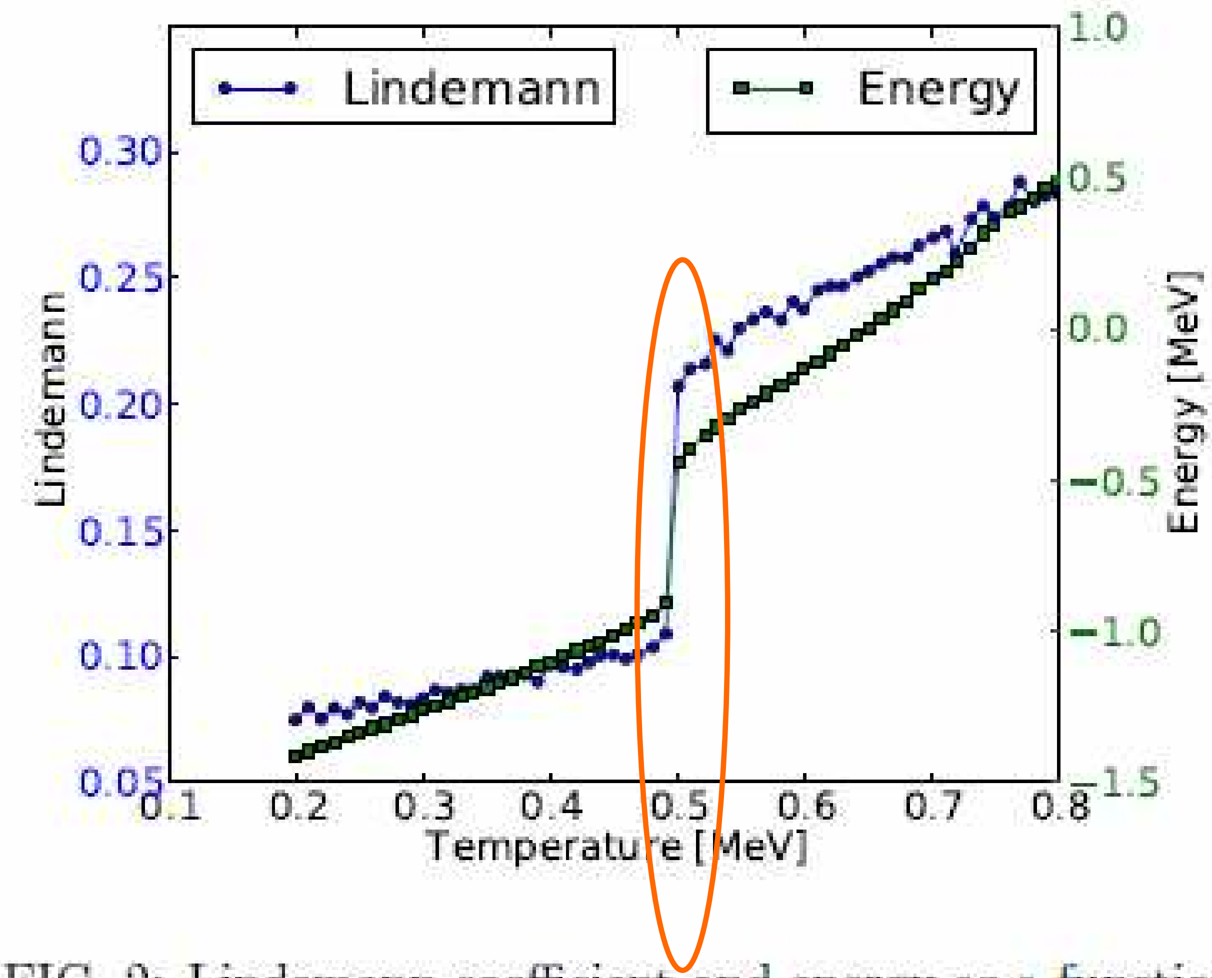
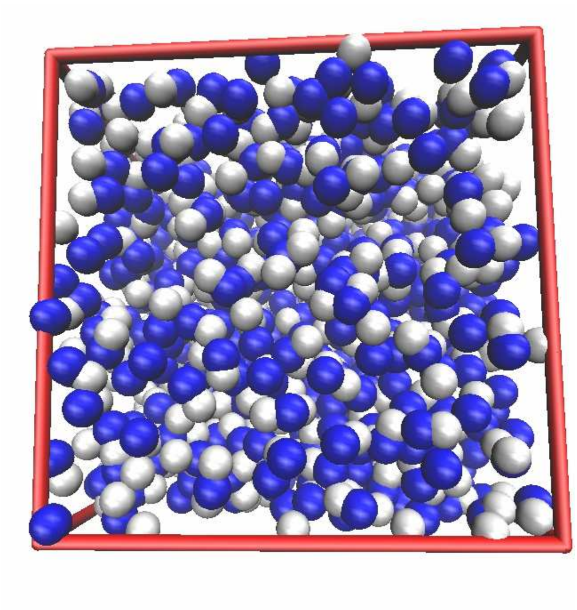


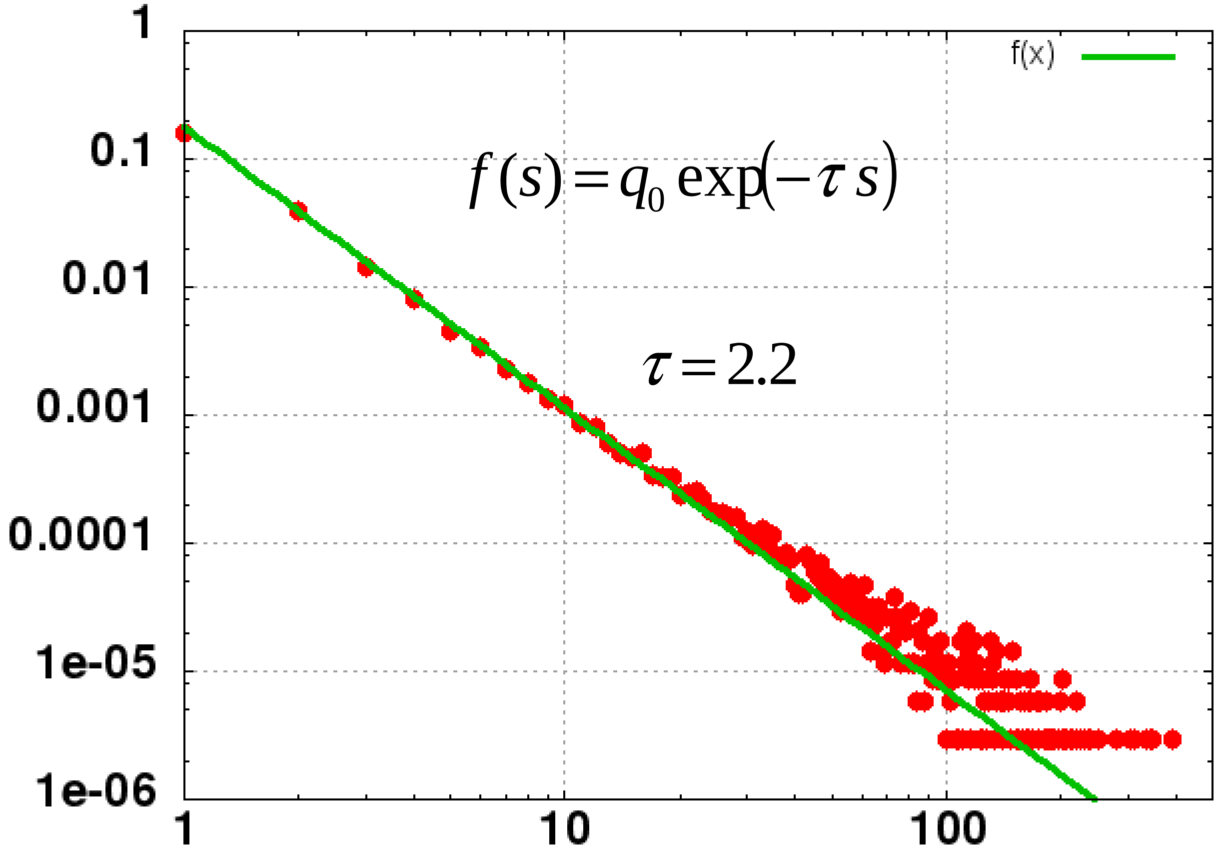
FIG. 2: Lindemann coefficient and energy as a function of temperature for a chosen density, $\rho = 0.05\,\mathrm{fm}^{-3}$. The sudden change in their value is a signal of a solid-liquid phase transition. We can see that both discontinuities are at the same temperature

Clusters in 3D with T

T=4.5 MeV

MSTE(rc=5.4)





Cuando se "enciende" Coulomb y si $\lambda > \lambda c$ aparecen
Las verdaderas pastas
Multiples estructuras en una celda
El potencial fija la escala

Transiciones de Fase "dentro de las pastas" "solido - liquido"

Clusters in Energy Space

Opacidad

y

enfriamiento NS

Neutrino production in Neutron Stars

URCA process

$$n \rightarrow p + e + \overline{\nu_e}$$

$$p + e \rightarrow n + \nu_e$$

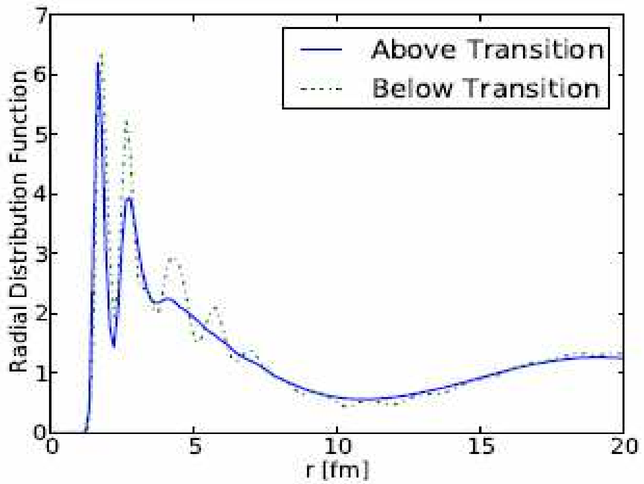
$$\lambda_\nu \approx 15\ fm$$

Structure Factor

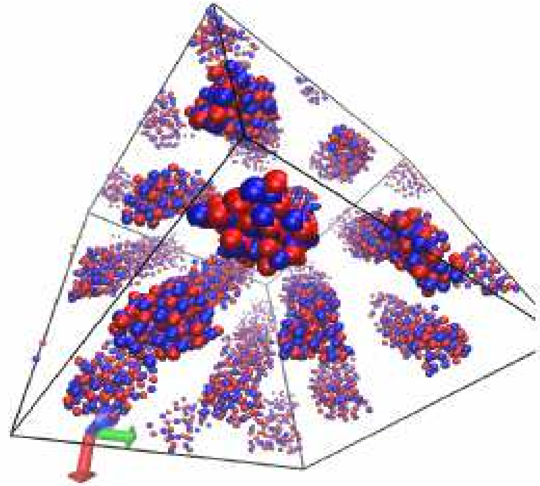
Correlación radial

$$S(q) = 1 + \rho \int_V \mathrm{d}r\, \mathrm{e}^{-iqr} g(r)$$

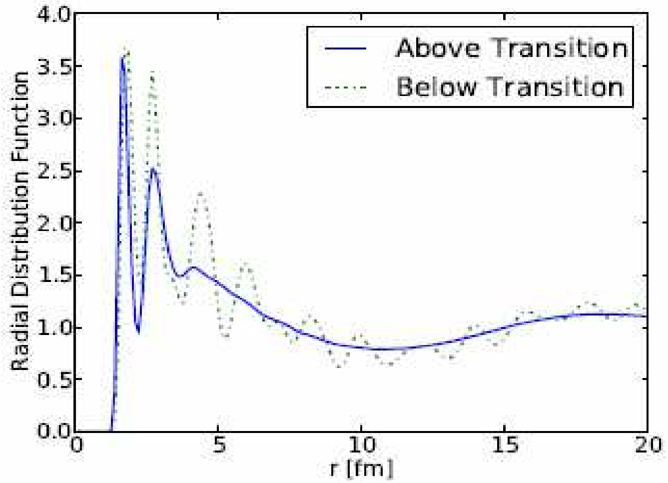
La función de correlación radial y la Temperatura



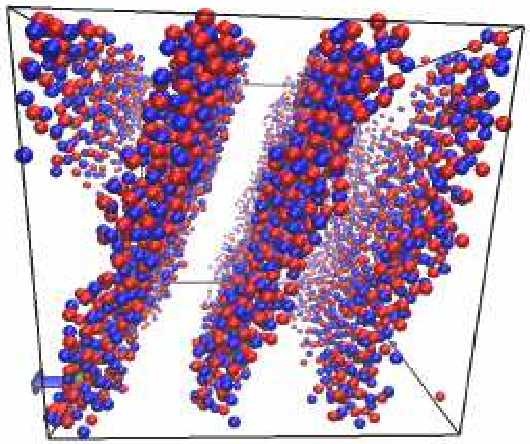
Radial distribution function for $\rho = 0.03\,\mathrm{fm}^{-3}$



Snapshot of the system in the liquid phase for $\rho = 0.03\,\mathrm{fm}^{-3}$

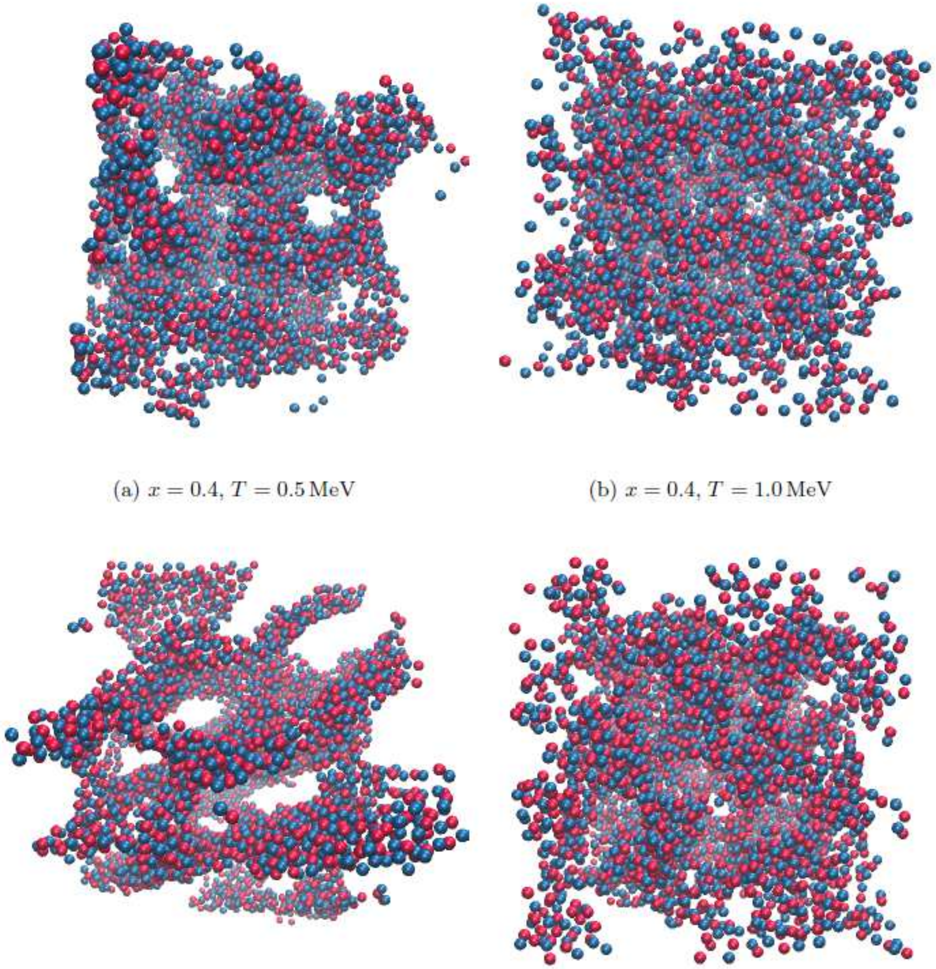


Radial distribution function for $\rho = 0.05\,\mathrm{fm}^{-3}$



Snapshot of the system in the liquid phase for $\rho = 0.05\,\mathrm{fm}^{-3}$

Morfologia de la “pasta” y la Temperatura



(a) $x = 0.4$, $T = 0.5\,\mathrm{MeV}$

(b) $x = 0.4$, $T = 1.0\,\mathrm{MeV}$

(c) $x = 0.5$, $T = 0.5\,\mathrm{MeV}$

(d) $x = 0.5$, $T = 1.0\,\mathrm{MeV}$

Figure 1: (Color online) Snapshots of a system with density $\rho = 0.04\,\mathrm{fm}^{-3}$ for different values of proton fraction and temperature, generated with VMD [32]. Structures obtained at $T = 0.5\,\mathrm{MeV}$ differ substantially. Nevertheless both show inhomogeneities.

Maximo Fragmento, X y la Temperatura (MSTE)

celda de ≈ 5500 particulas

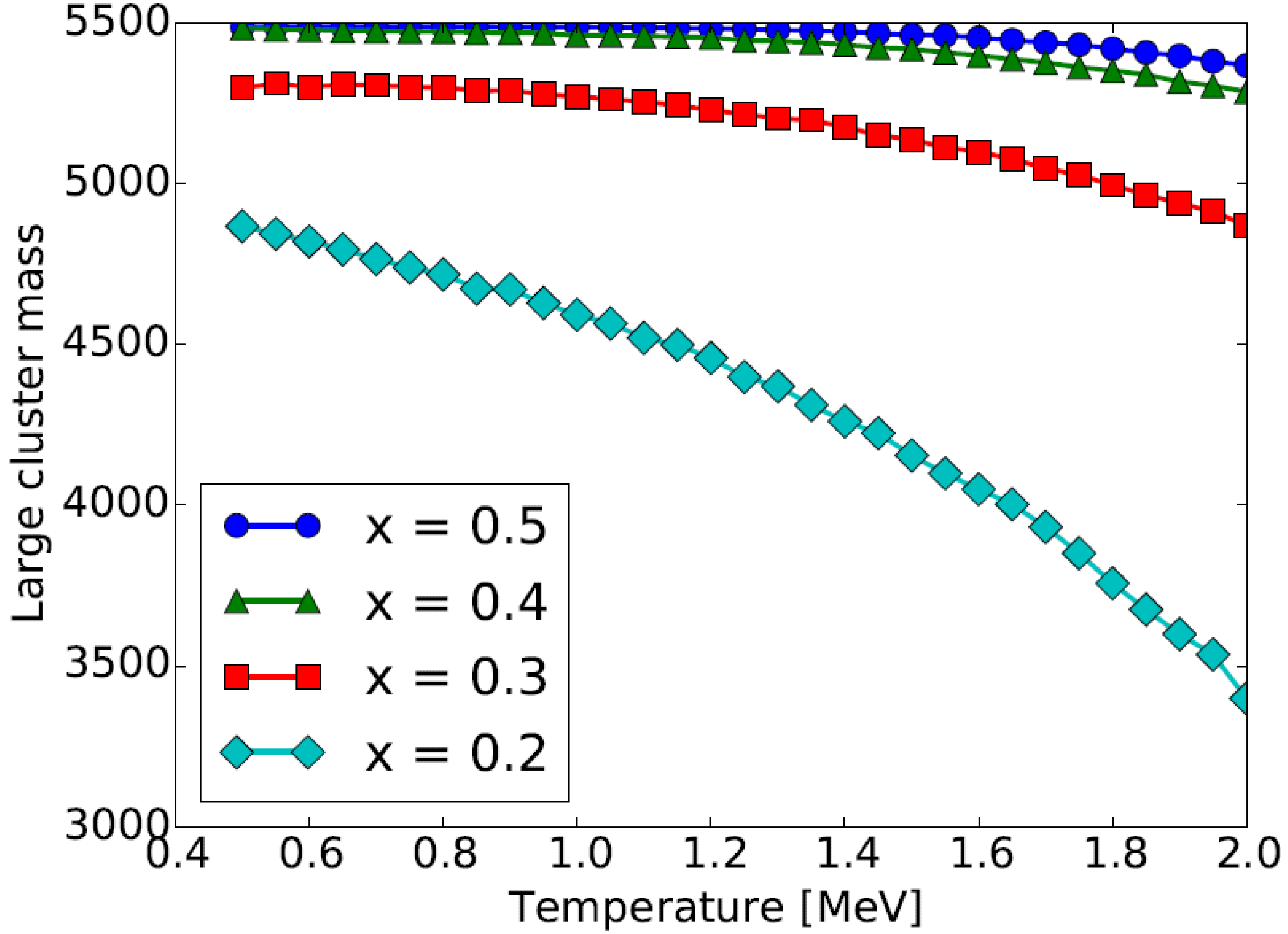
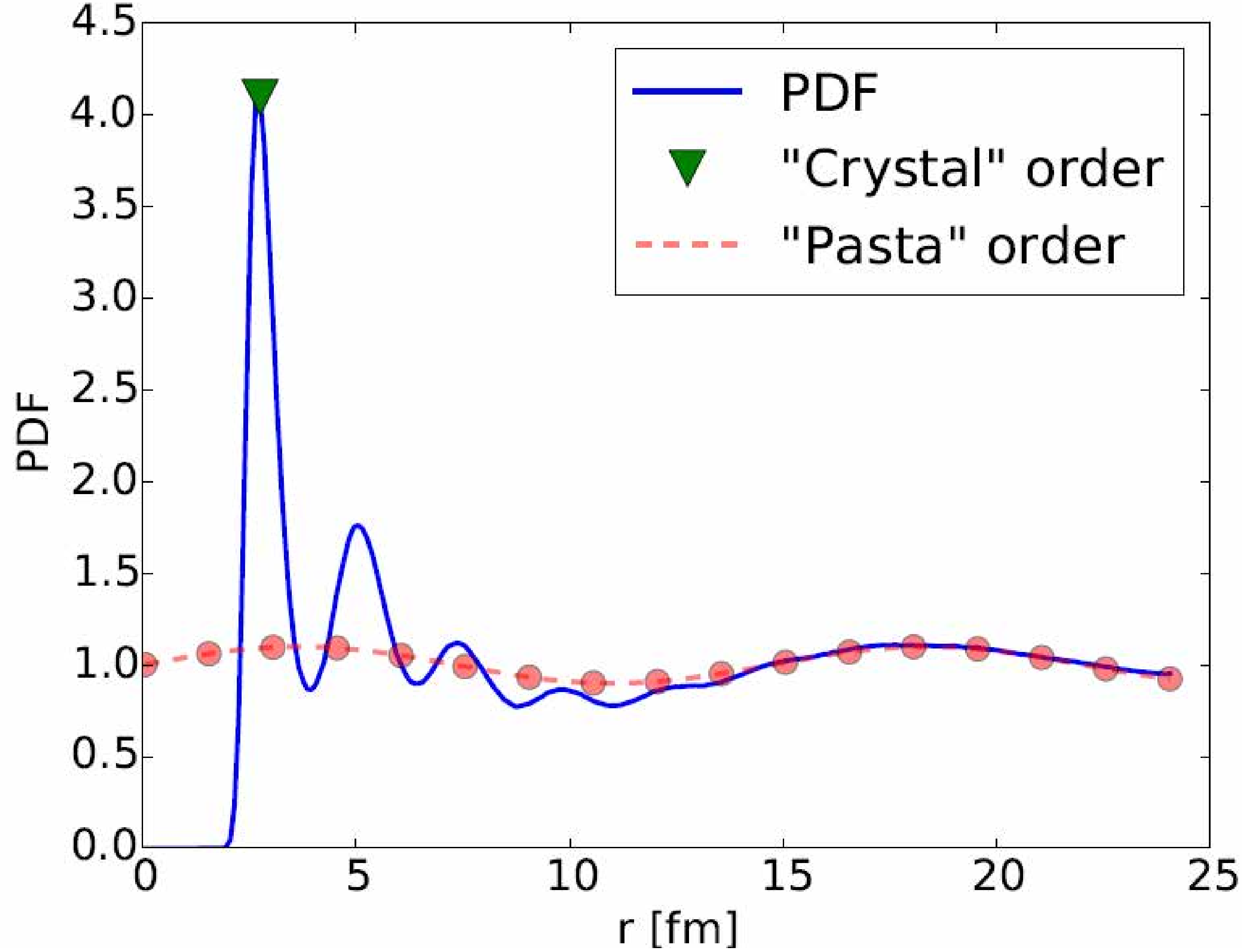


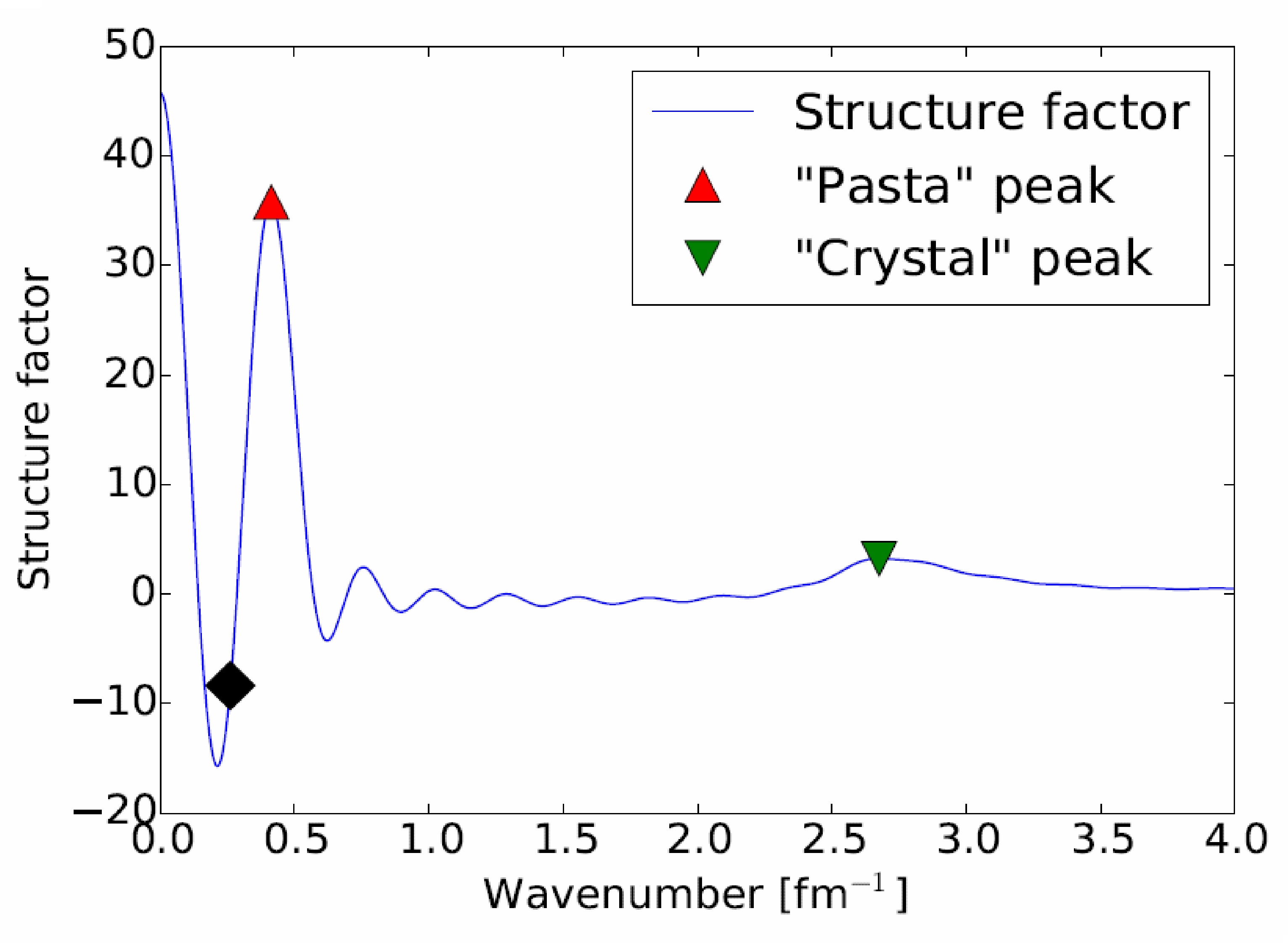
Figure 3: (Color online) Mass of the largest cluster for $\rho = 0.04\,\mathrm{fm}^{-3}$ for different values of x.

La función de correlación radial

X=0.5
T=0.5
ρ=0.05

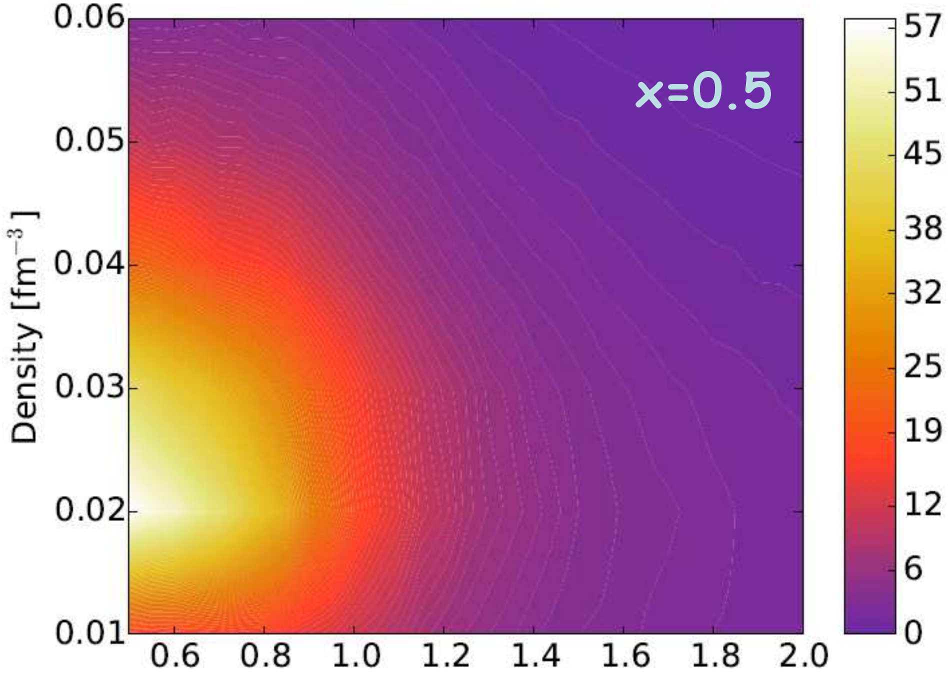


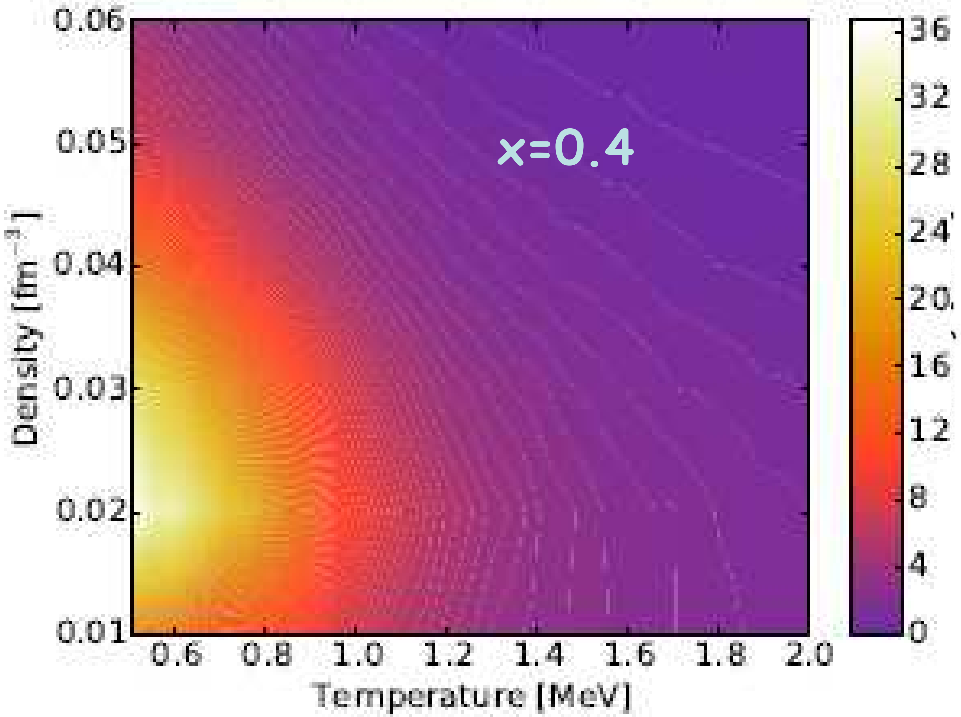
el factor de estructura

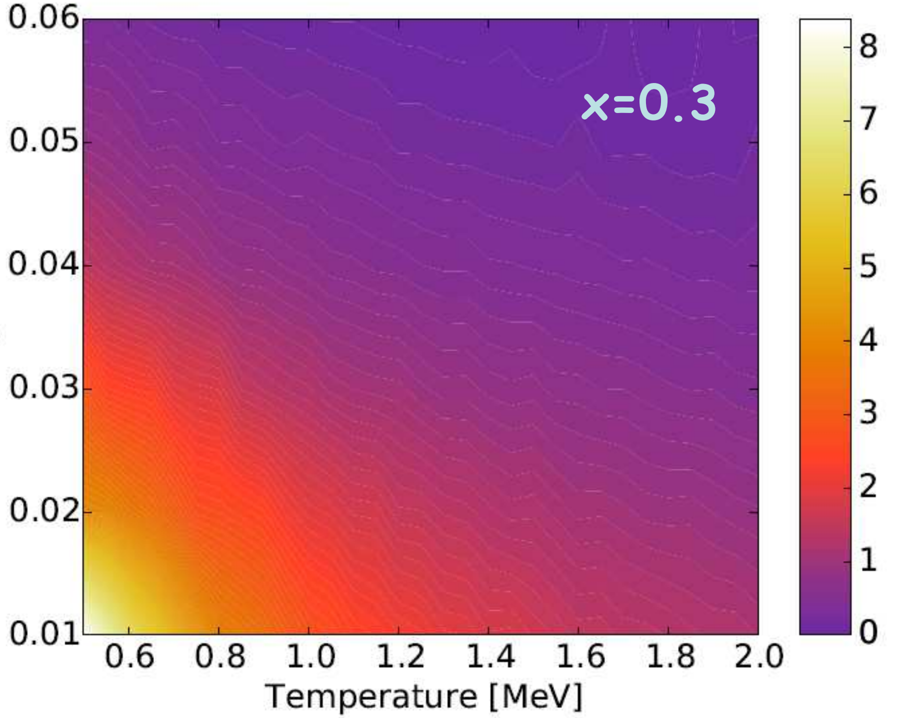


Absorption Peak

$$\lambda_{\nu_U}$$







Neutron Star Mergers

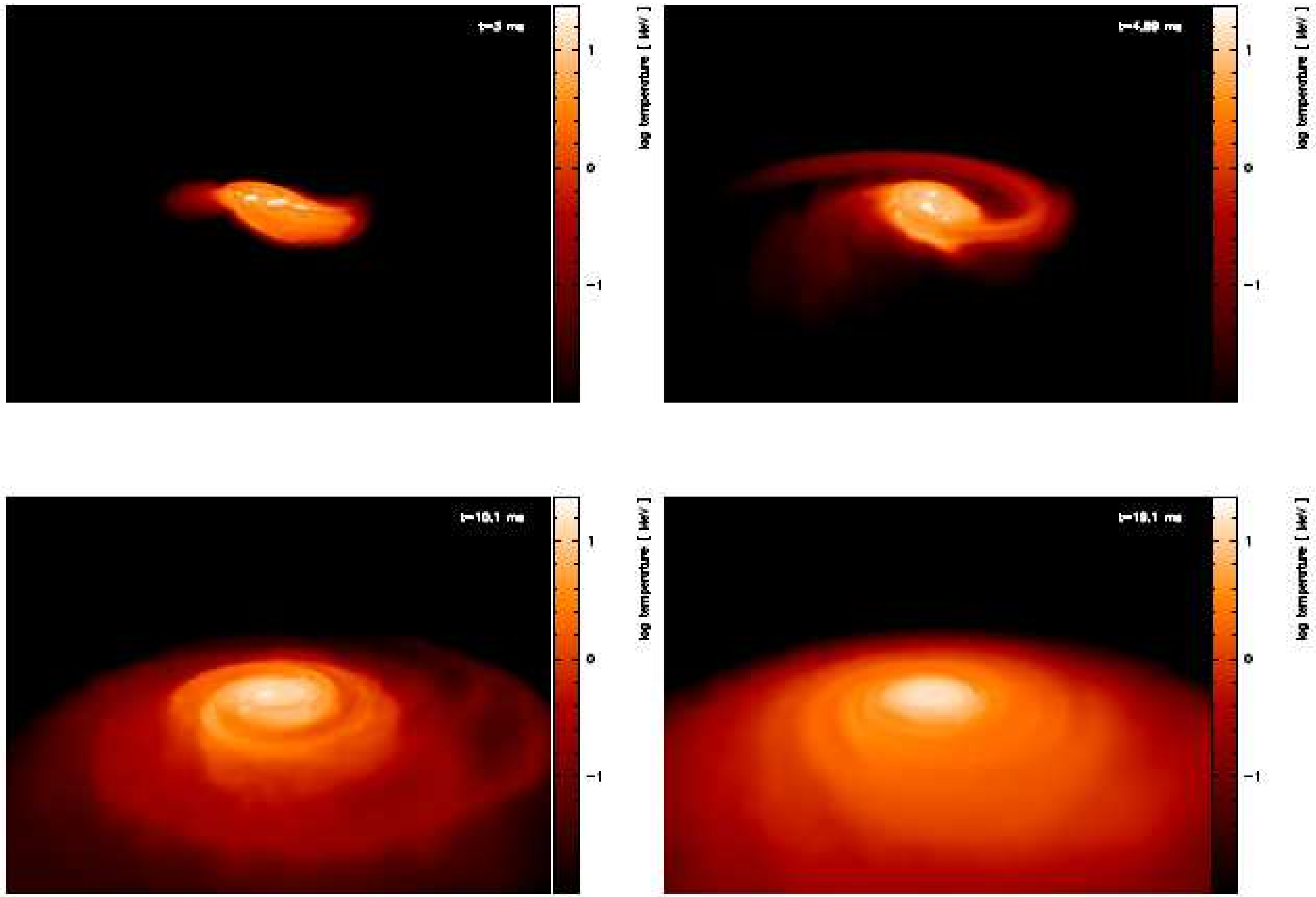
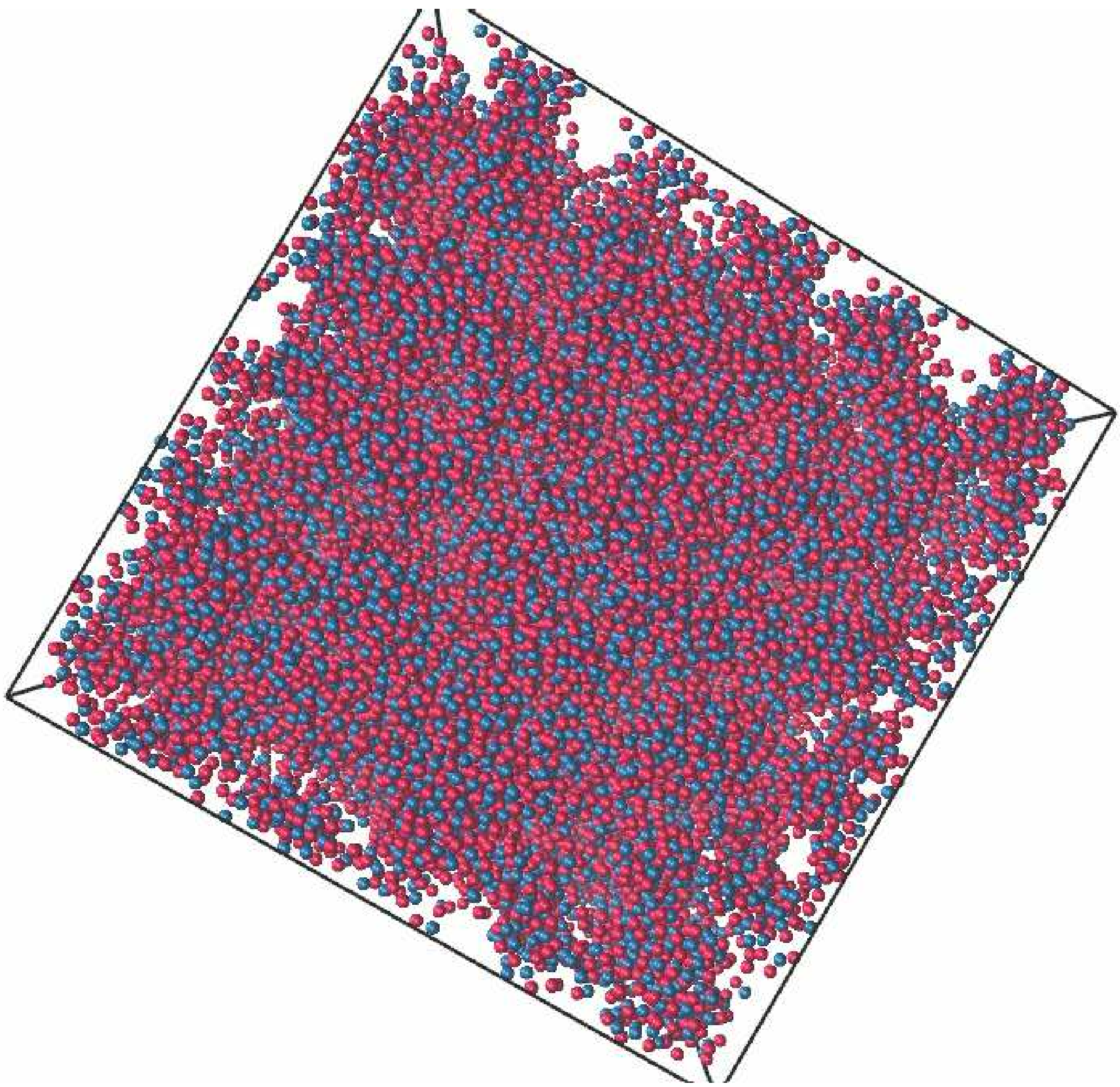
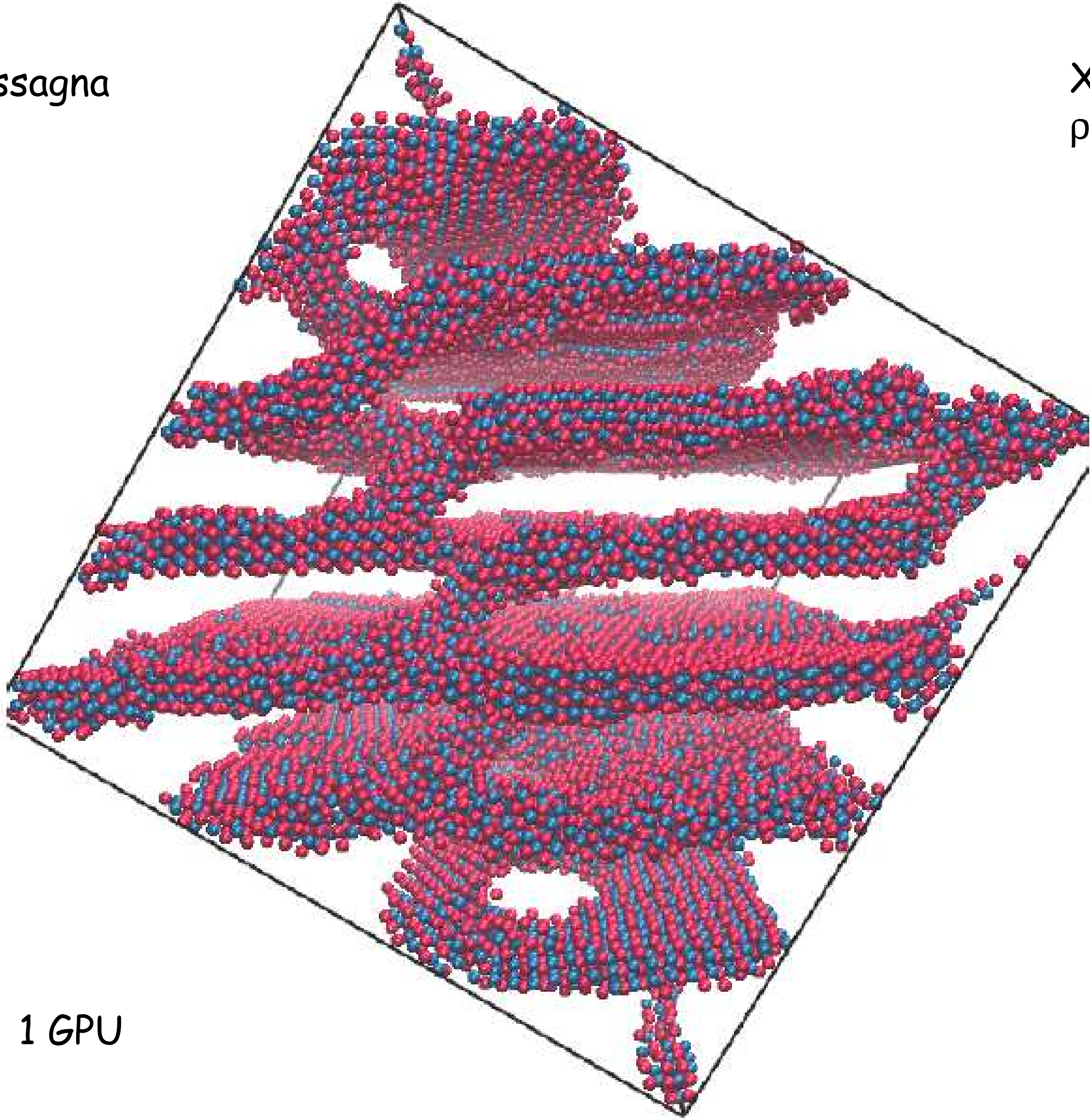


Figure 2. 3D rendering of the temperature distribution in the standard neutron star merger case (1.3 and 1.4 $M_{\odot}$, no spin; run H). The upper half of the matter distribution has been "chopped off" to allow for a view into the stars. To enhance the contrast, the upper limit of the colourbar has been fixed to 20 MeV. In the various vortices that emerge due to Kelvin-Helmholtz instabilities peak temperatures in excess of 60 MeV are temporarily reached.



cuasi Lassagna

X=0.4
ρ=0.04



N=51200 ! 1 GPU

Conclusiones :

- Sistemas con fuerzas competitivas sobrellevan una transición a Pastas a Temperaturas bajas
- Sistemas con interacciones del tipo hc + atracción de corto rango desarrollan pseudo pastas (1 por celda)
- Estos sistemas son apropiadamente descriptos vía
  - Minkowski functionals
  - g¨(r) - S(q)
  - Distribuciones de masa

- Para términos de Coulomb+debye screening debajo de λ_c pasa a 1 por celdas
- A baja temperatura las pastas son cristalinas
- Al subir la temperatura las pastas pierden su orden interno
- A temperaturas mayores aparecen pastas no tradicionales
- En todos los casos neutrino opacity, que disminuye con la temperatura
- Ambiente propicio para r-process?

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Thank you