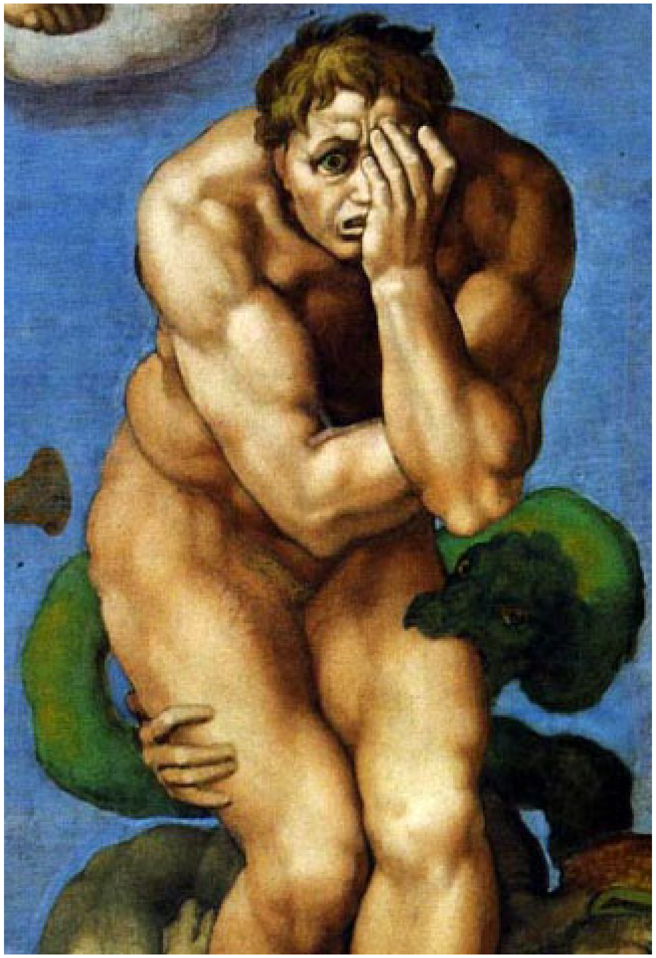
# *Nonuniform neutron rich matter: From the Laboratory to the Stars*

1. Parity Radius Experiment and the density dependence of the symmetry energy
2. Semiclassical model of nuclear pasta

C. J. Horowitz,   Philadelphia, August 2004

# All conventional matter is frustrated

- It is correlated at short distances from attractive strong interactions.
- And anti-correlated at large distances from coulomb repulsion.
- Normally these length scales are well separated so nucleons bind into nuclei segregated on a crystal lattice.



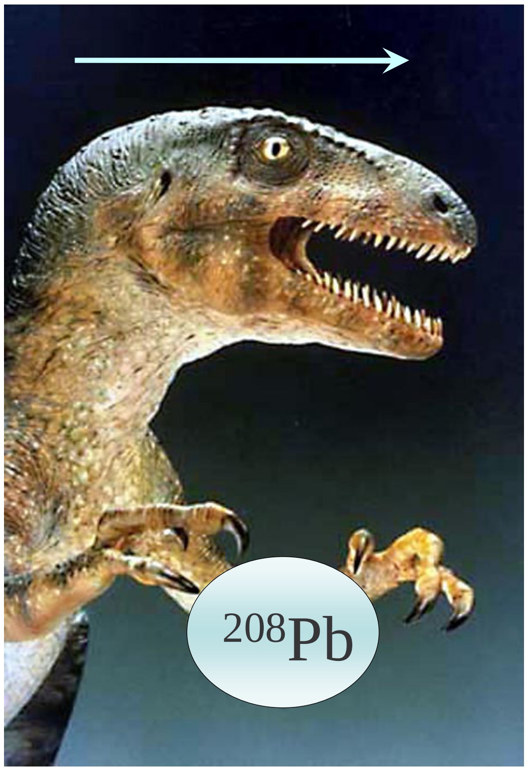
# Nuclear Pasta

- At great densities, the attractive nuclear and repulsive atomic length scales are comparable.
  - Leads to a complex ground state.
  - Can involve round (meat ball), rod (spaghetti), plate (lasagna), or other shapes.
- This “nuclear pasta” is expected in neutron star crusts and supernovae.
- It should have unusual properties and dynamics.

# Heavy Ion Collisions and Nuclear Pasta are Related

- Both driven by Coulomb and nuclear interactions.
- The Intermediate Mass Fragments in Multifragmentation are
  - Undercooked (not much time to equilibrate),
  - Undersized (role of Coulomb!),
  - Neutron poor, pasta.
- Need to extrapolate in isospin to more neutron rich systems.
  - RIA (more n rich nuclei)
  - Precession experiments with stable nuclei that provide crucial isospin information.
- Parity radius experiment (PREX) and density dependence of symmetry energy.
- Semiclassical pasta model and liquid vapor phase transition.

# Parity Radius Experiment (P-ReX)




Uses parity violating electron scattering to measure the neutron radius of $^{208}Pb$

P-ReX references:

http://cecelia.physics.indiana.edu/prex/

# Parity Violation Probes Neutrons

- Z boson couples to weak charge of neutron and proton:

  $Q_n$=-1, $Q_p = 1\text{-}4\sin^2\Theta_W \approx 0.$
- Weak charge of n $\gg$ that of p.
- Parity violating asymmetry in elastic electron scattering provides a purely electroweak probe of neutron density.

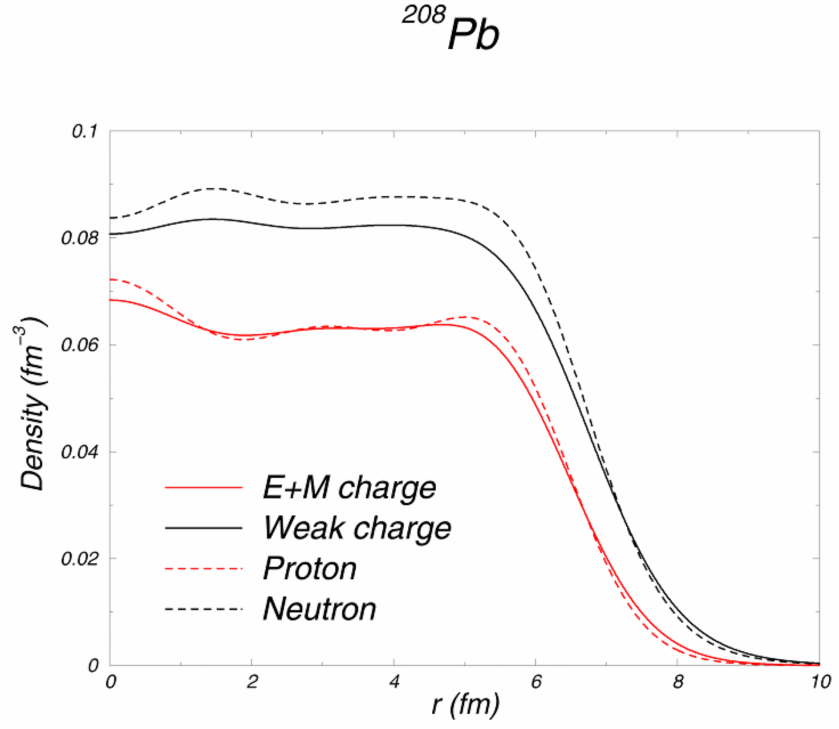
$$A = \frac{\frac{d\sigma}{d\Omega +} - \frac{d\sigma}{d\Omega -}}{\frac{d\sigma}{d\Omega +} + \frac{d\sigma}{d\Omega -}}$$

- In Born approx A measures ratio of weak to charge form factors.

$$A = \frac{G_F Q^2}{4\pi\alpha 2^{1/2}} F_W(Q^2)/F_{ch}(Q^2)$$

# Jefferson Lab Hall A exp.

- Elastic e scattering: $^{208}$Pb at 850 MeV, 6°.
- Measure A ≈ 0.6 ppm to 3%. This gives neutron radius to 1% (± 0.05 fm).
- Cleanly resolves skin: $R_n$-$R_p$ ≈ 0.2 fm.
- Theoretical interpretation of measurement is very clean.




- R. Michaels, P. Souder, G. Urciuoli spokespersons.

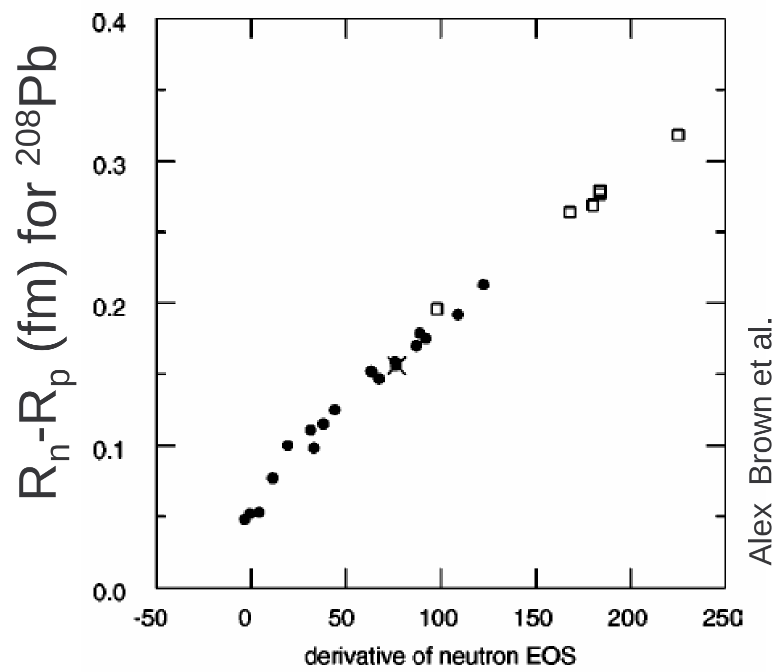
# Pb Radius Measurement

- Energy of neutron matter is E of nuc. matter plus symmetry energy.

$$E_{neutron} = E_{nuclear} + S(\rho)$$

$$P \rightarrow dE/d\rho \rightarrow dS/d\rho$$

- Pressure depends on derivative of energy with respect to density.
- Pressure forces neutrons out against surface tension. Large pressure gives large neutron radius.
- **Neutron radius determines P of neutron matter at ≈ 0.1 fm$^{-3}$ and the density dependence of the symmetry energy dS/dρ.**




Neutron minus proton rms radius of Pb versus pressure of pure neutron matter at ρ=0.1 fm$^{-3}$.

# Pb Radius vs Neutron Star Radius

- The $^{208}Pb$ radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above.
- Most interested in density dependence of equation of stare (EOS) from a possible phase transition.
- Want both low density (Pb) and high density (NS) measurements to constrain density dependence of EOS.
  - If Pb radius is relatively large then EOS at low density is stiff with high P. If NS radius is small then high density EOS soft.
  - This softening of EOS with density could strongly suggest a transition to an exotic high density phase such as quark matter, strange matter, color superconductor, kaon condensate…

# Simple Semiclassical Model of Pasta

**Contains basic frustration physics: nuclear binding and coulomb repulsion**

# Pasta Model

- Charge neutral system of n, p, and e.
- Large e Fermi energy makes them almost inert. [Electrons provide screening length $\lambda$ for Coulomb.]
- n, p interact via classical 2-body pot.

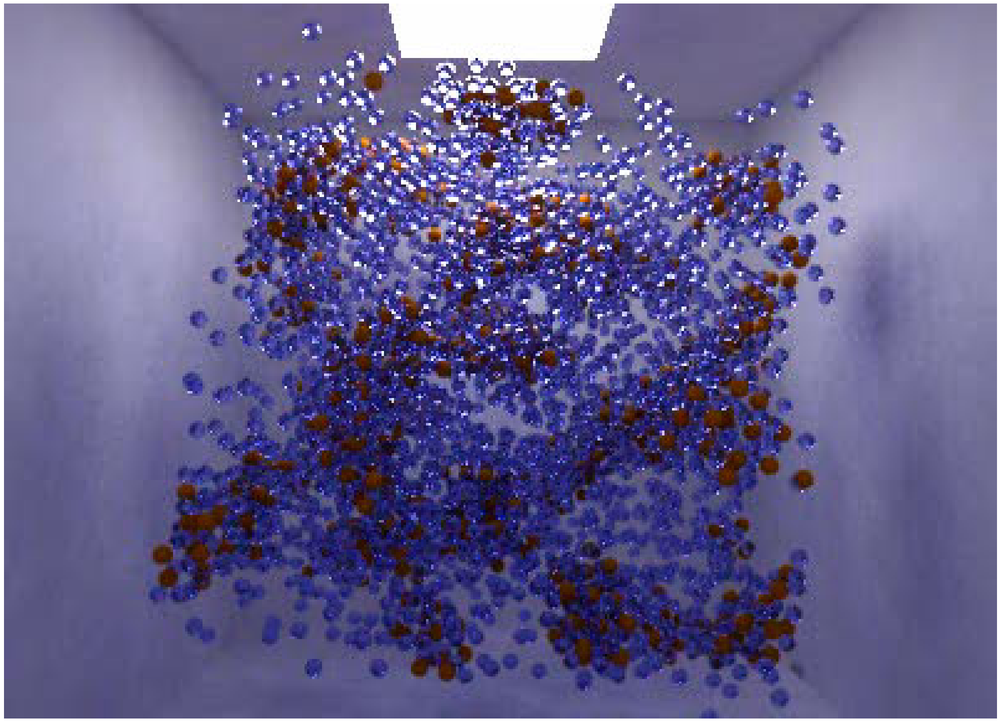
$$H = K + \sum_{i<j} v(r_{ij})$$

$$v(r)=a\,\mathrm{Exp}[-r^2/\Lambda]+ b_{ij}\,\mathrm{Exp}[-r^2/2\Lambda] + e_i e_j\,\mathrm{Exp}[-r/\lambda]/r$$

- 4 parameters a, $b_{pp}=b_{nn}$, $b_{pn}$, $\Lambda$ fit to binding E and saturation density of nuclear matter, reasonable E for pure neutron matter and some finite nuclei.
- Keep system at finite T to simulate some zero point motion and adjust parameters to account for Pauli repulsion.
- Details unimportant, model has basic frustration physics.

# Molecular Dynamics Simulation

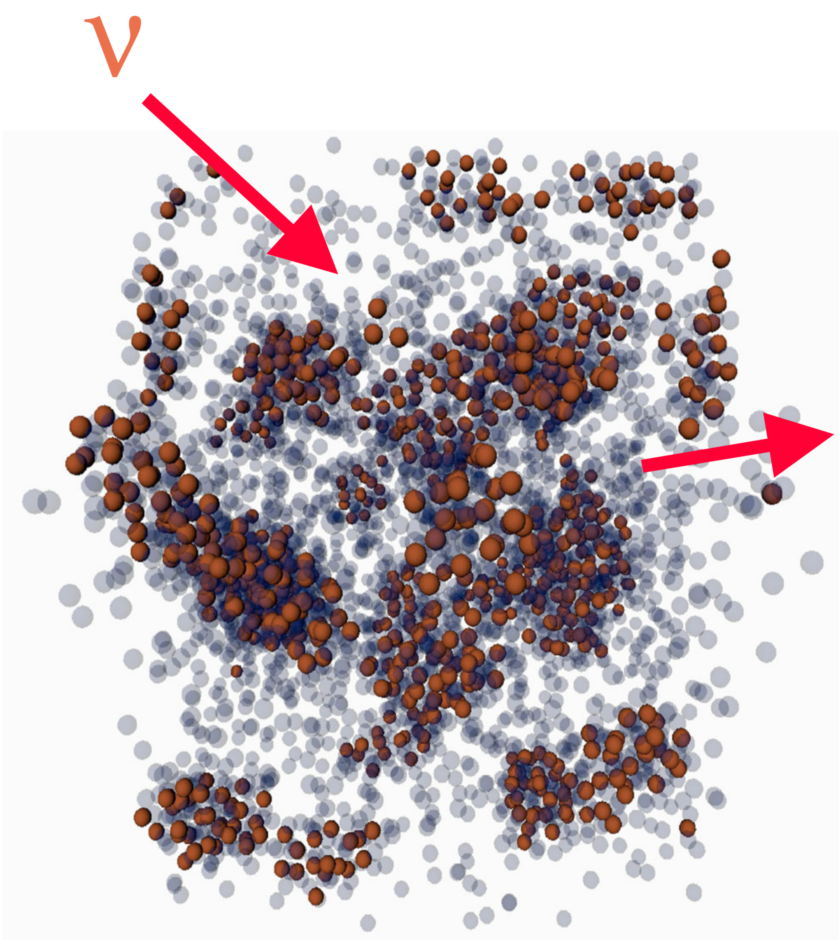
- Small run with 4000 nucleons [800 p (red), 3200 n (clear)]
- Density $\rho$=0.05 $fm^{-3}$
- Visualization by undergraduate J. Weiner.



- All pasta results for $Y_e$=0.2 and T=1 MeV.

# Neutrino Pasta Scattering

- Supernovae radiate 99% of their energy in neutrinos.
- SN dynamics very sensitive to how neutrinos interact with the matter.
- What is ν mean free path in pasta?
- What pasta modes can ν excite?



# Static Structure Factor

- Effective cross section per nucleon is

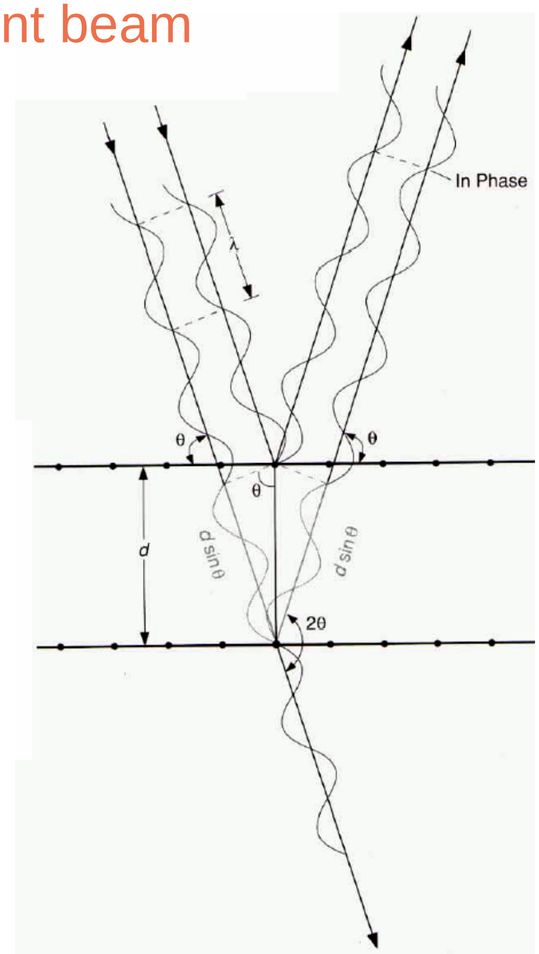
  $d\sigma/d\Omega = S(q)\, d\sigma/d\Omega|_{free}$

- Sum over all possible reflections.

  $S(q) \propto \sum_{i,j} \exp[iq \cdot r_{ij}]$

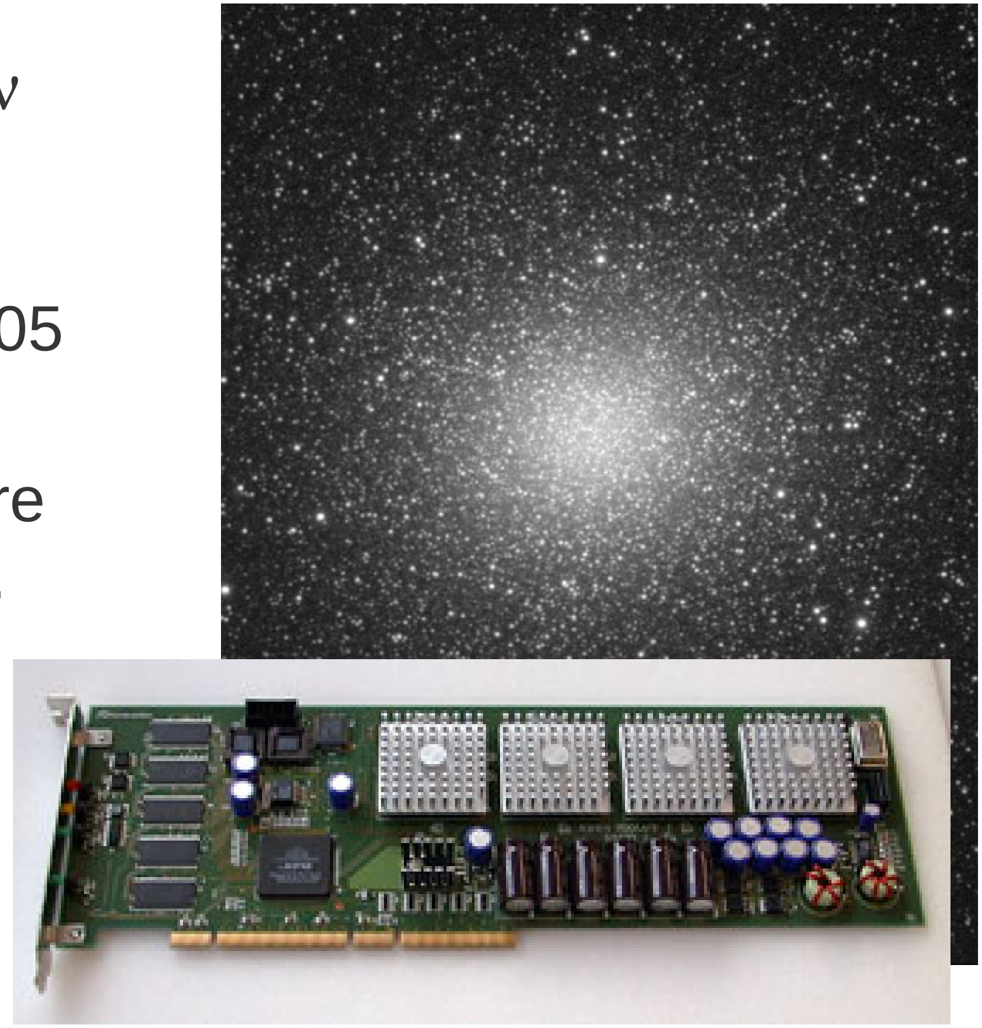
  $S(q)=1+\rho \int d^3r \; e^{iq\cdot r}\,(g(r)-1)$

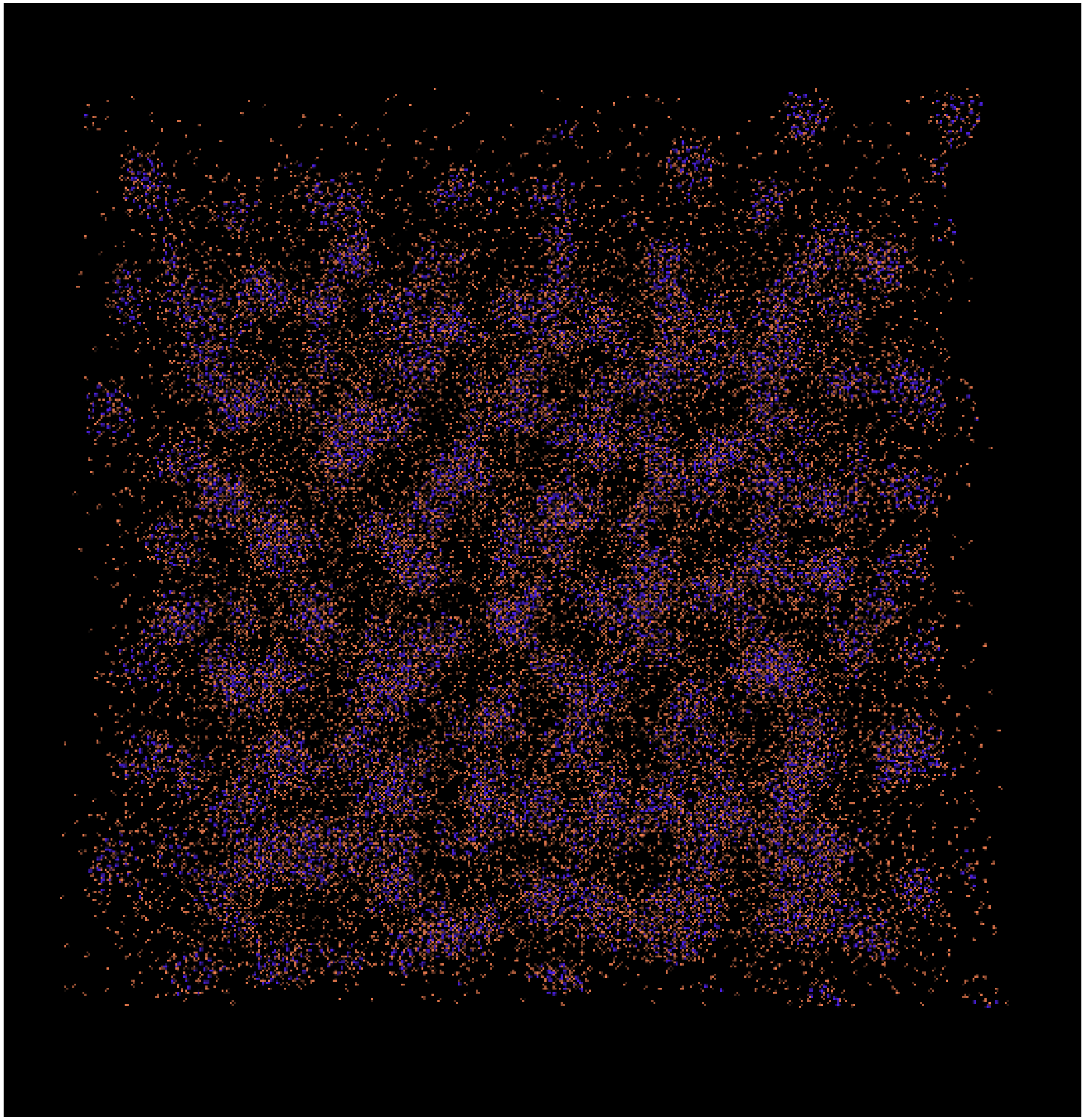
- S(q) gives the degree of coherence.



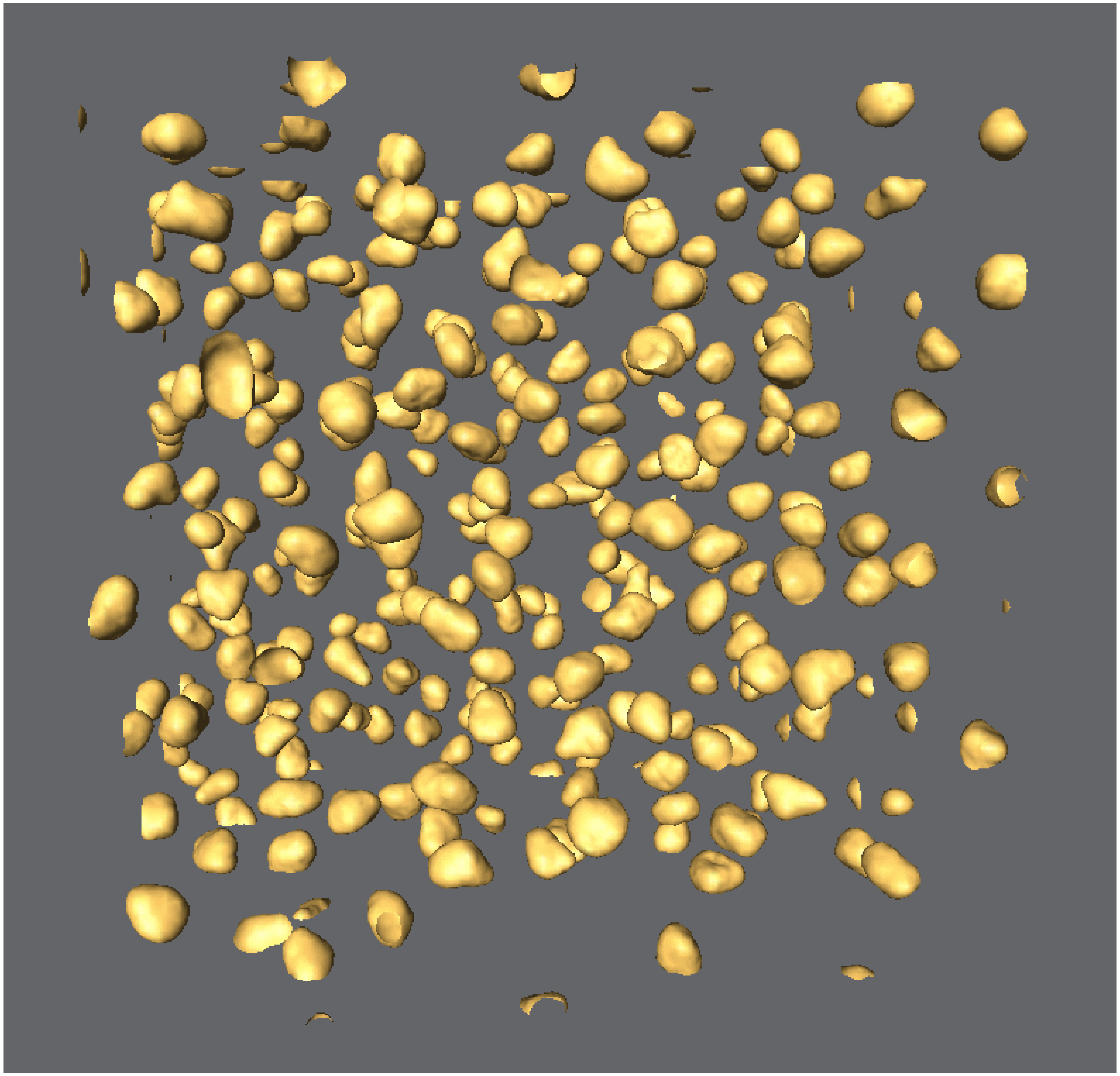
# Larger Simulations

- Wave length of 10 MeV $\nu$ is 120 fm. Hard to fit in box.
- $A=\rho\lambda^3 \approx 100{,}000$ at $\rho=0.05$ fm$^{-3}$
- Use MDGRAPE hardware to run larger simulations.
- Efficiently sums forces from all other particles.
- $\approx$ 90 times speed of single CPU.

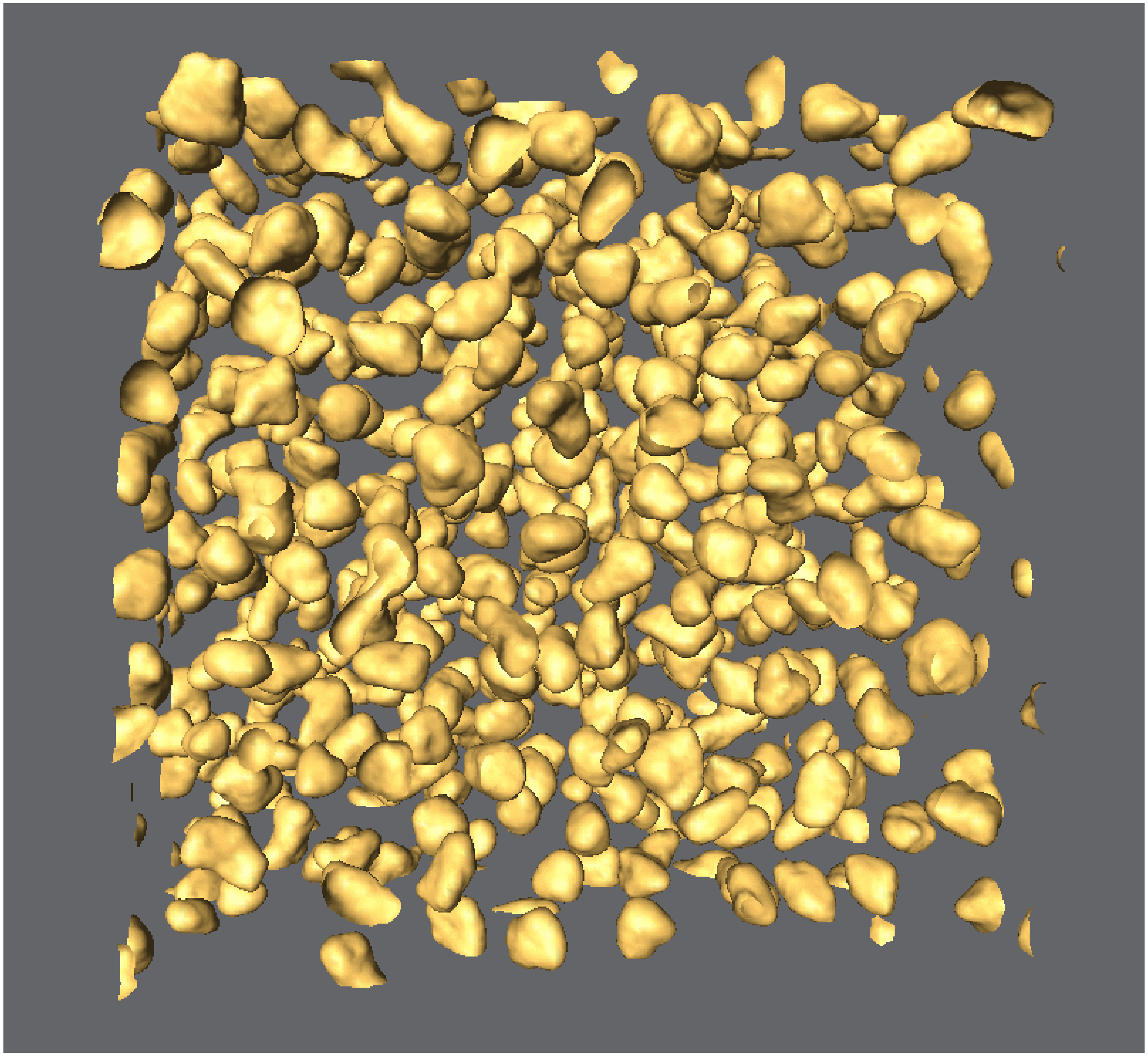




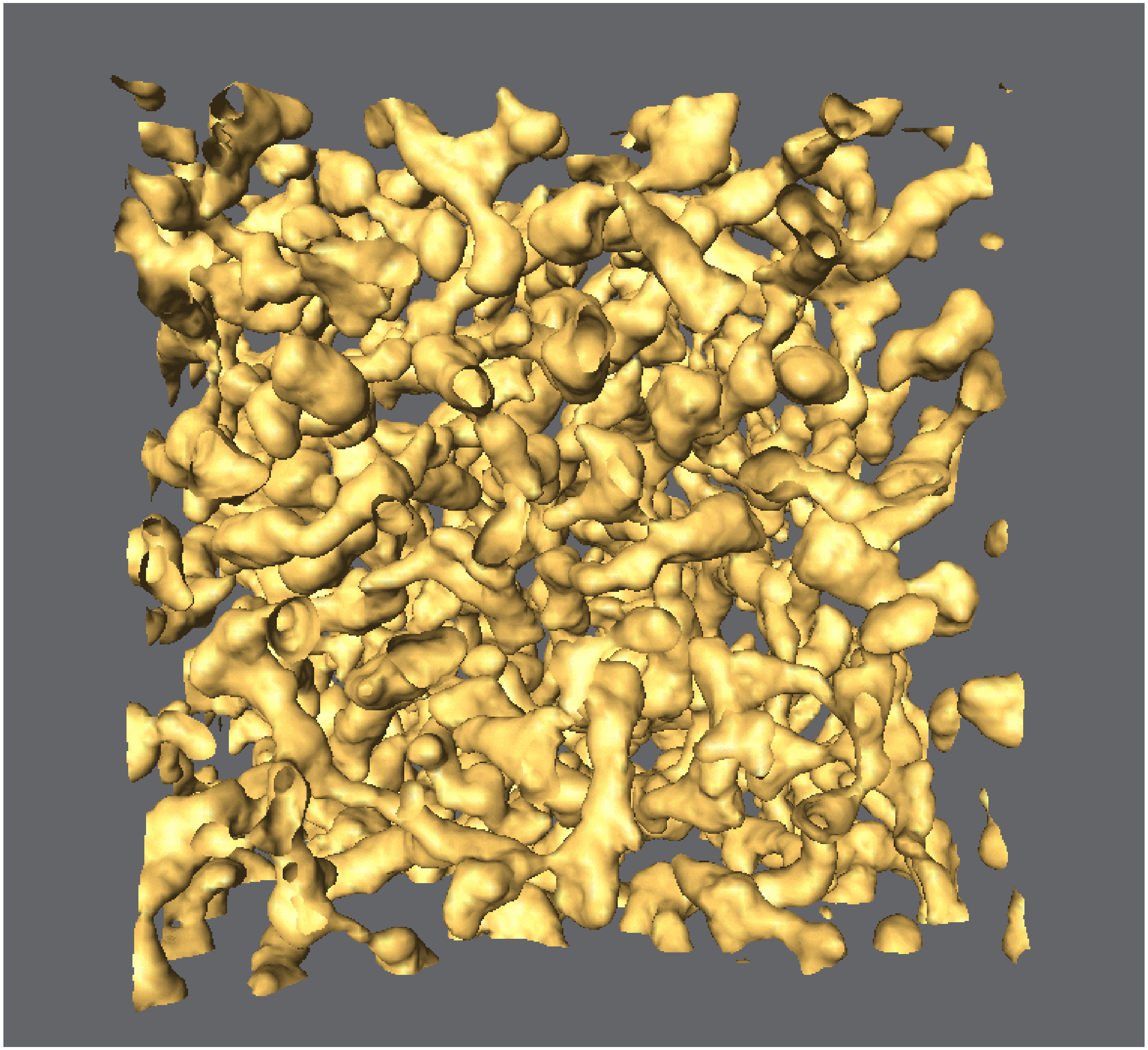
40,000 nucleons in simulation volume at $\rho$=0.01 fm$^{-3}$



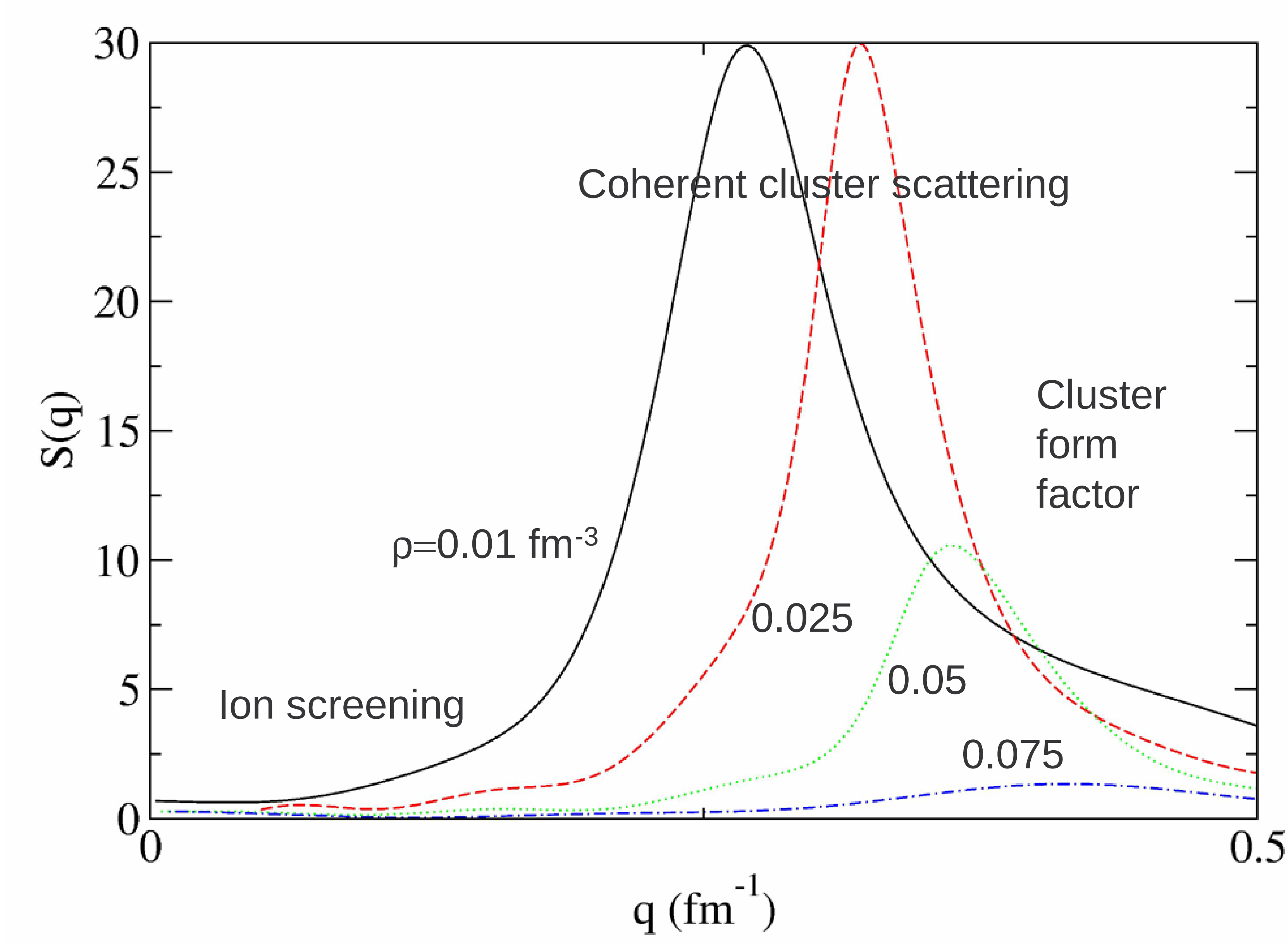
Proton density at $\rho$=0.01 fm$^{-3}$



Proton density at $\rho$=0.025 fm$^{-3}$



Proton density at $\rho$=0.05 fm$^{-3}$



30
25
20
15
10
5
0
0
0.5
S(q)
q (fm^-1)
Coherent cluster scattering
Cluster
form
factor
ρ=0.01 fm^-3
0.025
0.05
0.075
Ion screening

# Liquid Vapor Phase Transition

- In a first order phase transition, low density vapor is in equilibrium with high density liquid.
- Large density fluctuations arise as liquid is converted to/ from vapor.
- Static structure factor at q=0 related to density fluctuations.

$$S(q=0) = \frac{1}{N}[< \hat{N}^2 > - < \hat{N} >^2]$$

- Expect very large S(0) in two-phase coexistence region of simple first order phase transition $\rightarrow$ very short neutrino mean free paths in a supernova.
- We find no large enhancement of S(0) $\rightarrow$ system is ***not*** described by simple first order phase transiton.

# Phase Transitions in Systems With Two Conserved Quantities

- Need to conserve both mass (baryon #) and electric charge. [N. Glendenning]
- Density fluctuations in simple liquid vapor phase transition do not insure charge neutrality.
- Instead of simple liquid vapor transition have mixed phase region of both liquid and vapor $\rightarrow$ This is the nuclear pasta.
- S(0) in mixed phase is small from ion screening instead of being large from density fluctuations.

# Nuclear Pasta

- Competition between nuclear attraction and Coulomb repulsion leads to complicated ground state.
- Present in inner crust of neutron stars and supernovae.
- Pasta may be important for radio, x-ray, gravitational, and neutrino radiations.
- Simple semi-classical model predicts complex behavior.
- Calculated static structure factor used to describe neutrino mean free path from molecular dynamics computer simulations.

# Nuclear Pasta Family

- **Jorge Piekarewicz (FSU)**
- **Angeles Perez-Garcia (Post doc from Spain)**
- **Don Berry (IU High Performance Computing)**
- **Students:**
  - **Liliana Caballero and Helber Dussan**
  - **Joe Carriere (Neutron Stars)**
- Pasta simulations see: Phys.Rev. **C69** (2004) 045804 (astro-ph/0401079)
- Parity radius experiment see: http://cecelia.physics.indiana.edu/prex/