Exploring Nuclear Pasta Phases in Core-Collapse Supernova Matter

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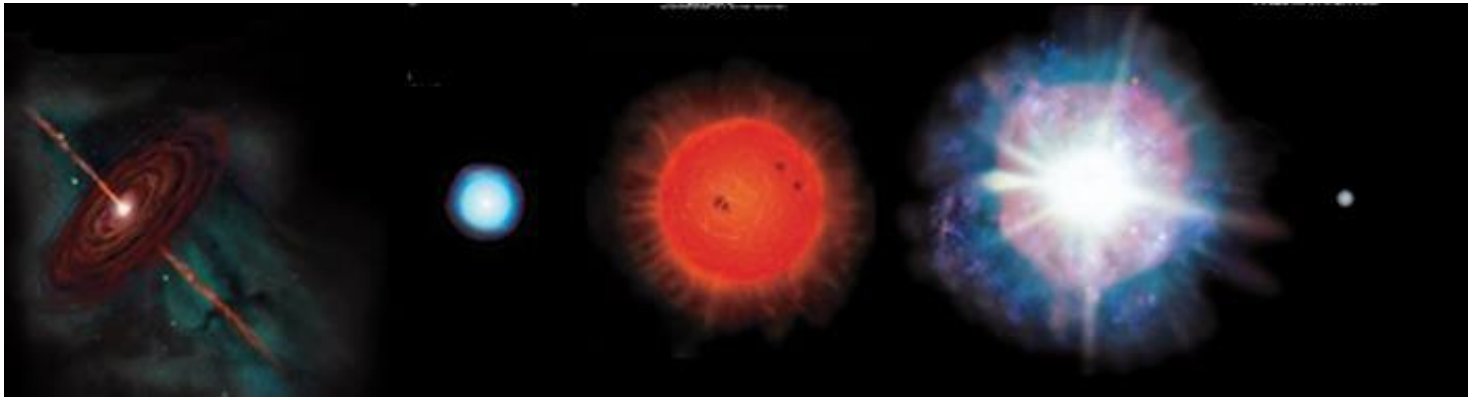
This presentation is based on H. Pais et al., PRL 109, 151101 (2012).

A self-consistent microscopic DFT calculation describes the formation, transformation and dissolution of nuclear pasta as the density increases in the core collapse of a supernova, with a new “cross-rod” shape being first identified in some density region.

When a massive star is dying …

- A massive star → Core-Collapse Supernova (CCSN)→ Neutron Star or Black Hole
- Gravity drives the collapse of the core, compressing all the matter together. Extremely compact nuclear matter forms in this process.
- Density ρ can grow to $\gtrsim \rho_s = 0.16\ \mathrm{nucleons/fm^3}$
- ρ_s is called nuclear saturation density, the density at the center of heavy nuclei.



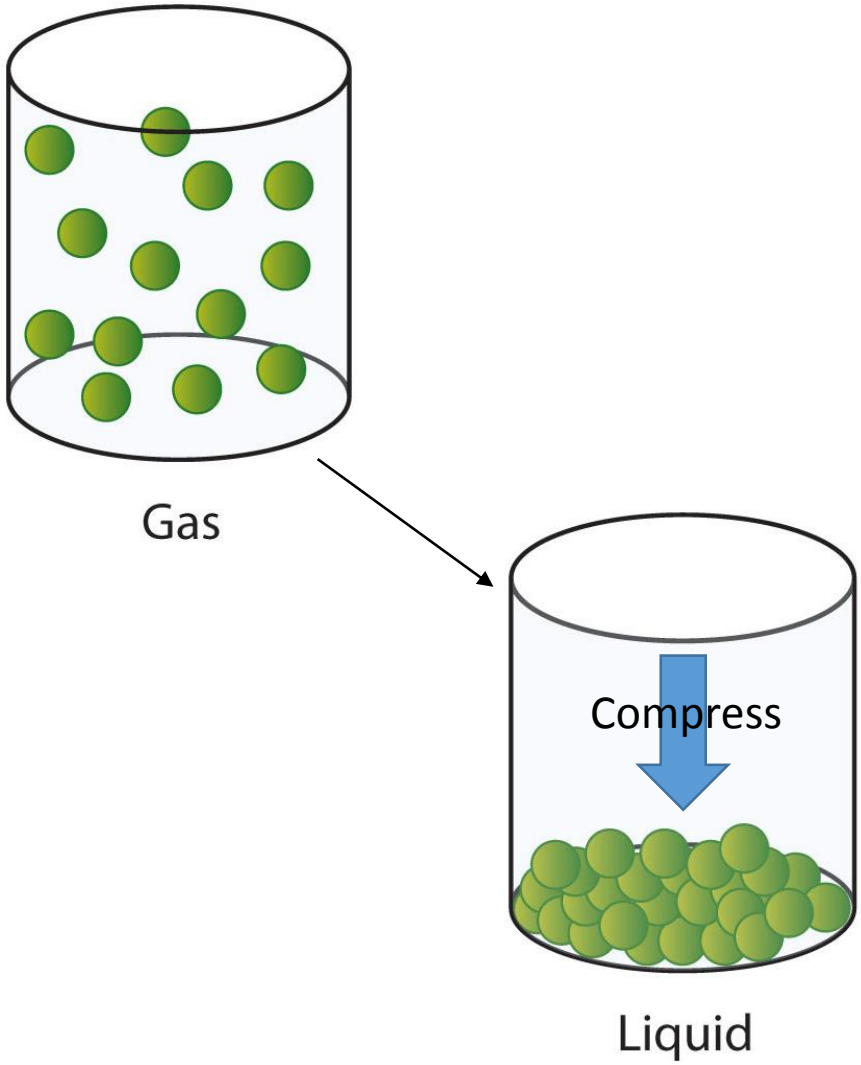
Picture taken from slides of C. Wrede

Phase transition in CCSN

- $\rho \ll \rho_s$ gas

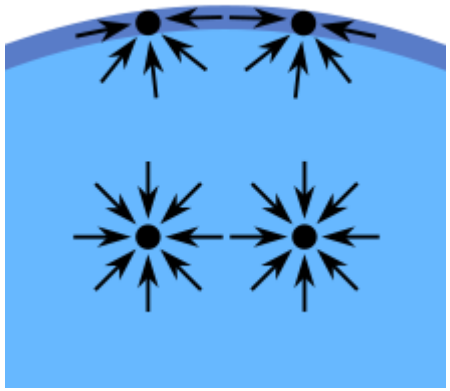
What will happen in the transitional region? (especially when ρ is just below ρ_s)

- $\rho \gtrsim \rho_s$ liquid (compact and homogeneous, just like an extremely large nuclei)



Nuclear pasta exists in the transitional region

Energy = (Volume) + (Surface) + (Coulomb)



Nuclear attraction tends to reduce the surface area and make the nucleus spherical (like surface tension).

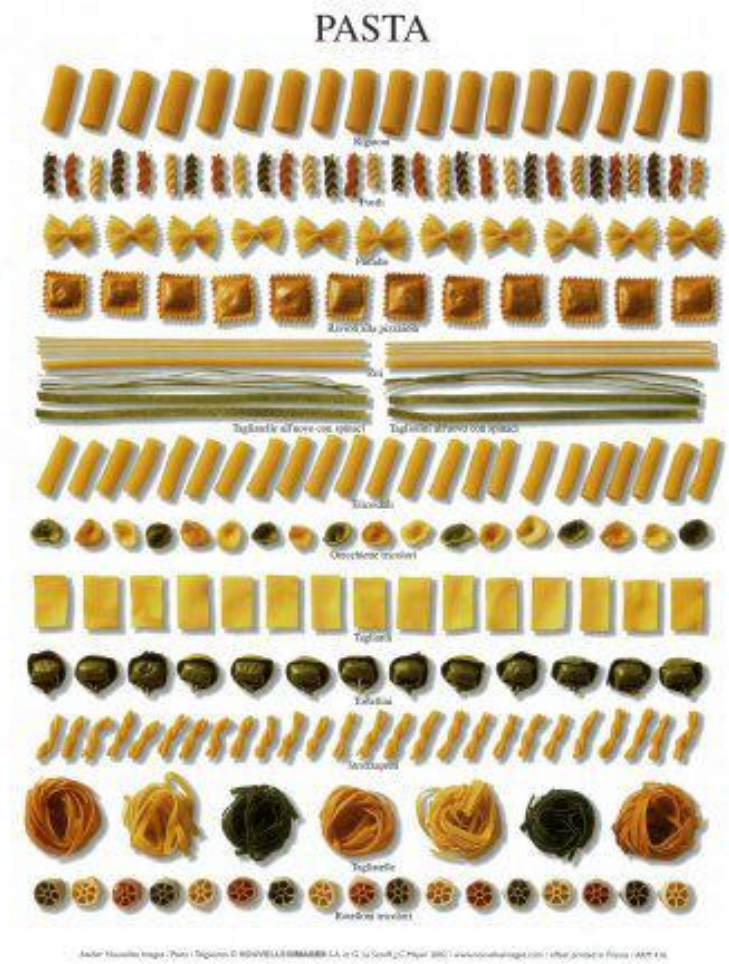
Coulomb force is repulsive and tends to make the nucleus deformed.

- Competition between nuclear attraction and Coulomb repulsion.
- When two nuclei almost touch each other, the energy of the system may be further lowered by connecting (fusing) them into a deformed, heavier nucleus.
- When ρ is just below ρ_s ($0.1\rho_s \lesssim \rho \lesssim 0.8\rho_s$), a large number of nuclei will be very close to each other and they can connect with each other to minimize the energy, forming some huge exotic structures.

Nuclear pasta exists in the transitional region

- Rods, slabs, cylindrical holes, spherical holes (bubbles) … Many kinds of pasta!
- Pasta can influence the <u>neutrino transport</u> in CCSN.
- Different forms of pasta → Different <u>equation of state</u> for supernova simulation

- What kinds of shapes are possible?
- Under what circumstances will one of these shapes appear or disappear?



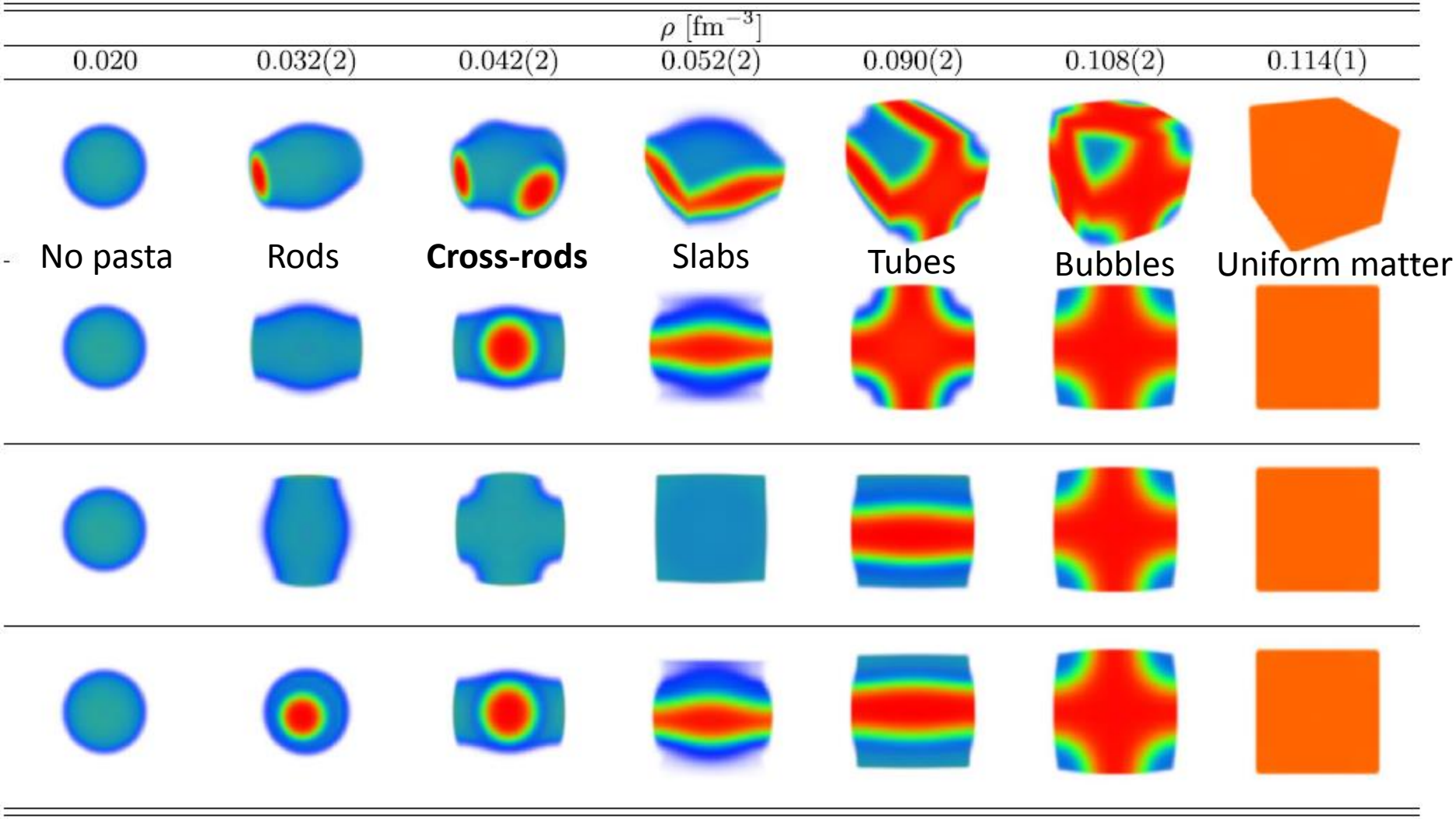
Picture taken from slides of G. Watanabe

Method

- Skyrme-Hartree-Fock calculation in three dimensions with a finite temperature
- Density functional: SkM*, SLy4, NRAPR, SQMC700
- Cubic cells, periodic boundary conditions, reflection symmetry
- Proton fraction 0.3
- Minimize the free energy w.r.t. the number of particles in a cell and quadrupole deformation
- Fully self-consistent microscopic calculation. Less simplification compared with previous works and more details of nuclear structure included.

Neutron density distribution

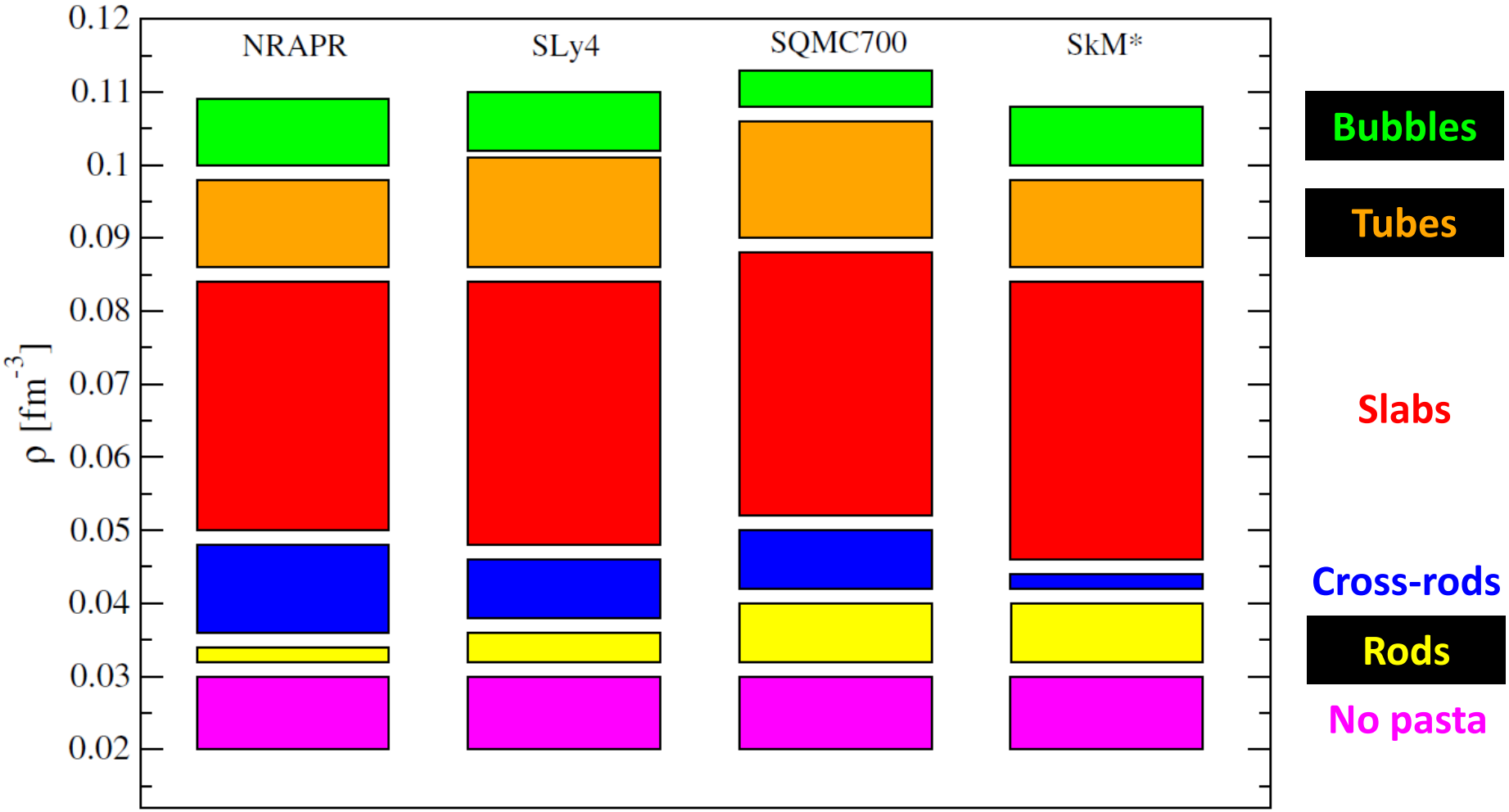
Temperature = 2 MeV
SQMC700



Density scale:
0.001 (dark blue)—0.02475 (light blue)—0.0485 (green)—0.07225 (light orange)—0.095 (red) fm^3

Transition densities between different phases

Temperature = 2 MeV



Conclusion

- The onset of nuclear pasta and its dissolution to uniform liquid in CCSN matter are identified by fully self-consistent calculations. The density regions for different pasta formations are also identified.

- On the currently used density and temperature grid, all accepted shapes have been identified with one new cross-rod shape.

- The results will be used to
  model neutrino transport in CCSN
  construct the equation of state for simulating the evolution of CCSN.

Thanks for your attention!

References:
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