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Inner crust
nuclear clusters in a see of neutrons and electrons

depth

density

800 m

Mantle

$0.05\ \mathrm{fm^{-3}}$

Unified description of the neutron star interior: Nuclear pasta mantle

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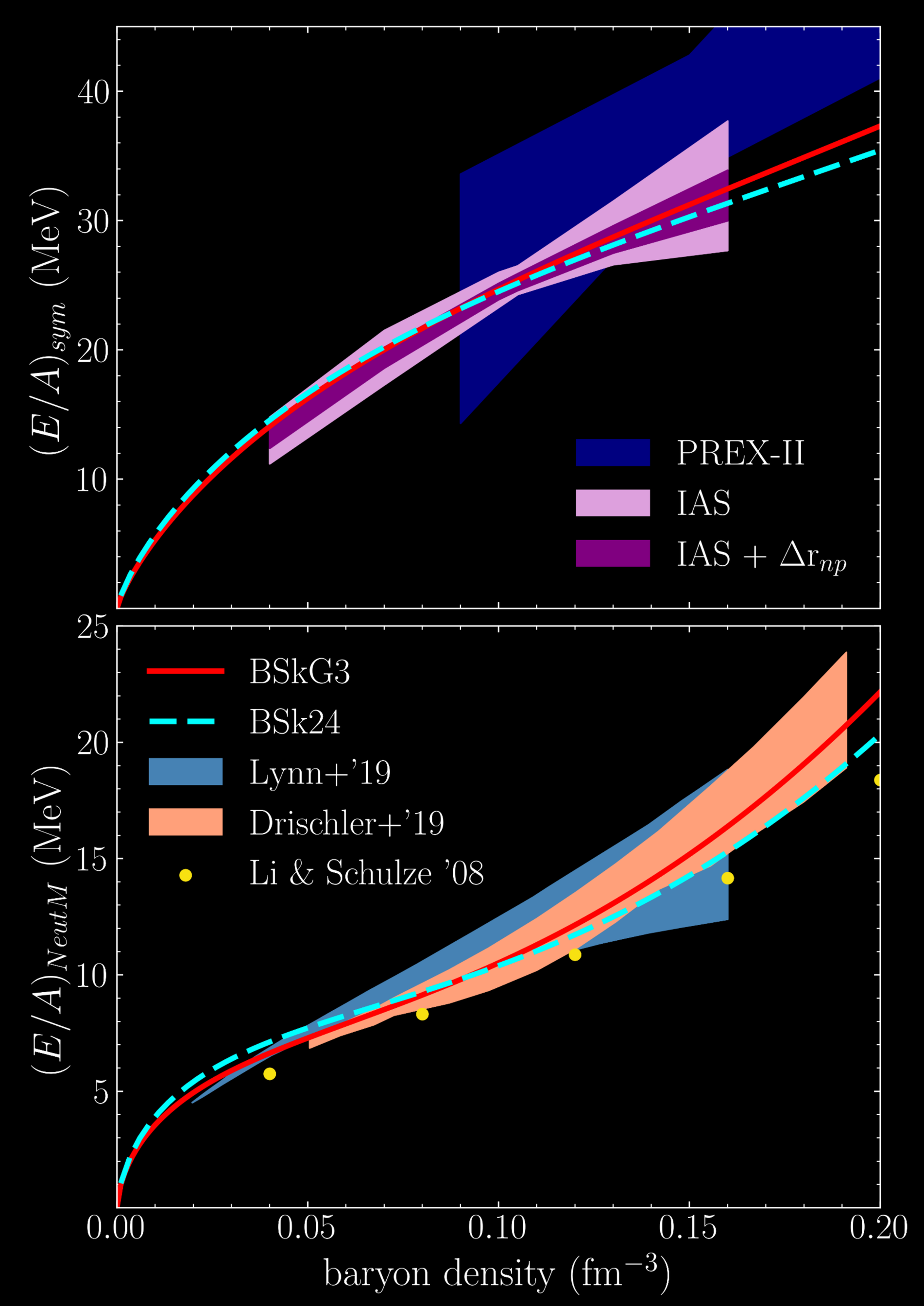
Abstract: The unified treatment of all regions of neutron stars (NS) is essential for the consistent description of various phenomena associated with the birth, life and death of NSs. To this end, we construct the family of BSk parametrizations based on the generalized Skyrme-type interaction capable of reproducing numerous experimental and theoretical nuclear data as well as fulfilling astrophysical constraints. Here, we employ the energy-density functional (EDF) theory with the latest BSk parametrizations for the most numerically challenging region, NS mantle. It is located between the crust and the core of a NS and consists of exotic nuclear pasta structures. We find that semi-classical models predict a broad mantle layer containing the same mass as the NS crust. However, incorporating microscopic corrections drastically reduces the pasta abundance and raises the question of whether pasta phases exist at all. In order to get a more definite answer, we aim at performing three-dimensional fully quantum-mechanical simulations and present here proof-of-principle calculations with the MOCCa solver.

BSk nuclear functionals

The BSk family is developed for multi-purpose applications including the study of NS structure, supernova explosions and r-process nucleosynthesis. They are based on the generalized Skyrme-type effective force, accounting for additional density and momentum-dependent terms, coupled with the realistic pairing interaction. The force parameters are accurately calibrated to reproduce the experimental nuclear data with nuclei being described within the Hartree-Fock-Bogoliubov (HFB) method considering (tri)axial deformations. The latest entry, BSkG3 [1], offers

- rms = 631 keV for 2457 masses from 2020 atomic mass evaluation
- rms = 0.024 fm for radii
- rms = 330 keV for primary fission barriers
- Symmetry energy in agreement with experimental data
- Neutron matter consistent with χEFT and Brueckner-Hartree-Fock calculations



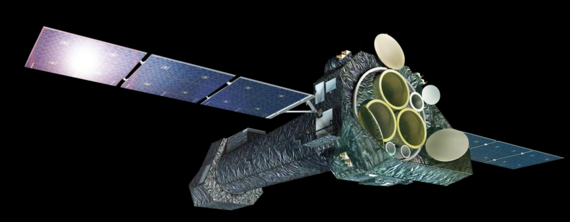
Pasta observable effects

Pasta phases determine the microphysical structure of the mantle, which is important for transport and mechanical properties. The latter resembles the ones of liquid crystals, giving rise to the name, mantle. The emergence of pasta can affect:

- Thermal and electrical matter conductivities
- Opening of direct Urca process
- Pinning and formation of superfluid vortices
- Elastic moduli and breaking stress

This makes pasta phases relevant for

- NS magneto-thermal evolution
- Quasi-periodic oscillations in magnetars
- Continuous gravitational wave emission
- Glitches

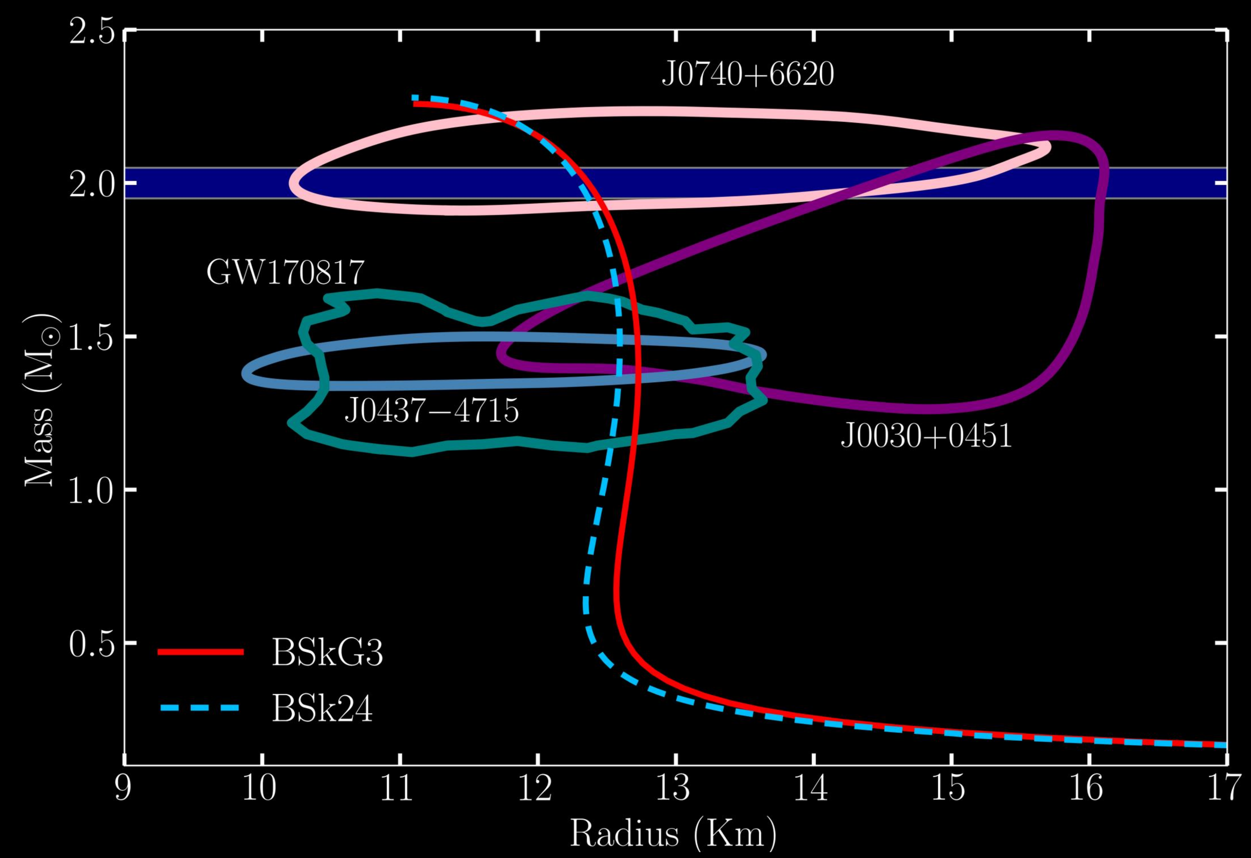


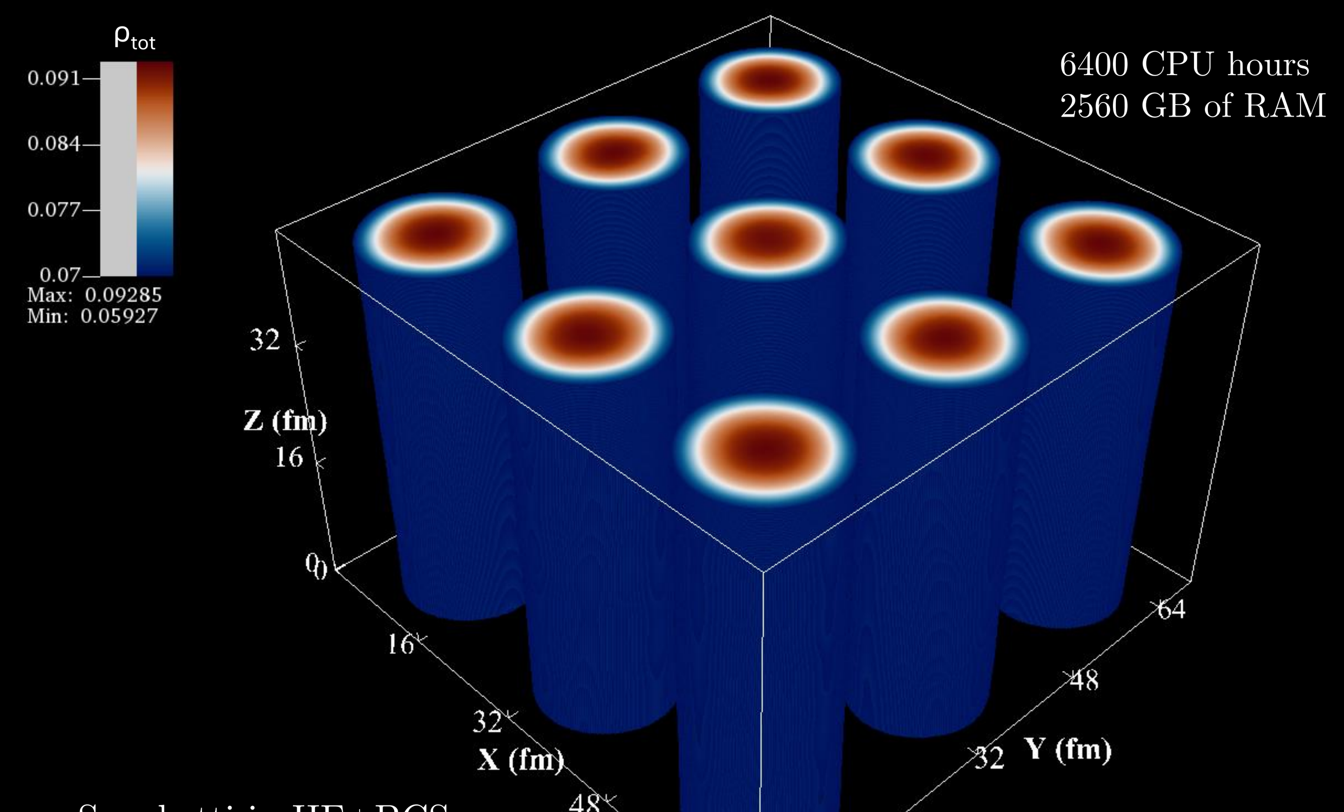
3D simulations

We employ 3D HFB code MOCCa [5] with BSkG3 to perform the most realistic pasta calculations. We equip MOCCa with periodic boundary conditions and improve its performance. To speed up the simulations we treat pairing problem in the Bardeen-Cooper-Schrieffer (BCS) approximation and use semi-classical solutions for the initialization.

Neutron star properties

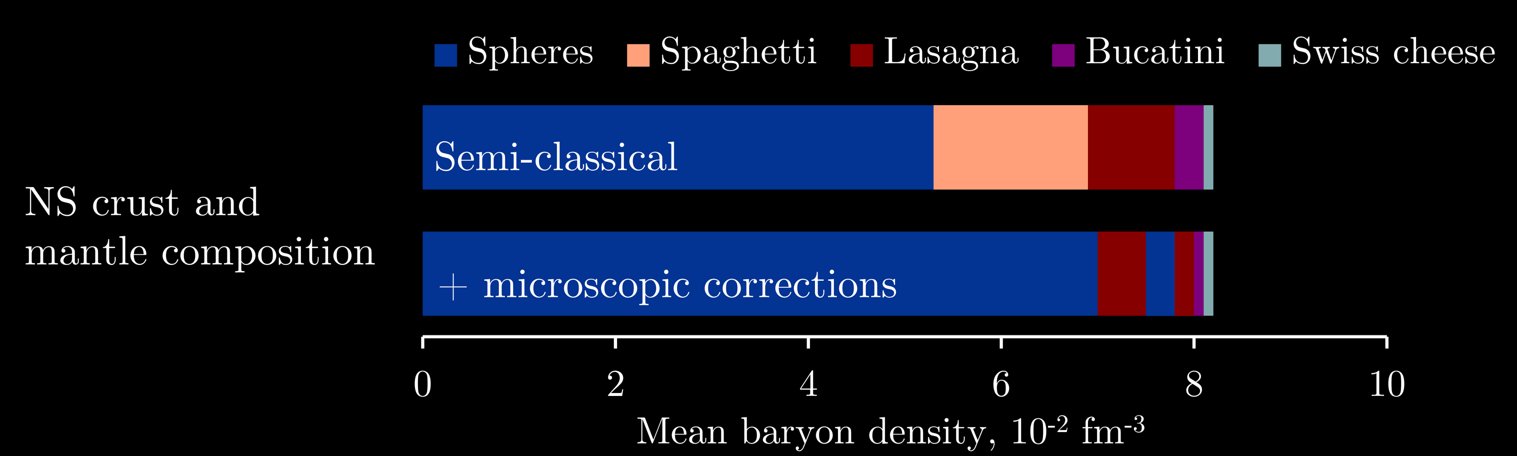
The NS equation of state (EOS) obtained with the BSkG3 parametrization and with our previous functional BSk24 [2] are compatible with the latest NICER data on three pulsars and the NS merger event GW170817. In addition, they allow for the direct Urca process inside $\approx 1.5 M_\odot$ NS, the property required by NS cooling observations.



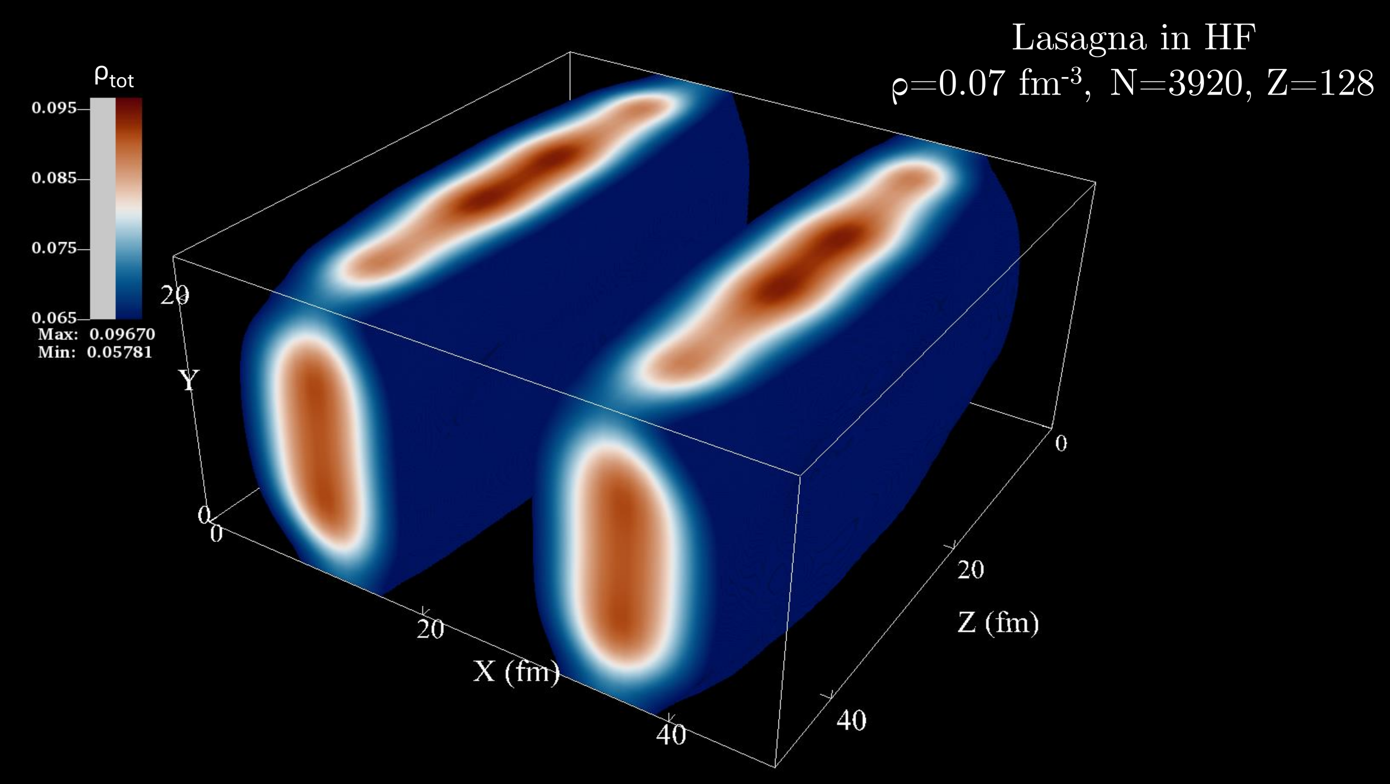


Spaghetti in HF+BCS
$\rho=0.07\ \mathrm{fm^{-3}}$, N=16164, Z=540

Calculations of the NS inner crust and mantle consisting of experimentally inaccessible inhomogeneous nuclear matter strongly rely on theoretical nuclear models. Namely, the EOS largely depends on the bulk nuclear matter properties, while the composition appears to be as well sensitive to the microscopic corrections [3,4]. Thus, it is crucial to employ microscopic EDF models with realistic BSk functionals to determine, in particular, the appearance of the mantle layer with exotic pasta-like structures.



Lasagna in HF
$\rho=0.07\ \mathrm{fm^{-3}}$, N=3920, Z=128



1000 m

Outer core
homogeneous mixture of nucleons and leptons

$0.08\ \mathrm{fm^{-3}}$

References

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3. N.N. Shchechilin, N. Chamel, J.M. Pearson, Phys. Rev. **C** 108, 025805 (2023)
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12 km to the center (71 m on the scale of this poster)

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