



SLS

Space Launch System

Lattice Boltzmann Method for Spacecraft Propellant Slosh Simulation

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- ◆ **Microgravity propellant dynamics continue to offer a formidable modeling challenge for the computational fluid mechanics community**
 - Analytical approaches to prediction of bulk behavior, e.g. tank forces and moments, degrades in accuracy below $Bo \sim 10$; small perturbations only
 - Flows dominated by surface tension; curved interfaces; fluid-wall contact angles approximately zero
 - Many semi-analytical or empirical methods that correlate well with theory rely on quasi-steady-state parameters and cannot accurately predict effects of transient flows, e.g. throttling, thruster pulses
 - Momentum transfer due to fluid must be computed accurately for simulation-based verification
- ◆ **Our research explores the applicability of the lattice Boltzmann method (LBM) to modeling of cryogenic propellant dynamics in microgravity**

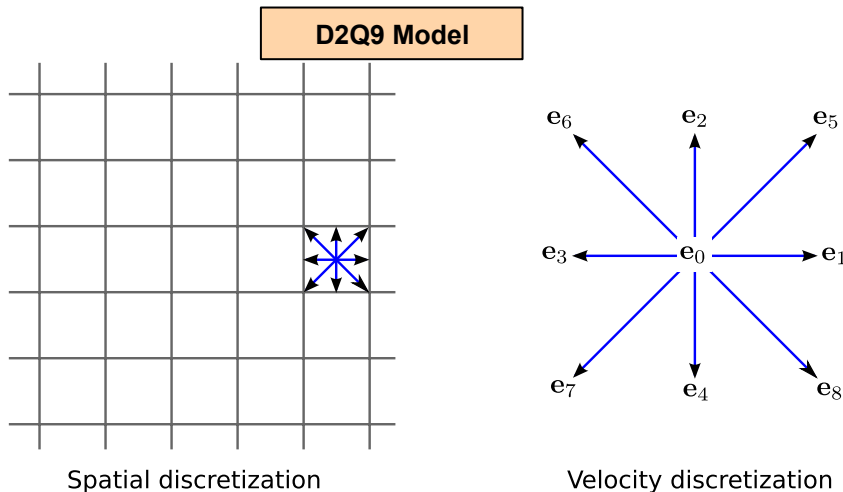
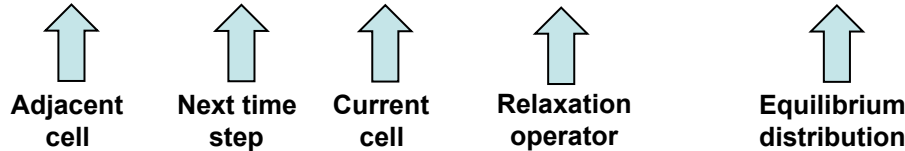


- ◆ The lattice Boltzmann method (LBM) is an emerging approach to CFM using an explicit temporal and spatial discretization of the continuous Boltzmann equation:

$$\frac{\partial f}{\partial t} + \xi^T \nabla_{\mathbf{x}} f + \mathbf{a}^T \nabla_{\xi} f = \Omega(f)$$

- Describes evolution of particle distribution functions, e.g. density distribution
- Regular Cartesian discretization of a 2XD position-velocity phase space on a lattice
- In discrete form, the lattice Boltzmann equation is given by

$$f(\mathbf{x}_k + \mathbf{e}\delta t, t_0 + \delta t) = f(\mathbf{x}_k, t_0) - \mathbf{A} (f(\mathbf{x}_k, t_0) - f^{\text{eq}}(\mathbf{x}_k, \mathbf{u}_k, \rho(\mathbf{x}_k))) \delta t$$



Conserved Moments

$$\rho(\mathbf{x}_k) = \sum_i f_i(\mathbf{x}_k)$$

$$\rho(\mathbf{x}_k) \mathbf{u}_k = \sum_i \mathbf{e}_i f_i(\mathbf{x}_k),$$

◆ **The fluid dynamics are propagated in two steps over multiple layers**

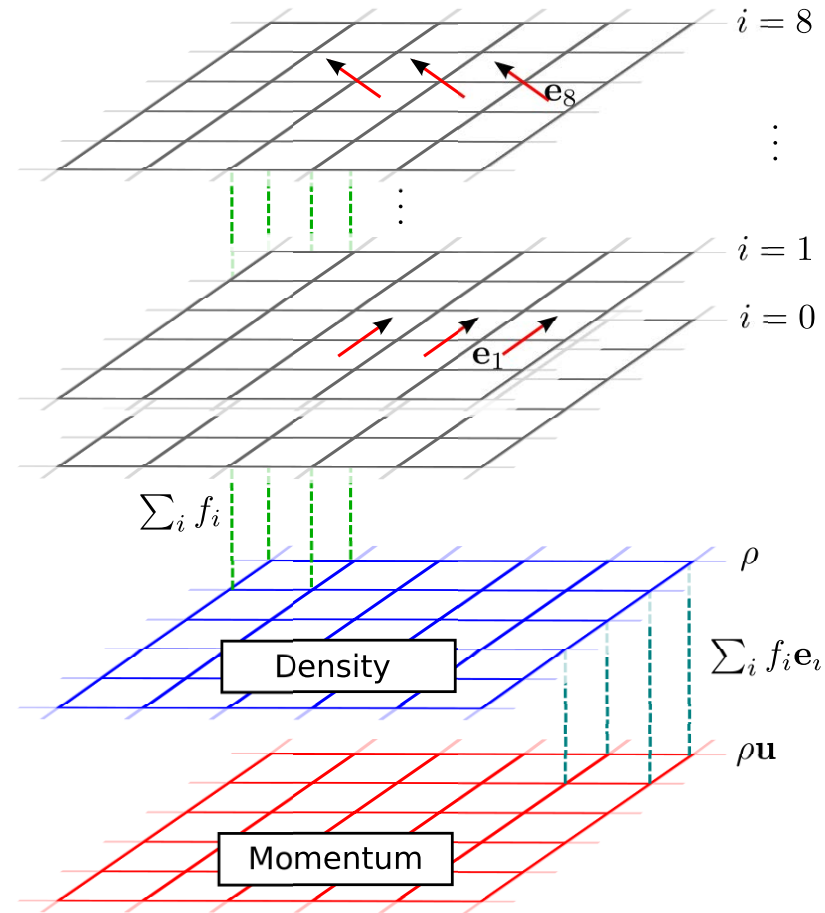
1. Advection (copy fluid density to adjacent cell: “streaming”)
2. Collision (simulate collisions by relaxing toward Maxwell equilibrium: “relaxation”)

◆ **Proper choice of units (time=space=1) and periodic lattice: no actual data copy**

- The streaming step is done using pointer arithmetic: *fast*
- Data locality (only need knowledge of adjacent cells): *parallelization*

◆ **Limitations:**

- Constant (wall) temperature: isothermal flow
- Effective speed of sound is related to the lattice physical parameters
 - Compressibility error increases as $M > 0.1$
 - Incompressible flow approximation is valid only for steady flow at low velocities
- Stability *decreases* as timestep decreases at a fixed kinematic viscosity



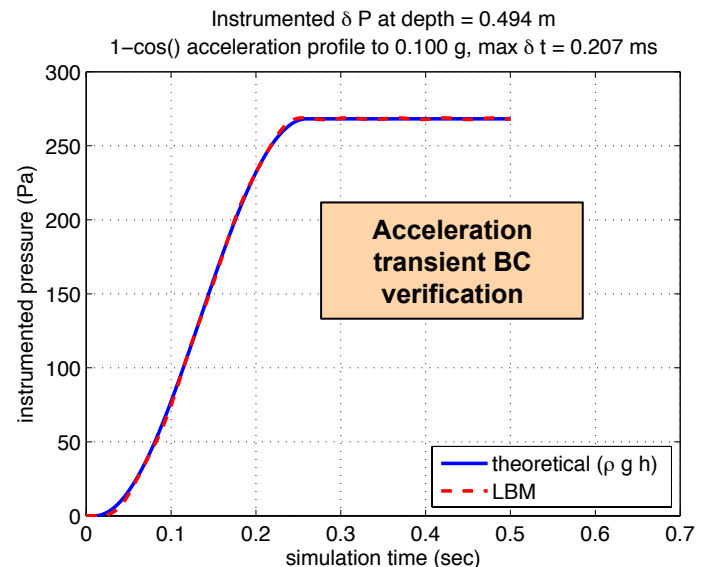
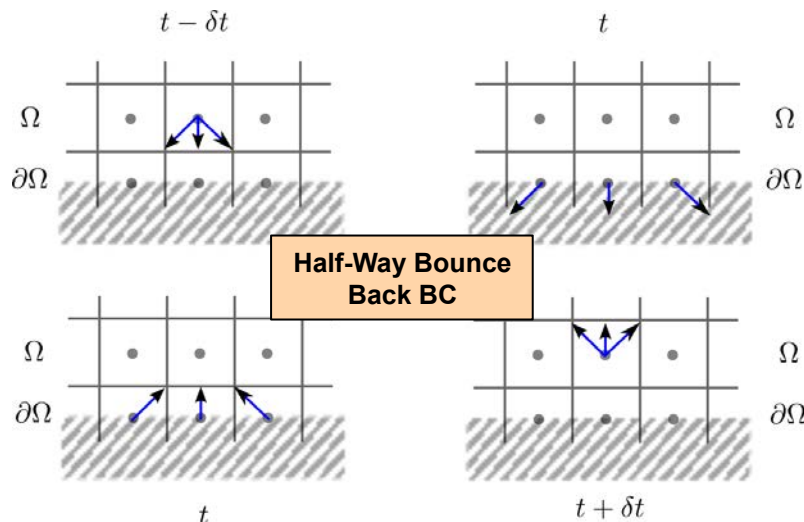


◆ **Wall boundary conditions are straightforward to implement**

- So-called “bounce back rule”: invert velocity distributions at boundary
- Reconstruct unknown distributions by storing in boundary for one timestep
- Not a hydrodynamically accurate BC, but simulates no-slip wall
- More accurate BCs are required for free slip, walls with high curvature, inlet flow, etc.

◆ **Relaxation operation and body forces**

- Body forces implemented using Kupershtokh exact difference method (EDM)
- Shift equilibrium distribution under action of force such that lattice remains in equilibrium
- Relaxation operation uses multiple relaxation time (MRT) scheme accounting for variation in kinematic viscosity with optional subgrid turbulence model



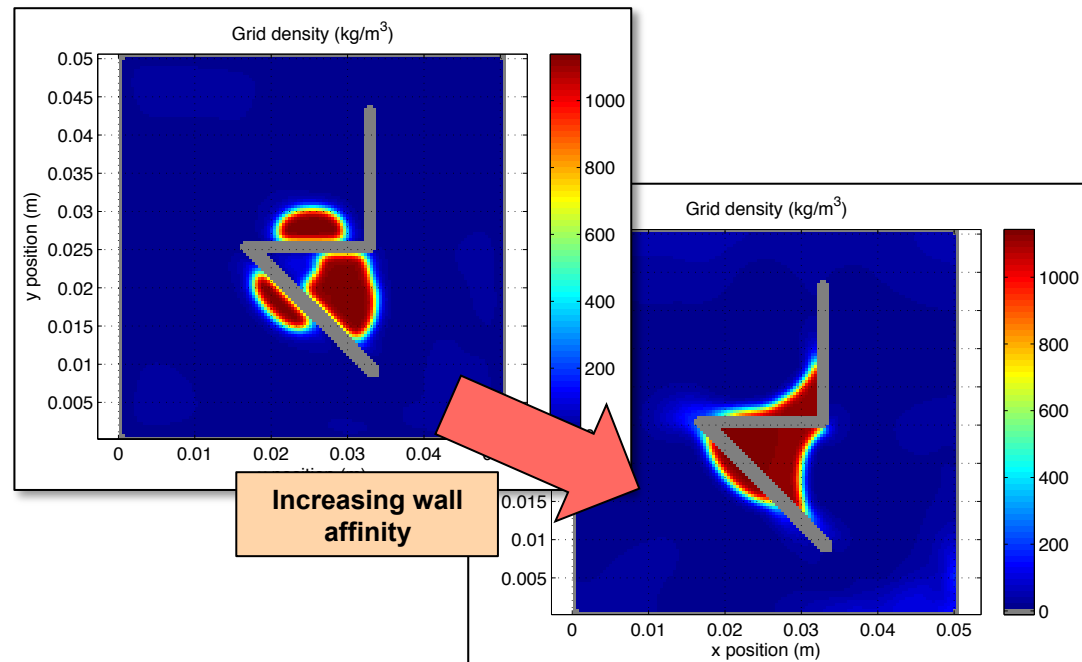
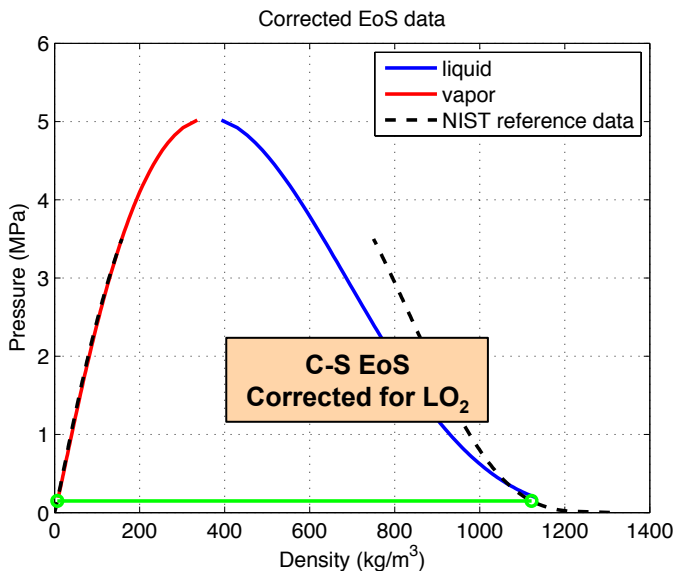
◆ **LBE models allow incorporation of multiple phases uniformly in the lattice**

- Phase separation explicitly depends on temperature and a real gas EoS
- We use the Carnahan-Starling EoS corrected for the target conditions (LO₂ @ 94K) in a Shan-Chen like pseudopotential model

$$p = \rho RT \frac{1 + b\rho/4 + (b\rho/4)^2 - (b\rho/4)^3}{(1 - b\rho/4)^3} - a\rho^2$$

- Phase segregation approximately obeys Maxwell construction (“mechanical stability”)

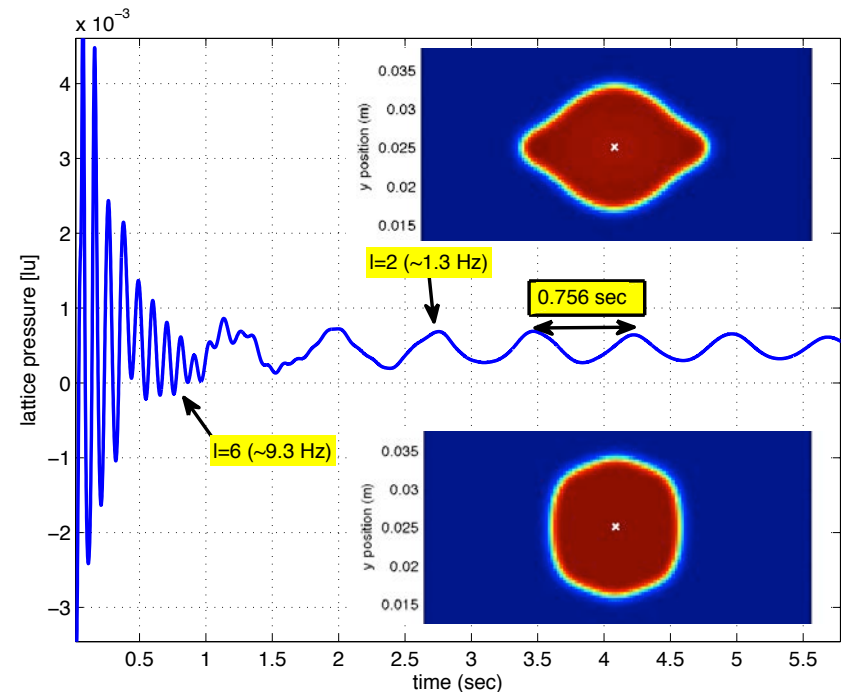
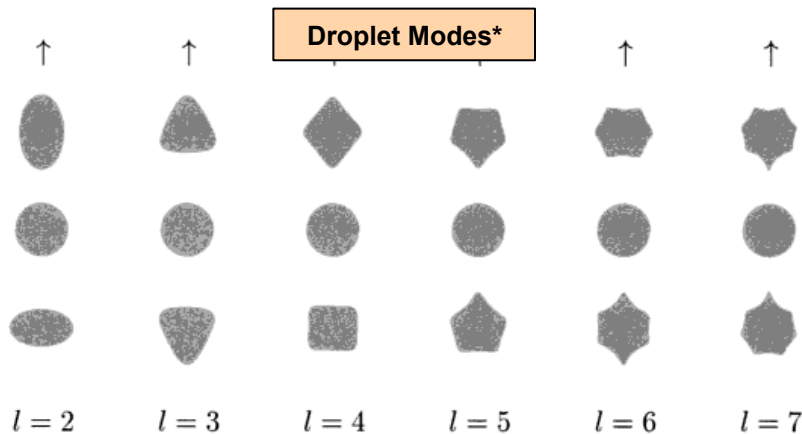
◆ **Parametric wall wetting model allows tuning of free surface contact angle**



- ◆ **The behavior of droplets in microgravity is dominated by surface tension**
 - Droplet dynamics provide a useful verification case due to analytical solutions
 - Oscillation of the free surface can be predicted by Lamb's equation
 - Effective surface tension can be determined from frequency

$$\omega^2 = \frac{l(l-1)(l+2)}{r^3 \rho_L} \sigma$$

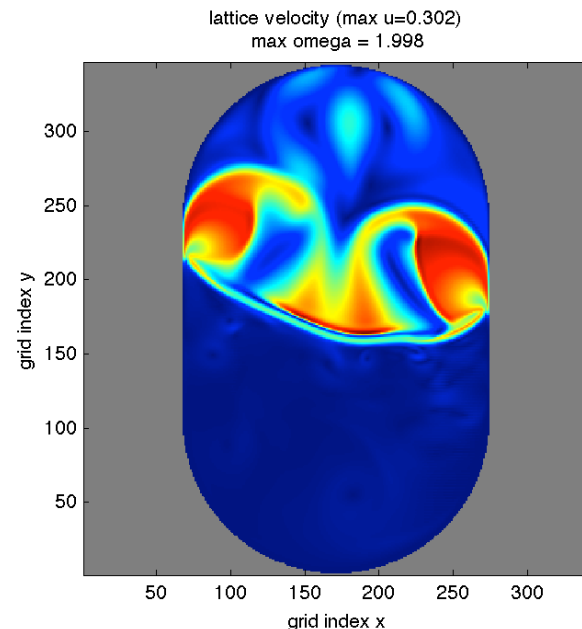
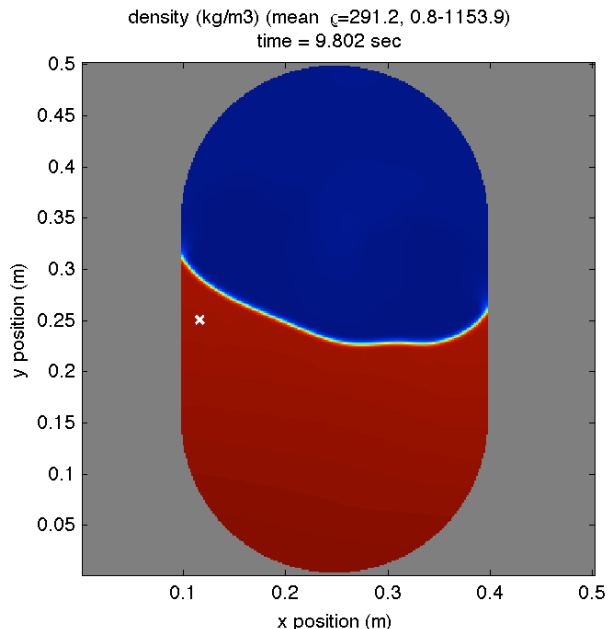
↑ Mode frequency ↑ Droplet radius ↑ Surface tension



*Frohn, A., and Roth, N. Dynamics of Droplets. Springer, 2000

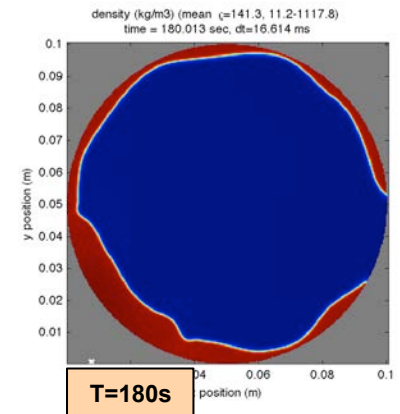
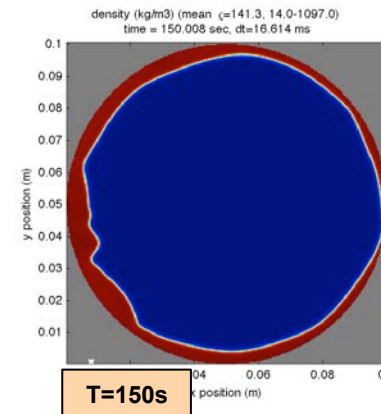
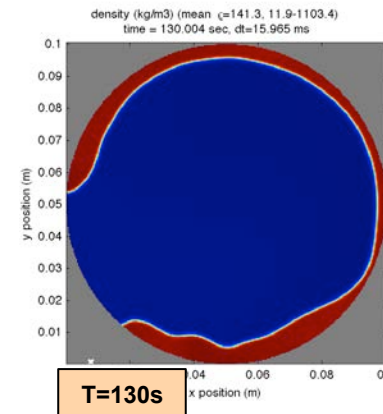
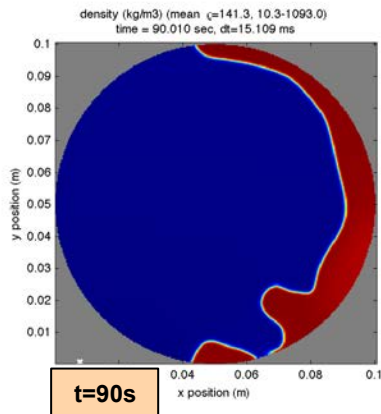
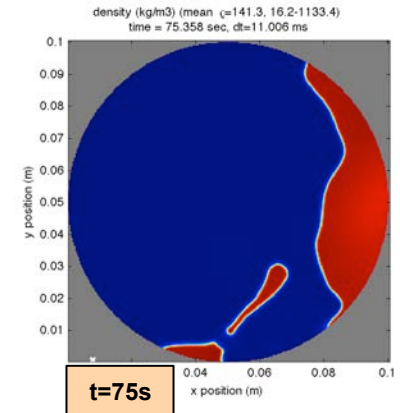
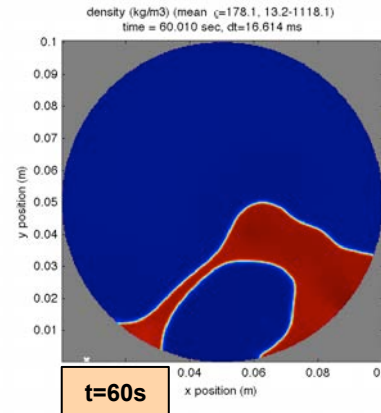
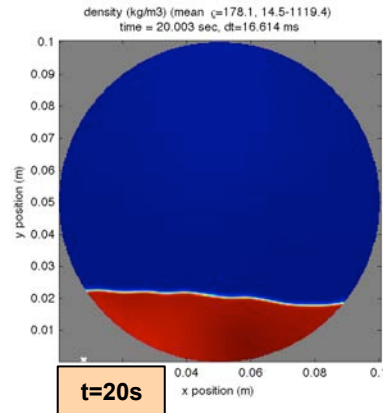
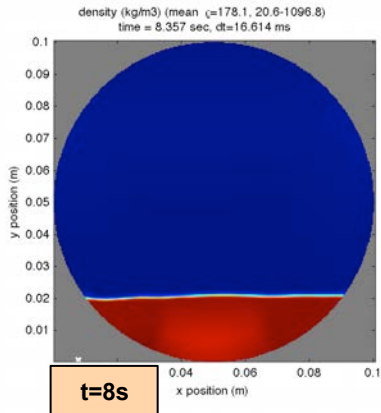
- ◆ **Propellant sloshing dynamics are of fundamental concern in spacecraft dynamics**
 - Analytical solutions exist for axisymmetric containers at high Bo
 - Below $Bo=1000$ modified analytical models must be used
 - Stable flow only (continuous free surface) and small perturbations
 - CFD solutions required for turbulent flow, transient phenomena, PMD simulation, etc.

- ◆ **LBE method verified using a flow regime near analytical limit**
 - 0.15 m cylindrical LO_2 tank with hemispherical ends @ 0.001 g ($Bo=20$)
 - Lattice size = 346^2 (4.1 MB)
 - Free decay from initial condition with acceleration 15 degrees from symmetry axis
 - First mode frequency matches analytical predictions very well ($f=0.055$ Hz)



◆ **LBM approach used for small domain simulation in microgravity**

- 0.1m spherical LO₂ container in microgravity
- High-g initial condition (settled fluid) and 0g at t=0 (20% fill fraction)
- Random perturbing acceleration (-3 dB @ 0.2 Hz, $g_{RMS}=0.00003$)
- Lattice size = 266^2 (2.4 MB)



- ◆ **Some promising results have been obtained in the application of the LBE to propellant sloshing dynamics and related microgravity fluid phenomena**
 - The LBE method has promise for simulation of thermodynamically consistent multiphase flows in cryogenic propellants
 - Fundamental stability limitations remain for very low kinematic viscosities (real fluids!)
 - Recent progress includes stability enhancement via adaptive time-stepping and improvement in surface tension model using multirange pseudopotential
 - Overcomes some stability and surface tension limitations by improving isotropy

- ◆ **Production simulation of cryogenic flows will require incorporation of thermal effects**
 - Thermal LBE codes are emerging and show some promise
 - Important to capture convective phenomena, for example, for modeling of long-term fluid circulation in propellant storage systems

- ◆ **Ongoing work extends the present proof-of-concept model to a 3D code**
 - Parallelization opportunities may allow simulation of CFD-in-the-loop with spacecraft GN&C 6-DoF simulations, for example, using GPU computing
 - Possible validation opportunities using existing microgravity fluid experiment data collected aboard International Space Station (ISS)
 - 3D code targeted for NASA Exploration Upper Stage (EUS) ullage settling and propellant management studies