The Chaotic Life of Mayonnaise

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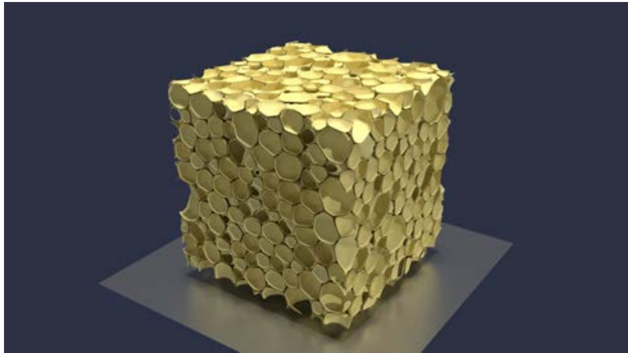
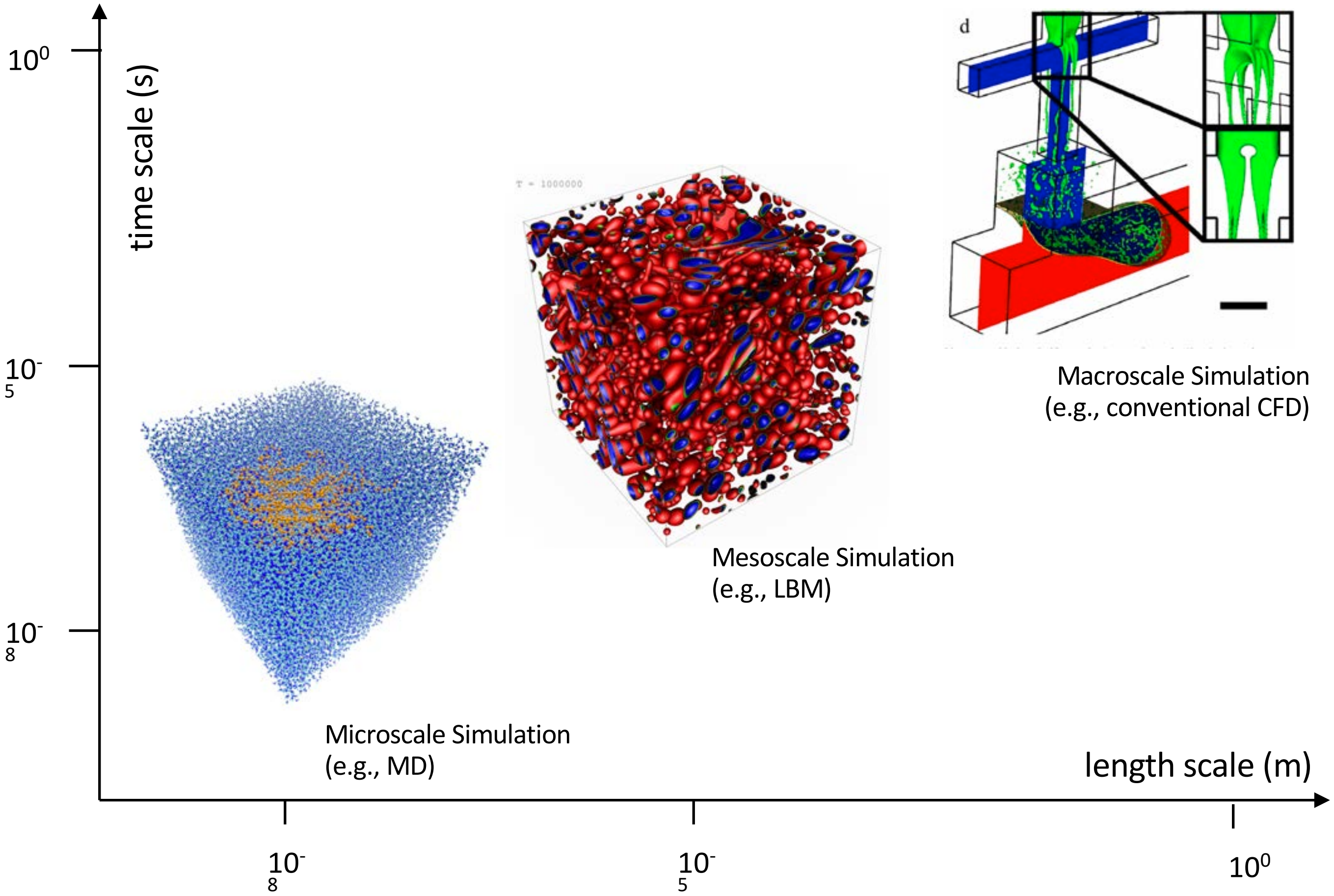
Outline

- The making of dense emulsions via large scale computer simulations
- Innovative approach for tracking droplets in dense emulsions
- Overview of the main results
- Conclusion and outlook



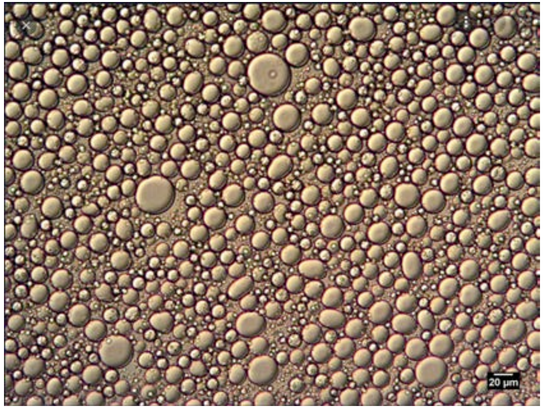
Relevant Scales in Fluid Dynamics



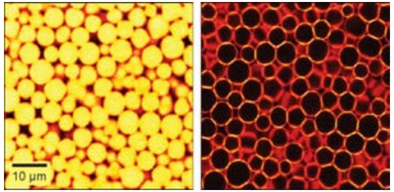
Introduction: Solid or Fluid?

2 Newtonian
simple fluids

Stirring



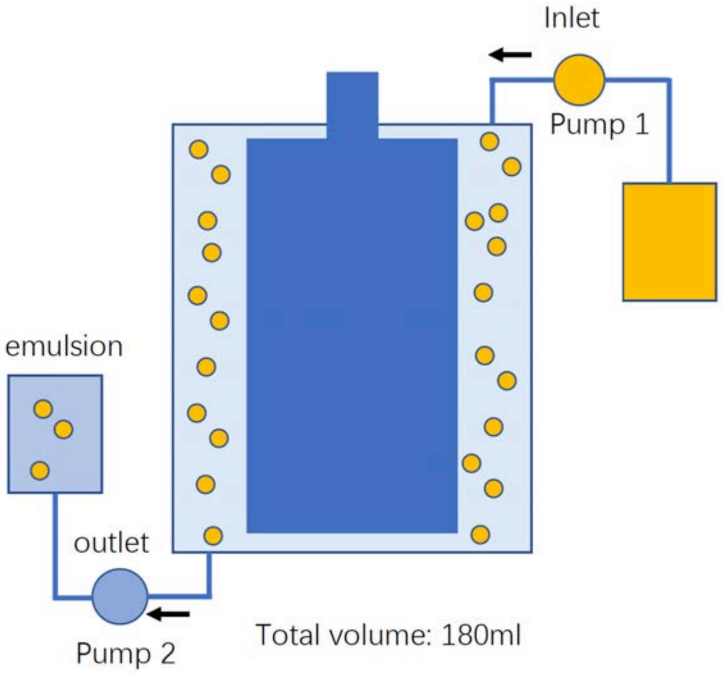
Surfactant &
(oil) Injection

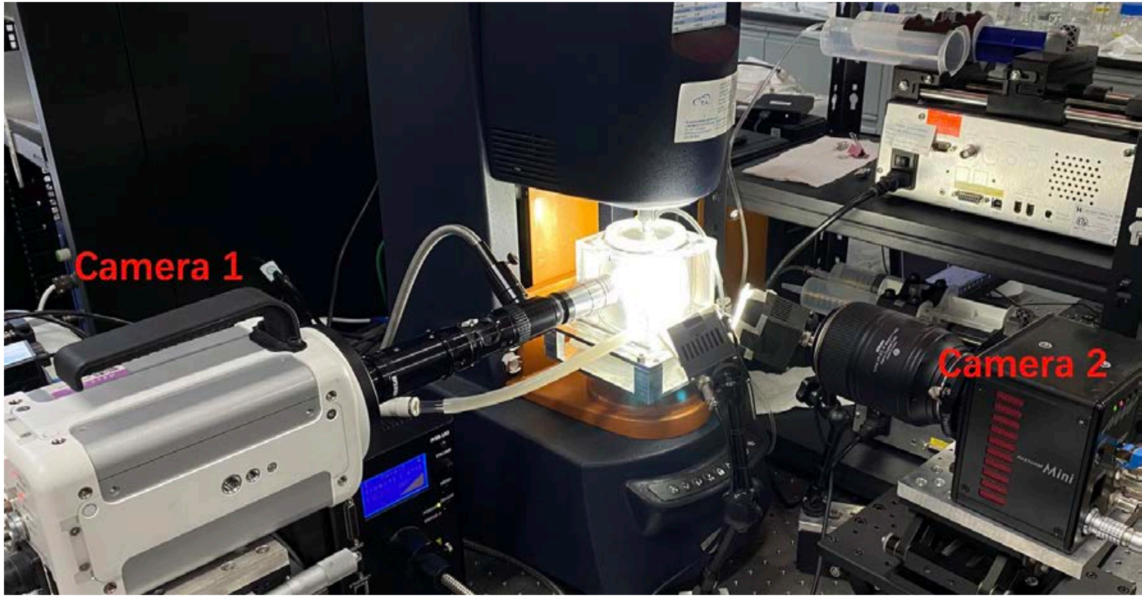


1 non-Newtonian
complex fluid

MCCLEMENTS, D. J. 2015 Food Emulsions: Principles, Practices, and Techniques. CRC press. MOIN, P. & MAHESH, K. 1998 Direct numerical simulation: a tool in turbulence research. Annu. Rev. Fluid Mech. 30 (1), 539–578.

Experimental set-up





* courtesy of Prof. Chao Sun and Lei Yi, Tsinghua University, Beijing, China

Scientific Challenge

- Complexity to describe these physical phenomena analytically
- Extremely challenging to be studied experimentally
- Numerically, high computational cost for modeling emulsions in three-dimensions, even at modest space and time resolution

Open Questions

- How are multi-component fluids emulsions produced via chaotic largescale stirring?
- How does the chaotic stirring and the droplets concentration influence droplets dynamics at the microscopic scale?
- How does the produced emulsion flow at the macroscopic scale, as a function of externally applied stresses?

Motivations

- From two simple fluids, to one complex fluid (yield-stress)
- Validate state-of-the-art computational models in 3D
- Study the process of turbulent emulsification in details
- Explore the physics of fluid emulsions
- Make via computer simulation what experiments can't do

MCCLEMENTS, D. J. 2015 Food Emulsions: Principles, Practices, and Techniques. CRC press. MOIN, P. & MAHESH, K. 1998 Direct numerical simulation: a tool in turbulence research. Annu. Rev. Fluid Mech. 30 (1), 539–578.





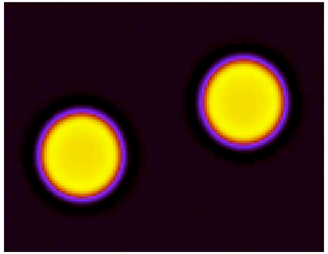
Methodology

$$F_i^{\alpha}(\boldsymbol{x}, t) = A\rho^{\alpha} \sum_{j \neq i} \left[sin(k_j x_j + \Phi_k^{(j)}(t)) \right]$$

Luca Biferale et al. Journal of Physics (2011)
Prasad Perlekar et al Physics of Fluids (2012)

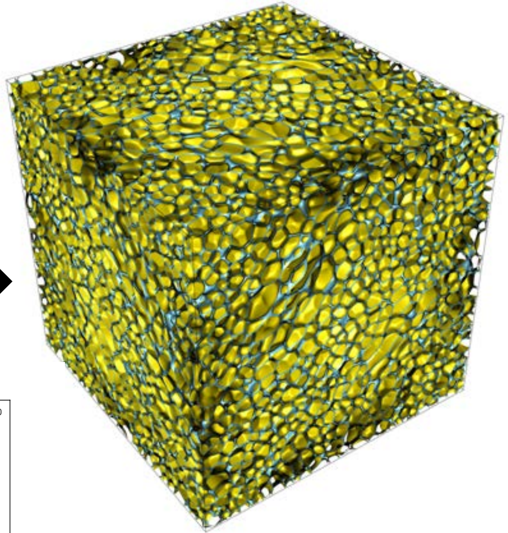
$$f_{\sigma a}(\boldsymbol{x} + \boldsymbol{c}_a, \boldsymbol{c}_a; t+1) - f_{\sigma a}(\boldsymbol{x}, \boldsymbol{c}_a; t) = -\frac{1}{\tau_{LB,\sigma}}\left(f_{\sigma a} - f_{\sigma a}^{(eq)}\right)(\boldsymbol{x}, \boldsymbol{c}_a; t) + F_{\sigma a}(\boldsymbol{x}, \boldsymbol{c}_a; t),$$

surface tension

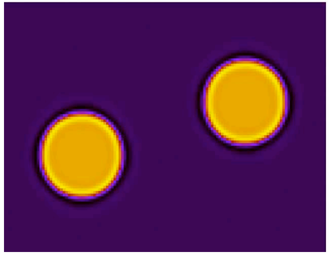


X. Shan & H. Chen, Physical Review E 47, 1815 (1993)
X. Shan & H. Chen, Physical Review E 49, 2941 (1994)
X. Shan, Physical Review E 77, 066702 (2008)
M. Sbragaglia & X. Shan, Physical Review E 84, 036703 (2011)

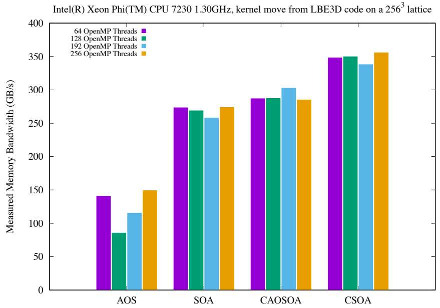
World-class Supercomputers



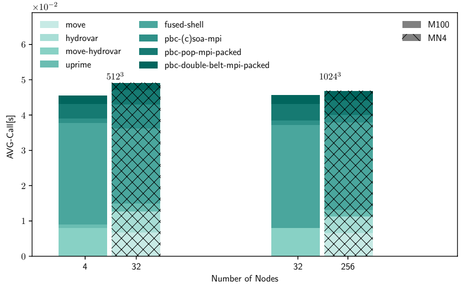
disjoining pressure



M. Sbragaglia et al. , Soft Matter, (2012)
Sbragaglia et al., Physical Review E 75, 026702 (2007)

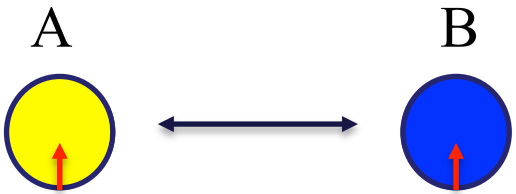


Marconi-100 Vs MN4



Girotto, I.; Schifano, S.F.; Calore, E.; Di Staso, G.; Toschi, F. Performance and Energy Assessment of a Lattice Boltzmann Method Based Application on the Skylake Processor. Computation 2020, 8, 44.

Modeling disjoining pressure



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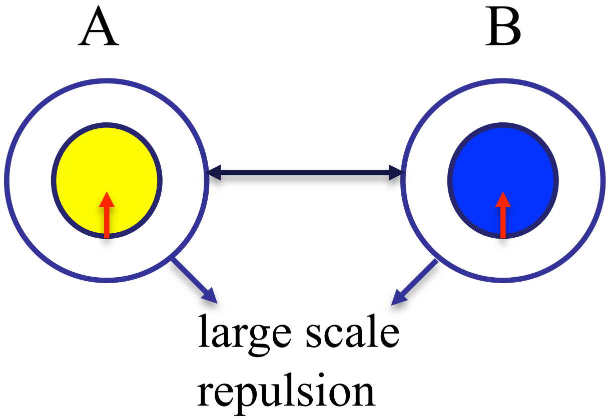

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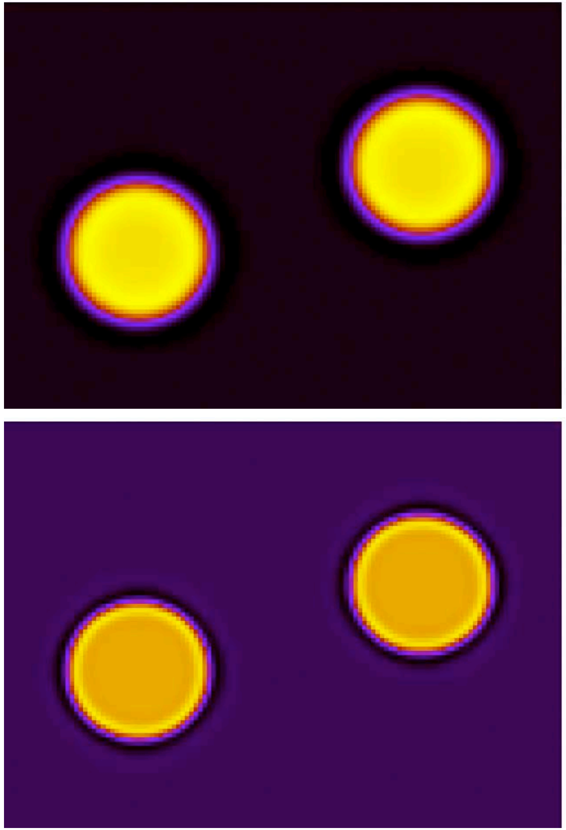


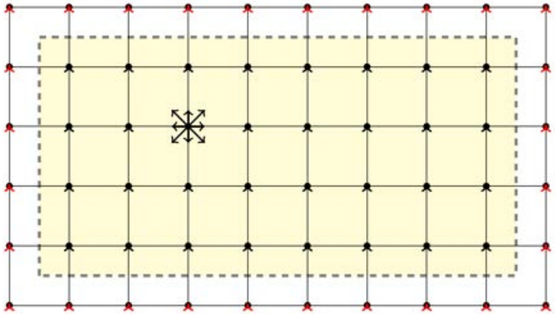
Parameters set from:
R. Benzi et al 2010 EPL 91 14003

The Multicomponent Lattice Boltzmann

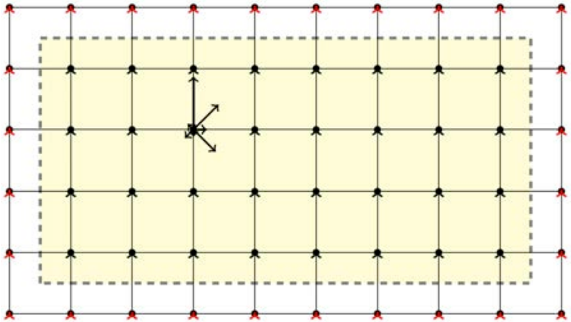
$$f_{\sigma a}(\boldsymbol{x} + \boldsymbol{c}_a, \boldsymbol{c}_a; t+1) - f_{\sigma a}(\boldsymbol{x}, \boldsymbol{c}_a; t) = -\frac{1}{\tau_{LB,\sigma}}\left(f_{\sigma a} - f_{\sigma a}^{(eq)}\right)(\boldsymbol{x}, \boldsymbol{c}_a; t) + F_{\sigma a}(\boldsymbol{x}, \boldsymbol{c}_a; t),$$

- f_a *is* probability distribution function for LBM populations of the the σ component
- $a = 0, \ldots, N$ indexes the population streaming with velocity c_a
- $\sigma =$ A or B component
- F_a is the interaction force, including short range attraction and long range repulsion
- The Lattice Boltzmann scheme is composed by two steps:

Streaming: only memory-to-memory copies



Collision: only (local) floating point operations



Lattice Boltzmann Method (LBM)

- Populations are first moved from lattice-site to lattice-site applying the propagate operator, and then are modified through a collisional operator changing their values according to the local equilibrium condition.

Equilibrium distribution

Time step

Discrete velocities

$$f_i(\mathbf{x}+\mathbf{c}_i\delta_t, t+\delta_t) = f_i(\mathbf{x},t) - \frac{f_i(\mathbf{x},t)-f_i^{eq}(\mathbf{x},t)}{\tau}$$

Lattce Boltzmann equation

i=0,1,…,8 in a **D3Q19 lattice**

Relaxation time

```
for all time step do
        < Set boundary conditions >
        for all lattice site do
                < Move >
        for all lattice site do
                < Hydrovar >
    for all lattice site do
                < Equili >
    for all lattice site do
                < Collis >
        end for
end for
```

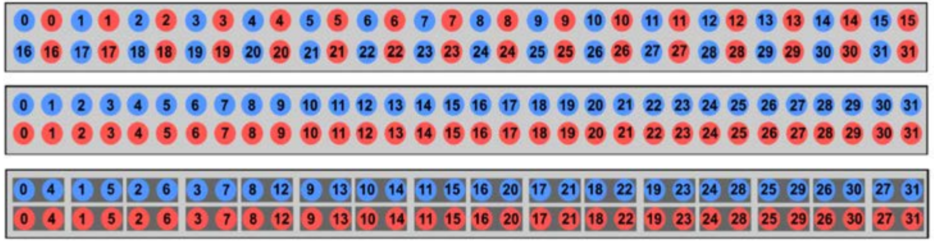
```
for all time step do
        < Set boundary conditions >
        for all lattice site do
                < Move >
        for all lattice site do
                < COLLIDE_FUSED >
        end for
end for
```

```
for all time step do
        < Set boundary conditions >
        for all lattice site do
                < FULLY_FUSED>
        end for
end for
```

Loop compression and better data locality!!

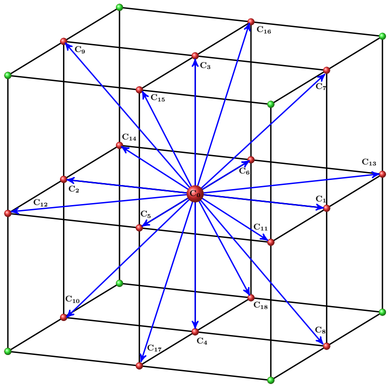
LBM Kernels Optimization

Lattice 4 x 8 (blue and red) population per site



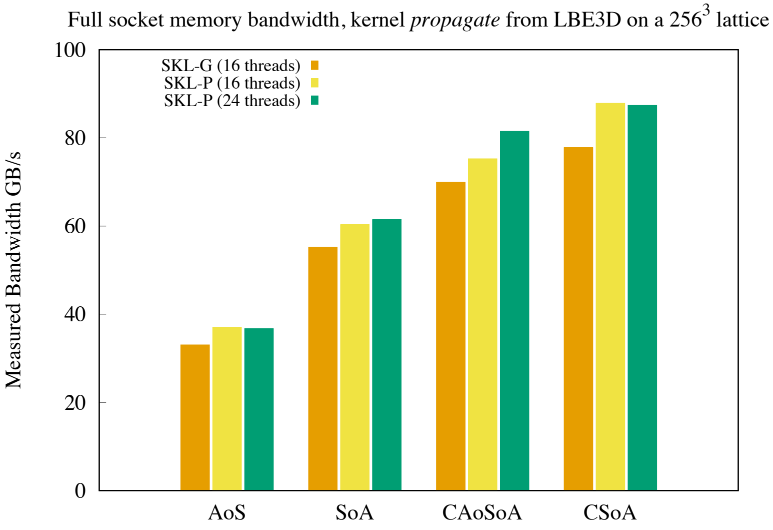
Girotto, I.; Schifano, S.F.; Calore, E.; Di Staso, G.; Toschi, F. Performance and Energy Assessment of a Lattice Boltzmann Method Based Application on the Skylake Processor. Computation 2020, 8, 44.

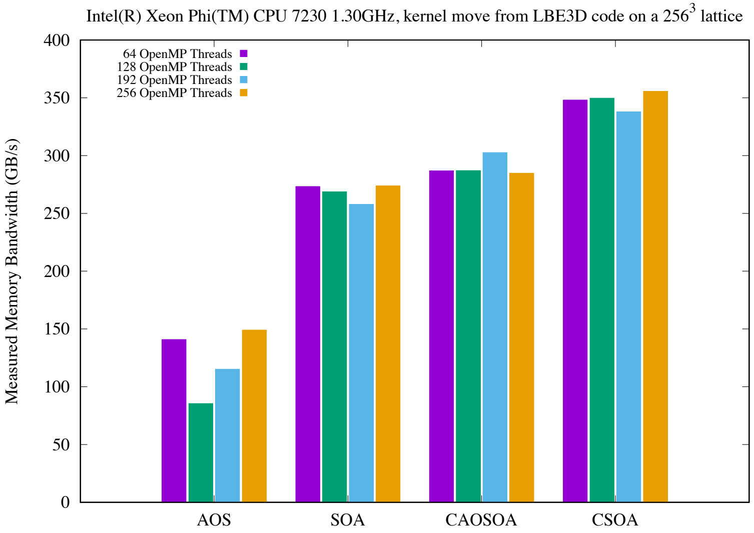
1 lattice point



1 population

256^3, 512^3, 1024^3 & 2048^3 lattice points!





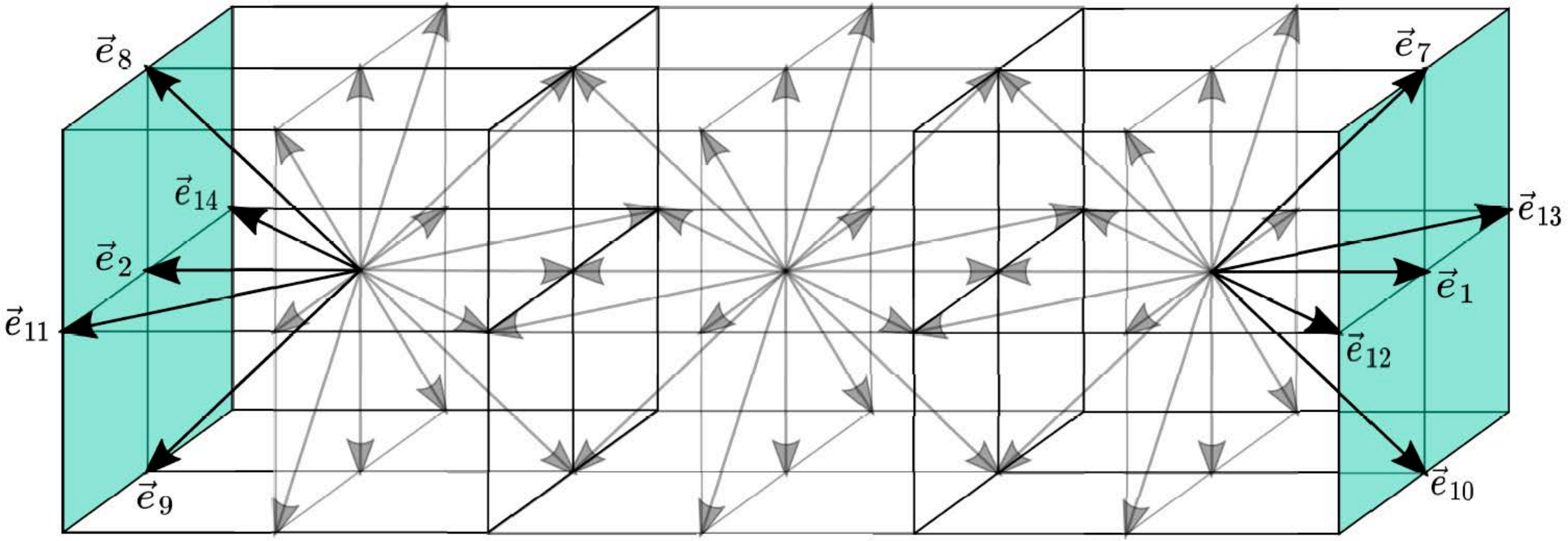
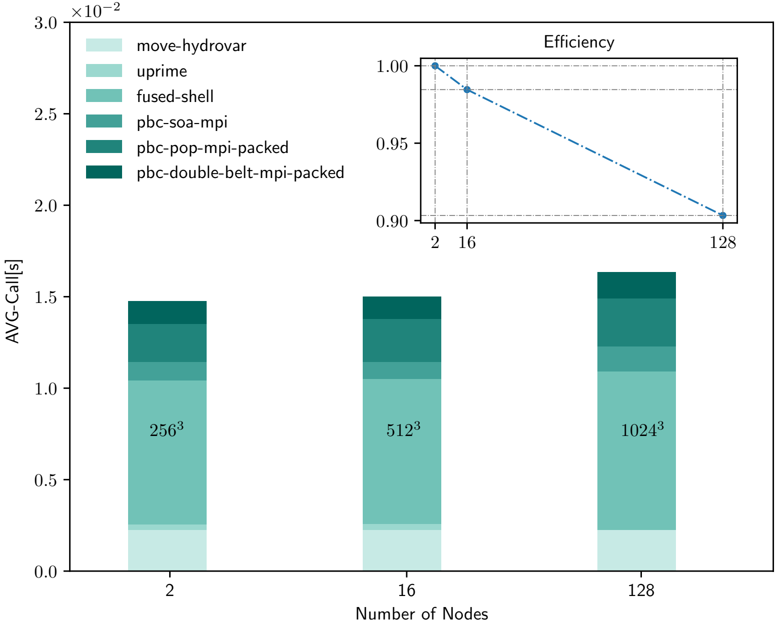
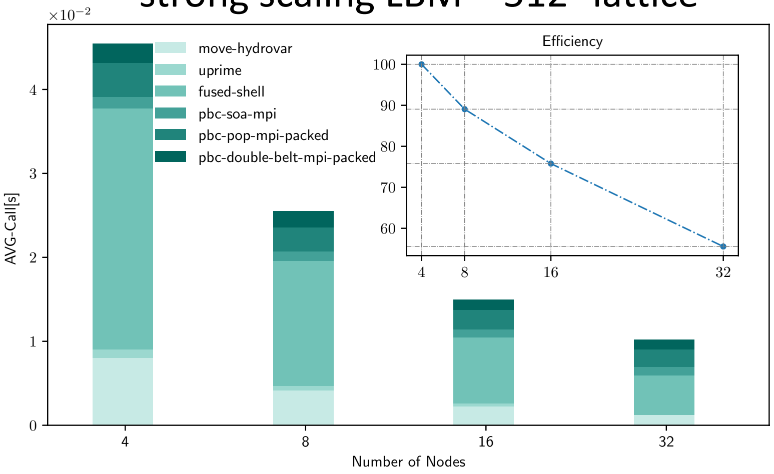


Figure 4: Graphical representation of a common `PBC` exchange along the x-direction. Three site points of 19 populations (D3Q19) are displayed, with the two sites at the extremes hosting the data to be exchanged. In a common implementation, the exchange would be performed for all data (19) included in the site, while in our optimization the exchange is reduced to only the data required (5) for a given direction (green). In this case, populations that need to be exchanged along the x-direction are highlighted. We implement a packing scheme, reported in Algorithm 3, to perform the data exchange with a single MPI call per direction (upper, lower), also on directions where data at the boundaries are non-contiguously stored in memory.

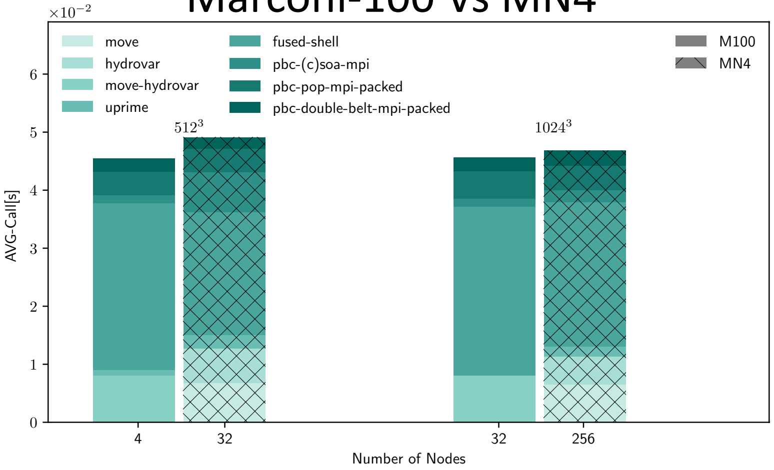
Multicomponent LBM for distributed multi-GPU (results on Marocni-100)



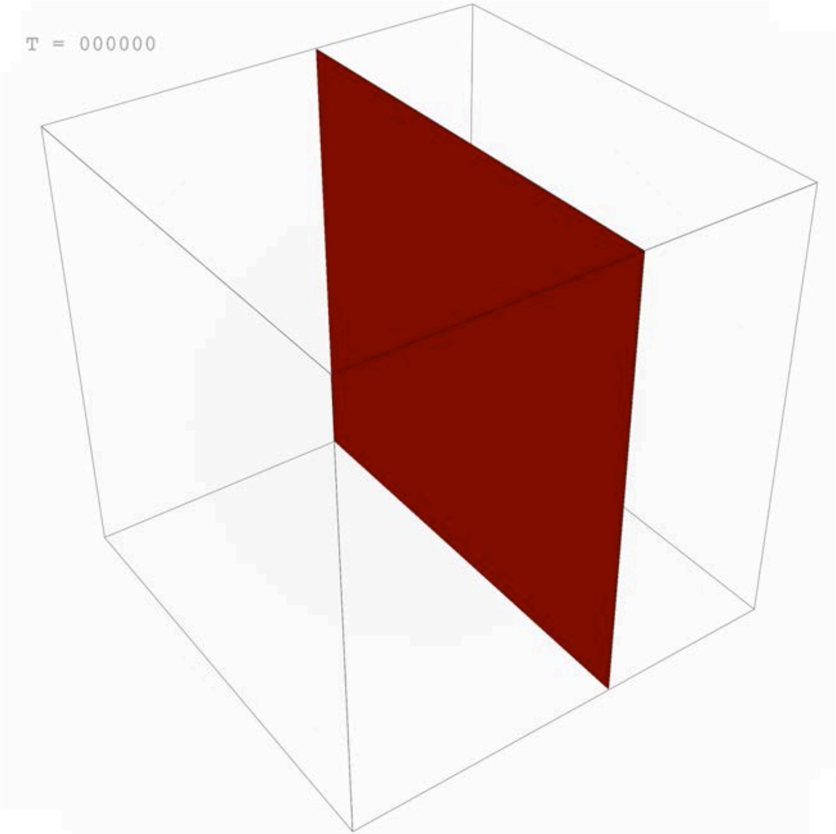
strong scaling LBM – 512³ lattice

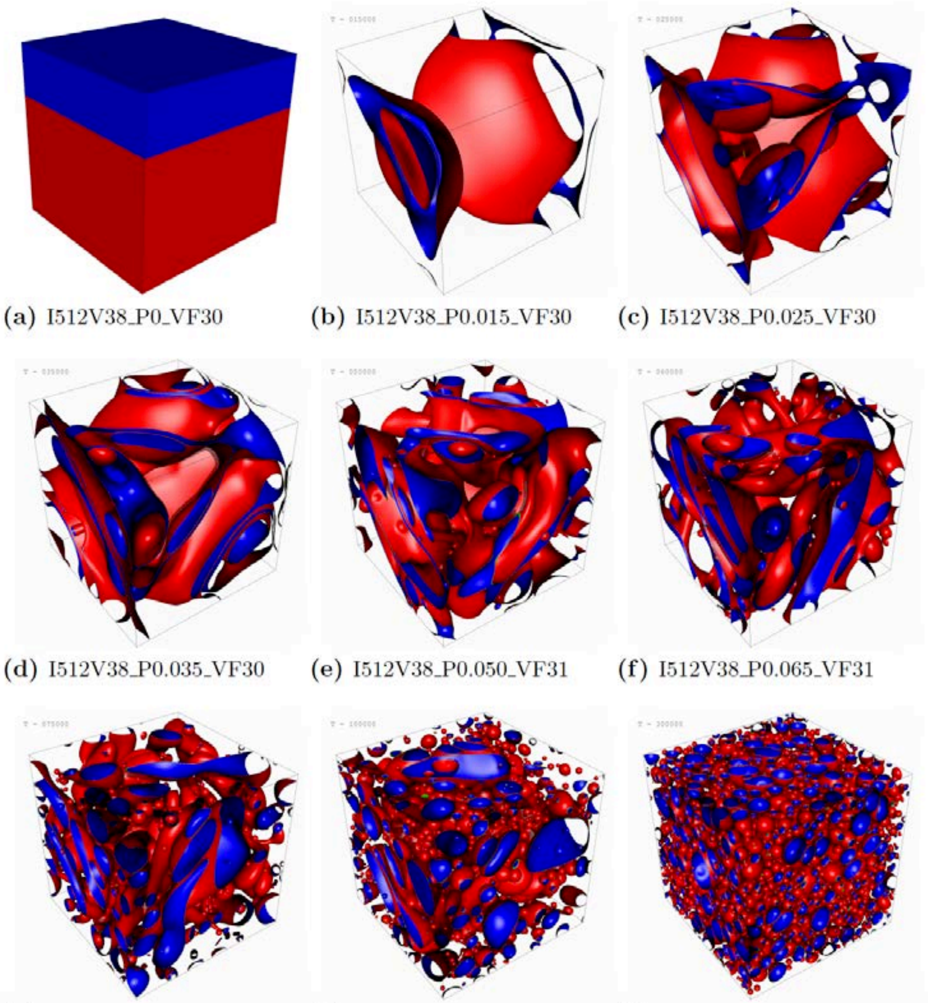


Marconi-100 Vs MN4



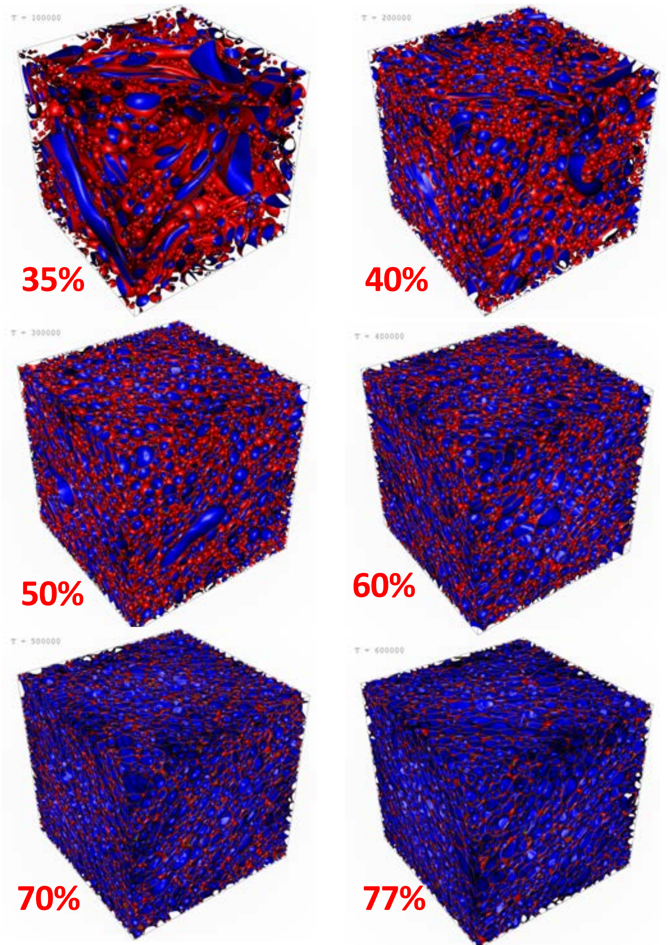
Interface Fragmentation





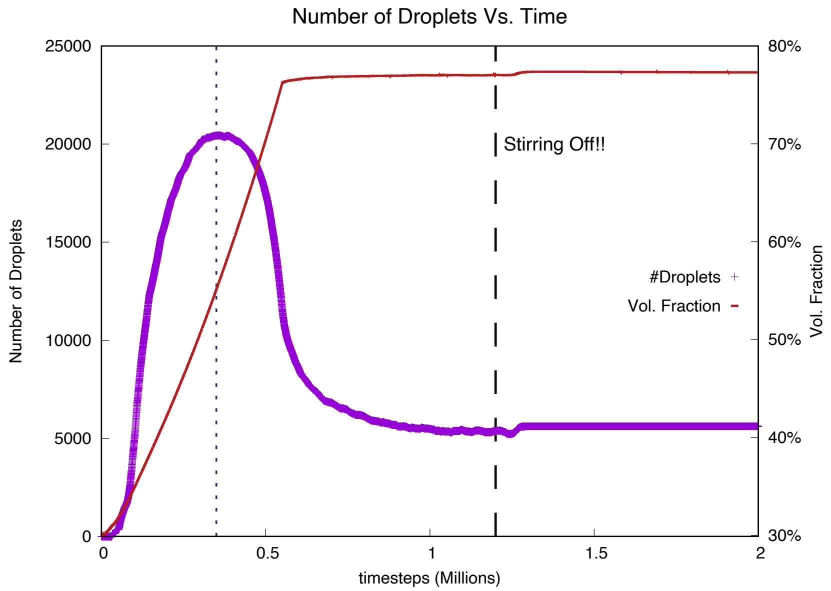
(a) I512V38_P0_VF30
(b) I512V38_P0.015_VF30
(c) I512V38_P0.025_VF30
(d) I512V38_P0.035_VF30
(e) I512V38_P0.050_VF31
(f) I512V38_P0.065_VF31
(g) I512V38_P0.075_VF32
(h) I512V38_P0.1_VF34
(i) I512V38_P0.3_VF38

The Making of Dense Emulsions



We slowly inject/remove mass of fluid such that :

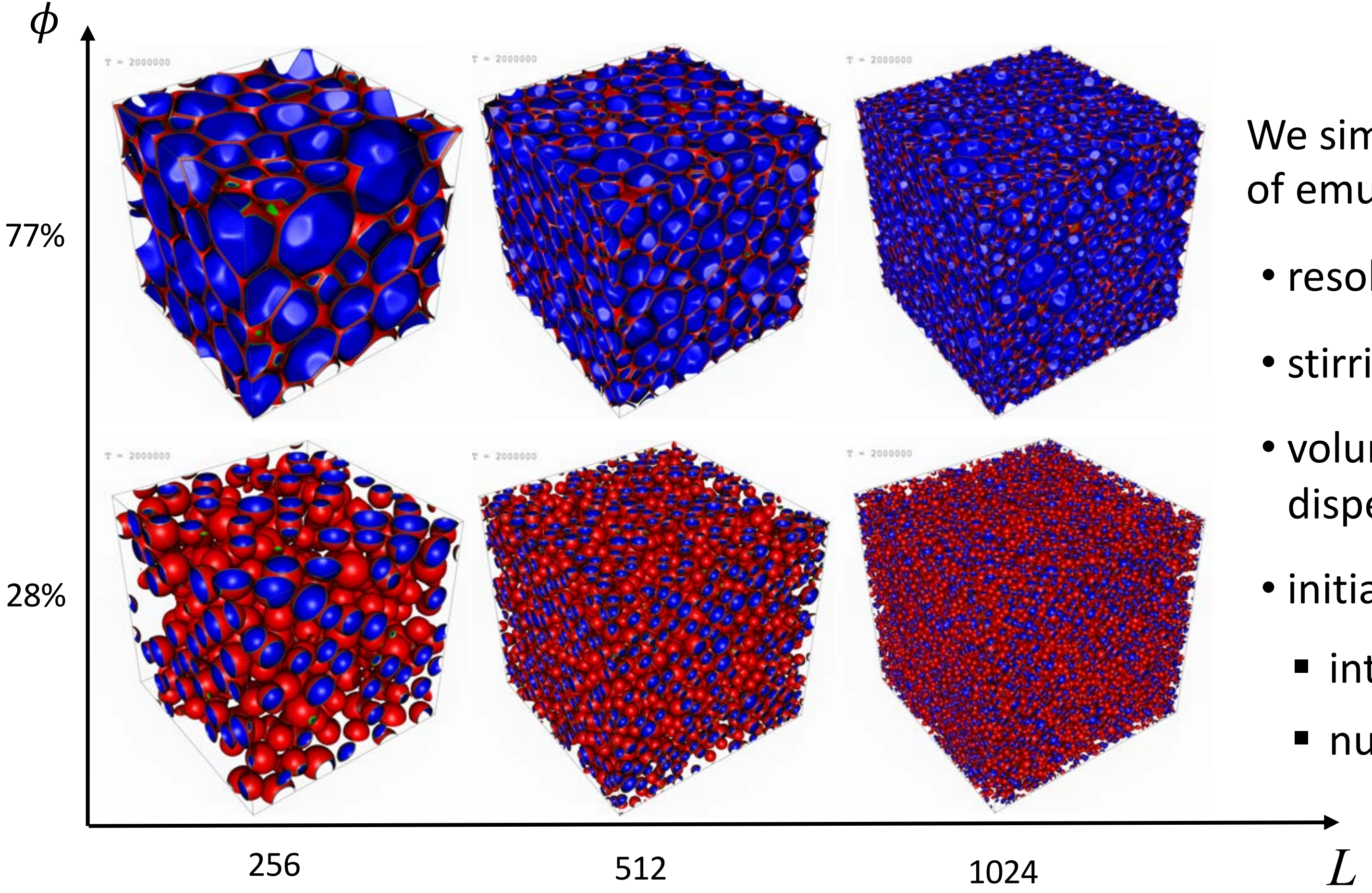
1. the total mass of the fluid component is preserved
2. the system adiabatically adjust to the new mechanical equilibrium



The emulsion is stirred via a large scale forcing, mimicking a classical stirring often used in spectral simulation of turbulent flows, as in:

- Prasad Perlekar, Luca Biferale, Mauro Sbragaglia, Sudhir Srivastava, and Federico Toschi. Droplet size distribution in homogeneous isotropic turbulence. Physics of Fluids, 24(6):065101, 2012.

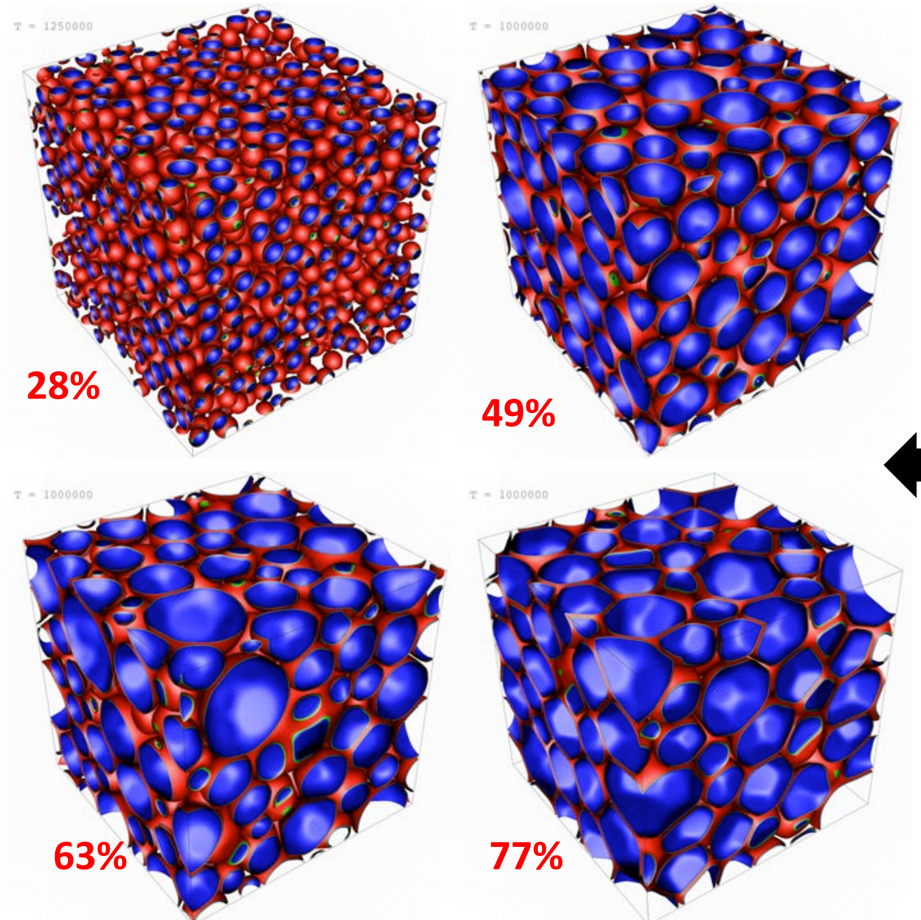
Exploration of the of the Parameter Space of Emulsions



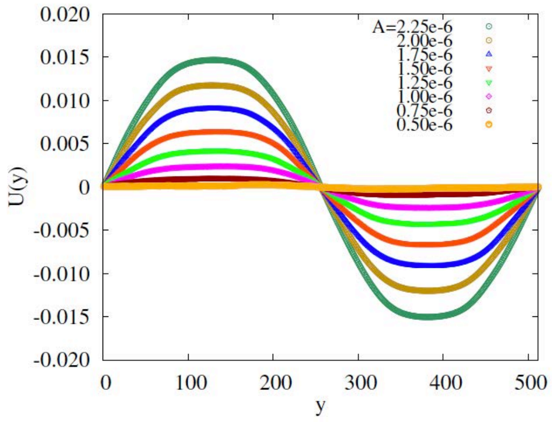
We simulated a large number of emulsions varying:

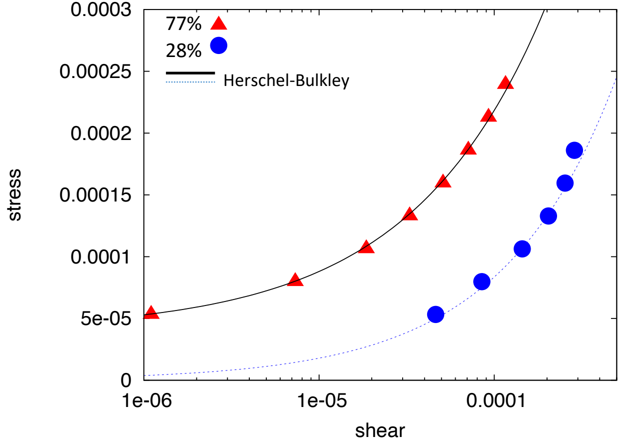
- resolutions (up to 2048^3)
- stirring amplitude
- volume fraction of the dispersed phase (ϕ)
- initial conditions:
  - interface fragmentation
  - nucleation

Is the final emulsion really dense and Jammed?



A = 1.0e-6

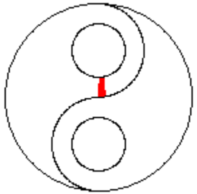




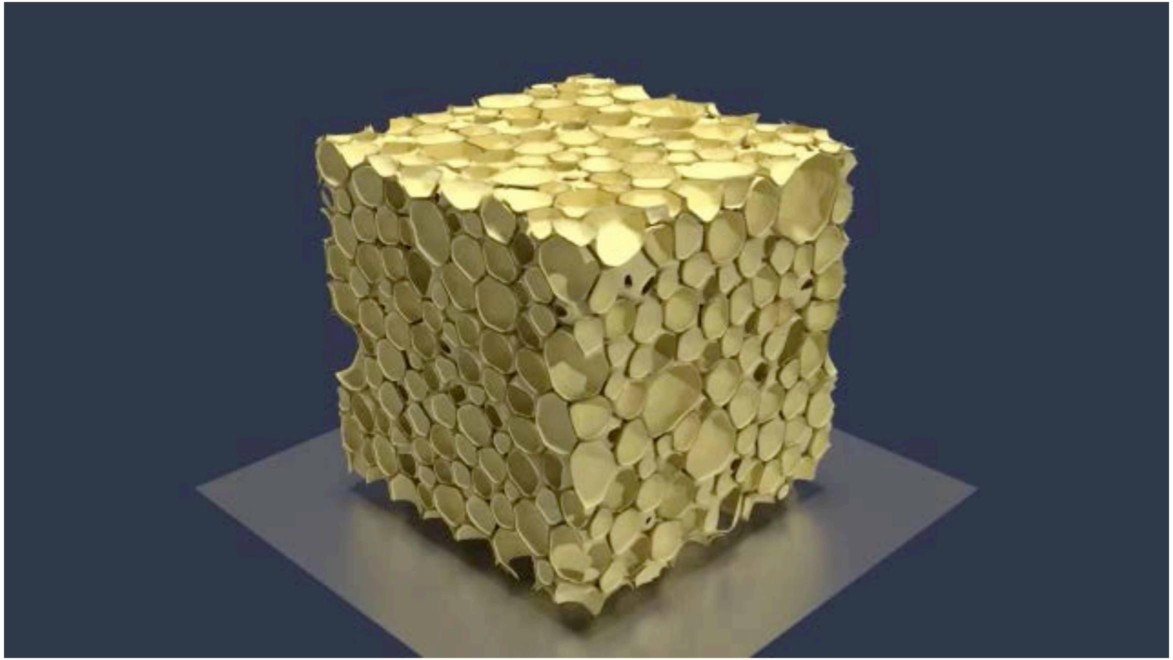
R. Benzi, M. Bernaschi, M. Sbragaglia, and S. Succi. Herschel-bulkley rheology from lattice kinetic theory of soft glassy materials. EPL (Euro-physics Letters), 91(1):14003, jul 2010.

Droplets Coloring Algorithm

Via a flood fill parallel algorithm* we can intercept and provide a quantitative descriptions of all droplets in the system



https://en.wikipedia.org/wiki/Flood_fill



The chaotic life of mayonnaise
DOI: https://doi.org/10.1103/APS.DFD.2019.GFM.V0032

*S. Frijters, T. Krueger, and J. Harting, “Parallelised Hoshen-Kopelman algorithm for lattice-Boltzmann simulations”, CPC

Droplets Tracking Algorithm

- In the domain at time t_1 there are N_1 droplets and at (an immediately later dump) t_2 there are N_2. We first round the continuum density field to a 0 or 1 values. This is achieved by the following operation:

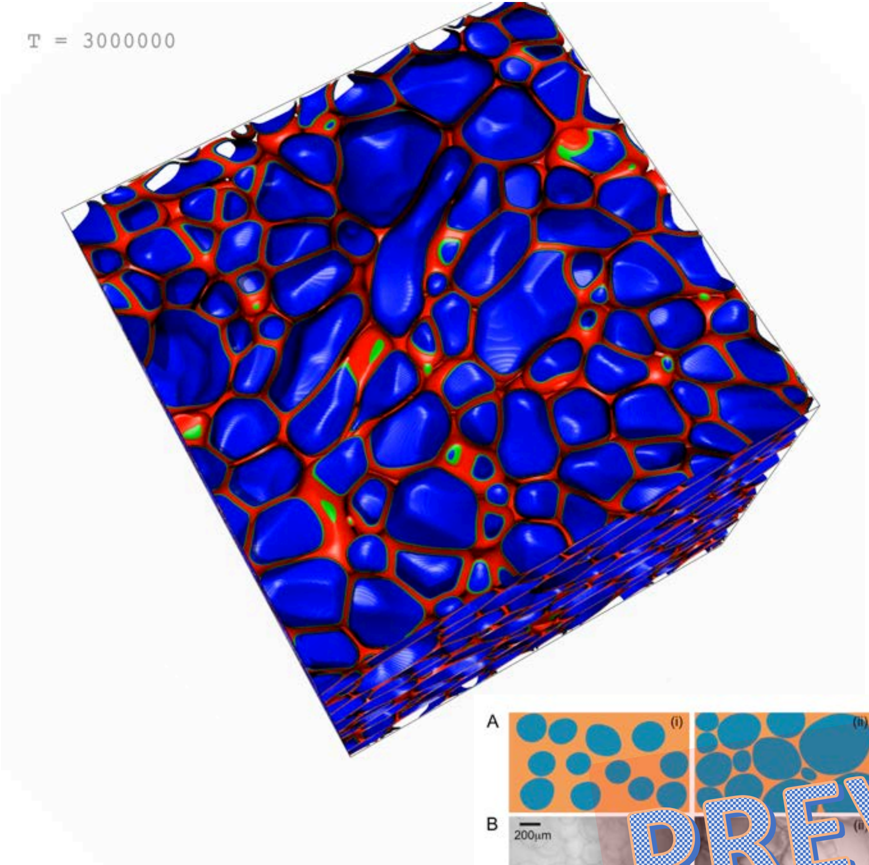
$$\rho_k(\boldsymbol{x}, t_1) = \theta(\rho_k^{(c)}(\boldsymbol{x}, t) - \rho_t)$$

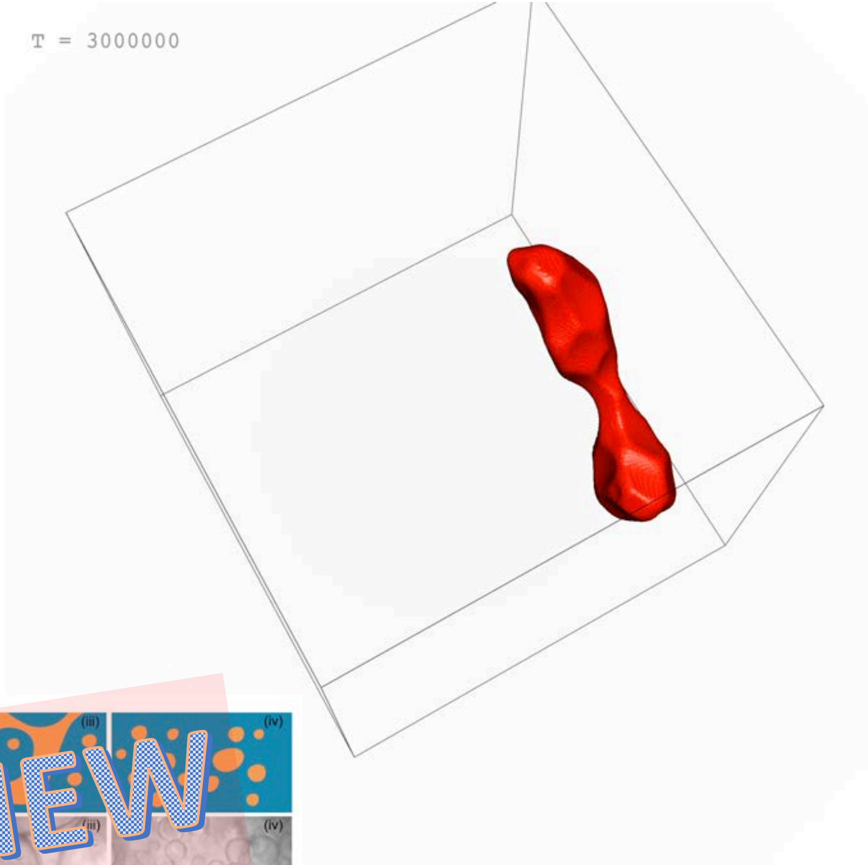
- The *initial* state of a single droplet k_1 at time t_1 is represented in the bra-ket notation from quantum mechanics as $| k_1, t_1 \rangle$ and the *final* state is represented by the following bra notation: $\langle k_2, t_2 |$
- We want to define a transition probability in order to track droplets in time, including coalescence and breakup events. The transition probability is give by the following bra-ket expression:

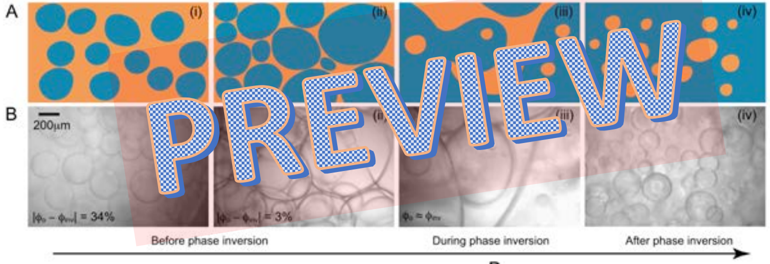
$$P_{k_1 \to k_2} = \langle k_2, t_2 | k_1, t_1 \rangle = \frac{1}{V} \int \rho_{k_2}(\boldsymbol{x}, t_2) \rho_{k_1}(\boldsymbol{x}, t_1) d^3x$$

- We apply the Kalman filtering, for considering the initial (t_1) velocity field of a given droplet
- By construction $\langle k, t | k, t \rangle = 1$. What happens if a droplet is just translating with uniform velocity? We expect that the maximal correlation will occur for:

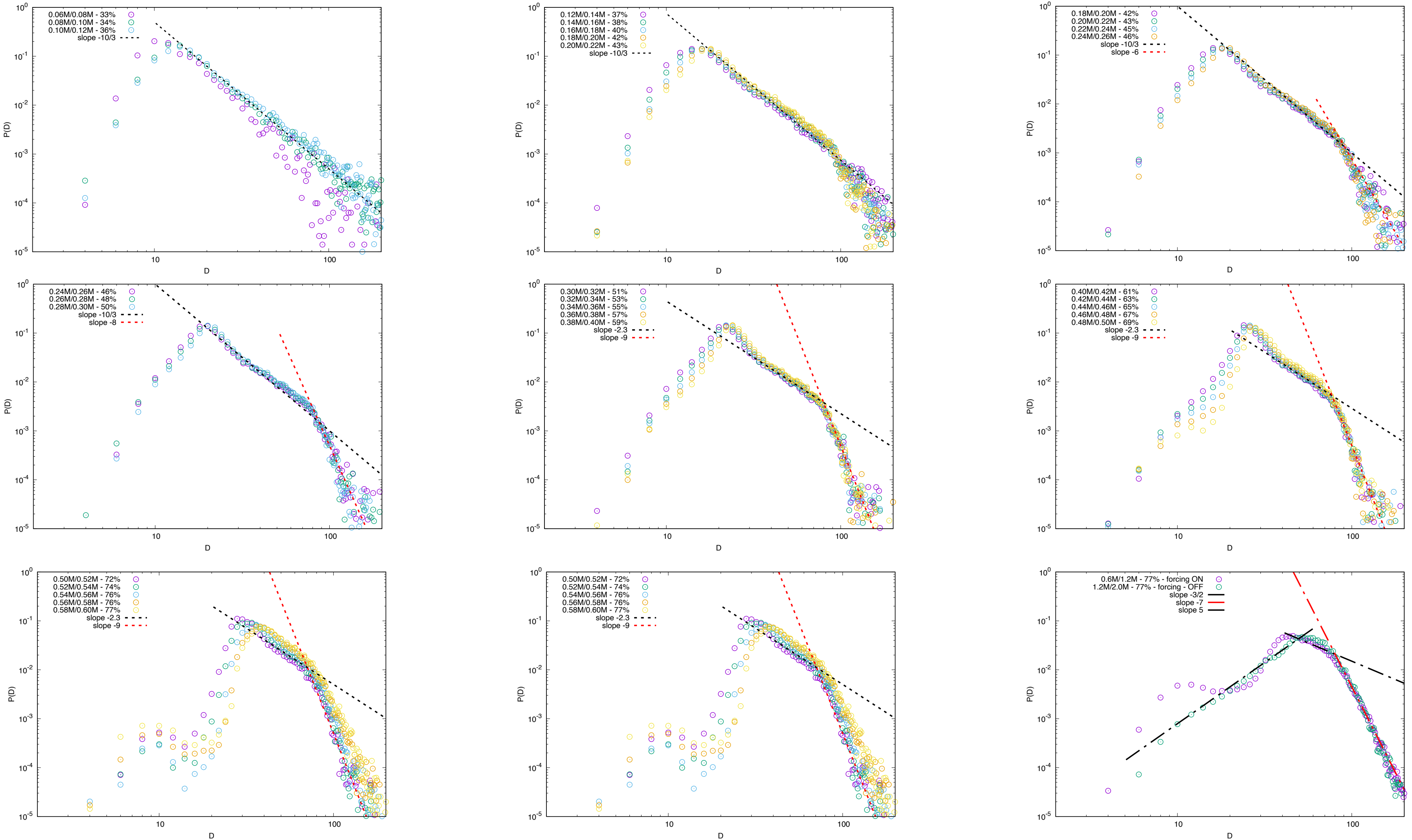
$$\langle shift(k, v \cdot dt), t + \delta t | k, t \rangle = \frac{1}{V} \int \rho_k(\boldsymbol{x} - \boldsymbol{v} \cdot dt, t + \delta t) \rho_k(\boldsymbol{x}, t) d^3x$$


T = 3000000


T = 3000000


A
(i)
(ii)
(iii)
(iv)
B
200μm
|φ₀ − φinv| = 34%
|φ₀ − φinv| = 3%
φ₀ ≈ φinv
Before phase inversion
During phase inversion
After phase inversion

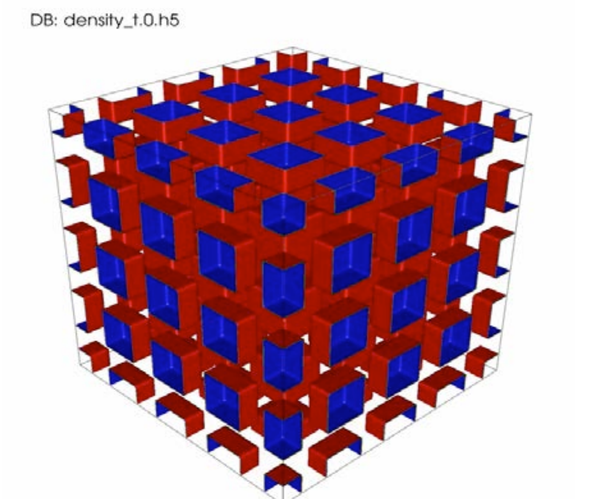
The chaotic life of mayonnaise: DOI: https://doi.org/10.1103/APS.DFD.2019.GFM.V0032

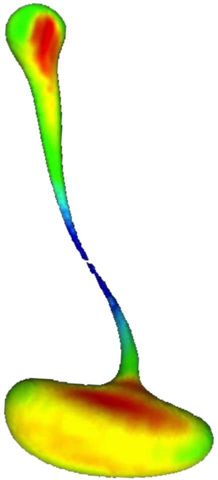


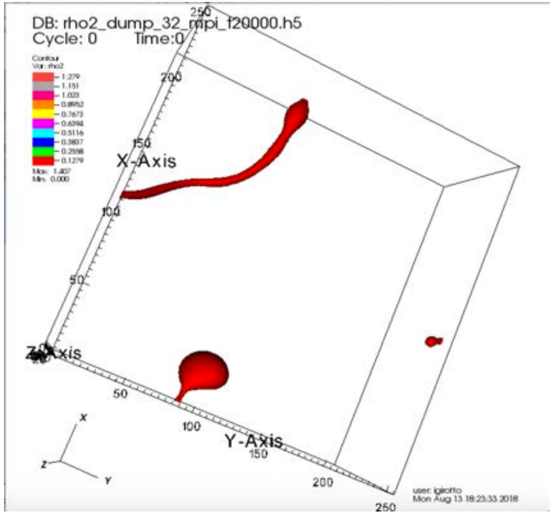
0.06M/0.08M - 33%
0.08M/0.10M - 34%
0.10M/0.12M - 36%
slope -10/3
0.12M/0.14M - 37%
0.14M/0.16M - 38%
0.16M/0.18M - 40%
0.18M/0.20M - 42%
0.20M/0.22M - 43%
slope -10/3
0.18M/0.20M - 42%
0.20M/0.22M - 43%
0.22M/0.24M - 45%
0.24M/0.26M - 46%
slope -10/3
slope -6
0.24M/0.26M - 46%
0.26M/0.28M - 48%
0.28M/0.30M - 50%
slope -10/3
slope -8
0.30M/0.32M - 51%
0.32M/0.34M - 53%
0.34M/0.36M - 55%
0.36M/0.38M - 57%
0.38M/0.40M - 59%
slope -2.3
slope -9
0.40M/0.42M - 61%
0.42M/0.44M - 63%
0.44M/0.46M - 65%
0.46M/0.48M - 67%
0.48M/0.50M - 69%
slope -2.3
slope -9
0.50M/0.52M - 72%
0.52M/0.54M - 74%
0.54M/0.56M - 76%
0.56M/0.58M - 76%
0.58M/0.60M - 77%
slope -2.3
slope -9
0.50M/0.52M - 72%
0.52M/0.54M - 74%
0.54M/0.56M - 76%
0.56M/0.58M - 76%
0.58M/0.60M - 77%
slope -2.3
slope -9
0.6M/1.2M - 77% - forcing ON
1.2M/2.0M - 77% - forcing - OFF
slope -3/2
slope -7
slope 5
P(D)
D

Real Time Monitoring Implementation

- Monitor droplets during the simulation for N timesteps to collect physical statistics
  - only post run analysis is not convenient at the target scale
- Droplets could be really big, of unpredictable shape and, distributed across the grid of processes

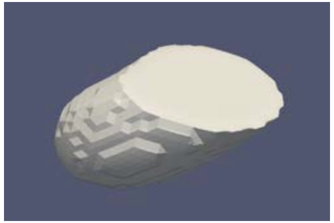






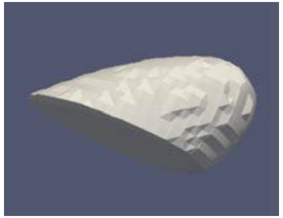
Parallel Flood Fill Algorithm

- The problems are:
  - identify all droplets’ chunks in a density field
  - identify whether a chunk is a single droplet or a chunk of a droplet composed of multiple chunks
  - droplet chunks can be spread among the processes
  - Periodic Boundaries Conditions are applied



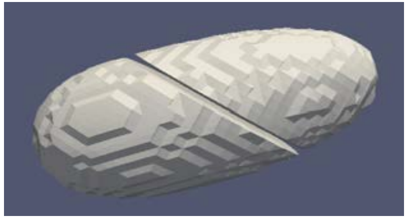
Process (X, Y, Z)

+

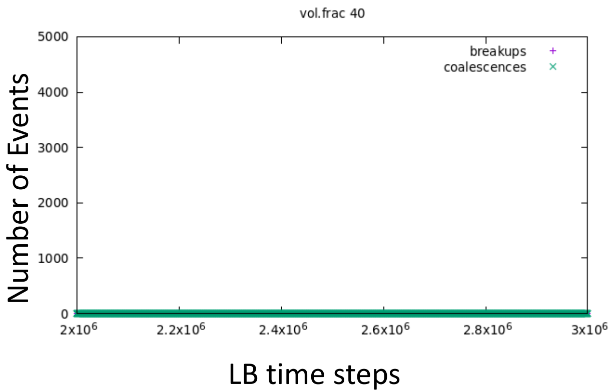


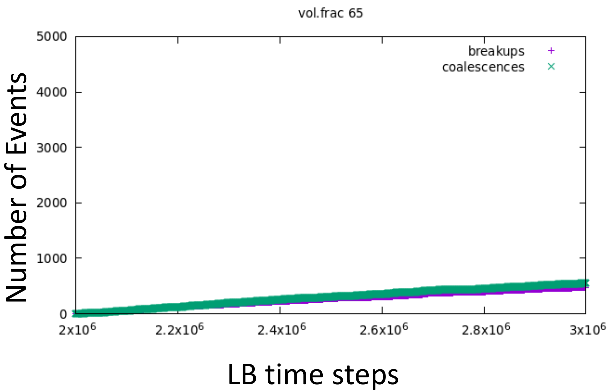
Process (X^1, Y^1, Z^1)

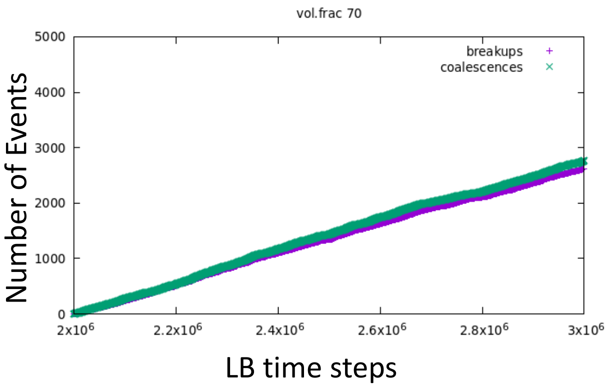
=

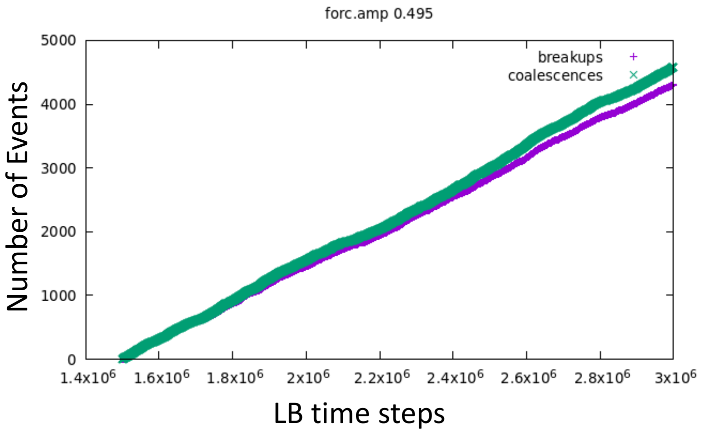


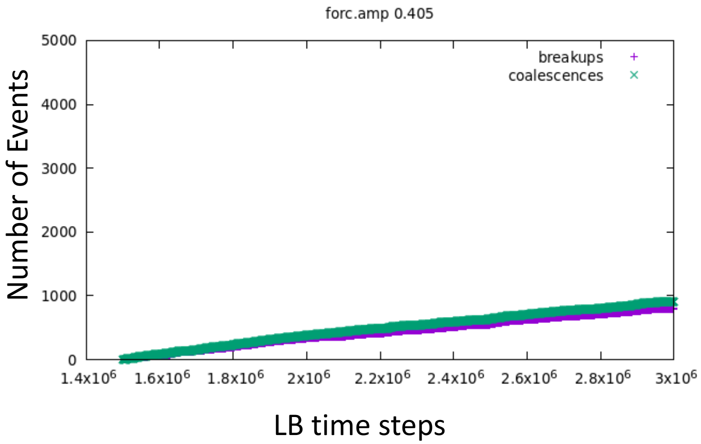
Droplets Dynamics: preliminar results /1



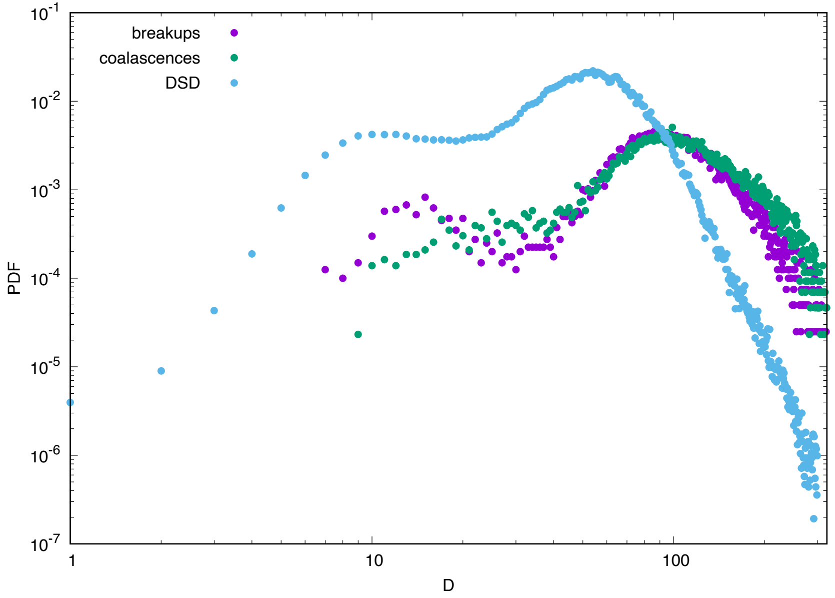


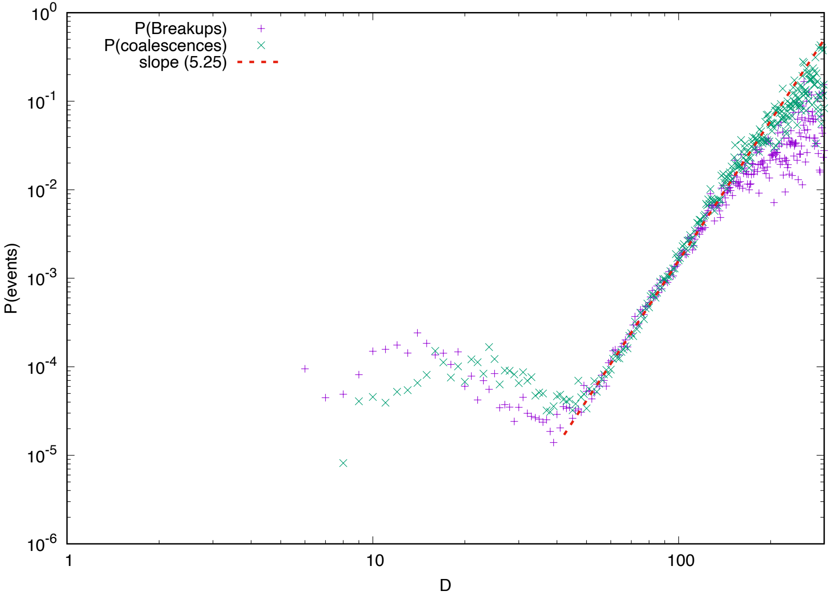






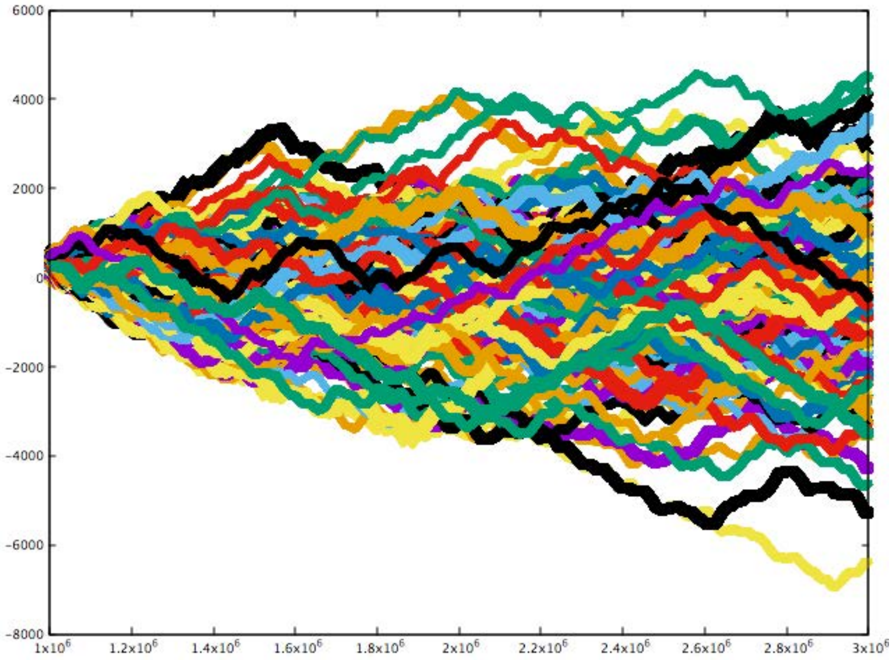
Droplets Dynamics: preliminar results /2





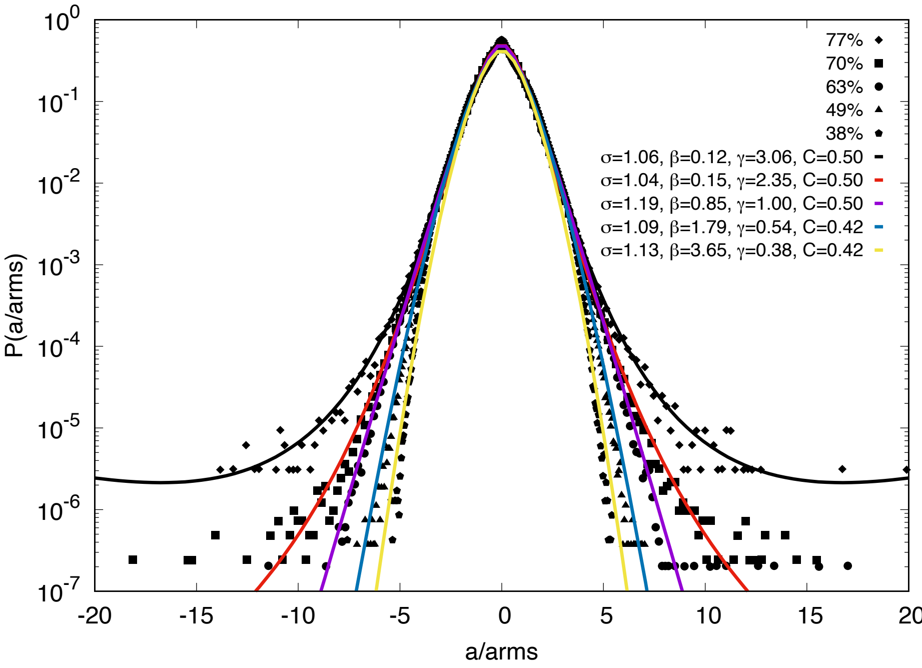
Droplets Dynamics: preliminar results /3

Absolute trajectories of all droplets existing throgouth a simulation of 2M time steps on a 512^3 box



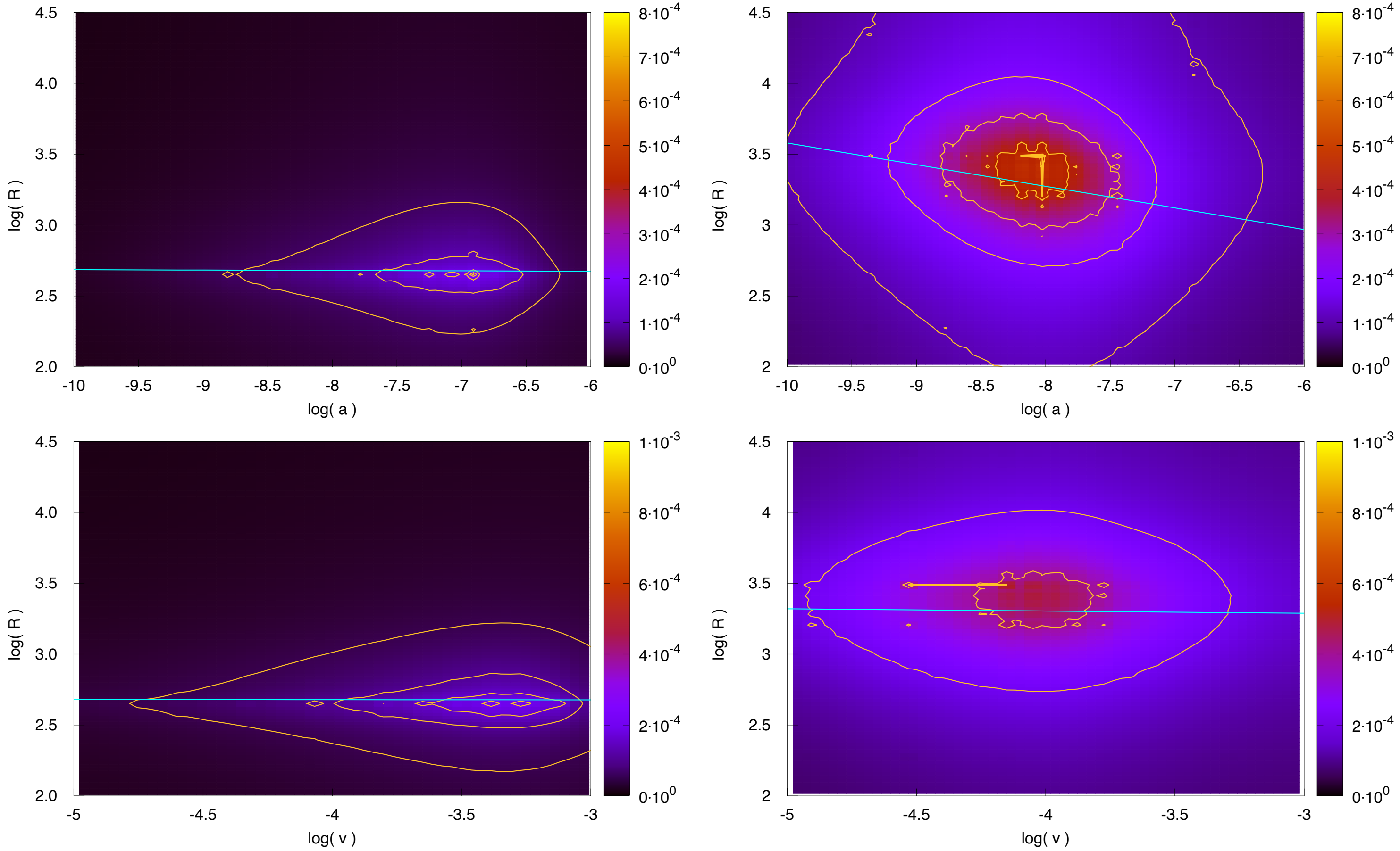
The PDF of accelerations fitted via the stretched exponential distributions:

$$P(x) = C \cdot \exp\left(-\frac{x^2}{(1+|x\beta/\sigma|^\gamma)\cdot\sigma^2}\right)$$



Dilute Emulsion (28%)

Dense Emulsion (77%)



Conclusions and outlook

- The LBM with surface tension and disjoining pressure, coupled with an externally injected forcing, can model the physics of dense emulsions at the mesoscopic scale
- We designed and developed a novel and efficient computational approach for accurately tracking droplets in dense emulsions, as a possible solution in order to extend the capability to study Lagrangian dynamics of the LBM, that intrinsically describe droplet at an Eulerian level
- The high Lagrangian tracking accuracy of our approach ($\epsilon < 10^{-5}$) allows to described the processes of emulsication at the mesoscopic level, showing relevant statistics droplet morphology, including droplet size distribution, PDF of droplets accelerations and velocities, as well as droplets dispersion.
- Our analysis also shows that the DSD of very dense emulsions present a bimodal distributions when flowing under chaotic flow, displaying a secondary peak about one order of magnitude below the mean peak for <R>, evidence of the relevant presence of small droplets (characteristics morphology of dense emulsions)
- The dynamics of 3D multicomponent emulsions can now be investigated in detail via computer simulations
- This work opens the opportunity to complement experimental studies on the multi-scale physics of turbulent multicomponent fluids, a key inshigt for industrial processes of emulsions

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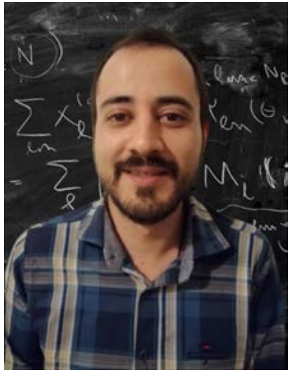
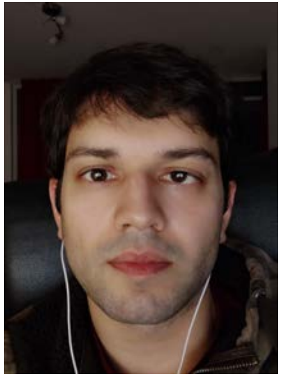


Saied Aliei (ICTP)



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