Turbulence- and particle-resolving numerical modeling of sediment transport

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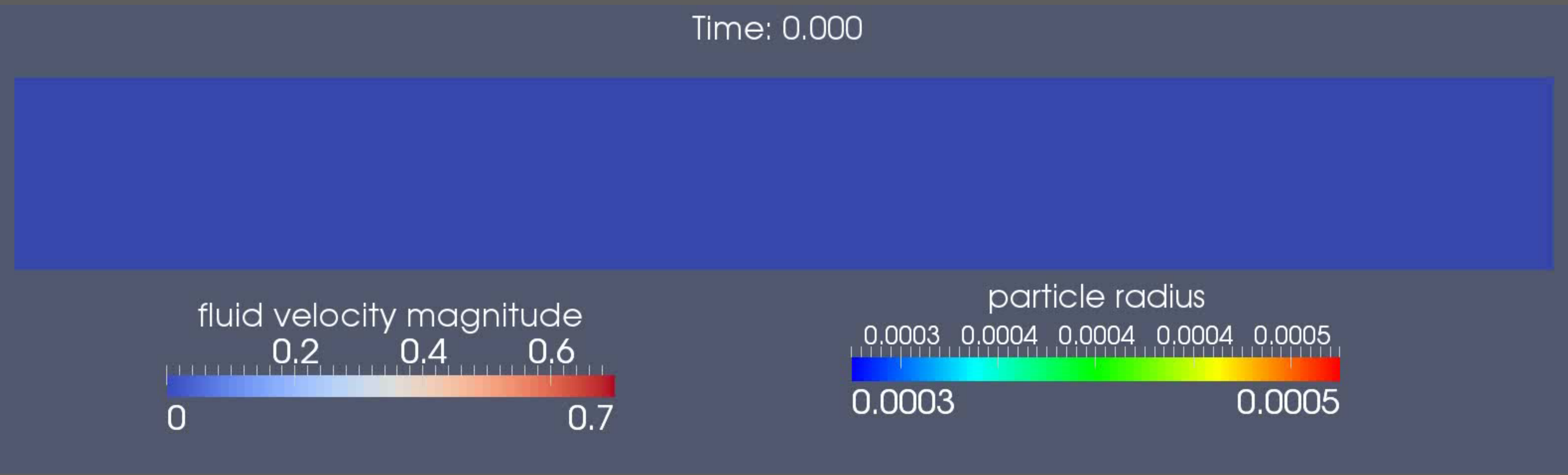
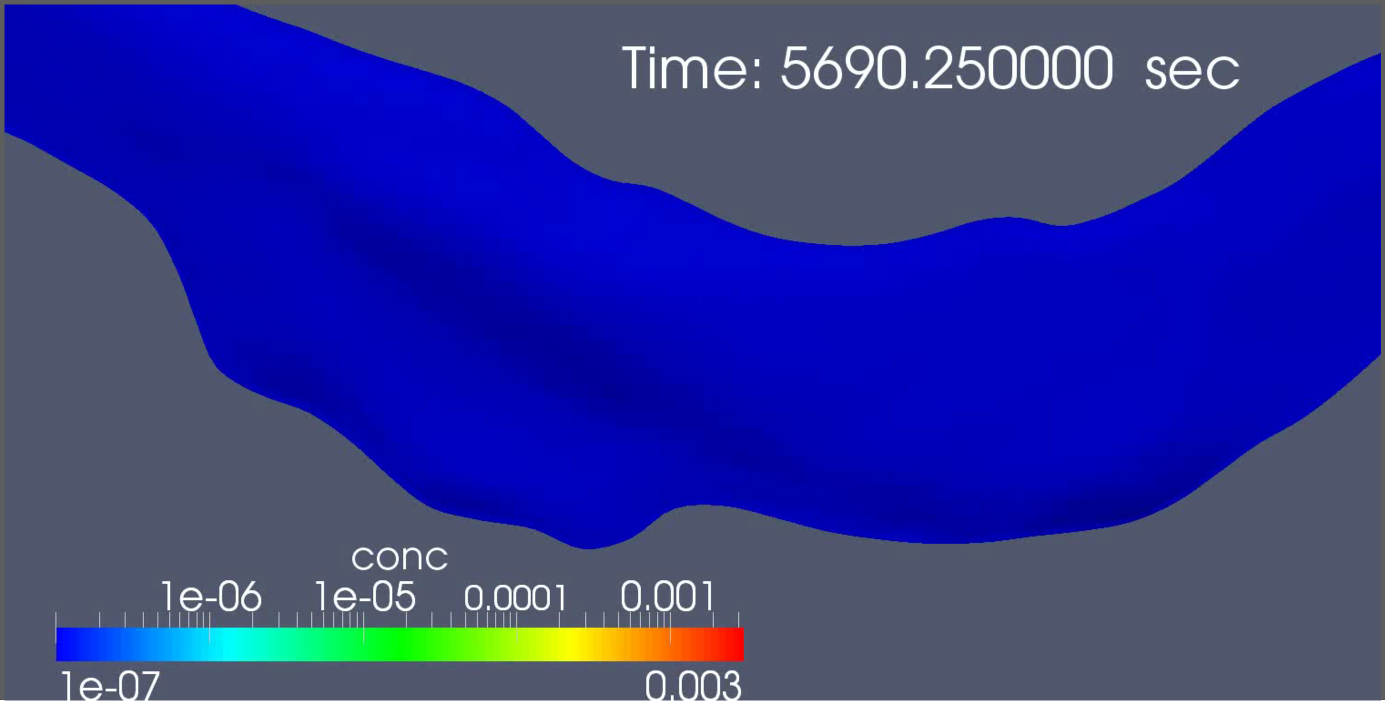


OpenFOAM

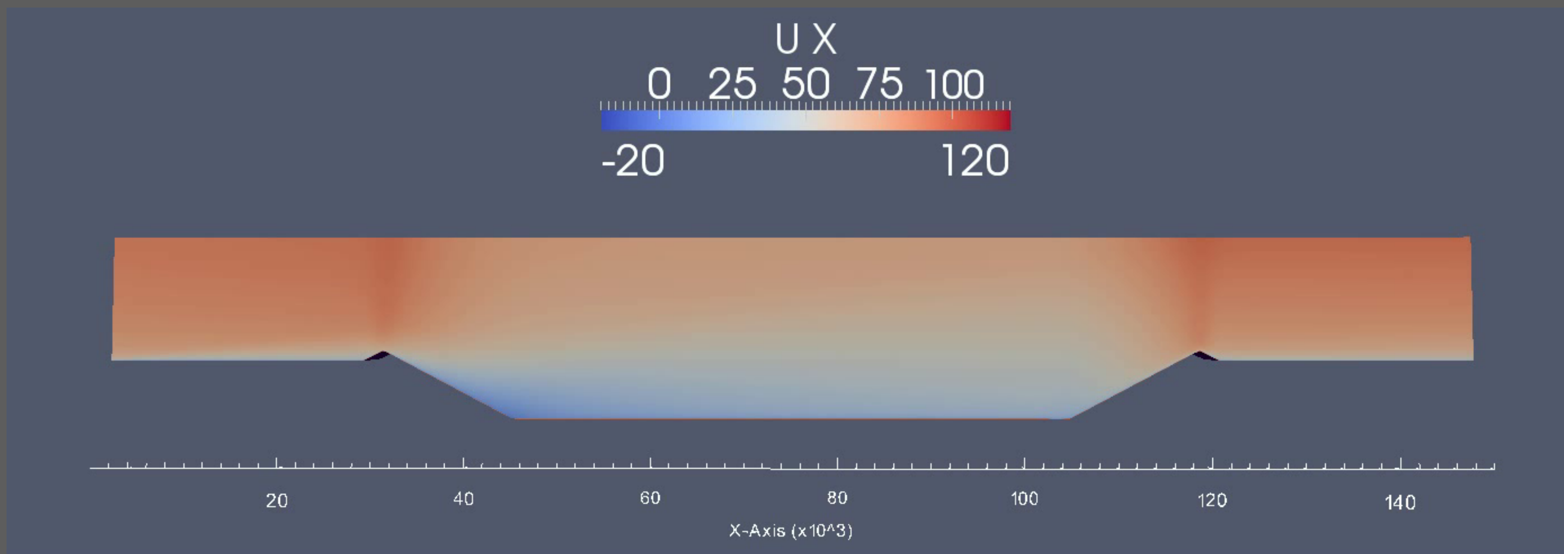
$$\frac{\partial c}{\partial t} + \nabla \cdot c\left(\vec{u} - \vec{w}_{settle}\right) = \nabla \cdot \nu_t \nabla c$$

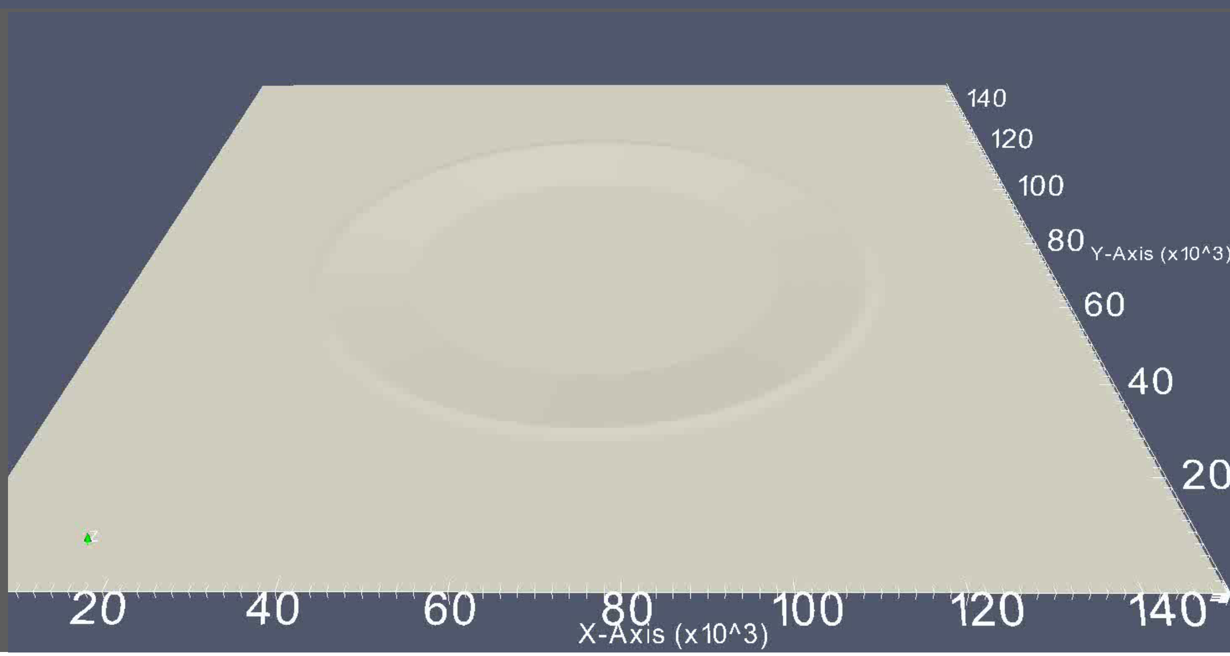
```
 solve (
fvm::ddt(conc)+ fvm::div(phi, conc)+ fvm::div(phis, conc) -
fvm::laplacian(nuSgs, conc)
);
```



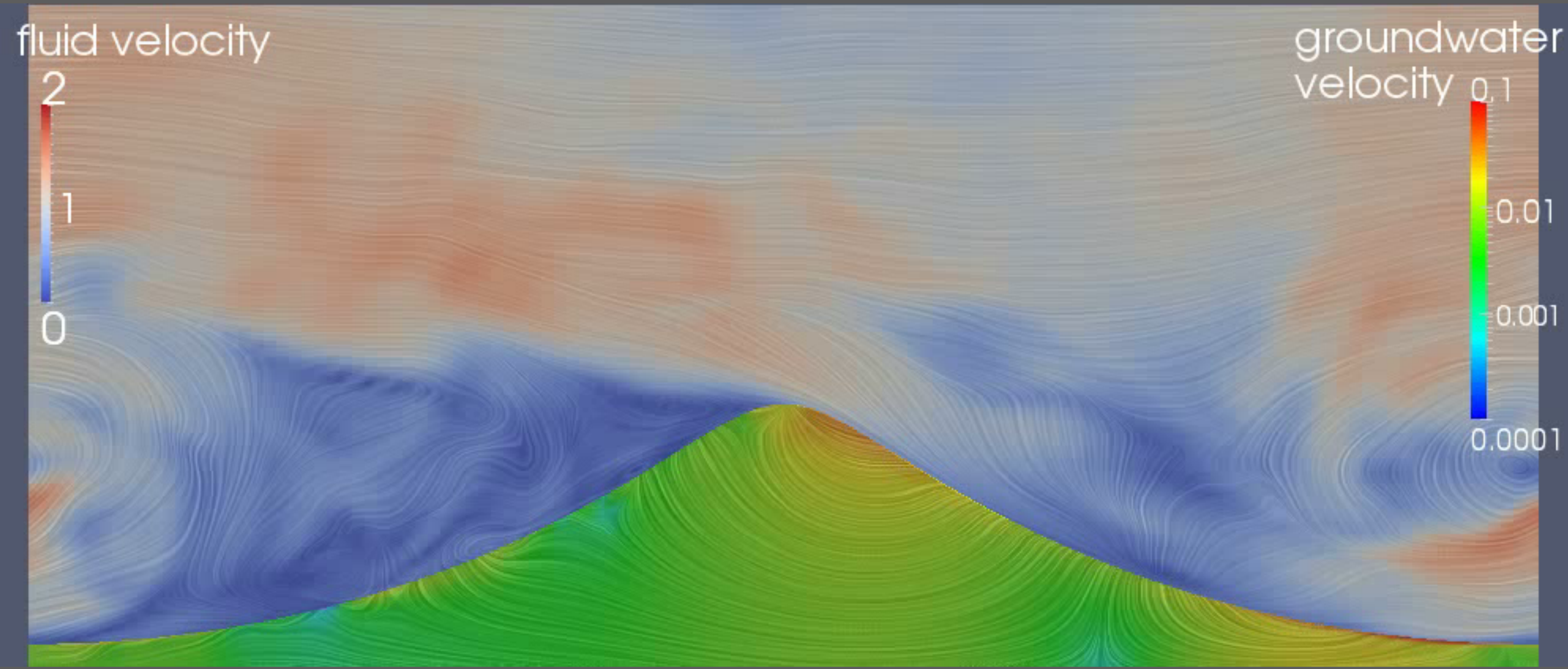
OpenFOAM for Morphodynamics

OF has dynamic meshing capabilities- e.g.Crater infilling by dunes on Mars

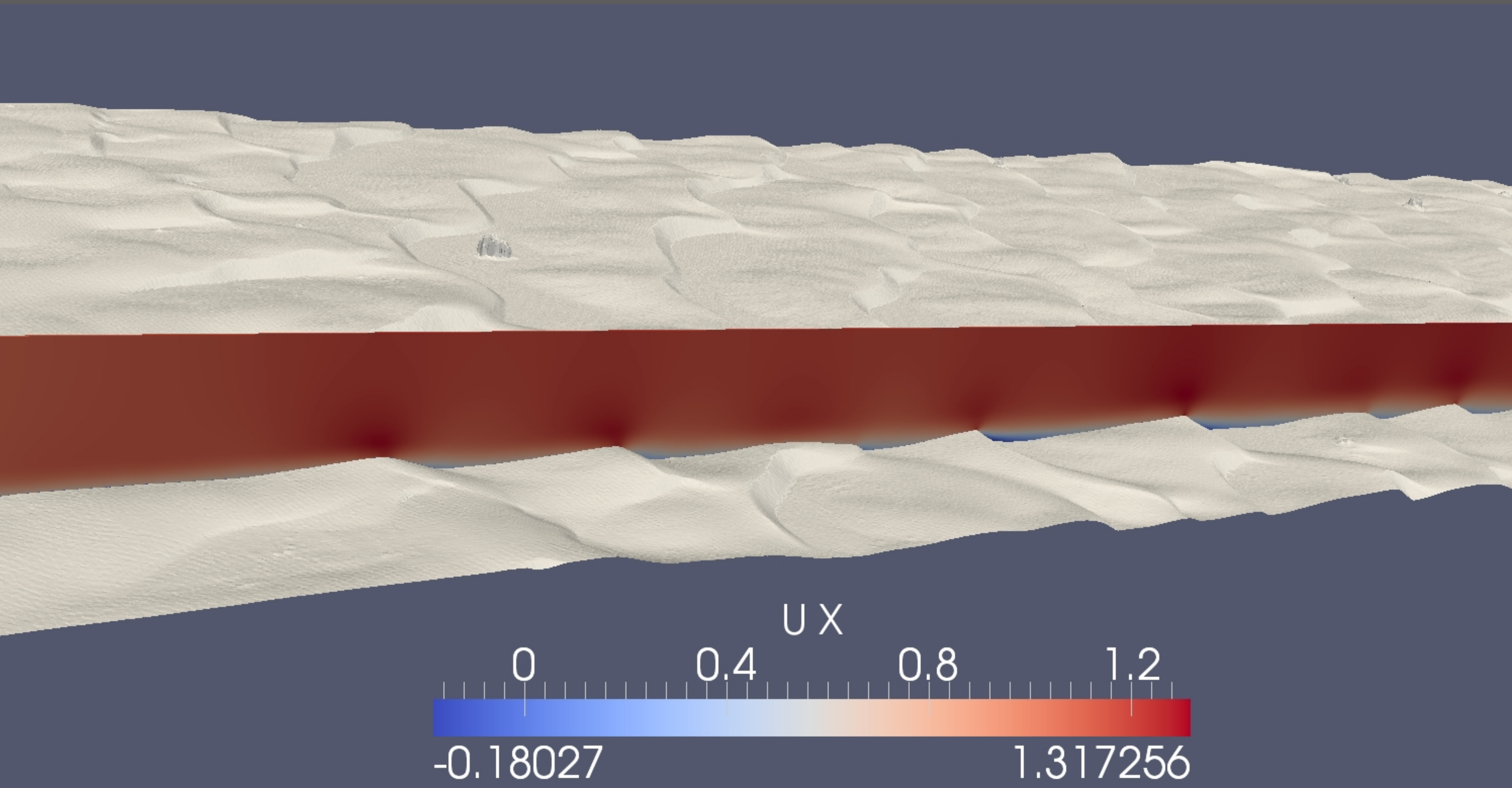




OpenFOAM easily couples different processes- e.g. turbulence and groundwater flow of ripple



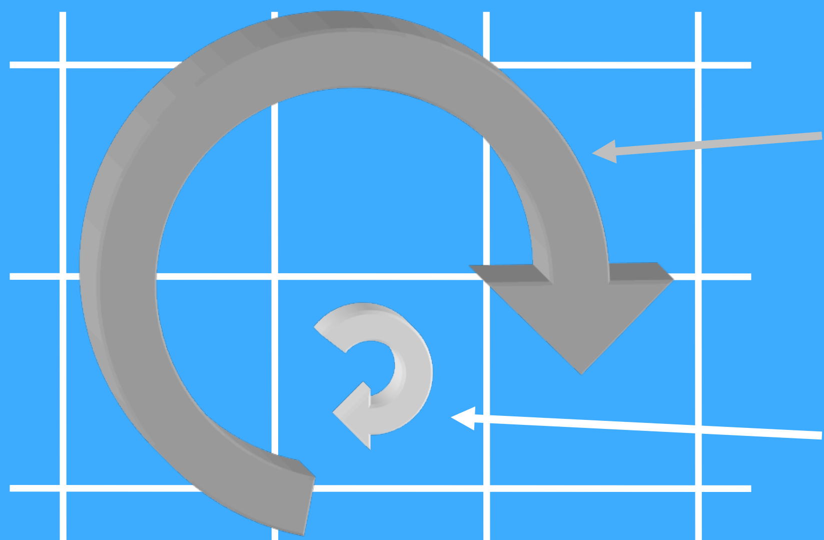
OpenFOAM grids rapidly from DEM (e.g.NCALM White Sands Data)



Large Eddy Simulation (LES)

N-S equations are spatially-filtered, NOT time-averaged.

$u = \overline{u}$ (spatially filtered) + u' (fluctuation)



Eddies, larger than grid scale, are directly calculated by spatially-filtered N-S equations.

Eddies, smaller than grid scale (sub-grid scale: SGS), are parameterized.

LES Model of Turbulence

LES model directly calculates turbulence scales larger than the grid

Here we use the dynamic subgrid-scale model proposed by Germano et al (1991) and modified by Lilly(1991)

Flow solver based on OpenFOAM finite volume CFD open source tools

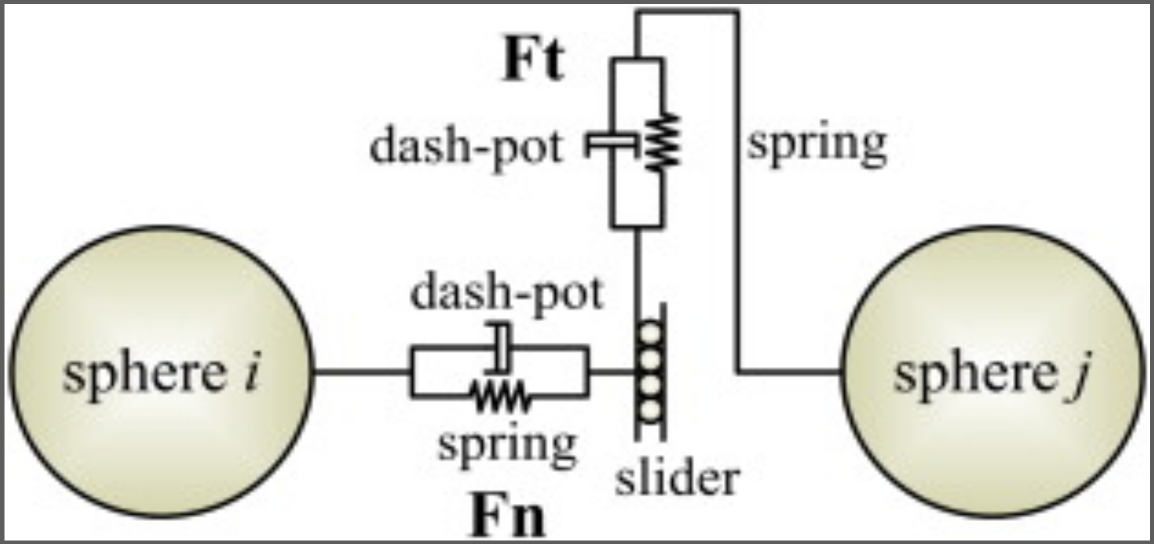
Advective terms are discretized with central differences- higher order schemes are difficult on unstructured finite volume grids

DEM- discrete element model

-sediment is modeled as spheres

-forces between the spheres are modeled using elastic contact theory

-interaction between particles (force chains and shear bands) are directly modeled



Discrete Element Model

We use the LIGGGHTS (C Kloss core developer) open source code based on LAMMPS (Sandia National Lab)

Simulations herein use a Hertzian non-linear formulation for the interaction between overlapping grains

parameters were adjusted to achieve an angle of repose in the range of natural sand

Coupled LES-DEM

- Coupled solvers based from the CFDEM open source project (C. Goniva core developer)
- The solver has four way coupling- mass and momentum is exchanged between the fluid and particles
- Herein we employ the Di Felice(1994) drag model modified for natural grains based on the experiments of Schmeeckle et al(2007) and pressure gradient force
- Both codes utilize domain decomposition for parallelization.
- The two code bases are coupled by MPI

Fluid conservation of mass and momentum

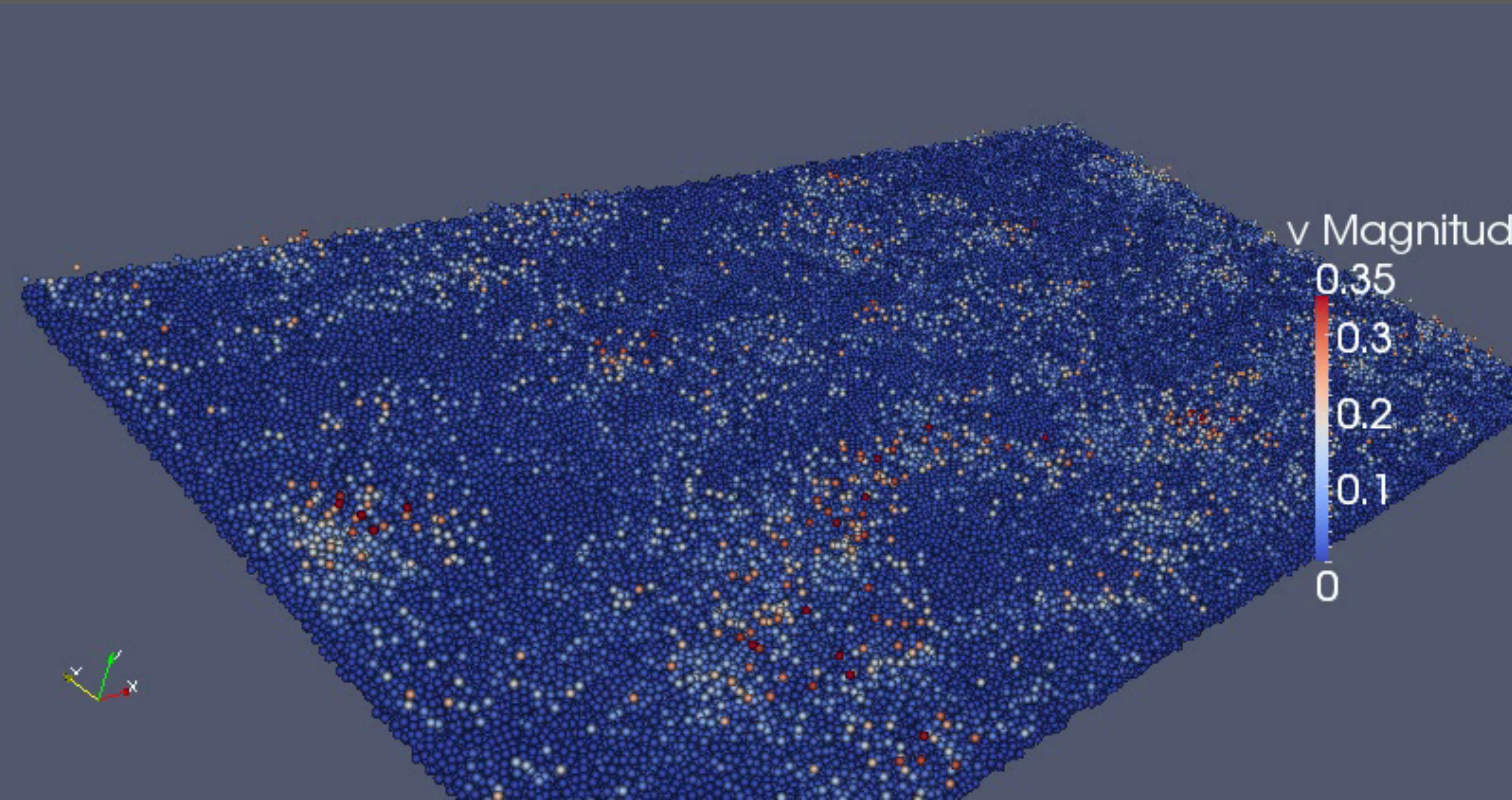
$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha u) = 0$$

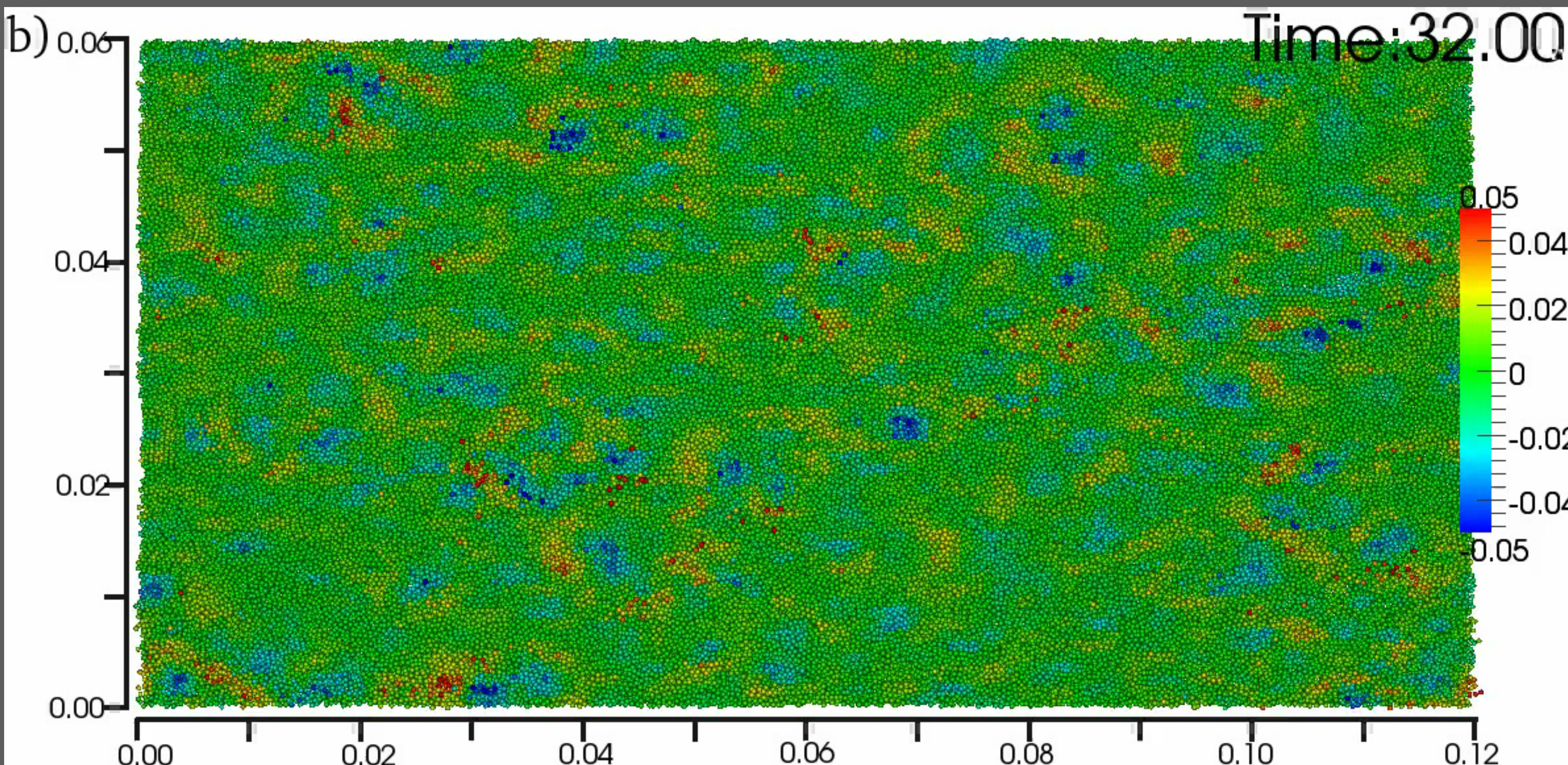
$$\frac{\partial \alpha u}{\partial t} + \nabla \cdot (\alpha u u) = \frac{-\alpha}{\rho} \nabla p + \nabla \cdot \tau - K_{sf} \left| u - u_{sed} \right|$$

K_{sf} is calculated at each grid cell by summing the forces of the solids on the fluid at each grid cell:

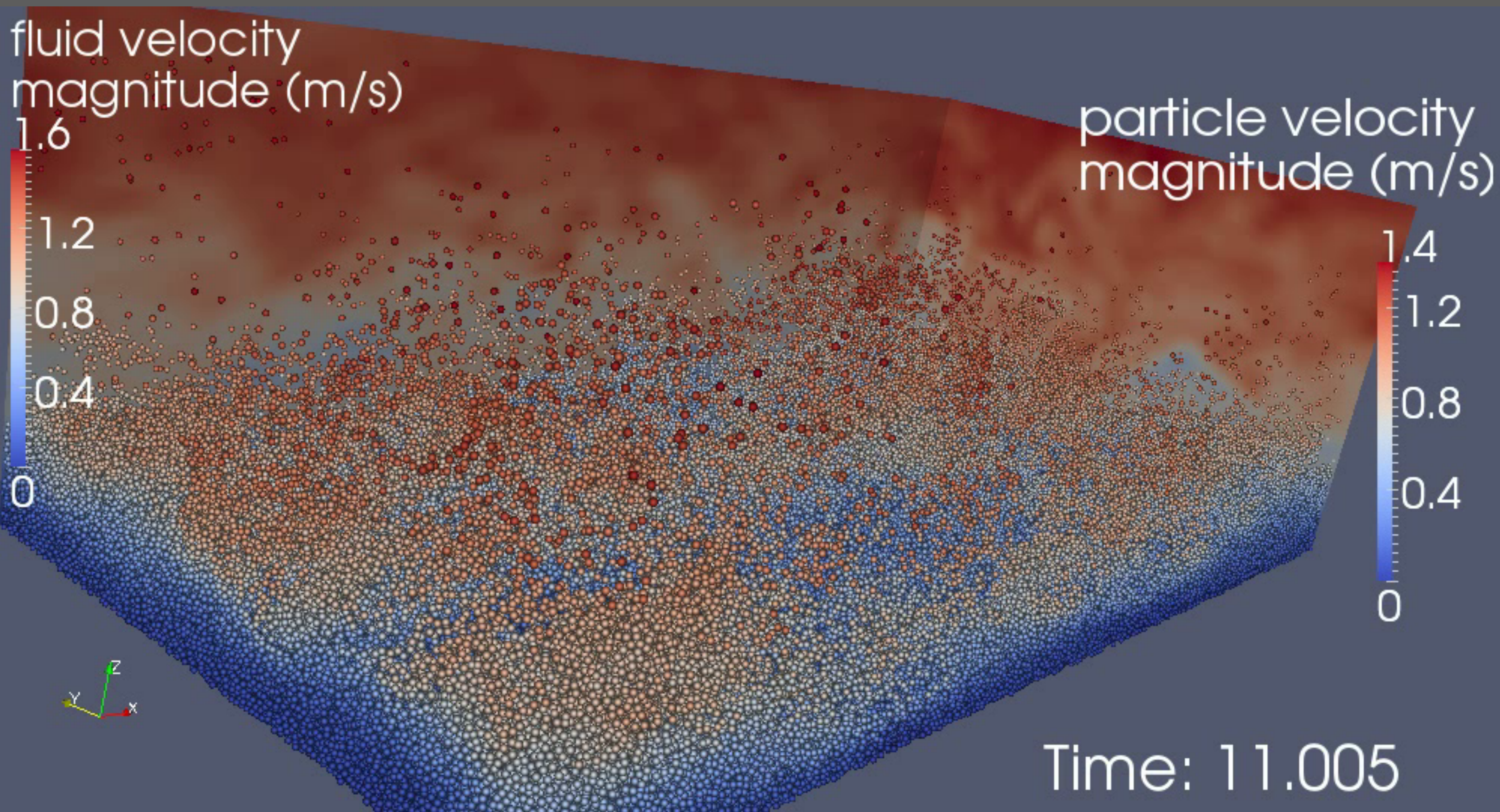
$$\rho K_{sf} = \frac{\sum f_{solid-fluid}}{(cellvolume) \left| u - u_{sed} \right|}$$

Bedload LES-DEM over a flat bed

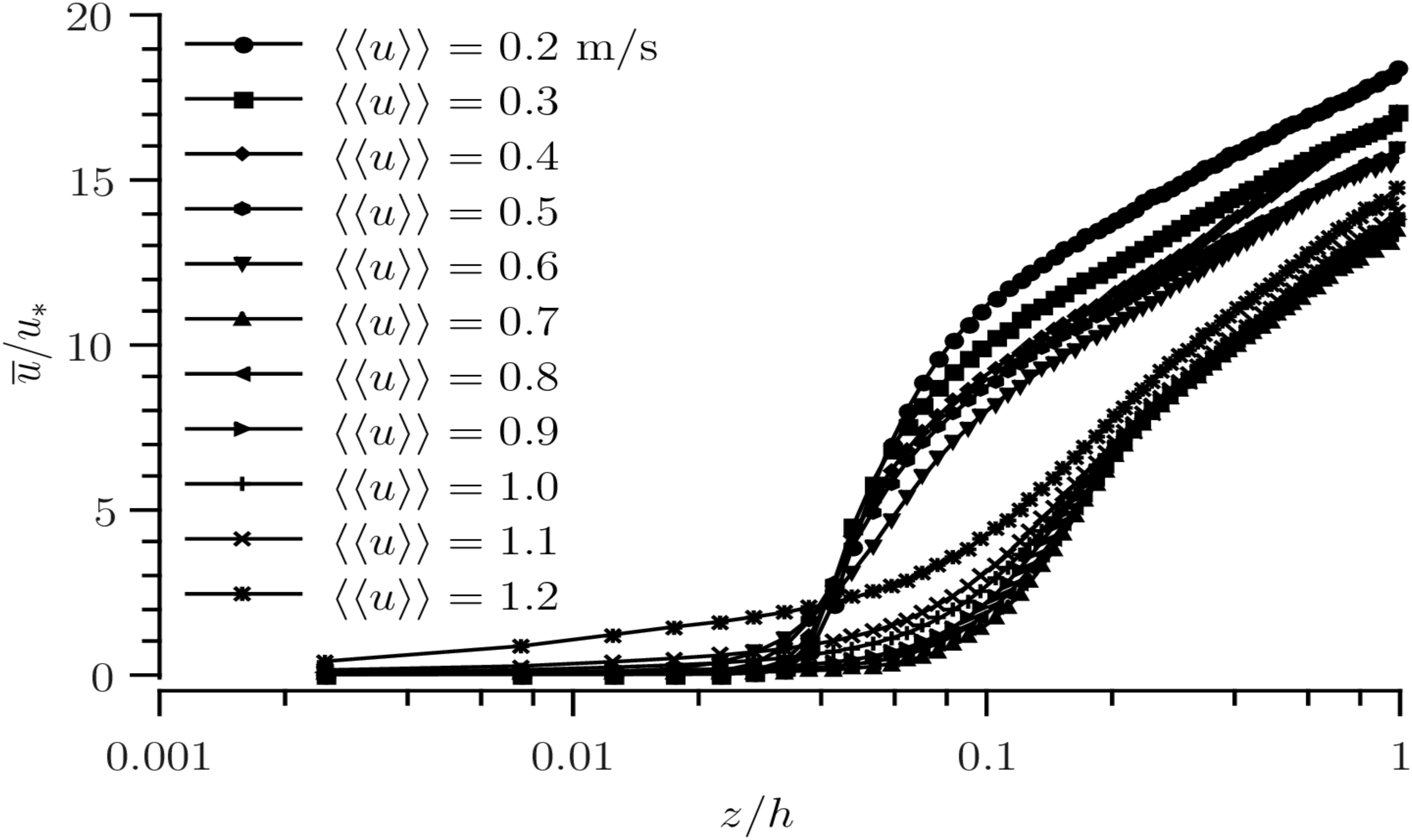


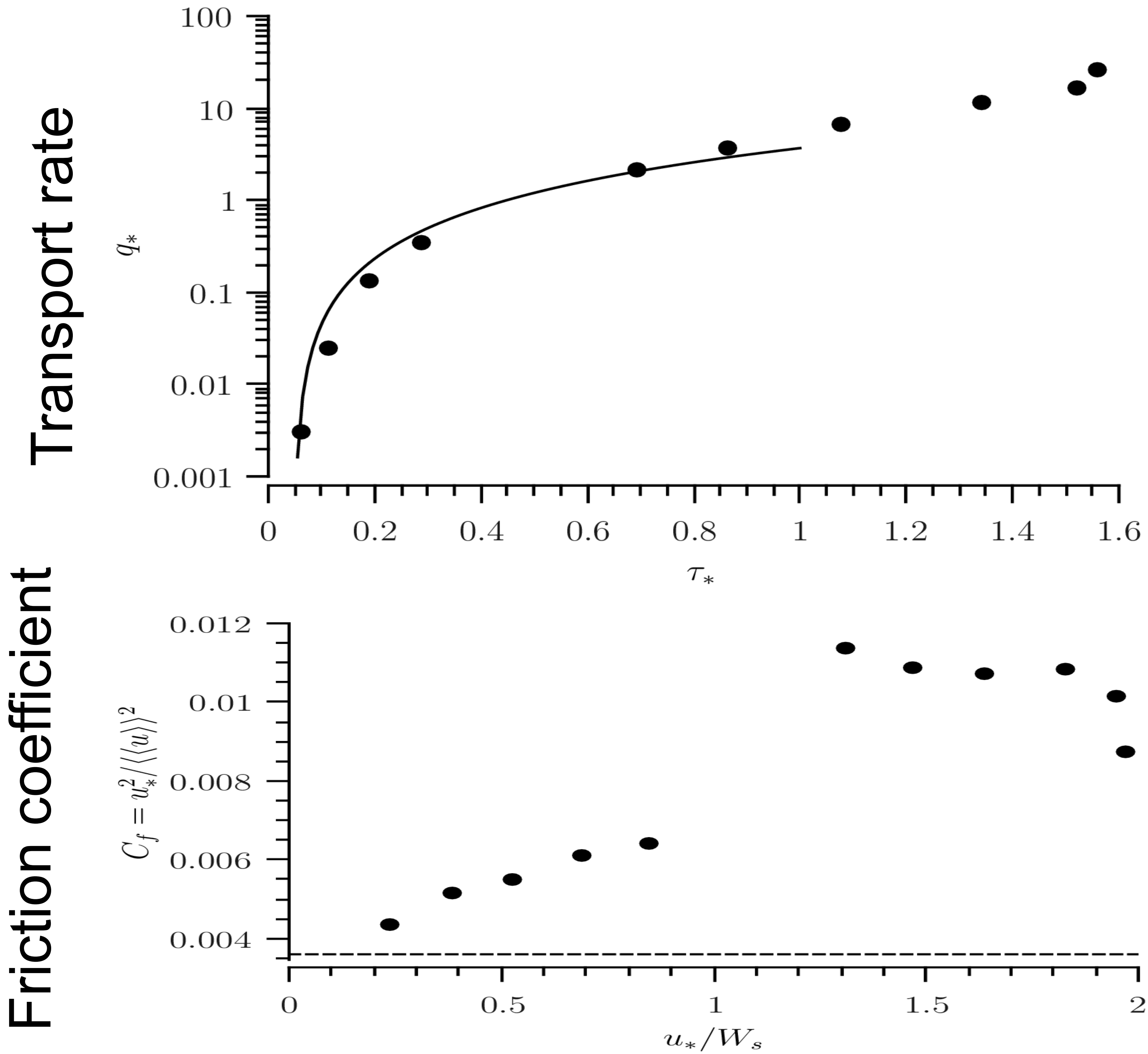


b)
Time:32.00
0.06
0.04
0.02
0.00
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.05
0.04
0.02
0
-0.02
-0.04
-0.05


fluid velocity
magnitude (m/s)
1.6
1.2
0.8
0.4
0
particle velocity
magnitude (m/s)
1.4
1.2
0.8
0.4
0
Z
Y
X
Time: 11.005

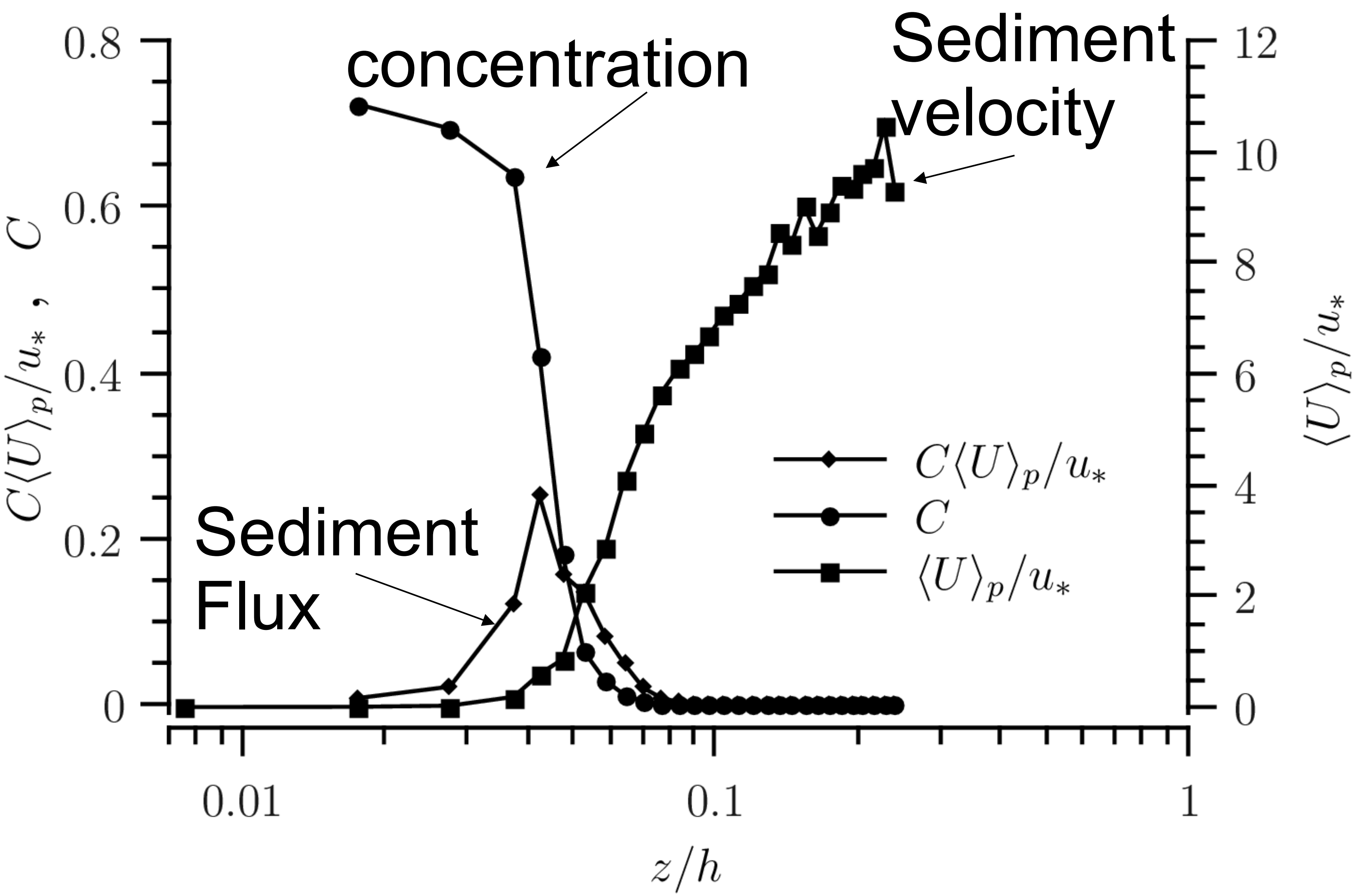
Velocity profiles over flat bed

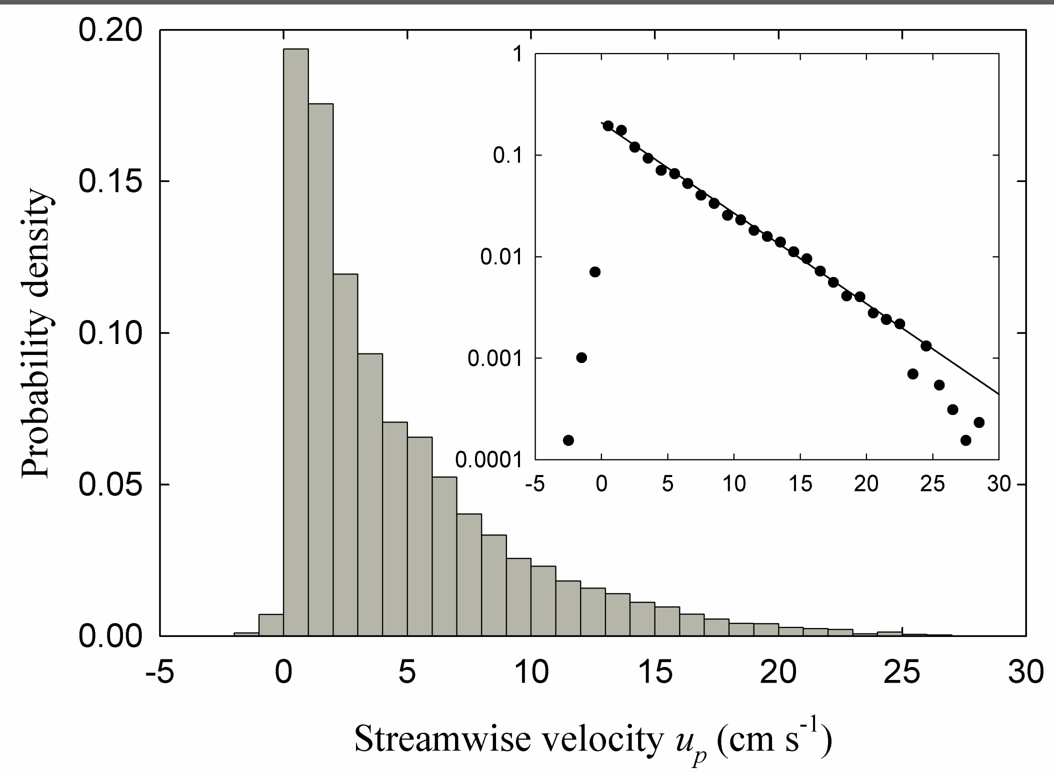


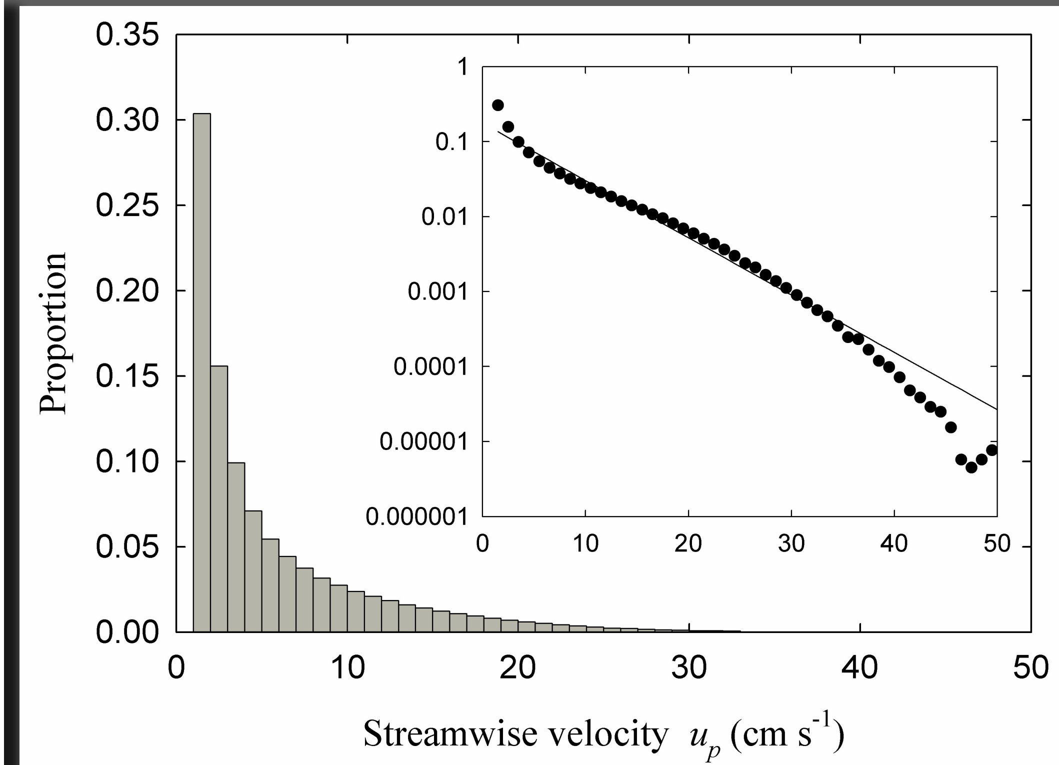


Transport rate
q_*
100
10
1
0.1
0.01
0.001
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
τ_*
Friction coefficient
$C_f = u_*^2/\langle\langle u\rangle\rangle^2$
0.012
0.01
0.008
0.006
0.004
0
0.5
1
1.5
2
u_*/W_s

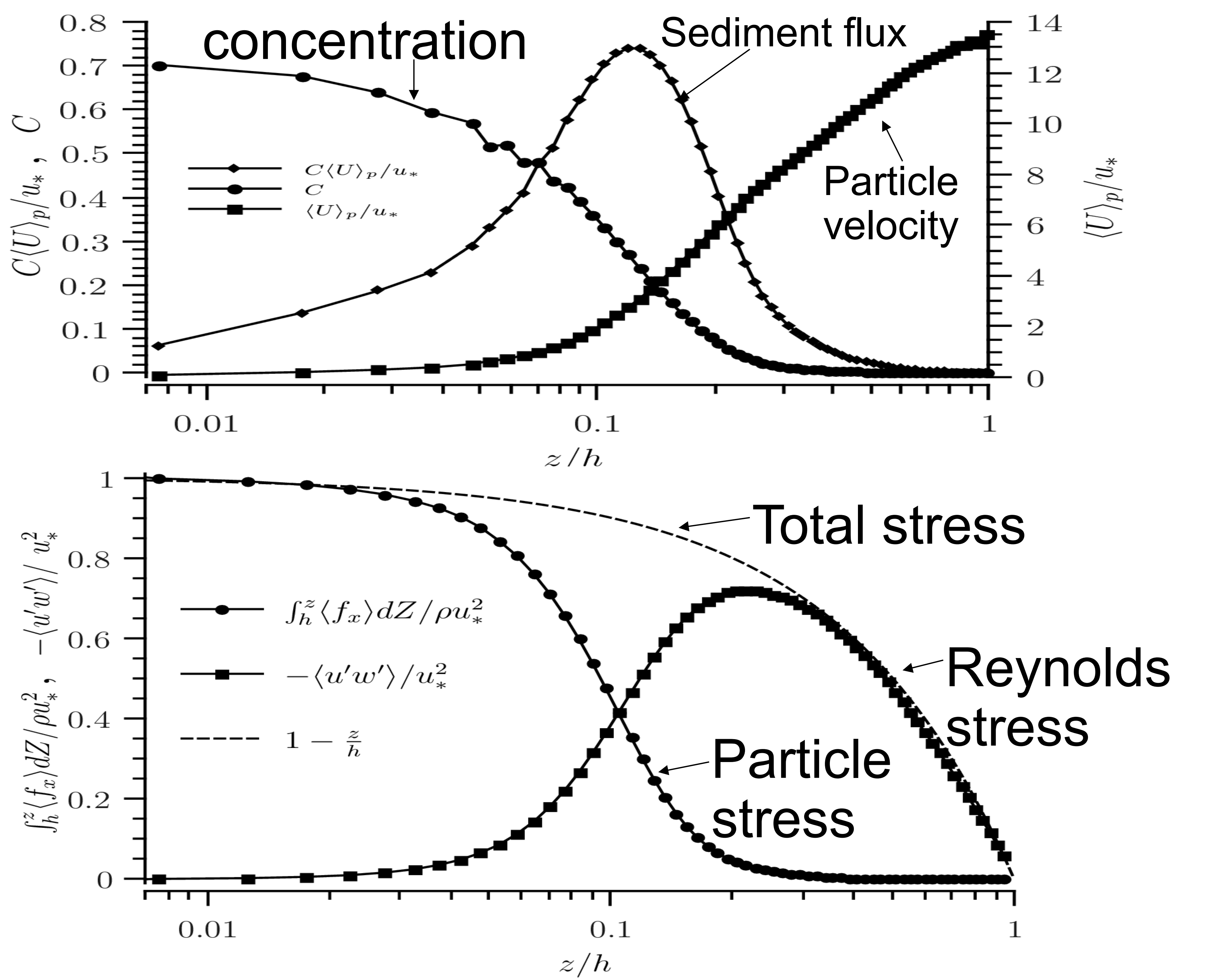
Bedload flux dominated by slower grains- saltation paradigm needs a shift



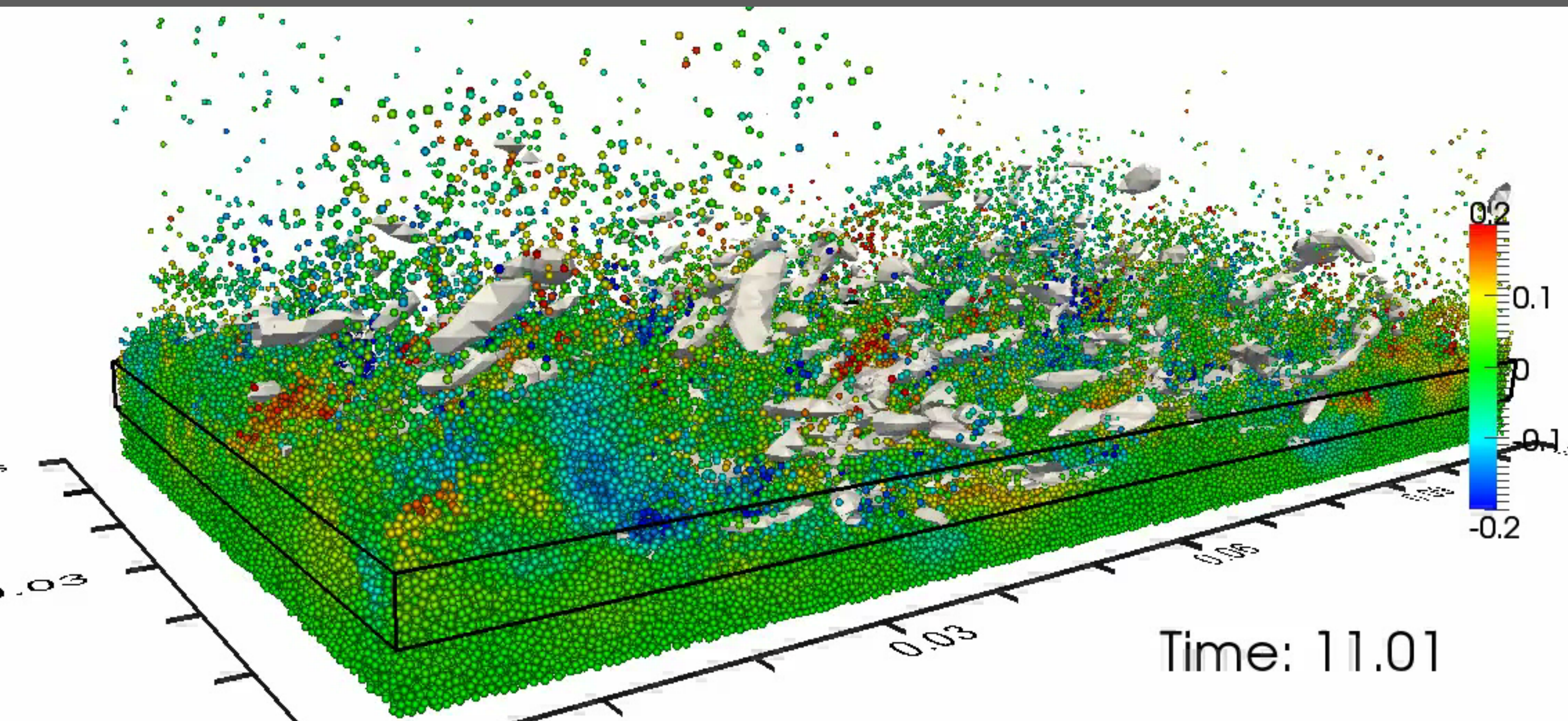




Furbish and Schmeeckle WRR 2013

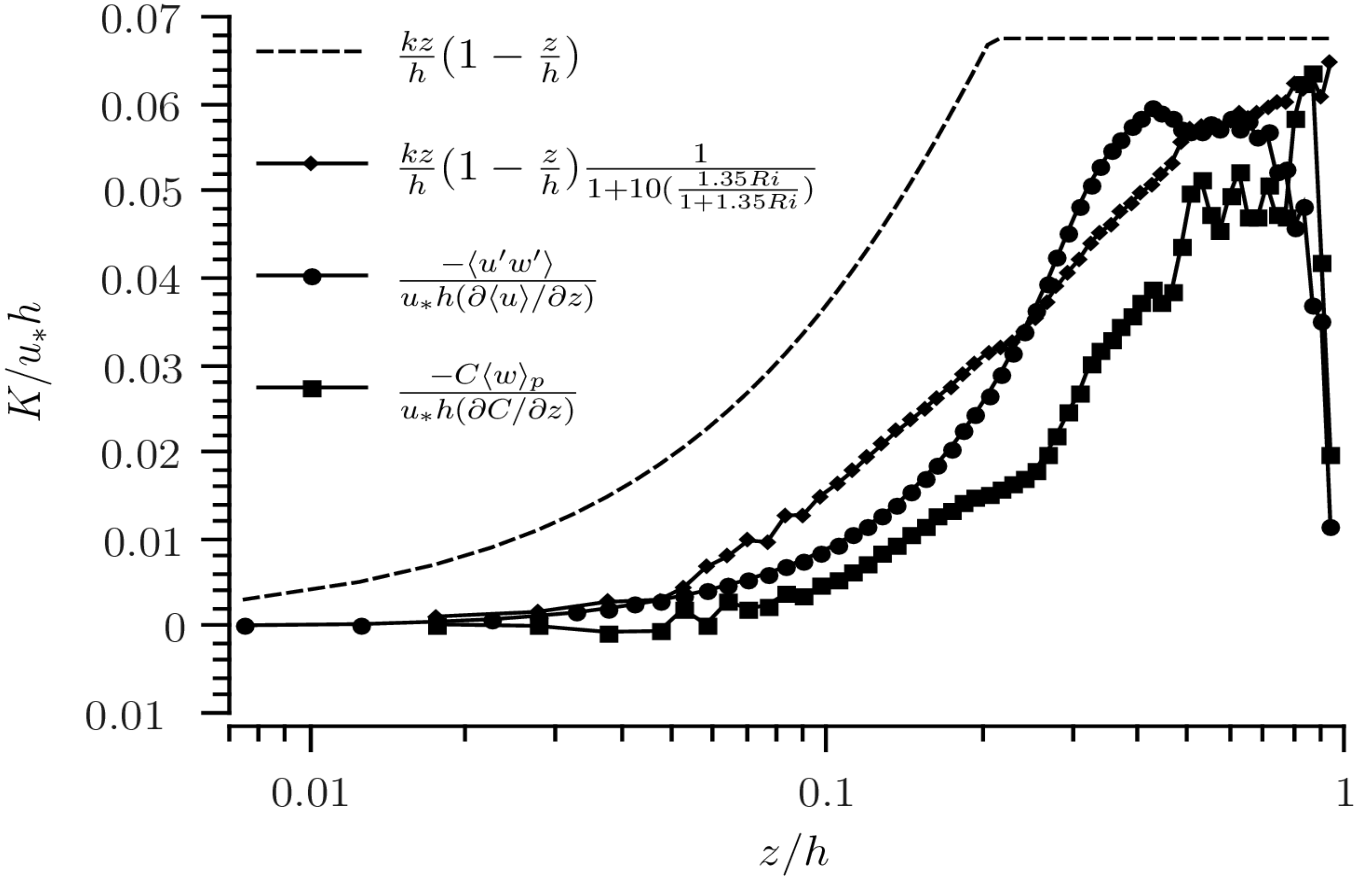


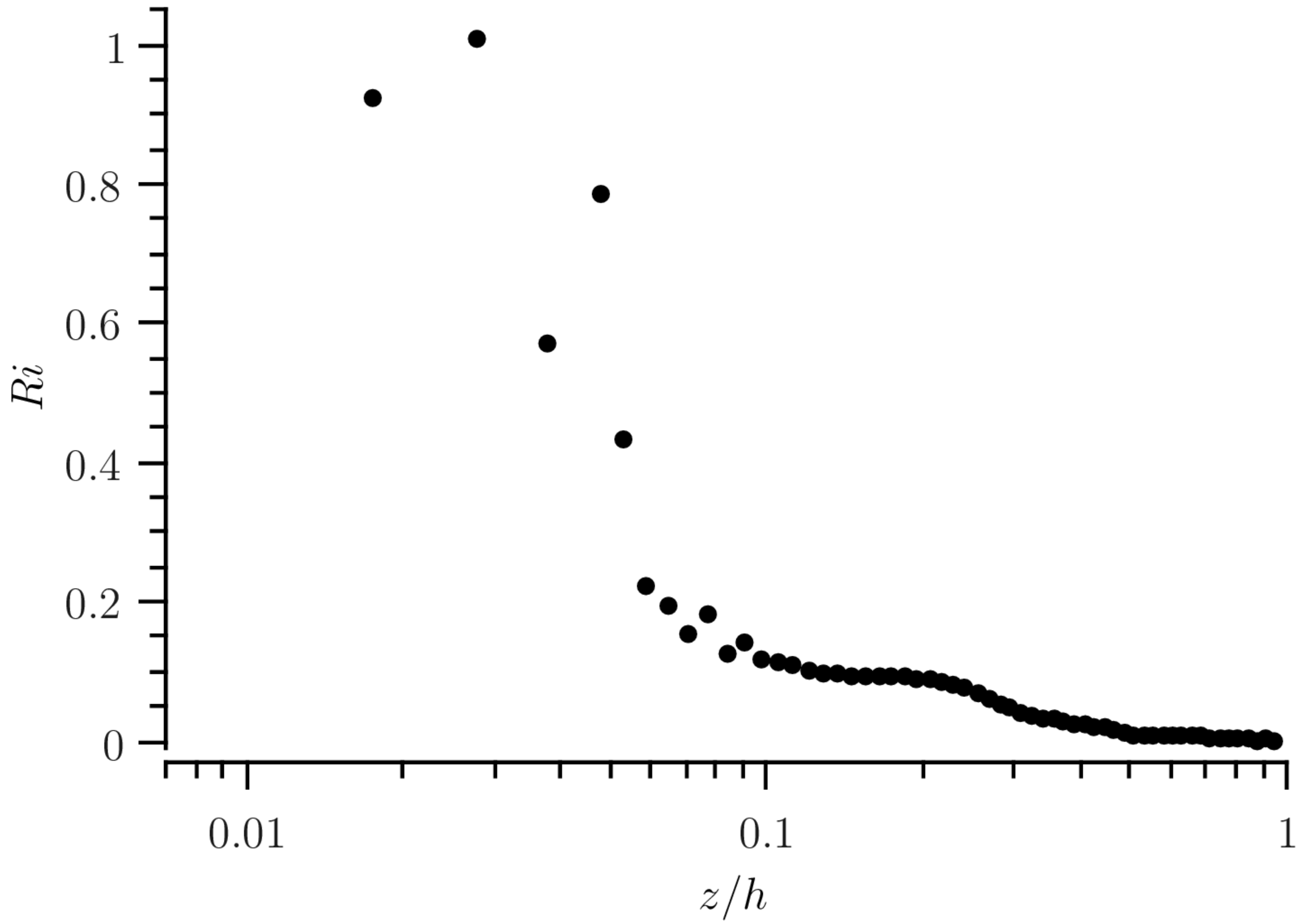
concentration
Sediment flux
Particle velocity
$C\langle U\rangle_p/u_*$
C
$\langle U\rangle_p/u_*$
$C\langle U\rangle_p/u_*$, C
$\langle U\rangle_p/u_*$
z/h
Total stress
Reynolds stress
Particle stress
$\int_h^z \langle f_x\rangle dZ/\rho u_*^2$
$-\langle u'w'\rangle/u_*^2$
$1-\frac{z}{h}$
$\int_h^z \langle f_x\rangle dZ/\rho u_*^2$, $-\langle u'w'\rangle/u_*^2$
z/h



0.2
0.1
0
-0.1
-0.2
0.03
0.03
0.06
Time: 11.01

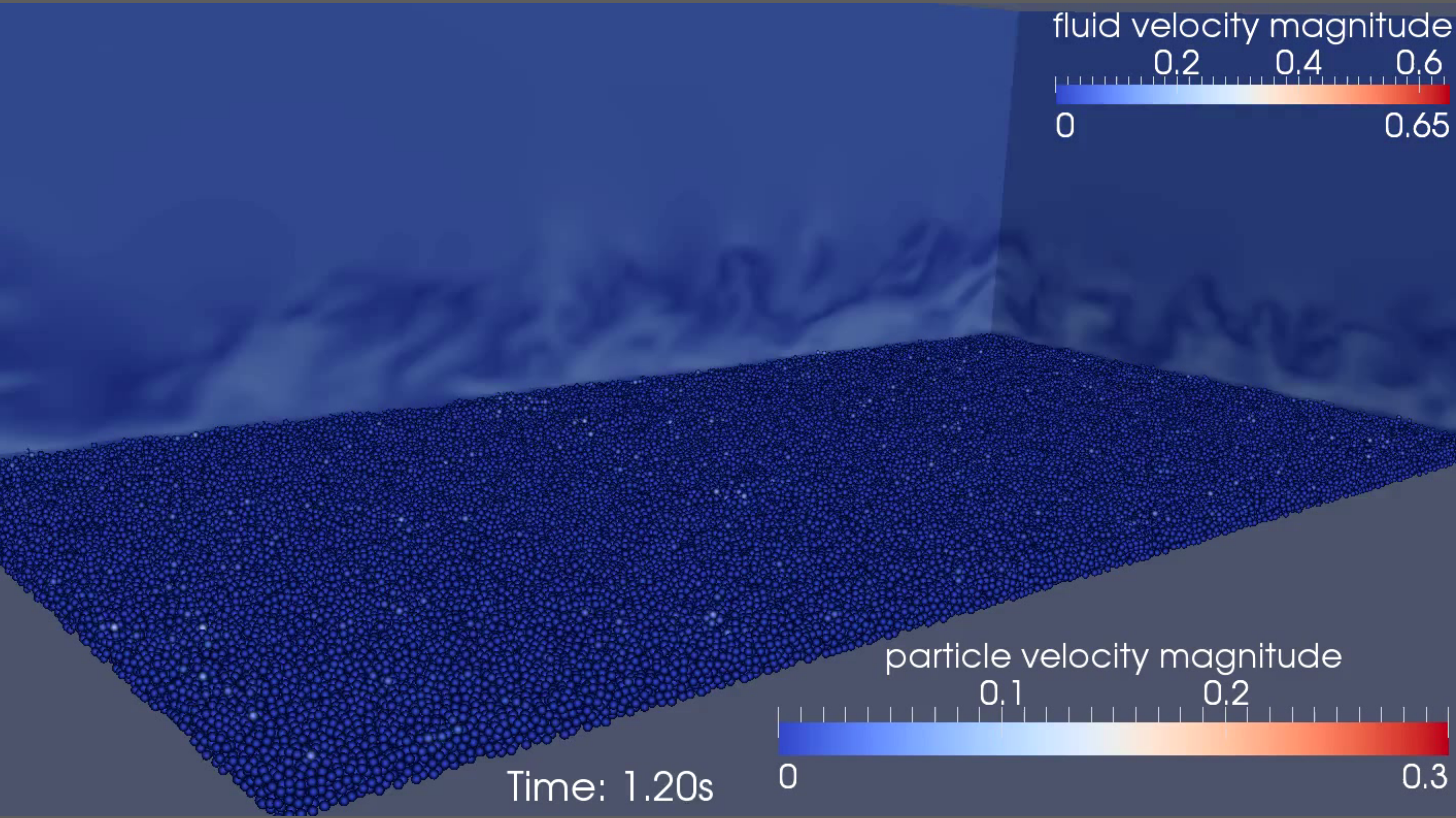
Momentum and sediment diffusivity- modified by stratification AND particle interactions

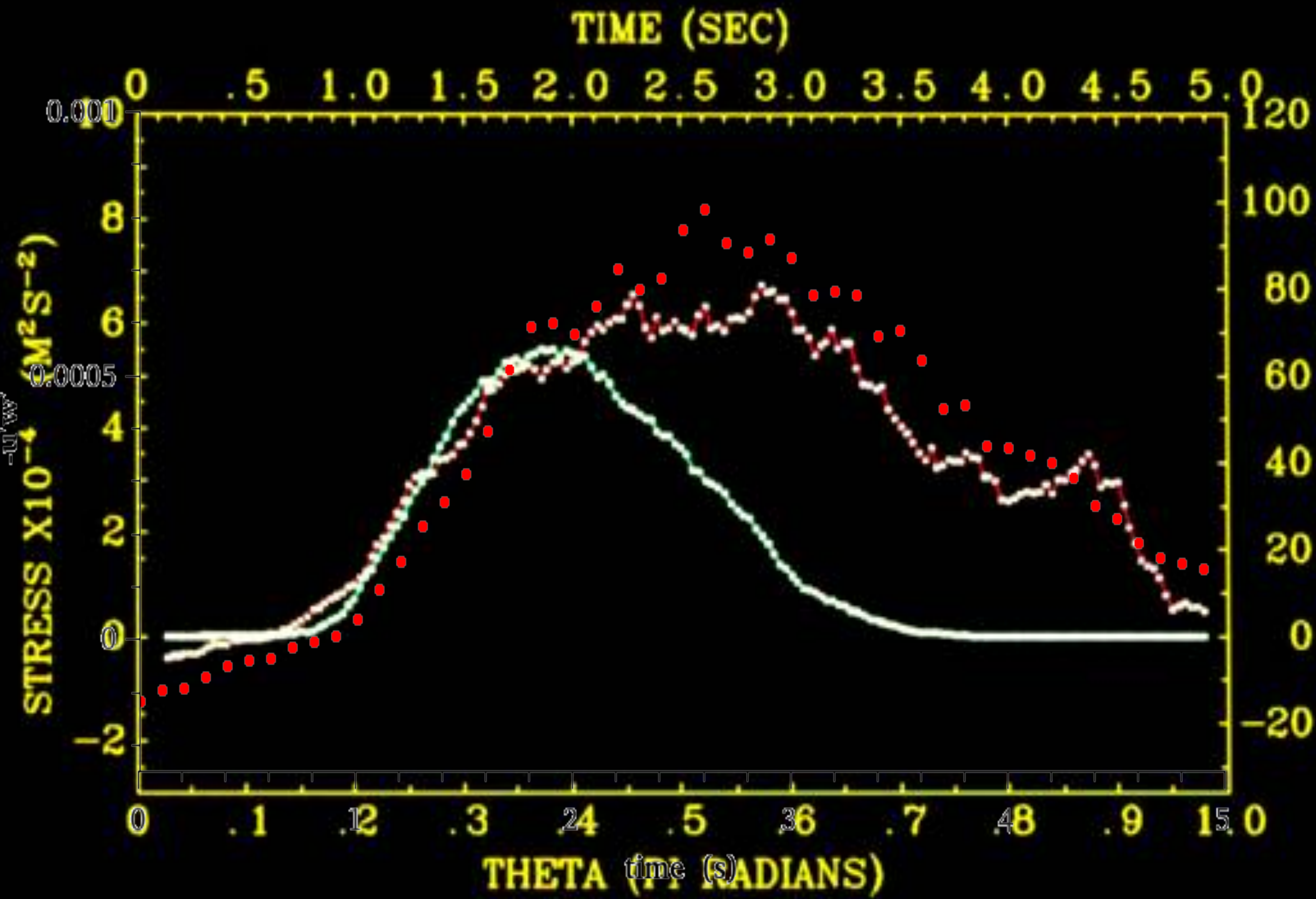




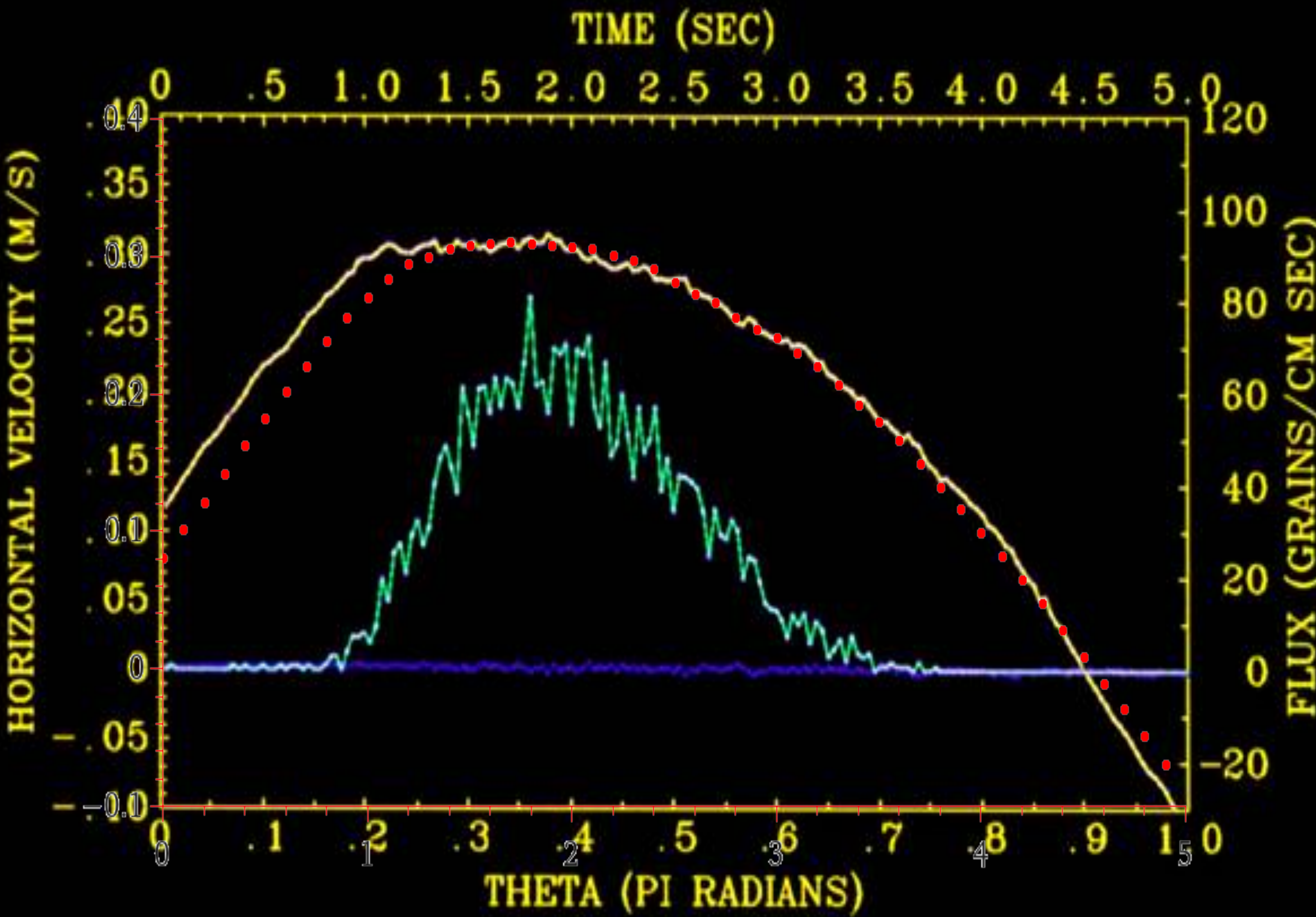
1
0.8
0.6
0.4
0.2
0
Ri
0.01
0.1
1
z/h

Bedload transport under waves

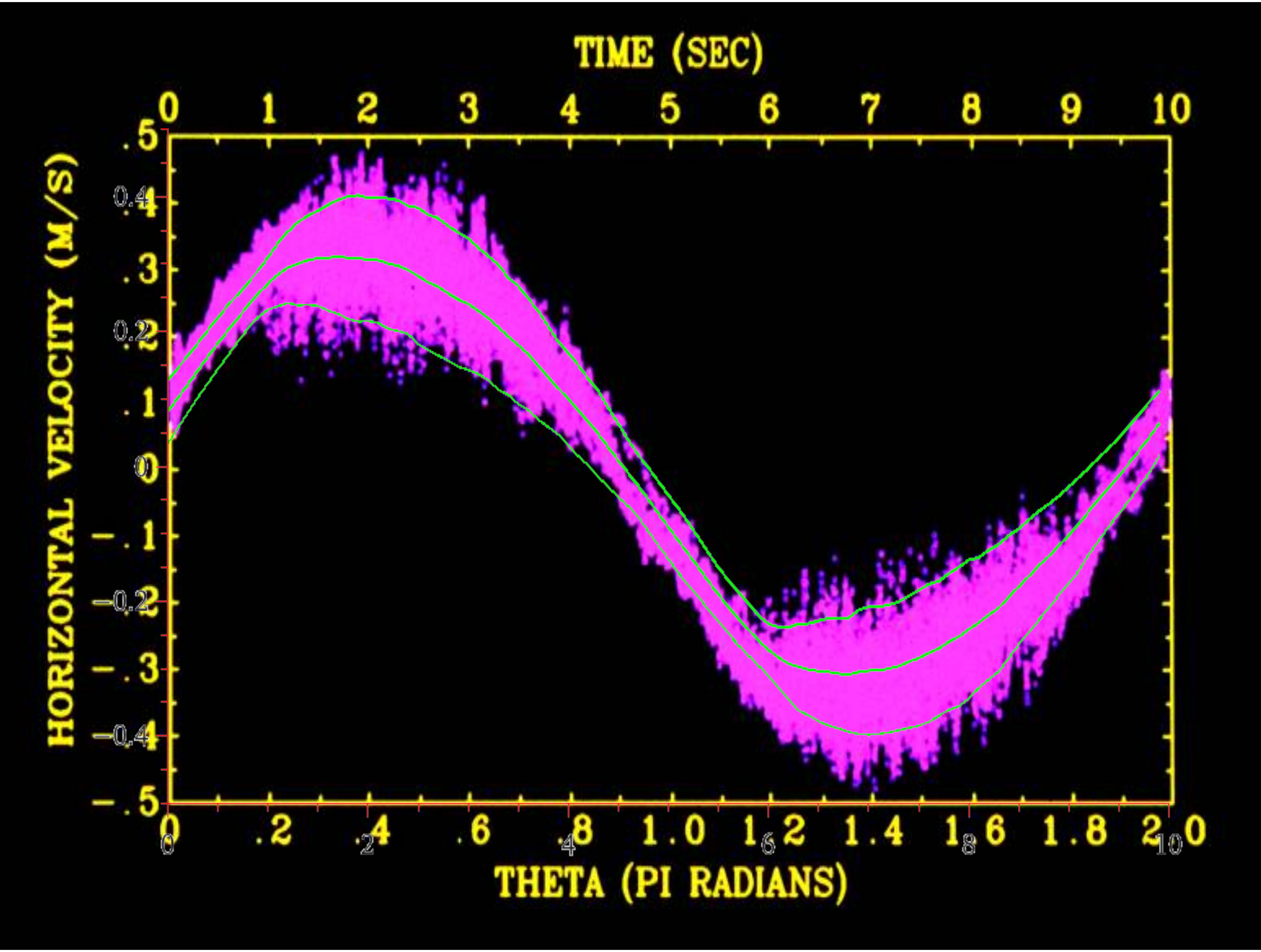




TIME (SEC)
0 .5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
0.001
0.0005
-u'w'
STRESS X10^-4 (M^2S^-2)
8
6
4
2
0
−2
120
100
80
60
40
20
0
−20
0 .1 .12 .3 .24 .5 .36 .7 .48 .9 15.0
THETA (PI RADIANS)
time (s)

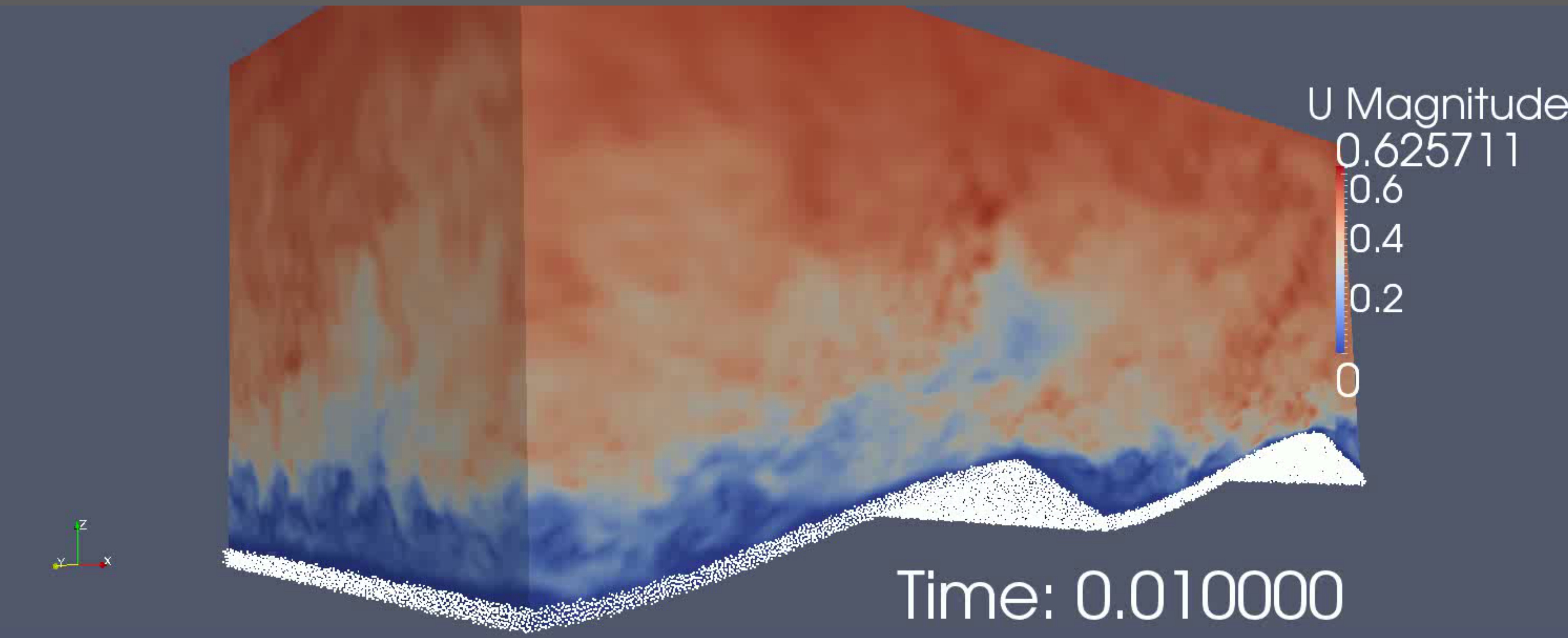


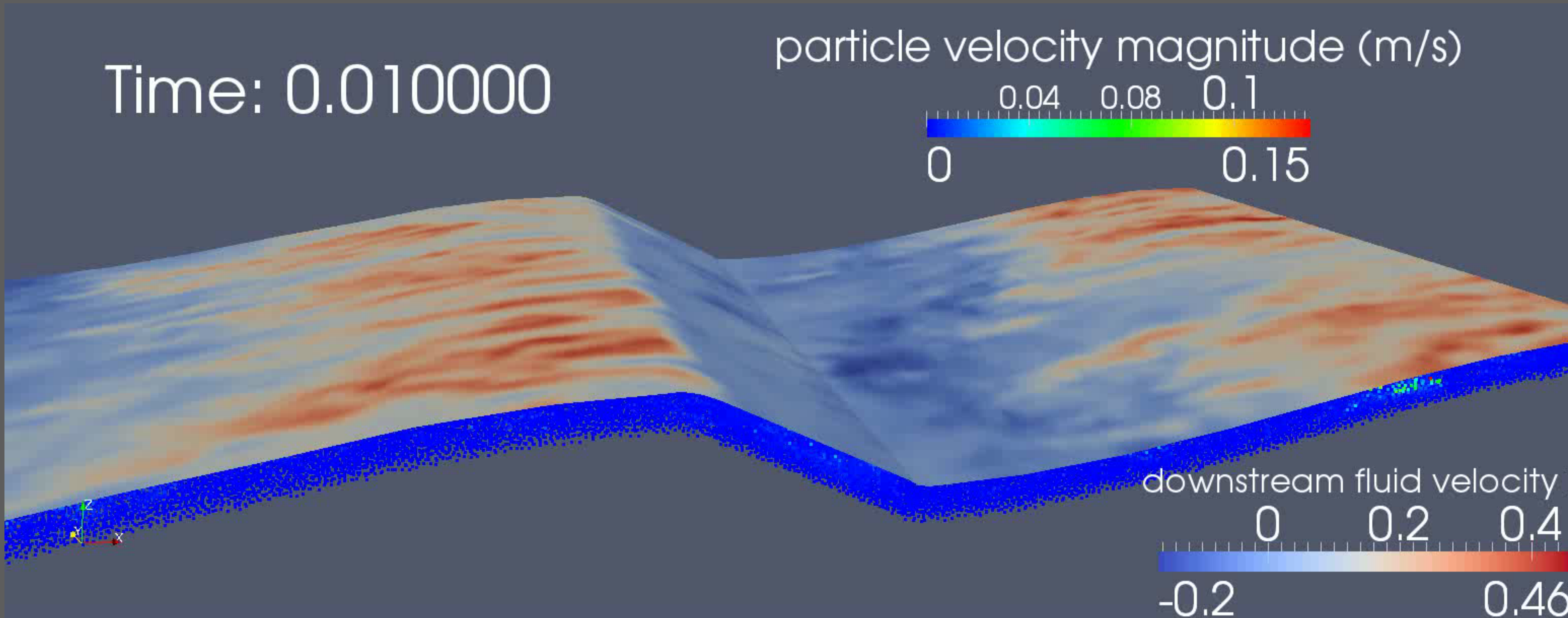
TIME (SEC)
0 .5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
HORIZONTAL VELOCITY (M/S)
.40 .35 .30 .25 .20 .15 .10 .05 0 -.05 -.10
0.4 0.3 0.2 0.1 0 −0.1
FLUX (GRAINS/CM SEC)
120 100 80 60 40 20 0 −20
THETA (PI RADIANS)
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
0 1 2 3 4 5

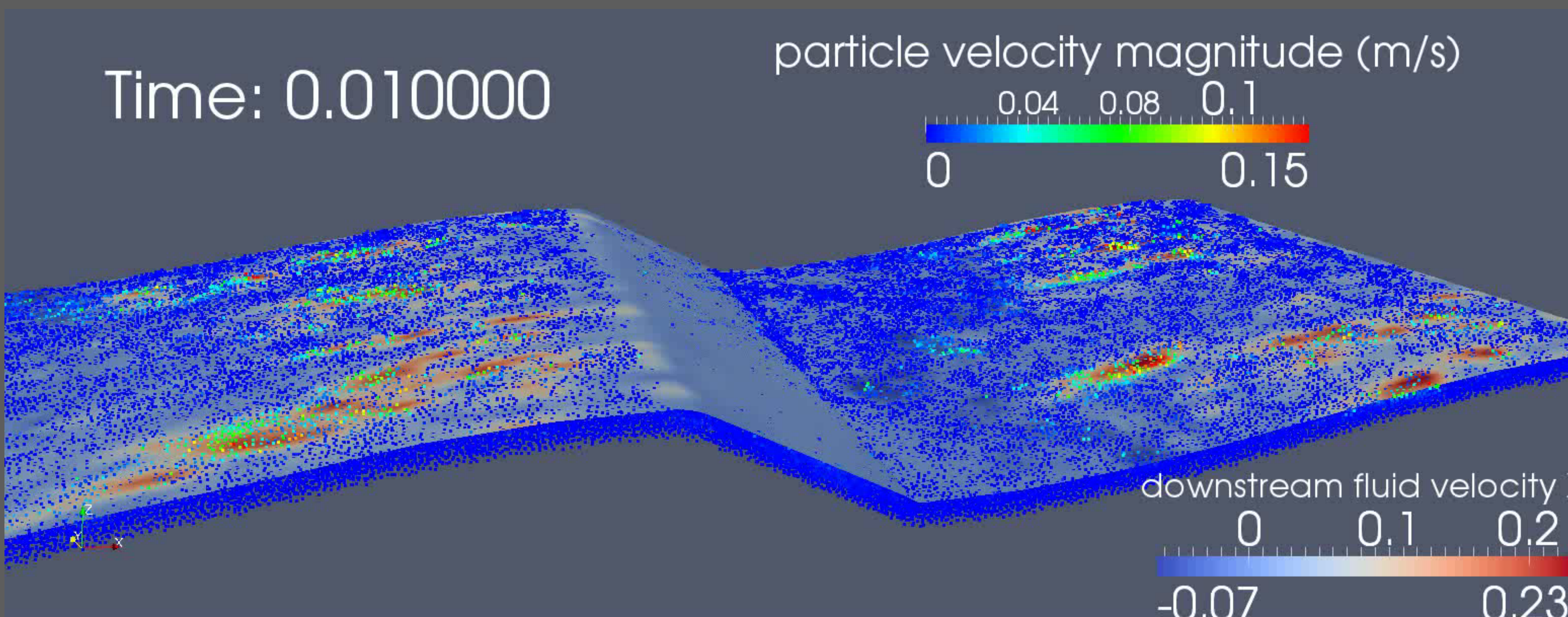


TIME (SEC)
0 1 2 3 4 5 6 7 8 9 10
HORIZONTAL VELOCITY (M/S)
.5 .4 .3 .2 .1 0 -.1 -.2 -.3 -.4 -.5
0.4 0.2 0 −0.2 −0.4
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
0 2 4 6 8 10
THETA (PI RADIANS)

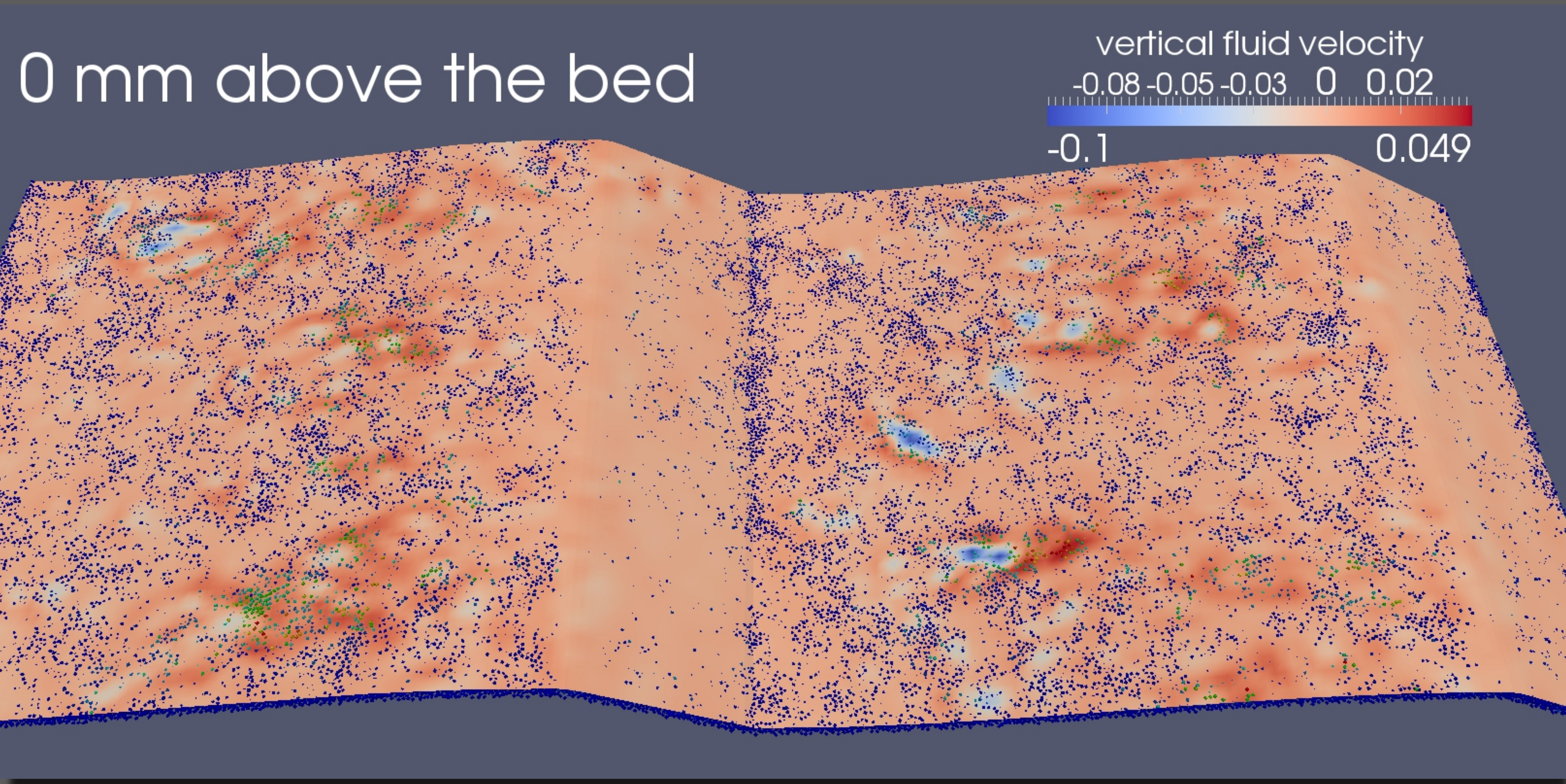
Flow over a ripple



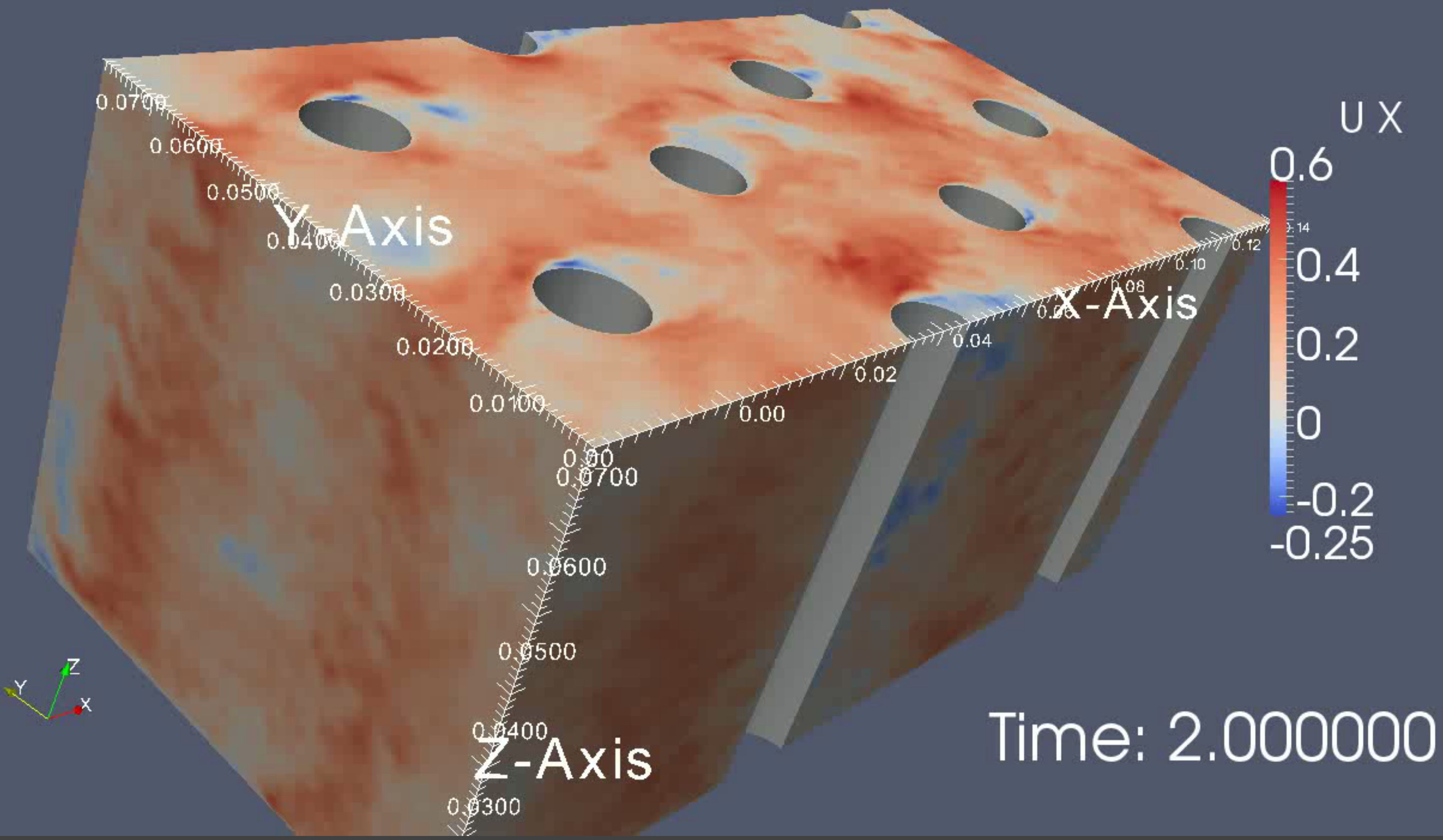

Time: 0.010000
particle velocity magnitude (m/s)
0.04 0.08 0.1
0 0.15
downstream fluid velocity
0 0.2 0.4
-0.2 0.46


Time: 0.010000
particle velocity magnitude (m/s)
0.04 0.08 0.1
0 0.15
downstream fluid velocity
0 0.1 0.2
-0.07 0.23

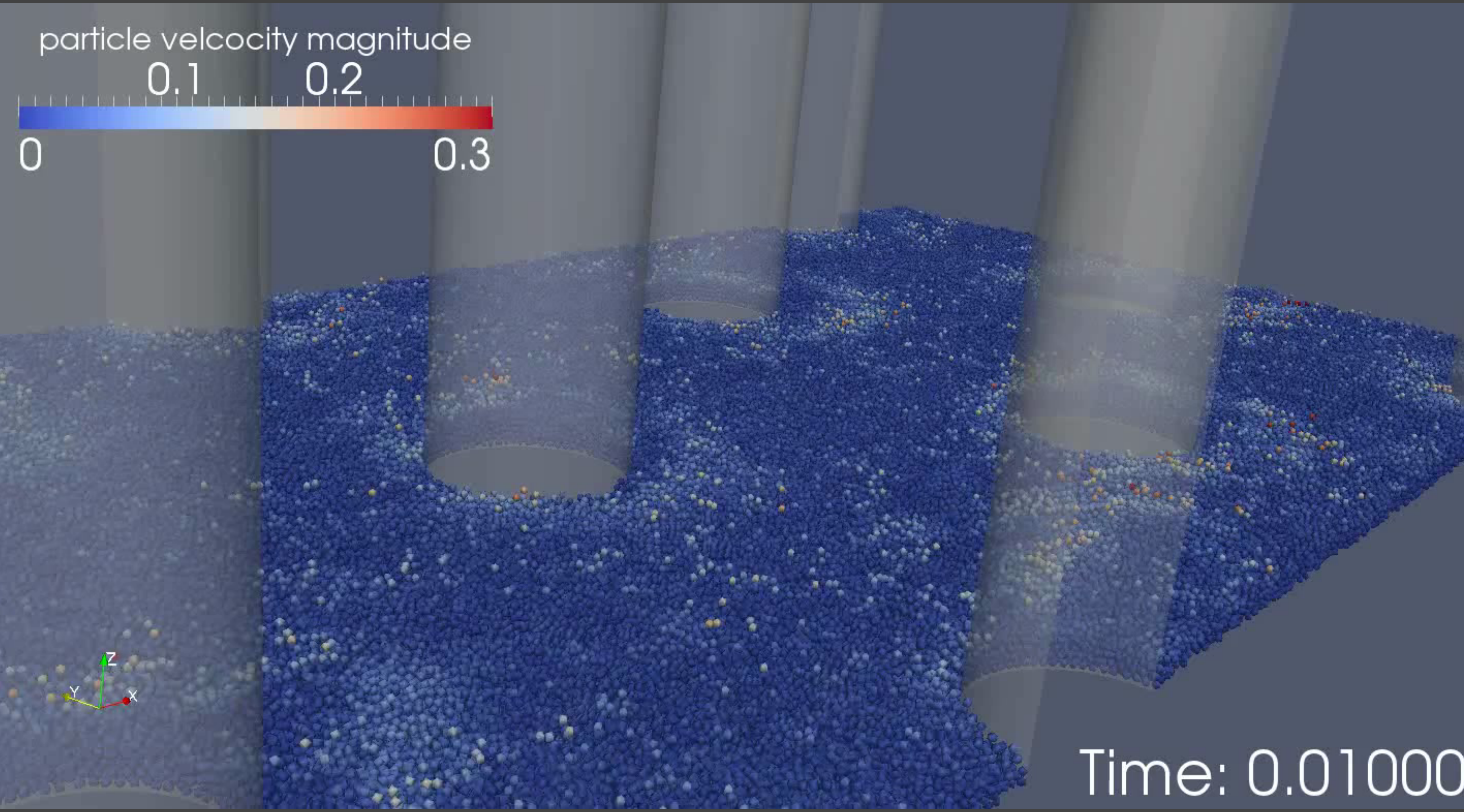
Vertical velocity at the bed



Flow through vegetation



•Flow in wake of cylinder greatly increases turbulence intensity and entrainment
•Positive vertical flow in separation bubble aids sediment suspension
•At the same depth-averaged velocity, vegetation dramatically increases sediment flux



Summary

OpenFOAM provides a comprehensive modeling library for earth surface simulations – unstructured grids and any vector pde's can be rapidly coded, gridded, and solved in parallel

LES-DEM, properly validated, provides sediment simulation data that is very hard (impossible?) to obtain by lab and field measurements

LES-DEM simulations show

-strong signature of turbulence on transport at all stages

- penetration of high velocity fluid into the bed responsible for entrainment

- Saltation paradigm emphasizes a relatively small part of flux