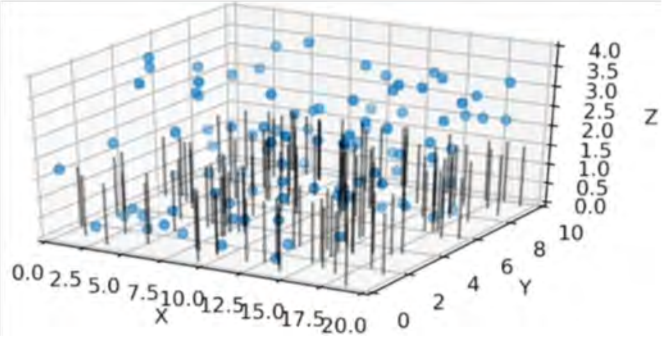
Modeling Movement and Persistence of Small Organisms in Flow



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THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

DEPARTMENT OF
MATHEMATICS

Outline

- Fluid flow through biological protective layers: a comparison of models
- Agent-based framework for organism movement in flow
- Current/future work

Biological protective layers

Cylindrical structures create microenvironments for tiny organisms.

Microscale and mesoscale:

- Trichomes (hairs on plants) can reduce evaporative losses and alter the environments for mold, bacteria, etc.
- Transmembrane proteins that form the endothelial glycocalyx shield endothelial cells from blood flow shear and alter the chemical composition of the extracellular environment.

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Macroscale:

- Macrophytes (large aquatic vegetation) cause background flow to be much slower than outside of the layer, reducing erosion and protecting organisms.
- Coral reefs create protective microenvironments that are nutrient rich and home to countless marine organisms.

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Examples of protective layers

Coral

Seagrass

Spanish moss

Short seagrass

Trichomes

Overall project goals:

- Are homogenized, steady flow fields sufficient to describe the fluid (e.g. Brinkman model), or are full 3D flows necessary?
- What is the minimum model necessary to describe the movement of zooplankton around a protective layer?
- Is unbiased Brownian motion + background flow sufficient to model active movement?
- What about advection diffusion instead? What kinds of behavior operate under what circumstances?

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ABM

Are homogenized flow fields sufficient to describe the fluid (e.g. Brinkman model)?

Resolving flows through many (flexible) cylinders across scales is challenging.

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We utilize physical and numerical models to describe fully 3D flows:

Physical models:

- Easily incorporate complexity and study organisms directly
- Detailed flow information is difficult to obtain due to optical access.

Numerical models:

- Provides highly resolved temporal and spatial information
- Can require significant computational power.

…then compare to analytic, homogenized 1D models.

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Are homogenized flow fields sufficient to describe the fluid (e.g. Brinkman model)?

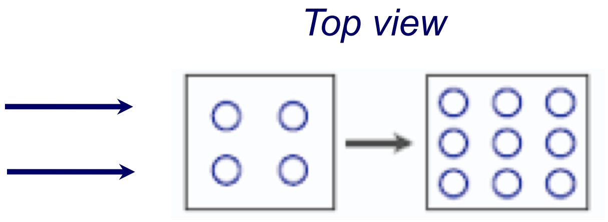
Limitations:

- We don’t know under what circumstances such models adequately describe the flow
- It is difficult to map a porosity to a particular geometry or volume fraction.

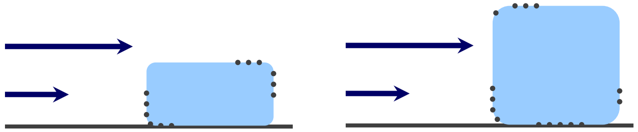
Factors that affect fluid flow through porous layers consisting of cylinder arrays

- The following parameters may be important to the boundary layer….

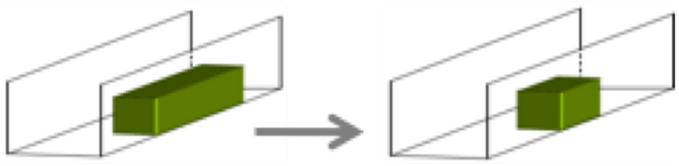
Volume fraction



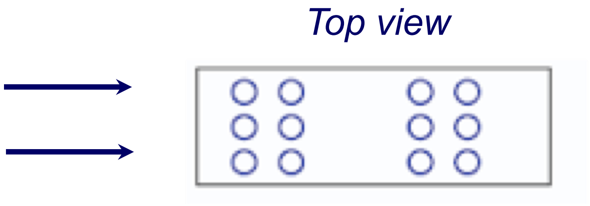
Cylinder height



Leaf length



Cylinder placement

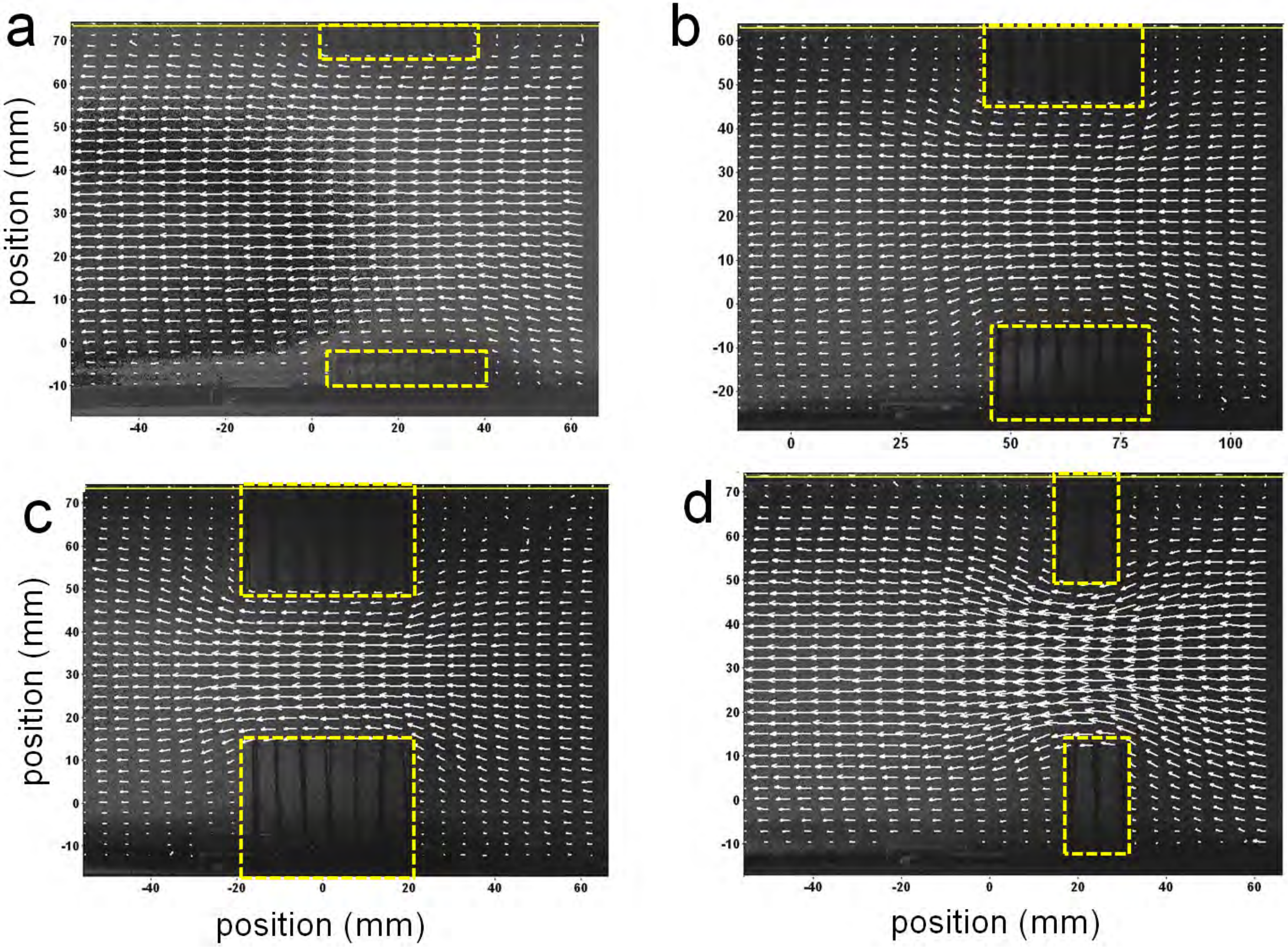


Reynolds number

Examples of protective layers: Scales and Reynolds number

Structure	**Diameter**	**Height**	**Gap**	**Re_d**
Glycocalyx	10-12 nm	150-400 nm	20 nm	O(-3)
Microvilli	90 nm	2.5 μm	165 nm	O(-3)
Aesthetascs	5.69-8.1 μm	347-648 μm	10-40 μm	O(-2)-O(1)
Bristled Wings	0.3-2.5 μm	25-200 μm	2-16 μm	O(-2)
Trichomes	28.1 μm	96.5 μm	65.6 μm	O(1)
Sea grasses	1 cm	10 cm – 1 m	2-20 cm	O(2)-O(5)
Sea oats	1 cm	1 m	10-40 cm	O(2)-O(5)

Physical model (flow through pins)



Strickland, Miller, et al. 2017, “Three-Dimensional Low Reynolds Number Flows near Biological Filtering and Protective Layers”

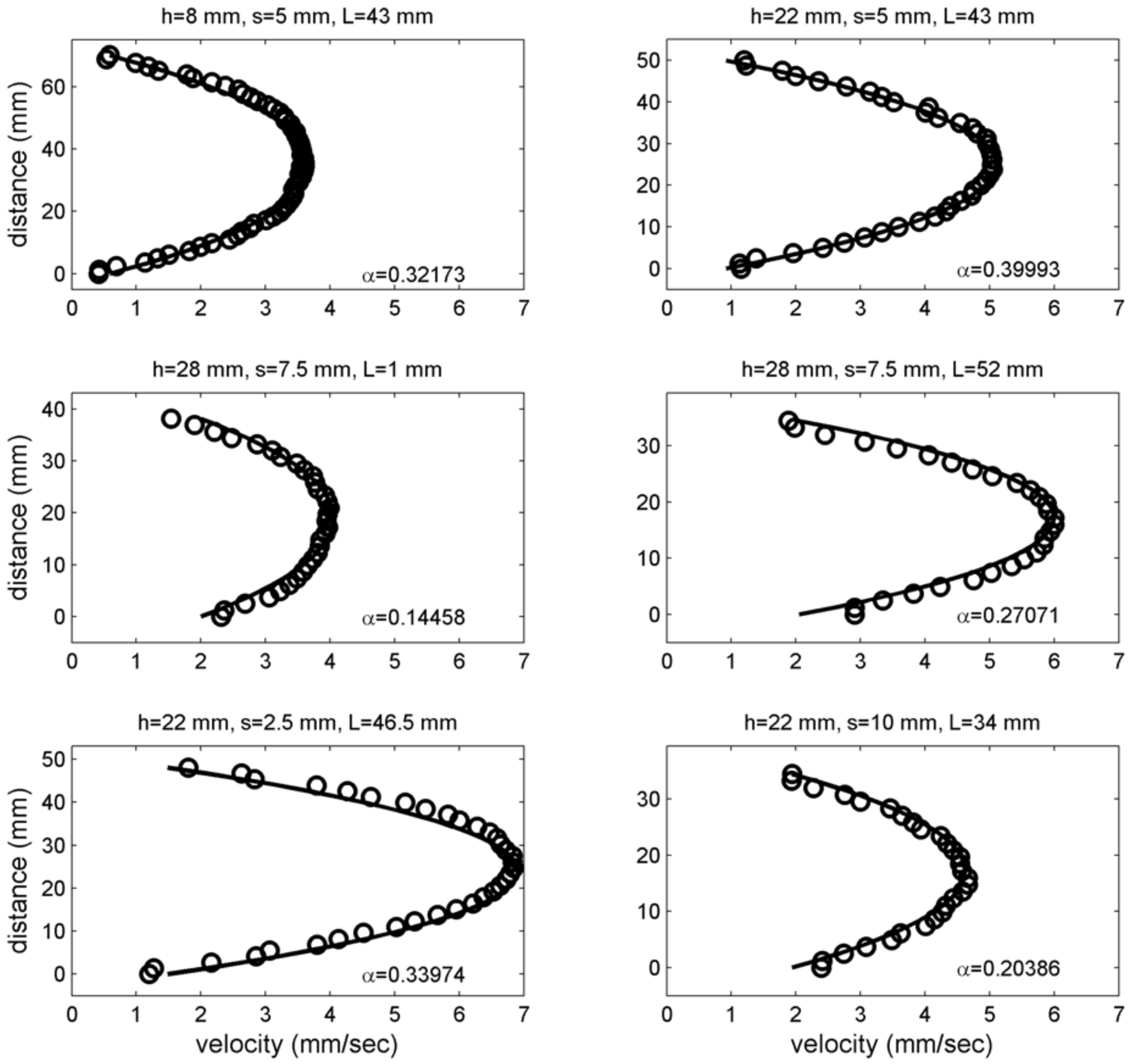
Analytic model

- Treat the cylinders as a porous layer rather than solving the Navier-Stokes equations around each individual component.
- Add a Brinkman term to the N-S equations:
  - *α is the inverse* of the hydraulic permeability
  - In regions without cylinders, *α(x,y) = 0*.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\alpha^2}{\rho}\mu u$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\alpha^2}{\rho}\mu v$$

Experiments vs. Brinkman model (best fits)



Numerical simulations of fully resolved flow: Immersed Boundary Method

Navier-Stokes Equations

$$\rho\left(\frac{\partial \mathbf{u}(\mathbf{x},t)}{\partial t}+\mathbf{u}(\mathbf{x},t)\bullet\nabla\mathbf{u}(\mathbf{x},t)\right)=-\nabla \mathrm{p}(\mathbf{x},t)+\mu\,\Delta\mathbf{u}(\mathbf{x},t)+\mathbf{f}(\mathbf{x},t)$$

$$\nabla\bullet\mathbf{u}(\mathbf{x},t)=0$$

Force applied to fluid

$$\mathbf{F}(r,t)=\mathbf{F}_{\mathrm{targ}}(r,t)+\mathbf{F}_{\mathrm{beam}}(r,t)+\mathbf{F}_{\mathrm{str}}(r,t)$$

Force spreading

$$\mathbf{f}(\mathbf{x},t)=\int\mathbf{F}(r,t)\,\delta\left(\mathbf{x}-\mathbf{X}(r,t)\right)dr$$

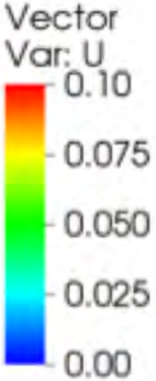
Velocity interpolation

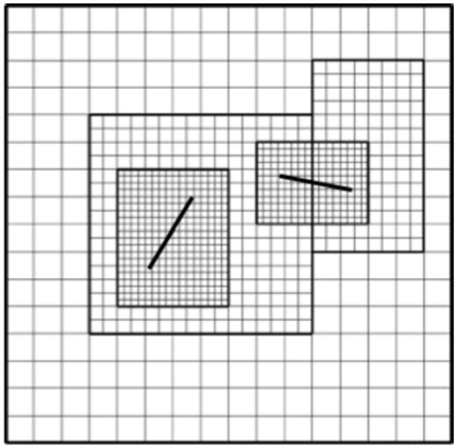
$$\frac{\partial\mathbf{X}(r,t)}{\partial t}=\mathrm{U}\left(\mathbf{X}(r,t)\right)=\int\mathbf{u}(\mathbf{x},t)\delta\left(\mathbf{x}-\mathbf{X}(r,t)\right)d\mathbf{x}$$

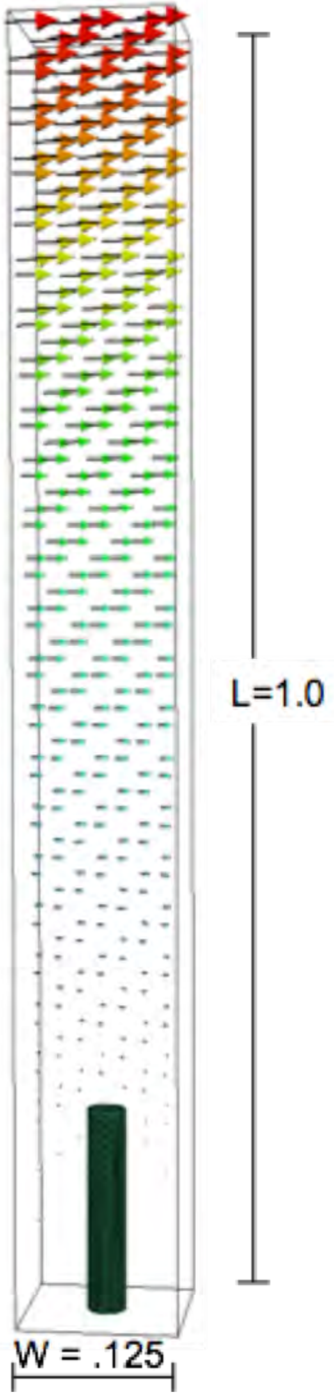
1. Solve the equations of fluid motion.
2. Move the boundary at the local fluid velocity.
3. Determine the force applied to the fluid as the deformation of the boundary and an external force.
4. Convert from Lagrangian to Eulerian variables (spread force to fluid).

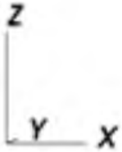
Numerical set-up

1. Background shear flow that is periodic in x- and y-directions.
2. Nearly rigid cylinders placed on bottom of domain.
3. An adaptive and parallelized version of the immersed boundary method is used (IBAMR).



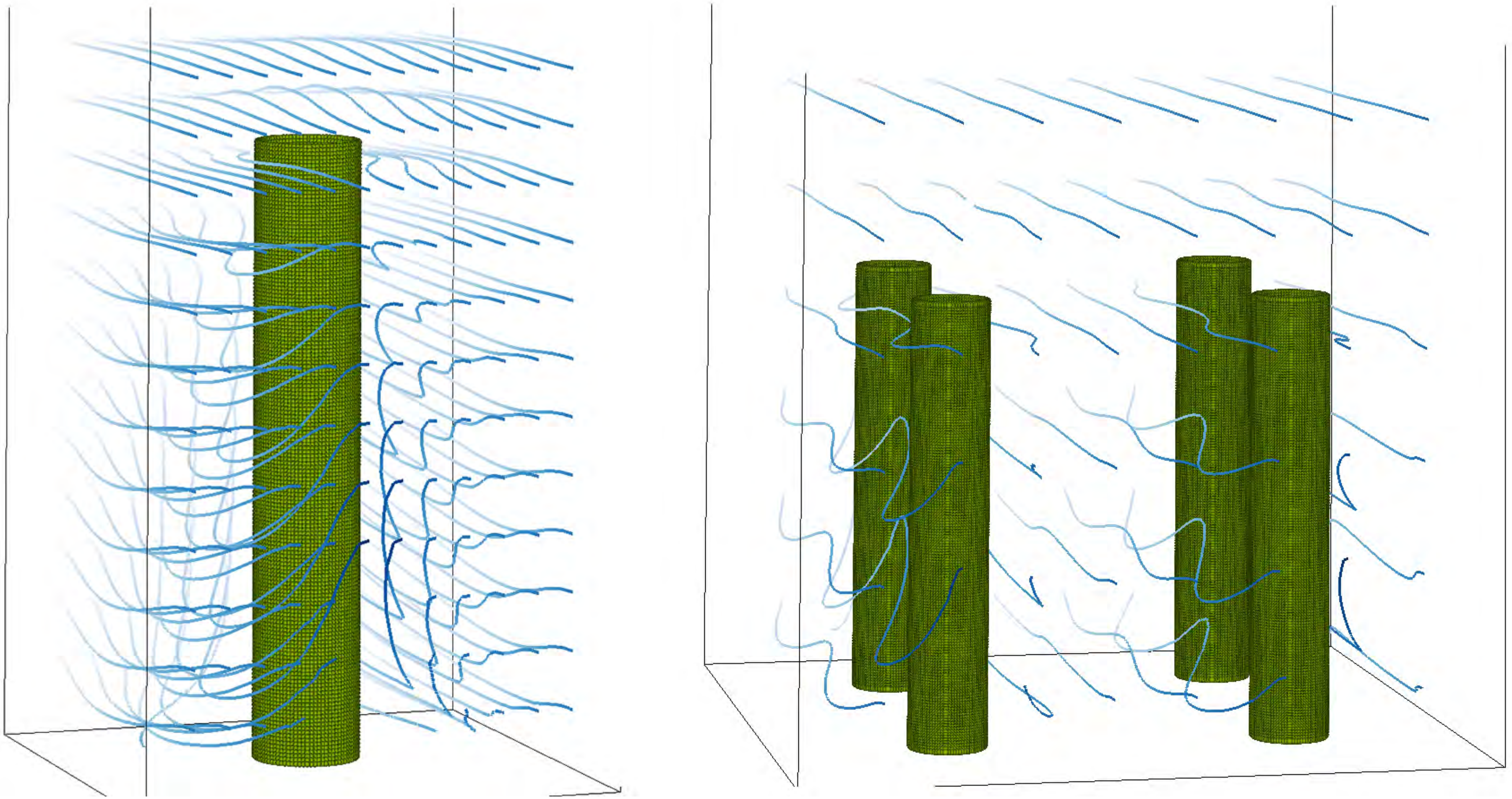






Griffith, B.E. "IBAMR: An adaptive and distributed-memory parallel implementation of the immersed boundary method." http://ibamr.googlecode.com

Avg. numerical flow is well approximated by Brinkman… but small eddies can exist.



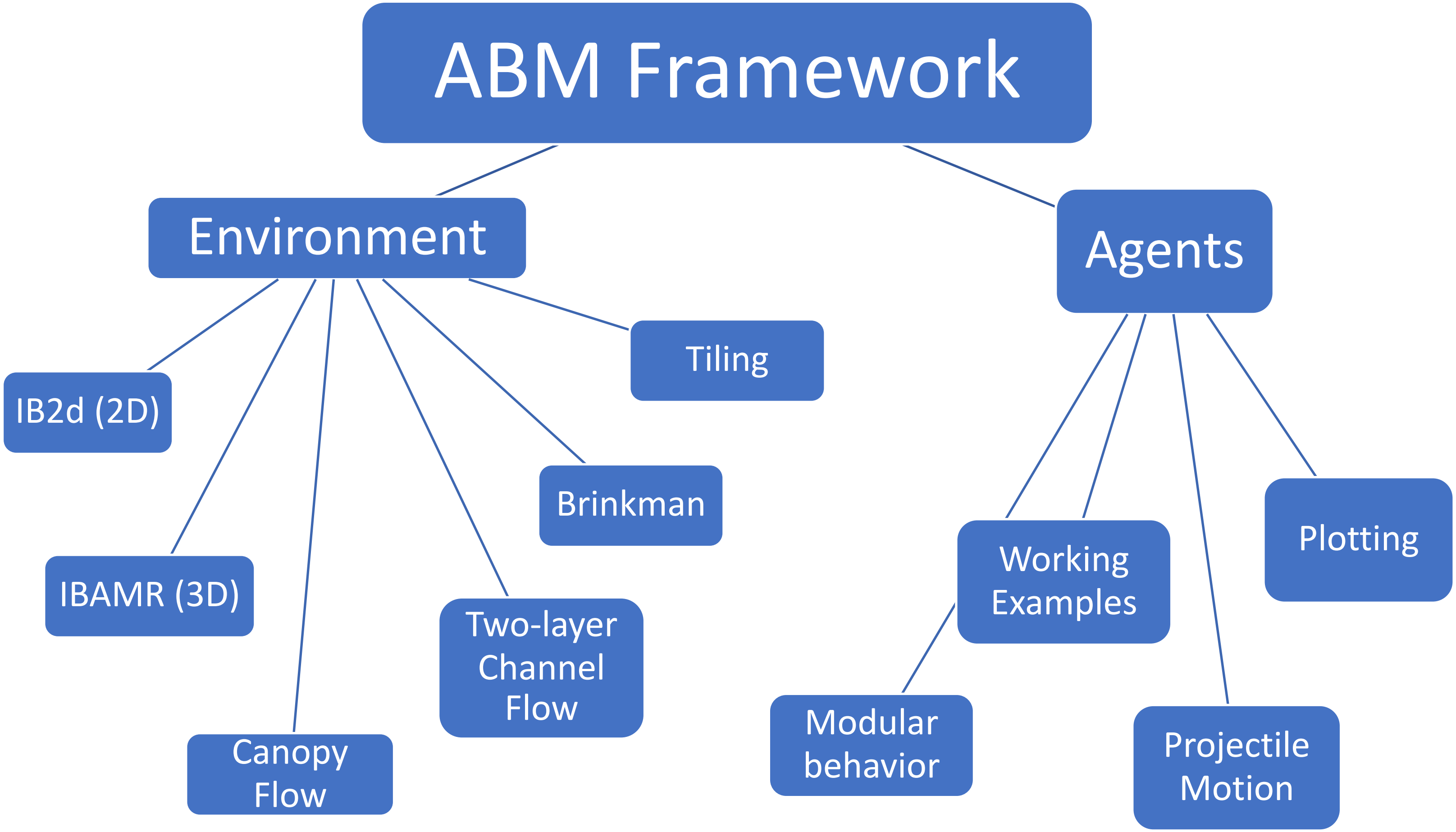
Strickland, Miller, et al. 2017, "Three-Dimensional Low Reynolds Number Flows near Biological Filtering and Protective Layers"

Project goals: What can an agent based model tell us about zooplankton?

- Are homogenized steady flow fields sufficient to describe the fluid (e.g. Brinkman model), or are full 3D and/or time varying flows necessary?
- What is the minimum model necessary to describe the movement of zooplankton into and out of a protective layer?
- Is Brownian motion added to the background flow sufficient to model active movement, or is it necessary to add behavior?
- Can behavior be modeled as biased diffusion?

WORK IN PROGRESS!

ABM framework: *Planktos*



ABM Framework

Environment

- IB2d (2D)
- IBAMR (3D)
- Canopy Flow
- Two-layer Channel Flow
- Brinkman
- Tiling

Agents

- Working Examples
  - Modular behavior
- Projectile Motion
- Plotting

https://github.com/mountaindust/Planktos

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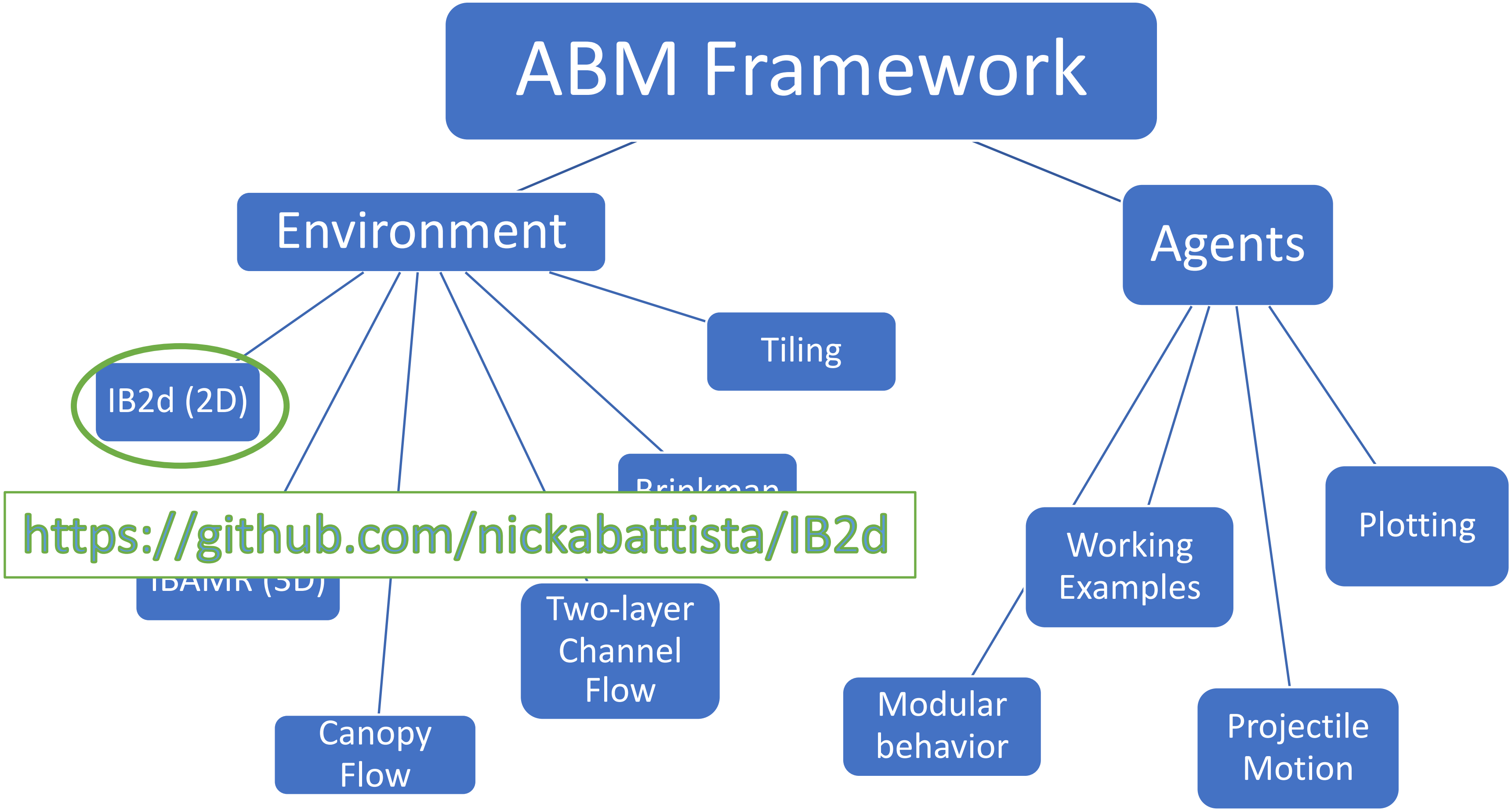

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https://github.com/nickabattista/IB2d

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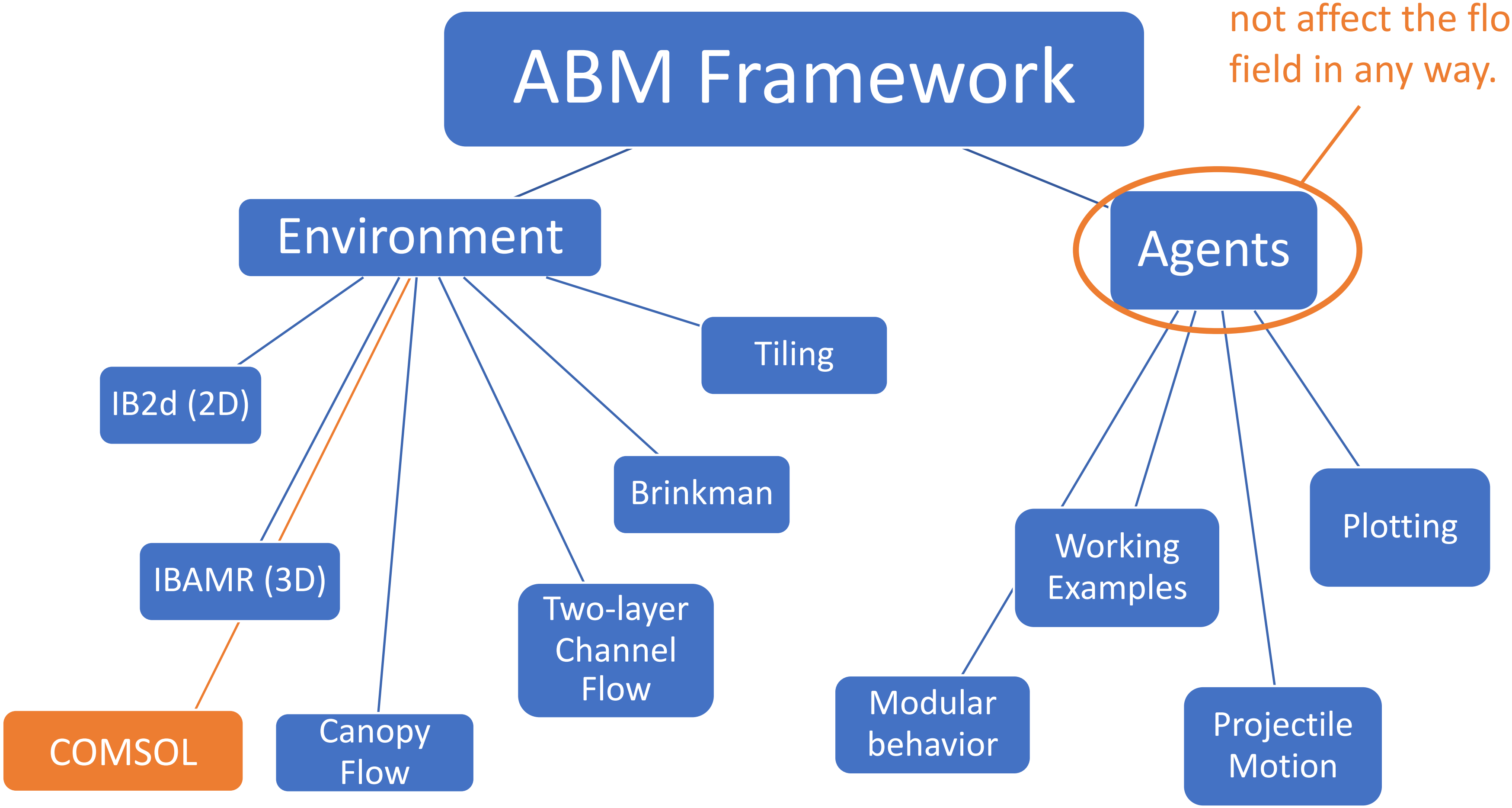

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Tiling

Brinkman

IBAMR (3D)

COMSOL

Canopy Flow

Two-layer Channel Flow

Working Examples

Plotting

Modular behavior

Projectile Motion

Currently, agents do not affect the flow field in any way.

https://github.com/mountaindust/Planktos

ABM framework: *Planktos*

```
#! /usr/bin/env python3

from sys import platform
if platform == 'darwin': # OSX backend does not support blitting
    import matplotlib
    matplotlib.use('TkAgg')
import numpy as np
import sys
sys.path.append('..')
import framework

envir = framework.environment(Lz=10, rho=1000, mu=1000)
U=0.1*np.array(list(range(0,5))+list(range(5,-5,-1))+list(range(-5,8,3)))

envir.set_brinkman_flow(alpha=66, a=1.5, res=101, U=U,
                        dpdx=np.ones(20)*0.22306, tspan=[0, 20])
envir.add_swarm()
s = envir.swarms[0]

print('Moving swarm...')
for ii in range(240):
    s.move(0.1)

#s.plot_all('ex_3d.mp4', fps=20)
s.plot_all()
```

- Written in Python
- Interfaces with 2D or 3D (time varying) flow data
- Some 1D analytical flow fields included
- 2D/3D plotting
- Relatively easy to add custom behavior and response to flow gradients

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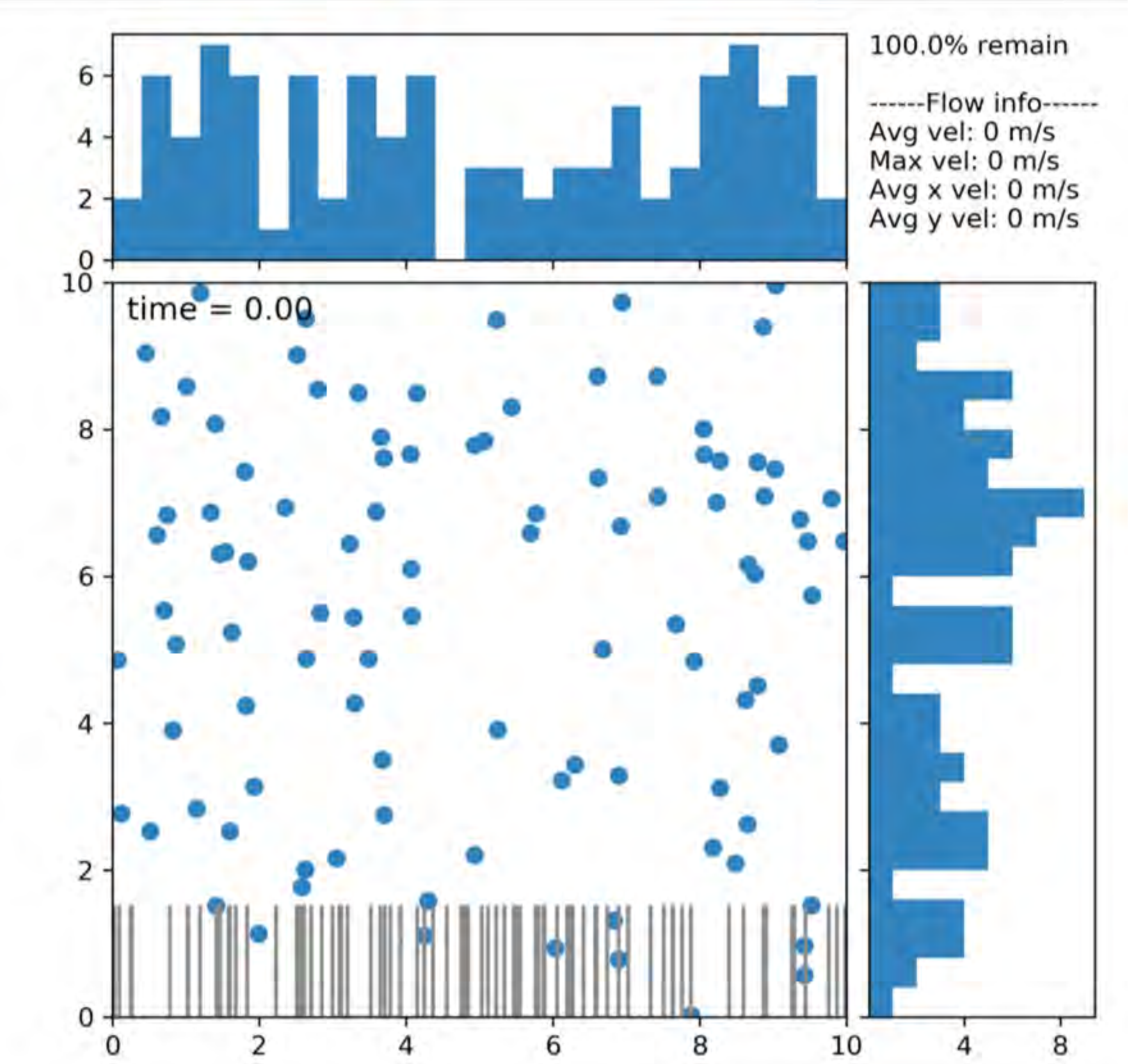
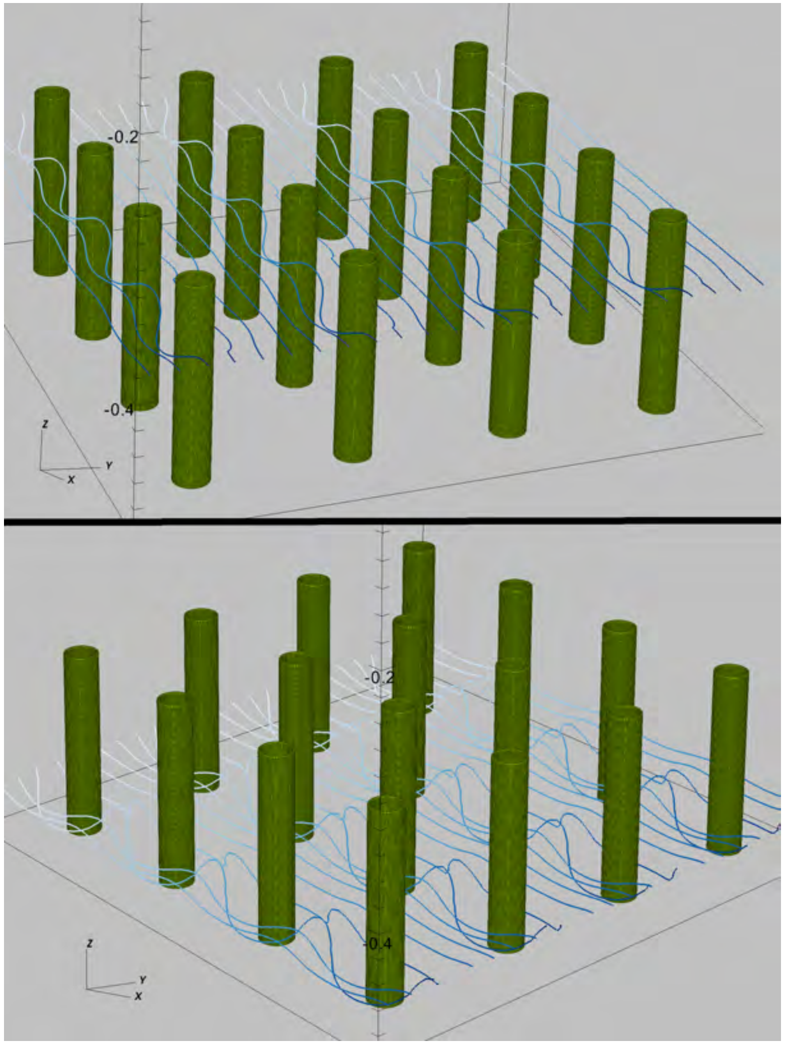


Example: 1D Brinkman flow

- 1.5 m homogenous porous layer
- Time varying flow specified at the top of the domain
- Tracer particles with jitter
- Histograms show relative x/y abundance

Example ABM simulation: IBAMR flow through cylinder array



Fluid specifications:

- 0.15 m tall cylinders in 0.5x0.5x1 meter domain
- Re_d 10
- Cylinders do not inhibit movement

Agent behavior:

- Agents are massless point particles
- Unbiased random walk with std of 1 cm
- Agents are advected by the flow field
- Agents are initialized at uniformly random positions

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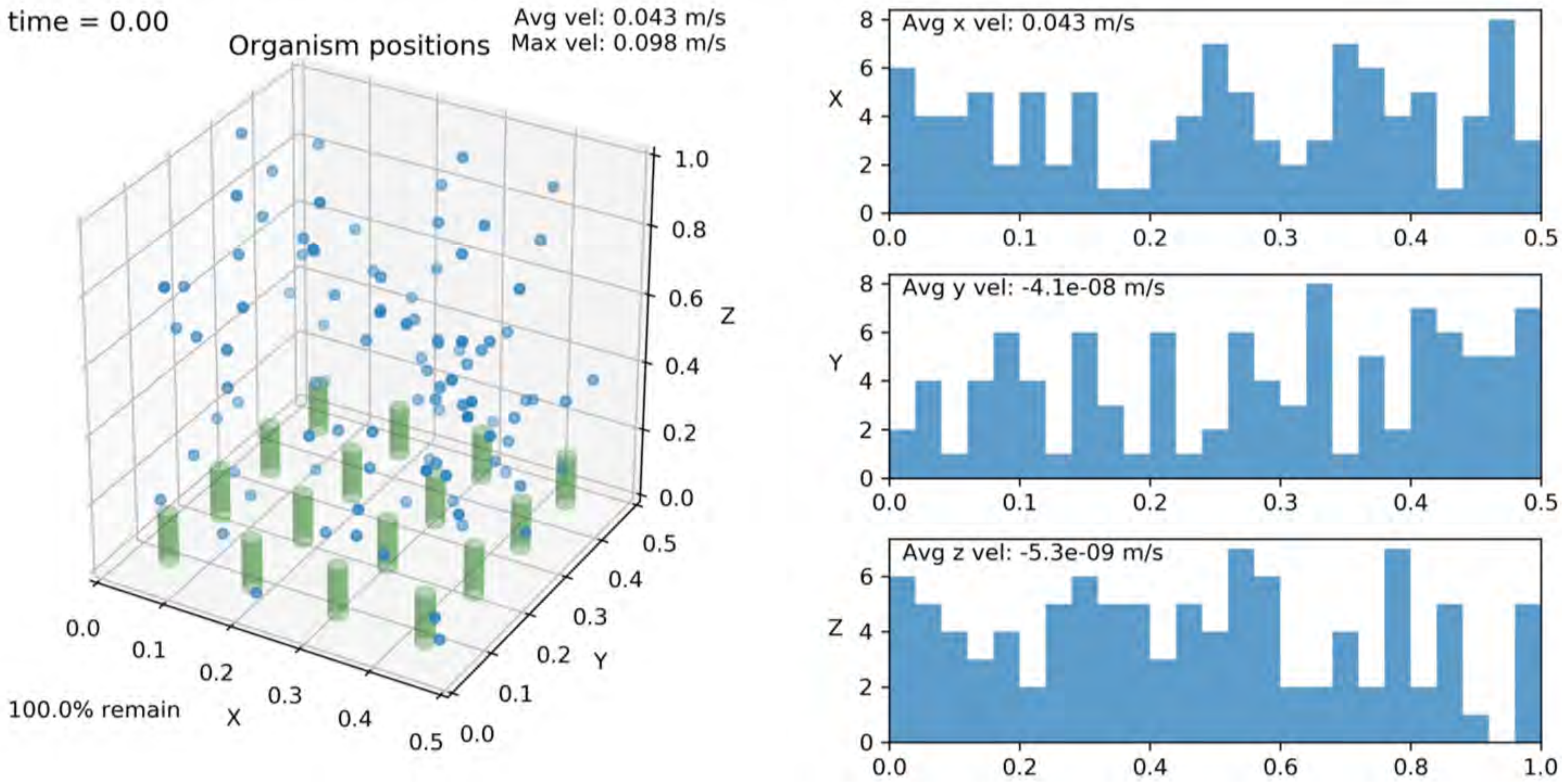

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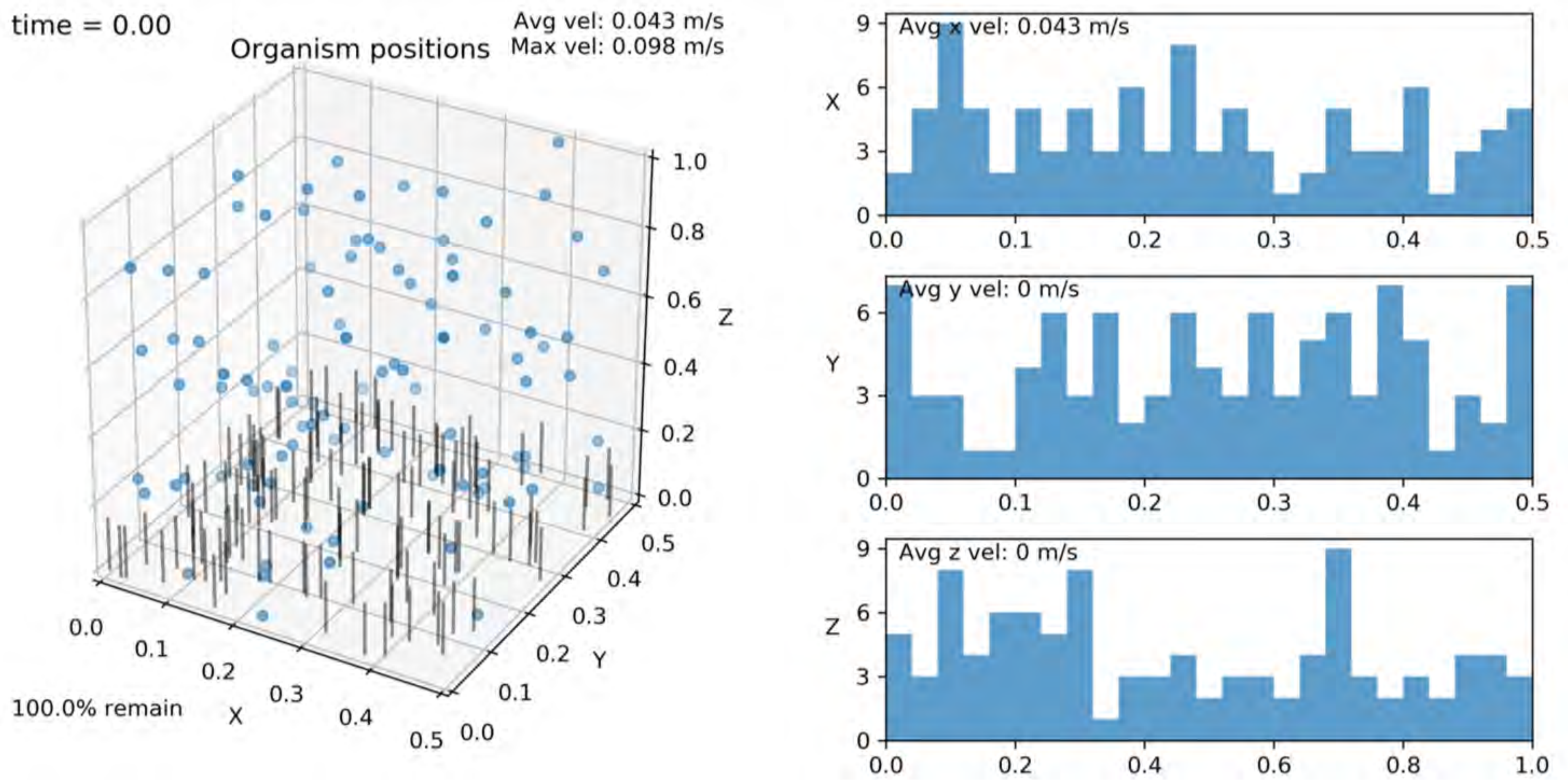
ABM simulation: Brinkman flow through similar porous region



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Current work

Obtain data from an idealized experiment: brine shrimp injected between cylinders in a flow field

- Measure flow fields through a protective layer using PIV and physical models
- Add brine shrimp to this flow and measure their distributions over time

Challenges:

- Illuminate and keep in focus a large section of the flow field
- Use diffuse light since brine shrimp are phototactic

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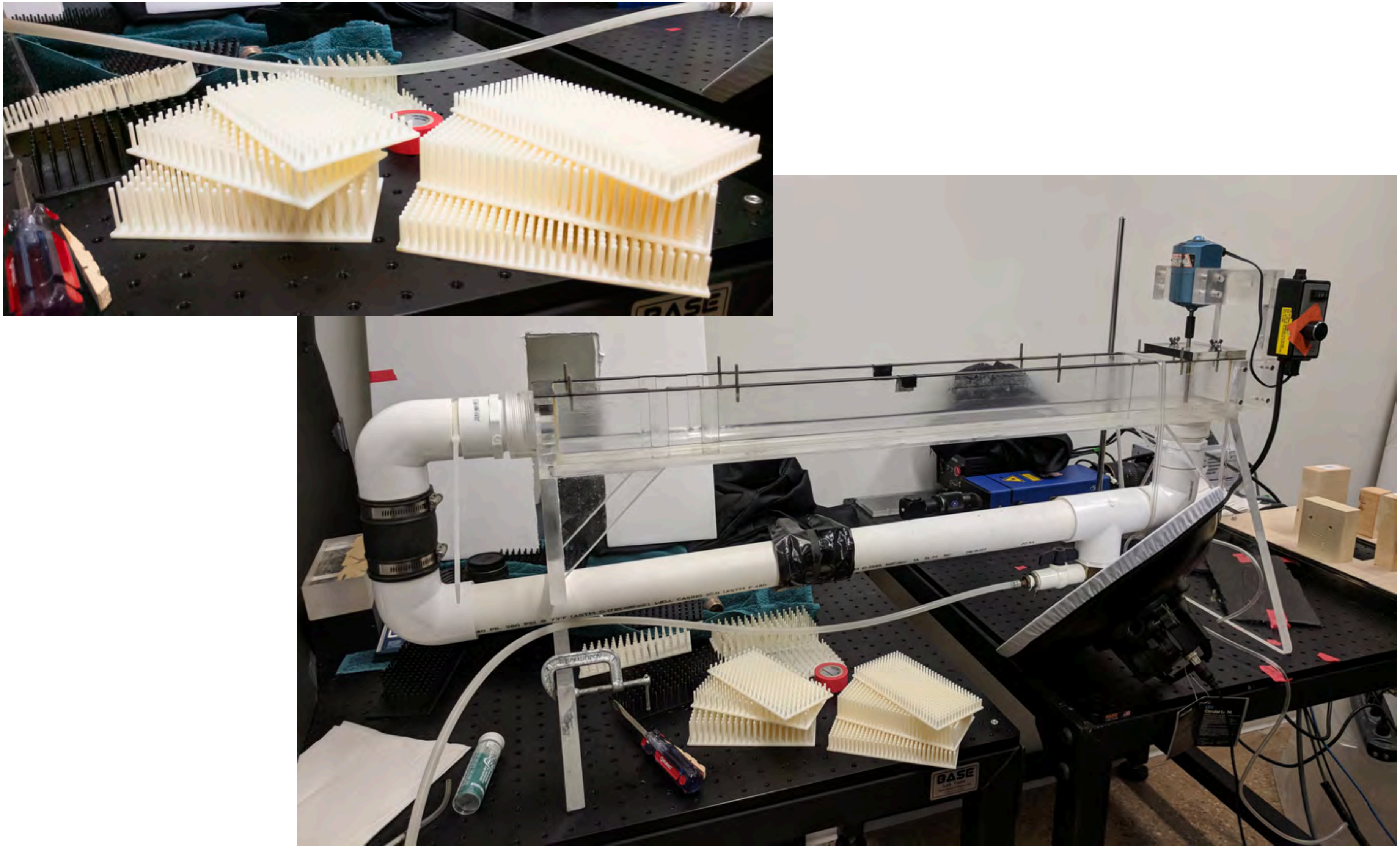

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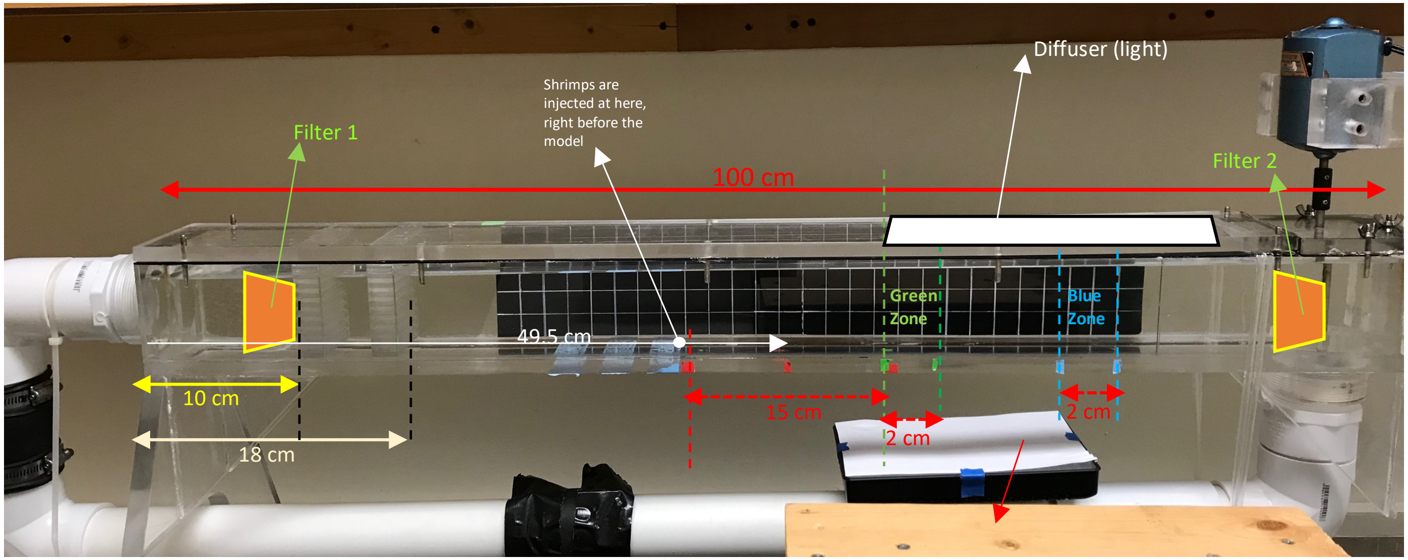

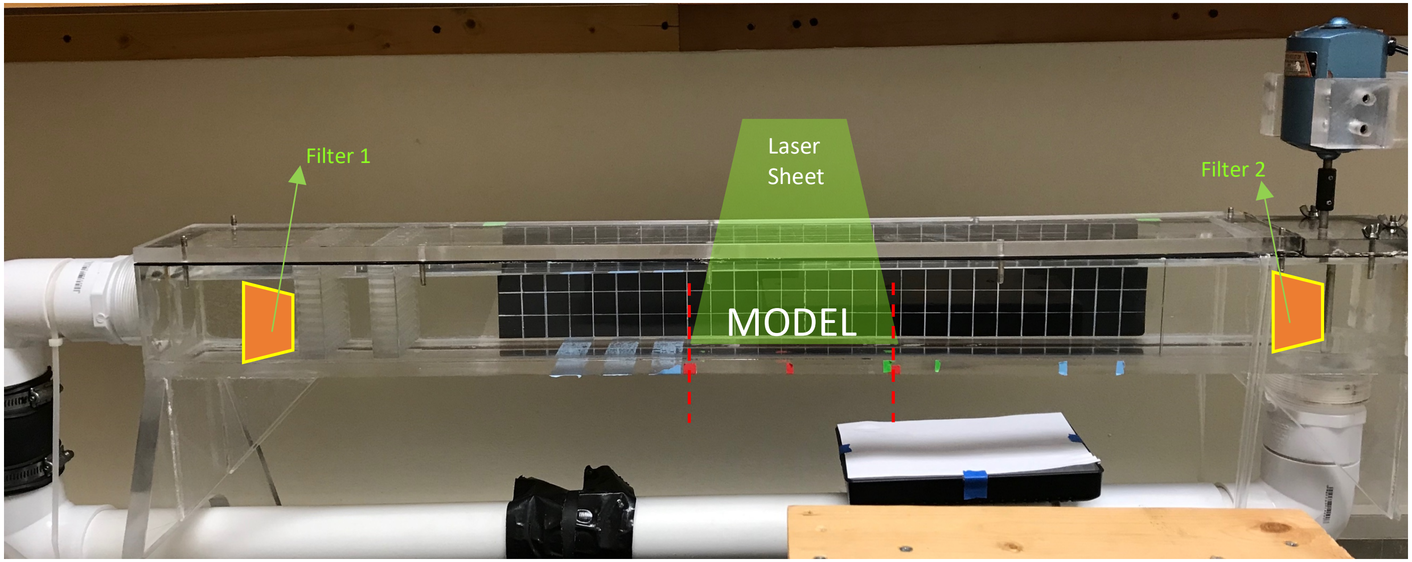

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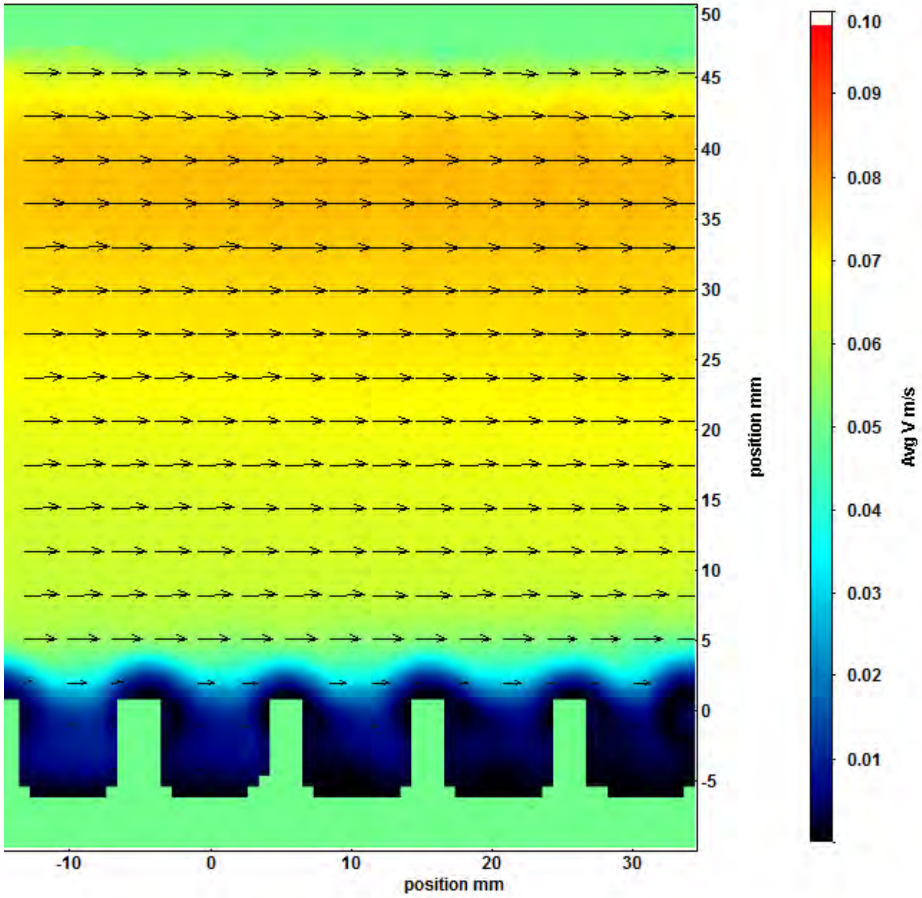
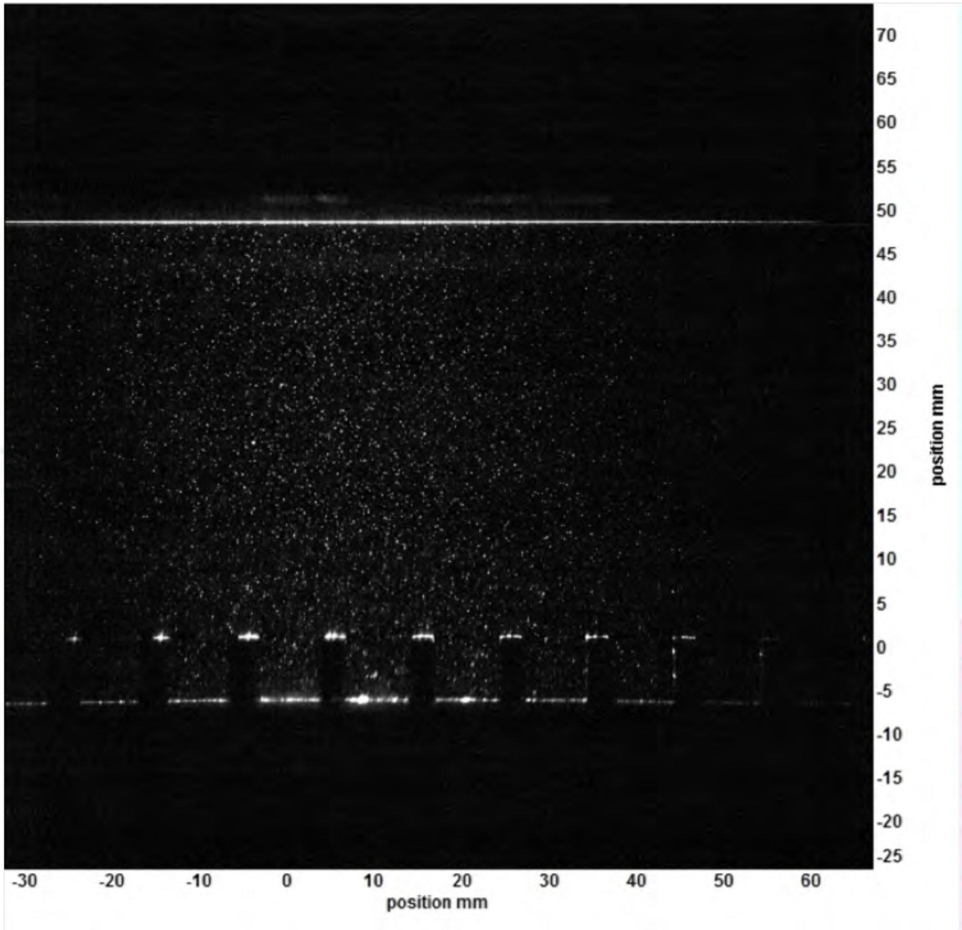
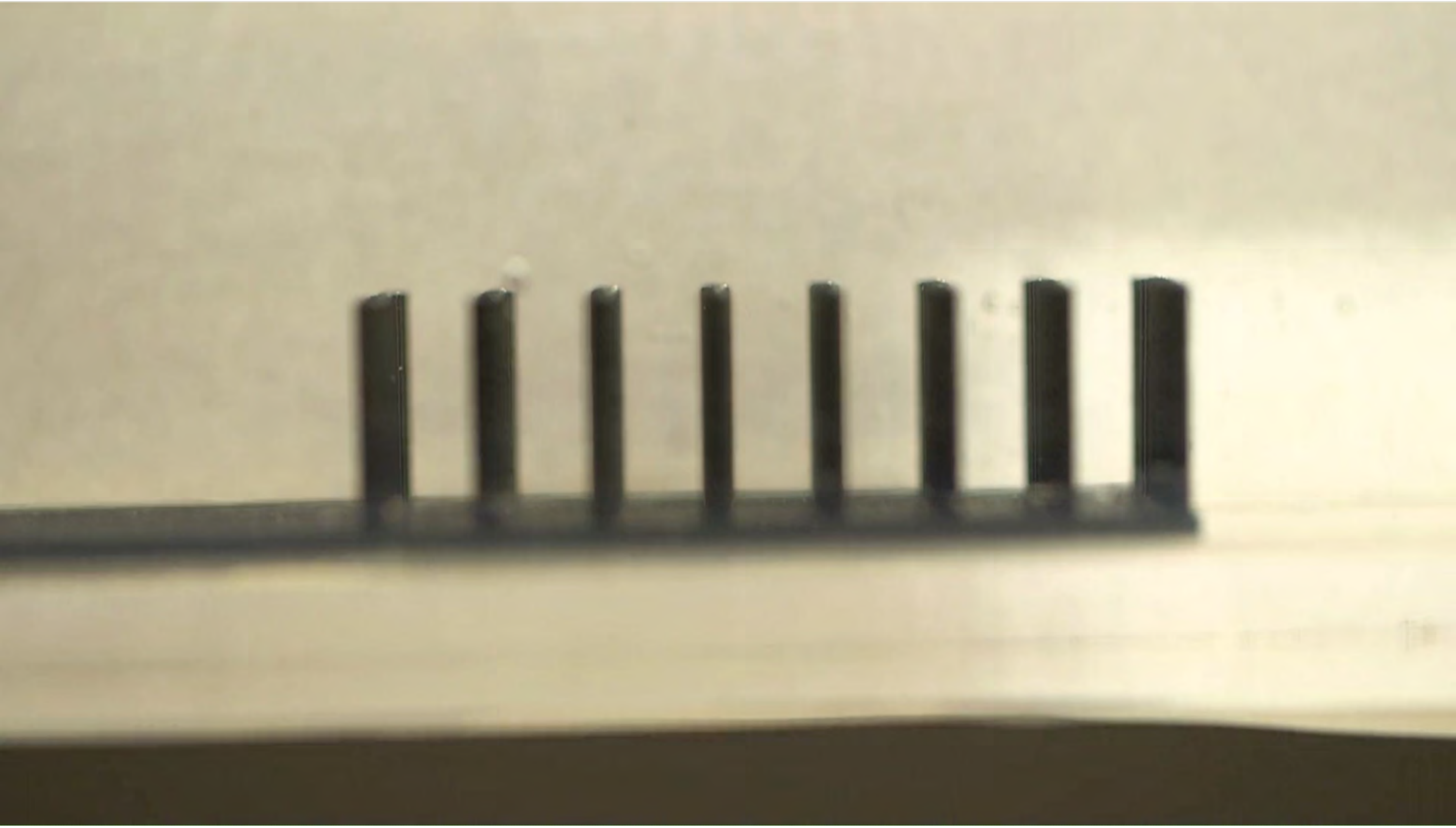




Brine shrimp movement



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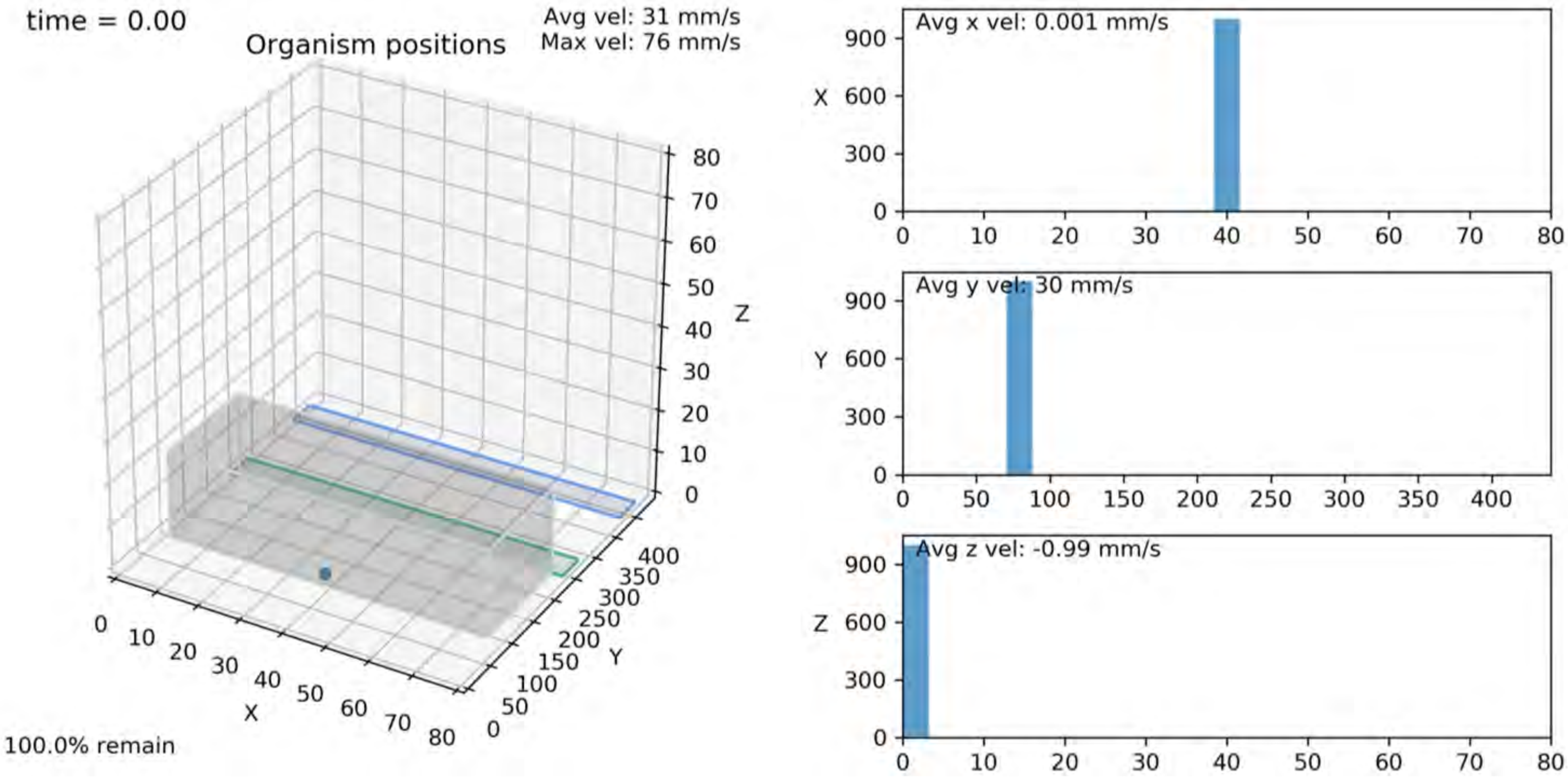
Example: ABM simple jitter simulation within IBAMR flow



Diffusion coeff. based on Kohler, Swank, Haefner, Powell (2010)

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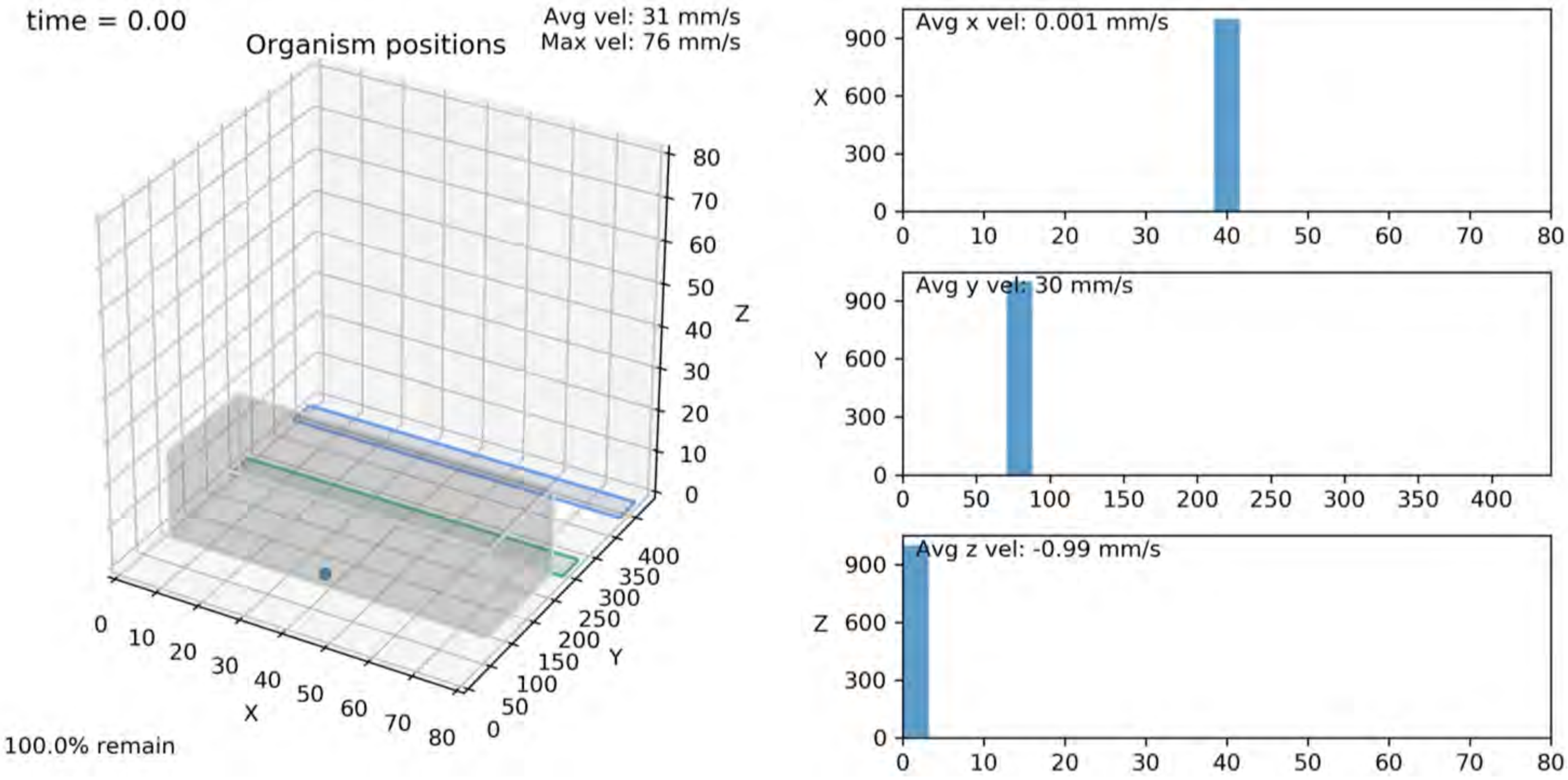
Example: ABM simulation within IBAMR flow with velocity gradient following



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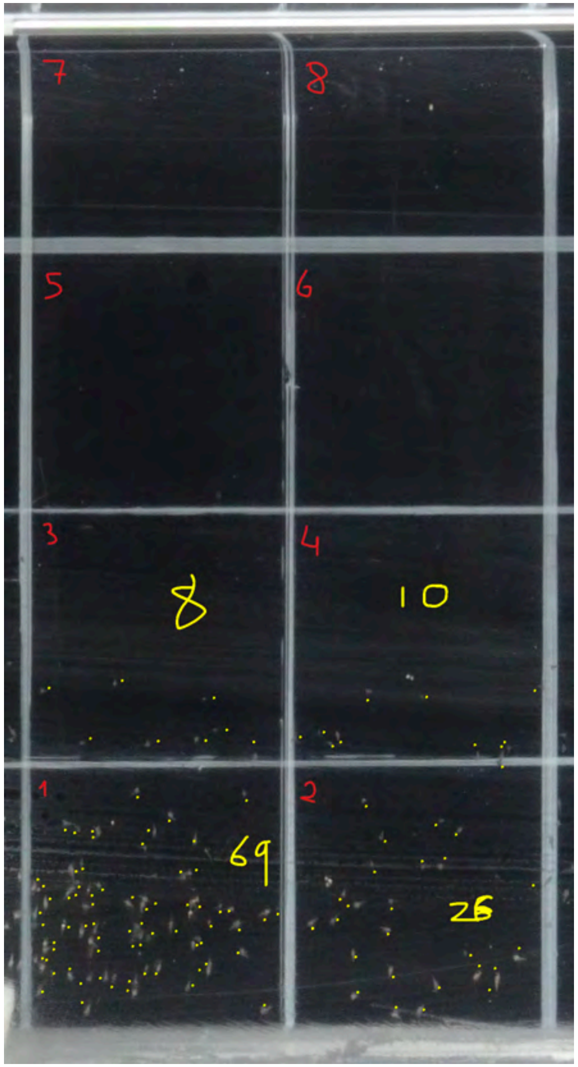
Next step: Compare counts over time in aggregate and in sections



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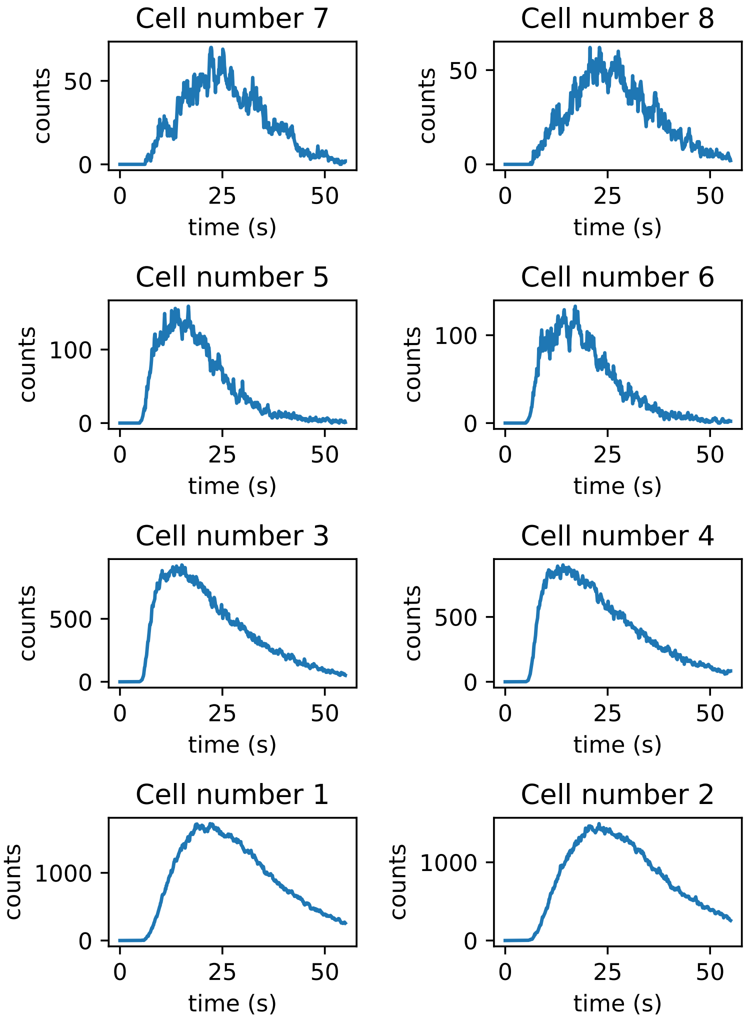

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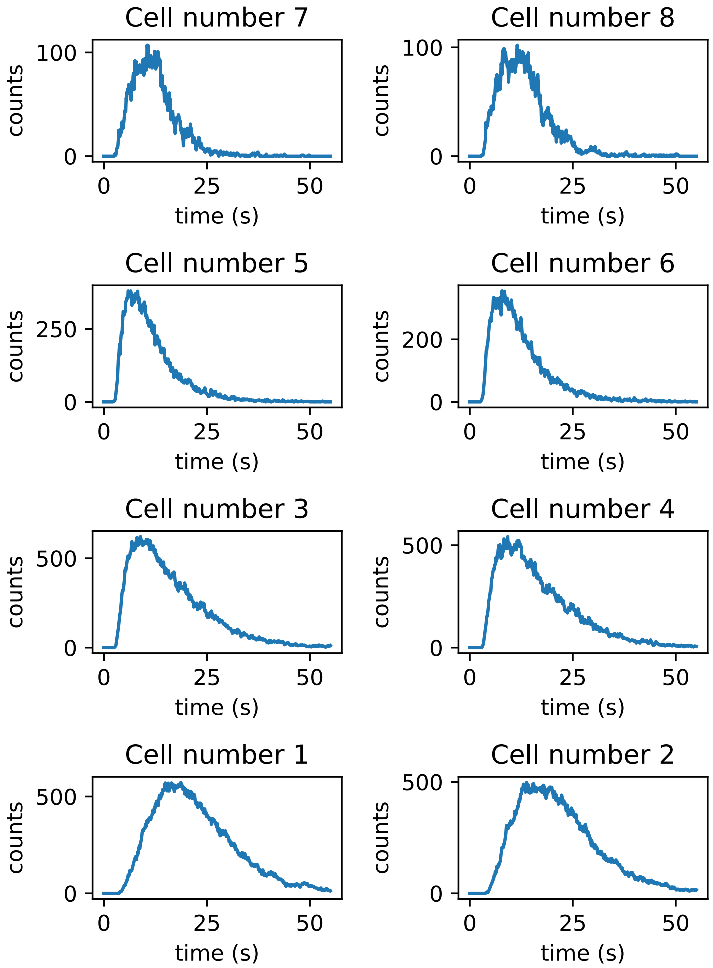
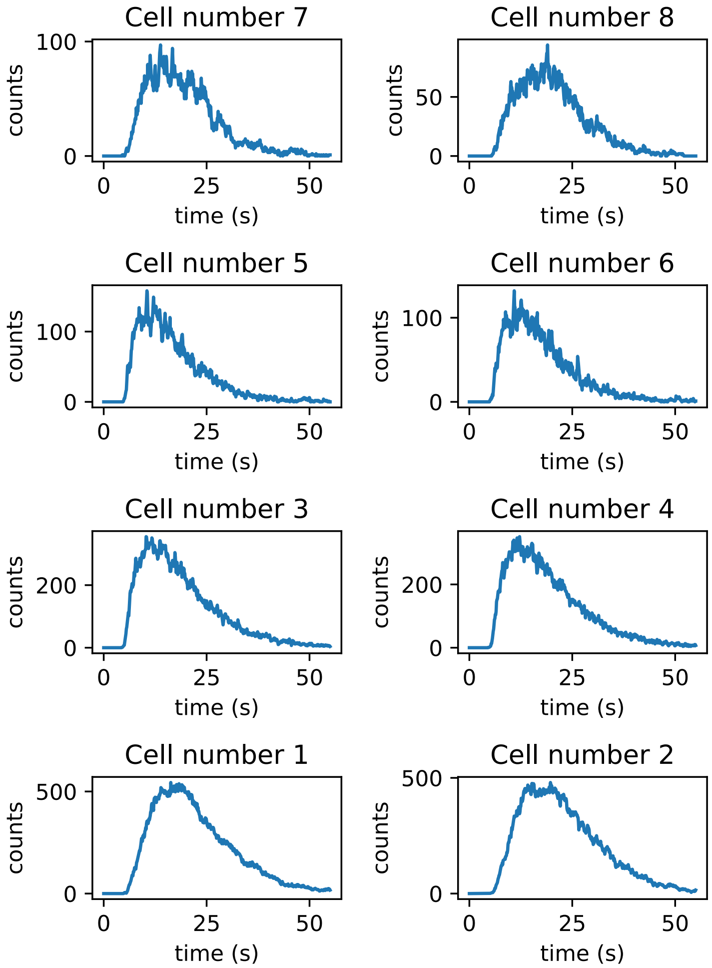


Green zone

flow



Blue zone

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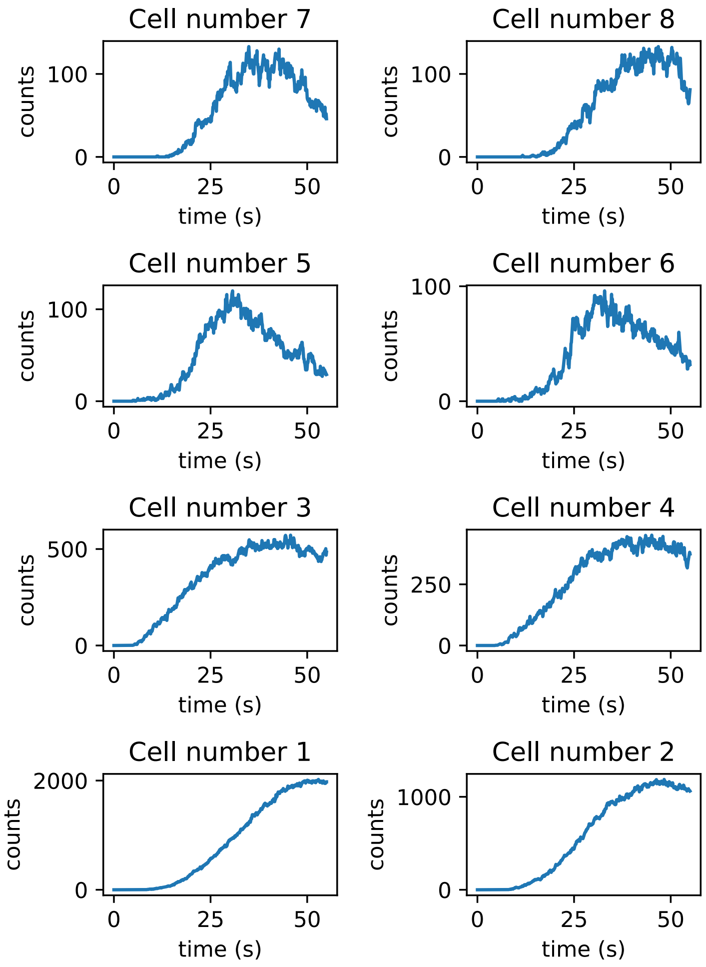

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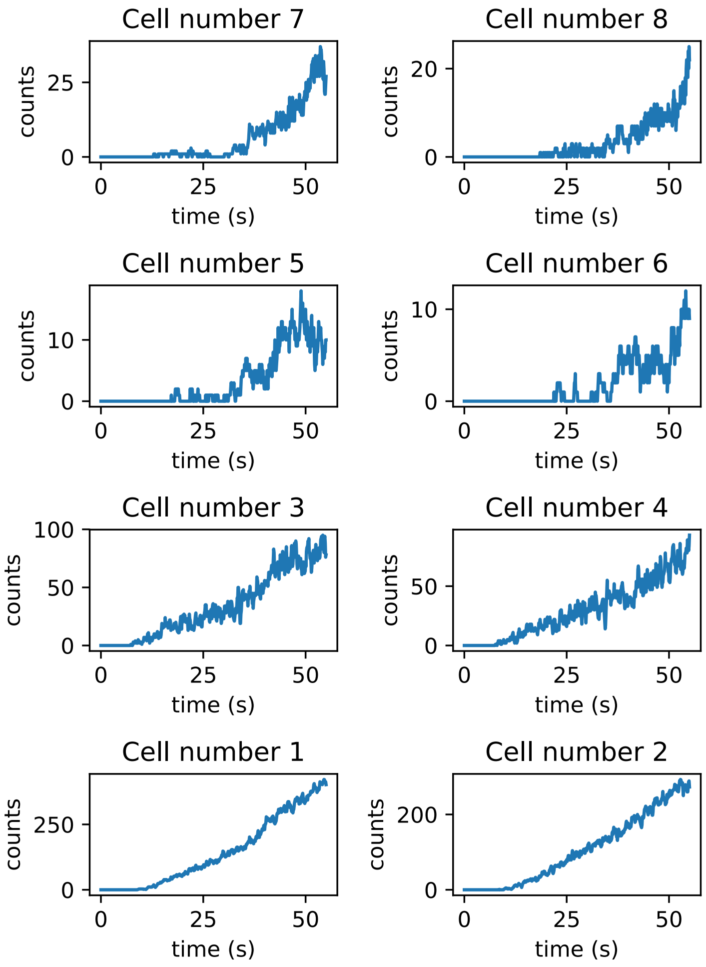
flow



Blue zone

Current and future work

- Compare numerical results to experimental results (need more computationally stable FSI data: COMSOL)
- Collect data on diffusion coefficients with conditions that better match our scenario
- Fine tune agent behavior. Does an attractive stimulus change results (e.g. light)?
- Specify a population-level, minimal analytic model. What is an efficient way to do model selection?

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Current and future work

- Compare numerical results to experimental results (need more computationally stable FSI data: COMSOL)
- Collect data on diffusion coefficients with conditions that better match our scenario
- Fine tune agent behavior. Does an attractive stimulus change results (e.g. light)?
- Specify a population-level, minimal analytic model. What is an efficient way to do model selection?

Thank you for your attention!

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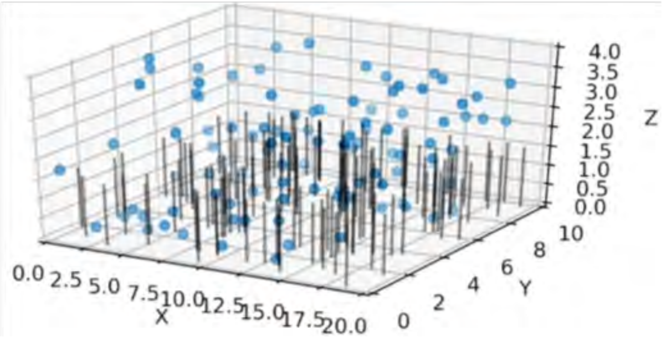

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