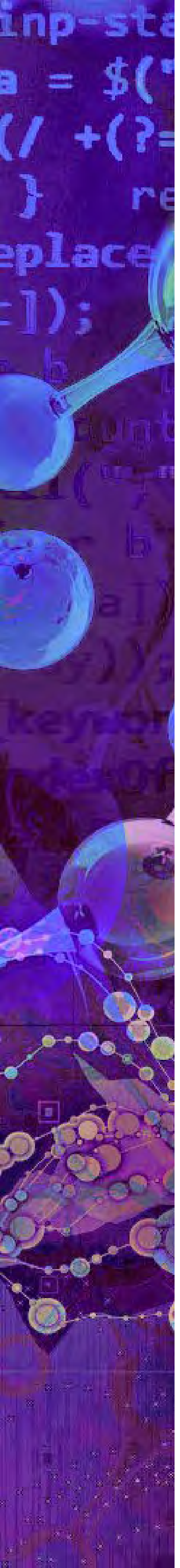


Pacific Northwest
NATIONAL LABORATORY

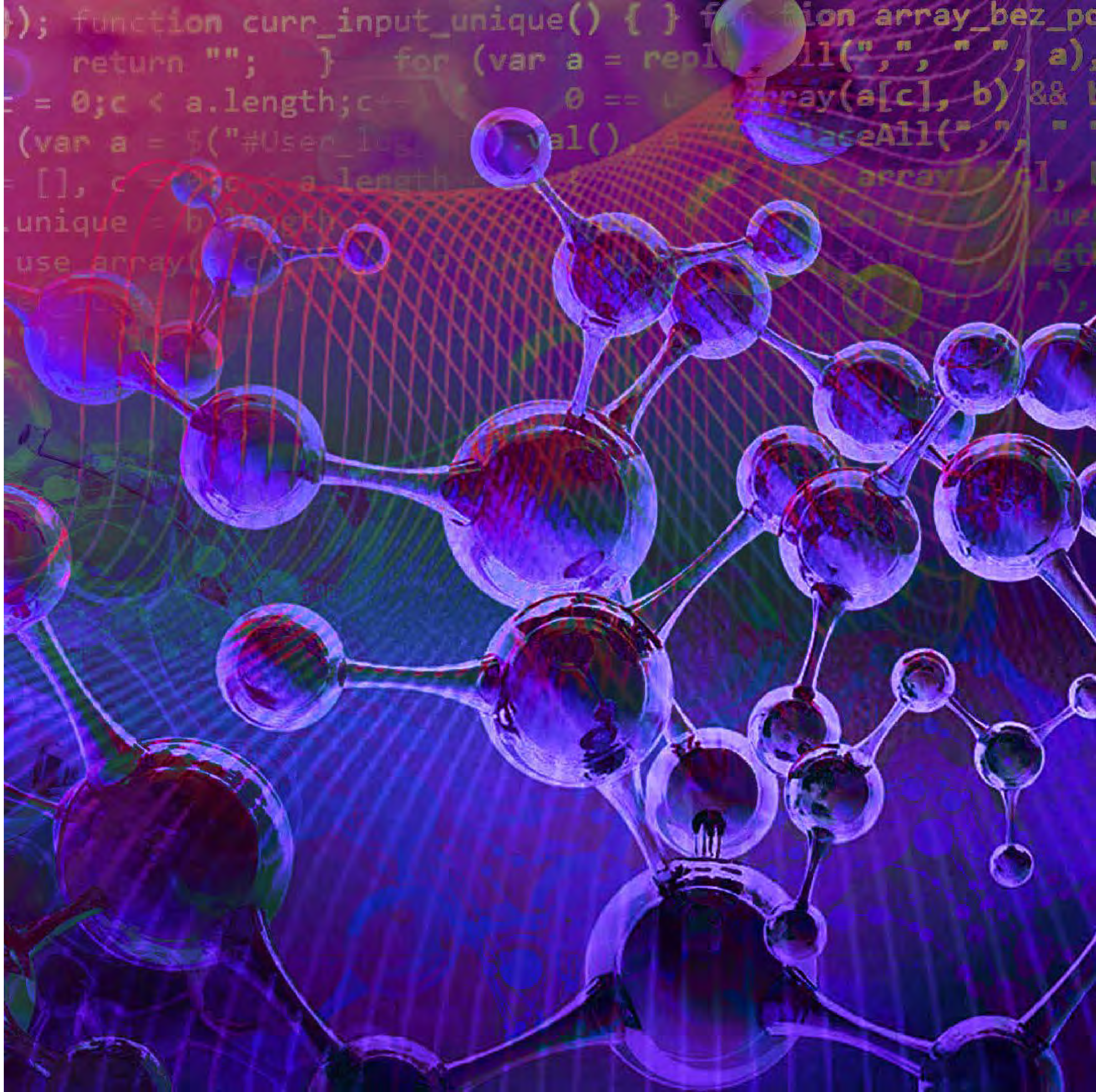
# A comparative study of dark matter flow & hydrodynamic turbulence and its applications

May 2022

**Zhijie (Jay) Xu**
Multiscale Modeling Team
Computational Mathematics Group
Physical & Computational Science Directorate
Zhijie.xu@pnnl.gov; zhijiexu@hotmail.com

U.S. DEPARTMENT OF ENERGY
BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy



# Preface

Dark matter, if exists, accounts for five times as much as ordinary baryonic matter. Therefore, dark matter flow might possess the widest presence in our universe. The other form of flow, hydrodynamic turbulence in air and water, is without doubt the most familiar flow in our daily life. During the pandemic, we have found time to think about and put together a systematic comparison for the connections and differences between two types of flow, both of which are typical non-equilibrium systems.

The goal of this presentation is to leverage this comparison for a better understanding of the nature of dark matter and its flow behavior on all scales. Science should be open. All comments are welcome.

Thank you!

# Hydrodynamic turbulence vs. dark matter flow

Key attributes of hydrodynamic turbulence:

- Disorganized, chaotic, random;
- Nonrepeatability (sensitivity to initial conditions);
- Multiscale in length and time scales;
- Intermittency in space and time;
- Dissipative and collisional
- Short-range interaction
- Velocity fluctuation
- Vortex as fundamental building block
- Maximum entropy distribution (Gaussian)
- Incompressible on all scales $\nabla \cdot \mathbf{v} = 0$
  - Divergence-free
  - Constant density
- Energy cascade from large to small length scales
- Vortex stretching responsible for energy cascade
  - Volume conserving
  - Shape changing
  - Uniform density
- Reynolds decomposition
- Reynolds stress for energy transfer between mean flow and random motion (turbulence)
- Closure problem, eddy viscosity, etc…
- Statistical theory: correlation/structure functions scaling laws in inertial range

Key attributes of dark matter flow:

- Disorganized, chaotic, random;
- Nonrepeatability;
- Multiscale in mass/length/time scales;
- Intermittency in space and time;
- Dissipationless and collisionless
- Long-range gravity
- Velocity & acceleration fluctuation
- Halos as fundamental building block
- Maximum entropy distribution?? (X dist.)
- Flow behavior is scale-dependent (peculiar velocity)
  - Small scale: constant divergence $\nabla \cdot \mathbf{v} = \theta$
  - Large scale: irrotational (curl-free) $\nabla \times \mathbf{v} = 0$
- Mass/energy cascade from small to large mass scales
- Role of halos for energy cascade??
  - Halos are growing, rotating, with nonuniform density
  - Is halo shape changing important?
  - Mass cascade facilitates energy cascade?
- Velocity/acceleration decomposition?
- What facilitates the energy transfer between mean flow and random motion??
- Self-closed model (analogue of NS) ?? Closure problem?
- Statistical theory: Kinematic and dynamic relations? Scaling laws?

Common features

Critical MOND acceleration $a_0$?

Deep MOND?

# Data repository and relevant publications

Structural (halo-based) approach:

| | |
|---|---|
| **0.** | **Data https://dx.doi.org/10.5281/zenodo.6541230** |
| 1. | Inverse mass cascade in dark matter flow and effects on halo mass functions https://doi.org/10.48550/arXiv.2109.09985 |
| 2. | Inverse mass cascade in dark matter flow and effects on halo deformation, energy, size, and density profiles https://doi.org/10.48550/arXiv.2109.12244 |
| 3. | Inverse energy cascade in self-gravitating collisionless dark matter flow and effects of halo shape https://doi.org/10.48550/arXiv.2110.13885 |
| 4. | The mean flow, velocity dispersion, energy transfer and evolution of rotating and growing dark matter halos https://doi.org/10.48550/arXiv.2201.12665 |
| 5. | Two-body collapse model for gravitational collapse of dark matter and generalized stable clustering hypothesis for pairwise velocity https://doi.org/10.48550/arXiv.2110.05784 |
| 6. | Evolution of energy, momentum, and spin parameter in dark matter flow and integral constants of motion https://doi.org/10.48550/arXiv.2202.04054 |
| 7. | The maximum entropy distributions of velocity, speed, and energy from statistical mechanics of dark matter flow https://doi.org/10.48550/arXiv.2110.03126 |
| 8. | Halo mass functions from maximum entropy distributions in collisionless dark matter flow https://doi.org/10.48550/arXiv.2110.09676 |

Statistics (correlation-based) approach:

| | |
|---|---|
| **0.** | **Data https://dx.doi.org/10.5281/zenodo.6569898** |
| 1. | The statistical theory of dark matter flow for velocity, density, and potential fields https://doi.org/10.48550/arXiv.2202.00910 |
| 2. | The statistical theory of dark matter flow and high order kinematic and dynamic relations for velocity and density correlations https://doi.org/10.48550/arXiv.2202.02991 |
| 3. | The scale and redshift variation of density and velocity distributions in dark matter flow and two-thirds law for pairwise velocity https://doi.org/10.48550/arXiv.2202.06515 |
| 4. | Dark matter particle mass and properties from two-thirds law and energy cascade in dark matter flow https://doi.org/10.48550/arXiv.2202.07240 |
| 5. | The origin of MOND acceleration and deep-MOND from acceleration fluctuation and energy cascade in dark matter flow https://doi.org/10.48550/arXiv.2203.05606 |
| 6. | The baryonic-to-halo mass relation from mass and energy cascade in dark matter flow https://doi.org/10.48550/arXiv.2203.06899 |

# Overview

- Some fundamentals of dark matter research
- Basic concepts in hydrodynamic turbulence
- Dark matter flow (SG-CFD) vs. hydrodynamic turbulence

- Theory of dark matter flow
  - Structural (halo-based) approach
  - Statistical (correlation-based) approach

- Applications of dark matter flow
  - Predicting dark matter particle properties
  - Understanding the origin of MOND
  - The baryonic-halo mass ratio and total baron faction

# About Me

## PROFILE: Zhijie (Jay) Xu

- Computational Scientist
- Team lead

## EXPERIENCE:

- Idaho National Laboratory (INL)
- Pacific Northwest National Laboratory (PNNL)

Grand canyon
Yellowstone

## EDUCATION:

- Zhejiang University
  Civil Engineering
- National University of Singapore
  Structural Engineering
- Rensselaer Polytechnic Institute
  Mechanical Engineering

## INTERESTS:

- Fluid dynamics
- Cosmological flow
- Multiscale Modeling

## HOBBIES:

- Travel
- Hiking
- Biking

## CONTACT:


- zhijiexu@hotmail.com
- Zhijie.xu@pnnl.gov