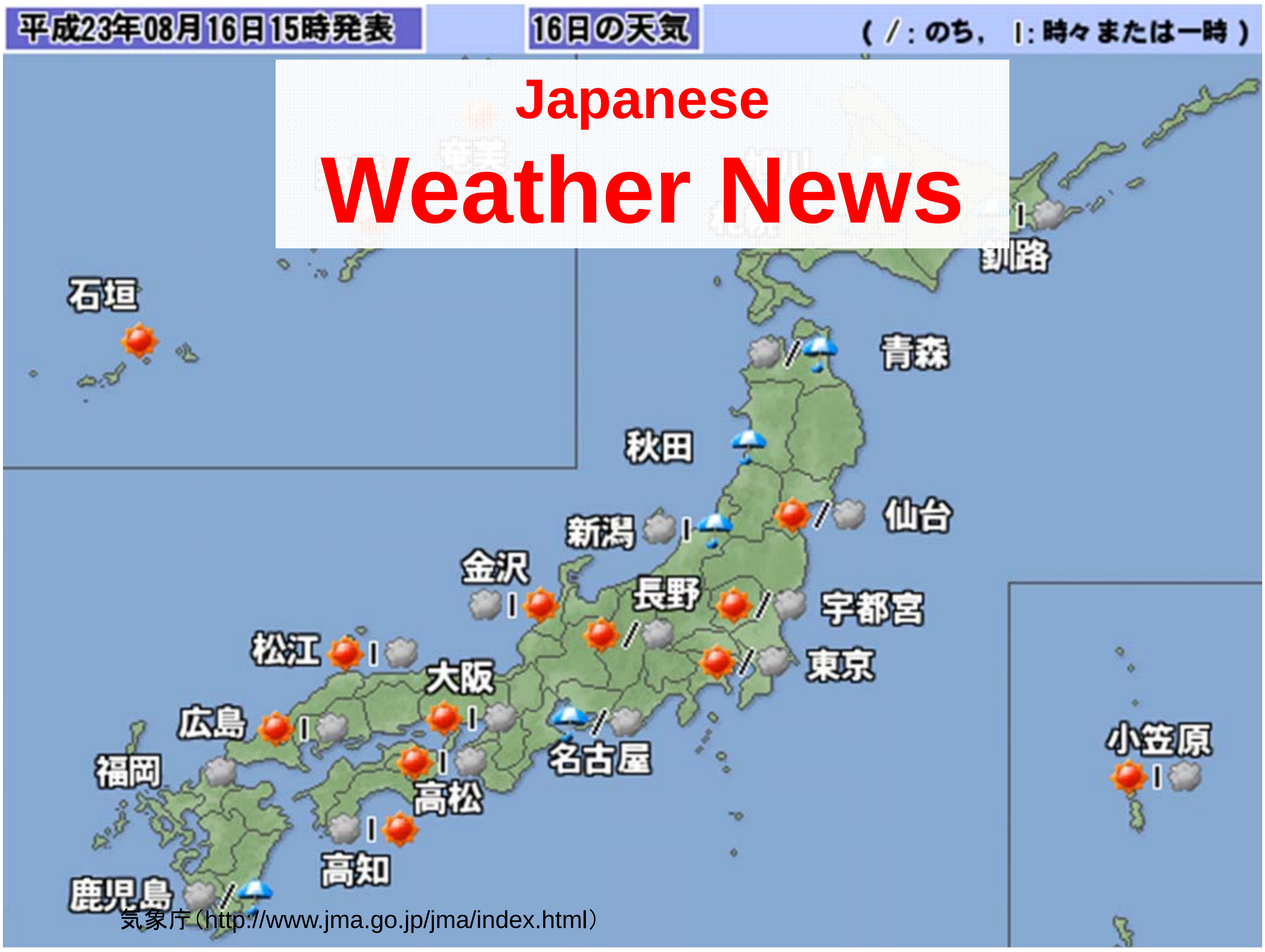
グリーンスパコン TSUBAME2.0 における大規模GPUアプリケーション

東京工業大学　学術国際情報センター

青木　尊之



気象庁（http://www.jma.go.jp/jma/index.html）

Next Generation

Weather Prediction

Collaboration: Japan Meteorological Agency

Meso-scale Atmosphere Model:

Cloud Resolving Non-hydrostatic model

Compressible equation taking consideration of sound waves.

Meso-scale

2000 km — **a few km**

Typhoon

Tornado, Down burst
Heavy Rain

WRF GPU Computing

■ WRF (Weather Research and Forecast)

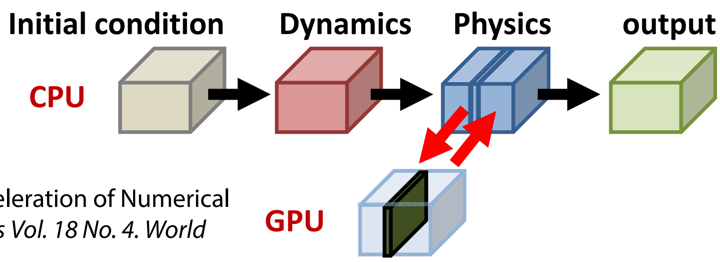
WSM5 (WRF Single Moment 5-tracer) Microphysics*

Represents condensation, precipitation and thermodynamic effects of latent heat release

1 % of lines of code, 25 % of elapsed time ⇒ 20 x boost in microphysics (1.2 - 1.3 x overall improvement)

WRF-Chem** provides the capability to simulate chemistry and aerosols from cloud scales to regional ⇒ x 8.5 increase

Accelerator Approach



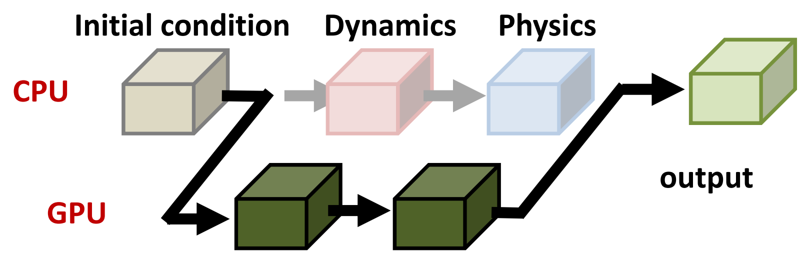
*J. Michalakes, and M. Vachharajani: GPU Acceleration of Numerical Weather Prediction. *Parallel Processing Letters Vol. 18 No. 4. World Scientific. Dec. 2008. pp. 531—548*

**John C. Linford, John Michalakes, Manish Vachharijani, and Adrian Sandu. Multi-core acceleration of chemical kinetics for simulation and prediction, *proceedings of the 2009 ACM/IEEE conference on supercomputing (SC'09), ACM, 2009.*

Full-GPU Implementation: ASUCA

GP GPU

Full GPU Approach



■ *ASUCA Production Code*

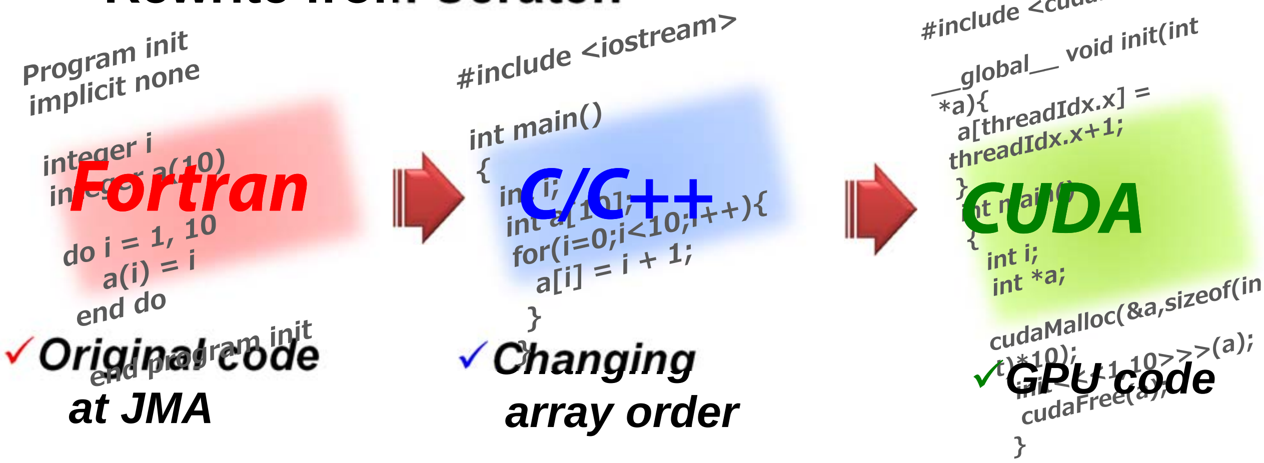
- ✓ ***A next-generation high resolution weather simulation code that is being developed by Japan Meteorological Agency (JMA)***
- ✓ ***ASUCA succeeds the JMA-NHM as an operational non-hydrostatic regional model at JMA***

J. Ishida, C. Muroi, K. Kawano, Y. Kitamura, Development of a new nonhydrostatic model "ASUCA" at JMA, CAS/JSC WGNE Research Activities in Atmospheric and Oceanic Modeling.

Entire Porting Fortran to CUDA

GP GPU

■ Rewrite from Scratch



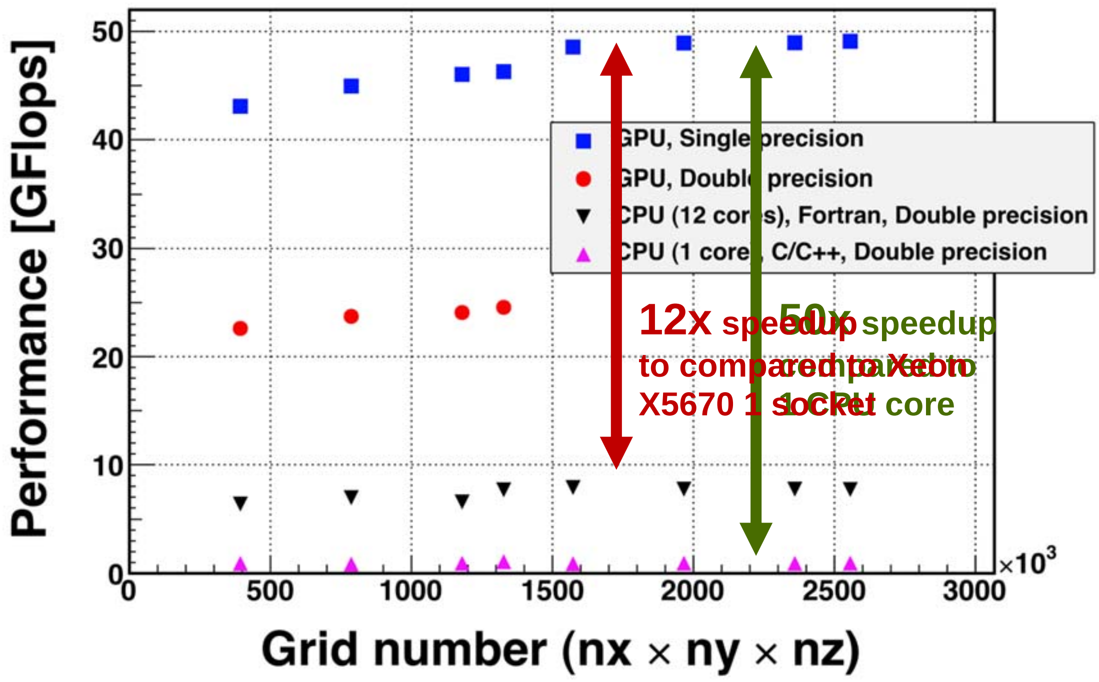
z,x,y (k,i,j)-ordering	*x,z,y* (i,k,j)-ordering	*x,z,y* (i,k,j)-ordering

■ 1 Year by Dr. Shimokawabe

Introducing many optimizations, overlapping the computation with the communication, kernel fuse, re-ordering kernel, . . .

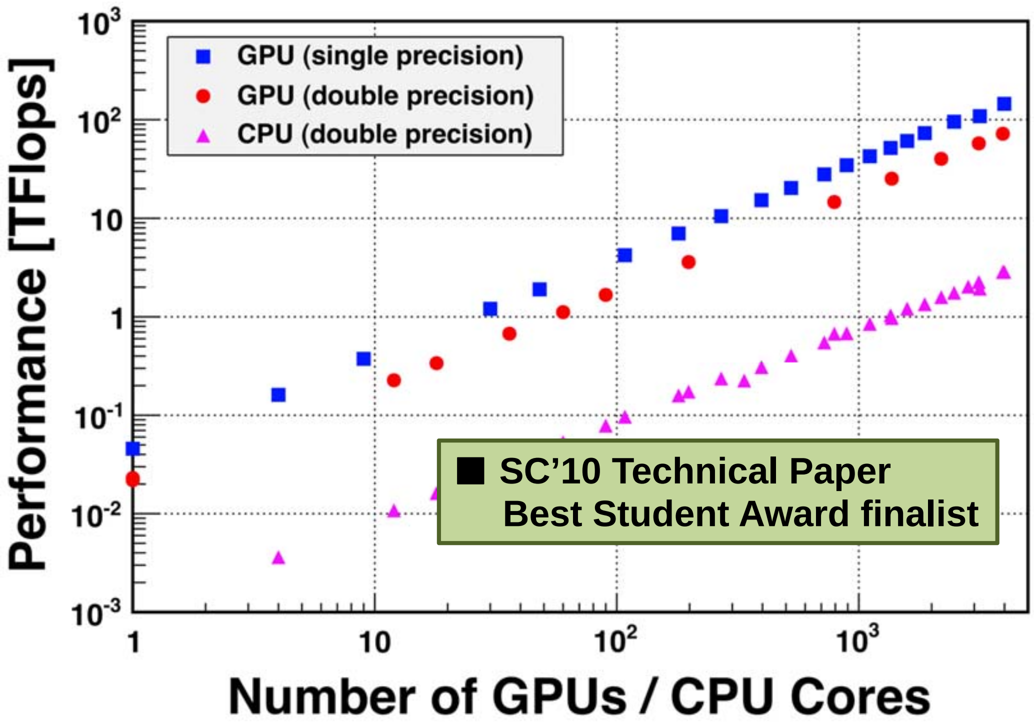
TSUBAME 2.0 (1 GPU)

GP GPU



TSUBAME 2.0 Weak Scaling

GP GPU

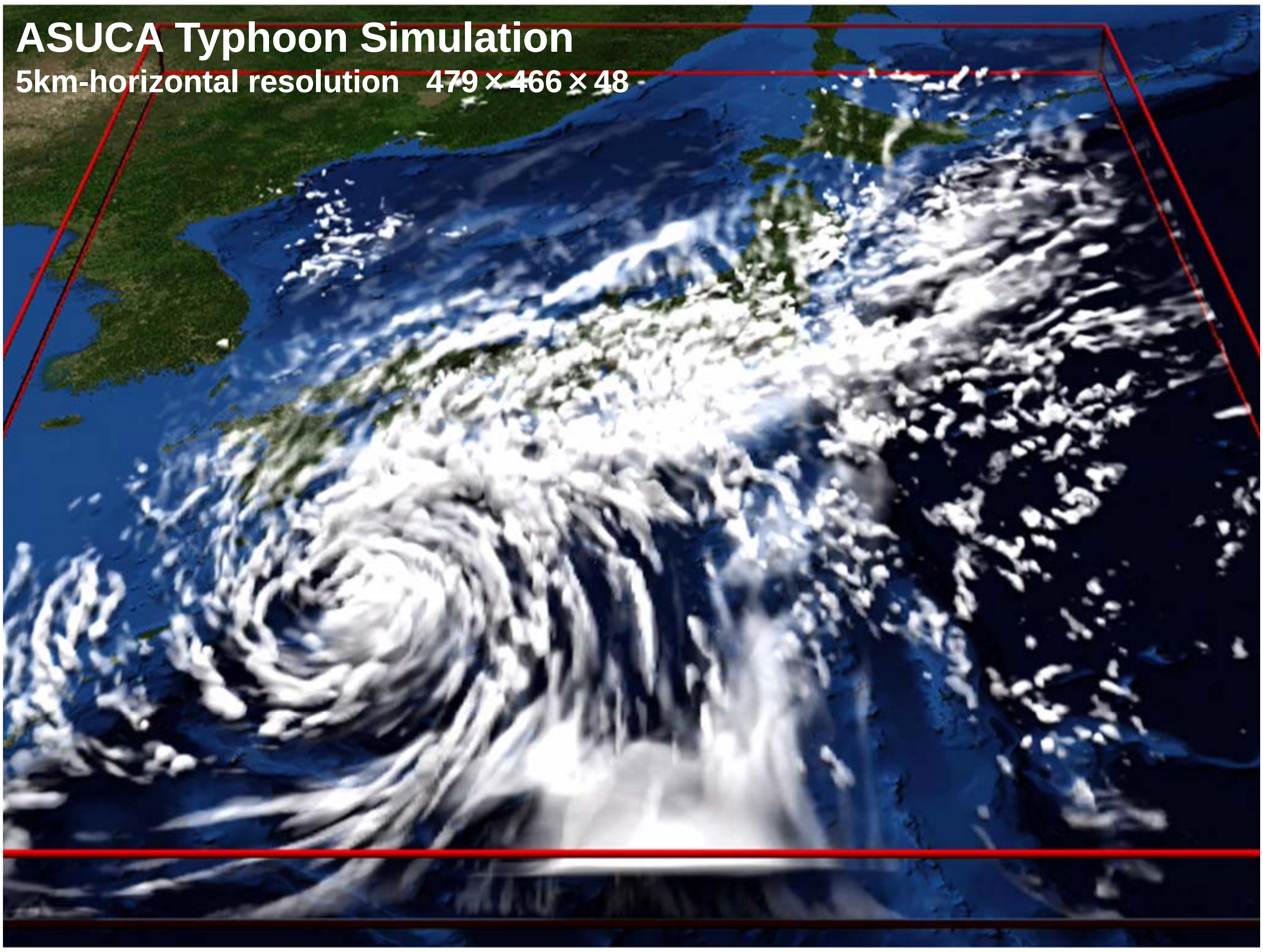


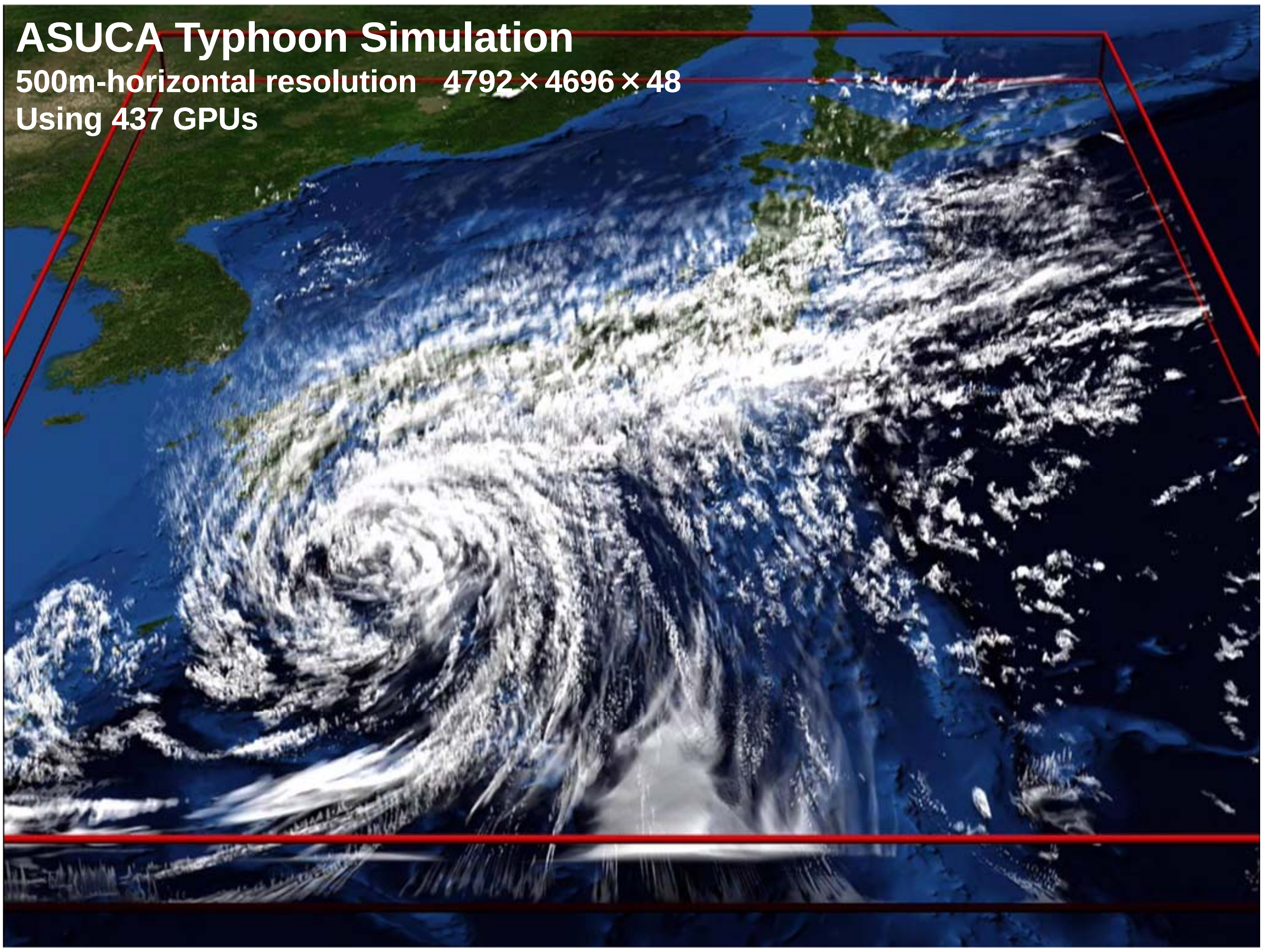
145.0 Tflops
Single precision

76.1 Tflops
Doublele precision

Fermi core Tesla M2050

3990 GPU

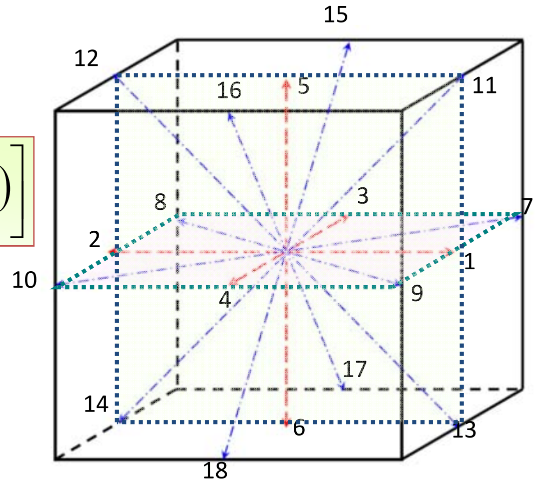

ASUCA Typhoon Simulation
5km-horizontal resolution 479×466×48


ASUCA Typhoon Simulation
500m-horizontal resolution 4792×4696×48
Using 437 GPUs

Lattice Boltzmann Method

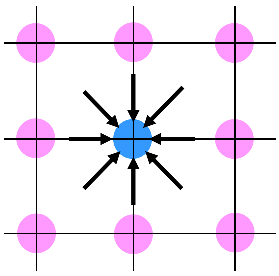
$$\frac{\partial f_i}{\partial t} + \mathbf{e}_i \cdot \nabla f_i = -\frac{1}{\lambda}\left(f_i - f_i^{eq}\right)$$

$$f_i^{eq} = \rho w_i \left[1 + \frac{3}{c^2}(\mathbf{e}_i \cdot \mathbf{u}) + \frac{9}{2c^4}(\mathbf{e}_i \cdot \mathbf{u})^2 - \frac{3}{2c^2}(\mathbf{u} \cdot \mathbf{u})\right]$$

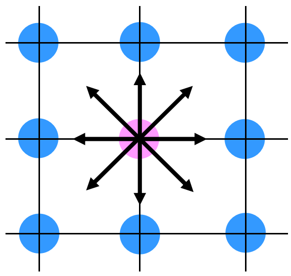


Strongly Memory Bound Problem:

Collision step:



Streaming step:



$$\tau = \frac{1}{2} + \frac{3\nu}{c^2 \delta_t}$$ relaxation time

ν : kinetic viscosity (SGS)

LES (Large-Eddy Simulation)

$$f_i(x + c_i\Delta t, t + \Delta t) = f_i(x,t) - \frac{1}{\tau_*}(f_i(x,t) - f_i^{eq}(x,t)) + F_i$$

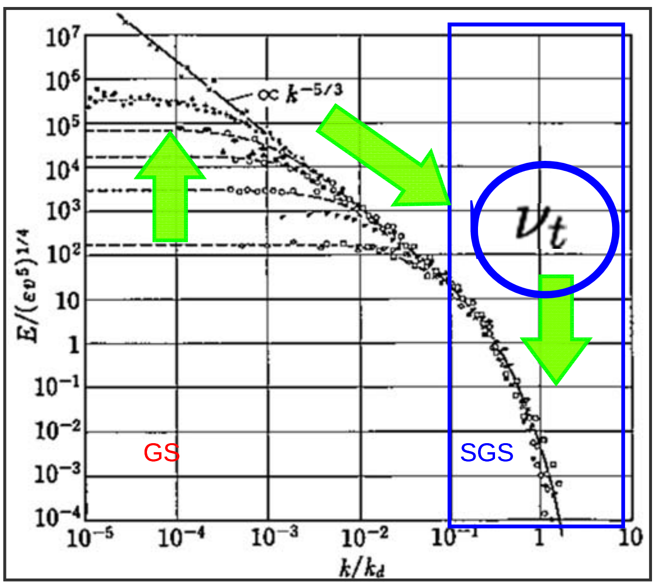
Relaxation time for LES model

$$\tau_* = \frac{1}{2} + \frac{3\nu_*}{c^2 \Delta t}$$

$$\nu_* = \nu_0 + \nu_t$$

Molecular viscosity and Eddy viscosity

Energy spectrum



Computational Area

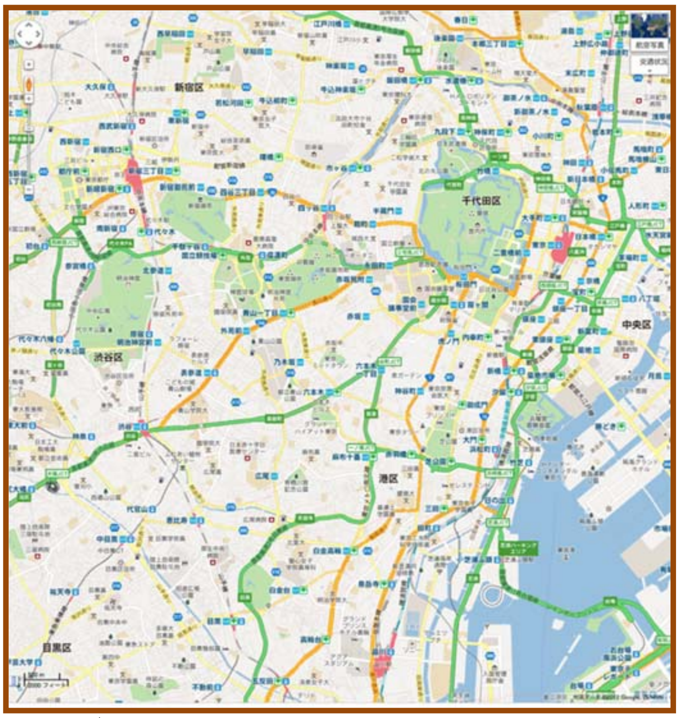
Major part of Tokyo

Including Shnjuku-ku, Chiyoda-ku, Minato-ku, Meguro-ku, Chuou-ku,

10km×10km

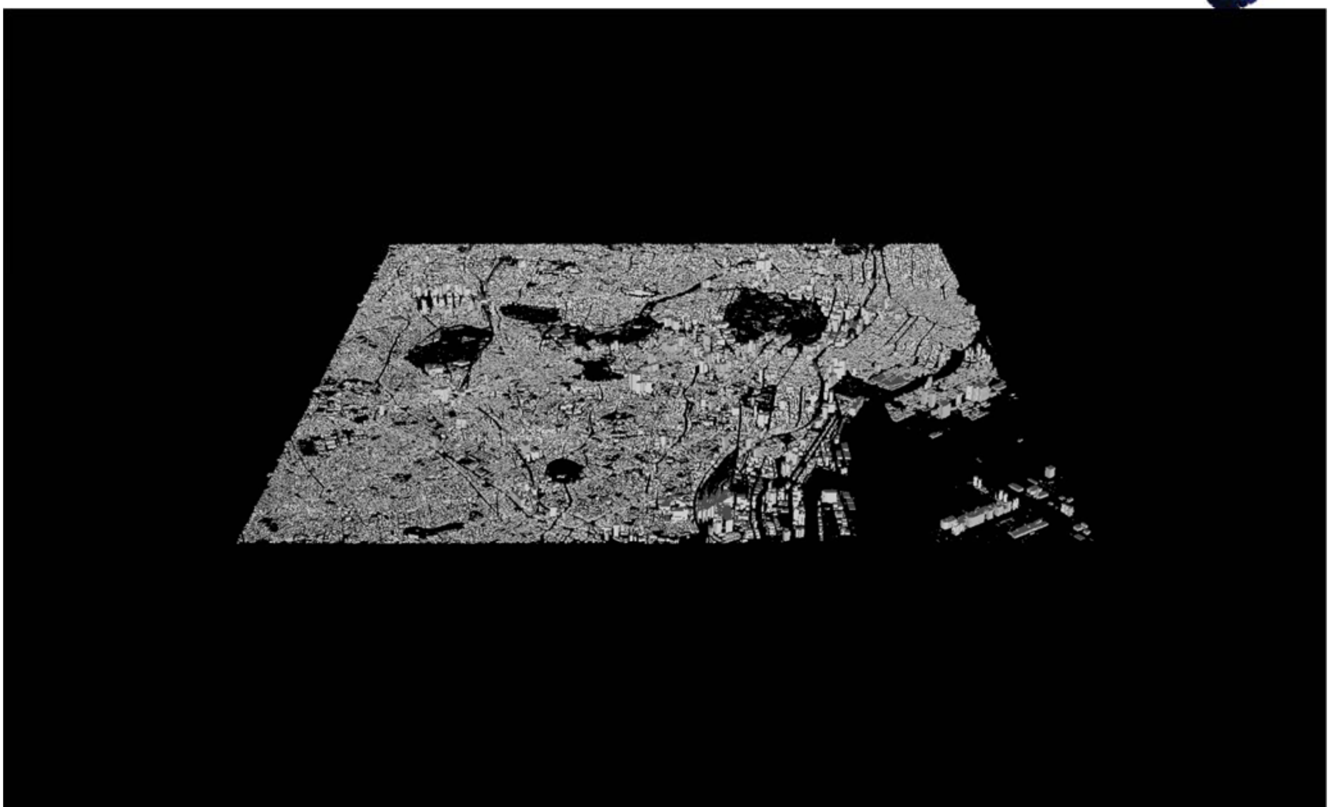
Building Data:

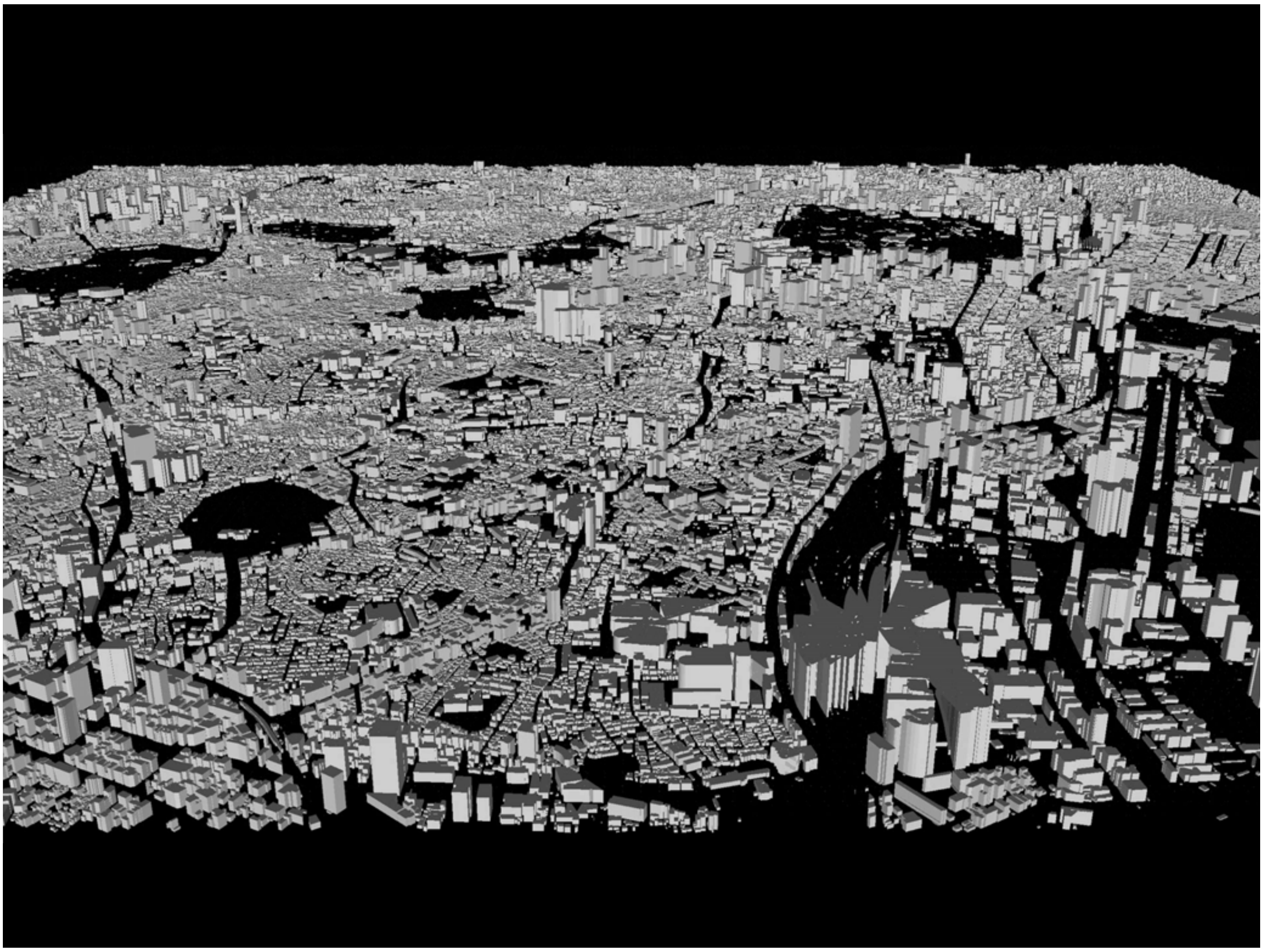
Pasco Co. Ltd.
TDM 3D

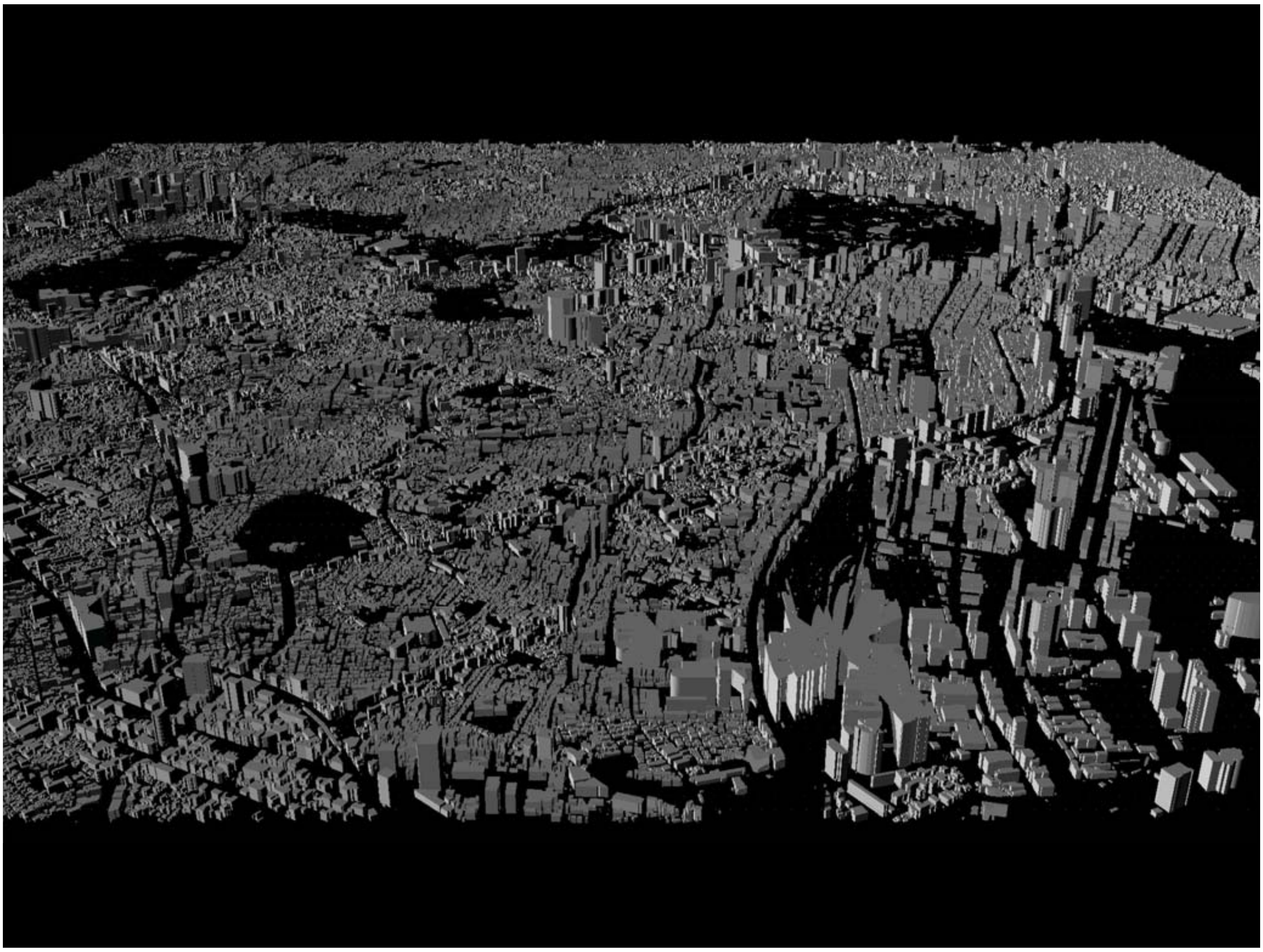


地図データ ©2012 Google, ZENRIN

Building Structures

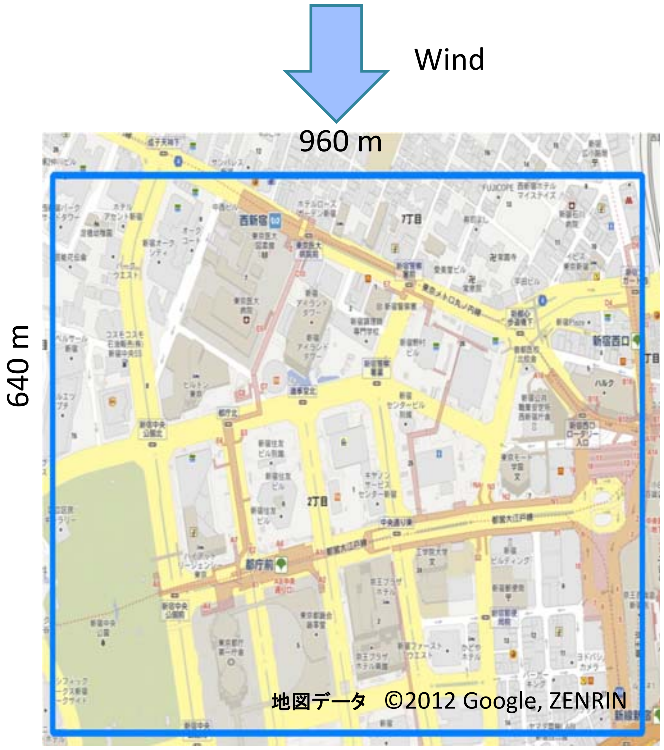




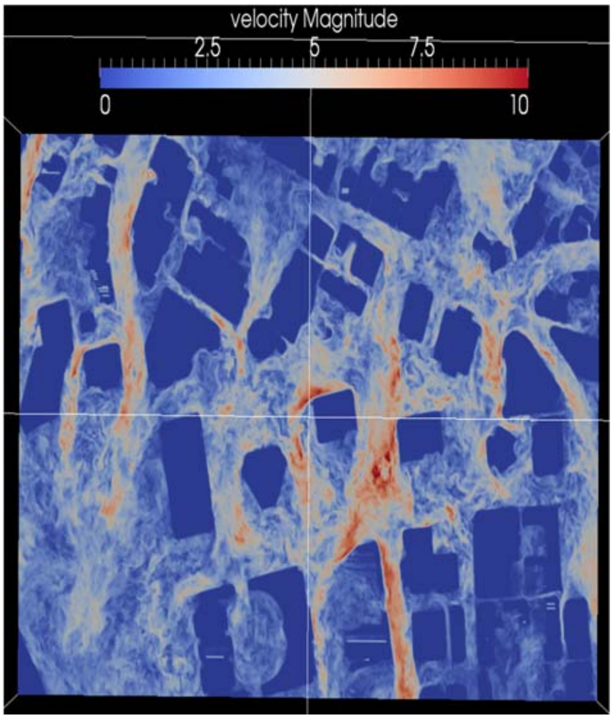


An Area Around Metropolitan Government Building

GP GPU

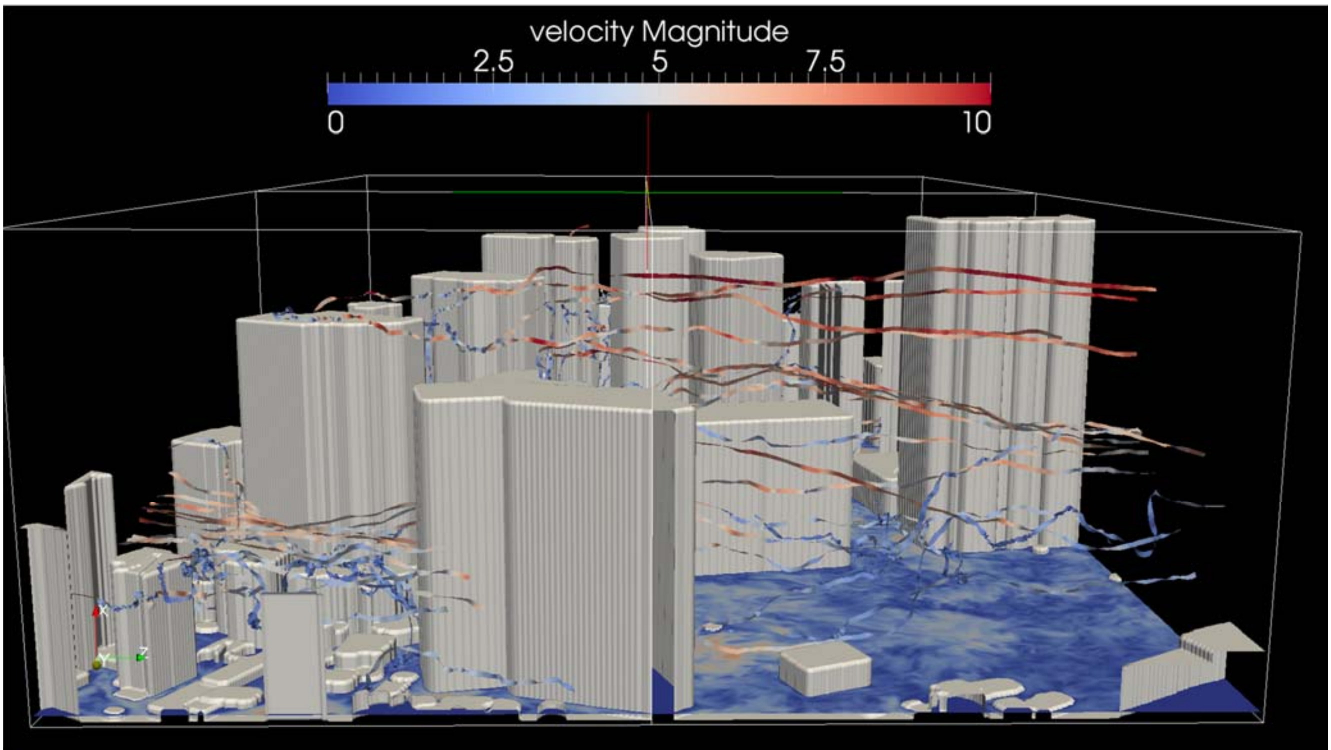


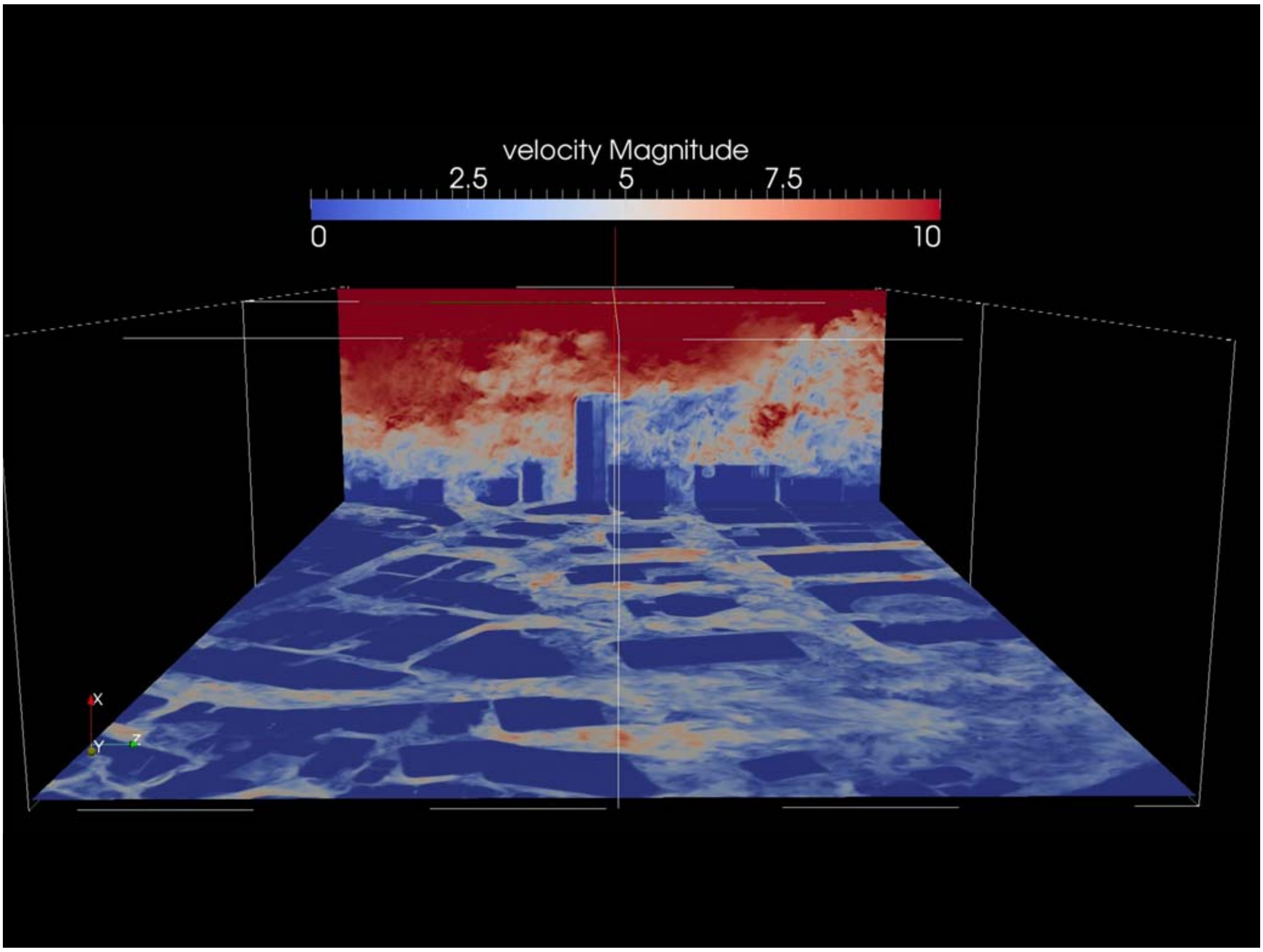
Flow profile at the 25m on the ground

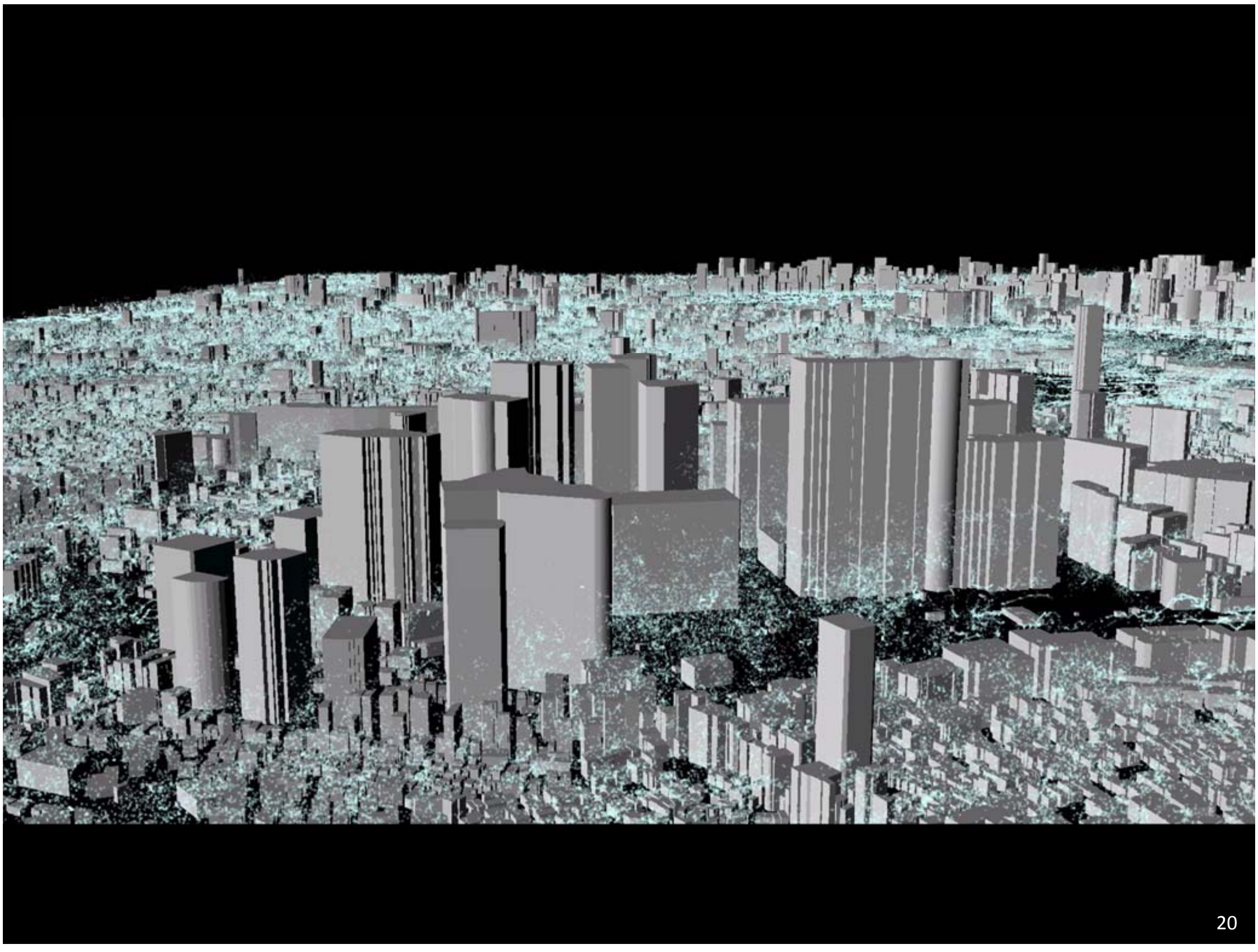


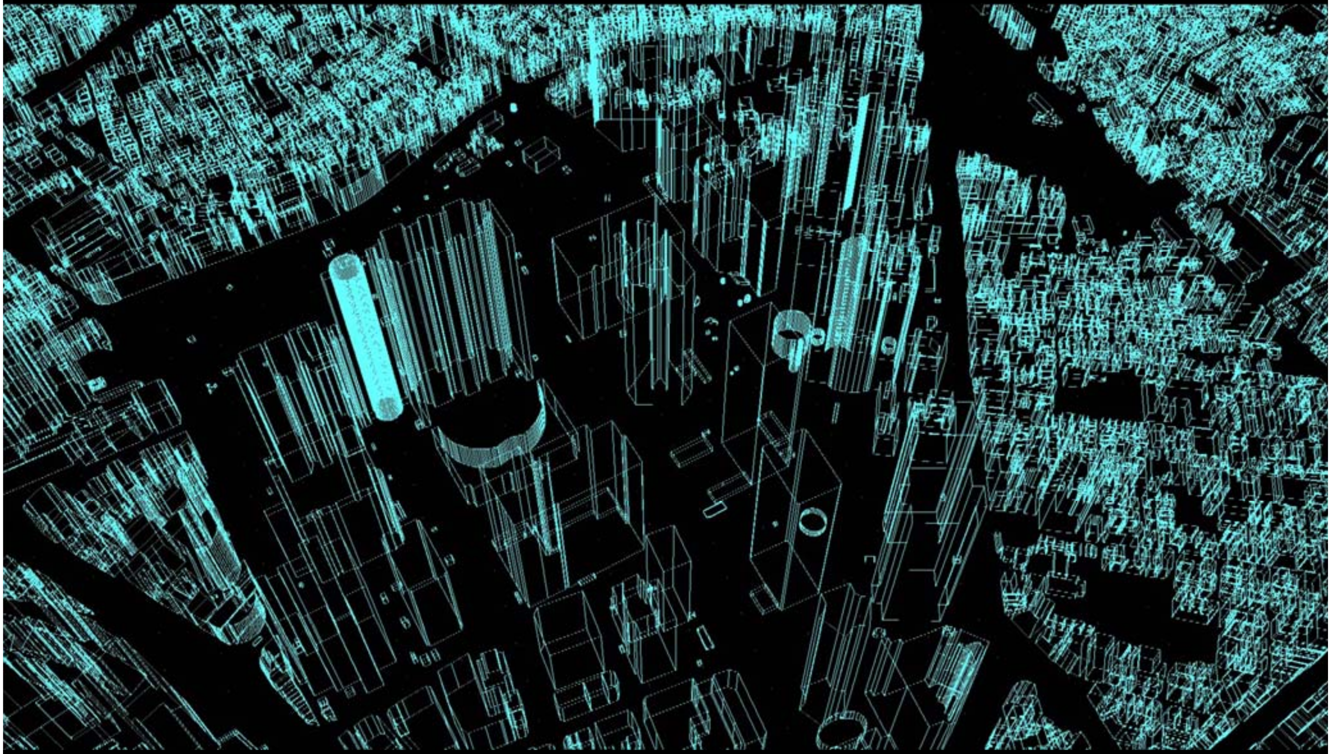
FLOW VELOCITY

GP GPU




velocity Magnitude
2.5
5
7.5
0
10
X
Y
Z





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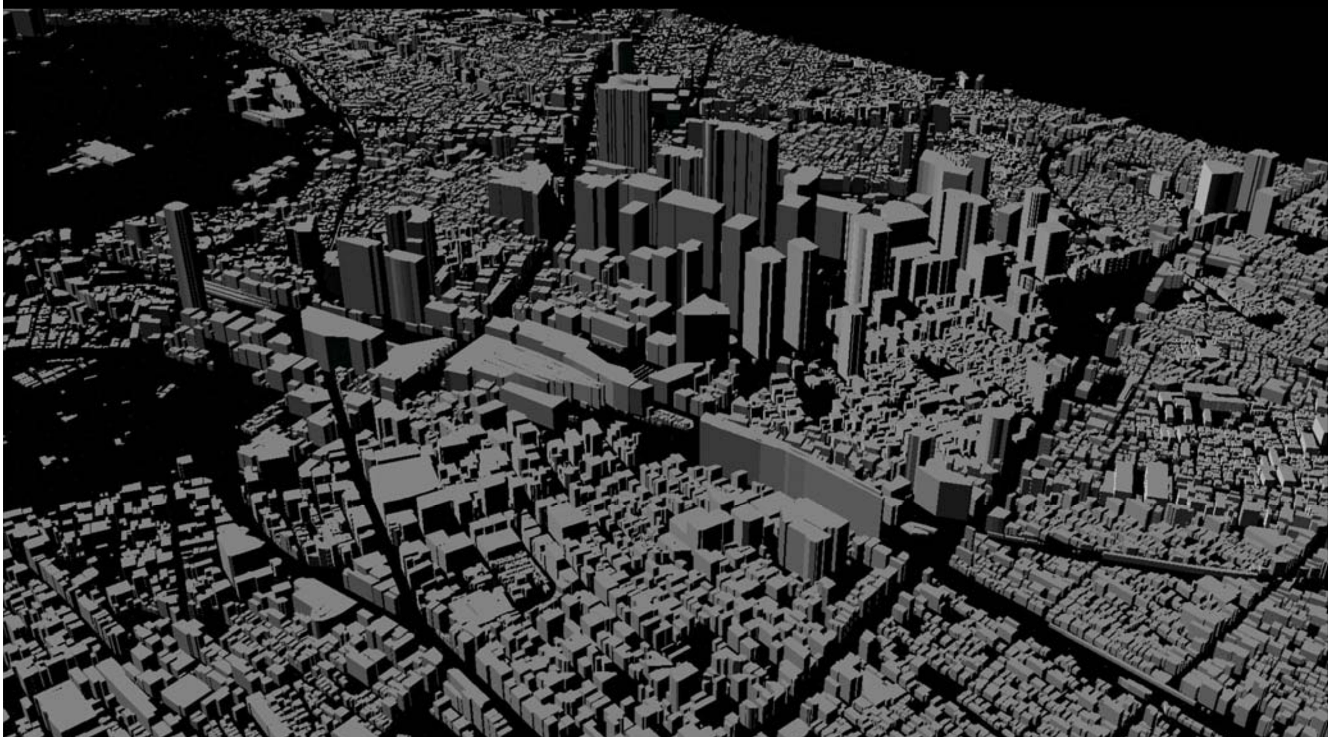

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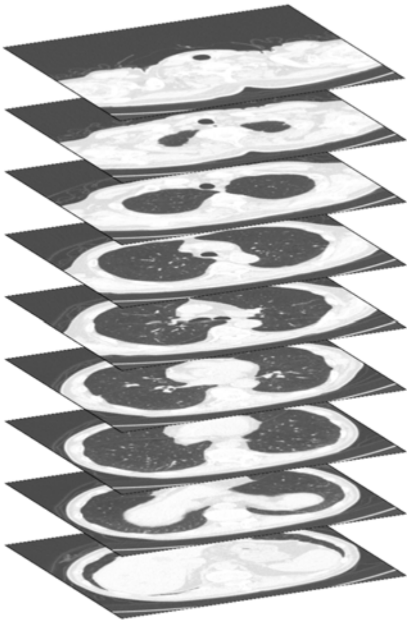
Pulmonary Airflow Study

Collaboration with Tohoku University

GP GPU

X-Ray CT images
512×512×512



「人体の不思議展」より

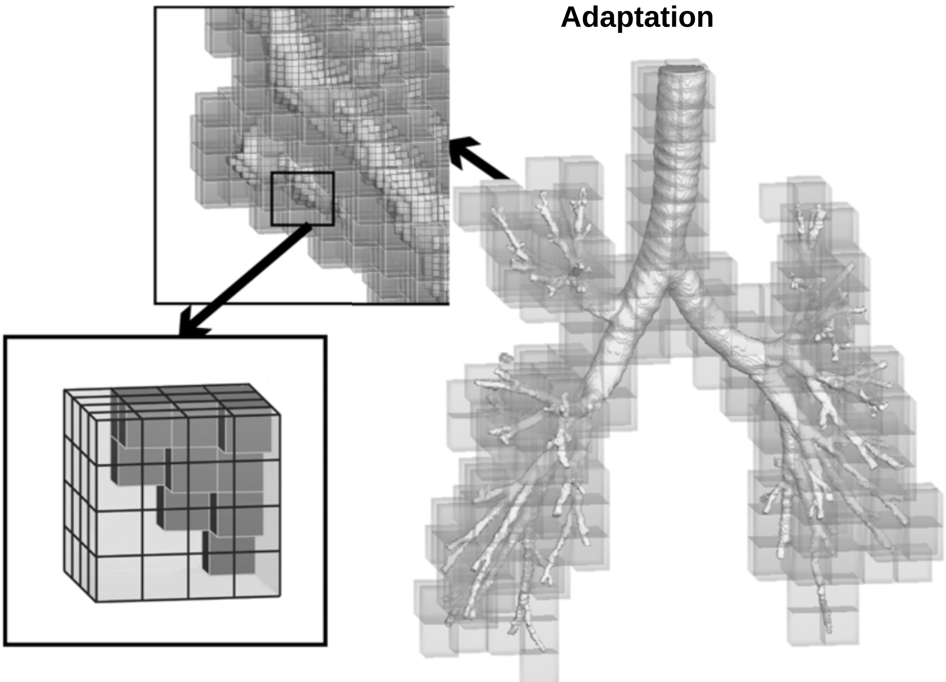
Airway structure Extraction

Pulmonary Airflow Study

Collaboration with Tohoku University

GP GPU

Level-0 Mesh Adaptation



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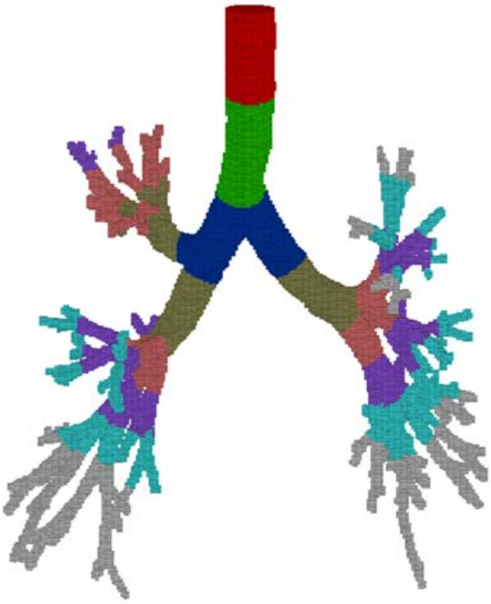
Pulmonary Airflow Study

Collaboration with Tohoku University



Assignment to multi-GPU

Two-Phase Flow Simulation

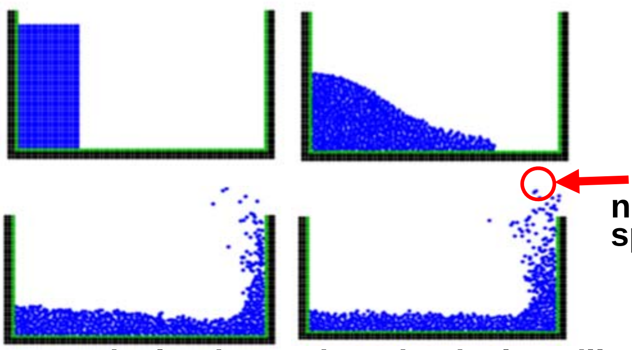
Particle Method
ex. **SPH**

Low accuracy
< $10^{6\text{-}7}$ particles

Mesh Method (Surface Capture)

- Navier-Stokes solver : Fractional Step
- Time integration : 3rd TVD Runge-Kutta
- Advection term : 5th WENO
- Diffusion term : 4th FD
- Poisson : MG-BiCGstab
- Surface tension : CSF model
- Surface capture : CLSVOF(THINC + Level-Set)

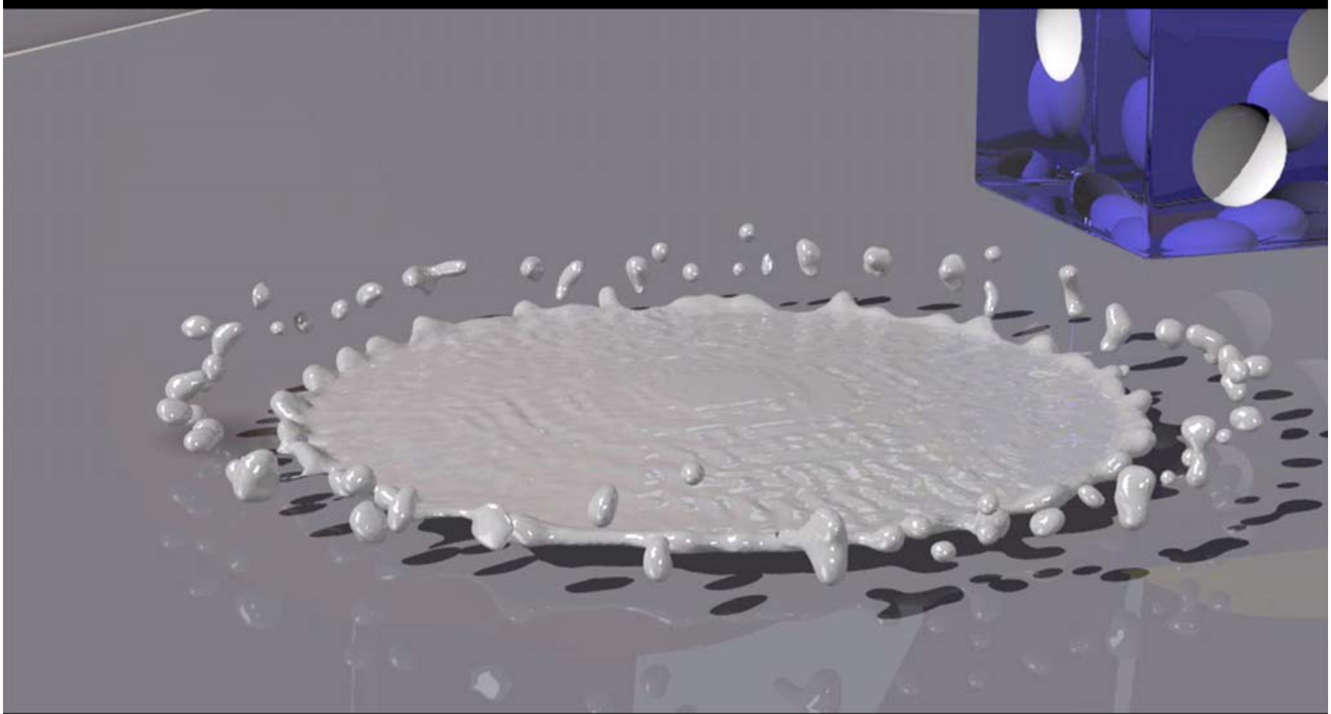
High accuracy > $10^{8\text{-}9}$ mesh points



Numerical noise and unphysical oscillation

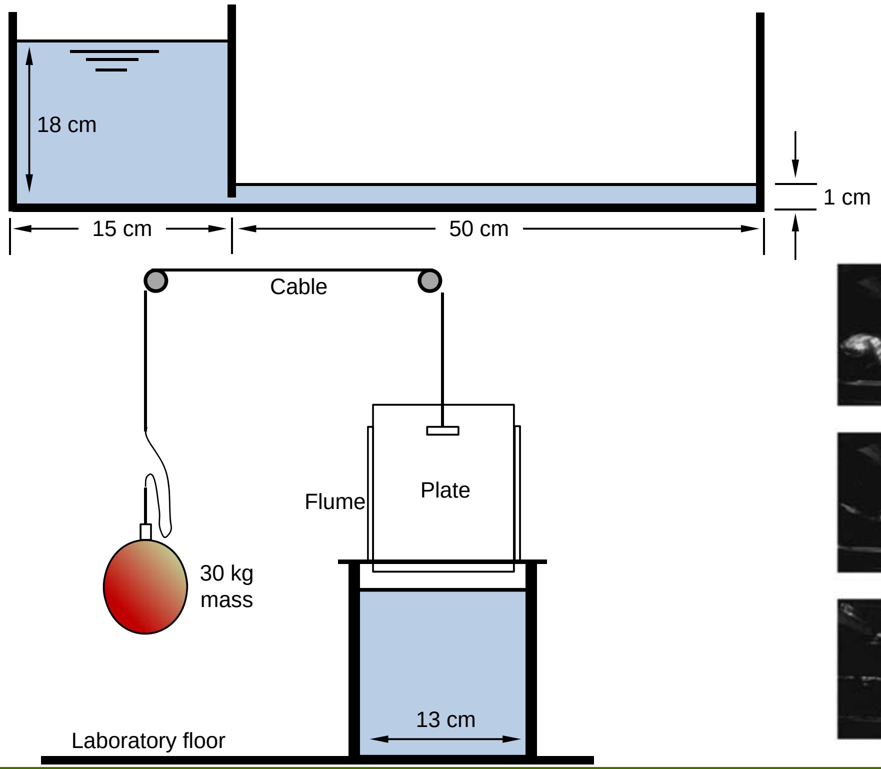
Milk Crown

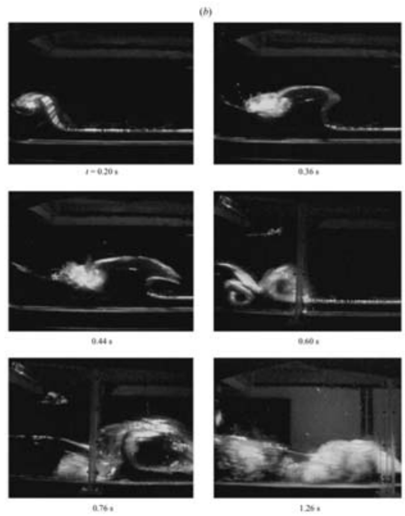
Drop on dry floor

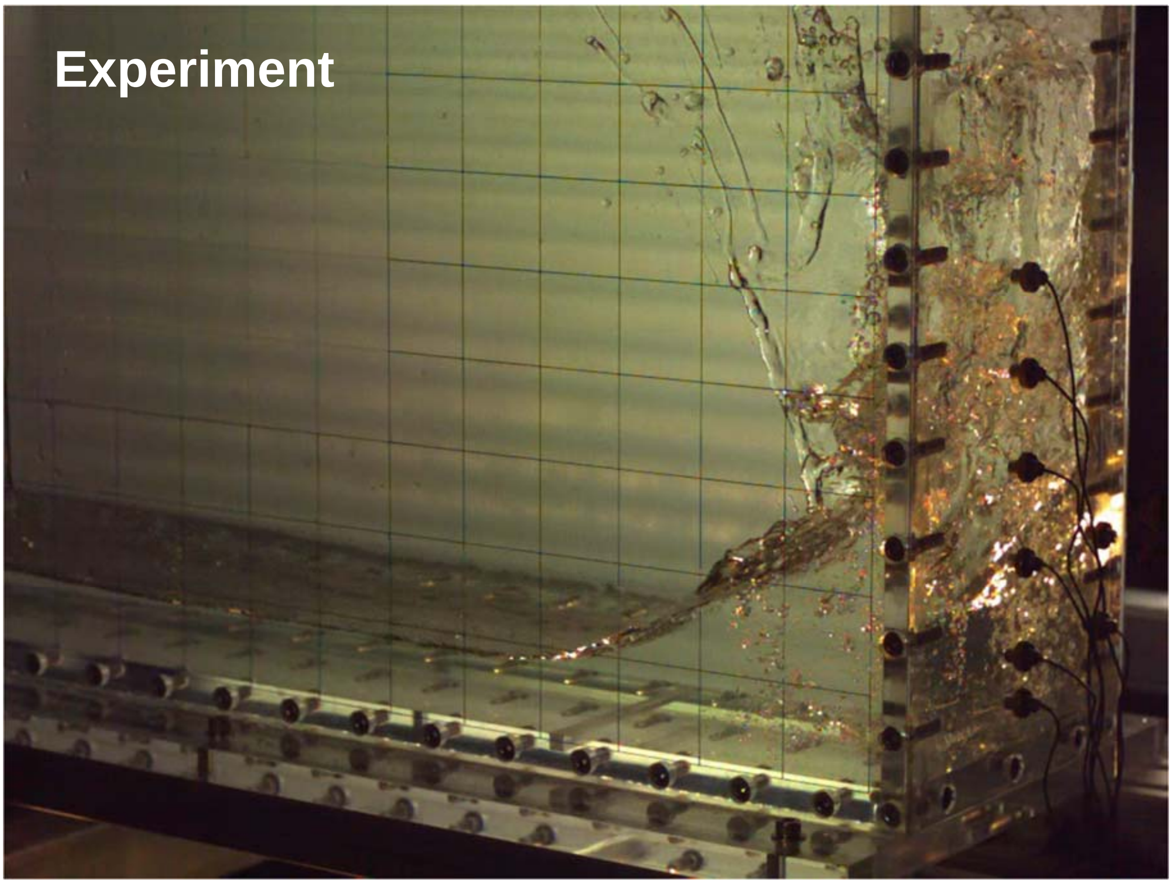


Dam-break flow

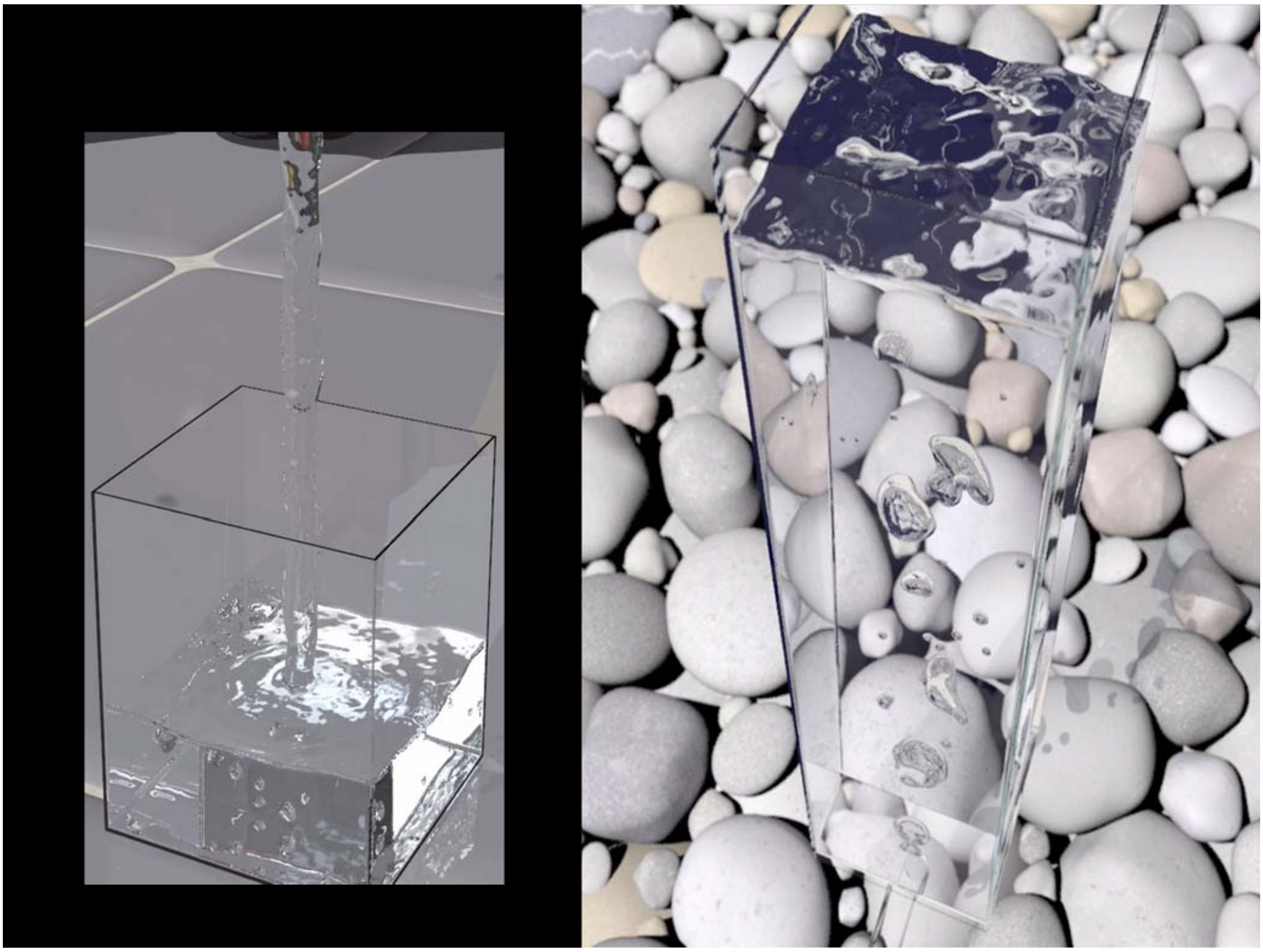
P.K.Stanby, A.Chegini and T.C.D.Barnes (1998)

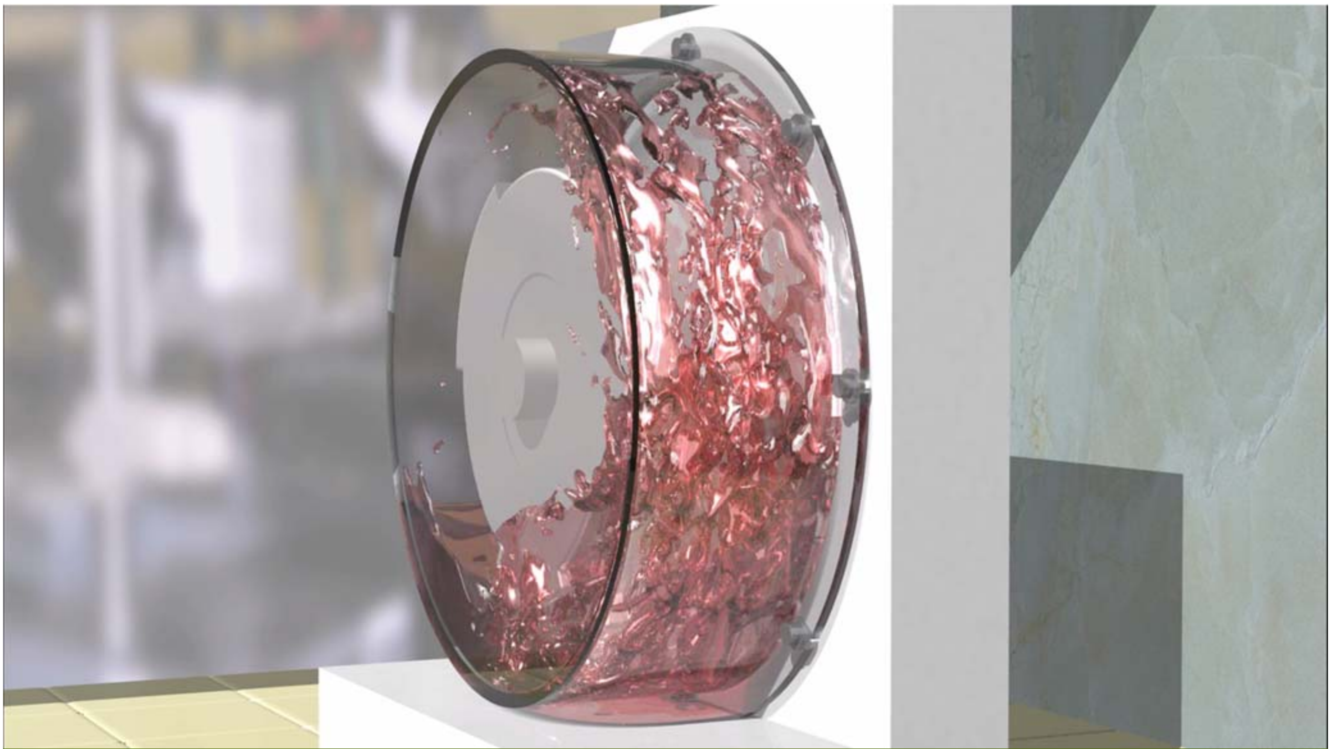






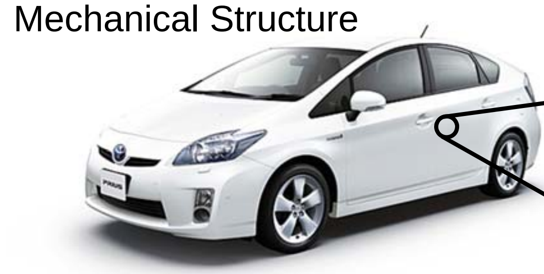
Collaboration: Prof. Hu and Dr. Sueyoshi, RIAM, Kyusyu University



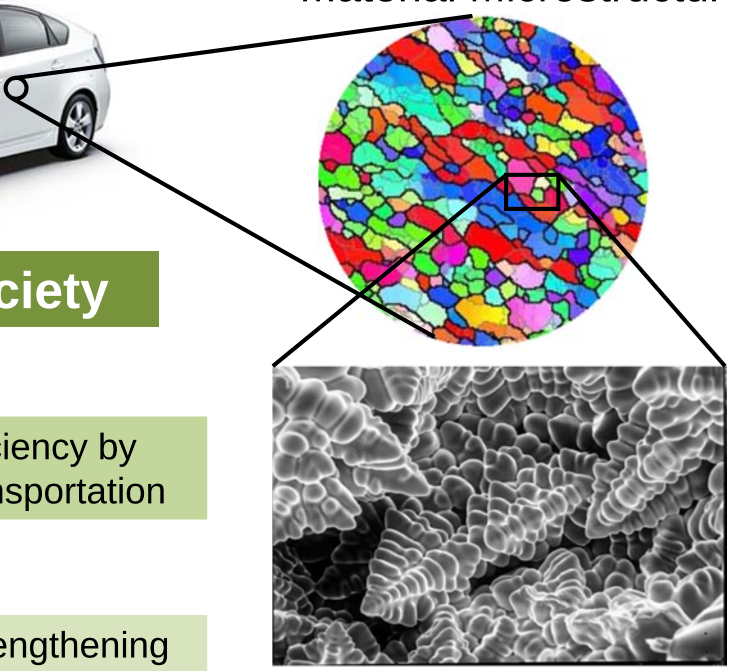


Development New Materials

Mechanical Structure



Material Microstructure



Dendritic Growth

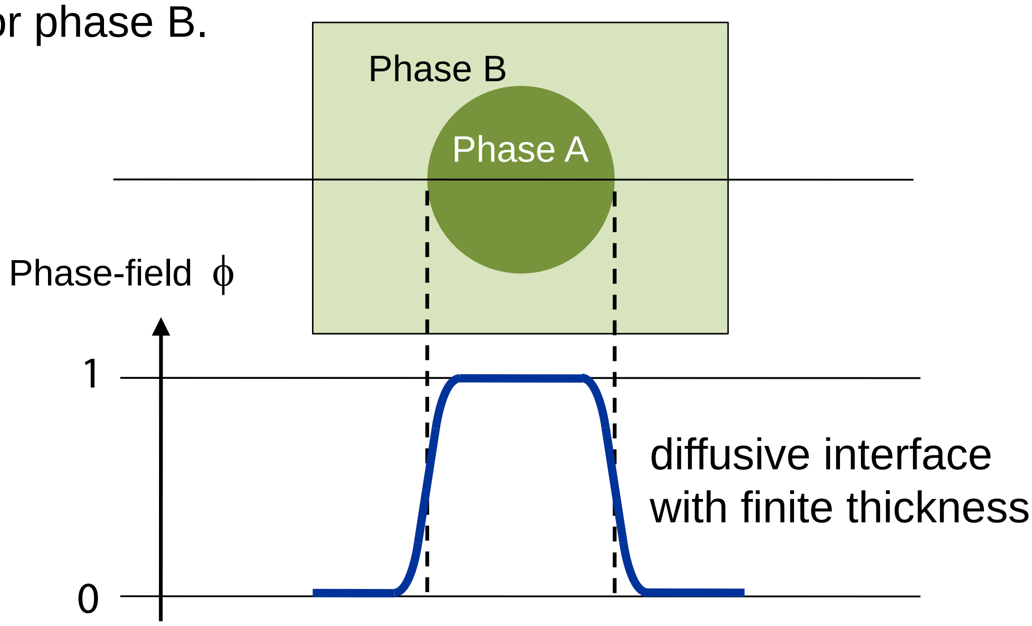
Low-carbon society

Improvement of fuel efficiency by reducing the weight of transportation

Developing lightweight strengthening material by controlling microstructure

Phase-Field Model

The phase-field model is derived from non-equilibrium statistical physics and f = 0 represents the phase A and f = 1 for phase B.



Al-Si: Binary Alloy

Time evolution of the phase-field ϕ

(Allen-Cahn equation)

$$\frac{\partial \phi}{\partial t} = M_\phi \left[\nabla \cdot (a^2 \boldsymbol{\nabla} \phi) + \frac{\partial}{\partial x}\left(a \frac{\partial a}{\partial \phi_x} |\boldsymbol{\nabla}\phi|^2 \right) + \frac{\partial}{\partial y}\left(a \frac{\partial a}{\partial \phi_y} |\boldsymbol{\nabla}\phi|^2 \right) + \frac{\partial}{\partial z}\left(a \frac{\partial a}{\partial \phi_z} |\boldsymbol{\nabla}\phi|^2 \right) - \Delta S \Delta T \frac{dp(\phi))}{d\phi} - W \frac{dq(\phi)}{d\phi} \right]$$

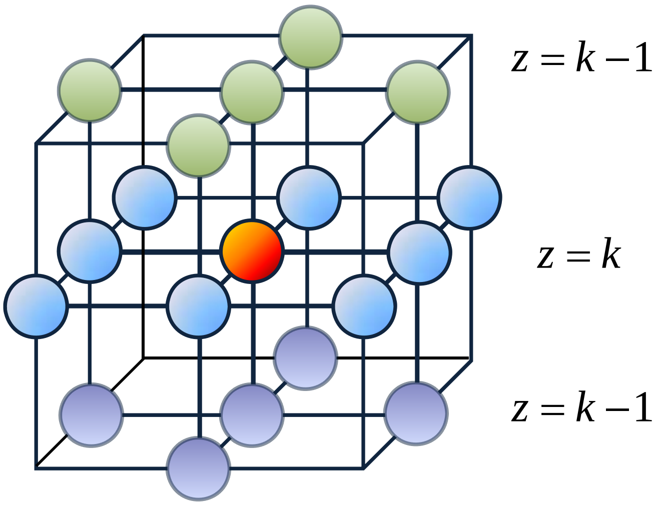
Time evolution of the condensation: c

$$\frac{\partial c}{\partial t} = \boldsymbol{\nabla} \cdot [D_S \phi \boldsymbol{\nabla} c_S + D_L (1-\phi) \boldsymbol{\nabla} c_L]$$

Finite Difference Method

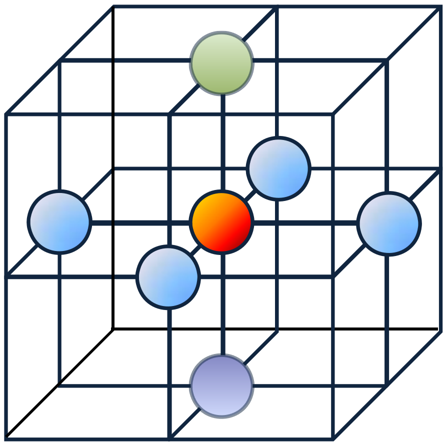
Phase Field : ϕ

19 points to solve $\phi_{i,j,k}$



Condensation : c

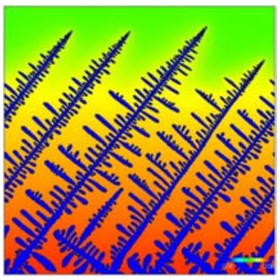
7 points to solve $c_{i,j,k}$



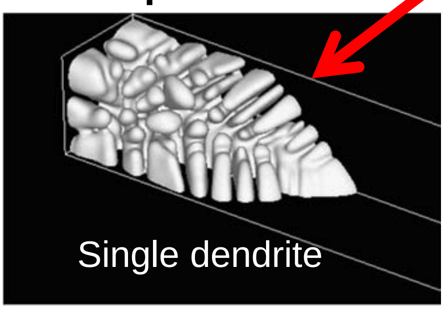
Requirement for Peta-scale Computing

Previous works

2D computation

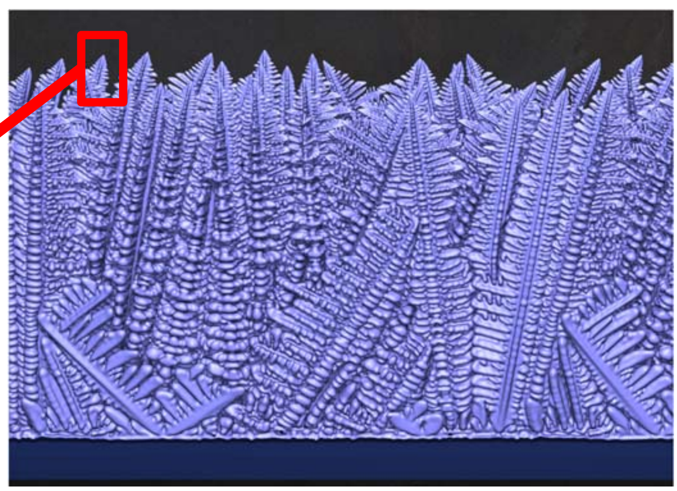


3D computation



×1000 large-scale computation

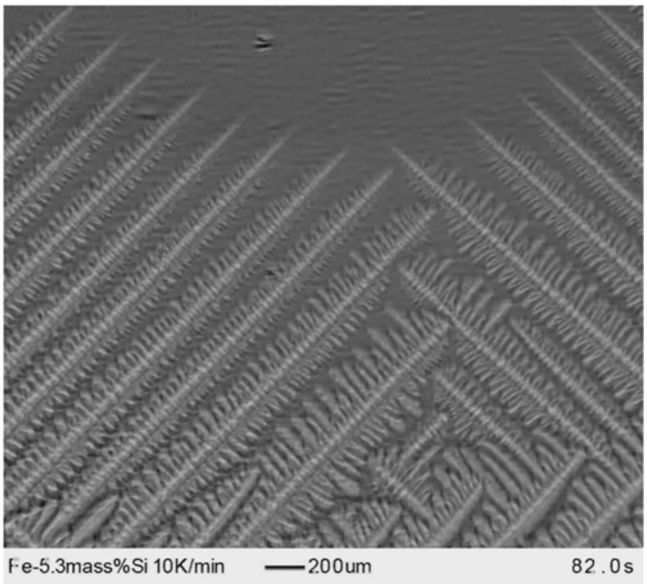
on TSUBAME 2.0



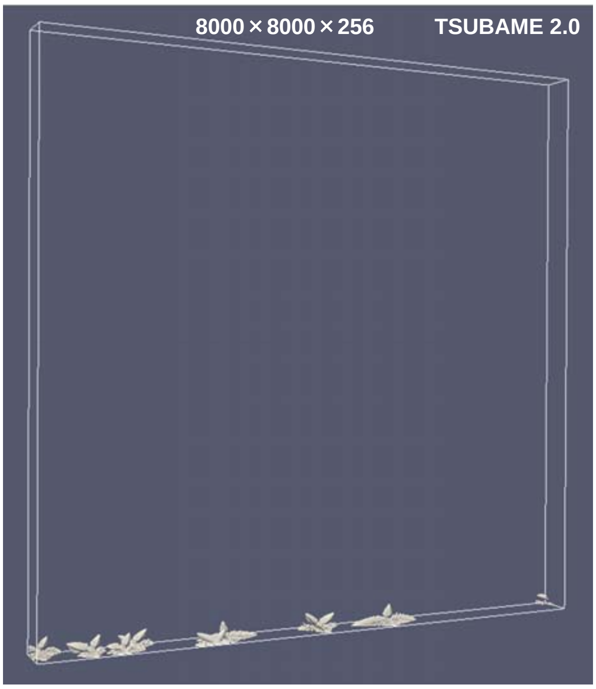
～ mm scale

Comparison with Experiment

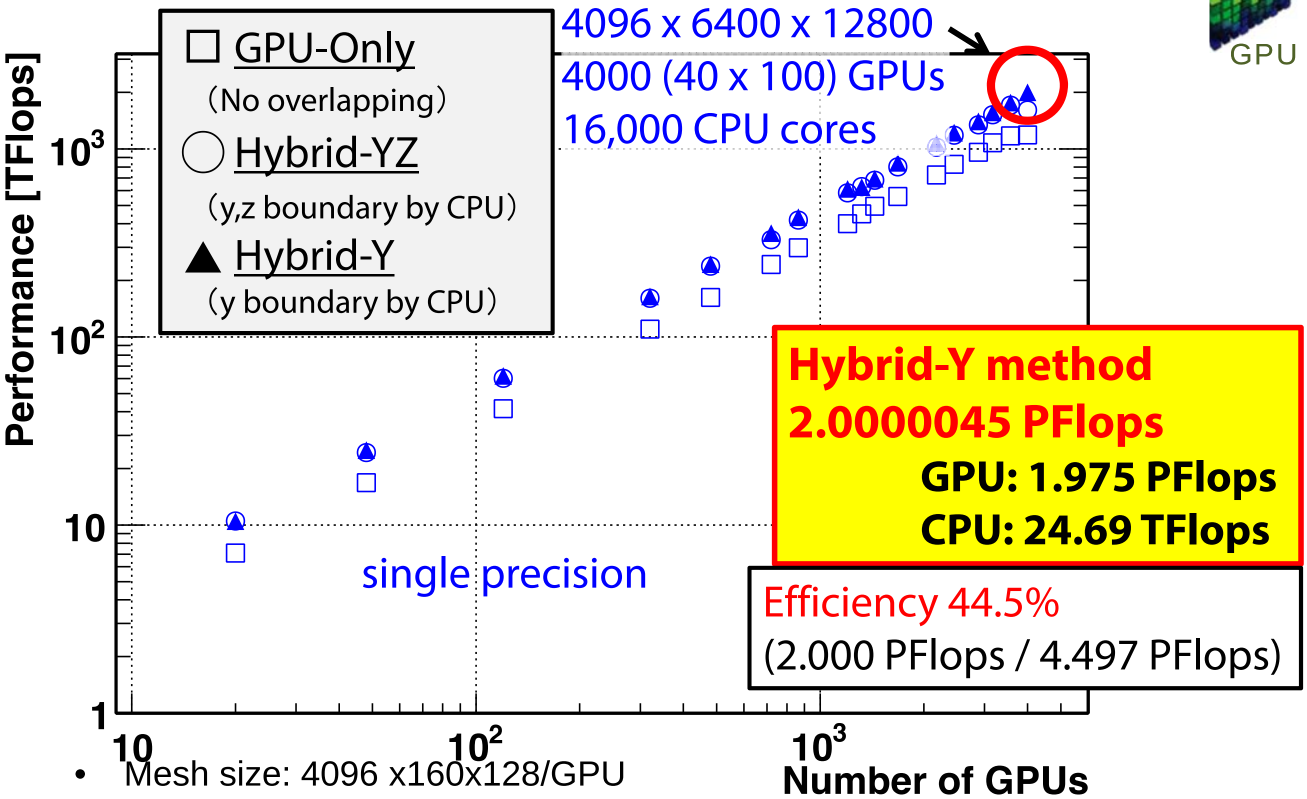
Observation:
X-ray imaging of Solidification of a binary alloy at Spring-8 in Japan by Prof. Yasuda (Osaka University in Japan)



Phase-field simulation



Weak scaling



- Mesh size: 4096 x160x128/GPU
- NVIDIA Tesla M2050 card / Intel Xeon X5670 2.93 GHz on TSUBAME 2.0