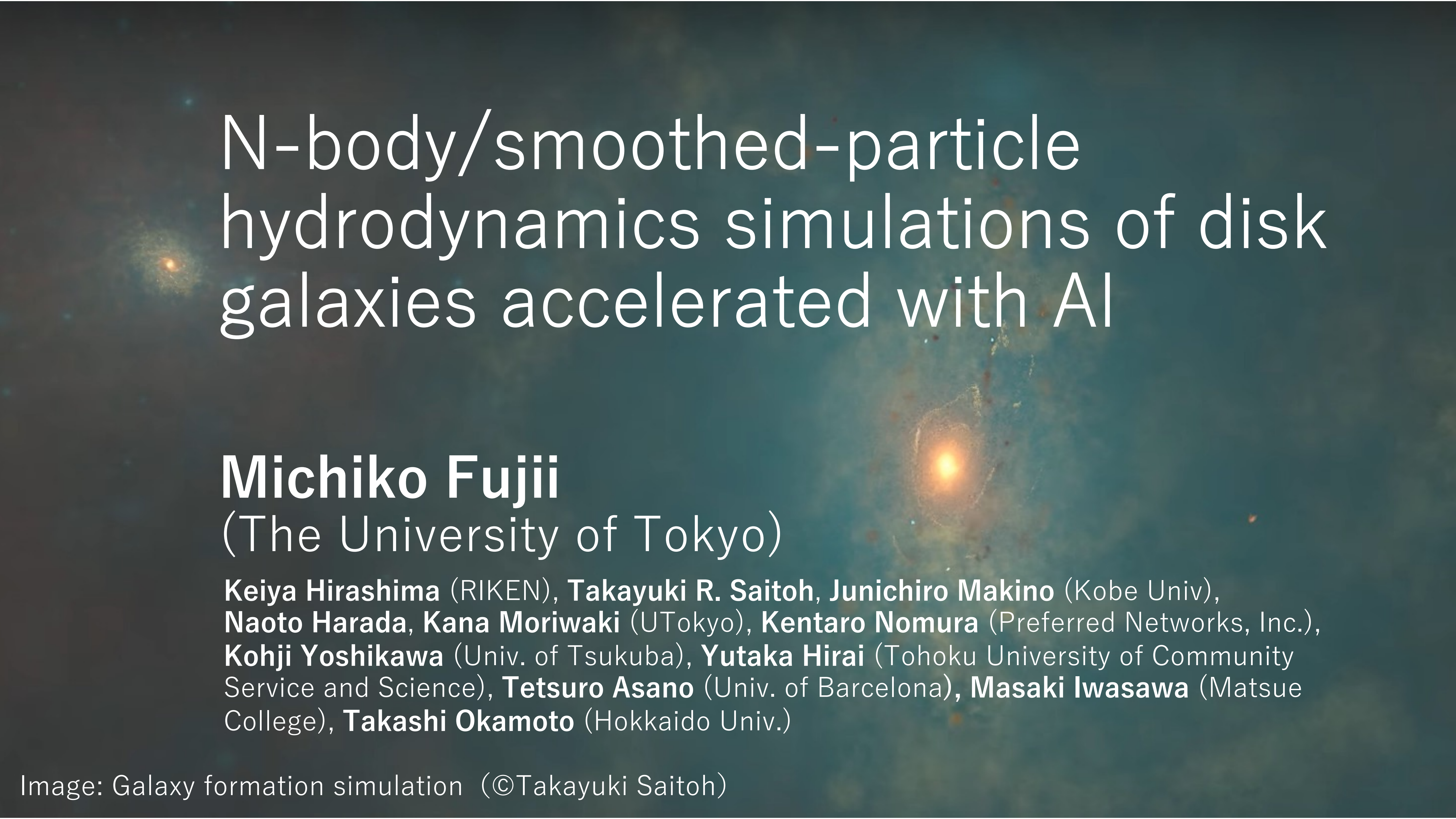

N-body/smoothed-particle hydrodynamics simulations of disk galaxies accelerated with AI

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Image: Galaxy formation simulation （©Takayuki Saitoh）

IAU Commission B1
Computational Astrophysics

President (2024-2027):
Michiko Fujii

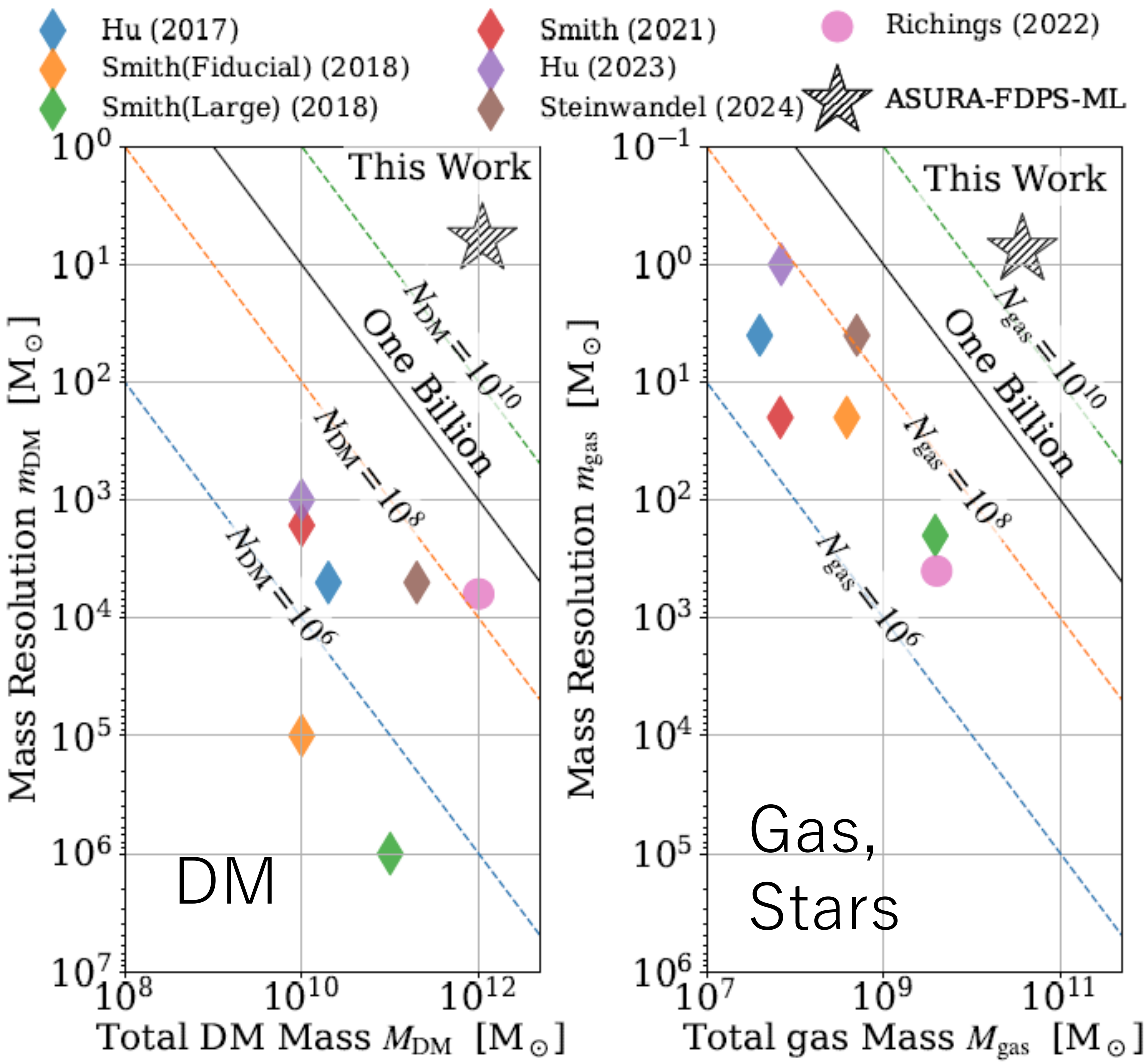
- Regular Newsletter
    - CB1 member can request to advertise upcoming workshops, schools, job opportunities, etc.
- Online/in-person workshop series: ChaICA
    - ChaICA6 in Mohali, India, Sep. 29-Oct 3.
- Submitting a LOI for a symposium in 2027
    - Symposium in 2019, Focus Meeting in 2024

- If you would like to join CB1, please email your name, affiliation, and research field to iau.commission.b1@gmail.com
- We need more contribution from East Asia!

Galaxy formation simulations

- 10^9 particles are maximum for current N-body/SPH simulations
  - Almost star-by-star resolution of dwarf galaxies
  - 100Msun resolution for MW size galaxies
- The number of stars of the Milky-Way disk 10^{10-11}
  - There is still a gap between simulations and real galaxies -> toward higher-resolution simulations

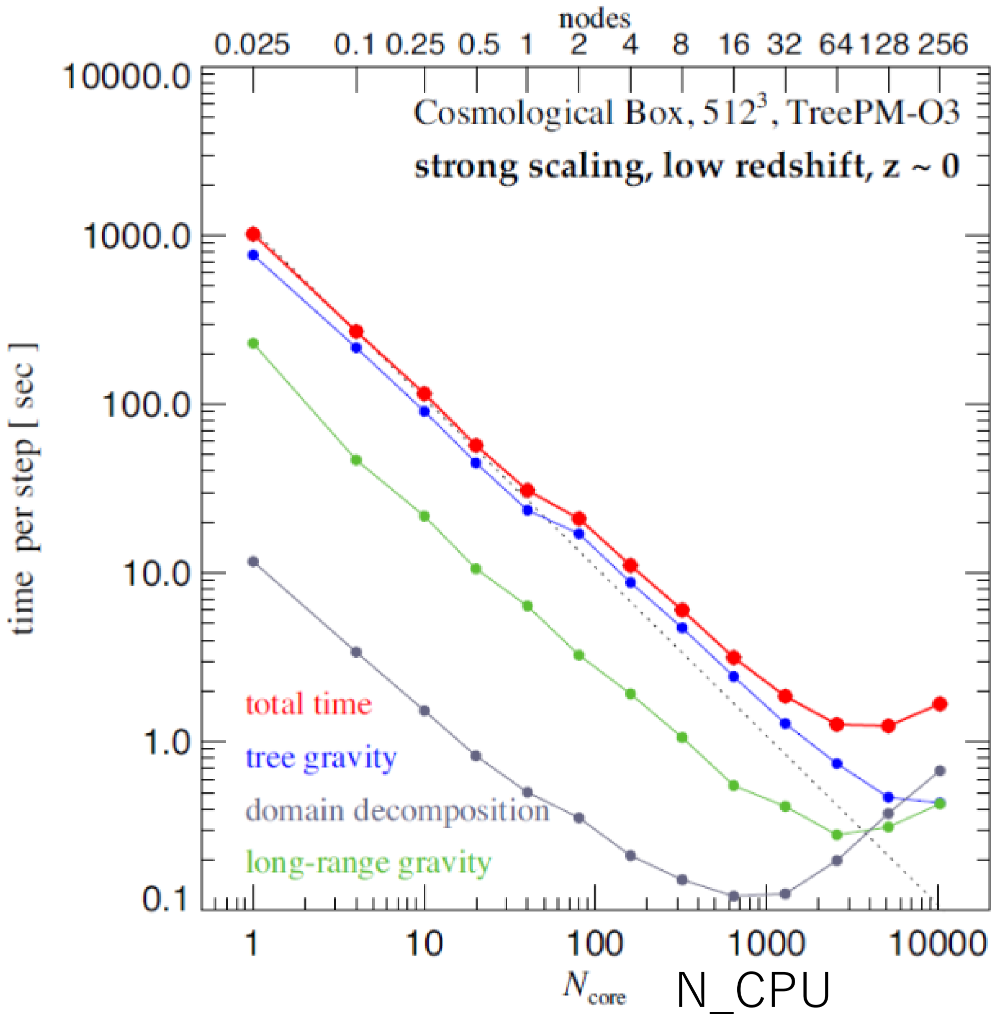
Hirashima et al. (2025, SC25, in press)



Difficulty of massively parallelized simulations

- **Timesteps**
  - Higher resolution reproduces finer structures, which are a tiny fraction
    -> require smaller timesteps to integrate them
    -> frequent updates are required
- **Communication**
  - Communication costs increase as the number of CPUs increases
  - Smaller timesteps increases the number of communications
  - Weak scaling does not help

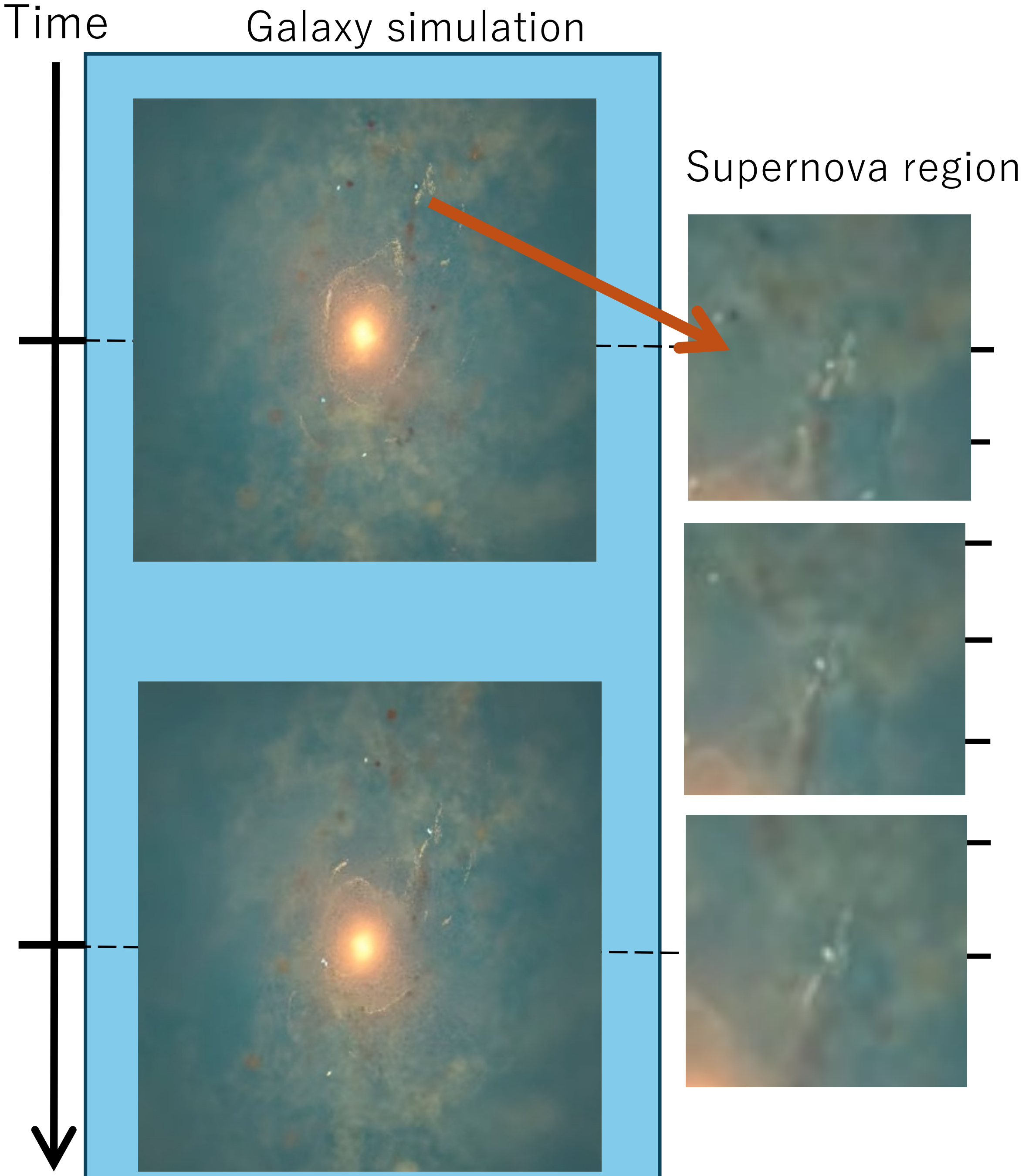
Gadget-4 (Springel+21), Fig. 63



Each node is equipped with two Intel Xeon Gold 6148 CPUs with 20 physical cores at 2.4 GHz.

Galaxy simulation case

- The spatial and time scales of galaxy structures can differ 5 order of magnitude
  - For example, distribution of dark matter is >100 kpc, but star-forming and supernova regions are <10 pc scale
  - Stars are formed in 10 K gas, but supernova heats the gas to $>10^5$ K
  - The timestep of the finest structure, e.g., the expansion of supernova shocked region, is typically ~100 yr
- Such short timestep regions are tiny compared to the entire galaxy
  - They worsen the load balance
  - Communication overhead (crucial for >10,000 nodes)



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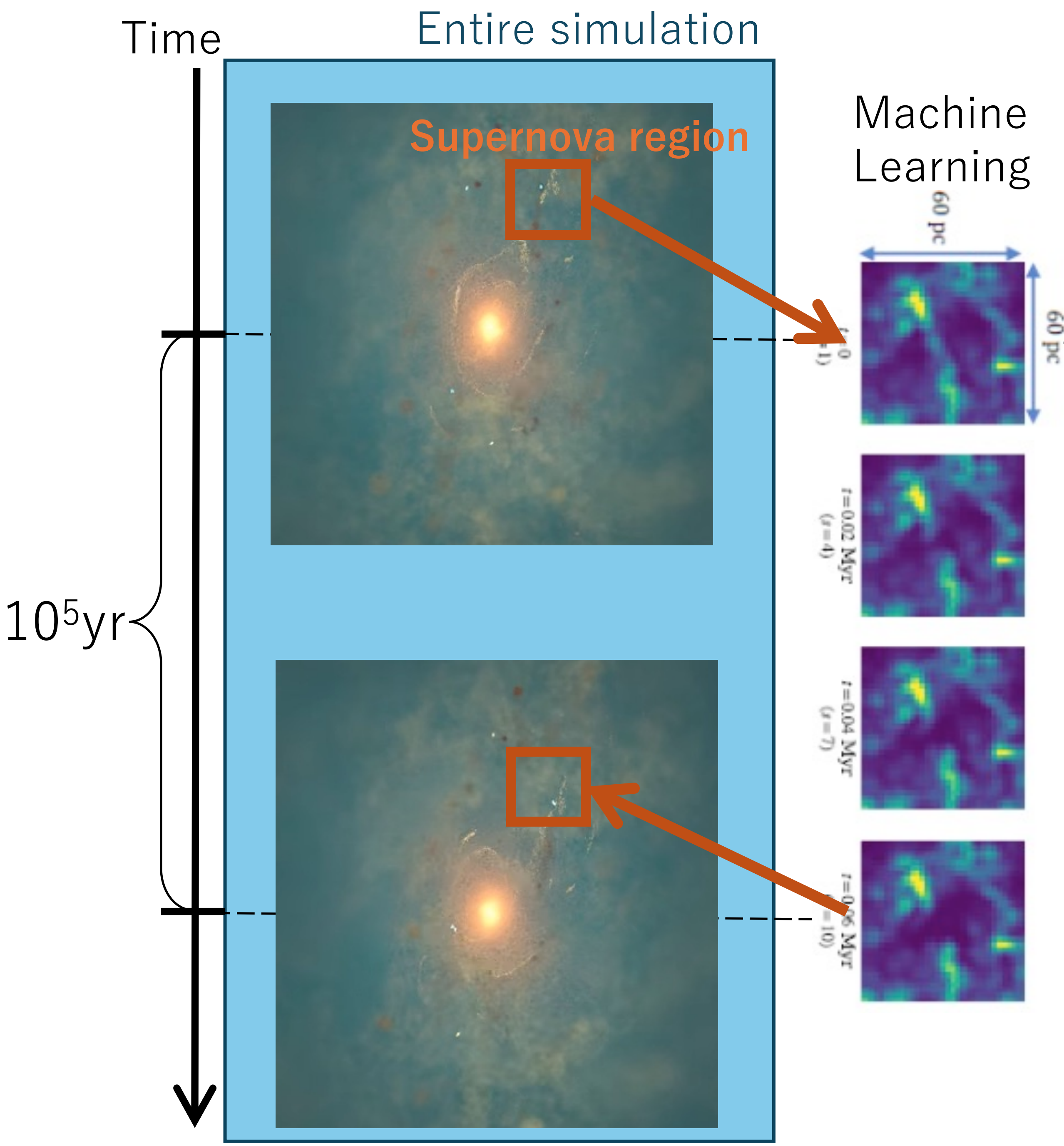
New Scheme with Machine Learning

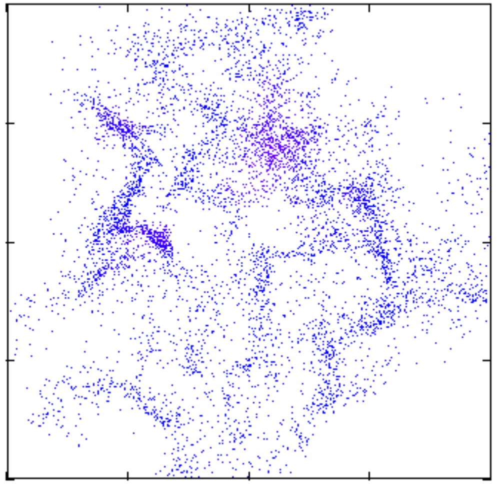
- Use machine learning forecasts instead of integrating with small timesteps
  - In current simulations, so-called sub-grid models are used for small scale phenomena such as star formation, early evolution of supernova explosion
- We developed a machine learning model to predict the time evolution of interstellar gas after 0.1 million year of a supernova explosion (Hirashima, Fujii, et al. 2023)
  - With this model, we can skip the integrations with small timesteps



Making Training Data Sets for Machine Learning

Perform 400 smoothed particle hydrodynamics simulations of an expanding supernova shell
Convert the particle data to a 3D mesh data (60pc x 60pc x 60pc box)

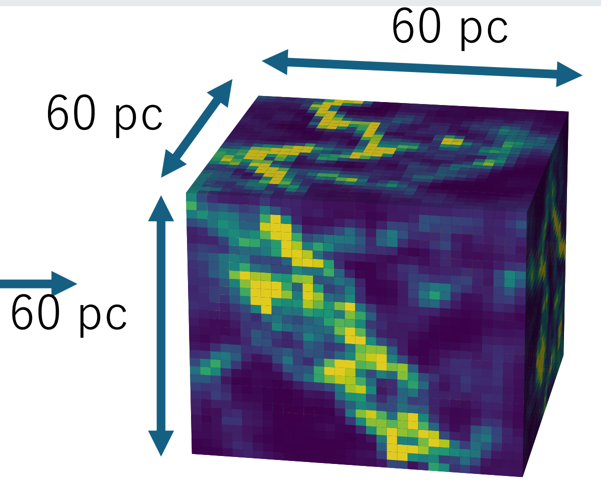
Initial gas temperature	10 [K]
Initial averaged gas density	40 ~ 60 [cm^{-3}]
Energy of supernova	10^{51} [erg]
Total gas mass	10^{6} [M$_\odot$]
Mass resolution of gas	1 [M$_\odot$]
Gravitational softening length	0.5 [pc]



Interpolation using

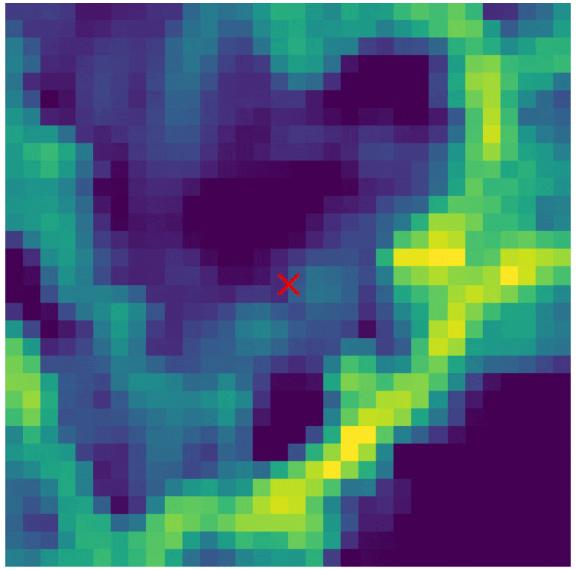
SPH summation

$$\rho_i = \sum_j m_j W(r_{ij}, h_j)$$

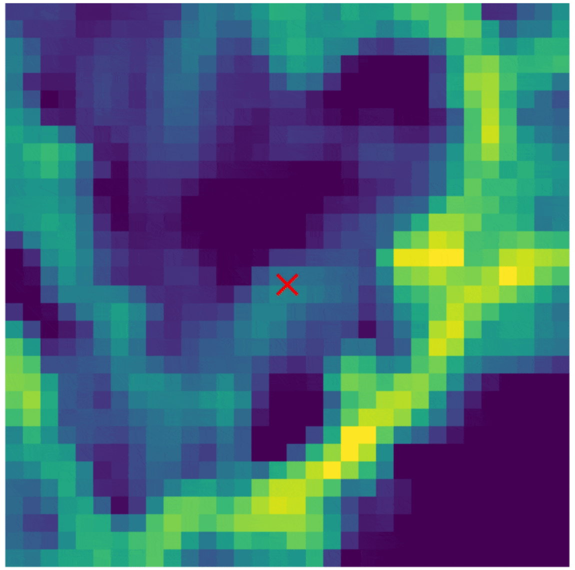


32^3 voxels (density distribution)

Prediction using Machine Learning

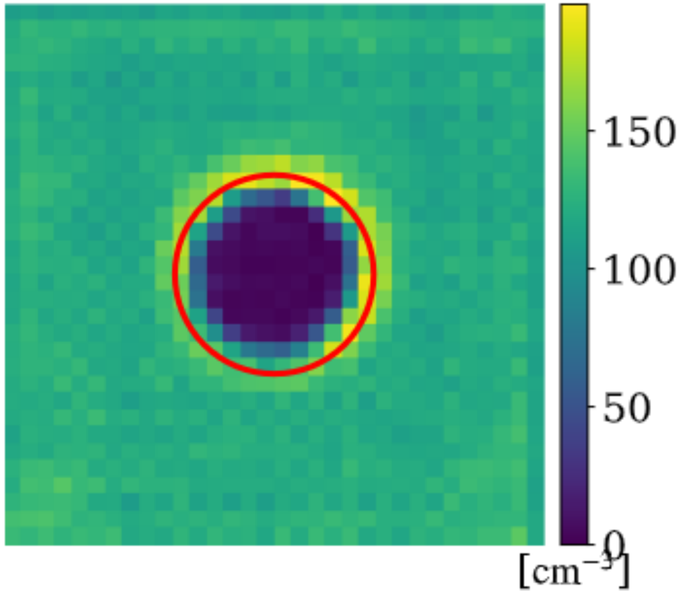


Simulation (t=0.007 Myr)



3D-MIM (t=0.007 Myr)

We confirmed that the model predicts spherical shells in the case of a uniform density

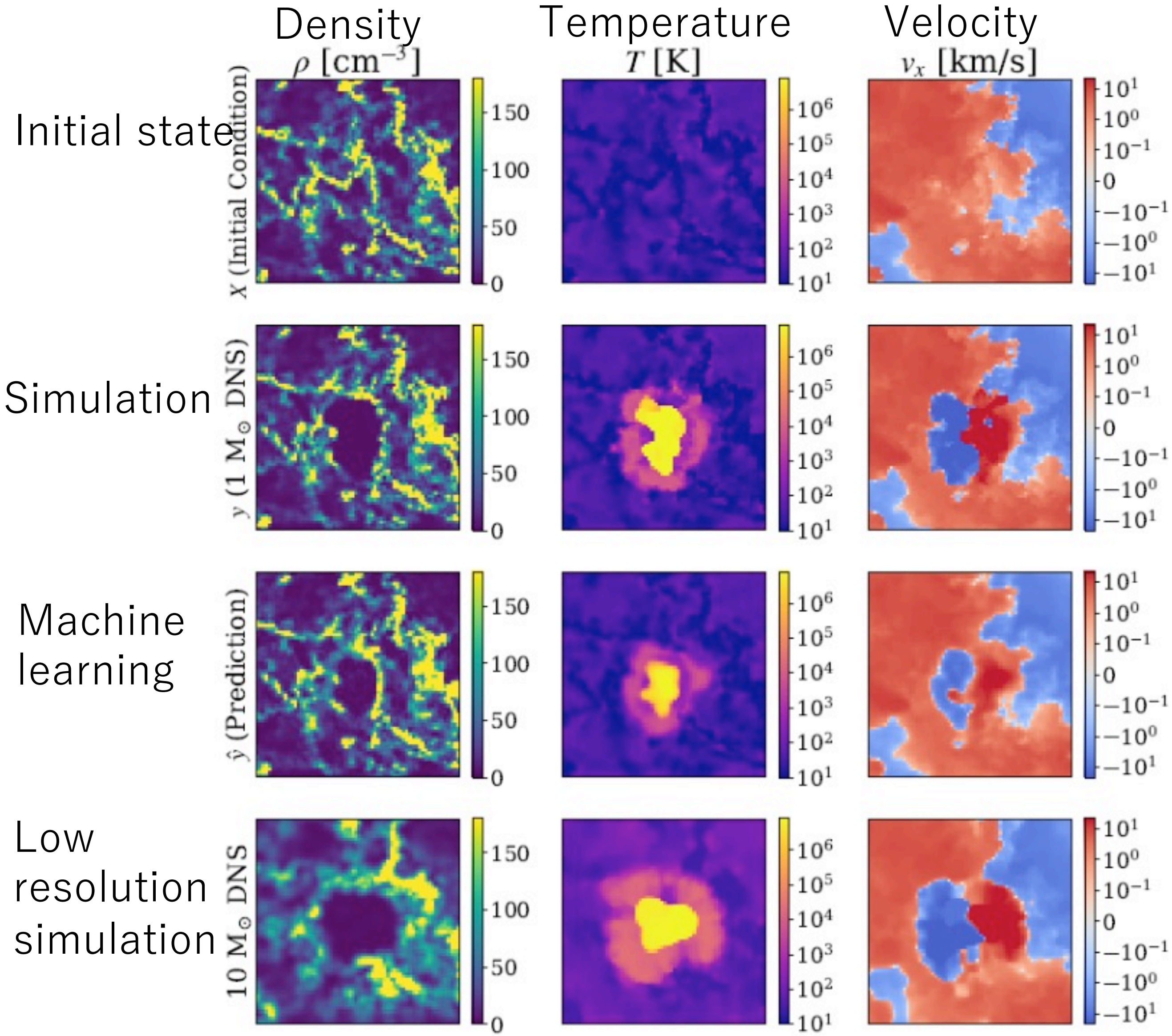


(a) Spherical

)

- Memory In Memory (Wang et al. 2018)
  - Generates 2D video -> We upgraded to 3D
  - Convolutional Neural Networks (CNN) based method
- We also tried U-Net

Temperature and velocity field

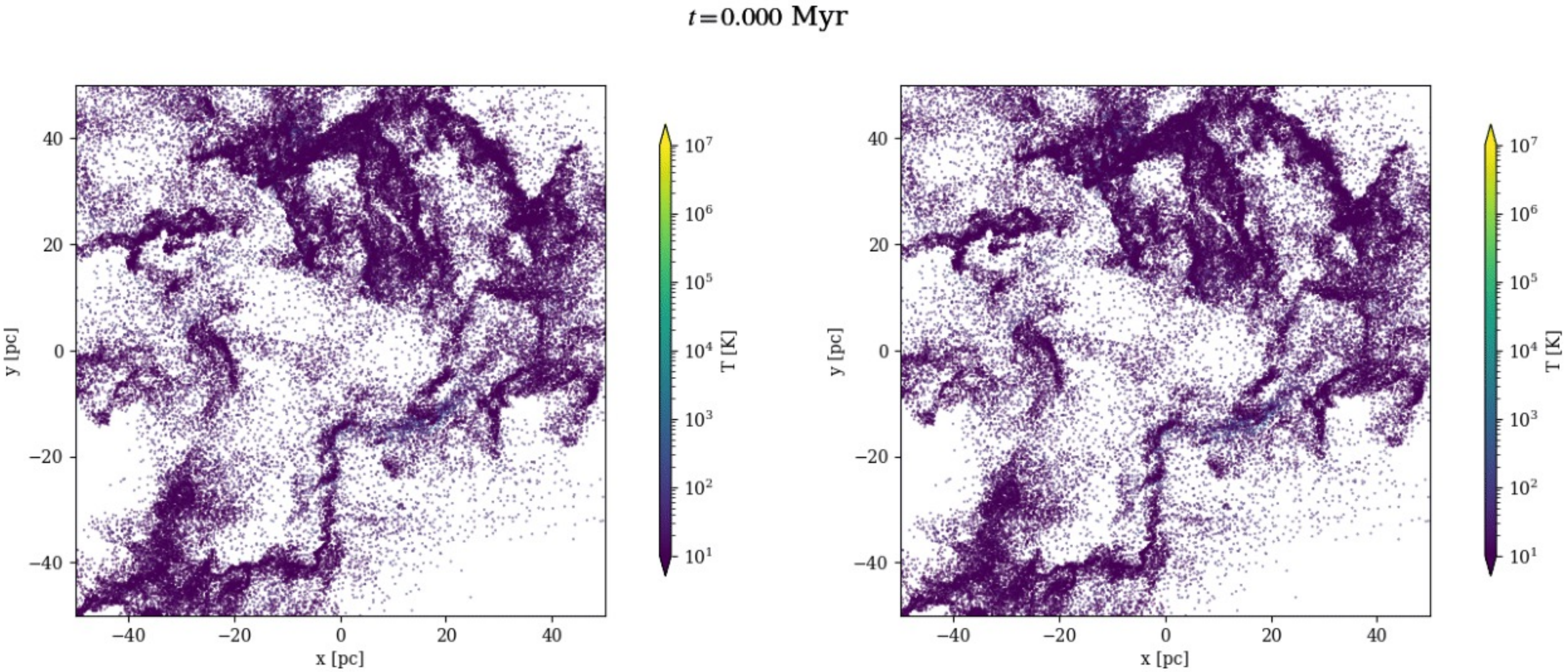


- Training data set is the same
- We developed a model to predict the temperature and velocity distribution as well as density
  - Using U-Net
  - Faster model is required to combine with galaxy simulations using supercomputers
- We checked the energy and momentum conservation
  - Not perfect but better than lower resolution simulations

Hirashima, Fujii et al. (2023)

Stability test

Hirashima et al. (2025)

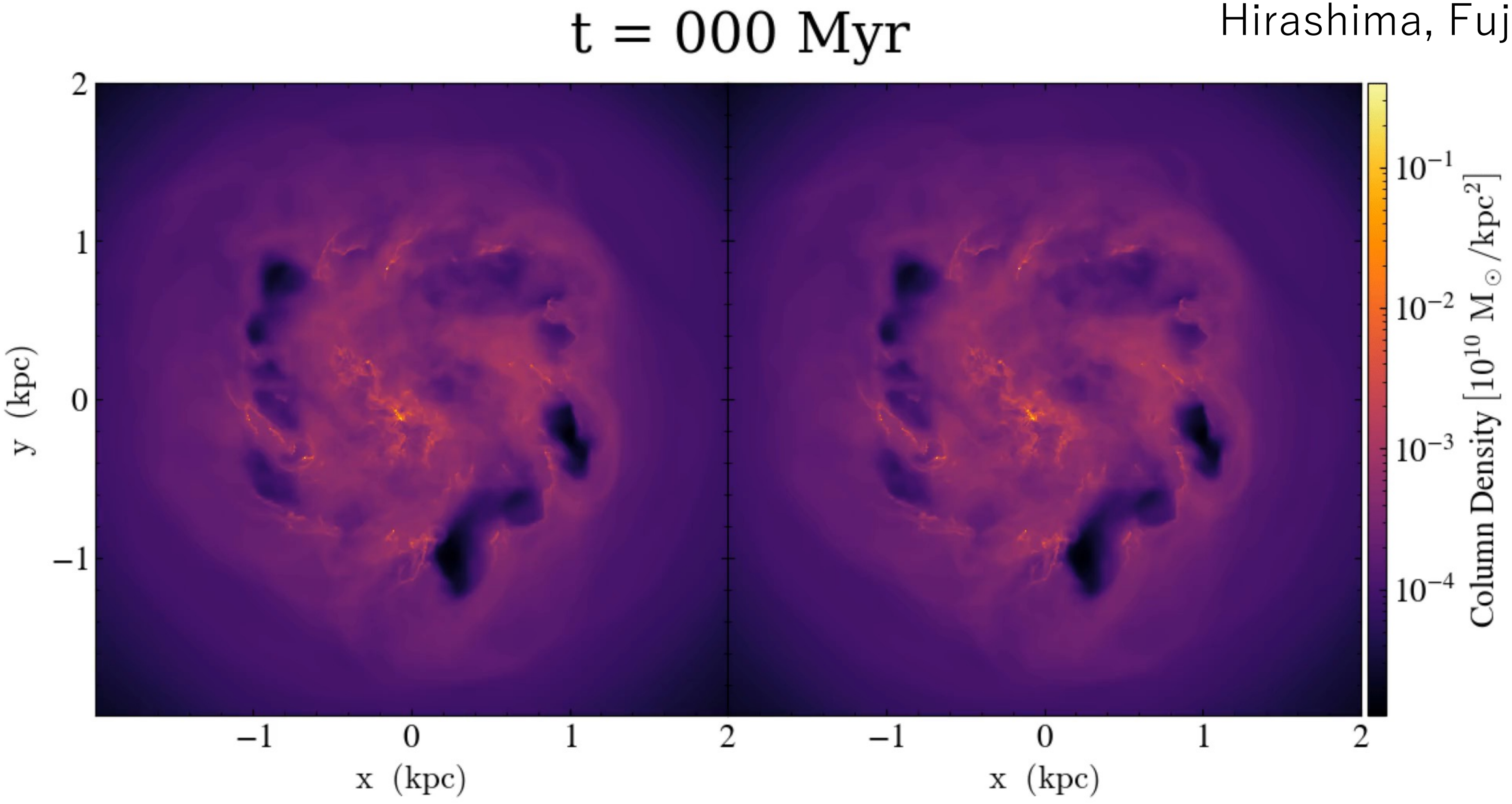


$t = 0.000$ Myr

- After 0.1 Myr, a SN shell suddenly appear
- We confirmed that the SPH simulation stably continued

Combining with galaxy simulations

Hirashima, Fujii et al. (2025)

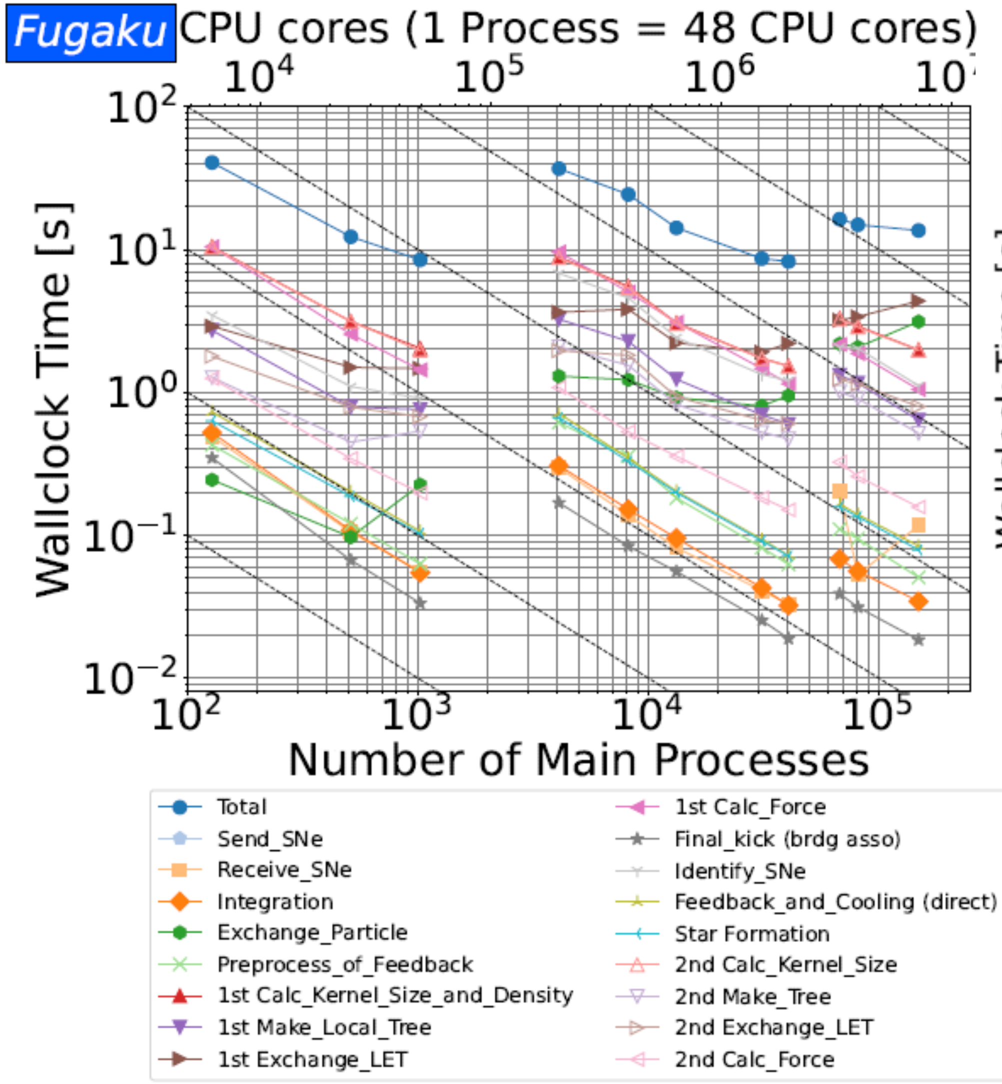


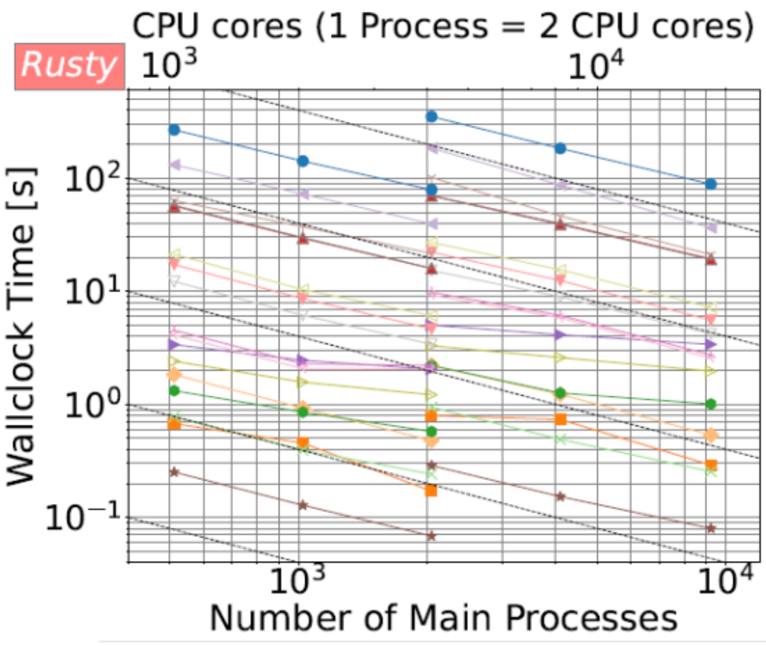
Pure simulation

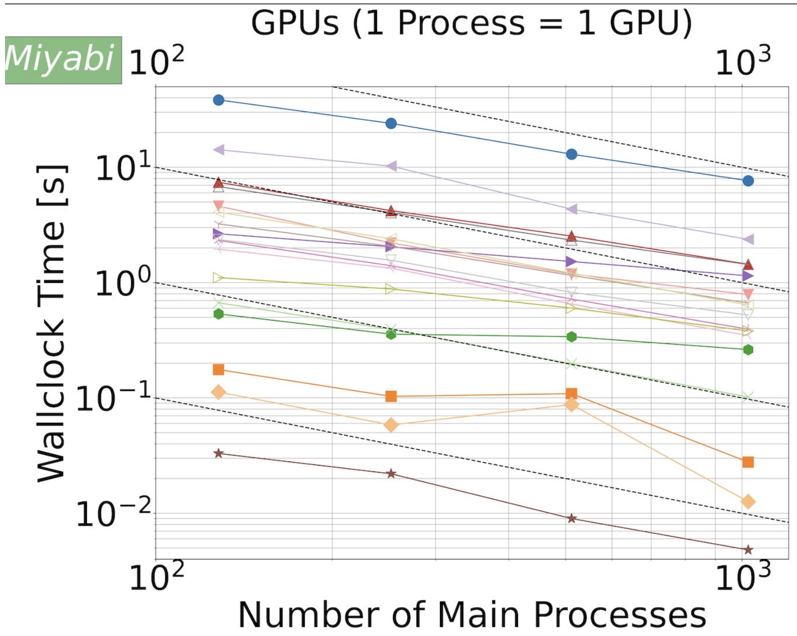
With machine learning

Scalability

Hirashima et al. (2025, SC25, in press)







- Good scaling with both CPU and GPU clusters
- MW size simulation is running on Fugaku!

Summary

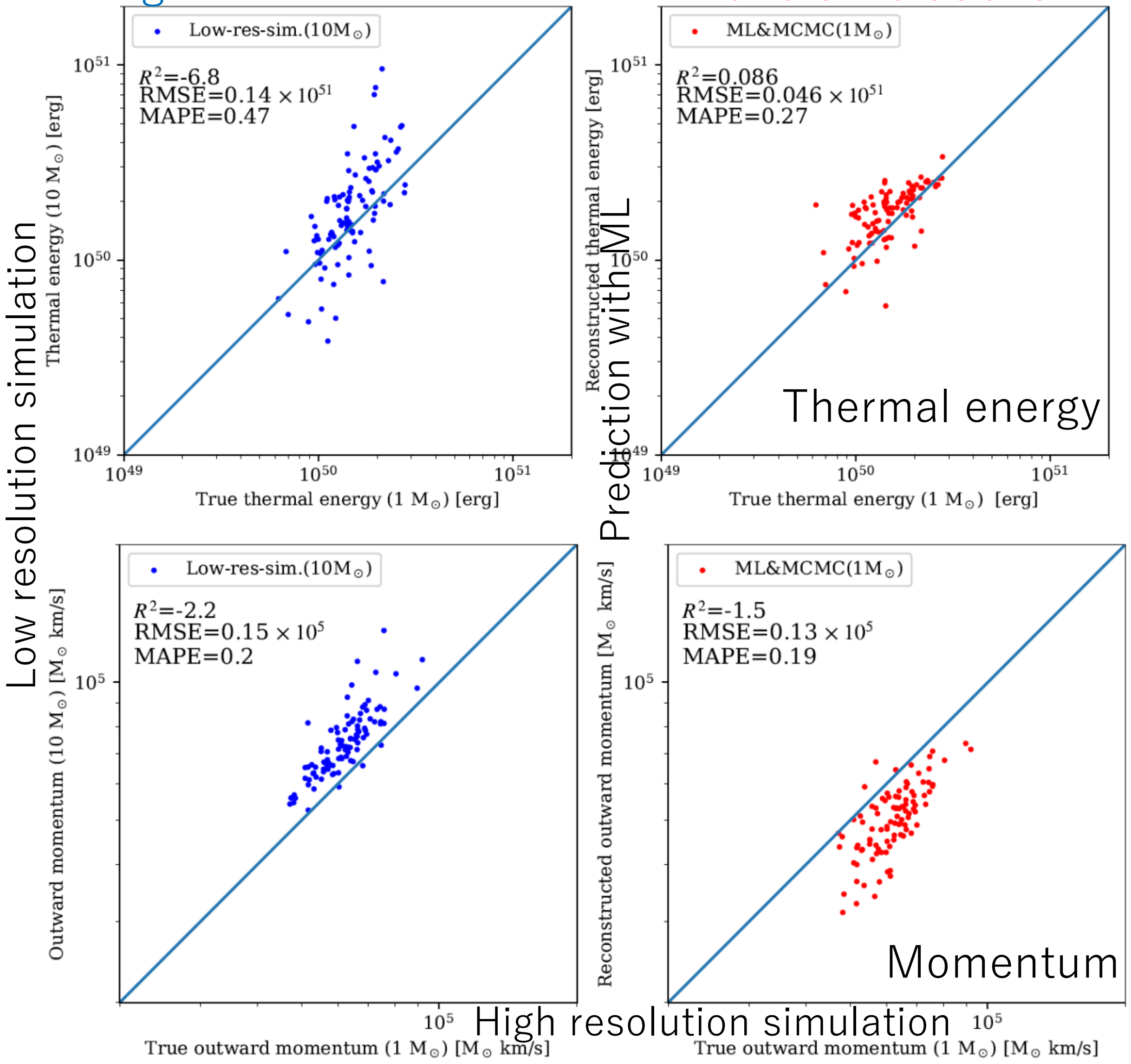
- So far, 10^9 particles per simulation is a maximum N we can use for galaxy simulations
- Small timesteps from small regions becomes a bottleneck for higher resolution simulations of galaxy simulations
  - Without solving this problem, we cannot reach a higher resolution even with future supercomputers
- We have developed a new simulation method with machine learning
  - So far, it looks working well, but we need more detailed evaluations
  - Good scaling with Fugaku, Rusty (CPU cluster) and Miyabi (GPU cluster)
- We are performing a simulation of a MW model using Fugaku

Accuracy

- Accuracy tests
  - Prediction using machine learning
  - Data convert from grid to particle data
- Evaluation
  - Energy and momentum conservation
  - Comparison with lower resolution simulations
- Next step
  - Evaluating global indicators such as star formation rate

Comparison between high and low resolutions

Comparison between ML and simulations



近年の天文の流体計算のAIによる予測の例

乱流の予測が多い。温度(内部エネルギー)を予測したものはない。

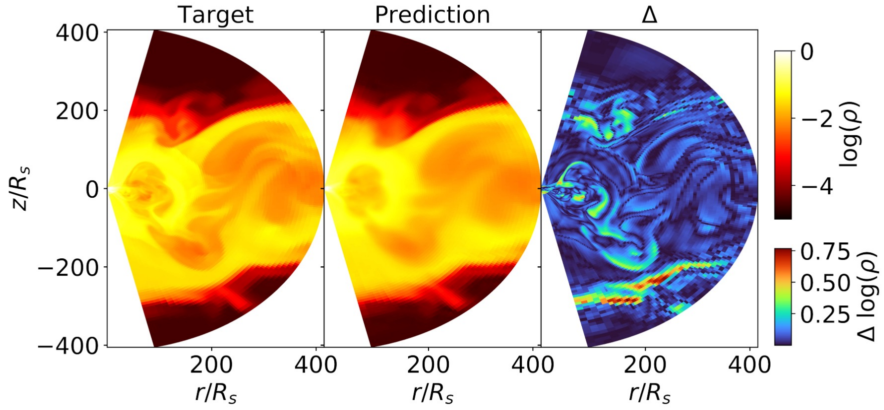


Figure 9. Density predictions by the multi-sim direct model, compared with the simulation PNST1 at $t = 172035M$.

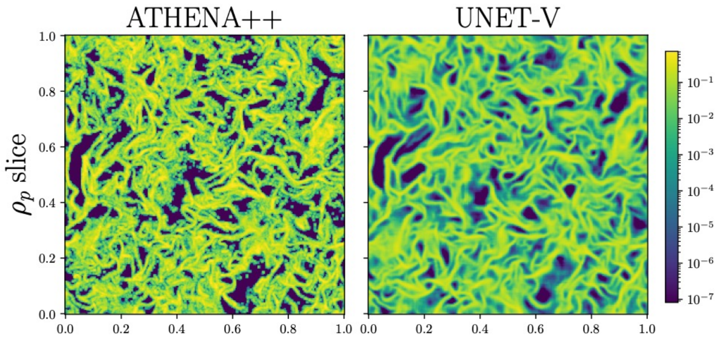
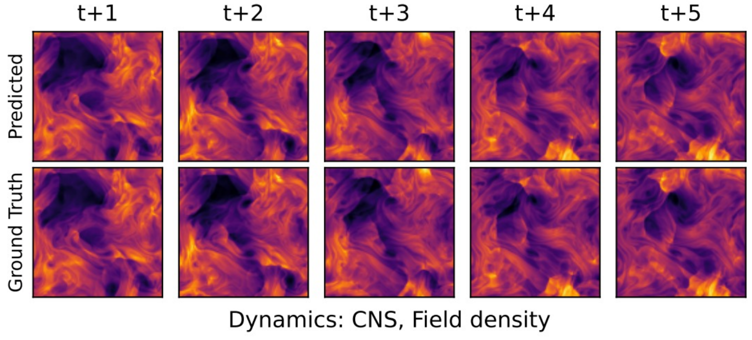


Figure 2. Particle density field slice ρ_p from ATHENA++ (left), UNET-V (center, a netwoparticles and gas) and UNET-R (right, a network trained on the absolute particle velocity), for a typreement between the predicted structures and the ground truth, though the network outputs are visuaa.

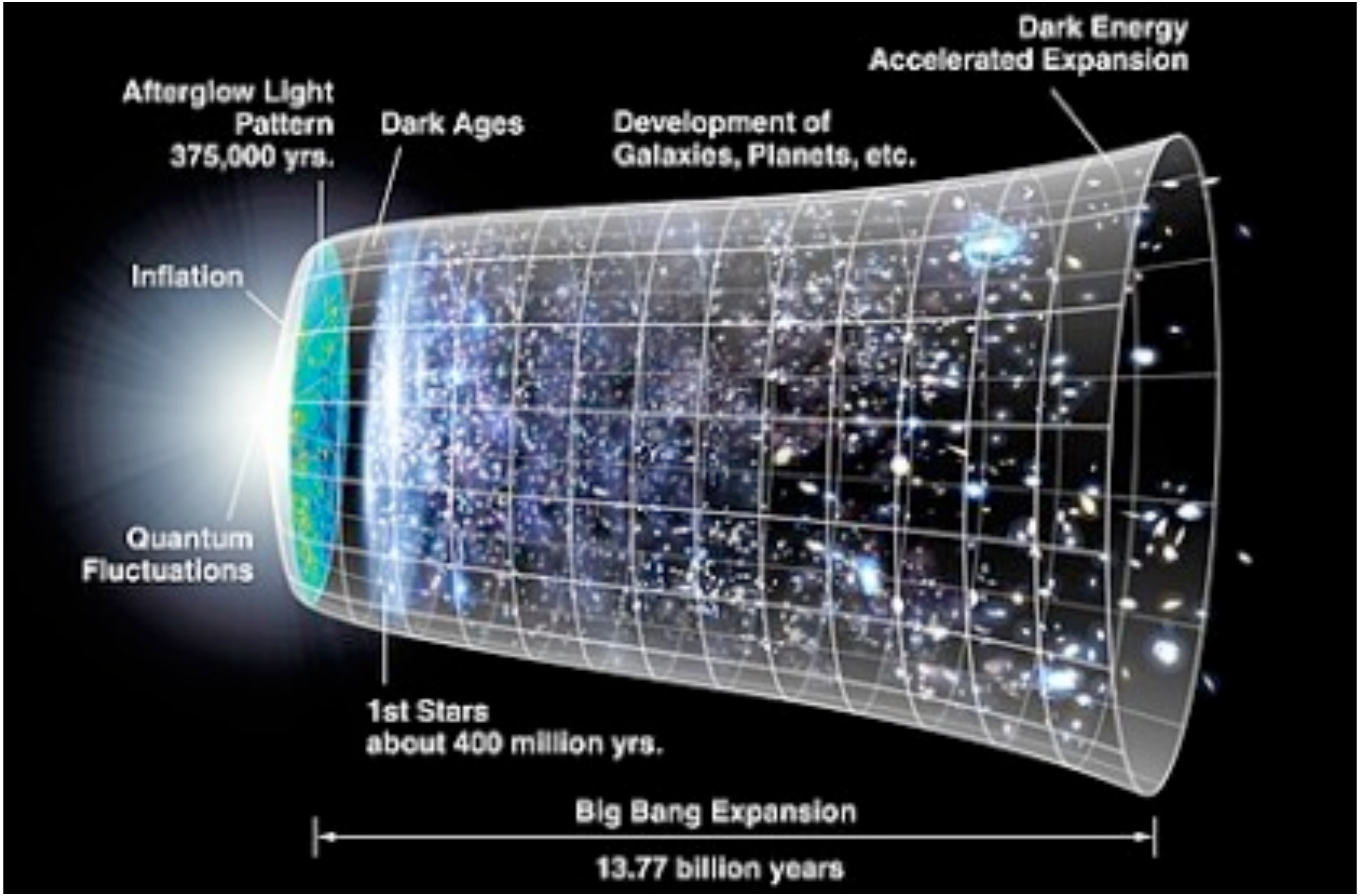


論文	Dataset	モデル	予測したもの	学習データを作ったシミュレーション
Duarte et al. 2022	ブラックホール周りの降着円盤	2D-Unet	密度	PLUTE (mesh)*
Chan et al. 2022	乱流中のダストの分布と運動	3D-Unet	密度と速度	Athena++ (mesh)
McCabe et al. 2023	乱流シミュレーション	2D-ViT	密度, 圧力, 2次元速度	PDE-Bench

*Mignone et al. 2009, 2012, ver. 4.4 (2021)

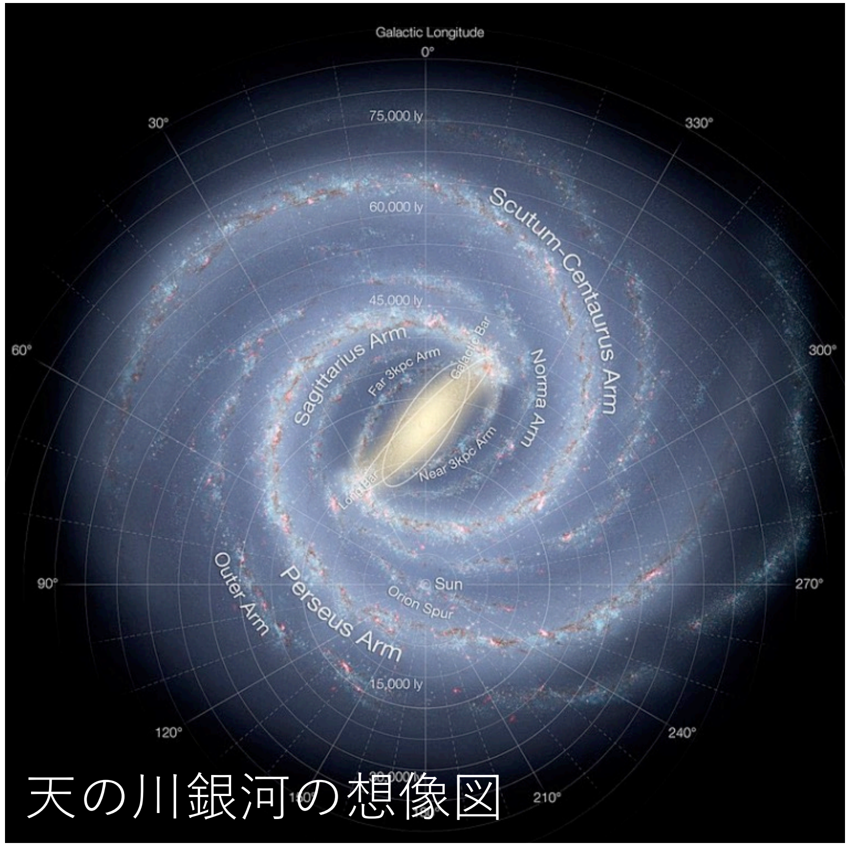
予備スライド

宇宙の構造形成


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

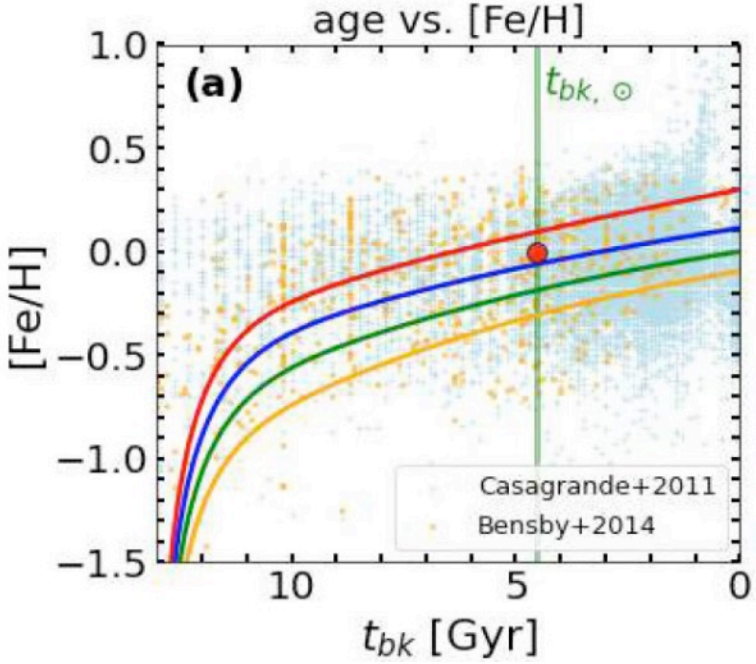
天の川銀河の進化史の解明

- 天の川銀河＝我々の住む銀河
- 円盤の中にいるため、横からしか見ることができない
- 観測できる星の位置、速度、年齢、元素組成などから、過去の進化を推測する

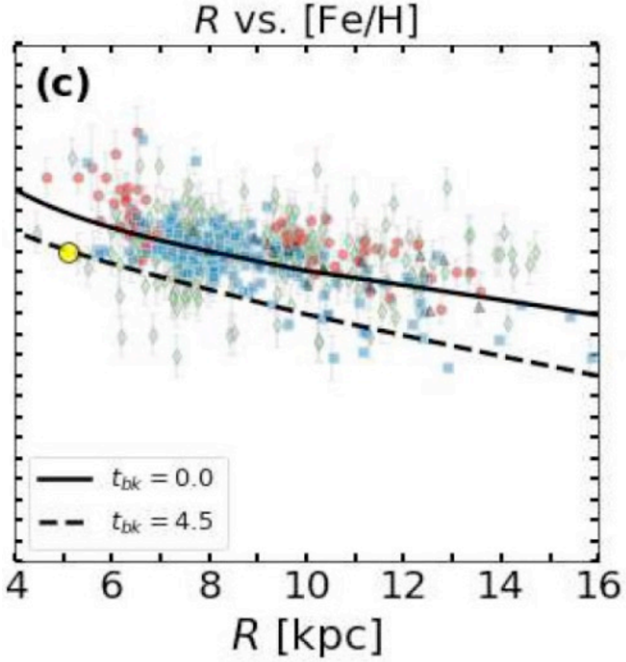


天の川銀河の想像図

星の年齢と含まれる
鉄の割合([Fe/H])



銀河中心からの距離と
含まれる鉄の割合([Fe/H])



鉄の割合は物質循環のサイクルが何回回ったかの指標